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An Overview of the Recent Wideband Transcutaneous Wireless Communication Techniques

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***Abstract* - Neuroprosthetic devices such as cochlear and retinal implants need to deliver a large volume of data from external sensors into the body, while invasive brain-computer interfaces need to deliver sizeable amounts of data from the central nervous system to target devices outside of the body. Nonetheless, the skin should remain intact. This paper reviews some of the latest techniques to establish wideband wireless communication links across the skin.**

I. Introduction

Transcutaneous data telemetry is a key function in a group of implantable medical devices, known as *neuro-prostheses*, which substitute sensory or motor modalities that are lost due to injuries or diseases [1]. Eliminating hardwired interconnects in these devices to keep the skin intact is necessary to improve the patient comfort and safety against the risks of infection and mechanical damage. Cochlear implants and visual prostheses need a large volume of data from external artificial sensors to interface with a large number of neurons and produce sensations with high enough quality and resolution that can support desired functions such as speech recognition or functional vision [1], [2]. The flow of information in these neuroprosthetic devices is mainly from outside (e.g. an artificial sensor) into the body and eventually to the central nervous system (CNS). This direction of dataflow is often referred to as the *forward telemetry* or *downlink*. The same neuroprosthetic devices often need to inform the external processing components of the system about the neuronal response immediately after stimulation to properly adjust the stimulation parameters [3]. There is also information about the internal operation of the implant that needs to be sent out to close feedback loops or ensure safe operation of the system [4]. This direction of dataflow that sends information from inside towards out of the body is often referred to as *back telemetry* or *uplink*. The data volume and required bandwidth for the downlink is much higher than uplink in the aforementioned applications.

There is another group of neuroprosthetic devices, known as invasive brain-computer interfaces (iBCI), that collect a massive amount of neural data from the CNS or peripheral nervous system (PNS) and send it across the skin to the external components of the system to be further processed in order to infer the patients' intentions [5]-[8]. The processed information can then be used to access computers, drive wheelchairs, or control the users' environments or motorized prosthetic limbs. The same neuroprosthetic devices need a transcutaneous downlink to adjust implantable device parameters such as gain and bandwidth, and possibly add sensory feedback through neural stimulation for better control of the movements and for a richer and more natural experience of the prosthetic limb [9]. The data volume and necessary bandwidth for the downlink is much lower in iBCI applications than the uplink.

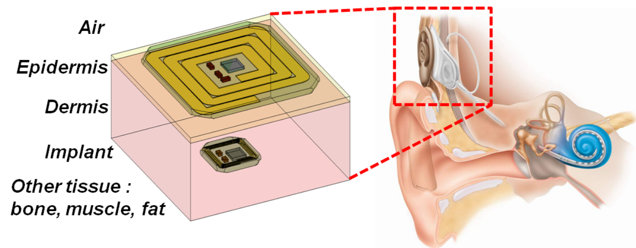

Fig. 1. Complex tissue environment has a significant impact on the design of optimal coils and antennas for transcutaneous communications [11].

There are several common design challenges among both categories of transcutaneous wireless link applications, which relate to the extremely limited space and power availability in the human body. There is also significant electromagnetic (EM) field absorption in tissue, stemming from its predominantly water content and conductive volume conductor that increases exponentially with frequency [10]. Hence, the higher the carrier frequency, the lower the EM field penetrates in the tissue and the more loss it experiences, which turns into heat. In neuroprostheses, high bandwidth needs to be achieved at the lowest possible carrier frequencies. In other words, the information content of every carrier cycle in wideband transcutaneous wireless links often needs to be much higher than similar free space wireless communications. Yet another challenge that also relates to the tissue volume conductor is the effects of surrounding environment on the electrical characteristics of the coils and antennas that establish the transcutaneous wireless link. Fig. 1 shows a simplified view of an implanted and an external coil in homogeneous tissue environment. These coils and antennas need to be specifically designed and optimized considering the tissue environment [11]-[14].

In this paper different types of transcutaneous wireless links have been described along with some of the most recent solutions that researchers have devised to address the above common challenges.

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II. TRANSCUTANEOUS COMMUNICATION METHODS

A. Reactive vs. Radiative

The area around any radio frequency transmitter can be divided into three regions: near field ($0 \sim \lambda$), transition zone ($\lambda \sim 2\lambda$), and far field ($2\lambda \sim \infty$), where λ is the carrier signal wavelength. Considering limitations in the choice of carrier frequencies for transcutaneous communications (< 1 GHz, λ > 30 cm) and the proximity of the transmitter (Tx) and receiver (Rx) in these applications, it can be concluded that almost all transcutaneous communications are within near field. In this region the field decays with distance, d, very rapidly at a rate of $1/d^3$ and the relationship between electric and magnetic fields are quite complicated [15], [16].

When the coils and antennas are much smaller than λ, interactions between coils and antennas in the near field are further divided into reactive ($0 \sim \lambda/2\pi$) and radiative ($\lambda/2\pi \sim \lambda$) regions. In the reactive region, energy is stored in the field very close to the antenna and it can return back to the antenna in a regenerative fashion without radiation if it is not absorbed by the Rx antenna or the surrounding medium. Interactions between the Tx and Rx antennas in this region are modeled and analyzed in the form of loosely coupled coils that constitute a transformer or parallel plate capacitors. Coils' mutual coupling in this case is highly dependent on their geometries, relative distance, and orientation. The coils' self resonance frequency (SRF) often limits the choice of carrier frequencies to 0.1 ~ 50 MHz. Since tissue is quite transparent in this frequency range, the loss mechanisms are mainly due to the coils' parasitic components [13].

In the radiative near field region, there is only radiant energy and no storage, although the relationship between magnetic and electric field components is quite different from the far field. Various Industrial-Scientific-Medical (ISM) bands have been employed in this region for body area networks (BAN) or for recording from freely behaving animals when it is possible to keep the antenna outside the subject's body [8], [17]. However, for fully implanted devices, the band that is mostly used in the radiative near field region is the Medical Implant Communication Service (MICS), which uses frequencies between 402 and 405 MHz with less than 300 kHz bandwidth per channel. The main advantage of the MICS, which offers a range of up to 2 m, over inductive coupling is eliminating the need for the external transceiver to touch the patient's skin. However, the highest reported data rates of 800 kBps are neither sufficient for neuroprosthetic devices nor iBCIs [18].

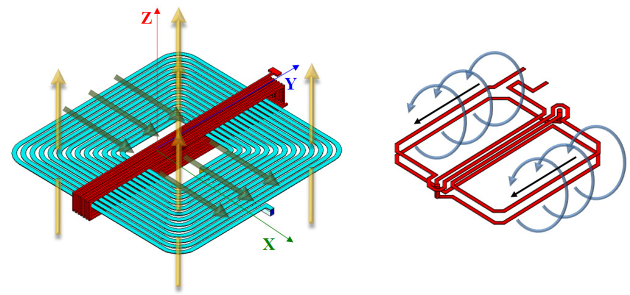
B. Single Carrier vs. Multi-Carrier

Unlike pacemakers, which can run for years on a primary battery, the power consumption of most neuroprosthetic devices is too high for primary or even rechargeable batteries. The high power consumption is mainly due to large number of stimulation sites and high stimulus rates, regardless of the internal electronics' power consumption. Extreme space limitation at the site of implantation is yet another reason that has so far rendered battery powered cochlear or retinal implants unfeasible. iBCIs which are expected to be implanted under the scalp also face the same limitation. These implantable devices need to be powered via a transcutaneous inductive link, and once the power transfer link is in place, it is quite reasonable to use the same power carrier signal for downlink data transfer [19]-[22]. In some cases the same carrier has also been used for the uplink through impedance modulation, also known as *Load Shift Keying* (LSK) [21]. This is the same mechanism that has been implemented in radio frequency identification (RFID) systems for not only powering the passive RFID tags but also establishing a bidirectional data link between the tag and the reader [23], [24].

The main advantage of using a single carrier for both power and data transmission is the relatively robust coupling between power coils, which can lead to more reliable data transfer. Another advantage is saving space by using the power coils for multiple purposes. On the down side, modulating the power carrier in any form or direction complicates the power Tx circuitry and reduces the power transmission efficiency, which eventually leads to more heat dissipation for the same amount of power delivered to the implant. A more important issue is the low power carrier frequency, which has a strict safety limitation because of its large amplitude. This can further limit the data transfer bandwidth in either direction to levels that are not sufficient for advanced neuroprosthetic devices.

As a result, the use of two or three carrier signals for power, downlink, and uplink has been proposed with each carrier having its own pair of coils or antennas in order to decouple the data transfer link bandwidth from the power transmission efficiency [25]-[27]. Aside from the size overhead, the use of multiple carrier signals within a space as small as an implant introduces new challenges, the most important of which is the strong power carrier interference with much weaker data carriers. Several researchers have offered solutions such as using orthogonal symmetrical coils [14], [25], coaxial coils with differential phase shift keying (DPSK) [26], [27], and shifted coplanar coils with offset quadrature phase-shift keying (OQPSK) [28]. Nonetheless, the most effective way to reduce interference is to separate out the carrier frequencies and take advantage of the band-pass filtering effect of the LC-tanks at resonance.

In the case of the orthogonal coils, a pair of planar spiral coils (PSC), shown in Fig. 2a, which geometries have been optimized based on the power carrier frequency and tissue volume conductor, are used for transcutaneous power transfer [11]. A second pair of coils is wound symmetrically across the PSC pair to establish the data transfer link. Orthogonal orientation and symmetry lowers the undesired mutual coupling between the two pairs without affecting the desired coupling within the pairs [14]. This will minimize the power carrier interference on the data carrier, which can benefit from any robust modulation technique. There are also other geometries, such as figure-8 shown in Fig. 2b,



(a) (b)

Fig. 2. (a) A pair of planar spiral coils (PSC) with relatively strong coupling can be used for transcutaneous power transfer. A second pair of coils can be wound symmetrically across the PSC pair for data transfer such that their fluxes are orthogonal and minimize the power carrier interference when the coils are perfectly aligned. (b) It is possible to use other symmetrical geometries, such as figure-8 coils, to attenuate the effects of external common mode magnetic fields [14], [25].

which can attenuate the effects of external common mode magnetic fields and reduce cross coupling from power coils.

C. Carrier Based vs. Pulse Based

Designers have devised a wide variety of modulation techniques for transcutaneous data telemetry, many of which are variations of the same methods used in free space communications. Attractive features in modulation methods chosen for this application are robustness against electromagnetic interference and coil misalignments, simple and low power modulation and demodulation circuitry, and high information content per carrier cycle (data rate to carrier frequency ratio, DRCF). For instance, in a method known as *phase-coherent Frequency Shift Keying* (pcFSK), every bit "1" is transmitted by a carrier cycle at f_1 and every bit "0" is sent by two carrier cycles at $f_0 = 2f_1$ [29]-[31]. The result is an FSK carrier with high DRCF ratio, while maintaining the same bit period to facilitate Tx-Rx synchronization. On the Tx side, a multi-resonant class-E converter can switch the carrier frequency based on the serial data bit stream at zero crossings [32]. The demodulator circuits on the Rx side detects incoming data bits by directly measuring the duration of each received FSK carrier cycle, and also generates a constant frequency clock, which can be used to sample the recovered data bits [29].

Even though modulating a carrier signal provides a robust mean to transfer data across the skin barrier, generation of the carrier signal at a power level that ensures sufficient signal to noise ratio (SNR) at the Rx involves consuming a considerable amount of power at the Tx, which is scarce on the implantable side. Therefore, it is better to keep the source of carrier signal outside of the body if at all possible. This implies that carrier based modulation techniques are more suitable for the downlink, and establishing a wideband transcutaneous data link for applications such as iBCIs that have a heavier load for the uplink is more challenging.

One possible solution, which was mentioned earlier, is the LSK. Even though data rates as high as 4 Mb/s have been reported via LSK [33], since this method relies on the power transfer link, its bandwidth is inherently limited for the

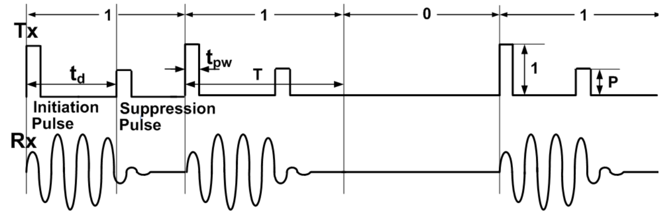


Fig. 3. PHM conceptual waveforms including their key parameters [34].

reasons mentioned in section II.B. Moreover, even though LSK consumes very little power and its implementation is as simple as adding a switch across the Rx power coil [23], it blocks the implant received power for the total period of time that the switch is shorted. While reducing the duty cycle can be helpful down to a certain level, there will still be a considerable reduction in the amount of power that can be delivered to the implant at high uplink data rates.

An alternative solution, recently proposed in [34] and [35], substitutes the carrier signal with a series of sharp and narrow pulses, requiring much less power to generate, which timing and amplitude are carefully selected to reduce the inter-symbol interference (ISI) at the Rx and make it easier to detect the serial data bit stream. This method, which is called *Pulse Harmonic Modulation* (PHM), takes advantage of the residual oscillation in high quality factor (Q) LC-tanks. To transmit each bit "1", the PHM transmitter generates a sharp pulse at the onset of the bit period to initiate an oscillatory response in the Rx high-Q LC-tank, as shown in Fig. 3. A second pulse is then generated with specific amplitude (P<1) and delay (t_D) with respect to the initial pulse that suppresses the oscillation across the Rx LC-tank well before the end of the bit period. No pulses are transmitted for bit "0". This method allows for reaching high data rates without reducing the inductive link quality factor, thus significantly improving the transmission range and selectivity of the data link in rejecting out of band interferes, such as the power carrier.

D. Electromagnetic, Optical, and Body Channel

Even though the majority of the transcutaneous wireless communication links utilize RF EM fields, researchers have begun using optical links for this purpose as well as the human body as the transmission channel to address some of the EM limitations. Optical links have the potential to reach bandwidths well above that of the current RF links, and they do not suffer from power carrier interference [7]. However, lasers and LEDs that can offer such a wide bandwidth are not yet as power efficient as their RF counterparts, and they can be very sensitive to misalignments. Light scattering and absorption in the tissue are two major problems that limit the use of optical links to areas that Tx and Rx are very close or the tissue is transparent such as the cornea, lens, and vitreous humor in retinal implants [36], [37].

Using the human body as the communication channel has been tried in 80's, and gained more attention in recent years [3], [38]. Using lower carrier frequencies within 30~70 MHz results in power saving, and the electrical signal attenuation through the body is less than the EM fields. In this method electrodes are used instead of antennas, which are smaller but not comfortable on the skin. Nonetheless, body channel seems to be a good option when there is a need for communication between two or more implantable devices.

III. Conclusion

Limitations in space, power, and frequency with strict safety requirements impose many challenges on the design of wideband transcutaneous links. Decoupling data carrier from power and leaving its source outside of the body, with careful design of coils and antennas geometries are the solutions offered here to address some of these challenges.

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