Abstract—High efficiency is vital for wireless powering link in biomedical implant application. This paper presents the analysis of the overall efficiency from the viewpoint of whole link and two important factors are elaborated. First, the choice of the optimal power carrier frequency should be tradeoff through the whole link, especially with consideration of power transfer, tissue-induced loss, and human safety, which is seldom highlighted before. Second, resonant coupling as a promising energy transfer method for implantable devices is analyzed and compared with conventional inductive coupling. Some initial results are given and further ongoing research is also included.

I. INTRODUCTION

Currently implantable biomedical devices are of great interest owing to their important and promising roles in modern medical areas. Wireless power delivery to biomedical implants, obviating the need for batteries or wire connections, can reduce the risk of infection and patient discomfort. Given the high power requirement and extreme size constraint, high-efficiency becomes vital for this wireless power transmission link design, especially in applications with harsh requirements such as neuroprostheses [1-2].

Inductive coupling has been a simple and common way to wireless power transmission over short distance for many years [3-4]. Previous studies have investigated it extensively and shown the efficiency of this method could be high but strictly limited to very short distance and drops exponentially with distance. One typical example is near-filed RFID technique, characterized by providing microwatt power with 1-2% efficiency. Specifically in biomedical application, on account of the unfavorable coupling conditions caused by small size, large separation, and even biologic tissue effect in vivo, the efficiency of the transcutaneous wireless power transmission is really poor. Moreover, the allowable tissue exposure to electromagnetic fields and regulated electromagnetic compatibility are also great concerns [5].

Our research aims at transferring milliwatt power to biomedical implants over comparatively long distance with high efficiency. This paper presents the analysis of the overall efficiency of the total powering link, and attempts to set up a figure of merit for parametric evaluation of the wireless power link from the system point of view. Among the factors related to the link efficiency, two key considerations are focused. One is the choice of power carrier frequency considering the environmental human tissue effect, and the other is wireless resonant coupling transfer inspired by the MIT’s work [6-8].

II. OVERALL LINK EFFICIENCY

The structure of a typical wireless powering link for biomedical implants is shown in Fig. 1, which can be grouped into three main parts: external power transmitting, transcutaneous power transfer from the outside body into the implanted device, and in-vivo power receiving and management. The above each part should be designed elaborately in order to obtain overall high efficiency. Additionally, the metrics of the wireless powering link in different applications are so diverse. The design goal herein is how to maximize the efficiency, within the size and spacing restrictions, to meet the power requirement, the displacement tolerance, and also the tissue safety standard [9] and Federal Communications Commission (FCC) regulations at the same time [10].

The bottle neck of the whole link efficiency is the transcutaneous power transfer part so far. The feature of our research different with previous ones is to decompose this problem into two aspects. One is the design of inductive link considering the coil geometry, placement and misalignment. The other is the choice of the optimal power carrier frequency taking maximum power transfer, environmental biological tissue absorption and tissue safety into consideration, which is seldom highlighted and detailed before.

Accordingly, four factors determining the link efficiency are summarized as follows: 1) power driver efficiency, mainly referring to power amplifier, 2) power carrier frequency, 3) transcutaneous energy transfer like inductive coupling efficiency, and 4) power conversion efficiency including limiter, rectifier and voltage regulator blocks.

III. OPTIMAL POWER CARRIER FREQUENCY

The choice of power carrier frequency is actually complicated if we scrutinize it from the link efficiency perspective since it is related to each part of the whole link and contains many tradeoffs. For example, coils generally have better Q at high frequency, while large operating frequency will lead to more sensitivity to parasitic, increased power requirement in the driver, and difficult implementation of CMOS rectifier.
However, low carrier frequency below 20MHz for power transfer is the common belief simply due to the tissue-induced loss and human safety [1-4]. As pointed out in the recent work [6], most analyses in previous bibliography assume that lower frequency would yield better transfer efficiency because tissue absorption increases with frequency. Based on this assumption, the quasi-static approximation to Maxwell’s equations is used and solving the diffusion equation tells that electromagnetic fields decay exponentially inside tissue. But in fact, the tissue should be modeled as the low loss dielectric in which displacement current is significant and full wave analysis of the Helmholtz equation reveals that the penetration depth is asymptotically independent of frequency at high frequency. As received power is proportional to the frequency, higher carrier frequency is seemingly better. The conclusion in [6] is the optimal frequency lies in the GHz-range for mm-sized transmit antenna and shifts to the sub-GHz range for cm-sized transmit antenna.

Unfortunately, the above conclusion is difficult to validate through simulation or experiment. The coil geometry and the tissue-induced loss, both affecting the choice of optimal power carrier frequency, are coupled together now. The difficulty exists in the decoupling of these two effects. Our original intention is to only consider the tissue-induced loss maximizing the power transfer efficiency at first.

One possible solution is to set up the verification model with the transmitting and receiving coils including the above two effects, and then the tissue effect may be de-embedded through the comparison with and without tissue. This is one of our ongoing jobs presently.

Alternatively, the magnetic Hertzian-dipole is used as the ideal point source to de-embed the effect of geometric sizes of the transmitting and receiving coils, which can also include any near-field effect. The transcutaneous powering link is built up with the commercial software HFSS, shown in Fig. 2. The composition of the spherically layered structure model is listed in Table I and the dielectric properties of the frequency-dependant dissipative human tissue are taken from [11]. The surrounding of the model is set by the radiation boundary (Absorption Boundary Condition) to reduce any reflection effect due to the finite boundary.

![Fig. 1 Block diagram of wireless powering link from the external battery to biomedical implants.](image1)

![Fig. 2 Spherically layered structure model for transcutaneous wireless power transfer.](image2)

### Table 1

<table>
<thead>
<tr>
<th>Spherically Layered Structure Model Setup in HFSS</th>
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<tr>
<td>Air box Absorption boundary condition</td>
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<tr>
<td>Sphere origin</td>
</tr>
<tr>
<td>Skin (dry)</td>
</tr>
<tr>
<td>Fat</td>
</tr>
<tr>
<td>Magnetic Hertzian Dipole excitation location</td>
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<tr>
<td>Lₚ·dl normal (loop Surface)</td>
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<td>Radius of surrounding sphere</td>
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Besides the power transfer efficiency and tissue-induced loss, the safety of human body tissue is also a strong concern since the absorption of electromagnetic energy is a function of frequency. Electromagnetic dosimetry shows that there exists resonance characteristic of the whole body SAR (Specific Absorption Rate) behavior of humans at intermediate frequencies, and the localized SAR has a great dependence on the permittivity values of human body part and diverse exposure conditions [5].

IV. WIRELESS RESONANT COUPLING

Research interest in wireless powering technology has resurfaced recently, ignited by the MIT’s demonstration which features the effectiveness in meter-order range based on the “strongly coupled magnetic resonances” [7-8]. Comparatively, existing inductive-coupling-based power transfer limited to transmission distance of about a centimeter, or near-field RFID technique extends the range by sacrificing efficiency. And also traditional far-field radiative power transfer suffers from the low efficiency. Therefore, it is necessary to appreciate the difference between this mid-range technology and the well-known close-range inductive coupling.

The physics behind this new technique is originally explained using the coupled-mode theory, which is too abstract for practical engineering evaluation. Here we try to present a circuit-theory-based analysis to bridge the gap.

Actually, the resonant coupling seems not a novel idea [4, 12]. The maxim power transfer efficiency between two coils in Fig. 4 (a) can be obtained at resonance as

$$\eta = \frac{k^2 Q_p Q_s}{1 + (1 + k^2 Q_p Q_s)^{1/2}}$$  \hspace{1cm} (1)

where $\eta$ is the efficiency of the wireless powering link, $k$ is the coupling coefficient between coils. $Q_p$ and $Q_s$ are the quality factors of primary and secondary coils respectively. Obviously, the bigger $k$ and $Q$, the higher efficiency. In real applications, the $Q$ is loaded by the source or load resistance, so the efficiency mainly depends on the $k$, which decreases monotonically with the distance between the coils.

For the four-coil system proposed by MIT, shown in Fig. 4 (b), the voltage transmission function can also be derived through the KVL equations, which can be written as (2) equivalently if we model the total link as a two-port network.

$$S_{21} = \frac{V_{load}}{V_{source}} \left( \frac{R_{source}}{R_{Load}} \right)^{1/2}$$  \hspace{1cm} (2)

To simply the derivation, the following assumptions are made. $Q_1 = Q_s = Q_l$ , $Q_2 = Q_s = Q_c$ , $k_{12} = k_{34} = k_{c}$ , $k_{23} = k_{lc}$ , $R_1 << R_{source}$ , $R_4 << R_{load}$ , and the uncoupled resonant frequency of each coil is $\omega_0$. Then the maximum efficiency can be derived and simplified to

$$\eta \leq \frac{k_{23}^2 Q_2 Q_3}{1 + k_{23}^2 Q_2 Q_3}$$  \hspace{1cm} (3)

where $k_{23}^2 Q_2 Q_3$ is defined as the critic factor. Actually, this result is same to (1) in nature.

Observed from (3), the maximum link efficiency is mainly dependent on the critic factor. For relatively large distance between transmitting and receiving, the coupling coefficient is small, while the efficiency can still be high as long as the critic factor is kept high. Hence, the low coupling $k_{23}$ between coil 2 and 3, due to the comparatively large spacing.

Fig. 4 Equivalent circuit models of the wireless powering link for (a) original inductive coupling structure and (b) newly proposed 4-coil structure.
is compensated by high $Q_2$ and $Q_3$; while the low $Q$ of loop 1 and 4, caused by the source and load resistance, is compensated by the high coupling $k_{12}$ and $k_{34}$, respectively [13]. This can be the intuitive explanation.

As for the application of this new technique to biomedical implants, it is still far away due to size constraint and tissue safety. First, more rigorous theoretical analysis needs to be given as a design guideline. Second, further exploration is needed for practical implementation. Two improvements are under investigation. One is to employ the planar structure instead of 3-D coil, and the other is to use the impedance transformation concept for close loop-to-coil coupling to simply the four-coil system.

V. CONCLUSIONS AND FUTURE WORK

Wireless power transmission from outside of human body into the implanted device in-vivo is research focus nowadays owing to its valuable and potential applications. The efficiency is vital to this wireless powering link, which directly means extended battery life and more flexible placement of the external source, and even relieved tissue exposure by electromagnetic fields. So the analysis of the overall efficiency from the viewpoint of whole wireless powering link is of great value.

To obtain the overall high efficiency, each part of the link should be optimized carefully and the transcutaneous energy transfer part is found to be the bottle neck currently. To make a breakthrough, two critical problems should be solved in our research.

The first point is the optimal frequency for the transcutaneous energy transfer. Actually, the choice of frequency is affected through the whole link. Even for transcutaneous energy transfer specifically, it contains two aspects, that is, the transcutaneous efficiency and inductive coupling efficiency. The decomposition of these two aspects is not highlighted before and the common belief is using low frequency below 20MHz.

Secondly, resonant coupling, as an innovative idea for energy transfer, inspired us to investigate its feasibility for biomedical implant application. The mechanism behind this technology needs to be scrutinized further and the practical implementation for implantable devices needs to be explored creatively.

In summary, within the size and placement limitation, the high-efficiency-oriented wireless powering link should meet the required output power, displacement and load tolerance, component variation, human safety and FCC regulations at the same time. Taken the complexity of the problem into account, a figure-of-merit of the link is desired to set up for system evaluation and theoretical guideline should be given for system design and optimization.

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