Battery lifetime modelling for a 2.45GHz cochlear implant application

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ABSTRACT
This paper proposes a high level model for transmission losses between a miniaturized emitter and an implanted receiver for cochlear implant application. According to these losses, the required emitted power is computed and the battery lifetime of the emitter is estimated.

The proposed study is based on wave propagation theory confronted with electromagnetic simulations. Electrical simulations are performed on the emission power amplifier which is the critical block in terms of power consumption.

Keywords
Biomedical implant, ISM band, power consumption, battery lifetime.

1. INTRODUCTION
Reducing system's power consumption has been a major concern for the semiconductor industry in the last years, and this is particularly true for biomedical chip in order to improve the comfort of implanted patients. Thus, taking into account the consumption of such integrated circuits at an early stage of design is required. To do so, the total consumption of the emitter has to be modelled at system level and the losses in the transmission channel have to be taken into account. Indeed, depending on the receiver sensitivity, the power delivered by the emitter's antenna can be adapted in order to optimize the battery lifetime.

In the case of cochlear implants, the propagation channel consists of a stack of skin, cartilage, fat and bone.

The available frequency ISM (Industrial, Scientific and Medical) bands are 40.65MHz, 433MHz, 900MHz, 2.45GHz and 5.7GHz [1]. It can be shown that the attenuation in the channel is proportional to the frequency and the optimal antenna size is inversely proportional to the frequency. In our case, as there is limited space available for the antenna, the maximal size is fixed to $5x8mm^2$ which means that the more the frequency increases the more the efficiency decreases [2].

The frequency that we chose is the 2.4-2.48 band, which provides a good tradeof between the size of the antenna and the losses in the transmission channel. The maximal emission power allowed in this frequency band is 10dBm [1] however, with battery energy of around 100mAh [3], this power has to be reduced to allow reaching a lifetime of around 1 week.

In this paper, we first propose an analytical modelling of the losses in the channel accounting for the different propagation mediums and we will deduce the power needed from the emitter to reach the receiver sensitivity. Then, we will propose a high level consumption model for the emitter amplifier depending on the efficiency. This model is extracted from SPICE simulations.

Finally, we will study how variations on the propagation channel and process corners affect the total consumption and we will show how the model can be implemented.

2. COMMUNICATION FOR COCHLEAR IMPLANTS
A cross section of a human head corresponding to the propagation channel for cochlear implant applications is given in figure 1. The diameter of the ear canal is around 5mm and the length about 1cm. These dimensions allow foreseeing that an emitter can be placed within this ear canal [4]. This emitter would consist in discrete miniaturized microphone and battery, and silicon integrated modulator and amplifier.

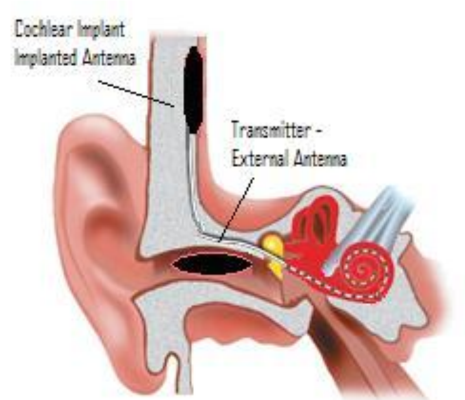

Figure 1: human head cross section

The receiver is located in the head above the ear at a distance of around 5cm from the emitter and is inserted between the skin and skull of the patient. It controls electrodes that are physically connected to the cochlea to stimulate the audio nerve.

According to the physical sizes dealt with, the maximal antenna sizes used for this application are $\lambda/30$ and $\lambda/10$ for the emitter and the receiver respectively.

The communication principle is depicted in figure 2.

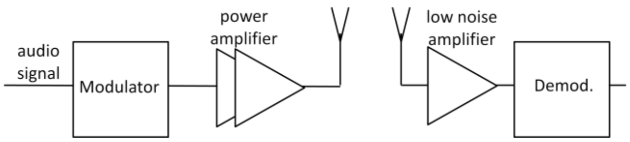

Figure 2: communication for audio implant

The audio signal (acoustic wave) is transformed into an analog electrical signal by a microphone and modulated using a 2.45GHz carrier. Then, the signal is amplified to have high enough amplitude for the transmission. The reception block consists in an analog or digital demodulator preceded by a low noise amplifier (LNA).

It should be noted that the emission part has to be very low power since the battery recharge is not convenient due to the size of the device while recharge solutions already exist for the implanted demodulator.

3. ANTENNA AND PROPAGATION CHANNEL MODELING

For both antennas, an RLC description is used [5] to model the losses and the frequency response while the losses are computed from the channel characteristics: relative permittivity, losses and thickness of each medium.

The equivalent model of the electromagnetic transmission is given on figure 3.

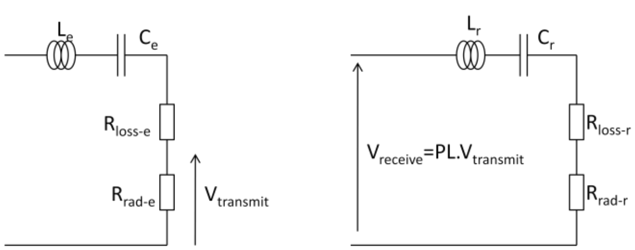

Figure 3: transmission model

The RLC equivalent circuit can be extracted from electromagnetic simulations. The parameters L and C are computed from the adaptation frequency and if we consider that the working frequency is close to the adaptation frequency, the equivalent model of the antennas becomes a single R_{loss}/R_{rad} circuit where $R_{loss}$and R_{rad} represent the loss and radiation resistances.

To compute the attenuation between the transmitted and received voltages, one has to study the transmission channel more in detail. In the case of a cochlear implant, the channel can be seen as a stack of three mediums with different characteristics as shown on the table 1 ([6], [7]).

Table 1: Transmission channel characteristics

medium	ε_r (F/m)	δ	T (mm)
skin	38	0.022	1
fat	5.3	0.117	34
cartilage	38.8	0.019	4

The losses occur during the propagation within a medium and also at the interface between two mediums.

The losses at an interface IL is equal to [8]

$$IL = 1 - |\rho|^2 \qquad (1)$$

with

$$\rho = \frac{\eta_1 - \eta_2}{\eta_1 + \eta_2} \qquad (2)$$

where $\eta 1$ and $\eta 2$ are the permittivity of each medium.

For the propagation within a medium, it is more convenient to determine the equivalent dielectric constant and losses [9]

$$\varepsilon_{eq} = \frac{\varepsilon_{skin} \cdot t_{skin} + \varepsilon_{fat} \cdot t_{fat} + \varepsilon_{cart} \cdot t_{cart}}{t_{skin} + t_{fat} + t_{cart}} \qquad (3)$$

Then, the path loss PL can be expressed as

$$PL = \left(\frac{\lambda_m}{4\pi D}\right)^2 \cdot exp\left(-\frac{D}{\delta}\right) \qquad (4)$$

With λ_m the guided wavelength expressed as a function of the equivalent dielectric constant and the wave length in free space λ_0:

$$\lambda_m = \frac{\lambda_0}{\varepsilon_{eq}} \qquad (5)$$

To finalize the model, one should take into account the antennas efficiency [2]. In the vacuum, the efficiency η_0 is defined as a function of the central frequency f_0 and the bandwidth BW:

$$\eta_0 = \frac{f_0}{Q \cdot BW} \qquad (6)$$

Where the quality factor Q is such that

$$Q = \frac{\lambda_0}{2\pi \cdot a} + \left(\frac{\lambda_0}{2\pi \cdot a}\right)^3 \qquad (7)$$

a being the maximal size of the antenna.

From this equation, the total antenna efficiency can be computed:

$$\eta_{ant} = \eta_0 \cdot (1 - \tan\delta) \qquad (8)$$

And the total efficiency is

$$\eta_{total} = \eta_{ant} \cdot (1 - |S_{11}|^2) \qquad (9)$$

4. TRANSMITTER MODELING

The consumption allowed to the system is such that the modulation has to be a basic one, such as two-state amplitude or frequency modulation in order to have low power consumption. The supply voltage is 1.2V, thus the amplitude of the modulated signal will be around 0.7V. The consumption model of this part is done assuming that the power consumption is constant as a function of time.

The critical part in terms of modeling is the power amplifier. Indeed one has to know precisely the available output power and the corresponding consumed power. To do so, it is usually a good idea to adopt a bottom up approach and run some SPICE simulation to fully characterize the power amplifier.

In the case of an amplitude modulation, the chosen topology for this amplifier is given in figure 4. It is composed of two blocks of two inverting stages and a matching circuit. The first block is mainly used to make the output impedance independent from the input impedance. The second block allows to vary the current across the amplifier and thus to modulate the reference signal.

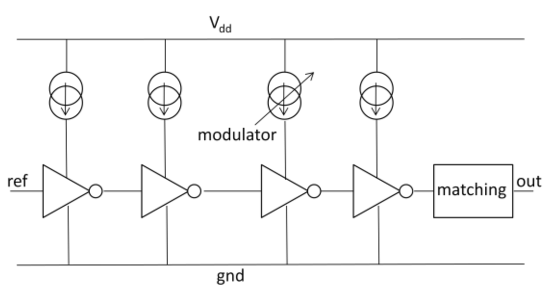

Figure 4: power amplifier topology

The first step during is to check that the gain is almost constant in the ISM band. This is usually the case as the relative bandwidth is very low (about 3%) and the corresponding simulation is represented in figure 5. As expected, the gain variations within the allowed frequency range are lower than the variations obtained by changing the bias voltage. This means that a single matching network is sufficient for bias voltages varying from 1.1V to 1.4V.

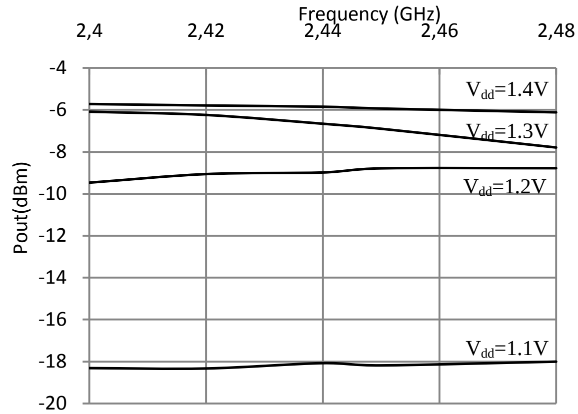

Figure 5: frequency response versus frequency

The output power is simulated and the corresponding results are given in figure 6 and 7. The characteristic of the output power can be modeled by a linear function of the PA consumption.

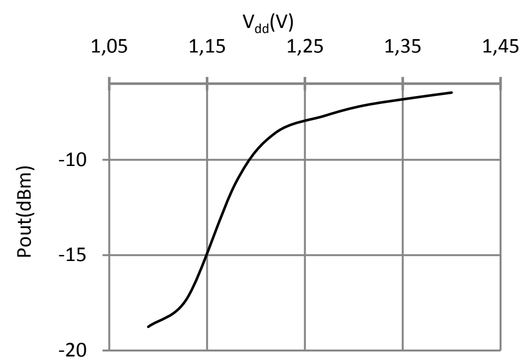

Figure 6: Output power versus bias voltage at 2.45 GHz

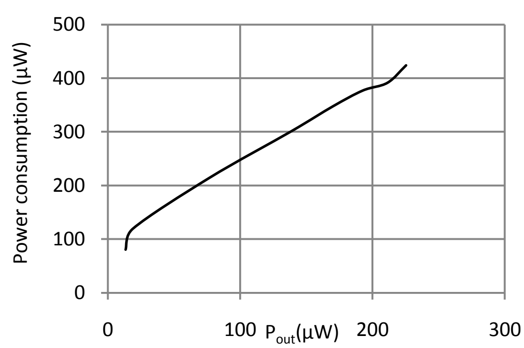

Figure 7: Power consumption versus output power

The receiver is mainly characterized by its sensitivity. Manufacturers have already exhibited sensitivity as low as -65dBm [5]. Furthermore, as the received signal is to be processed digitally and reconstruction algorithms are available during DSP processing, the signal over noise ratio (SNR) of the received signal does not need to be much high. Therefore, we can consider in a first approximation that only the magnitude of the signal has to be taken into account and that it should be within the detection range of the receiver.

5. MODEL IMPLEMENTATION

The battery lifetime model has been implemented in Simulink. The method for evaluating the lifetime is explained in figure 8.

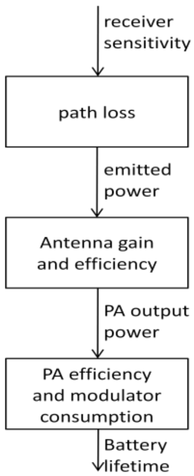

Figure 8: lifetime estimation method

First, the losses in the channel are computed according to the equations developed in part 3. It should be noted that the model accounts for fat, skin and cartilage thickness and those may vary from one person to another; e. g. for a child, the corresponding thicknesses will be lower than the ones of an adult, meaning that the losses will be lower. This is why corner simulations are required to evaluate the worst and best cases.

From the computed attenuation, and knowing the receiver sensitivity, it is possible to evaluate the required emitted power. This power is a function of the output power of the power amplifier and the antenna characteristics in terms of loss and radiation resistances and efficiency.

The power delivered by the power amplifier is then known and a back computation allows evaluating the consumed power and thus the battery lifetime.

6. SIMULATION RESULTS

Depending on the bias voltage, the output impedance of the power amplifier can vary from 50 to 60Ω as shown on figure 9. As a consequence, if we consider an antenna adapted to 50Ω, the increase of the reflection coefficient (S_{11}) will lead to a power loss according to eq. 9.

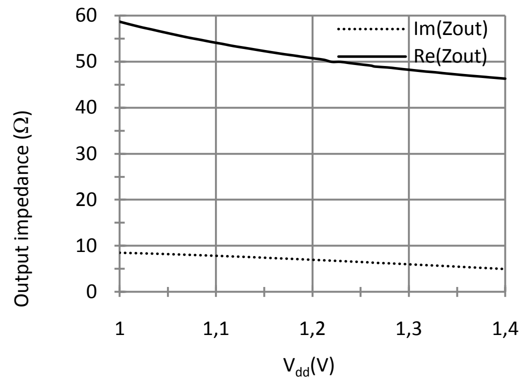

Figure 9: Output impedance as a function of power supply

However, in the worst case, the magnitude on the S_{11} is at most 0.2 corresponding to a loss of 1dB, which is negligible compared to the path loss.

Concerning the path loss, the typical, minimal and maximal attenuation are presented in table 2 according to the medium thickness.

Table 2: best- and worst case models

	T_{skin} (mm)	T_{cart} (mm)	T_{fat} (mm)	Loss (dB)
Best	0.5	2	20	-19.4
Typical	1	4	34	-25.5
worst	2	6	50	-30.4

To validate the channel model, we have confronted the analytical computations with electromagnetic simulations. For this purpose, we used HFSS with the channel configuration described in figure 10.

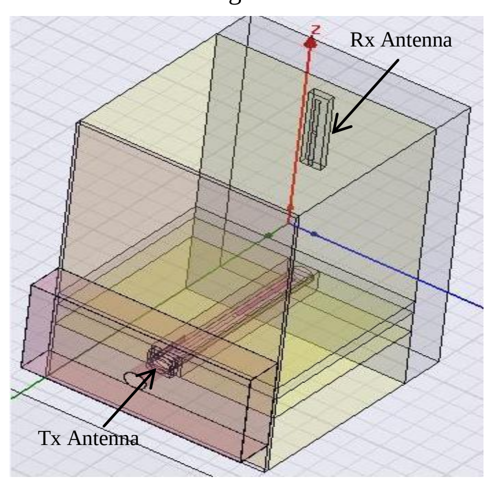

Figure 10: HFSS layout

To get the channel attenuation, radiating objects have to be added. So the first step is to simulate the frequency response of those objects and get the corresponding S_{11} parameters from which we can get the losses due to the antennas. Then, we can calibrate the S_{21} corresponding to the attenuation in the channel. It should also be noted that the antennas used for this application have to be omnidirectional as the shape of the ear canal can differ from one person to another.

So, to avoid transmission issues, the power has to be emitted within a high solid angle. The counterpart is that the available antenna gain is relatively low (about 2dBi).

One can observe a 6dB mismatch between simulation and analytical model which is quite an encouraging result if we consider that the equivalent model is assumed to be valid only for far field propagation though, in practice, the propagation in the first medium has to be considered as near field.

Using these results, high level transient simulations have been ran. The study case focused on a two-state amplitude modulation. The upper signal in figure 11 corresponds to the output of the power amplifier and the lower signal represents the received data with white noise added in the canal.

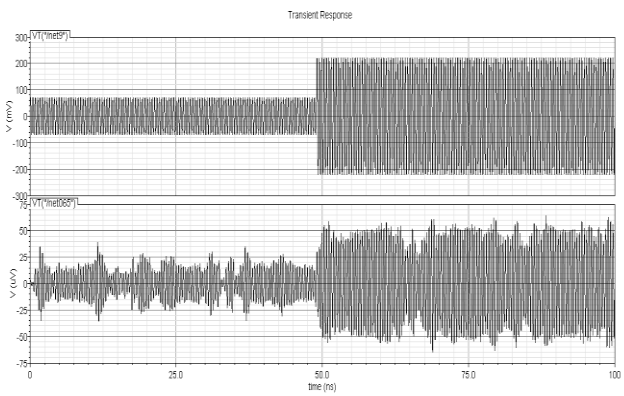

Figure 11: transient simulation of the transmission

From the required transmitted power (P_t), the consumption of the transmitter (P_{tot}) is derived assuming that the modulator power is constant and that the PA consumption (P_{PA}) is as described in figure 7. Table 3 reports the battery lifetimes in the typical, best and worst cases, depending on the losses in the propagation channel of table 2.

Table 2: best- and worst case models

	Pt (µW)	P_{PA} (µW)	P_{tot} (µW)	Lifetime (days)
Best	10	115	415	10
Typical	30	145	445	9
worst	100	250	550	8

7. CONCLUSION

A first order model for battery lifetime integrated within cochlear implant has been proposed. According to electromagnetic simulations, the model gives encouraging results leading to a few days approximations compared to few weeks lifetime.

This model showed the influence of human morphology in terms of fat, skin and cartilage proportion which results in a significant change in battery lifetime (about 20% between the best and worst cases). In comparison, doubling the amplifier or the antenna efficiency would lead to less than 10% increase of lifetime.

It should however be noted that the model is limited by the far field approximation and that developing a near field model would be of interest.

8. ACKNOWLEDGEMENTS

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