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Magnetic In-Body and On-Body Antennas Operating At 40MHz and Near Field Magnetic Induction Link Budget

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***Abstract*—Magnetic antennas are supposed to be less perturbed than electrical antennas in the presence of human body. In this study, initially transmitter spiral coil ingestible capsule (in-body) antenna and receiver magnetic square coil (on-body) antenna have been designed separately at 40MHz with a matching system. Then, a near field magnetic induction link budget has been established in the presence of a human body model. The efficiency (received power / transmitted power) of the magnetic induction link is found to be better than that of an electromagnetic link when both TX and RX antennas are opposite to each other. This phenomenon facilitates to minimize the power consumption and hence to increase the battery life of the wireless capsule. Furthermore, we observe that the magnetic link is efficient enough when the TX antenna, located at any position is randomly oriented while RX antenna is oriented horizontally and vertically to the human body surface.**

Keywords-component; Wireless ingestible capsule; magnetic coil antennas ; in-body/on-body antennas; homogeneous human body model; near field magnetic induction link budget

I. INTRODUCTION

The wireless ingestible capsule, placed inside the human body in the small intestine, needs to have compact antennas whose diameter is at most equal to 10.1mm that is equivalent to the diameter of a capsule [1].

The low-frequency magnetic antennas suffer from high magnetic power decrease with the inverse sixth power of the distance [2]. Whereas, the magnetic power is independent of the transmission channel properties and depends only on the permeability of the medium. The RF power is significantly absorbed by human tissues because of its sensitivity to the permittivity of the medium. Similarly, antenna's radiation efficiency too drops excessively through the human body and hardly exceeds 0.3 % [3, 4].

In this paper, in-body and on-body small magnetic coil antennas operating at 40 MHz are designed. The efficiency of the near field magnetic induction link through the human body, at different TX antenna positions and orientations, is estimated in order to realize an effective inductive link.

II. IN-BODY AND ON-BODY ANTENNAS DESIGN

The antenna's design and the inductive link modeling in the presence of the human body was carried out using High Frequency Structural Simulator (HFSS), a commercial full wave simulator software based on the Finite Element Method (FEM) techniques. The boundary conditions used for the simulation are the radiations. The in-body transmitter antenna consists of a 10.1 mm diameter, 6-turn spiral coil spaced by a distance of 0.25 mm while the line width is equal to 0.2 mm as depicted in Fig. 1.b. It is inserted into a cylinder having the size of a capsule (vitamin pill) filled with air. A 10x10x10 cm^3 cubic box, having a permittivity ε_r of 83 and a conductivity σ of 0.67 S/m, represents a layer of average human muscles at 40MHz and that is used to simulate the TX (transmitter) and the RX (receiver) antennas presented in Fig. 1.a, b and c. These parameters are calculated thanks to the 4 cole-cole method [5].

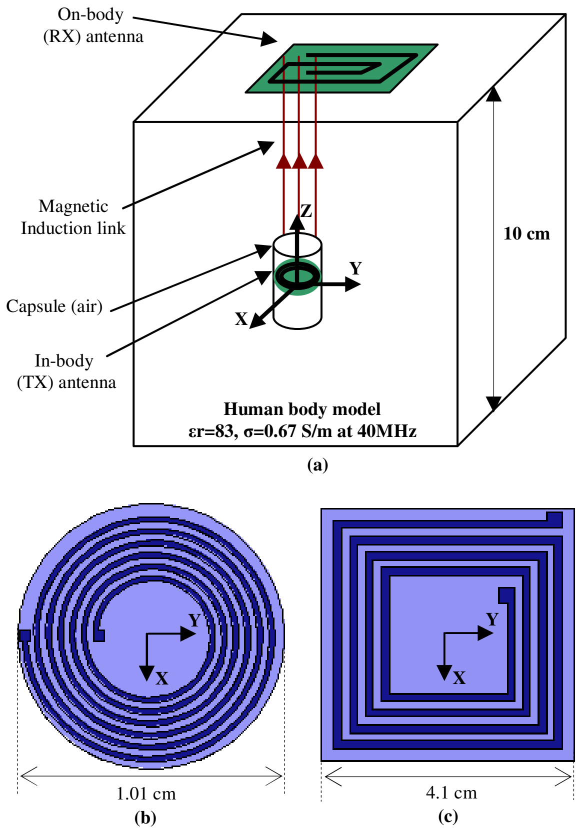

Figure 1. a. Magnetic induction link through the human body, b. spiral TX coil antenna geometry, c. square RX coil antenna geometry

The on-body coil comprises of a 4.1 cm x 4.1 cm, 4-turn squared spiral (Fig. 1.c) whose both, the line width (w) and the spacing between the turns (g) are set to 0.3 mm. The on-body receiver (RX) coil is placed at about 5.2 cm from the TX coil. The Rogers RT / duroid 5880 substrate of thickness h = 1.5 mm, εr = 2.2 and dielectric loss tangent = 0.0009 is used to design the in-body and the on-body antennas.

III. SIMULATION RESULTS

A. *Direct horizontal link:*

Initially, we consider that both TX and RX antennas are opposite to each other and the centre of both antennas is positioned at the origin that is at (oy) axis. We note this channel by direct horizontal link (HL) because the RX antenna is horizontal to the human body as presented in Fig. 1.a. This positioning suggests that the TX and the RX antennas are at their optimum performance.

Both in-body and on-body magnetic coil antennas are matched to a 50Ω cable close to 40 MHz using a matching system which includes two capacitors and one parallel resistor. The -10 dB impedance bandwidth is found to be of 0.34 MHz for the transmitter antenna while 0.33 MHz for the receiver antenna as represented in Fig. 2. The in-body and on-body antenna quality factors Q are estimated to be equal to 80 and to 65 respectively.

The field strength, narrated by mathematical expression (1) mainly depends upon the loop radius (R), the number of the loop turns (N) and the distance from the centre of the coil in the normal direction (z) [6].

$$H = \frac{I \times N \times R^2}{2 \times \sqrt{(R^2 + z^2)}^3} \quad (1)$$

If we consider a magnetic induction link between transmitting and receiving coil in near field, the received power P_R, expressed by the following relation (2) at the operating frequency depends on the quality factors (Q_T) and (Q_R), the efficiencies (η_T) and (η_R), the radii (r_T) and (r_R) of the transmitter and the receiver coils, the transmission power (P_T) and the distance between the transmitter and the receiver (d) [7].

$$P_R(\omega) = P_T \times \eta_T \times \eta_R \times Q_T \times Q_R \times \frac{r_T^3 \times r_R^3 \times \pi^2}{(r_T^2 + d^2)^3} \quad (2)$$

At 40 MHz, λ_0 = 750 cm, the wavelength into the muscle is calculated by [5] and that comes out to be 53 cm. So, considering the classic near field zone limit of λ/2π, we can conclude that it is possible to transfer power by near field magnetic coupling between TX and RX coils until a distance d stands equal to 8.5 cm.

The small intestine is located at about 5 cm deep from the surface of the skin [3]. The S21 response is calculated at almost 5.2 cm from the TX antenna (50 mm of muscle and 2 mm of air) according to the z direction in this study.

To estimate the power level received by a RX coil by magnetic induction, a near field magnetic induction link budget has been carried out. Fig. 3 reports the S21 transmission parameter in free space and in the presence of the human body when the transmitter coil antenna power is set to 1 W. The S_{21} response is slightly modified by the body presence. It decreases from - 20.7 dB in the air to - 22.1 in the human body at around 40 MHz and obviously the difference is only of 1.4 dB. Moreover, the efficiency, represented by the S21 parameter, is found to be equal to 0.6 % (-22.1 dB) and that is better than the electromagnetic link efficiencies of 0.1 % at 1.4 GHz and of 0.3 % at 402 MHz cited in [3] and [4] respectively.

For the capsule antenna, it is not possible to increase the TX antenna radii because it is supposed to be confined within the capsule. Contrarily, we can increase the RX antenna dimensions in order to improve the magnetic link performances. So, we have performed three link budgets while only the RX antenna parameters are modified. Table I summarizes the obtained results and shows that if we increase the RX antenna dimensions, the S21 parameter increases in spite of the deterioration of the RX antenna Q factor.

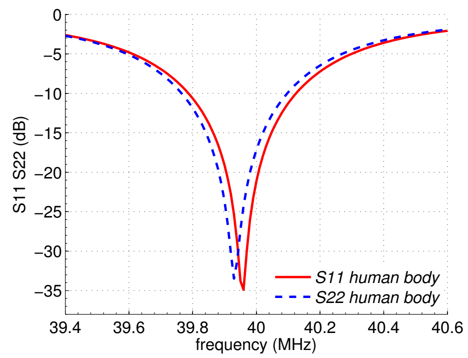

Figure 2. Simulated return losses of the in-body and the on-body antennas in the presence of themselves

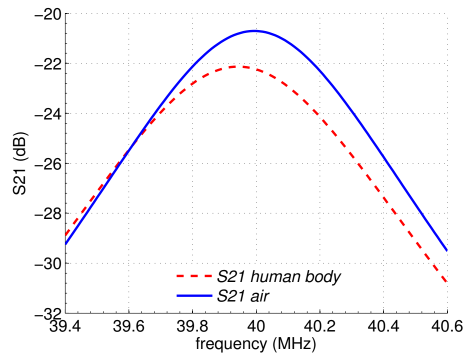

Figure 3. Simulated transmission parameter between the in-body and the on-body antennas in free space and in the presence of the human body

TABLE I. S21 PARAMETER ACCORDING TO DIFFERENT RX ANTENNA CHARACTERISTICS (N: TURNS NUMBER, W: LINE WIDTH AND G: GAP OF LINES)

N	Q	Dimensions	S21 (dB)	S21 (%)
3	*44*	*5 x 8 cm (w & g = 2 mm)*	*-20*	*1*
4	*65*	*4.1 x 4.1 cm (w & g = 0.3 mm)*	*-22.1*	*0.6*
6	*141*	*2 x 2 cm (w & g = 0.5 mm)*	*-28.3*	*0.15*

In the following analysis, we select the RX coil defined in the beginning (4.1 cm x 4.1 cm) while the z distance between the TX and RX antennas is kept constant and equal to 5.2 cm.

As the capsule antenna is to slide into the gastrointestinal tract randomly so it is necessary to analyze the influence of the TX antenna positions and orientations in the channel efficiency to evaluate the inductive link performances.

B. *TX antenna angle variation*

1) Angle variation in the horizontal link

Fig. 4 shows how we vary the orientation of the TX capsule antenna in the HL. The angle varies from 0 deg to 90 deg in the (YZ) plane. It is clear from Fig. 5 that the efficiency of this inductive link worsens above 70 deg. To make a remedy of this problem, we propose to orient the RX antenna perpendicularly to the human body surface: this link is noted vertical link (VL).

2) Angle variation in the vertical link

We can see in Fig. 6 the TX and RX antenna orientations in the VL and that is found to yield poor performances compared to HL, as it shown in Fig. 7, because the upper limit of S21 (-32 dB) that occurs at θ = 90 deg is inferior to the maximum of S21 found in the HL (-22 dB). While the angle θ is below 50 deg, this link is not effective any more.

3) Angle variation in the horizontal and the vertical links

Around 40 MHz, the S21 is maximum in both HL and VL as is shown in Fig. 5 and Fig. 7.

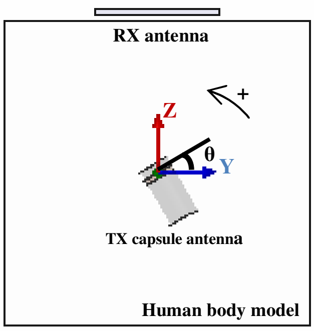

Figure 4. TX antenna angle variation in the HL

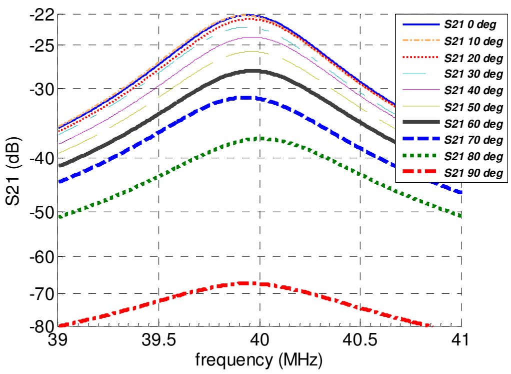

Figure 5. Simulated S21 parameter between the TX and RX antennas in the HL according to the frequency while θ varies from 0 to 90 deg

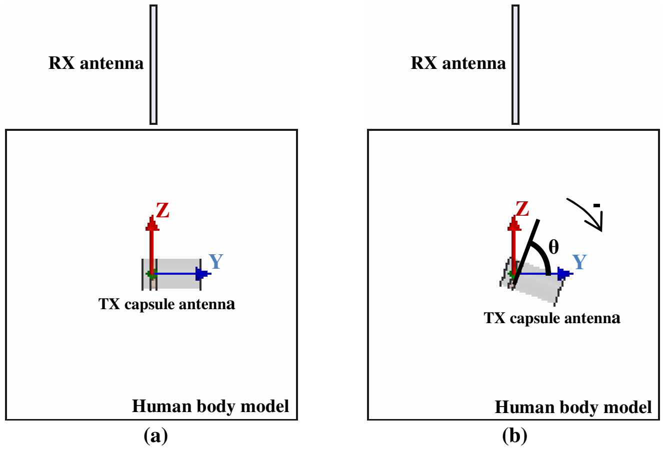

Figure 6. a. TX and RX antenna orientations in the VL; b. TX antenna angle variation in the VL

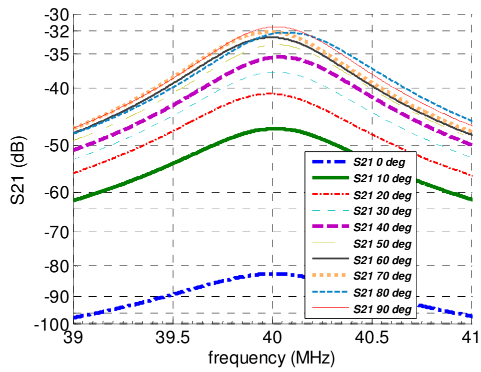

Figure 7. Simulated S21 parameter between the TX and RX antennas in the VL according to the frequency while θ varies from 0 to 90 deg

If we consider the S21 variation according to the angle θ in the HL and also in the VL, we can conclude that the HL and the VL are complementary as is shown in Fig. 8. In other words, if the HL losses its performances when θ is from 70 to 90 deg, the VL link became efficient and vice versa. So, the association of the HL and the VL allows to offer an efficiency better than -32 dB for all TX antenna orientations while the TX antenna is located in the center of the (oy) axis.

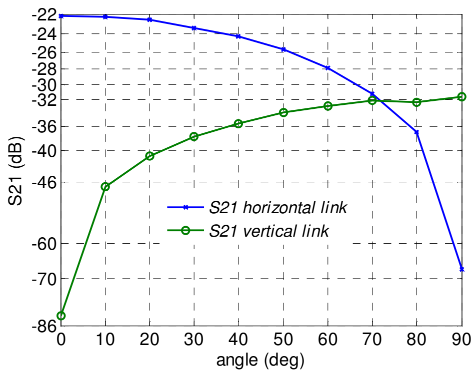

Figure 8. Simulated transmission parameter between the TX and RX antennas in both HL and VL according to the angle at 40 MHz

This suggest that we should set an array of RX antennas composed of vertical and horizontal sections so as to be always oriented to offer optimum inductive link.

C. *TX antenna position variation*

The position of the TX antenna can also be varied with reference to the RX antenna. For this, it is imperative to study the TX antenna position variations according to the (oy) axis.

1) *Position variation in the horizontal link*

If the TX antenna position changes in the y direction as depict Fig. 9, the performances of the inductive HL will also vary. But, even if the S21 decreases when the TX antenna retards away from the RX antenna, the HL efficiency is acceptable even at y = -3 cm or 3 cm which present the lowest S21 value (-28 dB/ 0.16 %) as it is shown in Fig. 10.

2) *Position variation in the vertical link*

In the same manner, we change the TX antenna position according to the y direction in the VL as describes Fig. 11. While the TX antenna shift in the y direction until a distance equal to 1.5 cm, the efficiency of the VL revealed in Fig. 12 drops to 0.04 % (-34 dB). So, if the y position of the TX antenna is more than 1.5 cm away from the RX antenna, the VL is not effective any more.

3) *Position variation in the HZ and the VT links*

Fig. 13 summarizes the results obtained if we change the TX antenna position in both HL and VL at 40 MHz.

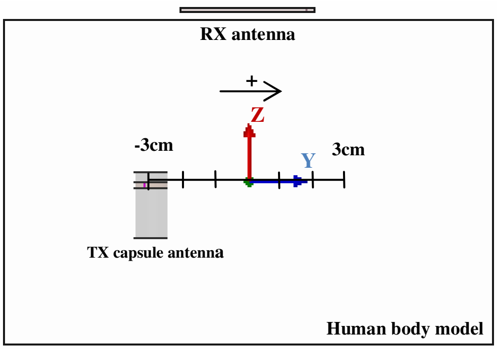

Figure 9. TX antenna position variation according to the (oy) axis in the HL

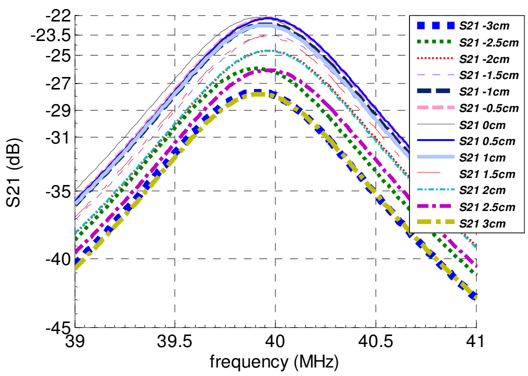

Figure 10. Simulated transmission parameter between the TX and RX antennas in the HL according to the frequency when y = [– 3 cm, 3 cm]

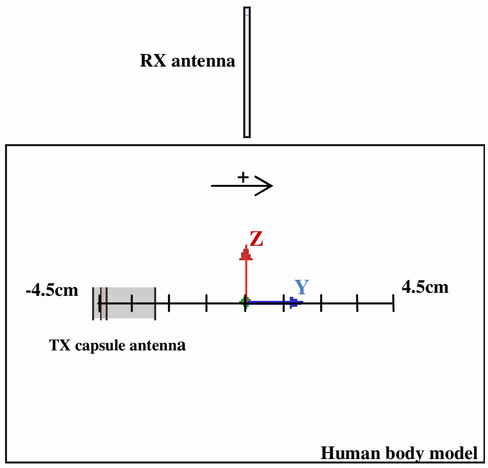

Figure 11. TX antenna position variation in the VL according to the (oy) axis

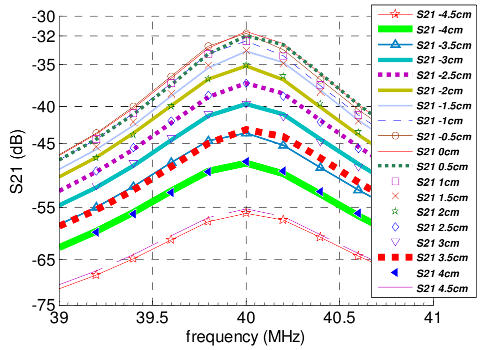

Figure 12. Simulated S21 parameter between the TX and RX antennas in the VL as a fonction as the frequency when y = [– 4.5 cm, 4.5 cm]

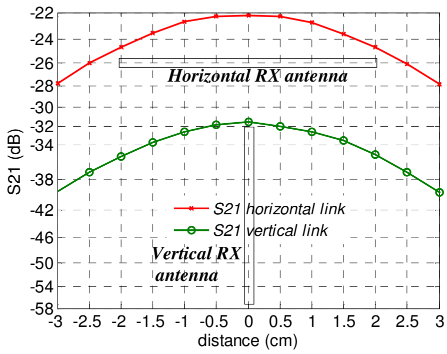

Figure 13. Simulated transmission parameter between the TX and RX antennas in the HL and the VL as a fonction as the distance at 40 MHz

The TX antenna orientation is considered optimum for each plot in Fig. 13: θ = 0 deg for the HL and θ = 90 deg for the VL. We note that the position of the TX antenna according to the (oy) axis corresponds approximately to the TX-RX antenna center spacing in the y direction. It is clear from Fig. 13 that if we consider only the TX antenna position variation, the transmission parameter of the HL is better than that of the VL whatever may be the position of the TX antenna, when d is -3 cm and 3 cm that is from centre to left and right y direction.

D. TX antenna angle and position variations

If it is assumed that the y-position and the angle of the TX antenna vary together, the behavior of S21 parameter at 40 MHz according to the angle is different for each y-position in the too cases of VL and HL as it is shown in Fig 14. We can conclude from these plots that:

- On each quarter of Fig. 14, corresponding to every TX antenna y-position, the combination of the HL and the VL allows to obtain an efficiency that is better than 0.03 % (-35 dB) which corresponds to the lowest transmission parameter in the critical case (y = -3 cm). So, we can say that, at each position, both HL and VL plots are complementary. For example, if y = -2 cm, when the angle θ vary from 0 to 40 deg, the S21 parameter of the HL, that decreases from -24 dB to -32 dB, is leading. Then, while θ is from 40 to 80 deg, the transmission parameter of the VL that drops from -32 dB to -34 dB is dominant. After that, when θ is from 80 to 90 deg, once again the S21 parameter of the HL is leading and increases from -34 dB to -32 dB.
- In the HL, the S21 parameter drops while θ vary from 0 to 90 deg for d = 0 cm whereas the transmission parameter decreases while θ is from 0 to 80 deg, 60 deg and 50 deg for y = -1 cm, -2 cm and -3 cm respectively and increases after these angles. This can be explained by the fact that the H-field lines received by the RX antenna, when the TX antenna is moved away from the received antenna can be optimized by the rotation of the TX antenna, but the optimum configuration is in the HL case when θ = 0° for each y-position.
- The S21 parameter variation in the case of the VL is weaker than that in the HL.

These results predict that the association of both vertical and horizontal segments of RX antenna is necessary to assure a better efficiency of the inductive link. Furthermore, this study allowed us to estimate the spacing between the horizontal and vertical sections of RX antennas in the on-body network.

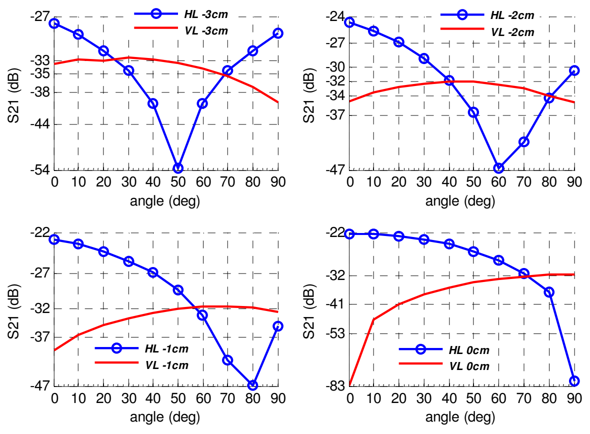

Figure 14. Simulated transmission parameter between the TX and RX antennas in the HL and the VL at different TX antenna positions as a fonction as the angle at 40 MHz

Thus, whatever the orientation of the TX antenna may be, while it is located anywhere in the y direction, in the limit of 2 cm spacing between the TX and RX antennas, the S21 value always stands between -22 dB (0.6 %) and -34 dB (0.04 %). We remember that the RX antenna sizes are 4.1 cm x 4.1 cm and can be reduced to 4 cm x 4 cm. Therefore, to obtain an effective inductive link using these RX antenna sizes, the proposed RX antennas network will be constituted by horizontal adjacent sections of RX antennas and vertical segments of RX antennas spaced by 2 cm.

IV. CONCLUSION

In order to characterize the near field magnetic induction link through the human body, antennas placed inside and outside the human body have been designed. Magnetic antennas have been chosen because the magnetic field is independent of human tissues. We have proved that the efficiency of this inductive link (0.6 %) obtained at the ideal case, is better than the efficiency of an electromagnetic link through the human body mentioned in the literature (0.3 %).

To take in an effective inductive link with a best power transfer, when the TX capsule antenna is located anywhere at any orientation in the gastrointestinal tract, the association of horizontal and vertical segments of on-body RX antenna is required.

In this study, the HL and the VL have been considered separately, we have to study the inductive link in the presence of the RX antenna array constituted of some sections of RX antennas in the horizontal and vertical orientations to evaluate the influence of these antennas on themselves and on the S21 parameter.

In capsule antenna, the diameter of the circular loop is limited by the capsule size; however, we can increase the turn number of the TX coil and the dimensions of the RX antenna to promise a maximum power transfer through the magnetic induction link.

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