Optimization of Microwave Power Absorption in Biological Tissues

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Abstract: - The phenomenon of microwave power absorption has recently become of increased public and research interest in various areas including such research topics as an EM power absorption by human head with closely coupled hand-held mobile phone and the problem of a perfect matched absorbing layers. Herein, we focus on a simplified 1-D transmission-line model. This model, being directly associated with normal incidence of plane-wave generated by infinite source sheet upon a lossy half-space, establishes a tight upper bound on the maximal (optimal) power absorption in a realistic mobile phone - human head configuration. Furthermore, the source impedance and the absorption/radiation efficiencies are obtained via an explicit closed-form expressions, leading to an explicit optimal power absorption criteria for highly lossy tissues.

Key-Words: - Power Absorption in Biological Tissues, Lossy Transmission Lines, Mobile Phones.

1 Introduction

Electromagnetic power absorption in biological tissue is a well-known phenomenon (e.g. [1], [2]). Its evaluation requires, in general, a solution of the 3-D frequency-dependent wave equation in complex configurations. Thus, a 3-D solution of the power absorption efficiency optimization problem, in similar configurations, may necessitate quite massive analytical and numerical efforts. With the rapid growth of computational resources in the last 15-20 years, numerical methods have become the mainstream of research in the area of investigation of absorption effects in biological tissues (particularly with reference to mobile phones). Several techniques have been utilized, e.g., the Method of Moments [3], [4], [5], the Finite Difference Time Domain technique [6], [7], [8], [9], [10], the Coupled Integral Equations procedure [4], and the Multiple Multipole algorithm [11]. Numerical methods essentially have the ability of supporting geometrically precise model and achieving accurate result. However, when seeking for canonical model, capable of providing a deep understanding of the basic power absorption mechanism as well as an explicit closed-form expression for the major parameters effects, an analytical approach should be preferred.

Herein, we focus on a simplified 1-D transmission-line model. This model, being directly associated with the problem of a normal plane-wave incidence upon a lossy half-space, establishes a tight upper bound on the maximal (optimal) power absorption in a realistic mobile phone - human head configuration. Furthermore, the source impedance and the absorption/radiation efficiencies are obtained via an explicit closed-form expressions.

2 Problem Formulation

The transmission-line model, depicted in Fig.1, consists of a point current source located at $z = z'$ in a semi-infinite lossless line (z >0). The current source excites a semi-infinite lossy line (z <0), acting as a load. Both transmission-lines are characterized by the parameters σ $\left(\sigma_0 = 0\right)$, ε $\left(\varepsilon_1 = \varepsilon_{r1}\varepsilon_0\right)$, and μ (assuming, for biological tissues, $\mu_1 = \mu_0$), via, $k_0 = \omega\sqrt{\mu_0\varepsilon_0}$, $Z_0 = \sqrt{\mu_0/\varepsilon_0}$, and $k_1 = n \cdot k_0$, $Z_1 = Z_0/n$, $n = \sqrt{\varepsilon_{r1}\left(1+\sigma/j\omega\varepsilon_1\right)}$, where, assuming harmonic time-dependence $e^{j\omega t}$, $\Im\left(k_1\right) \le 0$, $\Im\left(Z_1\right) \ge 0$.

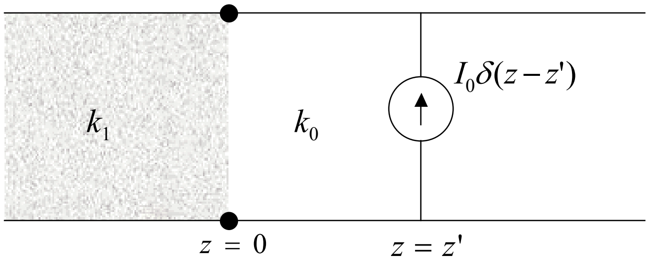

Fig. 1: One-dimensional model; a point current source loaded by a semi-infinite lossy transmission-line.

The voltage $V(z,z')$ and the current $I(z,z')$ representations along the transmission-line [12], [13] enable explicit expressions for the source input impedance and the power absorption efficiency :

$$
\begin{aligned}
Z_{in} &= R_{in} + jX_{in},\\
X_{in} &= -Z_0\rho_L \sin(k_0 z' - \psi_L/2)\cos(k_0 z' - \psi_L),\\
R_{in} &= 2(P_{rad} + P_{abs})/I_0^2 =\\
&= (Z_0/2)/\left[1 + \rho_L - 2\rho_L \sin^2(k_0 z' - \psi_L/2)\right],\\
\eta_{abs} &= P_{abs}/(P_{rad} + P_{abs}) =\\
&= 0.5\left(1 - \rho_L^2\right)/\left[1 + \rho_L - 2\rho_L \sin^2(k_0 z' - \psi_L/2)\right],
\end{aligned}
$$

where Γ_L, the reflection coefficient, is given by $\Gamma_L = (Z_1 - Z_0)/(Z_1 + Z_0) = \rho_L e^{j\psi_L}$.

3. Problem Solution

Defining the loss factors ζ and ξ via $\zeta \equiv \omega\varepsilon_1/\sigma_1$ and $\xi \equiv 0.5\,\omega\varepsilon_0/\sigma_1$, respectively, and noting that most biological tissues are characterized by $\xi << 1$, i.e., $Z_1 \to 0$, the reflection coefficient Γ_L can be expressed, up to $O\left(|Z_1/Z_0|^2\right)$, as $\Gamma_L \sim -1 + 2Z_1/Z_0$. This limit (i.e. the limit of high losses) leads to simplified explicit closed-form expressions for the source input impedance and the power absorption efficiency. The dependence of η_{abs} on ζ for various values of source location $k_0 z'$ is depicted in Fig.2 for $\xi = 0.01$.

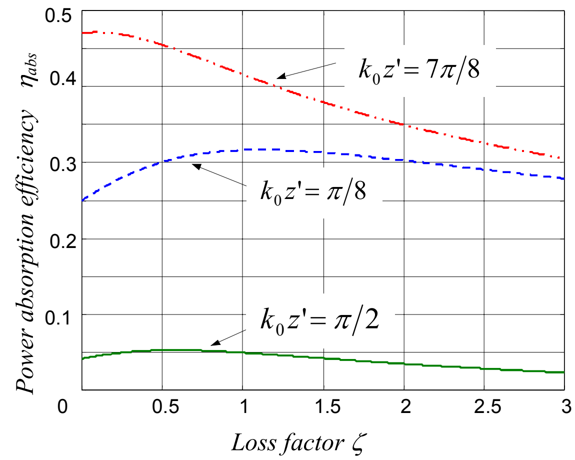

Fig. 2: Power absorption efficiency vs. loss factor ζ for different source locations.

Apparently, for each $k_0 z'$ there is an optimal ζ which maximizes the power absorption efficiency. It can be shown that the optimum exists only if the tissue is highly lossy, i.e. $\xi << 1$. Thus, it is desirable to focus on determining the set of optimal points $\zeta_{opt} = \zeta_{opt}(k_0 z')$. This goal is carried out explicitly and analytically through the requirement $d\eta_{abs}/d\zeta = 0$ at $\zeta = \zeta_{opt}$.

The results are succesfuly calculated by using, for $k_0 z' \approx \pi/2 + n\pi$, an explicit expression for ζ_{opt}, namely, $\zeta_{opt} = 1/\sqrt{3} + 8\sqrt{\xi}/[3^{5/4}\tan(k_0 z')]$.

This expression, the main result of our paper, assigns explicitly to every $k_0 z'$ an optimal value ζ_{opt}. The results agree well with exact numerical evaluations of the parameters at the optimal points, as depicted in Fig.3.

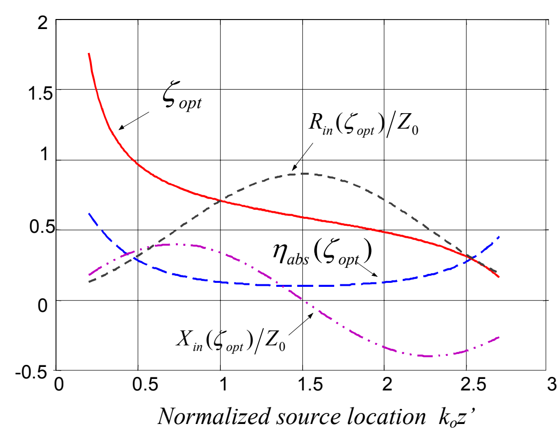

Fig. 3: Optimal loss factor, normalized source input impedance, and power absorption efficiency vs. normalized source location $k_0 z'$.

In conclusion, for all $k_0 z'$ there exists an optimal, uniquely specified, lossy transmission-line which maximizes the power absorption efficiency. The maximization of power absorption efficiency is most significant in the neighborhood of $k_0 z' = n\pi$.

As already indicated above, the limit of high losses renders an explicit closed-form solution for the power absorption optimization problem and the resultant expressions for the source input impedance and the power absorption/radiation efficiencies. Furthermore, results obtained upon using these expressions correlate very well with realistic recently reported data [14], [15], [16], as demonstrated in Table 1.

z' [cm]	Transmission-line model (840-915 MHz)	Ref. [14] (840 MHz)	Ref. [15] (915 MHz)	Ref. [16] (915 MHz)
1.5	42.2-45%	35%	-	46-60%
2	52.7-55.8%	42.7%	47.2%	57-67%
3	67.8-70.5%	50.5%	52.5%	72-77%
5	81.9-83.4%	72.3%	61%	-

Table 1. Radiation efficiency versus source point z'. The transmission-line model matches well the numerically calculated human head – mobile phone interaction [14], [15], [16].

4. Conclusion

The analytical scheme, which has been outlined in the previous sections, may serve as a first-order prototype model. This model is capable of obtaining explicit closed-form bounds on the power absorption efficiency of realistic problems. Furthermore, it can be extended to real 3-D bioelectromagnetic configurations [17] via the so-called Leontovich surface impedance [18].

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