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Uncertainty Quantification of Epithelial/Absorbed Power Density in 1-layered Planar Skin Model with Uncertain Tissue Electric Properties

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Abstract

This paper presents a stochastic approach to compute the absorbed power density (*APD)* on skin surface when exposed to radiation of halfwave dipole antenna. Skin tissue is modelled as 1-layered half-space with uncertain electric permittivity and conductivity. Formulation is based on numerical solution of Pocklington equation and corresponding field integrals. Stochastic Collocation (SC) method is used for uncertainty propagation in a black box manner. *APD* mean, variance, skewness, kurtosis and confidence intervals are computed at 10, 30 and 90 GHz for different antenna-body distances.

1 Introduction

Dominant biological effect due to exposure of humans to mobile communications systems of 5th generation (5G) is superficial tissue heating. According to IEEE 2019 [1] and ICNIRP 2020 [2] guidelines, this surface heating is quantified by absorbed power density (*APD*) above transition frequency of 6 GHz. Since it is a rather difficult task to validate *APD* values experimentally at frequencies above 10 GHz, a detailed study has been conducted in [3] where several numerical methods and averaging schemes for computation of *APD* inside human tissues are compared under different exposure conditions.

However, deterministic modelling assumes fixed values of input parameters, which contrasts with inherent uncertain nature of body tissue parameters. Namely, tissue ~~electric~~ permittivity and conductivity depend on ~~individual~~ age, health and gender. Furthermore, their values are obtained from in vitro measurements on human and animal tissues which fail to accurately represent realistic scenarios.

This paper proposes a stochastic approach to *APD* computation assuming the skin permittivity and conductivity to be random variables. Stochastic Collocation (SC) method used extensively in previous work by authors, e.g., in [4], is non-intrusive thus enabling the use of deterministic codes for *APD* computation as black boxes. APD is computed according to IEEE 2020 guidelines [1] while field levels on tissue surface are obtained from the numerical solution of field integral expressions [5].

The paper is organized as follows. Deterministic-stochastic *APD* computation is outlined in Section II and results in Section III. Concluding remarks are given in Section IV.

2 Deterministic-stochastic model for absorbed power density, *APD*

Geometry of interest consists of halfwave dipole antenna placed at distance *h* above 1-layered skin modelled as a half-space (Fig. 1).

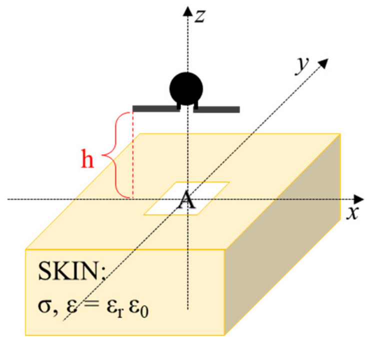

Figure 1. Dipole antenna above a 1-layered skin model.

Pocklington equation is solved by means of Galerkin-Bubnov Indirect Boundary Element Method (GB-IBEM) to obtain current along the dipole [5]. Then, the corresponding field integrals are solved numerically and the induced electric and magnetic field (*E* and *H*) on the tissue surface are obtained [5]. Finally, *APD* is computed according the standard definition [1]:

$$S_{ab} = \frac{1}{2A} \int_{A_{av}} Re(\vec{E} \times \vec{H}^*) d\vec{A} \tag{1}$$

where *A* is the averaging area.

In the stochastic part of the analysis skin relative permittivity and conductivity are modelled as random variables. Uncertainty is propagated to the output *APD* by means of Lagrange Stochastic Collocation (SC) method with Gauss-Legendre (GL) quadrature and full tensor grid [4]. Mean, variance, skewness, and kurtosis (μ, *Var*, *Skew* and *Kurt*) are computed as follows:

$$\mu = \sum_{i=1}^{N} APD_i \, w_i \tag{2}$$

$$Var = \sum_{i=1}^{N} (APD_I)^2 \, w_i - \mu^2 \tag{3}$$

$$Skew = \frac{\sum_{i=1}^{N} (APD_I)^3 \, w_i - 3\mu \cdot Var - \mu^3}{Var^{3/2}} \tag{4}$$

$$Kurt = \frac{\sum_{i=1}^{N} (APD_i)^4 \, w_i - 4\mu \cdot Skew \cdot Var^{3/2} - 6\mu^2 \cdot Var - \mu^4}{Var^2} \tag{5}$$

where N is the total number of deterministic simulations, while APD_i and w_i are i-th deterministic *APD* value and its corresponding precomputed weight [4].

3 Results

Frequencies of interest are f=10, 30 and 90 GHz. Antenna body distance is set to h=5, 10 and 15 mm at 10 and 30 GHz while at 90 GHz h=2, 5 and 10 mm. The total antenna input power is normalized to 10 mW [3] while the averaging surface is set to A=1 cm^2 and 4 cm^2 [1].

Frequency dependent nominal values of tissue electric conductivity and relative electric permittivity are set as follows: σ= 8.4824, 27.31 and 41.94 S/m, and ε_r=32.409, 16.63 and 6.826 in frequency ascending order, respectively, [3]. Their uniform distributions are designed by varying nominal values with ±20%.

SC convergence is tested by consecutive increase of GL points in one dimension, i.e., when only conductivity or permittivity is random in one-at-a-time manner. Number of 1-dimensional collocation points is 3, 5 and 7, thus leading to a full tensor grid of 9, 25 and 49 deterministic simulations in 2-dimensional case. The convergence of SC method in computation of *APD* mean, variance, skewness and kurtosis is depicted in Fig. 2. The absolute relative error of levels SC-3 and SC-5 are computed with respect to level SC-7. The convergence is satisfactory, particularly for mean and variance. The maximal absolute relative error is 0.45% for skewness at f=90GHz, h=10mm and A=1cm^2 which is rather low.

Furthermore, Fig. 3 depicts the crude estimation of *APD* confidence intervals, computed as mean ± 3 standard deviations. Confidence intervals are important measure of dispersion around the mean. The width of confidence intervals seems to be the widest at 90 GHz. However, the ratio of one standard deviation and the corresponding mean does not exceed the value of 3.2% no matter which combination of frequency, distance and control surface is considered. Therefore, it can be concluded that variations of skin relative permittivity and conductivity of 20% around nominal values do not introduce large uncertainty in the output *APD*.

Furthermore, *APD* skewness and kurtosis are given in Tables 1 and 2. All cases considered, skewness is between 0.1 and 0.2, thus indicating that the resulting *APD*

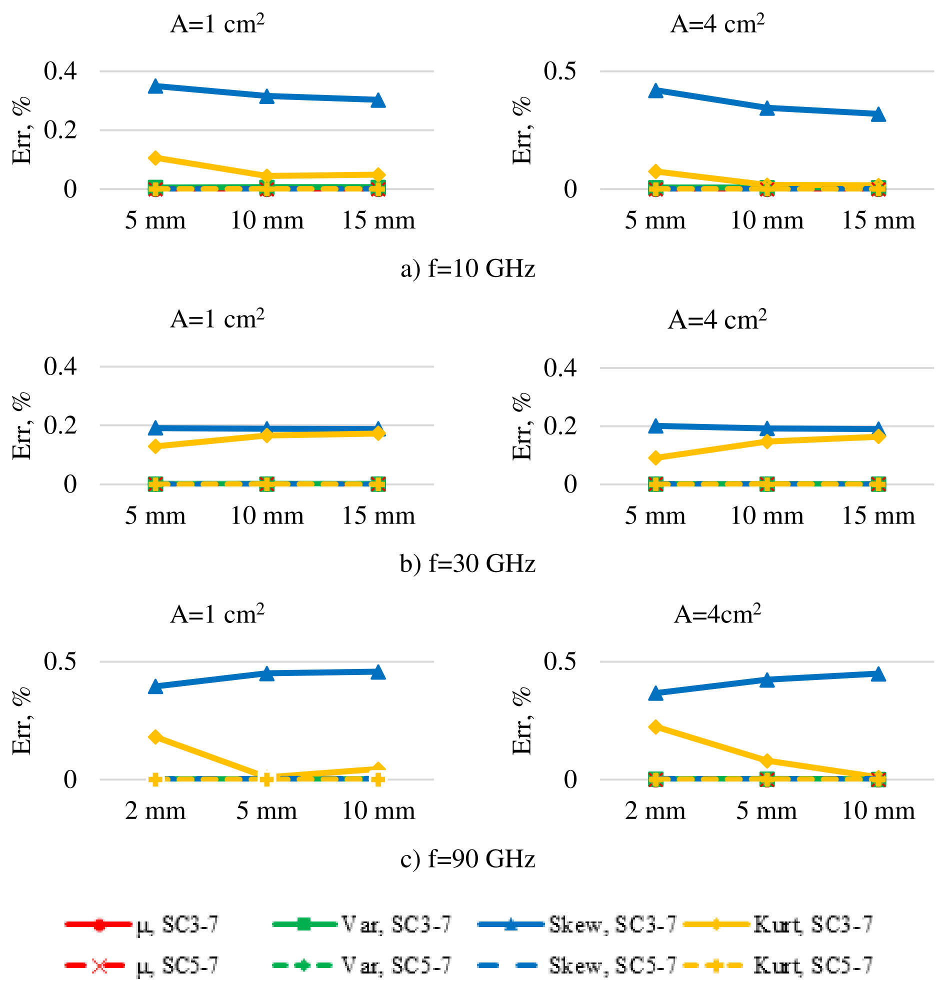

Figure 2. Absolute relative error, *Err* for *APD* mean (μ), variance (*Var*), skewness (*Skew*) and kurtosis (*Kurt*) at SC levels 3 and 5, i.e., 9 and 25 deterministic simulations, respectively. The reference level is 7, i.e., 49 simulations.

distribution is skewed very slightly to the right. The kurtosis is basically between 1.9 and 2.1 which is slightly below 3 (3 indicating the normal distribution).

Table 1. *APD* skewness

	f=10 GHz	*f*=30 GHz	*f*=90 GHz
***h* (mm)**	***A=1cm2***		
2 (5)	0.163433	0.208481	0.090261
5 (10)	0.194516	0.220544	0.102936
10 (15)	0.199247	0.223456	0.10812
***h* (mm)**	***A=4 cm2***		
2 (5)	0.187802	0.197194	0.090846
5 (10)	0.202269	0.214504	0.10193
10 (15)	0.202851	0.220264	0.106497

Table 2. *APD* kurtosis

	f=10 GHz	*f*=30 GHz	*f*=90 GHz
***h* (mm)**	***A=1cm2***		
2 (5)	2.012474	2.114749	1.84238
5 (10)	2.122495	2.155969	1.872214
10 (15)	2.136793	2.165654	1.887523
***h* (mm)**	***A=4 cm2***		
2 (5)	2.120457	2.072736	1.841103
5 (10)	2.15641	2.133117	1.863012
10 (15)	2.153042	2.153921	1.879998

Finally, Fig. 4 presents standard deviations from two 1-dimensional stochastic models, i.e., when skin conductivity and relative electric permittivity are random variables one-at-a-time. Standard deviation, *Std*, is obtained as a square root of variance. Although the 2-dimensional standard deviation is not very large, it is still possible to draw some conclusions regarding the impact of individual input parameters on output *APD* variation. Namely, the impact changes with frequency. At 10 GHz relative electric permittivity has higher impact than skin conductivity. However, at 30 and 90 GHz skin conductivity has larger standard deviation, therefore it is expected for skin conductivity to have larger impact on the total *APD* variance in this frequency range. The same behaviour can be observed no matter which control surface is used. Of course, different values are expected as depicted in Fig. 3.

4 Concluding remarks

Stochastic Collocation (SC) method for uncertainty quantification of absorbed power density, *APD,* at frequencies 10, 30 and 90 GHz and at various antenna-body distances for control surfaces 1 cm^2 and 4 cm^2 is presented. The radiation source is a halfwave dipole antenna, while skin tissue is 1-layered half-space with uncertain relative permittivity and conductivity.
SC method is non-intrusive, hence it is necessary to generate a set of *N* deterministic *APD* values to calculate

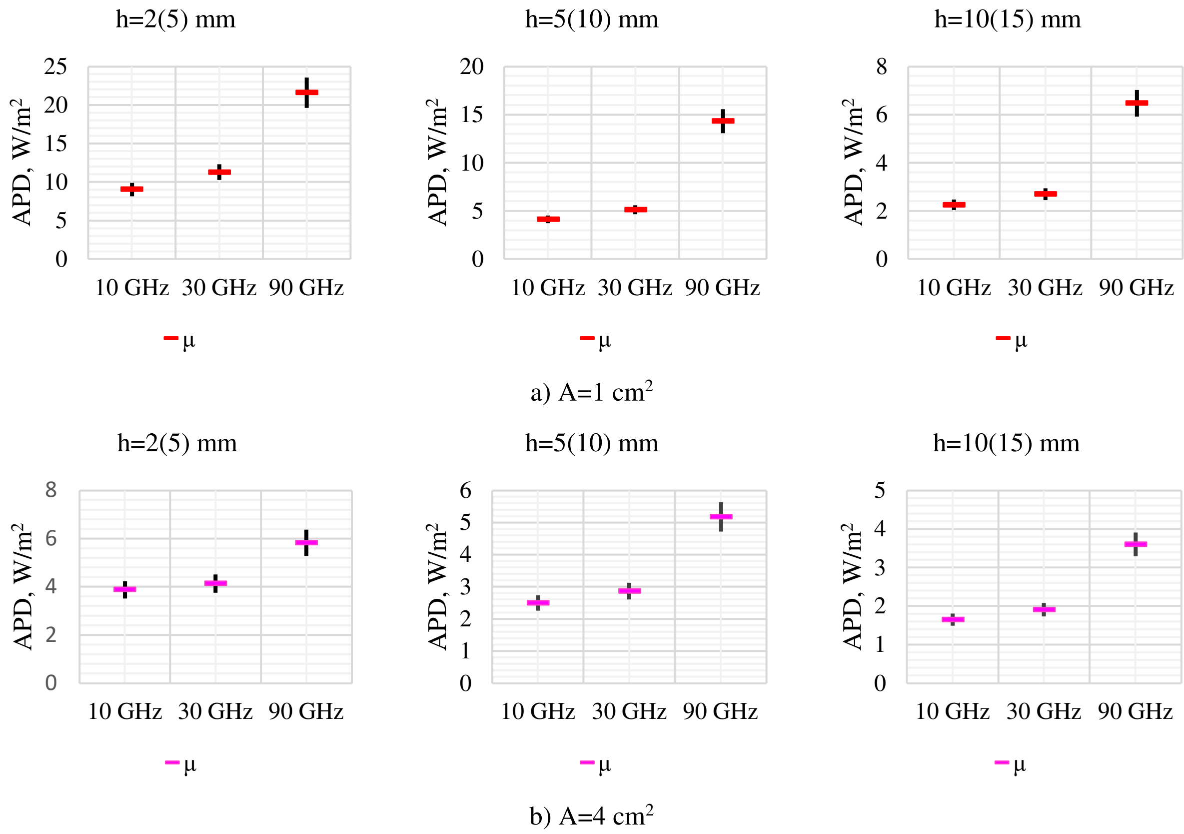

Figure 3. Confidence intervals for *APD* computed as $\mu \pm 3*Std$.

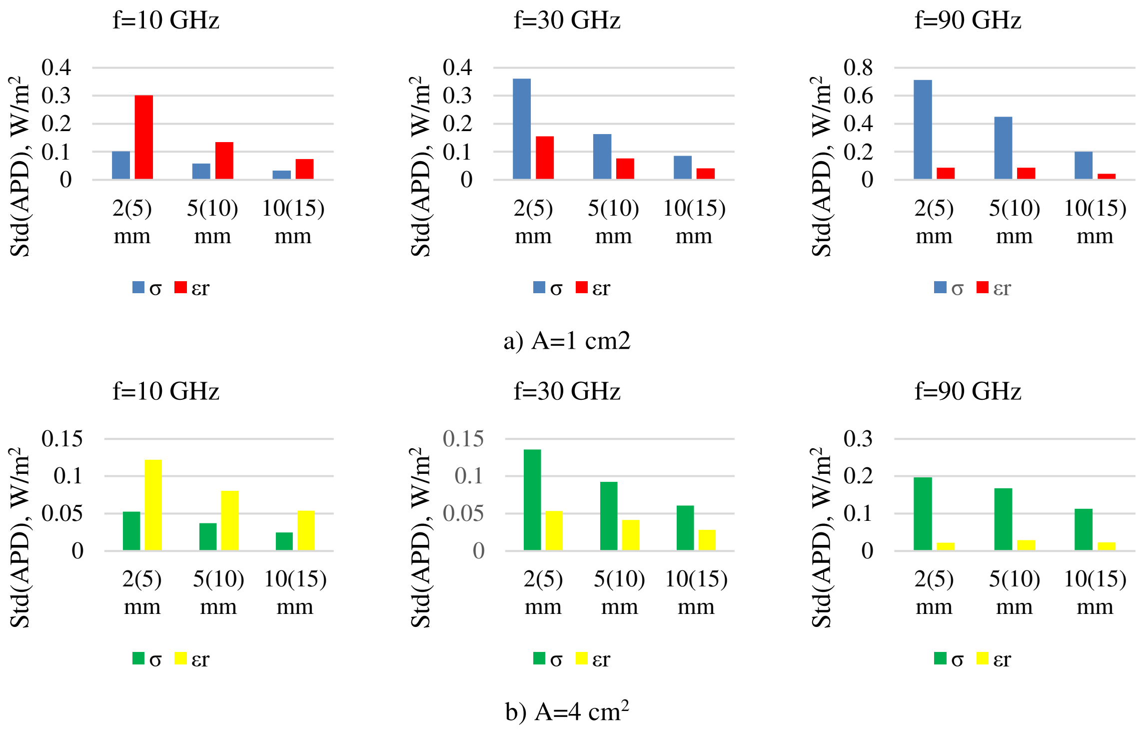

Figure 4. Standard deviation of *APD* for two 1-dimensional cases, i.e., when only skin conductivity is random variable and when only skin relative permittivity is random varaible.

stochastic moments. The deterministic code for *APD* computation is based on GB-IBEM solution of Pocklington equation for current and BEM formalism to determine the field irradiated by antenna.

Based on the presented results the following conclusions can be drawn:

- The convergence of SC method in computation of the first four stochastic moments, i.e., mean, variance, skewness and kurtosis for all combinations of frequency, antenna-body distance and control surface is satisfactory. Only 9 deterministic simulations of *APD* are needed to compute the stochastic moments.
- The variation of 20% around the nominal values for relative permittivity and conductivity does not cause significant dispersion of the resulting *APD*.
- At 10 GHz the impact of relative electric permittivity is higher than the impact of conductivity. However, skin conductivity is more significant at 30 and 90 GHz.

As the present work deals with a rather simple single-layer tissue model it should be considered strictly as an opener to the subject of stochastic deterministic modeling of APD. However, the future work will introduce antenna array as another radiation source, and 3-layered planar model consisting of skin, fat and muscle. Furthermore, stochastic-deterministic approach will tackle even more complex body models.

References

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