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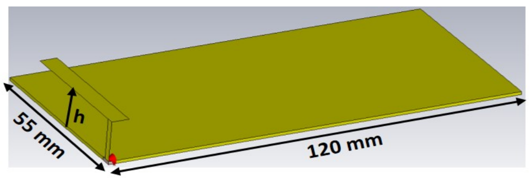

Fig. 1. Antenna on PCB with three different heights (h), where low-Q antenna has h=13 mm, high-Q antenna has h=2 mm and extremely high-Q antenna has h=1 mm.

***Abstract*—High-Q structures pose great challenges to their loss simulations in Time Domain Solvers (TDS). Therefore, in this work the thermal loss of high-Q antennas is calculated both in TDS and Frequency Domain Solver (FDS), which are then compared with each other and with the actual measurements. The thermal loss calculation in FDS is shown to be more accurate for high-Q antennas.**

I. Introduction

The frequency spectrum for mobile communication, due to the deployment of Long Term Evolution (LTE), is between 700 and 3800 MHz. This makes the antenna design in small form factors a huge challenge because of the fundamental limitation of antennas [1]. To address this, high-Q antennas can be utilized where the frequency range of interest is covered through tuning.

EM simulation software are typically used in the development phase of antennas for a product, long before any measurement of antenna performance is possible. Therefore, the accuracy of the simulation results is very important. Thermal loss (conductor and dielectric loss) calculation of electrically small high-Q antennas has shown not to be trustworthy using the Time Domain Solver (TDS) of commercial EM simulation software [2]. Therefore, the goal is to compare TDS and Frequency Domain Solver (FDS) in terms of thermal loss at low frequencies (700 MHz). Actual measurements are also performed to see how close the results of the two solvers are to measurements.

II. Antenna Design

Three simple Inverted L antenna (ILA) antennas are designed in a form factor of 120x55 mm^2. The low-Q antenna has a size of 40x5x13 mm^3, high-Q antenna has a size of 40x5x2 mm^3 and extremely high-Q antenna has a size of 30x2x1 mm^3, see Figure 1 and Table I. All three antennas from both solvers are matched using commercial circuit simulation software, and the matched impedances are then combined in the EM simulation software for obtaining total antenna losses. The low-Q antenna is matched using a series inductor (22 nH with Q=76), a shunt inductor (3.6 nH with Q=68) and a shunt capacitor (9.1 pF with Q=42). The high-Q and extremely high-Q antennas are matched using a series (22 nH with Q=76, 33 nH with Q=80) and a shunt inductor (3.6 nH with Q=68, 2.2 nH with Q=73).

TABLE I
UNLOADED AND LOADED Q OF THE LOW-Q, HIGH-Q AND EXTREMELY HIGH-Q ANTENNAS.

	unloaded Q	loaded Q
Low-Q antenna	4.2	3.6
High-Q antenna	142	58
Extremely High-Q antenna	290	74

The unloaded and loaded Q are defined as the antenna Q that is matched using lossless and lossy components, respectively. As seen in Table I, the difference between the unloaded and loaded Q increases somewhat exponentially as the antenna Q increases, which indicates that the loss in the components increases. The thermal loss also increases as a function of increasing antenna Q.

III. Simulation Parameters

As this work investigates thermal loss calculations in the TDS and FDS, the antenna and the Printed Cicuit Board (PCB) are made in annealed copper with a conductivity σ=5.80*10^7 S/m. Lossy FR-4 is chosen as the substrate with ϵ=4.3 and tan δ=0.025. The global mesh parameters, listed in Table II, are fixed throughout the simulations. In order to further improve the mesh towards obtaining converging results while maintaining low simulation time, the mesh density around the low-Q and high-Q antenna is increased locally (Dx=0.5, Dy=0.5, Dz=0.5). In the case of extremely high-Q antenna the local mesh is even denser (Dx=0.1, Dy=0.1, Dz=0.1).

TABLE II
TDS AND FDS GLOBAL MESH PARAMETERS.

TDS	
Lines/lambda	30
Lower mesh limit	20
Smallest mesh step	0.3

FDS	
Method	General purpose
Min. nr. of steps	20
Steps/lambda	4

IV. RESULTS

S-parameters are shown in Figure 2, where it is seen that the low-Q antenna covers the entire low band (700-960 MHz) at a SWR=3. The high-Q and extremely high-Q antennas have a bandwidth of 14 and 11 MHz, respectively. Note, the difference in bandwidth is very small despite of their unloaded Q values being very different, which is due to the increasing loss with increasing antenna Q.

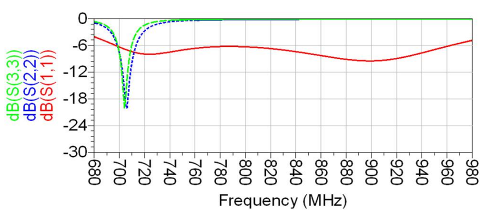

Fig. 2. S-parameters of the three antennas, where S_{11} is for the low-Q antenna, S_{22} is for high-Q antenna and S_{33} is for extremely high-Q antenna.

Table III presents the losses of low-Q antenna at three distinct frequencies. The Table shows reflection loss L_r, thermal loss L_t and component loss L_c. From the Table it is seen that L_t is somewhat similar in TDS and FDS.

TABLE III
LOSSES OF LOW-Q ANTENNA IN TDS, FDS AND MEASUREMENT.

	TDS			FDS			meas		
Acc.	-50 dB			1e-4			-		
Fr (MHz)	700	820	960	700	820	960	700	820	960
L_r (dB)	1.14	1.04	1.19	1.22	1.11	1.25	1.72	0.88	0.50
L_t (dB)	0.05	0.13	0.00	0.08	0.05	0.03	1.85	1.05	1.23
L_c (dB)	1.50	0.51	1.36	1.47	0.49	1.43			

Losses of the high-Q antenna are listed in Table IV, where it is seen that the L_t in TDS and FDS differs. TDS is even showing negative L_t, while FDS shows L_t closer to reality. In [3], it is shown that a self-matched antenna next to a PCB with an Q of 60 has L_t of 0.6 dB at 700 MHz. The high-Q antennas in this paper has more than double the Q. Therefore, FDS with L_t=0.5 dB seems to be more accurate. The L_c in TDS is higher compared to FDS, making the total loss in both solvers more similar.

The same results, with increased simulation accuracy, is shown in Table V. L_t in TDS is now positive, but fluctuates as the mesh is increased and do not seem to converge. In FDS the results are exactly the same.

TABLE IV
LOSSES OF HIGH-Q ANTENNA IN TDS, FDS AND MEASUREMENT.

	TDS			FDS			meas		
Acc.	-50 dB			1e-4			-		
Fr (MHz)	700	706	711	700	706	711	700	706	711
L_r (dB)	0.80	0.04	0.70	0.72	0.04	0.37	0.41	0.05	0.36
L_t (dB)	-0.19	-0.19	-0.32	0.51	0.50	0.49	4.78	4.21	3.88
L_c (dB)	3.80	3.60	3.45	3.04	2.94	2.86			

TABLE V
LOSSES OF HIGH-Q ANTENNA IN TDS AND FDS WITH INCREASED ACCURACY.

	TDS			FDS			meas		
Acc.	-80 dB			1e-12			-		
Fr (MHz)	700	706	711	700	706	711	700	706	711
L_r (dB)	0.77	0.02	0.63	0.72	0.04	0.37	0.41	0.05	0.36
L_t (dB)	0.19	0.19	0.06	0.51	0.50	0.49	4.78	4.21	3.88
L_c (dB)	3.52	3.35	3.23	3.04	2.94	2.86			

The losses of the extremely high-Q antenna are only simulated with highest simulation accuracy and listed in Table VI. The TDS shows Lt of only 0.5 dB while FDS shows around 1.6 dB, indicating again that FDS calculates L_t more accurate.

TABLE VI
LOSSES OF EXTREMELY HIGH-Q ANTENNA IN TDS, FDS AND MEASUREMENT.

	TDS			FDS			meas		
Acc.	-80 dB			1e-12			-		
Fr (MHz)	700	704	708	700	704	708	700	704	708
L_r (dB)	0.78	0.04	0.66	0.69	0.03	0.56	0.48	0.02	0.28
L_t (dB)	0.55	0.54	0.53	1.64	1.62	1.60	6.02	5.80	5.65
L_c (dB)	6.48	6.35	6.23	5.14	5.08	5.01			

V. CONCLUSION

In this paper the thermal loss calculations, for low-Q, high-Q and extremely high-Q antennas, in TDS and FDS are compared. It is shown that FDS calculates the thermal loss more accurate as antenna Q increases. However, due to the higher component loss in TDS both solvers show similar total antenna loss. For high-Q antennas the loss distribution in TDS is incorrect and FDS will be therefore more appropriate to use.

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