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The Effect of the User's Body on High-Q and Low-Q Planar Inverted F Antennas for LTE Frequencies

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***Abstract*—The influence of the user's body degrades small antenna performances. This paper investigates the detuning and the losses on high-Q planar antennas for small devices due to user proximity. The results at low frequencies for the Long Term Evolution (LTE) standard are compared to the results for a low-Q antenna. Two hand grips are studied and combined to a SAM (Specific Anthropomorphic Mannequin) phantom. It is shown that using the high-Q antennas the loss due to the mismatch is reduced but the absorption loss is increased.**

Keywords—PIFA; high-Q antenna; narrow-band antenna; tunable antenna; user's effect; detuning; hand effect; absorption loss; mismatch loss.

I. Introduction

Today's antenna designers have to deal with size challenges while building antennas for hand-held devices. The phone market is evolving towards smaller and slimmer designs which are contradictory with antenna limitations for more bandwidth at lower frequencies, in a limited space [1]. Another major constraint that antenna designers have to deal with for portable devices is the interaction with the user's body. The hand effect has been investigated, mainly in [2] - [4], and it has been found to detune the resonance frequency in an inductive way. The proximity of the user's head further disturbs the antenna near fields , causing more degradation of the resonance characteristics.

The Long Term Evolution (LTE) frequency spectrum extends mobile communication channels on 23 bands over frequencies between 700 MHz and 2.7 GHz. One way to cover the whole spectrum is to use tunable antennas - also called reconfigurable antennas. These antennas exhibit a narrow instantaneous bandwidth that can be tuned to resonate at different frequencies. In this sense they cover a large bandwidth.

Tuning techniques can refer to PIN diodes switches, Field Effect Transistors (FET) or Micro-Electro-Mechanical Systems (MEMS) switches among others. In all cases these mechanisms are used to change the current path on the antenna and introduce an additional reactance that will change the resonance frequency of the resulting antenna. In the following a variable capacitor connecting the antenna element and the Ground Plane (GP) is used.

This paper presents the effect of the user's body on a tunable Planar Inverted F-Antenna (PIFA) for frequencies between 700 MHz and 2 GHz. Low-Q and high-Q antennas are compared with respect to the detuning in frequency (Δf$_r$), the Absorption Loss (L$_A$) and the Mismatch Loss (L$_M$). Different hand grips are studied and further added to a SAM phantom. Section II presents the simulation parameters and the models used for the analysis. The results are presents in Section III and conclusions are disclosed in Section IV.

II. Simulation Parameters

A. Method

The following simulations are performed with a Finite-Difference Time-Domain (FDTD) software, using 1 mm space step size and an energy-based termination criterion. The handset was modeled with Perfect Electric Conductor (PEC) for the GP and the PIFA. The housing of the handset is simulated with a non lossy plastic : the relative permittivity ϵ_r is set to 3 and the conductivity σ to 0 S/m, in order to exclusively take into consideration the effect of the user's body. A capacitor is used to tune the antenna resonance frequency. The capacitor is also simulated as ideal, that is to say without an Equivalent Series Resistance (ESR).

B. Quality Factor (Q)

The investigated antennas are compared using their Q. The Q value that is considered hereafter is the Q for a perfectly matched antenna response at its resonance frequency. The antenna Q refers to the matched VSWR Q and it relates to the Matched Bandwidth (MBW) as shown in eq. 1 [5]:

$$Q_{fr} = \frac{2\sqrt{\beta}}{MBW_{fr}} \text{ , with } \sqrt{\beta} = \frac{VSWR-1}{2\sqrt{VSWR}}, \qquad (1)$$

where the characteristic impedance of the antenna is perfectly matched to the 50 Ω antenna's feed point resistance at the tuned frequency.

As tunable antennas are narrow-band in each operating frequency they are tuned to, their Q is rather high. Moreover the further away the antenna is tuned from its original resonance frequency, the higher its Q gets. This phenomenon is due to over-coupling with the GP, which resonates around 1.2 GHz when 100 mm long.

TABLE I
ANTENNA MODEL GEOMETRIES

Model	Volume occupied	Capacitance	Q
A1	40 x 22 x 5 mm^3	OFF	16
A2	40 x 22 x 2 mm^3	OFF	56
A3	40 x 22 x 2 mm^3	1 pF	360

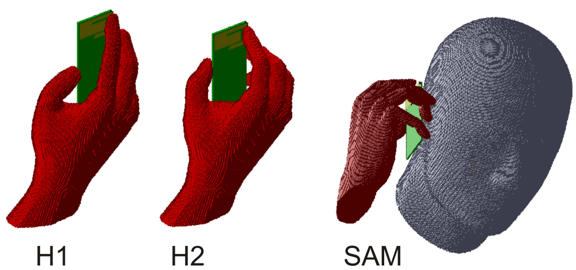

Fig. 1. Phantoms [6].

C. Antenna Models

The hand-held device used throughout the simulations is a candy-bar type, with a GP of dimensions 40 $\times$ 100 $\times$ 2 mm^3. Firstly a dual band PIFA is designed to operate at 900 MHz and 1800 MHz, covering the GSM bands.The antenna occupies a volume of 40 $\times$ 22 $\times$ 5 mm^3 and has a Q equal to 16. The antenna geometry is detailed in [7]. A lossless capacitor is placed between the PIFA and the GP. As there is no ESR modeled with the capacitor, its position only influences the frequency shift that can be obtained and the antenna Q. The distance between the feeding point and the tuning point is arbitrarily set to 20 mm. This set-up describes the first antenna model (A1), with the capacitor in the off-state.
Secondly the Q of this antenna is increased by reducing the distance between the PIFA and the Ground Plane (GP). This is the geometry of the second antenna model (A2). The initial distance separating the PIFA from the GP is reduced from 5 mm to 2 mm, which results in a Q for A2 raised to 56. Further the high-Q antenna is tuned to the LTE-700 band by switching to the on-state of the capacitor, where it provides a capacitance equal to 2 pF. The resultant antenna (A3) resonates at 720 MHz and has a Q of 360.
A1 will be denoted as a low-Q antenna whereas A2 and A3 will be high-Q antennas. The antenna geometries and characteristics are summarized in TABLE I. As the whole antenna structure is modeled as a PEC and the lumped component and phone housing are lossless, the source of all losses can only be in the lossy dielectric material used to model the user's hand and head.

D. Phantoms

The investigation uses realistic phantom head and hands, with a relative permittivity of the body tissue ϵ_r = 36 and a conductivity σ = 0.8 S/m at 900 MHz [2]. Two hand grips are used : the "firm" grip (H1) and the "soft" grip (H2). These two grips differ by the distance between the palm and the ground plane. In the "firm" grip case the center of the palm is at a distance of 20 mm from the PCB whereas in he "soft" grip the distance is twice larger. Fig. 1 shows the two grip models and the SA. In both grips, H1 and H2, the index finger is located in the antenna radiation area and in contact with the phone housing. Therefore it is responsible for the largest degradation of the antenna performance. The casing of the phone is not shown in the figures as it would mask the antenna description. In order to be able to compare the different antenna models the distance separating the SAM and the index finger in fixed for all the simulations and cases.

TABLE II
DISTANCES SEPARATING PHANTOMS AND RADIATING ELEMENTS [MM]

Antenna	$D_{GP,F}$	$D_{GP,H1}$	$D_{GP,H2}$	$D_{GP,SAM}$
A1	9	20	40	5
A2 and A3	6	17	37	8

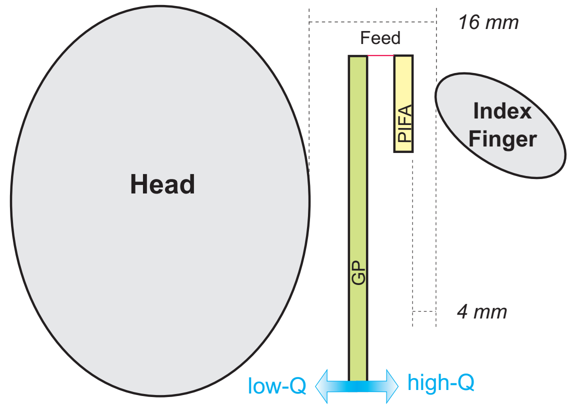

Fig. 2. Simulation set-up.

E. Simulation Set-up

In the proposed PIFA design the height of the antenna varies with the Q of the antenna. The higher the Q the smaller the height. It is known that most of the degradation due to the user's hand comes from the index finger, which is placed over the radiating element. In the proposed set-up the distance separating the index finger from the radiating element is fixed for all scenarios: 4 mm. In order to have comparative interactions from the index finger and the SAM a constant distance separates them: 16 mm. The set-up is shown in Fig. 2. Therefore the element that is "moving" to modify the antenna Q is indeed the GP. The GP thickness is 2 mm. The evolution of the antenna performances, with respect to its Q, considering the GP location is relevant since it is the main radiator at the low frequencies. To sum-up, when the Q gets higher the distance between the palm and the GP is reduced and the distance between the GP and the SAM is increased. TABLE II presents the set-ups for every grip and antenna model. The distances between the GP and the index finger, the GP and the palm of H1, the GP and the palm of H2 and the GP and the SAM are denoted $D_{GP,F}$, $D_{GP,H1}$, $D_{GP,H2}$ and $D_{GP,SAM}$ respectively.

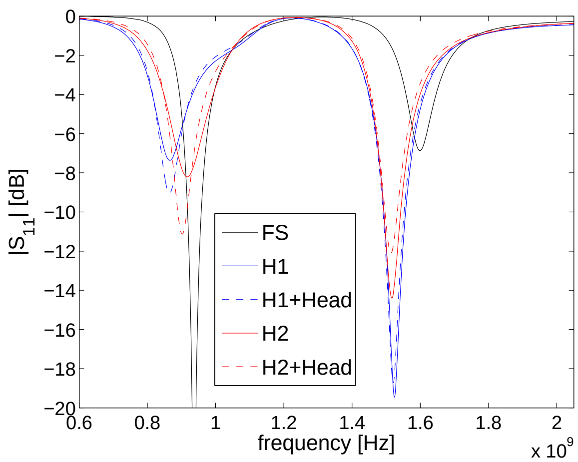

Fig. 3. |S11| parameter of the low-Q antenna with user's effect.

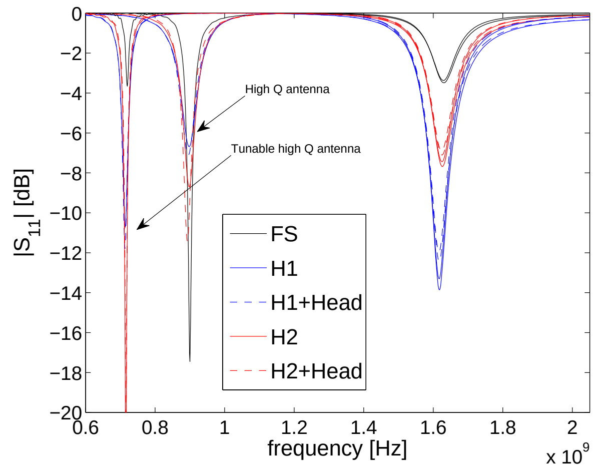

Fig. 4. |S11| parameter of the high-Q antennas with user's effect.

III. Simulation Results

The three above-described antennas are simulated. The user's effect on the return loss is shown in Fig. 3 and Fig. 4. It is further analyzed, with respect to the free space (FS) case in Tables III-V. The detuning (Δf_r), the bandwidth at -6 dB (BW) and the total loss (L_T) are compared to each other. On the one hand the distance of the GP to the palm changes with the antenna model and affects differently the radiation, since at low frequencies the GP is the main radiator. On the other hand the distance of the GP to the SAM changes with the antenna model as well, which further disturbs the radiation. The position of the finger is kept unchanged with respect to the antenna throughout the simulations. The simulation results will show if when the GP is closer to the hand but further from the head the effect of the user on the antenna performances is: unchanged, higher or lower. Furthermore this results will compare the user's effect on high-Q and low-Q antennas, thus on narrow-band and wide-band antennas.

As expected the "firm" and the "soft" grip disturb the antennas in the same way, but not up to the same level. In all cases the disturbance introduced by H1 is much larger than the degradation caused by H2. Two cases are studied: hand only and hand with SAM. The phone is placed beside the SAM and the hand in order to simulate the use case: "talk-mode". The SAM is then removed in order to isolate the effect of the hand alone.

A. Frequency Detuning

1) Low-Q case: In the low band A1 suffers an important detuning and mismatch from the addition of the user's hand and head. With H1 alone the antenna resonance is detuned more than 70 MHz whereas with H2 alone the detuning is reduced to 20 MHz. This difference is due to the tighter grip design that H1 exhibits. Mismatch to the 50 Ω feed line is due to the lossy material used to simulate the user's hand. Nevertheless the reflection coefficient is still match to an acceptable value: below the usual -6 dB threshold. The SAM adds further detuning on the case with H2, lowering the resonance frequency 35 MHz off the original one.

In the high band both grips and SAM detune the resonance frequency in the same way and to the same level.

2) High-Q cases: The detuning is significantly reduced for both high-Q antenna models, A2 and A3. The proposed high-Q designs experience in the low band a detuning of only 2 to 4 MHz for both grips, and 4 to 7 MHz with the SAM model. The high band resonance frequency is also almost unaffected by the addition of the user. Additionally for the high resonance frequency, the matching is improved and the bandwidth enlarged.

3) Tuned High-Q case: When the high-Q antenna is tuned to the LTE-700 band, its impedance response is above the conventional limit of -6 dB. However with the user interaction the matching is improved and the bandwidth enlarged. Even though the design seemed to not work in such low frequencies the user interaction actually helps without detuning. The tuning component does not degrade the observed high-Q performances with respect to detuning and matching.

B. Absorption and Mismatch Losses in the Low Band

The performances of the low-Q antenna, the high-Q antenna and the tuned high-Q antenna are compared in the TABLE III-V, with respect to losses. A1 and A2 have different locations, with respect to the user, and different Q values. A2 and A3 are placed in the same locations and only the Q is increased, due to the 2 pF capacitor.

1) Losses due to grips: The Absorption Loss (L_A) due to H1 increases from 4.7 dB to 8.8 dB, from the lowest antenna Q to the highest. As from A1 to A2 the GP is placed 3 mm closer to the palm, higher losses are expected. Between A2 with a Q=56 and A3 with a Q=360 the L_A increase is not significant, the jump occurs between A1 with a Q=16 and A2. With the other grip H2, the L_A level is similar to the one with H1 for the low-Q model. The loss increases significantly between the antenna models A2 and A3. In general H2 absorbs less power than H1 because of its looser grip.

TABLE III
USER'S EFFECT ON THE LOW-Q ANTENNA A1

	FS	H1	H1+SAM	H2	H2+SAM
f_r [MHz]	937	866	865	917	902
Δf_r [MHz]	0	71	72	20	35
BW [MHz]	70	64	64	87	81
L_A [dB]	0.0	4.7	9.8	4.3	9.8
L_M [dB]	0.0	2.3	2.5	0.8	0.9
L_T [dB]	0.0	7.0	12.3	5.1	10.7

TABLE IV
USER'S EFFECT ON THE HIGH-Q ANTENNA A2

	FS	H1	H1+SAM	H2	H2+SAM
f_r [MHz]	900	898	895	898	893
Δf_r [MHz]	0	2	5	2	7
BW [MHz]	20	20	24	30	30
L_A [dB]	0.0	8.3	11.4	4.8	9.6
L_M [dB]	0.0	1.0	0.9	0.6	0.5
L_T [dB]	0.0	9.3	12.3	5.4	10.1

2) Losses due to SAM and the grips: In the low-Q antenna model the L_A is unchanged whether it is the "firm" or the "soft" grip that is used as long as the SAM is included in the simulation. The user's head accounts for 5 dB of the total losses (9.8 - 4.7 or 9.8 - 4.3 , see TABLE III). In the high-Q designs the absorption loss due to the user (SAM and hand) is increased. However the participation of the SAM is actually decreased to ~3 dB as the distance between the GP and the SAM is increased and the Q gets higher (11.4 - 8.3 or 11.5 - 8.8, see TABLE IV and TABLE V). The total absorption loss due to the user with H1 is greater than 11 dB and there is not any degradation due to the further increase of the Q (that is to say to the increase of the capacitance of the tuning component). In the soft grip case H2 the total absorption loss increases only 1 dB between A2 and A3.

3) Total Loss (L_T): In the low-Q design the Mismatch Loss (L_M) is higher than in the high-Q designs and the L_A is smaller than in the high-Q designs. Nevertheless in the talk mode (SAM and hand) the total loss is equal to 12 dB for H1 and SAM on the three antenna models, and to ~11 dB for H2. The effect of the hand alone exhibits the L_T 2 dB higher for the high-Q designs compared to the low-Q design with H1. Moreover the lumped component does not affect the losses with H1, up to 9 dB. In the case of H2 alone, 5 dB total loss are observed in both A1 and A2. They are increased to 7 dB for the highest antenna Q model.

IV. CONCLUSION

In this paper high-Q and low-Q antennas where designed and compared with respect to their interaction with the user. The simulated antenna is a PIFA and its surface is unchanged from one model to another. The Q is modified by first reducing the height of the PIFA with respect to the GP, and then increasing the value of the tuning capacitor. Reducing the

TABLE V
USER'S EFFECT ON THE TUNED HIGH-Q ANTENNA A3

	FS	H1	H1+SAM	H2	H2+SAM
f_r [MHz]	720	714	713	716	716
Δf_r [MHz]	0	4	7	4	4
BW [MHz]	0	20	20	15	15
L_A [dB]	0.0	8.8	11.5	7.0	10.8
L_M [dB]	0.0	0.6	0.7	0.2	0.2
L_T [dB]	0.0	9.4	12.2	7.2	11.0

height of the PIFA of only 3 mm results in a significant increase of the Q. Two hand grips are compared, one is holding the phone tight and the other is more loose. The simulations with only a hand isolate the effect of the user's hand alone, as it is responsible for most of the degradation of the antenna performance. A SAM is further added to the simulations to reproduce a "talk mode" operation of the device.

It is observed that the high-Q antennas have a very reduced detuning when held, and in close proximity of the user - in both low and high bands. The L_M of the high-Q antennas is below 1 dB. Nevertheless the total loss is not improved because the absorption loss in the high-Q models is higher than in the low-Q model. With H1 the L_A is significantly higher for the high-Q antennas. This results in quasi-equal total loss for the three antenna models in all simulation environments: 11 to 12 dB of total loss in "talk mode" for both grips and three different antenna Q, from 16 to 360.

The response of a tunable high-Q antenna for the low LTE frequency bands is investigated when the user is located in the close proximity. The comparison with a typical low-Q antenna shows that the detuning is reduced by 95%, and the mismatch loss does not exceed 1 dB for high-Q antennas. However, the absorption loss is larger; hence the total loss remains similar in all cases.

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