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Feasibility study of 4G cellular antennas for eyewear communicating devices

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***Abstract*— A feasibility study of 4G cellular antennas operating in the LTE, GSM, DCS, PCS and WLAN2400 standards for wirelessly connected eyewear is presented. The target bands are 700-960MHz and 1.7-2.7GHz. The antenna designs are capacitive coupling element types, with simple layout printed on one side of the PCB substrate. Three different antennas are examined in terms of obtainable bandwidth potential, reflection coefficient and Specific Absorption Rate values considering two human head models (SAM and Visible Human) to provide general guidelines for advanced studies and further prototype fabrication. The SAR results indicate that the power should be limited especially for the 1g standards.**

***Index Terms*— eyewear, coupling element, LTE, GSM, SAR.**

I. Introduction

Among the past years, there has been an increasing interest and demand for various electronic devices having wireless connectivity: mobile phones, cameras, USB keys, wireless mouse and keyboards, printers and even watches. A recent interest has also risen for wirelessly connected eye-wear devices i.e. spectacle or glasses. Therefore, numerous competitors and a large number of ongoing studies exist on this subject, one of which is very well advanced and planned to be released on the market in 2014 [1]. This device uses Bluetooth 4.0 and Wi-Fi 802.11b/g protocols for connectivity around 2.4 GHz and the antenna is placed behind the ear similar to headset antennas for mobile phones [2, 3]. As the Bluetooth power levels are very small, the Specific Absorption Rate (SAR) values are not of concern [4, 5]. However, the eyewear connectivity is currently limited to Bluetooth and WLAN. Therefore, it is foreseen by telecommunication specialists that within the forthcoming years, these glasses could even replace mobile phones, the two major problems to be solved being the battery and the screen size for efficient integration, the latter being already addressed with the semi-transparent screen of the current eyewear prototypes to be released soon. In this context, there is clearly a need for 4G cellular antennas with satisfactory performance for next–generation eyewear devices as well as SAR compliance within the human head of the user.

In this paper, a feasibility study of 4G cellular antennas for eyewear covering 700-960MHz and 1.7-2.7GHz is presented, taking into account the SAR levels in the specific anthropomorphic mannequin (SAM) and Visible Human head (VH). Three possible antennas are evaluated with very simple printed coupling element (CE) antennas each of them associated with a bespoke matching network. In Section II, the antenna designs are explained in details and simulation results for reflection coefficient are given when the eyewear device is closely positioned to the head of the user. In Section III, the SAR analysis for the three antenna prototypes is presented for SAM and VH. Finally, a general conclusion is made in Section IV along with prospective work.

II. Antenna Solutions

It is a challenging issue to design a dual-band antenna able to operate within the 30% and 45% frequency bandwidth of 4G mobile communication standards (700-960MHz, 1.7-2.7GHz) in a space naturally limited by the end-product dimensions of eyewear. Since the wavelength is very large in comparison to the area reserved for the antenna in the lower operating band, we believe that resonant antennas are not appropriate. Therefore, we propose to use a non-resonant CE to benefit from the low quality factor of the chassis of the structure [6]. These simple structures, which are fed similarly to monopoles, excite currents on the PCB ground plane. The antenna can then be tuned to the desired operating band and suitable impedance value with the help of a matching network (MN). The simulated PCB model can be observed in Fig. 1. A realistic geometry was implemented from an existing prototype [1]. For this feasibility study, non-metallic frames were considered. However, previously metallic frames have affected antenna performance and SAR values [7-8]. The simulations were always carried out with the presence of two human heads (SAM and VH). As can be seen in Fig. 1, the total dimensions of the FR4 PCB are 160×20×0.8mm^3 with a perpendicular section of 32×20×0.8mm^3 towards the eye and with a missing section of 55×15×0.8mm^3 around the ear of the user.

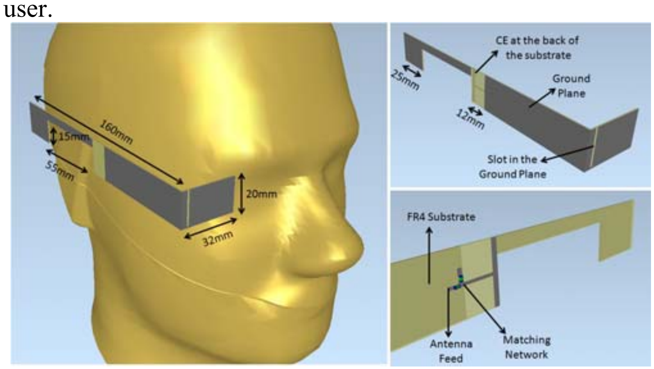


Fig. 1- Antenna model for Prototype-1 with SAM head

The analysis of the structure concluded there are only three possibilities to excite this PCB ground plane with a capacitive CE. The first consists of a CE placed in the middle of the long portion of the PCB, just in front of the ear of the user as a simple metallic strip 2mm wide, printed on the inner side of the substrate. Simulations are carried out in EMPIRE XCcel 6.01. The bandwidth potential (BP) of the antenna without the MN was evaluated with Optenni Lab commercial software [9]. This optimized BP, given for an optimized 2-element MN at each frequency point, is sufficient to cover our target high-band since being higher than 1GHz around 2.2GHz (Fig. 2). However, this BP curve shows it is not possible to additionally cover the 700-960MHz at the same time for this antenna placement, mainly because the CE position is not optimal for current excitation at those frequencies. Therefore, a 2-element MN (a shunt inductor of 3.2nH and a series capacitor of 1.8pF) was used at the feed of the CE to cover the 1.7-2.7 GHz band with a -6dB reflection coefficient. Also, we can see in Fig. 2 good agreement between the simulation results with the SAM phantom and VH model. The simulated radiation efficiency taking into account the lossy head is between 20% and 35% in the 1.7-2.7GHz frequency band.

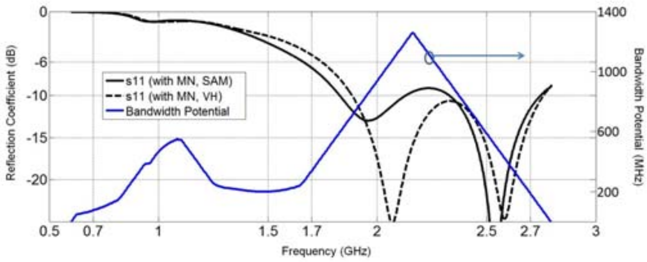


Fig. 2- Simulation results for Prototype-1

In the second antenna prototype, the CE is placed behind the ear (Fig. 3). It is evident from Fig. 4 that the BP is higher than prototype-1 both in low and high band due to the fact that the currents are better excited on the whole length of the PCB. With a MN consisting of two lumped components (a shunt inductor of 14nH and a series capacitor of 1.6pF), a dual-band response can be obtained covering 700-960MHz and 1.7-2.7GHz with a reflection coefficient below -6dB. The matching responses of the antenna on the SAM phantom and on the VH head are again in good agreement. The simulated radiation efficiencies are on average 9% in the low-band and 20% in the high-band.

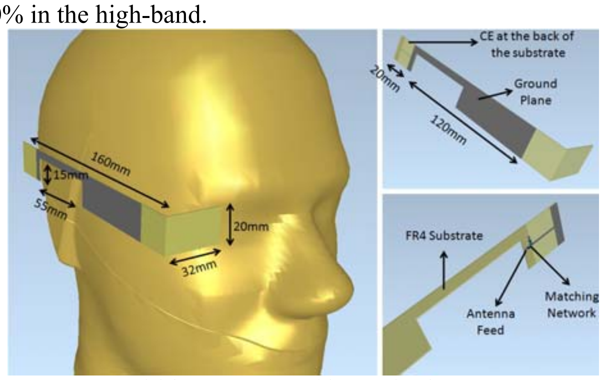


Fig. 3- Antenna model for Prototype-2 with SAM head

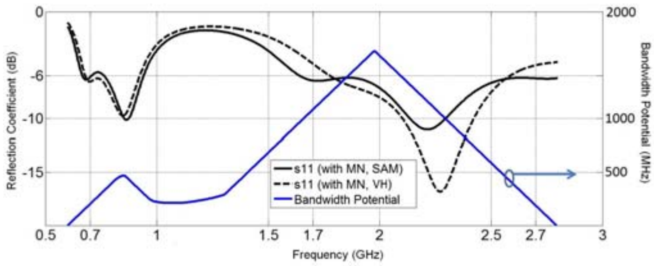


Fig. 4- Simulation results for Prototype-2

The CE in prototype 3 is placed at the other end of the PCB substrate, closer to the eye (Fig. 5). As seen in Fig. 6, a dual-band coverage can also be achieved for this antenna placement, using a MN of three lumped components (two series inductors of 8 and 12nH and a shunt capacitor of 0.2pF) at the antenna feed. The simulated radiation efficiency is around 14% in the low-band and 36% in the high-band.

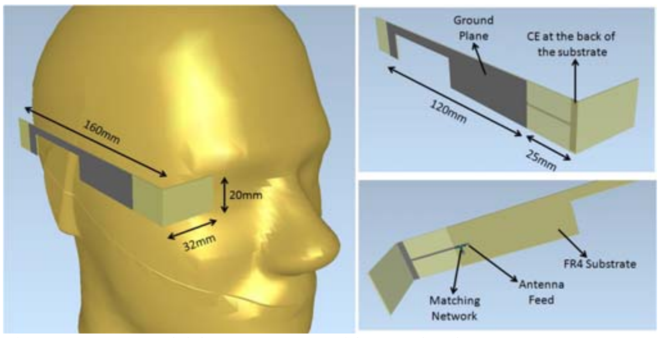


Fig. 5- Antenna model for Prototype-3 with SAM head

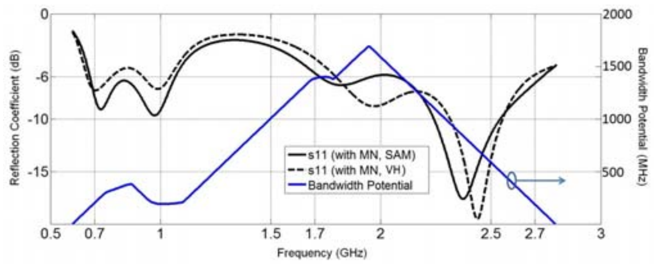


Fig. 6- Simulation results for Prototype-3

The radiation patterns of all three prototypes, shown in Fig. 7 for one frequency point in both low and high frequency band show an intuitive tendency to radiate away from the head like conventional mobile phones.

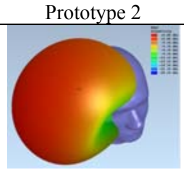
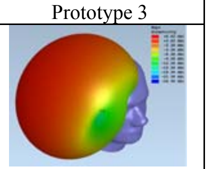
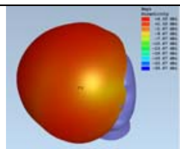
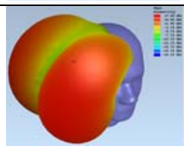
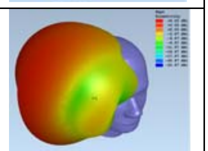
Freq.	Protototype 1	Prototype 2	Prototype 3
800 MHz			
2200 MHz			

Fig. 7- Simulated radiation patterns of all prototypes at 800 and 2200 MHz

III. SAR SIMULATIONS AND ANALYSIS

Over the last 20 years, there has been widespread scientific and public concern that electromagnetic fields radiated from mobile phones may be harmful to human health. The power transmitted from mobile phones is tightly controlled in order to limit the power absorbed in the head. The standard dosimetric parameter is SAR which is the power absorbed by a unit mass of tissue (W/kg). There are two internationally recognized standards: Europe, which defines a limit of 2W/kg averaged over 10g for 6 minutes [10] while the USA sets a slightly stricter limit of 1.6W/kg over 1g for 30 minutes [11].

Many papers have examined the SAR in the head from mobile phones with the SAM and heterogeneous heads [12-13]. The 1g SAR is typically nearly double the magnitude of the 10g SAR. The SAM phantom generally gives a higher (conservative) SAR value and it is well-known that SAR values from mobile phones are dependent on the frequency, the distance of the source from the head and the type of antenna. The SAR as a function of distance into a homogenous phantom decays at an exponential rate and is frequency dependent. The situation is more complex in real human heads, which consist of many tissues with different dielectric properties and hence discontinuous interfaces. These interfaces can cause parts of the body, for example the eye, to resonate where the electric fields are increased and do not decay with distance. The SAR in the eye can be particularly high at frequencies between 600 and 2400MHz depending on the size of the eye, the surrounding tissues, the presence of the eyelid, the angle of incidence and the polarization as the eye is not perfectly spherical [8, 14-15].

Previously the authors have shown that metallic spectacles can act as a passive scatterer and significantly increase the SAR in the human head and in particular the eye [8]. The eyes have received particular attention in the literature [8, 14-15]. As the metallic shape of the glasses extends around the front of the eye, it is important to use the anatomical head model which includes an eye – this can only be evaluated via simulations. All SAR results are normalized to 0.25W to account for the time averaged power over the different bands [13]. Note GSM 1800 should be reduced by an additional factor of 2 to normalize to 0.125W.

A. SAM phantom

The SAR results for the SAM phantom are shown in Table 1. They are normalized to both 0.25W incident power and 0.25W after considering the port mismatch (S11). Different liquid properties were used for the different bands and varied between (ε_r = 41.5; tanδ = 0.467) at 835MHz and (ε_r = 39.2; tanδ = 0.337) at 2500MHz. The values that are below the relevant SAR standards are in bolds and italics. The close proximity of the source to the head and the lack of shielding ground plane resulted in a higher SAR values than typical mobile phones. Note that the radiation efficiencies of the designed eyewear antennas are much higher than the total efficiencies traditionally obtained with modern mobile phones in the talk position, covered by the hand of the user (typically 5% in low band and 15% in high band). The SAR is above the 1g SAR standards in all cases while the 10g SAR values are generally acceptable. The SAR values with Prototype 3 are lower as the primary excitation is further away from the head.

TABLE I
SAR VALUES IN SAM PHANTOM (W/KG)

		0.25W incident power		0.25W power after S11	
Prototype	Freq (MHz)	1g SAR	10g SAR	1g SAR	10g SAR
1	1900	7.86	3.32	8.37	3.53
1	2200	4.31	2.07	4.88	2.35
1	2500	4.36	***1.54***	4.39	***1.55***
2	835	4.33	2.08	4.96	2.39
2	1900	2.97	***1.47***	3.89	***1.92***
2	2200	4.18	***1.99***	4.54	2.16
2	2500	3.68	***1.83***	4.69	2.33
3	835	4.17	2.03	5.50	2.68
3	1900	2.47	***1.18***	3.19	***1.53***
3	2200	2.22	***1.04***	2.60	***1.22***
3	2500	1.96	***0.82***	2.11	***0.89***

B. Visible Human phantom

The SAR results with the heterogeneous head are shown in Table II. The tissue properties in EMPIRE XCcel are dispersive and therefore automatically change with frequency. The SAR averaging volume did not include the pinna because it is considered as an extremity. The results are similar to the SAM phantom results in terms of distribution and the 1g SAR values are generally above the standards while the 10g SAR results are always below the 2W/kg limit. The heterogeneous head has a different external geometry and therefore all the distances from the antenna to the head are slightly changed. Except for Prototype 3 at 2500MHz, the SAR with the VH head is always less than with the SAM phantom. The radiation efficiency is around 10-12% at 835MHz but increases to 20% at the higher bands and even to 35% with Prototype 3. In those simulations, it was observed that the metallic section of the eyewear in front of the eye can launch a surface wave across the front of the eye. The SAR distributions are shown in Fig. 8. The maximum SAR always occurs at the side of the head. Secondary hotspots in the eye can be seen with Prototype 1 and Prototype 3 which needs further investigation in future studies.

TABLE II
SAR VALUES IN VISIBLE HUMAN PHANTOM (W/KG)

			0.25W Incident power		0.25W power after S11	
Prototype	Freq (MHz)	Eff (%)	1g SAR	10g SAR	1g SAR	10g SAR
1	1900	25.2	3.53	***1.64***	3.86	***1.79***
1	2200	36.0	2.90	***1.32***	3.04	***1.38***
1	2500	42.1	1.80	***0.85***	1.84	***0.87***
2	835	10.0	***1.50***	***0.97***	1.69	***1.09***
2	1900	19.8	1.64	***0.83***	2.03	***1.03***
2	2200	21.2	2.25	***1.09***	2.35	***1.14***
2	2500	20.9	2.51	***1.14***	3.04	***1.38***
3	835	12.7	1.32	***0.80***	1.88	***1.14***
3	1900	38.0	2.40	***0.91***	2.83	***1.07***
3	2200	33.3	2.32	***1.00***	2.82	***1.21***
3	2500	37.2	2.62	**1.01**	2.73	**1.05**

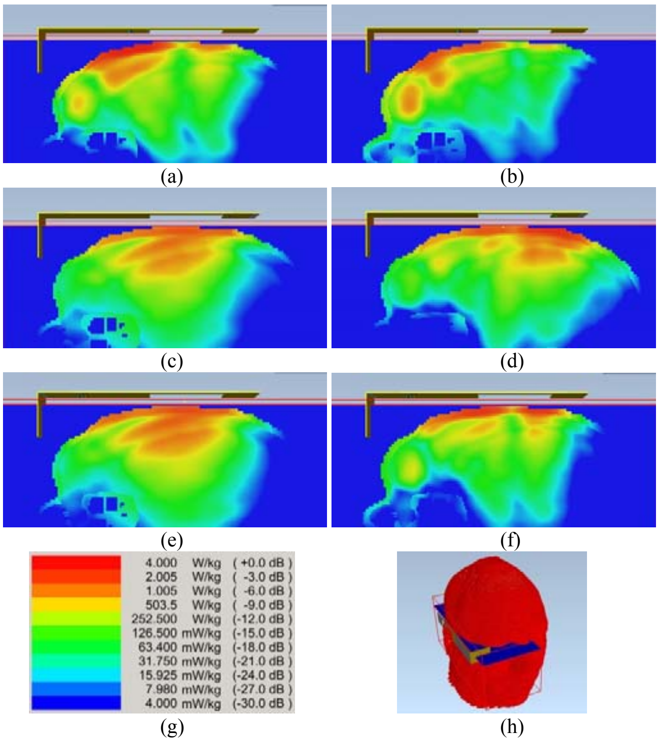


Fig. 8- The 1g SAR in the Visible Human head: (a) Prototype 1 at 1900MHz; (b) Prototype 1 at 2500MHz; (c) Prototype 2 at 835MHz; (d) Prototype 2 at 2500MHz; (e) Prototype 3 at 835MHz and (f) Prototype 3 at 2500MHz. (g) scale for all SAR diagrams; (h) location in the head were the SAR diagram are recorded.

IV. Conclusion

We have presented three possible locations for 4G cellular antennas on an eyewear device covering 700-960MHz and 1.7-2.7GHz. Average radiation efficiencies of 10-12% at 835MHz and from 20% to 35% at the higher bands were obtained, which to the best of our knowledge is state-of-the art. Generally, the SAR levels in the head would be above the 1g SAR standards but often below the 10g SAR levels when normalized to 0.25W. At certain antenna geometries and frequencies, hot spots are created inside the eye. Therefore, it is advised that the maximum power levels should be limited as is often the case with mobile phones. This feasibility study paves the way for future investigations: consideration of metallic frames, consideration of plastic casing around the PCB, consideration of the finger position for operation control and of course, fabrication and measurement of prototypes.

Acknowledgements

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