Design and optimization of circularly polarized antennas for mobile shooting of sport events.

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Abstract: A new circular polarized antenna model, operating at the lower ultrahigh-frequency (UHF) band, and for needs related to shooting sports events on the move, has been investigated with the aid of the COMSOL Multiphysics simulator. The reduced dimensions of the radiating system, to be hosted in the top case of the motorcycle used for shooting, pose a challenge to the antenna's design, since set a lower bound to the achievable operating frequency and a limitation in the antenna bandwidth. In addition, as the system is requested to operate without degradation for any possible reciprocal orientation between the transmitting mobile antenna and the receiving one installed on the helicopter, circular polarization (CP) needs to be adopted. To fulfill the above requirements, several antenna shapes have been considered and tuned to search for the best performances in the frequency range of interest. The simulated results have been confirmed in the prototypes by laboratory measurements.

Keywords: COMSOL Multiphysics; Circular polarization (CP); Shooting Sports Events; Ultra High Frequency (UHF) band, Dual-crossed-double-folded (DCDF) dipoles.

1. Introduction

During the most important TV and sport events, the deployment of a significant number of radio-frequency resources, used by radio cameras, radio microphones, communications systems, radio links and so on, needs to be efficiently coordinated throughout the whole duration of the event. For the special case of "*Giro d' Italia*", the most famous cycling tour in Italy, typically eight motorcycles are equipped with various facilities, including radio cameras, audio radio links for commentators, geolocalization means, etc. (Fig.1). Three helicopters and an airplane are employed above the race, two of them for video shooting, the others as "bridge", relaying the signals received from the motorcycles to a receiving station. The latter sends all of the signals to RAI mobile production control room situated in OB van at the finish line; here technicians mix the signals from the motorcycles, helicopters, still cameras, mobile interview team cameras, and RAI's finish-line commentary.

The video (shooting) and audio (commentators) motorcycles are equipped with complex A/V and transmission/reception devices and multiple antennas each. In particular, each commentator motorcycle must sends the commentary voice on the RF helicopter uplink, while receiving in turn a personalized signal (audio plus director's voice) from the production control room. Due to this "personalization", up to eight frequency slots are needed, usually allocated in the frequency gaps between TV channels, from 450 to 600 MHz. Some old audio transmission systems still use the TV frequencies around 200 MHz.

Figure 1. Motorcycles adopted for the cycling event "Giro d' Italia"

The radiating system adopted so far for the commentary was a cumbersome log-periodic UHF antenna placed near the commentator's seat; this poses serious problems in terms of personal safety.
Also, having an inherent linear polarization radiation, the currently used antenna system suffers from polarization mismatch on the communication link, due to the random relative orientation between the transmitting (motorcycle) and receiving (airborne) antennas. This results in a significant link margin loss during the activity of shooting sports events on the move.
The study carried out in the present paper is aiming to identify and design a more-optimized, low profile and compact antenna solution, to be placed in the motorcycle top case, in order to overcome the safety issues. The link impairment can be easily overcome by adopting a solution based on circular polarization (CP) that allows the correct reception from any possible reciprocal orientation between the

antennas. Taking in consideration the above requirements, an antenna's prototype has been numerically implemented using the RF module of the COMSOL Multiphysics software.
An extensive simulative analysis has been performed; laboratory tests performed on prototypes have proven good agreement with simulation results.

2. Dual-band VHF/UHF circularly polarized antennas

In a preliminary phase of the work, it was requested for the antenna to operate in a dual-band (VHF, UHF) configuration. However, the limited space available in the top case (about 40 cm x 20 cm), is conflicting with the VHF operation that would require somewhat larger dimensions. In facts, antenna size, bandwidth and efficiency are strictly related by the Chou's limit [1].
Some initial attempts of designing such dual-band antenna have been done with the aid of COMSOL Multiphysics software. The first approach was based on a two-arms Archimedean spiral structure [2].
This solution belongs to a specific category of antennas whose pattern and impedance are practically independent of frequency for all frequencies above the minimum cut-off value.
The general formula for this frequency independent antenna form is:

$$r = e^{\alpha(\varphi+\varphi_0)}F(\theta)$$

where r, θ, and φ are spherical coordinates, α and φ_0 are constants, and F (θ) is a theta function. The importance of frequency independent of the spiral antenna is that the frequency change only rotates the active region, the radiating area, along with the spiral arm. Therefore, scaling factor, α, determines the spiral arm's length and consequently the lower cut-off frequency of the antenna, allowing the frequency independent antenna to be scaled according to the desired frequency response. By choosing a scaling factor large enough to achieve the desired electrical performance, it is possible to obtain better overall performance.
In the light of the above considerations, in particular for the strictly limitations imposed by the antenna's size, i.e. the diameter, the spiral antenna was simulated (alone), showing a good CP performance only in the UHF band. As a next step, this basic model has been complemented with two flat, inductive-loaded short dipoles located symmetrically w.r.t. the spiral. Each dipole has been previously tuned to resonate at the desired VHF frequency (230 MHz). Then, the two dipoles have been connected to the existing flat spiral (Figure 2).

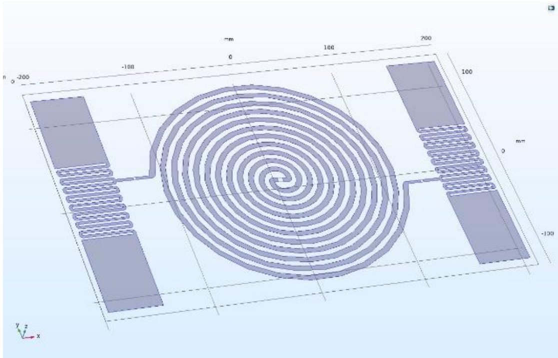

Figure 2. A dual-band VHF/UHF circularly polarized antenna

The connection points on the meander inductors have been optimized in VHF *by try and error* to achieve both a good CP performance in terms of *axial ratio* (AR)[1], and a satisfactory antenna gain at boresight for both 230MHz and low-UHF bands, as reported in Figure 3.

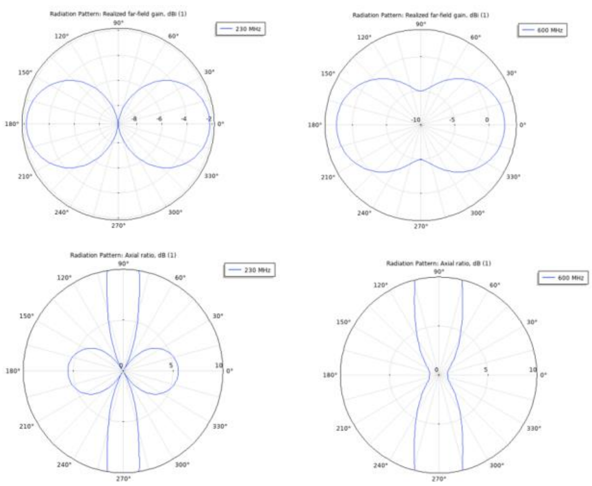

Figure 3. Antenna gain (top) and axial ratio (bottom) for the dual-band VHF/UHF circularly polarized antenna.

Another attempt has been done with a two-arms Archimedean spiral structure alone, trying to extend its operation down to the VHF range by applying radial perturbation at the spiral periphery (a so called "meander spiral antenna" [3]). This kind of structure is properly modeled by COMSOL Multiphysics in the Plane Geometry node by means of Parametric Curves including the equations in terms of the

[1] It is defined as the ratio between the transversal components of the electric far field. A good CP axial ratio is around 0 dB.

angular variable. Suitable parameters in the equations allow to describe the spiral pitch, the meander angular frequency and the radial modulation. Figure 4 shows the Work Plane view of the structure.

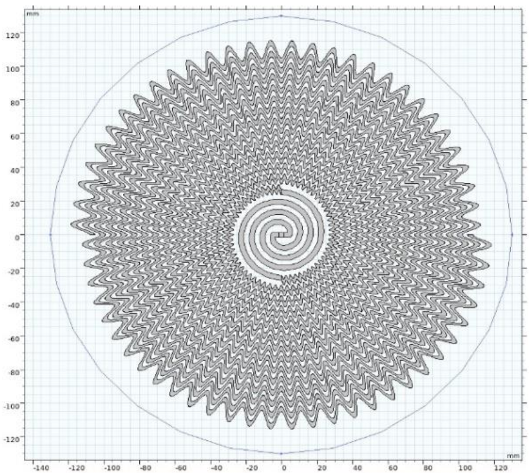

Figure 4. A meander spiral UHF circularly polarized antenna

Simulations have shown that, although the minimum usable frequency has actually extended towards the VHF range, the goal of 230MHz was not yet fully reached within the available antenna diameter.
The initial requests for bi-band operation have been subsequently relaxed: since the VHF link is used for legacy equipment, it has been decided to overlook this band in favor of the newest UHF radio equipment.

3. UHF–CP Archimedean spiral antenna with reflector

Besides the choice of the polarization's type, another important requirement to fulfill is the maximization of the energy transfer between the communication link. As a consequence, the antenna should be properly designed so as not to radiate downwards. A well-known solution to cut the backlobe energy consists in the adoption of a conducting plane reflector positioned at a distance of λ/4 [4]: the reflection of the wave in the back direction allows forward gain increment. In addition, in our case this choice allows us to isolate the radiating system from the underneath existing metallic equipment.
A simulative analysis has been carried out by using the parameter sweep in COMSOL in order to estimate the influence of the geometrical and electrical parameters on the antenna performance. In particular, in fig.5 the influence of the reflector distance on the antenna pattern and axial ratio is shown: as expected, the optimum distance is about 12cm, i.e. λ/4. However, the introduction of a ground plane results in worsening the axial ratio (as shown in Figure 5, bottom).

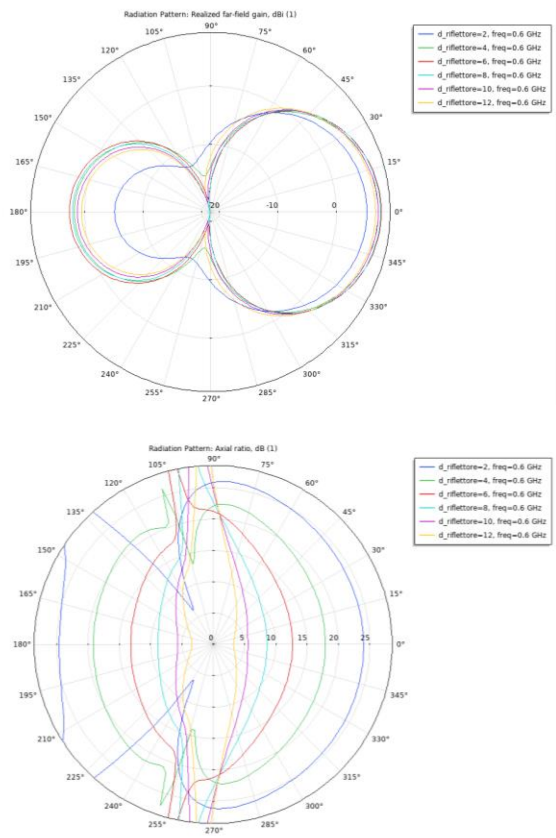

Figure 5. Antenna gain (top) and axial ratio (bottom) for the UHF circularly polarized Archimedean spiral antenna with reflector.

Figure 6. Antenna hosted in the top case of the motorcycle used for shooting events.

Due to the limited space available, in the prototype (fig.6) this size had to be reduced; nevertheless, the preliminary tests done during the "Giro d' Italia" competition in May 2019 proved this first solution to be satisfactory. The tests were performed using both the old linear log-periodic antenna and the CP antenna prototype, simultaneously measuring and logging the received signals strength. In Figure 7 the RF signals received from the linear polarization

antenna (green line) and the CP antenna (red line) are shown.
The results show comparable reception levels between the two antennas, but, while log-periodic antenna shows signal fading events, the CP antenna as expected, is immune to this problem.

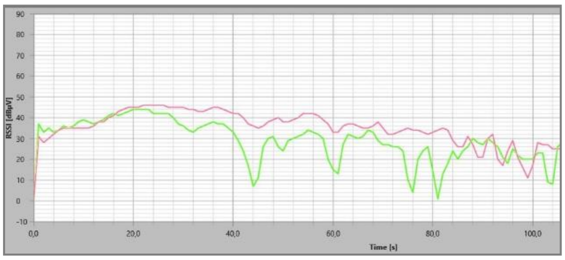

Figure 7. Received signals for the (old) log-periodic UHF antenna (green line) and the (new) Archimedean spiral antenna (red line).

The prototype antenna has been measured in the laboratory by means of a very near field scanner [5] (EMScan RFX2). The far-field antenna performance is reported in fig.8. The RHCP pattern and the axial ratio are in good agreement with simulated results (fig.5, d=8cm).

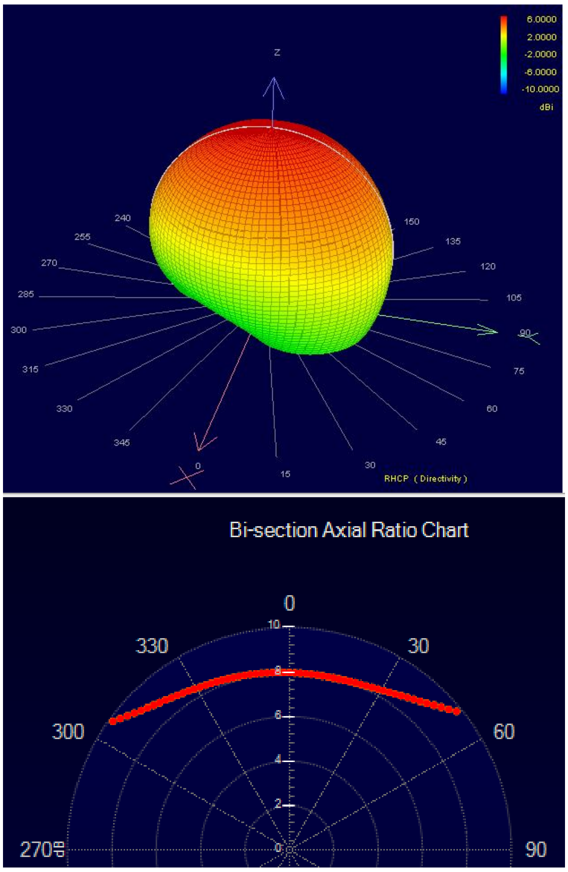

Figure 8. Measured prototype antenna performance. Up: RHCP far field pattern. Down: axial ratio.

4. Dual-Crossed, Double-Folded Dipole (DCDFD) antenna

The axial ratio issue can be effectively solved, at a price of increased circuit complexity, adopting a 4-phase feeding network. A simple "turn-style" antenna with metal reflector modeled in COMSOL Multiphysics has proven a good axial ratio, although resulting in a narrower bandwidth.
In light of the difficulties in constructing the antenna model satisfying the aforementioned requirements, it was decided to adopt a transmission line-like solution. The choice of the antenna shape is a function of the desired excitation.
The radiating system, obtained by cutting a metal plane with several slots, is cavity backed. Such discontinuities have been created in the conductive material, because it has been studied that they behave like inductances, being able to electrically enlarge the structure and therefore lower the resonance frequency of the same.
All geometric entities have been parametrized in order to enable the use of the COMSOL Optimization Module. The length of diagonal slots make the surface current flow in "meander" fashion, thus enabling the tuning the effective folded dipoles length.
The geometry of the realized model is reported in Figure 8.
The value of this approach is that the impedance of each dipole is quite high: the presence of a closely spaced metal reflector reduces the impedance so that the impedance value suitable for the feeding network can be reached.

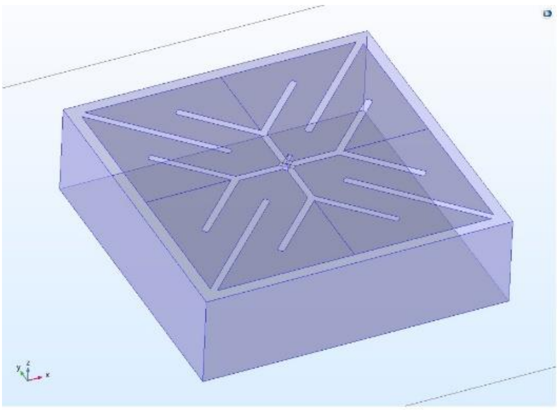

Figure 9. DCDFD circularly polarized UHF antenna

As objective function we choose to minimize the return loss by varying a total of five geometric parameters. In a first phase, a Monte Carlo method has been used trying to rule out possible local minima; then gradient method (Nelder-Mead) has allowed to refine the optimization.

5. Preliminary results for the DCDFD antenna

Intensive simulative efforts have been done in order to find the optimal configuration of the model in terms of realized gain and axial ratio.
Figure 10 shows the electric field distribution along the radiant structure at the operating frequency of 600 MHz. It is visible higher electric field along the edge of the structure, due to the presence of the dielectric and slots made in the metallic substrate. The behavior of the antenna in the far-field region is shown in Figure 11 where a quite satisfactory realized gain value is achieved. This antenna show also a very good axial ratio performance at boresight, increasing to satisfactory values at low elevation (Figure 12).
The antenna bandwidth performance optimization, as well as the 4-phase feeding network design is still ongoing at the moment.

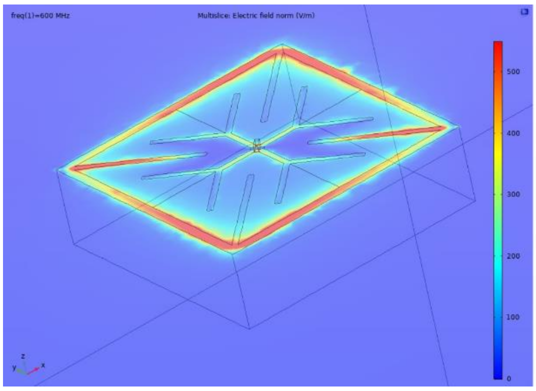

Figure 10. Dual crossed, double, folded dipoles UHF circularly polarized antenna

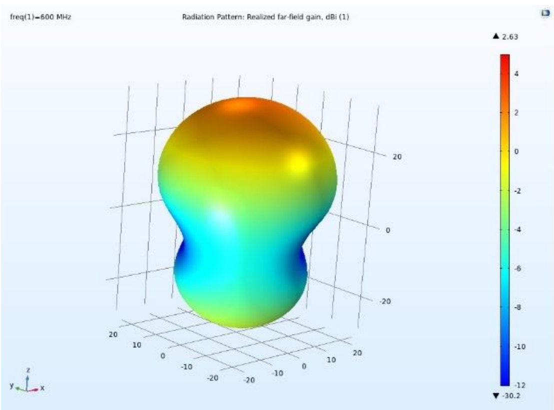

Figure 11. Realized gain for the DCDFD dipole antenna

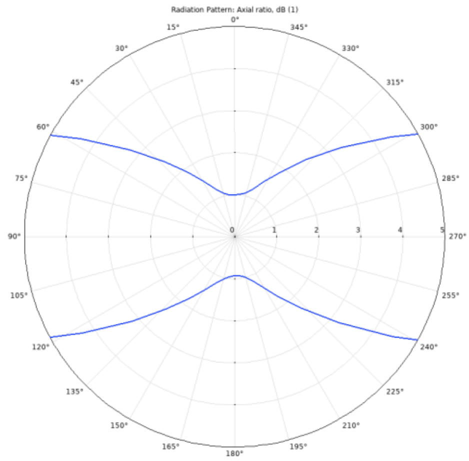

Figure 12. Axial ratio for the DCDFD antenna

6. Conclusions

Several circular polarized antenna structures have been studied with COMSOL Multiphysics, for shooting sports events on the move applications. The antennas performance have been investigated in terms of impedance matching, realized gain and axial ratio. Taking in consideration the limitations imposed by the antenna's size, a spiral antenna with reflector was simulated and then prototyped. The simulated results have been validated on the realized prototypes both in laboratory, by means of a Very Near Field Scanners, and in field tests (during the cycling event "Giro d'Italia" in May 2019) showing a better link performance in the UHF band compared to the old (adopted so far) log-periodic antenna. Further attempts to extend its operation down to the VHF range by applying radial perturbation at the spiral periphery (a so called "meander spiral antenna") have also been carried out.

Finally, a new Dual-Crossed, Double-Folded Dipole (DCDFD) antenna has been modelled. After intense simulative efforts, the stringent requirements imposed for the purpose of this type of antenna have been largely satisfied. Further improvements are still ongoing and the obtained results appear very promising.

7. References

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7. Acknowledgments

We would like to thank the whole COMSOL technical support staff in Brescia, with particular regard to Gabriele Rosati, for useful discussions and suggestions.