Wearable textile GPS antenna for integration in protective garments

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***Abstract*—In the context of wearable textile systems for rescue workers, the knowledge of the position of the mobile operator is a crucial information for coordination of interventions. For this purpose, a textile wearable GPS antenna is required. Such an antenna must be completely integrable into a protective garment and resistent against harsh environmental conditions. Moreover, its performance must be sufficiently resilient to real-work disturbances, such as the proximity of textile materials composing the garment and the wearer's human body. A GPS textile wearable patch antenna was designed in order to meet such requirements. Performance investigations on a realized prototype were carried out by means of measurements in open space and in two real-work situations, showing an excellent behavior in open-space and a slight performance degradation when textiles and/or human body are present. However, the performance of the proposed antenna are sufficiently satisfactory and promising for application in wearable textile systems.**

I. Introduction

Wearable textile systems for integration into protective garments for rescue workers represent nowadays an important field of research [1]. Such systems aim to provide continuous monitoring of life, activity and environmental parameters of the rescue worker, by means of wearable sensors that pick up the parameters from the body and/or surrounding environment (e.g. heart rate, pressure, body and environmental temperature, etc.). Then, this information needs to be sent in a wireless way to a base station, which continuously monitors the state and activity of the rescue worker, together with the parameters of the surrounding environment. When necessary, the base station may transmit useful information and/or alarms to the rescue worker. In particular, correct knowledge of the rescue workers' position at any time, is crucial for the base station in order to efficiently coordinate interventions. This information can be obtained from the Global Positioning System (GPS), using an appropriate GPS antenna. In the specific application of rescue workers, such antenna has to additionally respond to particular requirements. On the one hand, it must be possible to fully integrate the antenna into a protective garment for rescue workers. Thus, it must be made out of textile materials, which are robust to harsh environmental conditions in which rescue workers often operate, such as high temperatures, high humidity and presence of moisture. On the other hand, since a wearable antenna is worn by a rescue worker, it must be resilient to detrimental effects that the close proximity of the human body and textile layers of the protective garment may produce on the antenna performance.

In response to the above needs, we propose a GPS patch antenna, based on a flexible fire-resistant and water-repellent foam substrate, combined with conductive e-textile, such that the antenna does not hinder the movements of the rescue worker. Antennas made out of textiles, including circularly polarized antennas suitable for GPS applications, were already introduced in [2]–[4]. Up to now, only water-repellent substrates have been used to build wearable antennas [5]. As improvement, we designed and realized a GPS antenna based on a fire-resistant and water-repellent foam substrate, combined with flexible conductive textile materials resulting in a textile antenna that does not hinder the movements of the rescue worker. By using a truncated corner nearly square patch topology [6], circular polarization is achieved.

Moreover, in order to prove the performance robustness of the antenna in the vicinity of the human body and the covering textile layers of the protective garment, real-work measurements were performed of the three main parameters describing the antenna performance: reflection coefficient, axial ratio and antenna gain, in contrast to available literature [7], where the effects of the vicinity of the human body on reflection coefficient and gain pattern, were investigated by means of simulations only. Previous studies including measurements of such effects, were already presented by the authors of the present paper [8], for a similar textile GPS antenna, built on another substrate, with different dielectric properties, thus showing similar but not identical results.

In our analysis, each of the three parameters were measured in the three following situations: *antenna in open-space*, *antenna covered by additional textile layers* and *antenna integrated into a jacket, worn on a human body*.

II. Antenna Design

An antenna topology was chosen consisting of a nearly square patch with two truncated corners, with the feed point on the patch diagonal, as shown in Fig. 1. Such configuration allows to obtain right-hand circular polarization, as required from the GPS-L1 standard. The geometrical dimensions of the patch were optimized, by means of ADS Momentum®, in order to match the design goals, which impose a reflection coefficient lower than -10 dB (i.e. $|\Gamma| < -10$ dB) and an axial

TABLE I
PARAMETERS OF THE GPS ANTENNA

Optimized Parameters	Patch length $L = 83.48$ mm
	Patch width $W = 78.81$ mm
	Inset side length $c = 5.66$ mm
	Feed point $(\pm x_f, y_f) = (\pm 9.64, 16.5)$ mm
Fixed Parameters	Substrate Height $h = 5.55$ mm
	Conductive materials: Flectron® (patch and ground plane)
	Substrate material: protective closed-cell foam
	Substrate Permittivity $\varepsilon_r = 1.12$, tan$\delta = 0.003$

ratio smaller than 3 dB, over the entire GPS-L1 frequency band ([1.56342, 1.58742] GHz). After that, a prototype was realized, with the final parameters values obtained after optimization. The dielectric permittivity and loss tangent of the substrate, used in the optimization process, were previously determined by the method described in [9]. The geometrical and material parameters are shown in Table I. The simulated reflection coefficient of the optimized GPS antenna is displayed in Fig. 2, showing that the requirement on the reflection coefficient is satisfied, the reflection coefficient being lower than -10 dB over the entire GPS-L1 band. The simulated axial ratio as a function of frequency meets the design requirement as well, being lower than 3 dB over a band that covers completely the GPS-L1 band.

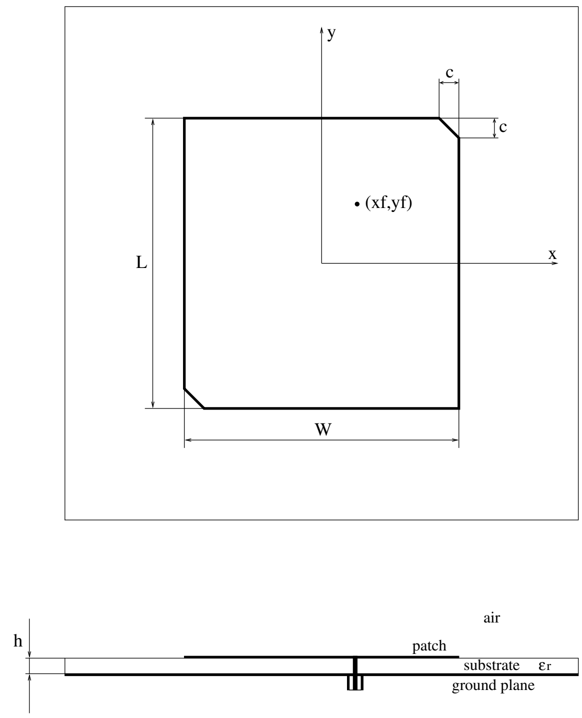

Fig. 1. Antenna geometry.

III. MEASUREMENTS IN REAL-WORK SITUATIONS

A measurement campaign was carried out, in order to investigate the performance of the realized antenna prototype. The performance was evaluated in terms of the three most important characteristics of the antenna, being the reflection coefficient, axial ratio and gain patterns.

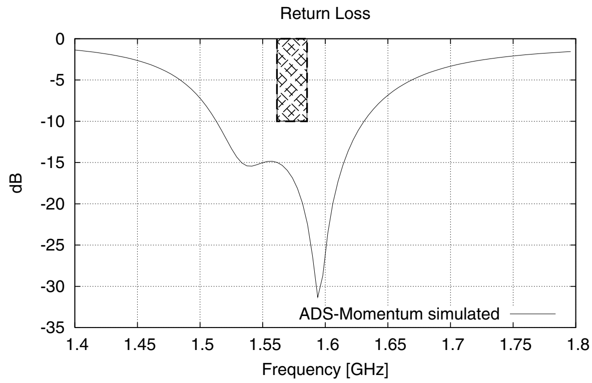

Fig. 2. Simulated reflection coefficient of the optimized antenna, in open space.

The performance was studied in three operating situations. First, the characteristics were measured in open space or, more precisely, in an anechoic chamber emulating an open-space situation. Next, the three characteristics were measured in two real-work situations: with the antenna covered by additional textile layers and with the antenna integrated into a protective garment for firefighters, worn by a real human.

In the first real-work situation the patch antenna was embedded in between several protective textile layers composing a firefighter jacket, as shown schematically in Fig. 3. Two layers are placed above the patch: an outer shell fabric layer and a combined moisture and thermal barrier layer, used to protect the firefighter and the antenna from harsh external environmental conditions. Below the ground plane, a liner layer is placed. This situation reproduces only the effect of integration of the antenna into a protective garment.

The second real-work situation is with the GPS antenna integrated into a real protective jacket for firefighters, worn by a real human. The antenna was integrated into the garment embedding it in between the textile layers, exactly as in the first real-work situation, and positioned in the back-shoulder area of the wearer. This situation reproduces the combined effect of proximity of textile materials surrounding the antenna and the close vicinity of the human body and is therefore the closest to the real operating situation of the antenna.

A. Reflection coefficient measurement

First, measurement of the reflection coefficient ($|\Gamma|$) as a function of the frequency, for the open-space situation, was performed, followed by measurements in the two real-work situations.

By comparing the obtained curves, as shown in Fig. 4, some conclusions can be drawn. The presence of the textile layers, above the antenna patch, produces a shift of the resonance frequencies of the two modes of the antenna (i.e. minima of reflection coefficient) towards lower frequencies, with respect to the open-space situation. When the antenna is integrated

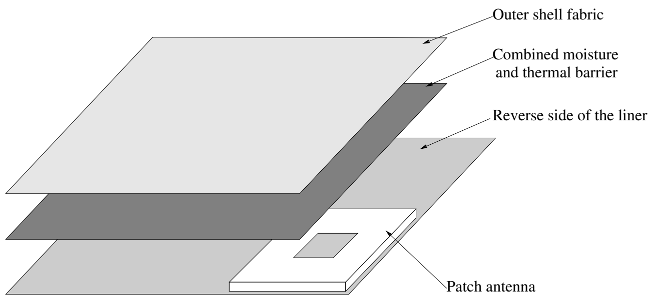

Fig. 3. Scheme of the antenna embedded into textile layers.

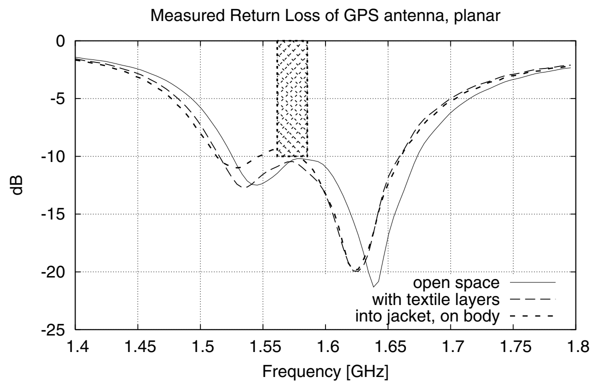

Fig. 4. Comparison of measured reflection coefficient for the three considered operating situations.

into a jacket and worn by a human body, the resonance frequencies also undergo a negative shift with respect to the open-space situation. However, in all considered cases, the reflection coefficient remains sufficiently satisfactory over the GPS-L1 band, being always lower than -10 dB in open space and when covered with textile layers, and lower than -9.4 dB when integrated into a jacket worn by a human.

The resonance frequencies of the two modes of the antenna, TM_{10} and TM_{01}, in the three operating situations, together with the frequency shifts of the two real-work situations with respect to open space, are summarized in Table II.

B. Axial Ratio Measurements

The axial ratio, along broadside, as a function of the frequency, was also measured for the three different operating situations. By comparison of the three obtained curves, displayed in Fig. 5, one notices a frequency shift of the minimum of the axial ratio in the two real-work situations, with respect to the open-space situation. The axial ratio remains lower than 3 dB, over the entire GPS-L1 band, in the open space situation. In the first real-work situation, that is when the antenna is embedded into textile layers, the axial ratio characteristic shifts towards lower frequencies, remaining lower than 4 dB over the GPS-L1 band. In the second real-work situation, that is with the antenna integrated into a firefighter jacket, worn by a human, the frequency shift is even larger and the axial ratio remains lower than 6 dB over the GPS-L1 band, that is above the limit

TABLE II
MEASURED RESONANCE FREQUENCIES AND FREQUENCY SHIFTS OF THE TWO RADIATING MODES, PRODUCED BY ADDITIONAL TEXTILE LAYERS AND INTEGRATION OF THE ANTENNA INTO A BODY-WORN FIREFIGHTER JACKET.

TM10	
$f_{10,1}$ (open space)	1.64 GHz
$f_{10,2}$ (with textiles)	1.625 GHz
$f_{10,3}$ (into jacket, on body)	1.625 GHz
$\triangle f_{10,21} = f_{10,2} - f_{10,1}$	-0.015 GHz
$\triangle f_{10,21}\%$	-0.91%
$\triangle f_{10,31} = f_{10,3} - f_{10,1}$	-0.015 GHz
$\triangle f_{10,31}\%$	-0.91%
TM01	
$f_{01,1}$ (open space)	1.545 GHz
$f_{01,2}$ (with textiles)	1.535 GHz
$f_{01,3}$ (into jacket, on body)	1.53 GHz
$\triangle f_{01,21} = f_{01,2} - f_{01,1}$	-0.01 GHz
$\triangle f_{01,21}\%$	-0.6%
$\triangle f_{01,31} = f_{01,3} - f_{01,1}$	-0.015 GHz
$\triangle f_{01,31}\%$	-0.97%

of the initial requirement. However, the values of the axial ratio at the center frequency 1.575 GHz remains on an acceptable value to achieve a GPS communication link, not exceeding the value of about 3.88 dB in all three considered cases. Moreover, the measured sense of polarization is Right Hand in all considered cases, as required from the GPS standard.

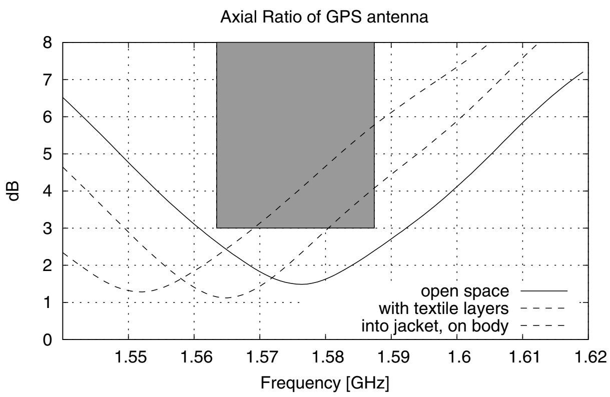

Fig. 5. Measured axial ratio as a function of frequency, along broadside, for the three considered operating situations.

The values of the minimum axial ratio, together with their corresponding frequencies, for the three operating situations, are summarized in Table III.

The frequency shift is probably due to the fact that the axial ratio as a function of frequency is very sensitive to small variations of the resonance frequencies of the two radiating modes of the antenna, produced by the presence of textiles and integration into a body-worn jacket. A larger 3 dB axial ratio bandwidth is therefore desirable, in order to account for such detrimental effects, present in real-work operation of the antenna.

IV. GAIN PATTERNS MEASUREMENTS

The gain patterns along the XZ-plane of the antenna, at the center frequency f = 1.575 GHz, were measured in anechoic

TABLE III
MEASURED MINIMUM AXIAL RATIO AND CORRESPONDING FREQUENCIES, FOR THE THREE CONSIDERED OPERATING SITUATIONS.

	Open space	With additional textile layers	Integrated into a firefighter jacket, on human body
f_{min} [GHz]	1.5775	1.565	1.5525
AR_{min} [dB]	1.5	1.12	1.29

TABLE IV
MEASURED MAXIMUM GAIN AND -3 dB LOBE WIDTH OF THE GPS ANTENNA FOR THE THREE CONSIDERED OPERATING SITUATIONS

	Open space	With additional textile layers	Integrated into a firefighter jacket, on human body
max(G_{XZ} [dBi])	8.4	8.34	7.52
-3 dB Lobe width XZ °	63	62.1	56.7

chamber, again for the three operating situations. The resulting curves are displayed in Fig. 6.

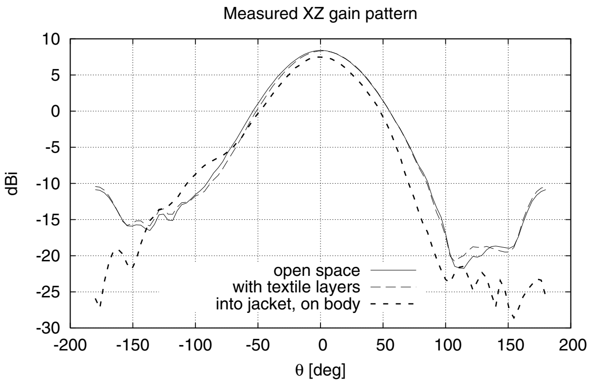

Fig. 6. Measured gain patterns, at f = 1.575 GHz, on XZ-plane, for the three operating situations.

When the antenna is operating in an open-space situation, it exhibits a measured maximum gain of 8.4 dBi along broadside, which is more than sufficient for a reliable wireless link.

Next, the measurements were repeated for the two real-work situations and compared to the open-space situation. As depicted in Fig. 6, one notices that the presence of textile layers produces a very slight decrease of the maximum gain with respect to the open-space situation, of about 0.06 dB, probably due to power dissipation in the textile materials, which contains some carbon to make the outer layer antistatic.

When the antenna is integrated into a human body-worn jacket, the maximum gain also decreases with respect to the open-space situation, by about 0.9 dB, and the main lobe width slightly decreases, probably due to power absorption in the jacket and in the human body.

The values of maximum gain and -3 dB main lobe width are summarized in Table IV, from which one notices that the obtained antenna gain and -3 dB main lobe width remain sufficiently high to guarantee a reliable communication link in all considered situations.

V. CONCLUSIONS

The proposed GPS antenna, completely made out of textile materials and fully integrable into protective garments for rescue workers applications, is capable of covering the entire GPS-L1 band, in open space condition. In real work-situations, that is with the antenna being covered by textile layers or integrated into a rescue-worker jacket, worn by a real human, the measurements showed that the performance slightly degrades, however remaining still acceptable. In conclusion, the proposed antenna represents a suitable candidate for use in wearable textile systems for rescue workers. However, for future developments, it is advisable to use improved design and/or feeding methods that allow to obtain a larger 3 dB axial ratio bandwidth, in order to account for possible frequency shifts caused by presence of textile materials and close proximity of the wearer's human body.

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