Active Textile Antennas in Professional Garments for Sensing, Localisation and Communication

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***Abstract*—New wireless wearable monitoring systems integrated in professional garments require a high degree of reliability and autonomy. Active textile antenna systems may serve as platforms for body-centric sensing, localization and wireless communication systems, in the meanwhile being comfortable and invisible to the wearer. New design strategies combined with dedicated signal processing techniques greatly enhance the robustness of these systems. On the one hand, the large amount of real estate available in public regulated services' garments may be exploited to deploy multiple textile antennas. On the other hand, the size of each radiator may be designed large enough to ensure high radiation efficiency when deployed on the body. This antenna area is then reused by placing active electronics directly underneath and energy harvesters directly on top of the antenna patch. We illustrate this design paradigm by means recent textile antenna prototypes integrated in professional garments, providing sensing, positioning and communication capabilities.**

I. Introduction

In recent years, lots of research was devoted to increase the operational safety and efficiency of police, army and rescue services. In particular, wearable electronic systems can greatly enhance the functionality of PRS garments by providing sensing, localisation and wireless communication capabilities. Smart fabrics and interactive textiles (SFIT), which are unobtrusively integrated into garments, do not hinder the movements during interventions, and, in the meanwhile, continuously monitor life signs, activities and environmental conditions, relaying these data wirelessly to a remote location for supervision by the operations coordinator. In addition, in hazardous situations, alarms and specific instructions can be fed back to each individual in action.

As SFIT systems are to be deployed in harsh conditions and during critical operations, their reliability and autonomy are two key concerns of the designers. To ensure sufficient autonomy without the use of heavy batteries, the electronics must be highly energy-efficient. As a lot of power is consumed in establishing wireless communication links, textile antennas are critical components, so they should preferably exhibit high gain and large radiation efficiency. Garments provide the space needed to deploy antennas with such characteristics, and by making use of a large ground plane, absorption of antenna radiation by the human body is also avoided. Yet, special care must be taken by designers of wearable antennas to counter degradation of antenna performance due bending, wrinkling and crumpling by the large flexible textile antenna [1]–[4] as the wearer moves around. Moreover, a good selection of materials is needed to avoid excessive substrate losses due to humidity trapped in the substrate fabric [5] and a TPU coating may be required to protect the antenna during washing [6]. In addition to increasing the power-efficiency of SFIT system, energy harvesters may be added to scavenge energy from one or more energy sources available in the neighbourhood of the body, in order to increase the operational autonomy.

In this contribution, we review design strategies to implement energy-efficient active wearable antennas with stable performance when integrated in professional garments that are worn during interventions. To improve reliability and autonomy of the active antenna modules, we integrate electronics on the planar textile antenna's feed plane, directly underneath its ground plane and position energy harvesters directly on the antenna plane. We outline the measures taken to ensure that the antenna performance is not reduced due to the integration of these additional components.

In Section II, we review the different strategies to design active textile antennas based on full-wave/circuit co-design and co-optimization. Integrating active electronic circuits directly underneath the wearable antenna, results in a compact communication module and avoids weak connections that easily break when put under stress during interventions. Next, in Section III, we increase the autonomy of wearable modules by integrating a set of solar cells on top of the antenna patch, without disturbing its radiation characteristics. We then move on to discuss two recent antenna designs for sensing, localisation and wireless communication applications. Section IV describes a wearable low-cost through-wall Doppler radar that may be deployed in PRS garments to detect moving persons behind walls and victims lying under rubble. In Section V, we outline the design and testing of wearable active dualband receive antenna for localisation by means of GPS and satellite communication through the Iridium system. Finally, we wrap up by drawing some conclusions in Section VI.

II. Full-wave/circuit co-design of active wearable antennas

Direct integration of active electronics circuits onto the wearable antenna reduces the number of connections and keeps RF paths short. This is, in particular, beneficial for circuits implemented on textile substrates and interconnections with e-textiles, as, on the one hand, substrate and conductive losses are typically more important compared to conventional rigid printed circuit board materials, and, on the other hand, soldering or press-fitting connectors onto conductive textiles results in weak links prone to breaking when subjected to stress incurred, for example, by movements. In addition, via connections should also be avoided, if possible, as these may also come loose when pressure is exerted onto the textile or foam substrate.

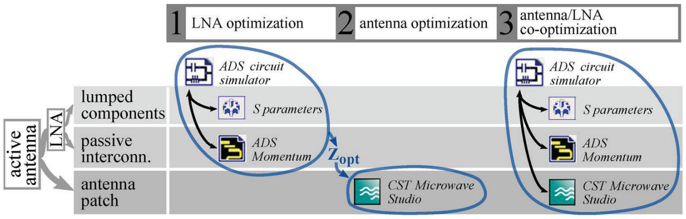

Fig. 1. Design strategy for optimal noise characteristics.

The design of active antennas requires a joint circuit/full-wave optimization to simultaneously design the antenna and the active electronics to meet the desired specifications. Typically, impedance matching and circular polarization may be desired for the antenna together with large available gain, input and output matching, and low noise figure for the low-noise amplifier (LNA) attached to the antenna output. Given the large number of design variables available for optimization, we devised two dedicated strategies to keep the design process manageable [7]. The first process puts forwards an optimal complex radiation impedance for the passive textile antenna, resulting in minimal noise figure at the LNA's output. This impedance is found in the first step of the full-wave/circuit co-optimization procedure for the active electronics only, producing a preliminary optimal LNA design. Next, full-wave optimization of the passive antenna is performed to fix the antenna dimensions that provide the optimal radiation impedance. In a final step, the complete active antenna is co-optimized to jointly maximize performance of both the antenna and the active electronics characteristics. This design flow for optimal noise characteristics without the need of a matching network is sketched in Fig. 1. It guarantees short RF connections and avoids excess losses due to components added for matching. The strategy makes use of the most suited simulators for each part of the active textile antenna. In particular, the passive antenna was modelled in the 3D full-wave frequency domain simulator of CST Microwave Studio, which is able to take into account the finite conductivity of the electro-textile Flectron, used as antenna plane and ground plane. As the LNA circuit is implemented on a thin polyimid flex, its interconnections can be modelled by means of the planar-3D full-wave simulator ADS Momentum. The reader is referred to [7], [8] for further details.

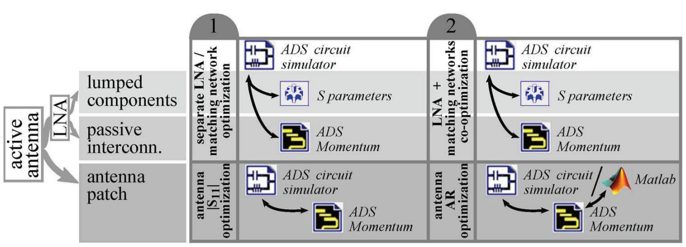

Fig. 2. Design strategy for optimal impedance matching.

Antennas for satellite communication typically exhibit stringent requirements in terms of circular polarization. Deforming the radiating structure together with optimization of the feed point may not suffice to meet the requirement that the axial ratio remains below 3dB over a sufficiently large bandwidth. If this is the case, the use of a quadrature hybrid should be considered. As implementations in wearable microstrip technology are typically too large at GPS frequencies, miniaturized off-the-shelf lumped hybrids are preferred. As these components have a fixed impedance level of 50Ω at their ports, the above described co-optimization strategy must be modified. Now, in a first step, to accommodate the discrete component, the antenna output and the LNA input are both separately matched to 50Ω. This requires a matching network to guarantee optimal noise performance for the LNA. In a second step, at the antenna side, axial ratio and antenna impedance are jointly optimized, whereas a full-wave/circuit co-optimization is performed on the complete LNA circuit. This design flow for optimal impedance matching of both the passive antenna and the LNA is sketched in Fig. 2. As all conductive layers are implemented by means of copper patterns on polyimid flex, only the planar-3D full-wave simulator ADS Momentum is used in the design process. More details are found in [7], [9].

III. Integration of Solar Cells onto Wearable Antennas

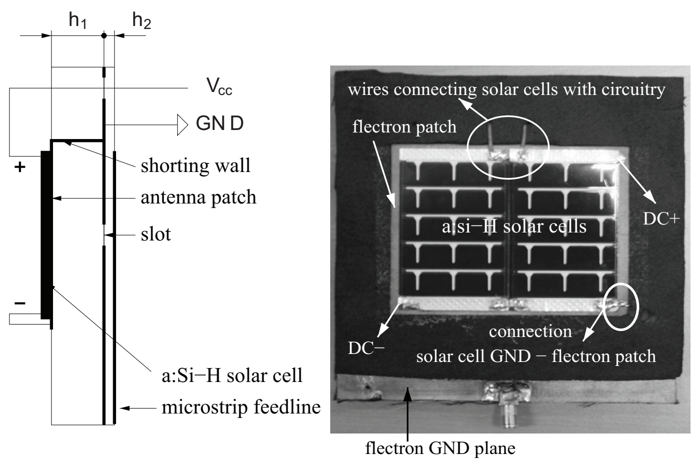

Fig. 3. Aperture-coupled shorted wearable solar patch antenna for 902–928 MHz UHF band.

An important remaining issue standing in the way of a commercial breakthrough of smart SFIT systems for PRS concerns ensuring sufficient autonomy without the need of heavy batteries and frequent recharging. Therefore, recent research concentrated on adding energy-scavengers to these systems, in order collect energy from the body and its environment to power the system. For modules in SFIT garments, solar energy and kinetic energy originating from body movement are the most important sources. In [10] it is shown that the antenna patch may serve as a platform for solar cells, thereby reusing the space consumed by the large antenna. In Fig. 3 we show the aperture-coupled shorted wearable solar patch antenna for communication in the 902–928 MHz UHF band. By adopting a PIFA topology for the textile antenna and by routing the feed wires of the solar cells along the shorting-wall of the antenna, the antenna radiation is not influenced by the presence of the energy harvester deployed on the antenna patch.

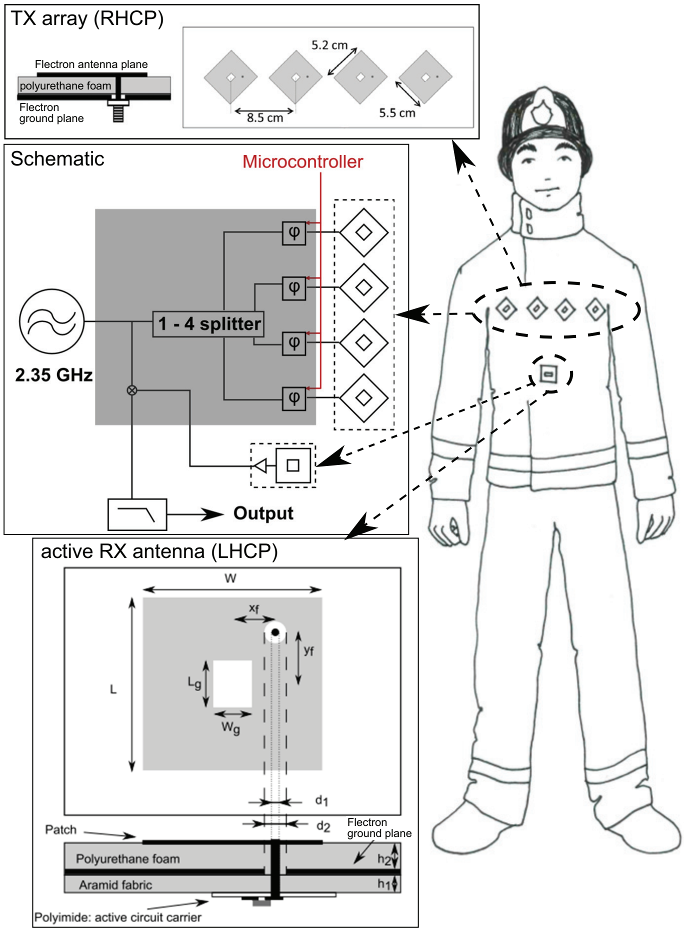

Fig. 4. Wearable through-wall Doppler radar (firefighter drawing by Laura Goethals).

IV. Wearable through-wall Doppler radar

The design procedure outlined in Section II was applied to construct a low-cost, low-weight, wearable Doppler radar system capable of detecting moving objects behind a barrier. As shown in Fig. 4, the transmit part of the Doppler radar consists of a four-element array of textile antennas. The beam emitted by this array is right-hand circularly polarized along all scanning angles and provides 9.2dBi gain. The element spacing of 8.5cm results in a large aperture and allows beamsteering from 15° to +15° with respect to boresight. At the receiving end, textile fabrics found in PRS garments were used to develop an active wearable receive antenna. Applying the design strategy for optimal noise characteristics outlined in Section II and shown in Fig. 1 results in 15.7dBi gain, 1.1dB noise figure, left-hand circular polarization, and a 3dB axial ratio beamwidth larger than 50°. Fig. 5 shows the spectrogram measured by the radar of a person walking at 1.5m/s at a position of 15° with respect to boresight, behind a closed fire-retardant door. A full description of the design, fabrication and validation of the wearable radar is found in [11].

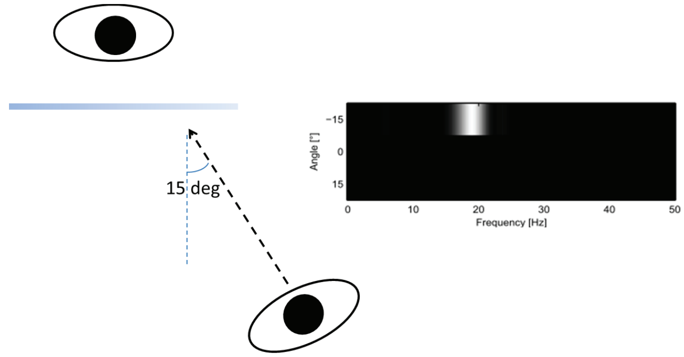

Fig. 5. Spectrogram measured by the radar of a person walking at 15° behind a closed fire-retardant door.

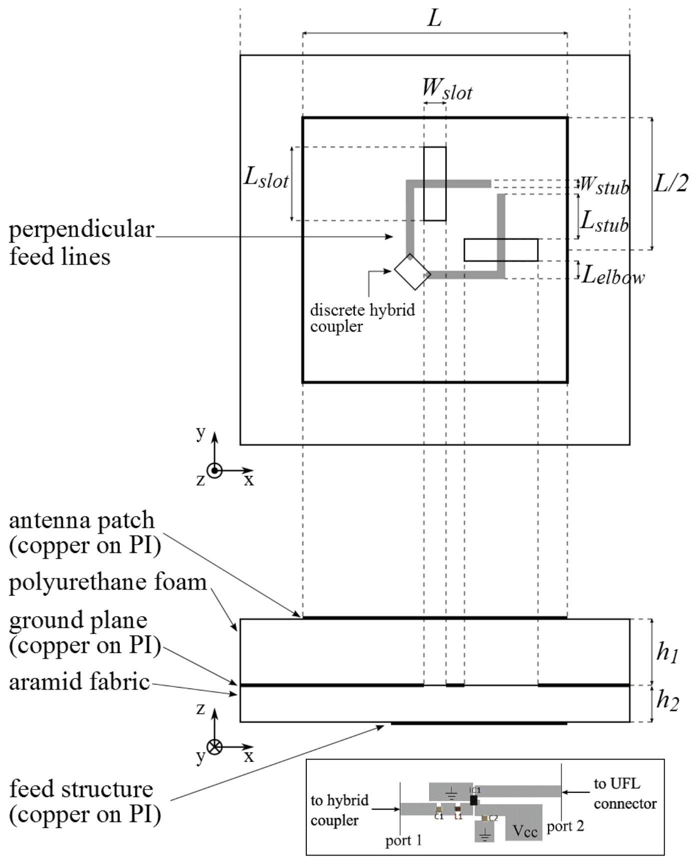

Fig. 6. Wearable active dualband receive antenna.

V. Wearable active dualband receive antenna for GPS and Iridium

The second design strategy outlined in Section II, following Fig. 2, was applied to design a wearable active dualband receive antenna for localization, relying on the GPS L1-band centered around 1.575GHz, and satellite telephony operating in the Iridium spectrum ranging from 1.616GHz to 1.6265GHz. The module contains a Maxim MAX2659 LNA chip directly integrated on the antenna feed plane, below the ground plane. Its output is robustly matched over a frequency band ranging from 1.36GHz to 1.7GHz, remaining stable under bending and on-body conditions. The discrete hybrid coupler provides circular polarization over a frequency range starting at 1.517GHz and extending beyond 1.7GHz. The active antenna provides a gain larger than 25dBi in a 1dB gain bandwidth of 119MHz. Even when deploying the antenna in a firefighter jacket worn by a test person, its return loss remains larger than 10dB and its axial ratio lower than 3dB both at the GPS and Iridium frequencies. For more details, the reader is referred to [7]

VI. Conclusion

Smart electronic systems for sensing, localization and wireless communications should exhibit robustness, reliability and a high degree of autonomy while not adding too much weight, nor hindering the movements of the wearer. In this paper, we exploit the large area available in professional garments to integrate flexible textile antennas. In turn, the wearable antenna is used as a platform for the integration of active electronics, on the feed plane directly below the ground plane, as well as for the integration of solar cells directly on top of the antenna patch. We presented dedicated design strategies that yield optimal active antenna characteristics. The two outlined strategies were applied to the design of a wearable through-wall Doppler radar for the detection of persons behind barriers and of a wearable active dualband receive antenna for localization via GPS and satellite communication in the Iridium band. The large area available in garments can also be exploited to deploy multiple antennas to improve the signal quality by means of diversity and MIMO techniques. For more details, we refer to [12]–[15].

Acknowledgment

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