Design and Evaluation of a Textile-Integrated GPS Receiver

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Abstract. *This paper presents a complete textile-integrated receiver for global positioning system (GPS) signals. It consists of a purely textile antenna together with a GPS module. Details of the design and fabrication process of the antenna are given together with simulation and measurement results. An efficient and simple fabrication process for textile antennas is also presented in this work. The textile antenna together with GPS module are covered by an additional water proof layer and integrated into a jacket. The proposed textile-integrated GPS receiver has been tested in a field test and showed good performance compared to a standard GPS device.*

Keywords

Textile-Integrated GPS Receiver, GPS, Textile Antenna, Circular Polarized Antenna, Smart Textiles

1. Introduction

The market for so called 'Wearables' (wearable electronics) is growing rapidly. An example for such wearables is an activity tracker which is able to monitor sport activities [1]. This monitoring can comprise e.g. the counting of steps, measurement of heartbeat or the logging of a jogging route by global positioning system (GPS). Such monitoring devices are very popular due to the resulting capability of collecting and analyzing information on the physical status as well as training progress of the wearer. Wearing such activity trackers for example on the wrist might however be uncomfortable during sport activities. The 'Textile-Integrated GPS Receiver' overcomes this problem by integrating a GPS system into clothes. Apart from the current trend for Wearables, such a textile-integrated GPS receiving system also addresses the trend towards Smart Textiles (also called: E-Textiles). In [2] Smart Textiles are defined as *'textiles that are able to sense stimuli from the environment, to react to them and adapt to them by integration of functionalities in the textile structure'*. For the textile-integrated GPS-receiver, the stimulus is the GPS signal received by the textile antenna.

There are plenty of publications which focus on the design and fabrication of textile or wearable antennas for GPS applications, e.g. [3], [4], [5]. Even though in [5] an active wearable antenna was connected to a commercial GPS receiver, publications about practical applications of passive textile antennas are still rare. Within the EU project 'PROETEX' (FP6-2004-IST-4-026987) advanced e-textiles for firefighters were developed which included localization via GPS. However, a conventional rigid GPS mouse was used for this purpose, the textile antennas developed within the project were just used for communication purposes [6]. Within the ESA/ESTEC project 'Textile Antennas' a purely textile antenna for operation in the Iridium and GPS band was developed. However, this antenna was practically evaluated by just connecting it to a commercial GPS receiver and observing the number of satellites in view and its signal strengths [7].

Therefore a textile-integrated GPS system with a purely textile antenna is designed and its performance evaluated by a field test that comprises a comparison between the proposed system and a standard GPS mouse with regards to a tracked route. The proposed textile-integrated GPS receiver is designed to operate at GPS L1-frequency of 1575.42 MHz. L1 band GPS signal is a Coarse/Acquisition code which results in 2 MHz bandwidth [8].

Following this introduction, the basic concept of the system is outlined in section two. In the third section of this paper basic theory, design and frabication process are outlined before the measurement results of a textile microstrip patch antenna are presented. In section four conventional electronics that are part of the textile-integrated GPS receiver are shortly presented. The results of a field test are presented in section five. In section six possible application scenarios are listed before this work is summarized in section seven.

2. Basic Concept

The system of the textile-integrated GPS receiver can be divided into two main parts by its textile characteristics. Fig. 1 illustrates a fundamental overview of the system. The antenna is representing the textile component since it is made of textile materials. The other components are conventional electronics (i.e. the GPS-Module, microcontroller, memory storage and battery) which are connected to the antenna. Conventional electronics are not made of textile materials and therefore represent the non-textile component.

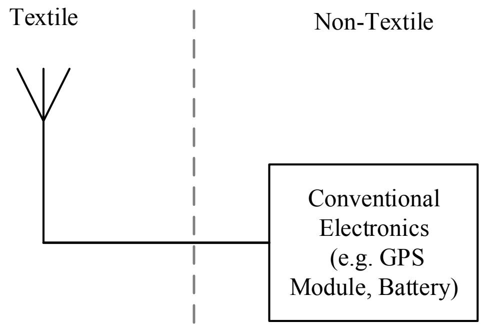


Fig. 1. Schematic of the basic concept for the textile-integrated GPS receiver.

3. Antenna

Recent research on textile antennas shows that the concept of conventional microstrip patch antennas can be well applied to textile antennas. This is mainly due to the following reasons:

1. Microstrip patch antennas are planar and thus can be well integrated into clothes.
2. With an appropriate integration the maximum gain of the antenna is directed away from the body of the wearer.
3. A microstrip patch antenna can be fabricated by simply stacking up the different textile layers of the antenna. Such processes are commonly used in textile engineering.

3.1 Microstrip Patch Antenna - Theory

A microstrip patch antenna is a planar antenna which consists of a conductive ground plane, a dielectric substrate and the conductive patch itself. The patch antenna can be fed by a microstrip feeding line. In comparison to other possible feeding methods, the microstrip feed is particularly advantageous for the integration into clothing where the height of the antenna is critical. Fig. 2 shows the lateral view of a microstrip patch antenna with a microstrip feedline. A patch antenna is mainly defined by the length L and width W of its patch. The values for these dimensions are usually defined via simulation, even though there are models which provide approximative formulas to determine the geometric structure of the patch. The following formulas for the width and the length of a linear polarized rectangular patch antenna are taken from [10].

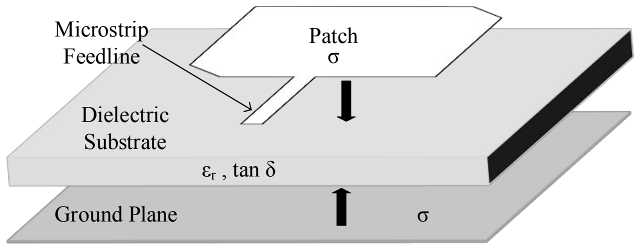


Fig. 2. Lateral view of a schematical microstrip patch antenna with microstrip feedline, adapted from [9].

Equation 1 shows a way to calculate the width of the patch, which leads to a good radiation efficiency. [10]

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

In order to just excite the fundamental mode, the length is chosen to half of the appropriate wavelength. The effect of fringing fields leads to electric extension $\triangle L$. Taking this into account, the corrected length of the patch is given by equation 2

$$L = \frac{1}{2f_r\sqrt{\epsilon_{reff}}\sqrt{\mu_0\epsilon_0}} - 2\triangle L \quad (2)$$

where ϵ_{reff} is the effective relative permittivity. For further information, please consult Balanis [10].

3.2 Materials and Fabrication

Materials A microstrip patch antenna consists of a conductive material which is usually copper and a non-conductive dielectric material. (See Fig. 2) Conventional (non-textile) patch antennas are usually rigid. Integrating rigid material into clothes is difficult and uncomfortable to wear. This is why the textile-integrated GPS receiver uses a purely textile antenna to receive GPS signals. The groundplane as well as the patch are made of conductive fabrics. These fabrics are usually woven fabrics coated with metals like nickel, copper or silver. To achieve a certain substrate height, textile substrates are often made from felt or nonwoven fabrics because these materials are thicker than normal woven fabrics.

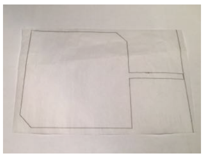
A conductive material is characterized by its conductivity (σ). Materials with a high conductivity produce less ohmic losses and are therefore preferable. Unfortunately, conductive textiles have lower conductivity than pure metals. The fabric Shieldex® Kassel by Statex Produktions & Vertriebs GmbH, Bremen, Germany is used in this work because it has a very high conductivity compared to other fabrics [9].

This is due to a double deposition process. Silver-plated polyamide threads are woven to a ripstop fabric and then additionally plated with copper on both sides. This process provides good conductivity which was confirmed by measurements: The measurement with a Split-Post-Dielectric-Resonator [11] reveals a conductivity of $\sigma = 1.6e6\ S/m$.

A dielectric material is described by its relative permittivity (ϵ_r) and dielectric loss factor ($tan\ \delta$). Theses parameters directly influence the wavelength in the substrate and consequently the operating frequency. Standard substrates have relative permittivities in the range of 2 to 5 and if using ceramics even up to 40. The higher the permittivity, the smaller the shape of the antenna can be. Textile substrates like felt or non-woven fabrics contain a lot of air, which has a relative permittivity of 1 [12]. Consequently, textile substrates have a lower effective permittivity, which results in a larger antenna shape. A needle-punched non-woven fabric is used in this work. It is made from Polyetrafluorethylen (PTFE) and normally used for filtration purposes. In [13] a similar substrate is used and the fabricated antenna shows good results. The PTFE non-woven fabric that is used in this work has a relative permittivity of 1.25 and a very low dielectric loss factor of 0.0039 at a frequency of 1.575 GHz. These values were determined by the transmission line method as described in [14].

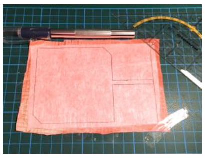
Fabrication The precise fabrication of the patch structure is important, since the microstrip patch antenna is mainly characterized by its shape. Usually, this necessary precision is ensured by an etching process which is used for the fabrication of conventional rigid antennas. Such a standard process is not available for textile antennas. Even though there are approaches to print the conductive structure on fabrics [15] or to cut it out with a 2D-plotter [16], in most of the publications regarding to textile antennas, antennas are cut by hand.

An cutting process by hand is also used in this work, but it comprises slight improvements by utilizing the precision of a standard bubble jet printer. Fig. 3. illustrates the manufacturing process. In addition to the materials described above, Bondaweb® (also called: Vliesofix®) by Freudenberg Interlining SE & Co.KG, Weinheim, Germany was used to improve the fabrication process. Bondaweb® is web adhesive on paper, which can be used for the assembly of different materials by ironing. It is very useful for the fabrication process since the antenna structures can be printed directly onto the paper. The layer of paper can be removed after the first ironing process.

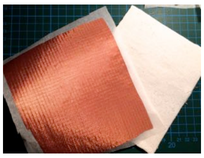


The structure is printed onto the paper side of Bondaweb®

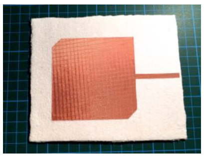
The Bondaweb® is ironed on a appropriate piece of the conductive fabric.



With aid of scalpel and ruler, the structure can be cut precisely along the printed lines.



The conductive fabric for the ground plane is cut and furnished with Bondaweb®. The textile substrate is also tailored.



The paper sites of the Bondaweb® are removed and all three layers are fused together by ironing.

Fig. 3. Illustrated fabrication process for textile antennas.

3.3 Design and Simulation

The demand to receive GPS signals results in the following two requirements, which mainly determine the concrete shape of the antenna:

1. Operating frequency is the GPS L1 Band (1.57542 GHz)

2. Antenna is right-handed circular polarized

The GPS antenna has circular polarization (CP) due to two reasons. Firstly, GPS signals sent by the satellites are circular polarized so that a circular polarized receiving antenna does not induce polarization losses. Secondly, a system with a circular polarized antenna is more robust against multipath effects. Receiving such multipath signals results in short time delays and therefore inaccuracies in the localization.

In this work, a patch antenna with 'Truncated Corners' is used which is easy to fabricate using the cutting process described above. The feasibility of this design with textile materials has already been proven in [12]. The idea behind the truncated corners is the simultaneous excitation of two different degenerated orthogonal modes. The excitation direction of these modes are indicated by the dashed arrows in Fig. 4. The two modes are ideally excited at the frequencies f_1 and f_2. The operating frequency f_r is restricted by $f_1 < f_r < f_2$. The proper choice of f_1 and f_2 results in a $90°$ phase shift between the two orthogonal modes. The superposition of the two modes at f_r leads to a circular polarized propagating wave [17]. As mentioned before, the antenna is fed by a microstrip transmission line which results in better integration into clothes [9] and is comfortable to wear [12].

The design goals correspond to the requirements, namely to minimize the return loss and the axial ratio at 1.57542 GHz. Axial ratio is a measure for the quality of the circular polarization and is 1 or 0 dB for a perfect CP antenna. Values for the return loss below -10 dB and below 3 dB for the axial ratio are acceptable.

The approximate adjustment of W and L defines the operating frequency, whereby W and L are nearly equal to each other. The perturbation area $c \times c$ scales inversely proportional to the quality factor of the antenna and by adjusting c the axial ratio can be minimized. A $\lambda/4$-Transformer is used to transform the impedance of the antenna to $50\ \Omega$. The substrate height h has influences on all these parameters and is here properly chosen to achieve a good efficiency of the antenna.

The perturbation dimension c has been calculated using equation 3 from [17]. $\triangle S$ is the perturbation area and S is the area of the patch. Q_t is the total quality factor of the antenna.

$$\frac{\triangle S}{S} = \frac{c^2}{W \cdot L} = \frac{1}{2Q_t} \tag{3}$$

The previous approximate formulas for the patch dimensions give good initial values for the simulation. These have then been optimized in simulation using CST MICROWAVE STUDIO® to achieve the required performance before being fabricated. The optimized values are presented in Tab. 1.

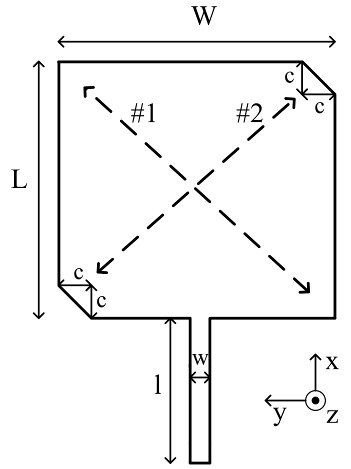


Fig. 4. Shape of the patch.

The simulation results (return loss and axial ratio) are presented in Fig. 5 respectively Fig. 6. The designed antenna achieves a *S11* of -31.3 dB and an *axial ratio* of 0.37 dB in the simulation.

L	**82.2 mm**
W	**81.6 mm**
c	**9 mm**
w	**4.8 mm**
l	**43.6 mm**
h	**2 mm**

Tab. 1. Optimized values for the dimensions of the patch.

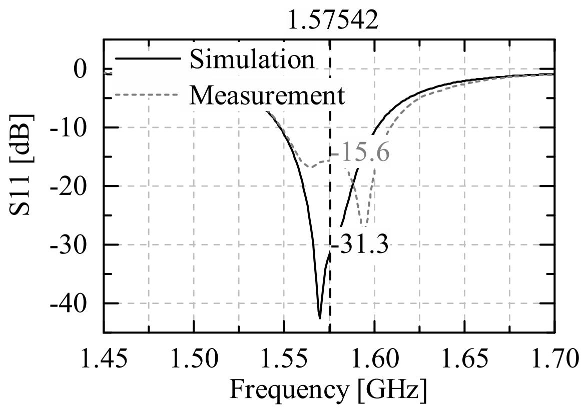


Fig. 5. Return loss over frequency.

3.4 Measurement

The textile antenna was fabricated using the steps explained in section 3.2. The fabricated antenna shows a good matching to 50 Ω in terms of S11 as shown in Fig. 5 and a good agreement to simulation results in term of axial ratio as shown in Fig. 6. The farfield realized gain pattern of the antenna has been measured in the spherical near field measurement chamber at Institute of High Frequency Technology at RWTH Aachen University. The measured realized gain pattern at the operating frequency is shown in Fig. 7.

Regarding S11, differences between measurement and simulation are observable. The mode with the higher frequency is shifted to a higher frequency. However, since the S11 is still less than -10 dB and the axial ratio is near to 0 dB, this means that the small frequency shift does not have a strong effect.

4. Conventional Electronics

This section shortly presents the conventional components that are important for the overall system. The GPS signals are received by the textile antenna. For the filtering, amplifying and demodulation of the signals, the NEO-6M chip by u-blox AG, Thalwil, Switzerland is used in this work as shown in Fig. 8 a). This cost-effective chip provides a good accuracy of 2.5 meters and a fast Time-to-first-Fix of 27 seconds [18]. Time-to-first-Fix is the time period until the chip can determine a position fix after being turned on. The u-blox® chip provides a serial interface with an adjustable

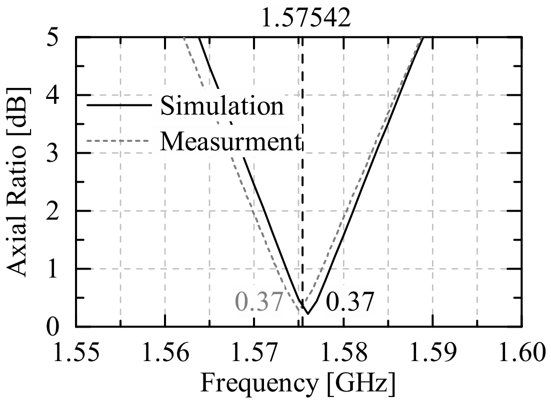


Fig. 6. Axial ratio over frequency.

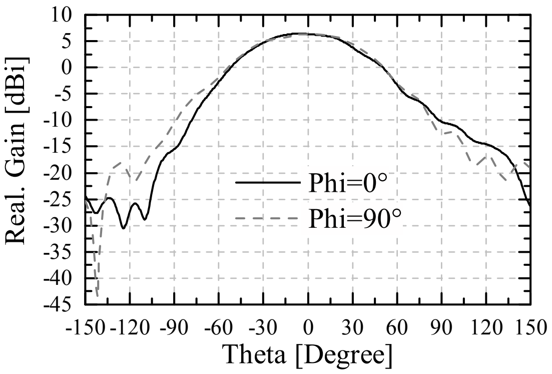
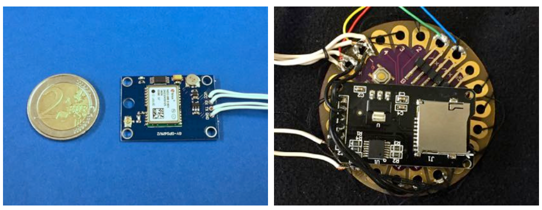


Fig. 7. Realized Gain of fabricated antenna over theta for RHCP.

baud rate. In the prototype of the textile-integrated GPS receiver, the u-blox chip is connected to a Lilypad Arduino board via the serial interface. This board comprises the microcontroller ATmega328V by Atmel® and can be easily attached to fabrics by embroidery or sewing due to holes at the edge of the round board specifically designed for this purpose. The board with an additional SD-Card slot is shown in Fig. 8 b). The microcontroller reads the u-blox chip and saves the important data of the positioning on a memory storage. The whole circuitry is powered by a USB-battery.



(a) (b)

Fig. 8. (a) GPS module with GPS Chip NEO-6M by u-blox®, (b) Arduino Lilypad with additional SD-Card slot.

5. Integration & Field Test

For the prototype, the antenna is sewed onto a jacket as shown in Fig. 9. A thin coaxial cable has been used to connect the antenna to the GPS-module. In order to protect the system against water penetration, the antenna is covered by an additional layer of water-repellent fabric. The antenna is placed on the shoulder region for a better view towards the sky.

Fig. 9. Image of jacket, which comprises the textile antenna which is covered by the blue fabric and a GPS mouse.

In order to evaluate the textile-integrated GPS receiver, a field test under realistic circumstances was performed. For this field test a test person wore the jacket as shown in Fig. 9 and rode a bicycle following a pre-defined route. In order to provide the possibility of a direct comparison of the textile-integrated GPS receiver to a conventional system, the jacket also contains a GPS mouse [19]. Consequently, both systems can be directly compared. The result of this evaluation is presented in Fig. 10. The blue and red lines represent the tracked routes by the textile-integrated GPS receiver and the standard GPS mouse, respectively. Although the textile antenna was covered by an additional water proof layer, our proposed system still performs as good as the standard GPS mouse and shows a good agreement with the real route. The two systems are also compared by calculating the average number of satellites in view. Both systems almost have the same average number of satellites in view as shown in Tab. 2. From these results it can be concluded that both receiver systems have a very similar performance over a certain period of time, which leads to a very promising functionality of the textile-integrated GPS receiver.

Textile-Integrated GPS receiver	**10.82**
GPS mouse	**10.98**

Tab. 2. Average number of satellites in view.

6. Applications

Beside the above mentioned application as an activity tracker, a textile-integrated GPS receiver can be used in a

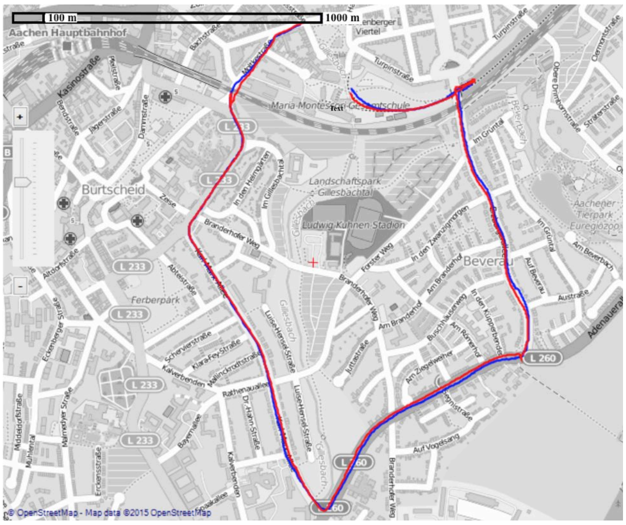


Fig. 10. Illustration of the tracked route (891 recorded positions), blue line represents the tracked route by the textile-integrated GPS receiver and red line represents the tracked route by the GPS mouse. The map data is from OpenStreetMap (® OpenStreetMap contributors). Its license can be found here *www.openstreetmap.org/copyright*.

variety of other applications. These include medical applications, e.g. the localization of patients suffering from dementia. The system could also be used by outdoor enthusiasts or anyone else during their activities to track their localization. For such an application the textile-integrated GPS receiver could be combined with an alarm button and additional textile antennas for communication to provide data or voice signals as well as the location in case of emergencies.

7. Conclusion

The work in hand presents a textile-integrated GPS receiver. It has been implemented and integrated into a jacket and then evaluated in a real field test. The textile-integrated GPS receiver includes a fully textile passive circular polarized antenna with attractive characteristics for GPS applications. The proposed fabrication process results in a good agreement between antenna's simulation and measurement results. The real field test reveals that the textile-integrated GPS receiver has a similar performance to the standard GPS mouse used for the comparison. This promising textile-integrated GPS receiver can be well integrated into clothes and thus a wide field of applications is introduced.

Acknowledgements

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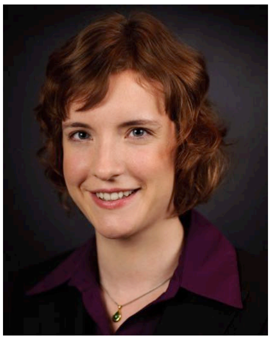

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