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Textile NFC antenna for power and data transmission across clothes

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Abstract

In this article, it is shown how a smartphone can be used together with an e-textile structure, such as smart clothing, or any other smart home textile structure, smart composite, etc, to power it and to send and receive data generated by the e-textile by using the magnetic induction phenomenon through textile materials. This has been achieved using the NFC communication protocol and NFC compatible fully textile antennas without any electronic components such as resistors, inductors or capacitors. Our NFC antennas have been realized by embroidery and geometrical shapes using conductive threads. All the antennas realized have been tested to show their capacity to send the power and to send and receive data from sensors, in particular by testing their resonant frequencies, which are 13.7 MHz and 13.83 MHz, and their quality factor, which are 45 and 55, respectively. The approach used in this work facilitates the design and production of smart textiles and their reliability and washability, as they do not need any more to be equipped with power supplies such as batteries and data acquisition and interface cards, that are not laundering and cleaning friendly and are very difficult to be realized on flexible structures making them textile compatible. Therefore, we believe that in the future, a smartphone placed in specific locations in our clothing (pockets) equipped with our antennas will help the development and the market readiness of future generations of smart textile structures. The realized prototypes will enable to create a sensor network by acting as a current extension transmitting power and data.

Keywords: textile, antenna, power supply, near field communication, embroidery

(Some figures may appear in colour only in the online journal)

1. Introduction

In the past few years, the evolution of textile materials and garments naturally turns to electronics and smart textiles [1]. In other words, clothes are now able to analyze and respond to external stimuli such as temperature, relative humidity or heart beats [2, 3]. It is, in particular, the progress in spinning technology that enabled the manufacture of current conductive threads [4]. Indeed, conductive threads can be obtained by a covering process where conductive fibers, for example, silver, cover a textile thread core. Also, a classic twisted process enables to get conductive threads where conventional and conductive filaments are twisted. This conductive textile yarns enable the creation and integration of electronic circuits into clothes to bring functionalities [5]. However, smart textiles need a power supply to work, consequently, it is necessary to connect a battery and a data treatment device (non-textile) to the circuit. This significantly limits the use and the mobile character of smart textiles. Moreover, the multiplication of subsystems leads to many connectors which increases the numbers of potential weak points and reduces the robustness of the whole device. The data transmission requires to analyze and respond to an external stimulus, which can also be ensured by the subsystem of the current line, but it needs a physical connection between the different textile and non-textile parts [6].

A simple way to get free of these previous constraints is to use a wireless technology enable to transfer power and data. Thus, a smartphone could serve as an energy supply and data acquisition card for a smart or an e-textile structure. In that case, the washability and reliability of the e-textile structure equipped by sensors and actuators, but with the power supply and the data acquisition realized by a smartphone are less an issue as all the sensitive parts belong to a smartphone that is fully 'detachable'.

Moreover, the design and realization of such an e-textile structure is facilitated and requires just an adapted software IOS or Android application and of course a well-known and standardized communication protocol able to transfer the energy and the data.

In the case of garments, the Near Field Communication (NFC) technology seems to be consistent since the power transfer ratio is satisfying and the distance between all subsystems is close. The NFC technology is based on the magnetic induction principle. Nowadays, the NFC system can be found in many devices such as debit and credit cards for wireless payment, identification cards, and garment labels for automatic detection at checkout or mobile phones for wireless charge [7–10]. In this technology, the power and data transfer is guaranteed by antennas, which are also RLC circuits resonant at 13.56 MHz. The wavelength in air is close to 22 m, which involves the use of wire antenna, more precisely a loop antenna. Usually, in classic electronics, NFC antennas are realized on a PCB rigid substrate; but in recent years, flexible substrate NFC antennas have been largely developed [11]. The evolution of printing techniques enables to engrave them on several new materials, for example on thin films [12, 13]. Accordingly, antennas could be partially integrated into clothes through encapsulation or simply by bonding or inclusion [14]. However, to fully integrate antennas into garments, it was necessary to develop antennas made of textile materials. Recently, Xu *et al* develop a textile loop coil [15] in which a capacitor can be connected to create an NFC antenna resonant at the desired frequency. The use of textile materials was also considered in the field of electromagnetic metamaterials [16]. It is also possible to develop a patch antenna made of textile materials [17]. The power transmission through textile materials has already been studied, in particular with the use of flexible antennas, and several operating frequencies can be considered [18, 19]. Regarding the NFC protocol, which is studied in this article, the operating frequency is 13.56 MHz. Recent studies show the feasibility to transfer power through a textile substrate at this frequency [20, 21].

Through this paper, the development of a fully textile NFC transmission device without any electronic component, i.e. an RLC circuit resonant around 13.56 MHz is presented, and also a transmission line connecting the antennas amongst them. There are two principal benefits of such a system. First, it removes the rigid components present in classic electronics, such as a capacitor and an inductance. It enables to reduce connection points and can make the system more robust. Second, it aims to create power transmission lines around the body without physical limitations. For example, different clothes (from trousers to tee-shirt or socks) may be connected and transfer power and data wirelessly. The device is composed of a conductive thread made of twisted copper and PET monofilaments from Tibtech innovation company. It includes two textile flat spiral antennas linked by a two-wire line. Obtained results highlight a loss between the two antennas around 6 dBμA m^{-1}. That is enough to light an LED or read a tag with a mobile phone.

The most significant achievement of our approach is the design and realization of the textile embroidery technique of an NFC antenna without any electronic components needed for its proper functioning. It means that the antenna inductance L and its capacitance C are obtained only by using the embroidery technique following a particular geometrical design and using a high-quality conductive thread.

In this paper, the development of the flexible textile NFC antenna by proposing the embroidery technique is first presented, the conductive threads, the antennas design, the manufacturing of the transmission system and finally the data and power transmission from trousers to socks or shirt are then introduced. In the second part, called Results and discussion, the antennas and transmission lines characterizations, the power transmission, the data transmission, the prototype technical specification, and the electrical model are exposed. Finally, the conclusion is given.

Table 1. Technical specification of the Tibtech innovation company conductive thread.

Yarn	Linear Resistance [Ω m^{-1}]	Tex [g m^{-1}]	Outer wall [μm]	Max Voltage [V]
TibTech—Datatrans	4.20	0.18	28	48

2. Flexible textile NFC antenna development

2.1. Conductive thread

The conductive yarns used to develop the prototypes are produced by the Tibtech innovation Company. It presents a linear resistance of 4.2 Ω m^{-1}; table 1 shows the technical specification of the conductive thread. It is composed of 4 copper strands twisted on multiple PET filaments protected by an insulating cover of the same PET filaments. The PET filaments from the core have a radius of 13.5 μm ($\pm$0.04%). Polyester has a relative permittivity between 2.8 and 4.5, in this case, the presence of a lot of air reduces the value near to 1 [22]. Microscope photography of the thread structure without the insulating part is presented in figure 1. The natural coiled shape of the conductive part provides the yarn a very small intrinsic inductance, that can be ignored in this study. Also, the covering ratio of the conductive part on the core is 42.56% ($\pm$0.3 %).

2.2. Embroidery technique

First, the embroidery process to produce flat loop antennas has been selected because of its flexibility and the possibility to

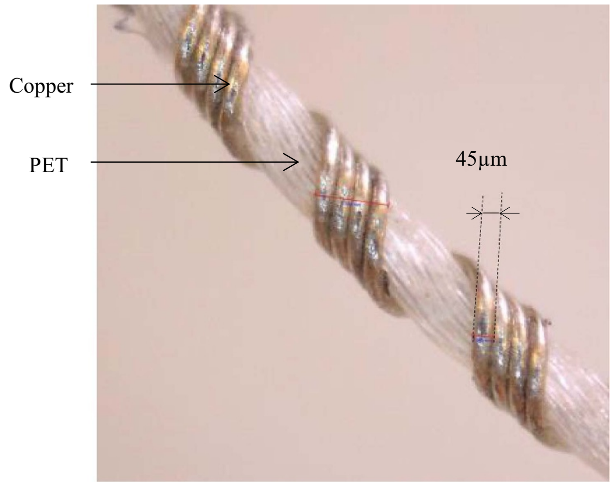


Figure 1. Microscope photography of the conductive thread structure without the outer insulating cover.

bring easily electronic properties to the textile substrate. This process has the benefit of dropping textile threads accurately and repeatably on a textile substrate. This process also enables the use of conductive textile yarns and realizes most geometric shapes with accuracy near 0.5 mm.

The embroiderer machine model used is a 'JF-0215-495' from the ZSK company, Germany, it is composed of a needle performing vertical movements to deposit the upper embroidery thread on the textile substrate. It is also composed of a plate making movements in the plane perpendicular to the direction of needle movements, on which the textile substrate is fixed. Finally, it consists of a bobbin containing a spool of lower bobbin thread used to fix the upper embroidery thread; it performs a rotary movement and has a small hook to catch the embroidery thread.

The operating principle of the process is shown in figure 2(a) the needle is lowered to deposit the embroidery thread on the textile support. (b) Once the needle has passed through the holder to reach the bobbin, the bobbin turns to catch the upper embroidery thread. (c) The needle moves up while the bobbin continues to rotate to pass the upper embroidery thread around the lower bobbin thread. The latter will be used to attach the upper embroidery thread to the support. (d) The tray moves to create the pattern and a new cycle starts again. And figure 2(e) displays photography of the ZSK embroiderer with the embroiderer and (f) zoom on the needles.

The conductive yarn is used as the lower bobbin threads because its trajectory is more rectilinear than the upper embroidery threads (cf figure 2). Moreover, stresses endured by the lower bobbin threads are softer, that enables to use of larger and stiffer threads. Moreover, stresses endured by the lower bobbin threads are softer, that enables to use of larger and stiffer threads.

2.3. Antennas and transmission lines design

The antennas design is conceived to provide resistance, inductance, and capacity to the circuit to create an RLC circuit resonant at the desired frequency, i.e. 13.56 MHz. The antennas are composed of 12 turns plane circular spiral with an outer radius of 40 mm, as presented in figure 3(a) photography. The spiral structure enables to influence of the resistance (R), the inductance (L) and the capacity (C) values by varying the number of turns. Then, the distance between two current lines is also an important parameter, it impacts the circuit capacity. The current line is composed of three overlapped conductive threads, as shown in the schematic of figure 3(b), where the half period, l = 4 mm and the width, e = 0.5 mm. The three overlapped threads are embroidered successively and soldered at the ends to form a single current line. Finally, to connect the antenna to the impedance analyzer, an SMA connector has been soldered directly to the threads, as shown in figure 3(a). This SMA connector is only used to perform measurements, it is not destined to practical use.

The number of turns and the radius of the antenna has a direct impact on the inductance; consequently modifying these parameters enables to choose the desired inductance. Then, the capacity of the antenna depends on the amount of conductive materials (in the surface) close to each other. Therefore, the number of turns and the radius enable to modifying distinctly the capacity of the circuit. To determine a good combination to obtain a resonant frequency at 13.56 MHz, the evolution of inductance and capacity versus the number of turns and the radius has been studied. Obtained results have enabled to create a linear model approximating the resonant frequency according to the geometrical parameters. To evaluate the inductance versus the radius and the number of turns two sets of experiments have been conducted. First, the number of turns has been set to 1 and the radius has been varied from 25 mm to 50 mm. Second, the radius has been set to 40 mm and the number of turns has been varied from 1 to 12. The results have shown a linear evolution of the inductance in both cases. Taking into account their potential applications, the radius has been set to 40 mm to correspond to commercial NFC antenna on the market. Then, the capacity of transmission lines versus its length and width has also been measured to determine its impact on the resonant frequency of the whole device.

The role of the transmission line is to transfer the power and modulated signal received by the antenna to another embroidered antenna or a terminal component. Figure 4 displays the 'antenna+transmission line' photography (a) and the corresponding electrical schematic (b). The presence of a transmission line composed with three wires containing each four twisted strands necessarily produces modifications in-circuit electrical parameters. According to the equivalent electrical circuit given in figure 4(b), the total impedance of the structure results in the following expression:

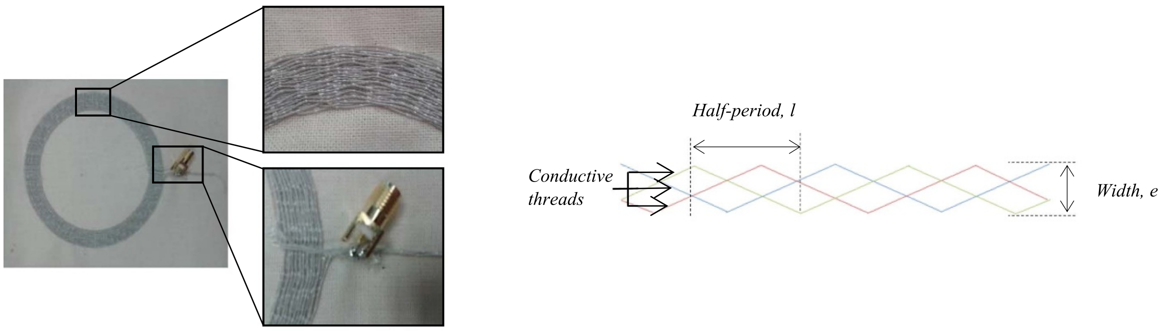
$$Z = r + \frac{R + jL\omega}{1 + jRC\omega - LC\omega^2}$$

where $\omega = 2\pi.f$ and $C = C_1 + C_2$ C_1 and C_2 being respectively the capacity of the transmission line and the intrinsic capacity of the antenna.

Likewise, the transmission line can be considered as a small inductance; however, the very weak value of the distance

(e) (f)

Figure 2. (a)–(d) Schematic operating principle of a textile embroiderer. (e) ZSK embroiderer and (f) zoom on the needle.



(a) (b)

Figure 3. (a) An NFC textile antenna photography with zooms on current lines and the SMA connector and (b) the schematic representation of the current line.

between both cables enables to ignore it. Finally, the total current line length is bigger, so the total resistance too. Equations (1) and (2) can be used for the computation of the resonance frequency.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

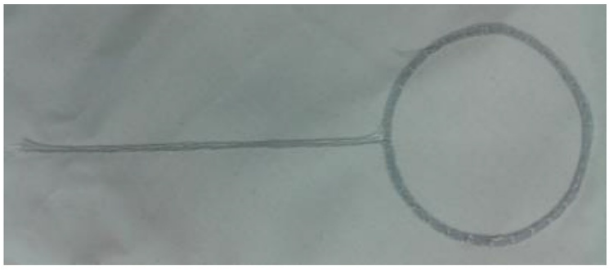
The equivalent circuit of figure 4(b) and equation (2) have been used to adapt the resonant frequency at 13.56 MHz. The resistive parts noted r for the transmission line for

$$f_0 = \frac{1}{2\pi\sqrt{L(C_1 + C_2)}} \tag{2}$$

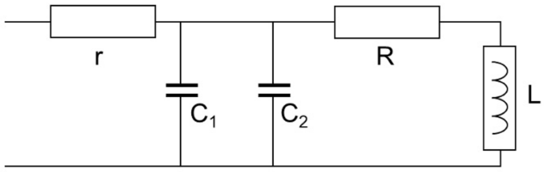
the spiral antenna act mainly on the quality factor, thus on the performance of the transmission of power and signal.

2.4. Manufacturing of transmission systems

The device described in the previous part enables to convert a magnetic field into a current and vice versa. The following described prototype is designed to transfer a magnetic field,

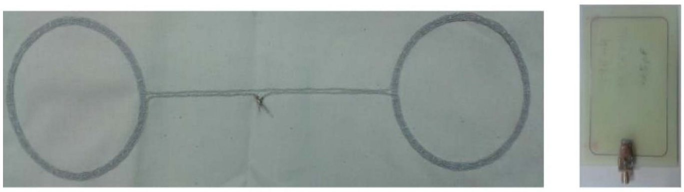


(a)

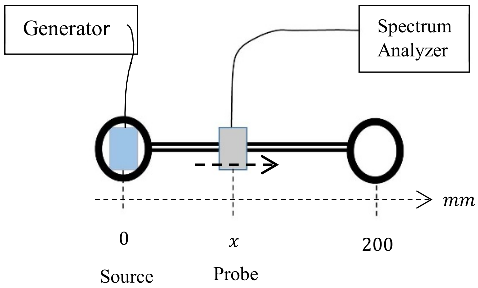


(b)

Figure 4. (a) Photography of the antenna and transmission line prototype and (b) Equivalent circuit of the antenna and transmission line.



(a) (b)



(c)

Figure 5. (a) An NFC transmission system photography, (b) the source and probe antenna and (c) the experimental protocol schematic.

therefore power and data, from a point to another through textile materials. It can be considered as an extension device for a magnetic field, and it can be used to associate and connect several garments to create a sensor network around the human body.

The prototype is realized thanks to the same embroidery process. It has been realized by connecting two identical antennas with a transmission line, in this case, a six turns and 40 mm outer radius antenna and a 200 mm length, 0.75 mm gap transmission line. Figure 5(a) shows a photography of the transmission system.

3. Results and discussion

All the measurements were carried out under the conditions of temperature and relative humidity of our standardized laboratory, i.e. 21 °C and 65% of relative humidity.

3.1. Antennas characterization

First, for antennas, the measured characteristics are the resonant frequency and quality factor. Those measurements are carried out by using an impedance meter Agilent 4259 A. The approach consists of measure the real and the imaginary part of the impedance between 1 kHz and 20 MHz. The presence of resonance from the impedance curves is deduced when the imaginary part comes to zero. About the quality factor, it is calculated by the following relation (3):

$$Q = \frac{f_0}{\Delta f} \tag{3}$$

Where Δf is the bandwidth of the resonant structure.

The resonant frequency and quality factor of the antennas alone (12 turns antenna) are both displayed in figure 6(a) and highlight an annulation of the impedance imaginary part at 13.83 MHz. The bandwidth has been determined graphically and the use of equation (3) has resulted in a value equal to 55 for Q, the quality factor. Such antenna exhibits a bandwidth of the order of 240 kHz that is acceptable to transfer energy and an NFC low rate modulated signal.

In a second phase, the same measurement on the six turns antenna connected to the 200 mm length transmission line has been performed. The results are presented in figure 6(b). Adding the transmission line required to decrease the number of turns of the coil antenna to maintain the resonant frequency in the range as the previous one, i.e. 15.89 MHz. However, the quality factor (Q = 45) is slightly lower because the transmission line brings more resistance to the circuit, but it is still acceptable and enables to transfer of power despite a resonant frequency shifted [15].

It is very important to notice that a very high quality factor will transmit more power but inside a small bandwidth, resulting in a bad transmission of the modulated signal at higher rates.

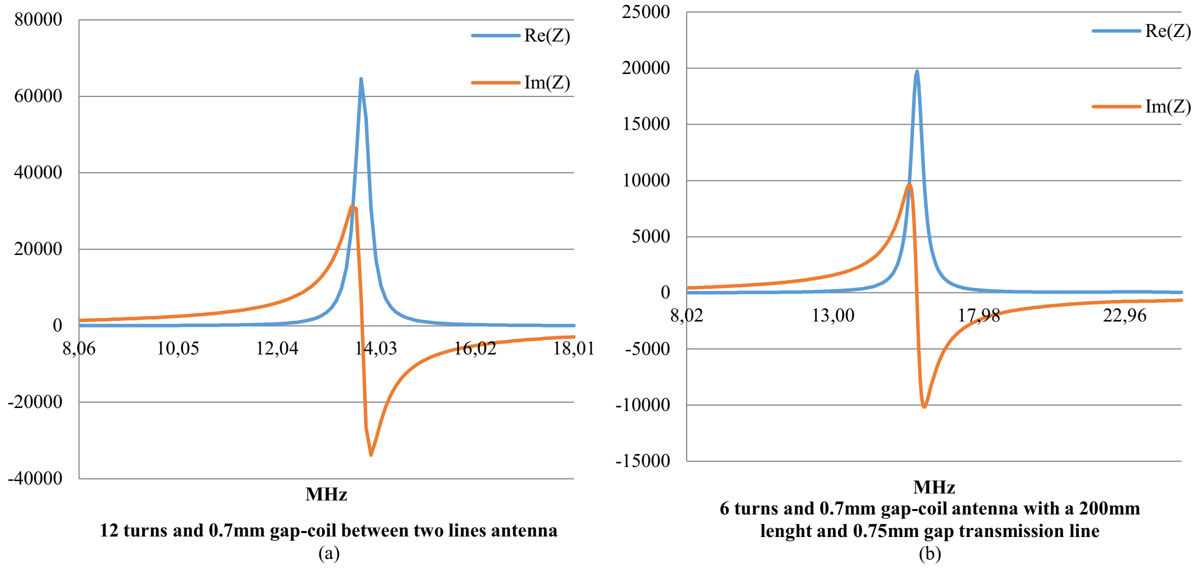


Figure 6. Impedance's evolution versus the frequency of (a) the 12 turns and 0.7 mm gap-coils spiral antenna and (b) the 6 turns and 0.7 mm gap-coil antenna and a 200 mm length/0.75 mm gap transmission line.

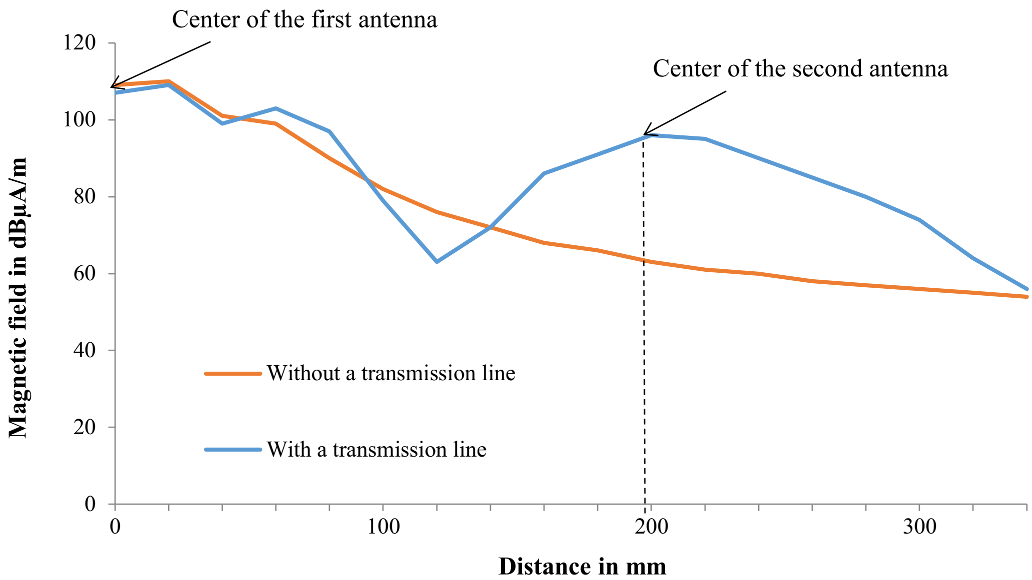


Figure 7. The comparison of the two curves of the magnetic field evolution in function of distance.

3.2. Power transmission

Second, for the transmission system, it has not been possible to connect the impedance meter because the electric circuit was closed. The structure has been measured by a spectrum analyzer connected to a one-turn rectangular loop printed antenna, shown in figure 5(b). Also, the structure has been powered by a 13.56 MHz and 5 V pp sinusoidal signal emitted by a second identical antenna, figure 5(b). The assembly diagram is shown in figure 5(c).

A measure of the magnetic field emitted by the source only has also been realized to use it as a reference.

As expected, the field without transmission system undergoes a strong attenuation (-56 dBμA m^{-1} at 400 mm) as the probe moves away from the source, 1 cm above the plane of the embroidered structure. About the transmission systems, at first, the magnetic field decreases sharply, reaching a minimum of 63 dBμA m^{-1} at 120 mm, which is -46 dB compared to the maximum value obtained in the axis of the source antenna (109 dBμA m^{-1} reference level). This evolution corresponds to the location when the probe shifted from the axis of the source antenna and measures the field emitted uniquely by the transmission line. So, the two parallel wires transmission line does not produce any detectable magnetic field.

Then, from 120 mm, the value of the magnetic field increases to reach a maximum of 96 dBμA m^{-1} at 200 mm, which corresponds to an attenuation of 13 dB compared to the

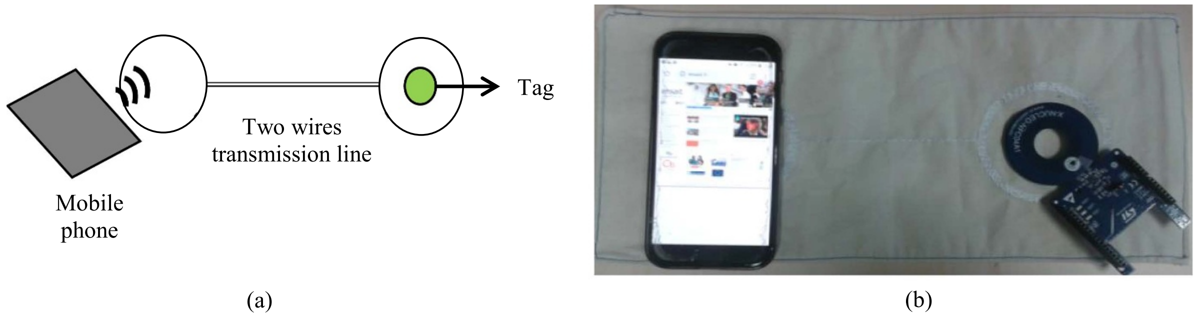


Figure 8. Schematic of the data transmission experiment (a) and the corresponding photography (b).

Figure 9. The NFC antenna prototype connected to an LED (a) and the same antenna power supplied by a mobile phone (b). The NFC antenna connected to an LED combined with the transmission system (c) and the same device power supplied by a mobile phone (d).

reference level measured in the axis of the source antenna. This maximum value corresponds to the location when the probe antenna is aligned with the axis of the second circular antenna. The comparison of the two curves of the magnetic field evolution versus the distance displayed in figure 7 highlights that the transmission system enables to transfer of power with a minimum of losses.

In this wireless transmission system, the role of the first antenna is to transform the magnetic field from the source into an electric current, therefore it is distributed over the whole transmission system because the two antennas are in series. The second antenna transforms the current present in the circuit into a new magnetic field. Therefore the increase of the signal detected by the probe is generated by the presence of a second inductance in the circuit. Between the two antennas, the detected magnetic field reaches a minimum because the two lines of the transmission line are very close and their respective currents are in opposite directions, which has the effect of attenuating the induced magnetic field.

3.3. Data transmission

The data transmission tests have been realized as a proof of concept. The aim is to read a tag via the textile NFC transmission system thanks to a mobile phone or a tablet, as explained in the diagram shown in figure 8(a) and in the experimental setup photography of figure 8(b). The NFC tag is ST Microelectronics 'X-Nucleo-NFC04A1' mainly composed of an NFC antenna and an NFC chip programmed to open a website page when an NFC compatible mobile phone or all other NFC readers, approach. In this case, the NFC tag has been encoded to open the ENSAIT laboratory website thanks to an Arduino. The reading of the NFC tag could be made by the mobile phone through the transmission system. Therefore, the data transmission can be ensured by the NFC textile transmission systems. Also, a lot of NFC tags could be read by the mobile phone, such as door pass, metro pass, or NFC debit card. That means, to a certain extent, the transmission system can be used to transfer a modulated signal to send or receive data.

3.4. Application

To illustrate our study about textile NFC technology, a device able to transfer the power of a magnetic field to light a LED without electronic component (except the LED) has been prototyped. This LED represents a possible sensor requiring power and communication. Moreover, the magnetic field can be created by several sources, in our case; a mobile phone (NFC compatible) has been used.

The prototype is composed of 6 turns, 0.7 mm gap-coil between two lines antenna and a 200 mm transmission line connected to a LED; and a transmission system. Figure 9(a) displays the antenna prototype connected to the LED by soldering and (b) the same device wireless power supplied by a mobile phone. While figures 9(c) and (d) show photography of the same prototype combined with the transmission system, with wireless power supply by mobile phone (d) and without (c).

4. Conclusion

Through this article, several textile communication devices based on the NFC technology that can be combining to transfer energy and data all around the human body have been presented. First, an NFC textile antenna able to transfer energy and data at 13.56 MHz has been developed. The conducted experiments have shown that is possible to develop NFC antennas only by using textile materials and processes. Moreover, the measured performances highlight the viability of textile NFC prototypes. To use sensors or a light all around the body, it is possible to connect this antenna, with small modifications, to a transmission line. Then, in the case of communication between discontinuous cloths (for example from trousers to shirt), a tuned transmission system to transfer data and energy via magnetic induction can be used. This textile NFC transmission system enables to improve significantly the range of NFC technology without too many losses, and the development of a potential human-centered sensor network without connection point. Also, this textile NFC communication device is developed only with textile materials and does not require rigid electrical components. Moreover, the large flexibility of the embroidery process enables us to consider future industrial development. Finally, the 100% integrated communication device could be used in many sectors, such as medicine, security or sport by facilitating and centralizing all data and energy sources in one device: the mobile phone.

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