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A Wearable NFC Antenna Sewn on Leather Substrate for Immersive IoT Applications

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ABSTRACT

The Internet of Things (IoT) is considered a promising realm of innovation and revenue generation for the forthcoming years, revolutionizing the way we interact with objects, other people and the world. With an unprecedented but realistic target of trillions of interconnected devices, the IoT calls for technological innovations that lie in the heart of rapid, low-energy and user-friendly communication between people and things. In this respect, the Near Field Communication (NFC) protocol offers advanced efficiency and applicability with low energy consumption, ease of use, flexibility, and increased payload. NFC tags may be embedded in everyday objects, including clothing and apparel, offering an immersive user experience. Wearable NFC antennas and NFC tags embedded in clothing have been presented in the past; nonetheless, in this paper we present, to the best of our knowledge, the first reported development of a NFC antenna on leather substrate. The proposed antenna is sewn using stainless steel thread and operates at the 13.56 MHz frequency range. It may be used alongside with NFC tags in leather apparel like clothing, shoes, accessories, etc., thus extending the possible use cases and applications of the NFC technology and offering an all the more immersive experience for the end user.

KEYWORDS

internet of things, near-field communication, NFC antennas, leather antennas, wearable antennas

INTRODUCTION

With the outbreak of 5G networks being imminent, a large bouquet of technologies and services is expected to reach consumers, promising a substantial quality of life improvement in many and unprecedented ways. Among 5G technologies, the Internet of Things (IoT) lies on a long-awaited developing infrastructure of trillions of interconnected nodes that communicate with each other and with people, thus offering an immersive user experience and interaction with the environment [1]. Important IoT platforms include the LTE-M and NB-IoT standards with paid subscription, as well as open technologies [2-4]. In this context, the Near-Field Communication (NFC) technology is considered

to be an IoT-enabling technology that offers seamless, ubiquitous interaction with things, while at the same time being energy efficient and easy to use for the end-consumer [5-6]. NFC is considered to be an IoT enabler and enhancer, since the former will offer numerous and more intrusive use cases to the latter, making information reading and writing upon (i.e. interacting with) objects feasible remotely [7]. Moreover, NFC offers the ability to connect devices that would otherwise remain unconnected (e.g. unpowered devices), but also provides additional data security at multiple levels [8].

Recently, NFC has been proposed to be integrated into clothing and apparel, using wearable implementations of NFC antennas and textile-embedded NFC chips [9-11]. In general, wearable devices are an exciting frontier in science and technology. With rapid advancements in miniaturization, together with denser and denser processor packages, the capacity for truly wearable devices is becoming a reality. Moreover, wearable devices are expected to play their part in the adoption of the IoT vision. In this respect, the capacity of purely textile devices is still considered to be underrated, mainly due to the relatively immature technology of wearable components that are purely made of textile materials. Nevertheless, the pioneering research in this field has already delivered a multitude of wearable components, mainly distributed ones, like antennas and transmission lines. A systematic review of wearable textile RFID sensors is available in the work of Luo et al. [12].

In this context, textile antennas have attracted significant research resources, also due to their potential to be used for communications and medical applications in a seamless manner [13-14]. Wearable antennas partially based on textiles were firstly presented by Salonen et al. [15]. Purely textile antennas have been also proposed like the ones by Hertleer et al. [16] and Vallozzi et al. [17] that both reported purely textile antennas operating at 2.4 GHz. Other works include a parametric study of textile antenna performance vs. the distance from the human body by Alomainy et al. [18], demonstrating the importance of the vicinity of the wearable antenna to the human body; dual-band antennas reported by Zhu and Langley [19]; as well as the studies of the effect of bending and crumbling by Bai and Langley [20]. Kennedy et al. presented a textile antenna array for body-centric applications, which exhibits robust performance with moderate amounts of bending [21]. Sankaralingam and Gupta developed a rectangular patch for deployment on different cotton substrates, while comparing rectangular and circular shapes [22]. On the same page, Osman et al. developed an ultra-wideband (UWB) antenna using Jeans fabric as a substrate while the radiating element and ground plane were made from copper tape [23]. Coosemans et al. manufactured and tested a prototype in which they integrated a textile antenna and a sensor for electrocardiogram monitoring in order to observe the symptoms of Sudden Infant Death Syndrome [24], while Catrysse et al. manufactured a textile belt in order to monitor the electrocardiogram and respiration rate of children [25].

As long as NFC antennas are concerned, it should be pointed out that the term “antenna” is a convention since NFC communication is achieved via coupling rather than radiation. More specifically, antennas’ size is typically in the order of a wavelength of the operating radio-frequency (RF). As an example, consider the operating frequency of 13.56 MHz, at which a large variety of NFC hardware operates. In this case, the corresponding wavelength would be slightly larger than 22 m, which means that an efficient antenna should have a size of ~ 11 m, while its radiation region would start at around 11 m as well [26]. As such, typical NFC antennas are essentially closely-coupled coils that are communicating with each other via inductive emission coupling. Nevertheless, the term NFC antennas is used in excess, and we adopt it herein for convenience to the reader and compatibility with the literature.

Having said that, wearable and textile NFC antennas have also been reported in the literature, but not to the same extent like other antenna technologies. The potential use of wearable NFC devices for pervasive health monitoring was discussed by Prabhakar et al. [27] and the use of RFID tags in retail shops clothing merchandise was presented by Serra et al. [28]. Further on, the design and performance analysis of a purely textile antenna for NFC applications was presented in 2017 [29]; various embroidered wearable antennas for NFC and RFID were proposed by Jiang et al. on 2019 [30]; and finally, very recently, a body temperature and sweat sensing system based on smart textile NFC components was proposed [31]. In parallel, industry-driven research is developing alternative technologies for deploying NFC antennas and chips in textiles and clothing [32-34].

In this paper, we present an NFC antenna that is developed using stainless steel yarn sewn directly on leather substrate. We intend to use this technology in order to embed NFC tags within leather clothing and apparel, like jackets, shoes, bags and accessories, etc. Strikingly enough, the ieeexplore database returns no results when using the keywords “NFC” and “leather” [35]. To the best of our knowledge, no NFC antenna using natural or artificial leather has been reported in the literature, either with sewn yarns or any other means of conductive routes development. As long as the sewing process is concerned, it is noted that most textile antennas in the literature are embroidered and only a few cases of antennas that are directly sewn on a fabric substrate (not leather) are reported [36-37]; more specifically, oftentimes an antenna is reported as “sewn”, while in reality it has been embroidered [38-39]. Furthermore, antennas over a leather substrate are also reported in the literature but they do not use sewing (or embroidery) or conductive yarns, and are not reported for NFC applications. Some examples include the inkjet-printed antenna on leather [41], the solid metal conductive antenna attached on leather [41], or the CPW-fed wearable antenna that was implemented by attaching a copper foil over leather substrate [42].

Our proposed NFC antenna operates at the 13.56 MHz frequency range and exhibits an input inductance of about 1.7 μH at this frequency, making it suitable for NFC applications. Herein, we

present the design and implementation procedures, and present numerical and analytical vs. experimental results, concluding that there is substantial compatibility among them. We also compare our proposed antenna vs. the measured performance of commercially available flexible NFC antennas and demonstrate that the former exhibits better or comparable performance with respect to the latter.

DESIGN AND NUMERICAL RESULTS

The design of NFC antennas needs to take into account the available technology and materials, the volume of space that is being made available to the designer, and the fact that the NFC antenna self-inductance plays an important role to coupling distance. In other words, the larger an NFC coil (i.e., NFC antenna) the larger its inductance and, consequently, the larger the communication distance, and vice versa. As such, the large area that is typically made available in clothes makes them an advantageous platform for developing NFC antennas. Moreover, the larger available surface allows for a larger number of coil spiral turns, thus increasing the inductance of the resulting antenna. There are no rules of thumb, but generally it is considered that an inductance value of at least $1\ \mu\text{H}$ is adequate for an NFC antenna to operate properly.

Referring to Figure 1, a typical printed-circuit board (PCB) NFC rectangular antenna is a flat rectangular coil of outer dimensions equal to a_0 and b_0 . The width of the microstrip is equal to w , while its thickness, t (conductor thickness), is much smaller than w . Furthermore, the gap between the turns is equal to g and the number of turns is equal to N .

Figure 1. Generic rectangular layout of an NFC flat-surface antenna

Assuming a perfect electric conductor, the corresponding inductance of the coil is calculated by [43-44]:

$$L_A = (2M_1 + 2M_2 + 2L_1 + 2L_2) \cdot N^E \quad (1)$$

where E is a correction factor attributed to the shape of the coil, N is the number of coil turns, and

$$M_1 = \frac{\mu_0}{2\pi} \left[\alpha \cdot \ln \left(\frac{2ab}{d(a + \sqrt{a^2 + b^2})} \right) - 2b + \sqrt{a^2 + b^2} \right], \quad (2)$$

$$M_2 = \frac{\mu_0}{2\pi} \left[b \cdot \ln \left(\frac{2ab}{d(b + \sqrt{a^2 + b^2})} \right) - 2a + \sqrt{a^2 + b^2} \right], \quad (3)$$

$$L_1 = \frac{\mu_0 a}{16\pi}, \quad (4a)$$

$$L_2 = \frac{\mu_0 b}{16\pi}, \quad (4b)$$

$$d = 2\sqrt{\frac{t \cdot w}{\pi}}. \quad (4c)$$

in the above equations, μ_0 is the magnetic permeability of the vacuum, w and t are the width and thickness of the conductor trace, respectively, and a and b are the corresponding average length and width of the inductor calculated by:

$$a = a_{avg} = \sqrt{\frac{a_0^2 + (a_0 - 2N(g + w))^2}{2}}, \quad (5a)$$

$$b = b_{avg} = \sqrt{\frac{b_0^2 + (b_0 - 2N(g + w))^2}{2}}. \quad (5b)$$

Based on the above equations, a rectangular NFC antenna is designed. For the purposes of this implementation, a 100 % stainless steel yarn by Tibtech was used (type 316L [45]), while the diameter of the yarn was measured equal to $w = 0.3$ mm. Aiming at an inductance larger than 1 μH , we obtain the following values for the parameters of the proposed antenna: antenna length $a_0 = 78$ mm, antenna width $b_0 = 47$ mm, the gap between the coil lines $g = 3$ mm, the number of turns $N = 4$, the fitting parameter, $E = 1.5$. By substituting the above parameters' values in the preceding equations, we obtain a calculated inductance of the proposed antenna equal to $L_A = 1.41$ μH . This is an initial estimation of the self-inductance of the proposed NFC antenna, while a more precise calculation is based on a fullwave electromagnetic simulation with a commercially available tool.

We then proceeded in modeling the calculated NFC antenna using the commercial electromagnetic simulation software CST Studio Suite 2019 (module CST Low Frequency). The stainless steel thread was simulated using cylindrical conductors of diameter equal to $w = 0.3$ mm, which is equal to the measured width of the conductive yarn. The yarn's conductivity was measured with a digital multimeter and found equal to $1.489 \cdot 10^6$ S/m, a value that is compatible with the specifications provided by the yarn manufacturer [46]. The cylindrical conductors' material was created into the CST materials library. The layout of the NFC antenna follows the one depicted in Figure 1 with the calculated values as discussed above. The background material was set to normal with a dielectric constant equal to 3, according to results for leather substrates' dielectric constant that we have obtained via past measurements [47]. A perspective and a top view of the CST antenna model are depicted in Figure 2.

Figure 2. (a) Perspective and (b) top view of the NFC antenna simulated with CST Studio Suite 2019

Simulated results of the NFC antenna regarding its self-inductance and quality factor vs. frequency are depicted in Figure 3, for the range between 1 to 20 MHz. At the frequency of 13.56 MHz, the simulated self-inductance is equal to $1.443 \mu\text{H}$ while the quality factor is equal to 5.5. The self-inductance remains relatively stable between 1 and 20 MHz, while the quality factor is increasing monotonously, implying that the corresponding Ohm losses of the antenna remain relatively stable within the same frequency range. Furthermore, the value of $1.443 \mu\text{H}$ is very close to the theoretically calculated value of $1.41 \mu\text{H}$, and both are exceeding the rule of thumb threshold of $1 \mu\text{H}$ for an efficient NFC coupling between readers and tags. Please note that Figure 3 includes both simulated and measured results of our antenna, for the sake of brevity. The implementation of the proposed antenna and the corresponding measurements are discussed in Section 3 below.

Figure 3. Simulated and measured results of the proposed NFC antenna, a) Self-inductance and (b) Quality factor, Q

IMPLEMENTATION AND EXPERIMENTAL RESULTS

The simulated antenna is implemented using stainless steel yarn and an industrial grade sewing machine. First, we drew the pattern of the conductive traces on the leather sample using a piece of chalk. Then, we sew the conductive yarn directly on the leather while following the drawing of the pattern. We used one bobbin with the stainless steel yarn for the top pattern and one bobbin with a typical cotton yarn (Madeira Aerofill thread) for the bottom pattern. The sewing machine that we used was a Duerkopp Adler, model H-type 967 ECO and was provided by ENSAIT. The antenna sewing was preceded by training on the aforementioned sewing machine, and then a series of trial sews on test substrates. Finally, the proposed antenna was sewn upon a leather substrate of thickness equal to 2.4 mm; the leather sample that we used was a fully processed cow leather (dyed and finished) and was provided by the company “Caterina Firenze” of Tirana, Albania.

Figure 4(a) illustrates a photo of the implemented antenna. As it can be easily seen in the photo, the antenna sewn on the textile fabric has several manufacturing defects that are attributed to the rigidity of the leather substrate in contrast to a conventional textile fabric, e.g. cotton or other. It is considered that these defects are not typically present when sewing on e.g. cotton or other textile fabric but are typical when using a semi-rigid substrate like a leather one. However, as it will be shown by our measurements findings below, these slight defects are not affecting the overall performance of the antenna and the latter remains within the specified performance even in the presence of such defects. The applicability of the proposed antenna is herein demonstrated by comparing its measured characteristics to those of two commercially available NFC antennas; Figures 4(b) and 4(c) illustrate two photos of the aforementioned commercial NFC antennas.

Figure 4. (a) The NFC antenna sewn on leather with stainless steel yarn, (b) the “large” commercially available NFC antenna, and (c) the “small” commercially available NFC antenna

Then, the proposed antenna was measured within the premises of the University of West Attica using a Wayne Kerr, model 6500B, 20 Hz – 50 MHz impedance analyzer. We used two wire leads and snap clips in order to connect the antenna to the analyzer ports. Prior to antenna measurement, the instrument was calibrated with open and short loads. Then, the self-inductance and the quality factor of the device under test were measured and the results exported via USB for further analysis.

Figures 3 and 5 illustrate the measured self-inductance, L , and the quality factor, Q , of the implemented NFC leather antenna; Figure 3 vs. the simulated values and Figure 5 vs. the commercial antennas' values. From the diagrams it is evident that the self-inductance and the quality factor of the implemented antenna at the frequency of 13.56 MHz are equal to 1.7 μH and 4.71 respectively. The self-inductance value is slightly larger compared to the designed value of 1.41 μH and the simulated value of 1.443 μH . There is a slight discrepancy between the measured and theoretical/simulated self-inductance values of the order of 0.3 μH or 15 %. This discrepancy is considered to be due to the losses of the leather substrate and the inaccuracies of the implemented sewn antenna pattern.

On the other hand, the measured quality factor value is slightly inferior compared to the simulated one with a value of 4.71 at 13.56 MHz, vs. 5.5 that is the simulated quality factor value. There is a slight discrepancy between the measured and simulated quality factor values that is also attributed to the inaccuracies of the implemented antenna pattern on the leather substrate.

It is considered that the measured results adequately follow the simulated ones, in both the order of magnitude and the curve shape. The self-inductance is fairly stable with respect to frequency, with a slight tendency to decrease for larger frequencies. On the other hand, the quality factor values are comparable to commercially available ones, while their diagram demonstrates a wide bell-shape indicating that the losses of the antenna sample are not changing linearly with frequency.

Figure 5. Measurements results of the proposed NFC leather antenna and the small and large size commercially available antennas (a) self-inductance, L , and (b) quality factor, Q , vs. frequency

As already mentioned, two different commercially available NFC antennas were acquired and measured for comparison purposes. The first commercial antenna is a small size antenna with dimensions 25 mm in length and 15 mm in width, model ANFCA-101-2515-A02 by Abracon [48]. The second one is a large size antenna with dimensions 59 mm in length and 46 mm in width, by Molex [49]. Both commercial antennas are operating at the 13.56 MHz frequency range and constitute of printed coils on flexible (plastic) surface. We selected flexible NFC antennas in order to provide a realistic comparison of our antenna with commercial products of similar target applications.

Measurements results regarding the self-inductance and quality factor of the commercial are illustrated in Figures 5(a) and 5(b) respectively, both vs. the measured values of the proposed leather antenna. The self-inductance and quality factor of the commercial antenna #1 (small size antenna) at 13.56 MHz are equal to 0.25 μH and 6.67, respectively. On the other side, the self-inductance and quality factor of the commercial antenna #2 (large size antenna) at 13.56 MHz are equal to 2.55 μH and 9.43, respectively. Compared to the corresponding measured values of 1.7 μH and 4.71, respectively, of the proposed antenna, we conclude that the latter exhibits better or comparable inductance with the commercial ones but slightly inferior quality factor – perhaps due to the expected higher ohmic losses. It is considered that the proposed antenna is suitable for NFC applications and, furthermore, it is straightforwardly comparable to currently available commercial implementations but with the capacity for increased pervasiveness and unobtrusive usage in everyday clothing and accessories.

Furthermore, due to the nature of the leather, the implemented antenna is practically unstretchable. Nonetheless, we did perform measurements while trying to put tension on it, but the results did not change at all. Regarding bending, we also performed measurements with progressively larger bend curvatures up to a maximum of a curvature corresponding to an arc of a circle with diameter equal to

10 cm. The effect on the self-inductance and the quality factor of the implemented antenna was slightly increasing with frequency but remained negligible nevertheless, i.e. in the order of less than 2 % in the worst case. This robust behavior of the proposed antenna vs. bending is attributed to the low measured frequencies of under 20 MHz and is a further indication on its applicability.

Finally, regarding the repeatability of the results, we performed the aforementioned measurements multiple times but we did not observe any variations among different measurements.

CONCLUSION

A wearable leather antenna was designed, implemented and measured for usage in NFC applications. Measurements results indicate that the proposed antenna is better or comparable to commercially available flexible NFC antennas, in terms of both self-inductance and quality factor. More specifically, the self-inductance of the proposed antenna is 1.7 μH at 13.56 MHz (i.e. the center frequency of the NFC band), while the self-inductance of the small commercial antenna is 0.25 μH and that of the large commercial antenna is 2.55 μH . Furthermore, the quality factor of the proposed antenna is 4.71 at the same frequency, while that of the small and large commercial antennas are 6.67 and 9.43, respectively. It is also noted that the measured results of the proposed antenna are in good agreement with the simulated and theoretically predicted ones.

To the best of our knowledge, an NFC antenna on leather substrate has not been presented in the literature before, while the aforementioned results indicate that leather may be successfully considered as a candidate material for developing NFC antennas and related applications. As such, the NFC technology and convenience may be expanded to a large variety of leather products, including clothing, apparel and accessories. Furthermore, the applicability of using sewn stainless-steel thread for NFC antenna development on leather is demonstrated. As such, the sewing of apparel may be combined with the sewing of NFC antennas, thus creating hybrid multifunctional structures that are functional from both a mechanical and an electrical point of view.

Author Contributions

Conceptualization – Mitilineos SA, Kallivretaki AE, Vassiliadis S, Kazani I, Guxho G, Dassonville F and Koncar V; methodology – Mitilineos SA and Kazani I; software – Dassonville F and Koncar V; validation – Kazani I and Guxho G; formal analysis – Mitilineos SA and Vassiliadis S; investigation – Mitilineos SA, Kallivretaki AE, Vassiliadis S, Kazani I, Guxho G, Dassonville F and Koncar V; resources – Dassonville F and Koncar V; data curation – Mitilineos SA, Kallivretaki AE, Vassiliadis S, Kazani I, Guxho G, Dassonville F and Koncar V; writing-original draft preparation – Mitilineos SA; writing-review and editing – Mitilineos SA, Kallivretaki AE, Vassiliadis S, Kazani I, Guxho G, Dassonville F and Koncar V; supervision

– Vassiliadis S, Guxho G and Koncar V; project administration – Vassiliadis S and Koncar V; funding acquisition – Vassiliadis S and Koncar V. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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