J. Lorenzo, A. Lázaro, R. Villarino and D. Girbau. “Diversity Study of a Frequency Selective Transponder for Wearable Applications”, IEEE Transactions on Antennas and Propagation, vol. 65(5), pp. 2701-2706, March 2017.

doi: 10.1109/tap.2017.2681435

URL: https://ieeexplore.ieee.org/document/7875416

Diversity Study of a Frequency Selective Surface Transponder for Wearable Applications

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***Abstract*—This paper presents a semi-passive RFID system in the 2.45 GHz ISM band. The transponder (or tag) is based on a modulated Frequency Selective Surface (FSS). The FSS is composed of dipoles loaded with varactor diodes that modulate the radar cross section. The FSS transponder is designed to work for wearable and on-body applications and is used for reading and transmitting information from different sensors placed on the body. Experimental results locating the FSS at different positions in real scenarios and also at different places on the body are provided. Multiple FSS have been used to explore spatial and polarization diversity techniques in order to mitigate the deep fadings that can happen during communication. Noticeable diversity gain has been obtained in both cases without using antenna diversity in the reader. Finally, the paper describes a proof-of-concept experiment of the communication where two FSSs send digital data using a Frequency Shift Keying modulation.**

***Index Terms*—FSS transponder, RFID, wearable application, spatial diversity, polarization diversity.**

I. Introduction

THE recent investigations relating to flexible substrates and conductive inkjet printing [1] have enabled sensors and electronic circuits to be integrated on-body for wireless body area networks (WBAN) with particular interest in their application in medicine, entertainment and body monitoring in sports [2]. This technology has presented several challenges in terms of the size, weight and energy consumption of the devices intended for wearable applications. Active devices are often proposed for wireless communications in WBAN. These networks are often based on commercial transceivers such as Zigbee (IEEE 802.15.4) or Bluetooth devices or WIFI (IEEE 802.11) in the 2.45 GHz ISM band [2]-[4], or ultra-wideband (UWB) [3][4]. In addition to active devices, there has also been research into wearable passive UHF Radio-Frequency IDentification (RFID) sensors [5]-[7]. The main advantage of these devices in comparison to other sensor technologies is their lower cost since the tag identification property can also be used as a sensor. However, its performance is still limited compared with commercial sensors. In addition, passive tags take their energy from the RF interrogating signal. One of the most important challenges in wireless devices for wearable applications is the effect of the body on electromagnetic propagation, especially in the detuning of the antenna and reduction of the antenna efficiency (for example in dipoles or monopoles) when they are in contact with the body [8][9]. These effects produce a noticeable reduction on the read range in UHF tags when they are attached to the body because the tag does not receive enough power to wake up the internal integrated circuit [9]. Several types of antennas that are compatible with wearable applications are specifically designed both for narrow band [10][11] and UWB systems [12] to prevent this problem. A typical solution in narrow band design consists of a patch-like antenna integrated into the fabric textile. Spacers located between the antenna and the body or patches that are a few millimeters thick can be used to reduce the losses caused by the body and thus improve the antenna efficiency [10][11]. The thickness of these antennas and the multilayer designs limit their use in wearable applications [12].

Manuscript received Oct. 7, 2016. This work was supported by Spanish Government Project TEC2015-67883-R, H2020 Grant Agreement 645771–EMERGENT and Grant BES-2012-0539802. The authors are with the Department of Electronic, Electric and Automatic Control Engineering, Universitat Rovira i Virgili, 43007 Tarragona, Spain.
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Some of these challenges are less serious if semi-passive or battery-assisted tags (BAP) are employed. In particular, a commercial sensor can be integrated into semi-passive tags and multisensory design can be obtained. For example, a semi-passive solution in the UHF band in which the communication is based on backscattering was recently proposed for Internet of Things (IoT) applications [13]. The main advantage of a semi-passive platform compared to active transceivers is related to power consumption, which is generally determined by the current consumption of the digital core (microcontroller) and the sensors [13]. The cost of these tags in production is lower than that of wireless active sensors (e.g. using Bluetooth or Zigbee standards) and the battery life time is considerably higher and is translated onto simpler power circuits (i.e. rechargeable batteries and charging circuits are not required). However, the communication problems are not completely solved because they are based on backscattering.

Another challenge is attenuation due to the body itself causing NLOS propagation [9][14-17]. Diversity techniques have been proposed in order to combat fading in indoor and WBAN scenarios [18-19]. Spatial diversity is widely applied in mobile base stations and portable devices [16-17]. However, up to now, most studies on channel communications for WBAN focus on active transponders with transmitters [18-19]. The simplest spatial diversity technique consists of switching between several spaced antennas connected to the reader. This solution is often used to improve the reliability in passive UHF RFID systems in logistic dock doors. But the implementation of this infrastructure with several antennas is expensive, especially in domestic environments for telemedicine applications. However, there are few studies on channel diversity for multiple backscattering tags [20-21] and especially for wearable applications [8][9].

Recently, modulated frequency selective surfaces (FSS) have been proposed as transponders in RFID applications. Previous works show the feasibility of these transceivers for localization applications based on UWB radar [22] or FMCW radars [23-24]. A previous work [25] proposed a semi-passive RFID system based on a low-power consumption modulated frequency selective surface (FSS) to be placed on-body for wearable applications using backscattering communication in the 2.45 GHz ISM band. In [25], a temperature sensor that modulates the backscattered field of an FSS is also included as

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a preliminary proof-of-concept. Read ranges higher than 3 m have been shown under near line-of-sight (LOS) conditions.

This work presents a study to determine the feasibility of applying the FSS transponder proposed in [25][26] to wearable applications in real environments. While [25][26] addressed the design of the transponder, this paper focuses on the communication aspects in real environments, and is specifically aimed at increasing the read range and the probability of establishing the communication successfully. Diversity is proposed as a key solution for FSS-based transponders, since several FSSs can be modulated simultaneously sharing the low-frequency modulating signal coming from a sensor using wires that can be integrated into the textile fabrics. The large bandwidth of the FSS provides a degree of robustness in front of the detuning caused by the changes in the electrical properties of the body [25][26]. This robustness simplifies the design for wearable applications. The same FSS can be directly on contact with the skin or spaced for small textile materials without additional or minimal adjustments (fine tuning of dipole length). The FSS can be located in different parts of the body or using different surface area depending on the application. Therefore, the aim of this work is 1) to study the feasibility of channel diversity techniques for on-body communication systems based on backscattered modulated FSSs and 2) to demonstrate the capability of this topology for integrating commercial sensors that control all the FSS responses simultaneously. Digital transmission of sensor data using Frequency Shift Keying (FSK) modulation is implemented to demonstrate this point.

The paper is structured as follows: the operation principle and background theory are presented in section II. Channel measurements are used to evaluate limitations to communication caused by multipath propagation. Both spatial and polarization diversity are proposed as means of overcoming these drawbacks. Section III presents a performance evaluation of spatial and polarization diversity techniques using multiple on-body tags. Section IV describes a communication experiment where two FSSs send digital data using FSK modulation. Finally, section V draws the conclusions.

II. Wearable Tag Based on Modulated Frequency Selective Surface

The present article proposes the use of various modulated FSS as semi-passive tags for wearable applications working in the unlicensed ISM 2.45 GHz. This band was chosen because it the size of the antennas to be reduced (both in the reader and in the tag), although the permitted power is lower and the body losses are higher than in the UHF RFID band.

Figure 1 shows a schema of a modulated frequency selective surface (FSS) for on-body communications. The FSS is composed of dipoles loaded with varactor diodes. The varactors are reverse biased to produce the maximum capacitance change between the two states. Therefore, the power consumption is lower than the one produced in case of using PIN diodes as switching elements [23]. When the bias is switched between 0V and Vcc (typically 3V for lithium-ion battery power devices) the capacitance of the diodes changes and produces a variation in the radar cross section of the FSS. The diodes are biased by means of high value SMD resistances (10 kΩ) that block the RF signal through the feed lines. These feed lines are orthogonal to the dipole arms to reduce interference when they are radiating. They are connected to a modulator that consists of a low frequency Voltage Controlled Oscillator (VCO). It is possible to send analogue information from sensors actuating over the control voltage. Because the communication system is based on backscattering, the power consumption is noticeably lower than in wireless systems that use complex radios with transmitters. A temperature wireless sensor using this procedure has been presented in [25] as a proof of concept. In this sensor the frequency of a low-power 555 timer is controlled by a negative temperature resistance (NTC). The design procedure and performance of the FSS on the body has been described in [25]. A low cost Silicon Varactor Skyworks SMV1247-079LF is used in the prototype. The varactor capacitance is 6.5 pF and 0.95 pF for V=0 (ON state) and V=-3V (OFF state), respectively. The parasitic inductance and resistance are 0.7nH and 2 Ω, respectively. The FSS is implemented using 100 µm thickness flexible Ultralam 3850 substrate. The length of the dipoles has been designed so they can be attached to the body and was calculated by performing numerical simulations with Ansoft HFSS. The dipole length is adjusted to resonate about 2.45 GHz. The length is L=25.6mm and the width is 2 mm. The separation between dipoles is 10.24 mm. The FSS is directly on contact with the body without any spacer. The number of dipoles used in the prototype is 7.

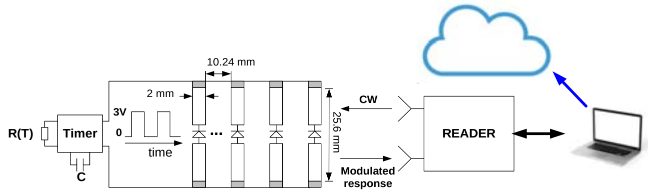

Fig. 1. Modulated frequency selective surface for on-body communications, connected to a temperature sensor [23].

The communication between the tag and the reader is based on backscattering. The backscattered signal is demodulated in the reader using a homodyne receiver. The received signal is converted to baseband with a mixer and sampled with an analog to digital converter. A simple quasi-monostatic configuration (bistatic with a small separation between the transmission and reception antennas) is implemented. A custom software defined radio (SDR) reader prototype is described in [25]. Both Amplitude Shift Key (ASK) or Frequency Shift Key (FSK) digital modulation can be implemented with minor modification of the demodulating software implemented in Matlab. In addition to Time Division Multiple Access (TDMA), a simple mechanism based on Frequency Division Multiple Access (FDMA) can be also implemented in the case of multiple users or sensors to change the carrier frequency of the modulated signal.

III. CHANNEL DIVERSITY MEASUREMENT RESULTS

The theoretical read range was obtained from the free space model [25], which is not very realistic in indoor or wearable applications. One of most important problems in RFID application is multipath interference. One way to combat this problem consists of exploring antenna diversity techniques. The operating principle behind antenna diversity is based on a set of multiple antennas that receive different signal levels due to the different propagation channel conditions; therefore these signals are only partially correlated. Thus, if one antenna is in a deep fade, another one is likely to be able to provide enough signal level. In multipath propagation environments, such as in indoor environments or WBAN applications, when the signal in the direct line-of-sight (LOS) path is sometimes partially blocked or shadowed, each antenna suffers a different fading attenuation. Diversity antenna techniques have been applied to wireless and mobile communications [16-17] for years as well to RFID applications [20-21]. In on-body communications, the body often blocks the direct line of sight (LOS) between the tag and the reader. Thus, various FSS can be located at different parts of the body so that one is always likely to be in LOS can therefore be modulated with the same data from one sensor (see section IV). A couple of wires inside the textile or the belts make it easier for the microcontroller board and the FSS to connect and thus send the low frequency modulating signal from the sensor. Therefore, a key point of the proposed structure is that the multiple tag antennas are not connected using an RF coaxial or any other transmission line, thus avoiding the difficulty of integrating such lines into flexible substrates. This section describes some experiments in order to demonstrate the feasibility of channel diversity with modulated FSS placed on the body.

A. Spatial diversity

A commonly employed solution is spatial diversity for reception based on the use of two or more spaced receiver antennas. Diversity from a transmitter is also possible. However, such techniques are difficult in handheld readers because multiple antennas are needed, thus increasing the size of the readers. The benefits of this type of diversity have been reported in the literature, especially for mobile communications. According to the experimental results described in [20-21], a bistatic reader can perform better than a monostatic one (a circulator is also unnecessary).

The first experiment consisted of determining the fading level in a typical indoor environment (laboratory). Fig.2 shows the backscattered power variation as a function of the interrogating frequency. The FSS is located on the arm pointing to the reader (LOS situation) at a fixed distance (2 m). The results show deep fadings depending on the frequency. The received signal suffers large attenuations (up to 25 dB) at some frequencies due to the multipath. The approximate coherence bandwidth (i.e. the minimum frequency separation in which it can be assumed that two components are uncorrelated) is in the order of 5 MHz. This value is estimated from the frequency difference between the consecutive maximum and minimum in the receiver power (Fig.2). In wearable applications, the realistic transmission frequencies vary from a few kHz to 1 MHz. Hence the channel can be considered flat because the channel bandwidth is smaller than the coherence bandwidth.

Some experiments have been conducted in order to show the effectiveness of spatial diversity. Fig.3. (inset) shows a photograph of two tags attached to the surface of a cylindrical piece of ham used as a phantom to emulate the arm. Experimental results presented in [25] conclude that measurements performed in both the phantom and the body are similar. The spacing between tags is approximately 25 cm (2 λ). The tags are composed of FSS modulated with a low frequency oscillator. Furthermore, the phantom is located in a LOS scenario with respect to the reader. Fig.3. shows the received average power as a function of distance and the standard deviation over the frequency band 2.2-2.5 GHz. In the case of two tags, the two FSS are simultaneously modulated by the same oscillator. It can be seen that the power received at each tag is different and be concluded that the correlation coefficient between both tags is low. It can also be observed that the power received using both tags simultaneously is approximately 3 dB higher than the strongest signal received for any of them separately for all the distances. Space diversity at the mobile base station requires between antennas to be separated by around tens of wavelengths to reduce mutual coupling [16]. This is because the multipath arrival is over a narrow angle spread [16]. However, as shown in [16-17], diversity spacing can be small under wide multipath angle spread conditions. This occurs in outdoor urban environments and for the indoor operation of mobile/personal terminals. In keeping with the classic correlation theory [17] in mobile terminals (Clarke's model), the spatial correlation coefficient follows the first species zero order Bessel function $J_0^2(2\pi x/\lambda)$, where x/λ is the separation between antennas in terms of wavelength. Hence a spacing of 0.5λ is enough to demonstrate that the correlation coefficient is low and spatial diversity is effective (in space diversity in mobile terminals, there is seldom any interest in having a larger spacing than the first zero of the correlation function).

Fig.3 also shows that the power deviation increases proportionally to the distance and the average power tends to follow the ideal path slope of -4. These effects are because at short distances and using directive reader antennas (an 8.5 dB gain in this work), the propagation is under LOS conditions since the reader illuminates the tags directly. Under these conditions the signal received follows a Rice probability distribution function (pdf). For long distances other surrounding objects fall inside the reader antenna beamwidth. Consequently the probability of multipath interference is higher than in the previous case and the propagation can be considered close to a NLOS situation. Therefore, the pdf of the received signal tends towards a Rayleigh pdf. Finally, it can also be deduced from Fig.3 that the overall average received power increases when two tags are simultaneously modulated, thus increasing the efficiency of the radio link.

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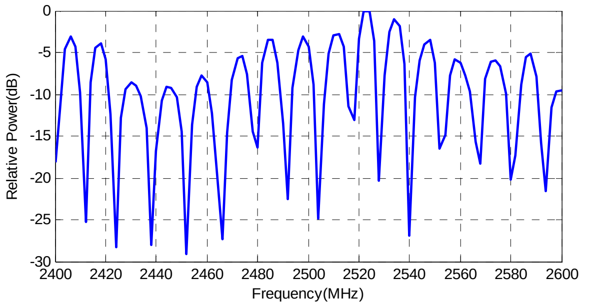

Fig.2. Measured relative received power backscattered by a FSS placed on the body as a function of the interrogating frequency.

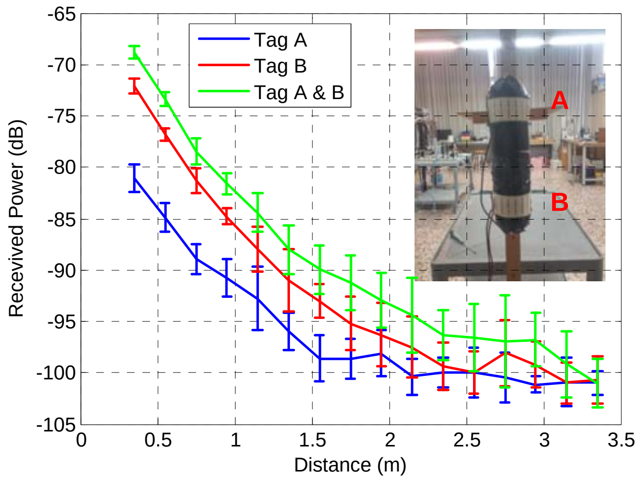

Fig. 3. Measured average power and standard deviation obtained from tag A, tag B and both tags placed together in the phantom in the range frequencies of 2.2 to 2.5 GHz.

Another experiment using a couple of tags instead of just one was conducted in order to evaluate the improvements achieved with spatial diversity technique. To this end, two set-ups are considered. In the first, the two tags are attached each to one arm (see Fig.4, case B). In the second, one of the tags is located on the arm and the other one on the chest (see Fig.4, case C). Additionally, measurements from a single tag attached to the arm are taken as a reference (see Fig.4, case A). Several measurements at different locations inside a semicircle with a 2 m radius were taken in the laboratory. Fig.4 shows the cumulative density function (CDF) as a function of the received power.

Diversity gain (DG) is a merit figure useful for indicating the advantages of using multiple antennas as opposed to a single one [17]. It is defined as the increase caused by diversity combining in the Signal-to-Noise ratio (SNR) for a given level of cumulative probability or reliability [17]. The diversity gain for a given cumulative probability p is given by:

$$DG(dB) = \gamma_{div}(p) - \gamma_1(p) = CDF_{div}^{-1}(p) - CDF_1^{-1}(p) \quad (1)$$

where γ_{div} is the SNR of diversity and γ_1 is the SNR of a single branch. The diversity gain can be calculated from (1) by inverting the CDF functions (with and without diversity, CDF_{div} and CDF_1, respectively). For a fixed value of CDF, the difference between the stronger channel and the curve indicates the diversity gain. Table I summarizes some diversity gain measurements (in dB) for a reliability level of 99% (p=0.01) and 90% (p=0.1). It can be shown that the diversity gain increases to 10 dB when the two tags were placed at each arm. The diversity gain is a function of the correlation between antennas and power imbalance, and improves when these two parameters decrease. In spatial diversity systems, the envelope correlation between the branches is a function of the separation between the antennas. In general, the correlation tends to decrease when the separation between antennas increases. This effect is observed in Fig.4. In the case where one of the tags is attached to the arm and the other is placed on the chest (Fig.4, Case C), the distance is reduced to 1/2 of that for Case B in Fig.4 (tags attached to both arms).

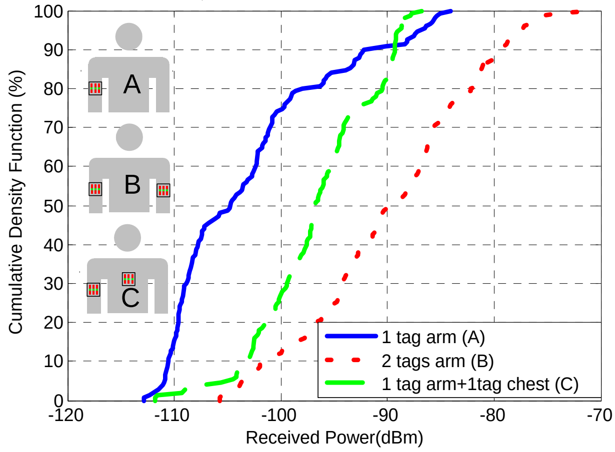

Fig.4. Cumulative distribution function of the power received from the tags at different locations on the body. A - 1 tag placed on the arm (solid line), B - 2 tags, one on each arm (dotted line) and C - 2 tags, one on the arm and one on the chest (dashed line).

B. *Polarization diversity*

The tag is designed to be linearly polarized. The reflected signals that reach the reader can undergo polarization changes depending on the medium through which they are travelling, producing an important decrease in the signal received. More complicated FSS with dual polarization could be investigated; however, the problem can be solved by using polarization diversity without increasing the tag complexity. This technique combines signals from antennas with different polarizations (i.e. orthogonal or circular) at the reader. For instance, circular polarized antennas are used in passive RFID UHF applications, in which the tag orientation is unknown. To prove this concept, the feasibility of using two closely spaced FSS with different (orthogonal) dipoles was investigated. Fig.5 compares the CDF when a single tag and two orthogonal tags are used. The diversity gain increases by about 10 dB for p=0.1 and 5.2 dB for p=0.01 (see table I). The results from the polarization diversity technique show that reliability improvements are possible using only a linear polarized antenna connected to the reader receiver, thus making it easier to use, especially in handheld units.

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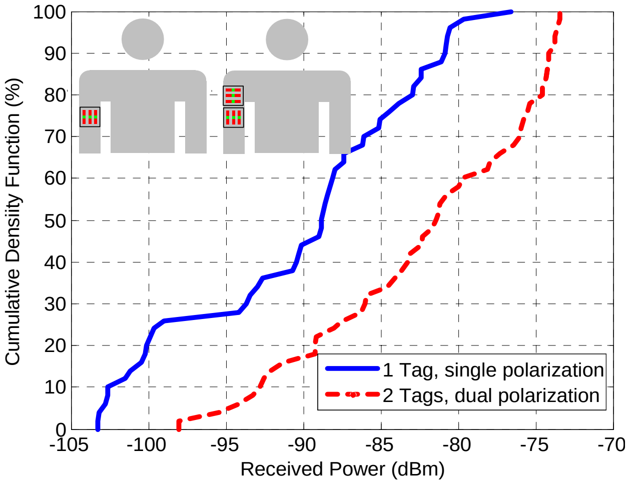

Fig.5. Cumulative distribution function of the power received from the transponder placed on the arm for one (solid line) and both polarizations (dotted line).

TABLE I
DIVERSITY GAIN FOR DIFFERENT CASES

Probability *p*	Spatial Diversity Arm-Arm (dB)	Spatial Diversity Arm-Chest (dB)	Polarization Diversity (dB)
0.01	6.0	1.0	5.2
0.1	8.7	7.4	9.7

IV. DIGITAL MODULATION OF FSS

The modulated FSS can be used to transmit data from sensors. Different modulation schemas can be considered to this end. Analog frequency modulation, as seen in Fig.1, can be used to sense changes in capacitance or resistance by controlling the frequency of an oscillator connected to the FSS [25]. Then, the modulation frequency becomes a function of the magnitude to be sensed. However, advanced sensors normally require a microcontroller with an analog-to-digital converter (ADC) to perform the measurement, or sometimes communication with the sensor is through an I2C interface. Therefore, digital information must be sent. As a proof of concept, the present study proposes a typical platform based on an Arduino-compatible Adafruit Flora device, specially designed for wearable/textile applications. Several commercial sensors are compatible with this platform using the ADC integrated in the microcontroller or the I2C interface bus (see Fig.6). FSK modulation is implemented. One of the digital outputs of the microcontroller generates a tone during the bit time at frequencies f_1 or f_2, depending on the bit value, which is used to modulate the diodes of the FSS. Fig.6 shows a block diagram of an experiment where an optical heart rate monitor based on an LED and photodiode is connected to the finger (see Fig.7). The internal ADC of the microcontroller digitizes the output of the photodiode, whose amplitude is modulated by the blood flow. From the ADC samples, the heart rate is obtained by measuring the time between two consecutive peaks. The average heart beat rate is periodically sent by simultaneously modulating two FSS, one at each arm. Fig.8a shows the spectrogram of a typical received frame. The mark and space frequencies (f_1 and f_2) are clearly visible. The frequency deviation between the mark and space frequencies is 100 Hz in this example (f_1=2425 Hz, f_2=2525 Hz). A non-coherent FSK demodulator is implemented [27]. The outputs of the filters in the demodulator are compared. If the output from the upper branch is larger than that from the lower branch, it is decided that a mark signal (bit 0) was transmitted. Space (bit 1) detection is similarly performed. Fig.8b depicts the demodulated data at the output of the FSK demodulator. The structure of the frame can be shown in Fig.8b. Each frame is composed of bits that are used as start frame identifier, then other bits are transmitted to identify the sensor, and finally the data. Data from several sensors and checksum bits can be easily integrated by exploiting this communication protocol.

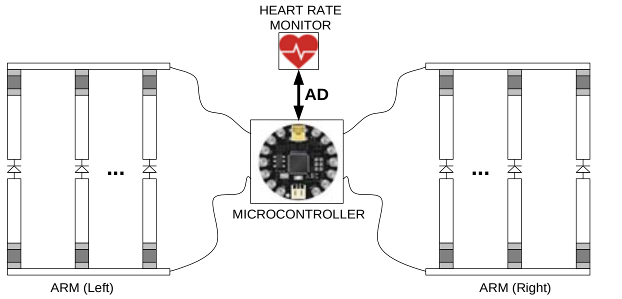

Fig.6. Block diagram of the demonstrator composed by a heart rate monitor connected to a microcontroller that modulates two FSS, one on each arm.

Fig.7. Photograph of the experiment.

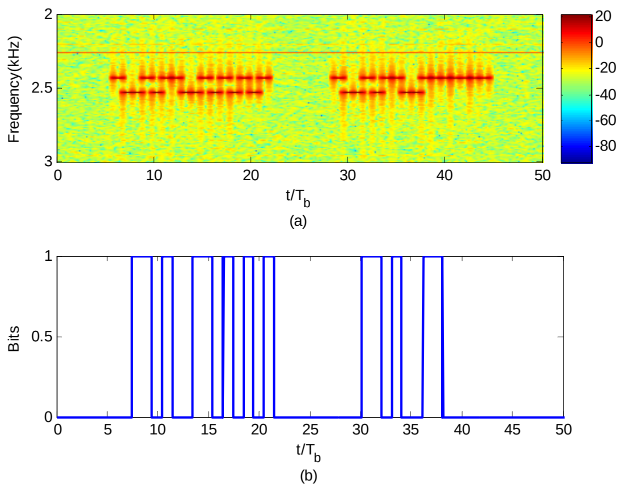

Fig.8. Spectrogram (a) and demodulated signal (b) as function of the time normalized by the time of bit (T_b).

V. Conclusion

This work deals with the feasibility of using semi-passive tags based on backscattered modulated FSS for on-body applications. Specifically, it addresses all the communication problems in real environments by exploring the use of diversity, and takes advantage of this topology to integrate on-body sensors. The experimental results demonstrate that a read range of about 3 meters can be achieved using a FSS with 7 elements in the 2.45 GHz ISM band. The effects of multipath propagation in a typical scenario are experimentally evaluated. These results show that deep fades make the communication difficult. In order to combat this fading, the feasibility of a two-branch diversity scheme for an on-body radio propagation environment has been studied. Two types of diversity techniques have been proposed (spatial and polarization diversity). Diversity implemented with FSS transponders makes it possible to easily integrate on-body sensors, since each sensor can simultaneously modulate all the transponders' responses by means of a wired DC connection (not an RF connection). To this end, a demonstrator based on two FSS and a communication protocol based on FSK modulation have been presented. This study opens up the possibility of integrating semi-passive tags based on FSS into on-body applications, especially in those where high duty cycle communications and long life batteries are required.

References

[1] W.G. Whittow, A. Chauraya, J.C. Vardaxoglou, X. Li, R. Torah, K. Yang, S. Beeby, J. Tudor "Inkjet-Printed Microstrip Patch Antennas Realized on Textile for Wereable Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 71-74,2014.

[2] M. Rasyid, B. Lee, A. Sudarsono,"Wireless body area network for monitoring body temperature, heart beat and oxygen in blood", *in International Seminar on Intelligent Technology and its Applications (ISITIA)*, pp. 95-98, 2015.

[3] B. Latré, B. Braem, I. Moerman, C. Blondia, P. Demeester, "A survey on wireless body area networks," *Wireless Networks*, vol.17, No.1, pp.1-18, 2011.

[4] S.Movassaghi, M.Abolhasan, J.Lipman, D.Smith, A.Jamalipour, "Wireless body area networks: A survey," *IEEE Communications Surveys & Tutorials*, vol.16, No.3, pp.1658-1686, 2014

[5] G.Marrocco,"Pervasive electromagnetics: Sensing paradigms by passive RFID technology," *IEEE Wireless Communications*, vol. 17, no 6, pp. 10-17, 2010.

[6] S. Merilampi, P. Ruuskanen, T. Björninen, L. Ukkonen, L.Sydänheimo, "Printed passive UHF RFID tags as wearable strain sensors," *in 3rd IEEE International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL)*, pp. 1-5, Nov.2010.

[7] S. Amendola, R. Lodato, S.Manzari, C. Occhiuzzi, and G.Marrocco, "RFID technology for IoT-based personal healthcare in smart spaces," *IEEE Internet Things J.*, vol. 1, no. 2, pp. 144–152, Apr. 2014.

[8] S. Manzari, C. Occhiuzzi and G. Marrocco, "Feasibility of Body-Centric Systems Using Passive Textile RFID Tags," in IEEE Antennas and Propagation Magazine, vol. 54, no. 4, pp. 49-62, Aug. 2012.

[9] D.O. Oyeka, J.C. Batchelor, A.M. Ziai, J. Wheeler, S. Yeates, "Tag diversity of inkjet printed body-worn radio frequency identification integrated medical sticking plasters for wireless monitoring," Healthcare Technology Letters, Vol.3, No.4, pp.257-262, 2016.

[10] G. A. Conway and W. G. Scanlon, "Antennas for Over-Body-Surface Communication at 2.45 GHz," *IEEE Trans. on Antennas and Propagation*, vol. 57, no. 4, pp. 844–855, Apr. 2009.

[11] S. Zhu and R. Langley, "Dual-Band Wearable Textile Antenna on an EBG Substrate," *IEEE Trans. on Antennas and Propagation*, vol. 57, no. 4, pp. 926–935, Apr. 2009.

[12] M. Klemm and G. Troester, "Textile UWB Antennas for Wireless Body Area Networks," *IEEE Trans. on Antennas and Propagation,* vol. 54, no. 11, pp. 3192–3197, Nov. 2006.

[13] M.S.Khan, M.S.Islam, Hai Deng, "Design of a Reconfigurable RFID Sensing Tag as a Generic Sensing Platform Toward the Future Internet of Things," *in IEEE Internet of Things Journal*, vol.1, no.4, pp.300-310, Aug. 2014 .

[14] D. Kim, M. A. Ingram, and W. W. Smith, Jr., "Measurements of Small-scale Fading and Path Loss for Long Range RF Tags," IEEE *Transactions on Antennas and Propagation*, vol. 51, no. 8, pp. 1740–1749, 2003.

[15] J. Grosinger, M. Fischer, "Evaluating on-body RFID systems at 900 MHz and 2.45 GHz," *In IEEE Fourth International EURASIP Workshop on RFID Technology (EURASIP RFID),* pp. 52-58, Sept.2012.

[16] R.G.Vauhan and J.Bach Andersen, "Antenna diversity in Mobile Communications," *IEEE Trans. Veh.Technol.*, vol.26, no. 4, pp.149-172, Nov. 1987.

[17] C. B.Dietrich, K. Dietze, J.R. Nealy, W.L. Stutzman, "Spatial, polarization, and pattern diversity for wireless handheld terminals," IEEE Transactions on Antennas and Propagation, vol.49, No.9, pp.1271-1281, 2001.

[18] P.A. Catherwood, W.G. Scanlon, "Body-centric ultra-wideband multi-channel characterization and spatial diversity in the indoor environment", *IET Microwaves, Antennas and Propagation*, vol. 7, no. 7, pp. 61-70, 2013.

[19] M. Marinova, A. Thielens, E. Tanghe, L. Vallozzi, G. Vermeeren, W. Joseph, H. Rogier, L. Martens," Diversity performance of off-body MB-OFDM UWB-MIMO", *IEEE Transactions on Antennas and Propagations*, vol. 63, no. 7, pp. 3187-3197, July 2015.

[20] J. D. Griffin and G. D. Durgin, "Gains for RF Tags Using Multiple Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 56,no. 2, pp. 563–570, 2008.

[21] J. D. Griffin, G. D. Durgin "Multipath fading measurements at 5.8 GHz for backscatter tags with multiple antenas," *IEEE Transactions on Antennas and Propagation,* vol. 58, no 11, p. 3693-3700, 2010.

[22] A. Lazaro, A. Ramos, D. Girbau, R. Villarino, "A Novel UWB RFID Tag Using Active Frequency Selective Surface," *IEEE Transactions on Antennas and Propagation*, vol.61, no.3, pp.1155-1165, March 2013.

[23] A. Lazaro, J. Lorenzo, R. Villarino, and D. Girbau, "Backscatter Transponder Based on Frequency Selective Surface for FMCW Radar Applications," *Radioengineering*, vol. 23, no. 2, pp. 632-641, Jun. 2014.

[24] A.Lazaro, J.Lorenzo, R.Villarino, D.Girbau, "Modulated Corner Reflector Using Frequency Selective Surfaces for FMCW Radar Applications," 46th European Microwave Conference (EuMC),4-6 Oct. 2015, Paris

[25] J.Lorenzo, A.Lazaro, R.Villarino, D.Girbau, "Modulated Frequency Selective Surfaces for wearable RFID and sensor applications," *IEEE Trans. on Antennas and Propagation*, Vol.64, No.10, pp. 4447 – 4456, 2016.

[26] J. Lorenzo, A. Lazaro, D. Girbau, R. Villarino, and E. Gil, "Analysis of on-Body Transponders Based on Frequency Selective Surfaces," Progress In Electromagnetics Research, Vol. 157, pp.133-143, 2016.

[27] A.B.Carlson, P.B.Crilly, Communication Systems, *McGraw-Hill Education*, 5th ed. New York, USA, 2010. ISBN: 2010. 0073380407