22nd IMEKO TC4 International Symposium & 20th International Workshop on ADC Modelling and Testing
SUPPORTING WORLD DEVELOPMENT THROUGH ELECTRICAL&ELECTRONIC MEASUREMENTS
IASI, ROMANIA, September 14-15, 2017

Characterisation of transmission of digital signals trough stainless steel conductive thread embroidered in T-shirts

Sabin Banuleasa[1], Radu Munteanu Jr.[1], Alexandru Rusu[2], Dan Iudean[1], Alecu Mihnea[3]

[1]*Technical University of Cluj-Napoca, Cluj-Napoca, Romania, sabin.banuleasa@gmail.com*
[1]*Technical University of Cluj-Napoca, Cluj-Napoca, Romania, radu.a.munteanu@ethm.utcluj.ro*
[2]*Lexion Engineering SRL, Bucharest, Romania, alexandru.rusu@lexionengineering.ro*
[1]*Technical University of Cluj-Napoca, Cluj-Napoca, Romania, dan.iudean@ethm.utcluj.ro*
[3]*Medicine and Pharmacy University "Carol Davila", Bucharest, Romania*

***Abstract* – This paper studies the electrical properties of ultra-thin stainless steel conductive thread wires embroidered into cotton. This study investigates the possibility to use the wires as interconnects between electrical modules that are measuring the human body's electrical signals. The focus is on using common and commercially available materials and parts in order to demonstrate the feasibility and easiness of supplying power and digital signals to devices integrated into common clothing, such as a cotton T-shirt. In order to get as close as possible to real world scenarios, ex. where an athlete can wear this T-shirt, several tests have been identified, like causing mechanical strain and shearing, using salt water to simulate heavy perspiration and putting in parallel uninsulated signal transmission lines to determine the data loss rate. The goal of the study is to prove that uninsulated conductive stainless steel embroidered wires are a solution to today's needs for interconnecting devices in clothing and also to come forward with improvements that can be brought to future developers of such systems.**

Keywords – textile wires; stainless steel conductive thread; wearable electronics; embroidered wires; Internet of Things;

I. INTRODUCTION

This paper presents the study of the electrical characteristics of transmission of power and digital signals that pass through textile wires made of stainless steel, that are embroidered into a common cotton T-shirt. These wires interconnect sensors and devices in order to provide DC power supply and data transmission. They need to sustain heavy mechanical pressure (stretching, shearing etc.) and carry data signals with low error rate when soaked with salty water (to simulate perspiration).

In the context of creating a truly wearable electronic system that is able to monitor the body's vital signs [1], a crucial role is played by the way the devices integrated in the T-shirt or placed on the skin surface (that capture EKG data, respiration rate, galvanic skin response etc.), are powered and are able to communicate with a low error rate. There is the possibility to make each sensor and control unit independent by integrating a battery for power supply (like small Li-Ion rechargeable batteries) and using radio signals for communications (benefiting of modern protocol like Bluetooth Low Energy 4.0), but that will add to the complexity of the devices and the system, will increase costs and will increase the weight and size of the devices which will directly influence the comfort of the clothing worn by the subject. Recent research in the domain [2] shows how sensors, wiring and concept have evolved and enable the medical industry to provide solutions to real world problems around the performance and comfort of wearable electronics.

This paper tries to cover the most common usages of unisolated stainless steel textile wires embroidered into a cotton T-shirt(commercially used products or similar research focus on using isolated or die-coating the cloth [3]), therefore the characterisation of the electrical signals passing through these wires has been done in various scenarios, ex. applying mechanical strain to simulate the stretch or shearing of the cloth, by applying plain water and salty water to simulate accidental spilling and respectively sweating during intense physical activities, and also by submitting the wires to electrical or electro-magnetic interferences that can be generated from nearby wires or common cell phones.

The main focus is converting the analog signals from the sensors to digital data that can be transmitted error-free, be stored in digital memories and easily processed by powerfull DSP (digital signal processing) modules integrated in microcontrollers. The raw analog signals from sensors like EKG are commonly converted by dedicated ADC (analog to digital convertor) units.

II. RELATED RESULTS IN THE LITERATURE

Numerous prototypes have been made in effort to integrate medical monitoring electronics into clothing with the scope of monitoring the EKG (Electro-Cardiogram) signal [4], [5], [6], temperature [7] or respiration intensity and rate [1], [8].

One of the critical parts to these systems is the supplying with electrical power and ensuring a low error rate communication between the sensors and the microcontrollers. Therefore, a series of approaches have been identified, the most popular being the usage of conductive wires, either uninsulated metal wires embroidered into textile [7], yarn mixed with metal [9], hybrid structure textile [10], conductive paste printed on the cloth [11], planar-fashionable printed circuits [6] or simply insulated metal wires [12]. For the goal of using low-cost, broadly available, conductive wires that integrate optimally in the T-shirt (by optimal meaning a combination of low-cost, low-weight, easiness of embroidery and high comfort while worn by the subject), we have chosen to test the use of stainless steel conductive thread, which is 100% made from stainless steel, can be easily be embroidered, lightweight and is soft at skin touch. Due to its metallic composition, the electrical conductivity properties seem promising.

Regarding the sensors and microcontrollers placed on PCB (Printed Circuit Boards), they need to have relative small dimensions to the T-shirt, be lightweight and flexible. Some tests were even made with boards of flexible rubber or plastic [13] and even coated with Statex (PA66) mold [9].

III. DESCRIPTION OF THE METHOD

The electric characterisation of a type of conductive wires can imply a wide range of physical properties and therefore be submitted to numerous tests. The scenarios chosen and the properties pursued have been scoped down to those of interest in the context of the integrated devices used and the activities that the T-shirt will be put through.

Following this, we have first determined the linear resistance of the stainless steel wires (wires of 0.5 mm diameter) and the digital signal transmission of the wires, in diverse conditions: suspended in air, wet from plain water (to simulate accidental spill) and wet from salty water 1% NaCl (which is more than the saline physiological solution of 0.9%, in order to simulate heavy perspiration due to intense physical activities).

Secondly, the wires were embroidered into cotton cloth in order to test the electrical interference between them while the cloth was dry, wet and salty wet. Trough one wire a square 0 – +5V signal was generated, with a load of 1k Ω resistor and one LED in series, and trough the other wire, two atmega328 microcontrollers were programmed especially for the tests to communicate via serial protocol through their hardware USART circuit at 57600 baud rate, with 8 data bits and one start and one stop bit. The protocol used for communication is a custom made one, similar to TCP, with start and acknowledgement packets. We have setup a software that can initiate on one end a transmission request and then wait, within a pre-set timeout, for an expected 32Bytes array of data. If it succeeds, there is an acknowledgement sent back and the process restarts from the beginning. There has been set an arbitrary value of 10 000 cycles that takes 72 seconds to fully complete. When the program finishes, it prints the number of packets lost, resulting the error rate %. In this way, we could reliably measure the packet rate loss between two devices through a stainless steel conductive wire submitted by electrical interference from a nearby wire with a salty water bridge. This laboratory scenario tries to reproduce the real-world situation where we have two wires embroidered into a T-shirt to relay two devices, and the subject is undergoing intense physical activities.

For the tests to be complete, an addition has been the application of mechanical strain on the cloth: loose, straightened and slightly tensed (stretched), in order to simulate the stretch and shear of a T-shirt.

In all fof the test, the wires have been placed in parallel, at a distance of 18 mm when hanged in air, and with a variable distance when embroided in cotton, see each test for the precise distance. The resistance measurement system used was a digital multimeter with +- 0.8% accuracy and resolution of 0.1Ω.The water bridge has been applied only for the cotton cloth tests, see Fig 1.

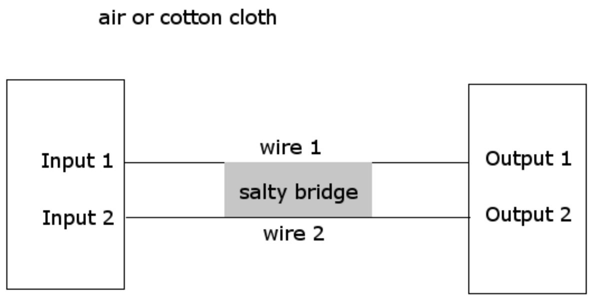

Fig. 1. Setup of the wires suspended in air and embroided into cotton cloth.

IV. RESULTS AND DISCUSSIONS

The tests were made by suspending the stainless steel conductive wires in air, at room temperature, and selectively soaking them in water and salty water, Fig. 2.

Fig. 2. Setup of the wires suspended in air

A. Single wire, suspended in air, dry conditions

This scenario has been setup to measure the electrical characteristics of the chosen stainless steel textile wire in air at room temperature, with the wire either being loosen, stretched and slightly tensed, see Tables 1a and 1b.

Table 1a. Resistance measured [Ω] for scenario A.

Scenario/wire length [cm]	10	20	35
wire loose	7.49	16.12	24.28
wire straightened	6.81	14.33	20.65
wire slightly tensioned (stretched)	6.32	12.64	18.21

Table 1b. Resistance measured [Ω] for scenario A.

Scenario/wire length [cm]	50	100
wire loose	35.99	80.25
wire straightened	30.36	59.53
wire slightly tensioned (stretched)	26.47	56.11

The linear resistance could therefore be calculated from these measurements and laid out in a visual graph, see Fig. 3.

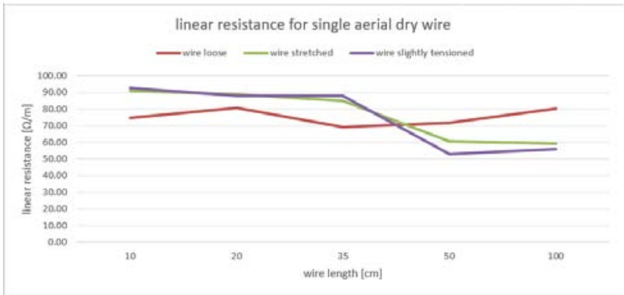

Fig. 3. Linear resistance versus wire length [Ω/m], scenario A.

B. Single wire, suspended in air, wet conditions

This scenario has been setup to measure the electrical characteristics of the chosen stainless steel textile wire in air at room temperature, with the wire being wet (plain water) and either loosen, straightened and slightly tensed (stretched), see Tables 2a and 2b.

Table 2a. Resistance measured [Ω] for scenario B.

Scenario/wire length [cm]	10	20	35
wire loose	7.02	15.69	25.98
wire straightened	6.43	15.09	22.07
wire slightly tensioned (stretched)	6.08	12.88	19.86

Table 2b. Resistance measured [Ω] for scenario B.

Scenario/wire length [cm]	50	100
wire loose	32.08	67.47
wire straightened	29.12	58.58
wire slightly tensioned (stretched)	25.85	54.74

The linear resistance could therefore be calculated from these measurements and laid out in a visual graph, see Fig. 4.

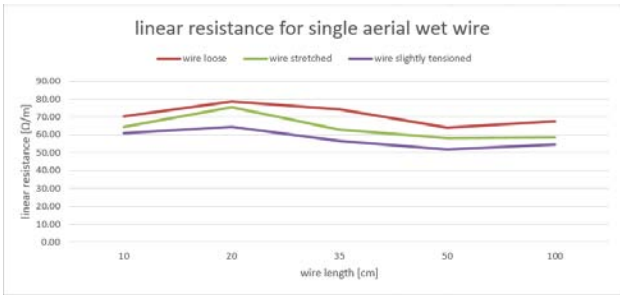

Fig. 4. Linear resistance versus wire length [Ω/m], scenario B.

C. Single wire, suspended in air, salty wet conditions

This scenario has been setup to measure the electrical characteristics of the chosen stainless steel textile wire in air, room temperature after being soaked into salty water (1% NaCl) and either loosen, straightened and slightly tensed (stretched), see Tables 3a and 3b.

Table 3a. Resistance measured [Ω] for scenario C.

Scenario/wire length [cm]	10	20	35
wire loose	6.56	16.09	22.83
wire straightened	6.43	15.22	20.72
wire slightly tensioned (stretched)	5.99	12.89	18.85

Table 3b. Resistance measured [Ω] for scenario C.

Scenario/wire length [cm]	50	100
wire loose	30.48	67.01
wire straightened	27.34	61.80
wire slightly tensioned (stretched)	25.51	55.32

The linear resistance could therefore be calculated from these measurements and laid out in a visual graph, see Fig. 5.

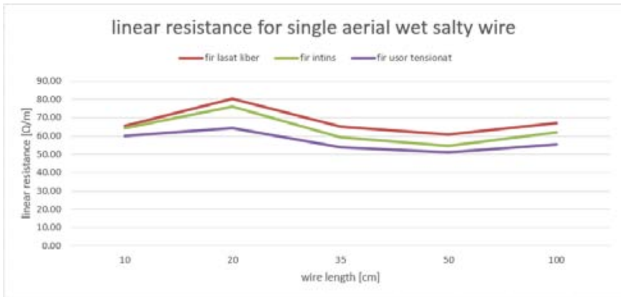

Fig. 5. Linear resistance versus wire length [Ω/m], scenario C.

D. Single wire, suspended in air, dry conditions, square signal

This scenario has been setup to measure the distortion of a square signal through the wire, suspended in air at room temperature.

First test consists of a 100 cm long wire, dry, and a 0,5kHz signal.

The second test consists of a 100 cm long wire, dry and a 100 kHz signal, see Fig. 6.

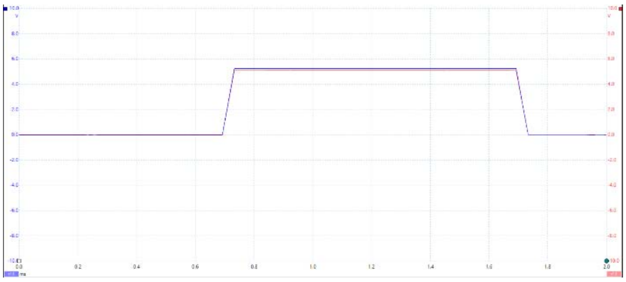

Fig. 6. Transmission of square signal 0,5kHz, input (blue), output (red), scenario D.

The second test consists of a 100 cm long wire, dry and a 100kHz signal, see Fig. 7.

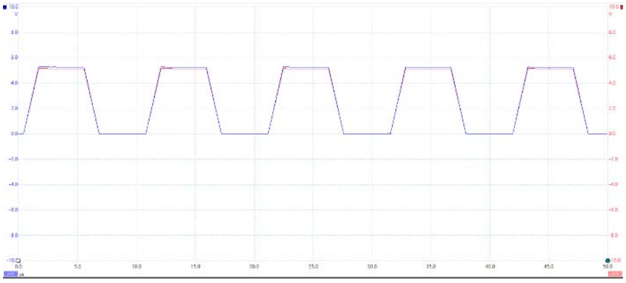

Fig. 7. Transmission of square signal 100KHz, input (blue), output (red), scenario D.

E. Single wire, suspended in air, dry conditions, square signal

This scenario has been setup to measure the data transmission error rate through the single wire suspended in air, in 3 conditions: dry, wet and salty wet. The tests were made with wire lengths of 10 cm and 100 cm. The wires were kept straight for these tests, see Table 4 and Fig. 8.

Table 4. Error rate [%] for digital transmission for scenario E.

Scenario/wire length [cm]	10	100
Dry wire	0	0
Wet wire	0	0
Salty wet wire	0	0

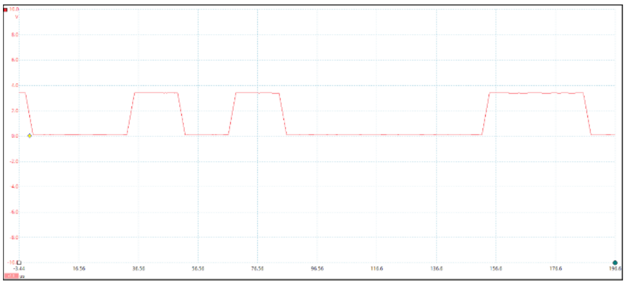

Fig. 8. The form of the transmitted digital serial signal (0 - +5V at baud rate 57600).

F. Interferences between two wires, suspended in air, digital transmission

This scenario has been setup to determine the EMI (electro-magnetic interferences) between two wires, suspended in air, in dry conditions at room temperature.

The first wire was in closed circuit where a signal of 100 kHz square 5V was generated and the second wire was left loose. The two wires were at 1cm distance.

In the first test, the second wire (red) was not grounded.

In the second test, the second wire was grounded.

In the third test, the second wire was in a closed circuit were serial data was transmitted (by hardware USART as in previous test at point D). See Fig. 9.

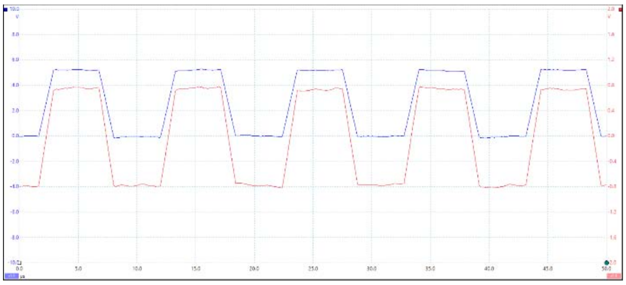

Fig. 9. Electromagnetic induction of two suspended wires, blue – signal generated, red – signal detected in the second wire, 1 cm distance.

In the second test, the second wire was grounded, see Fig. 10.

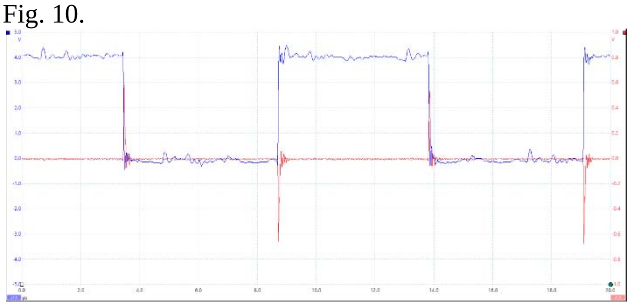

Fig. 10. Electromagnetic induction of two suspended wires, blue – signal generated, red – signal detected in the wire, grounded, 1 cm distance.

In the third test, the second wire was in a closed circuit were serial data was transmitted (by hardware USART as in previous test at point D), see Fig. 11.

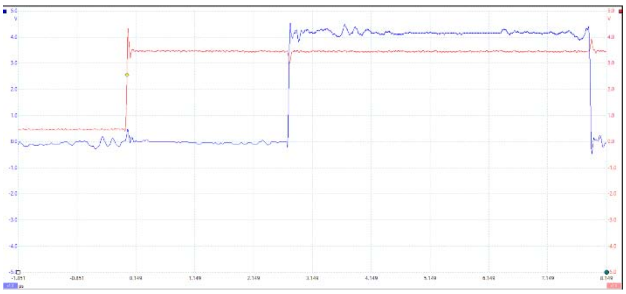

Fig. 11. Electromagnetic induction of two suspended wires, blue – signal generated, red – signal detected in the second wire with serial transmission, 1 cm distance.

G. Interferences between two wires, embroidered in cotton cloth, digital transmission

This scenario has been setup to determine the electrical interference between two wires embroidered into cotton clothing which is soaked in salty water (1/100 salt) to simulate perspiration of the subject when wearing the T-shirt, see Fig. 12.

Fig. 12. Two stainless steel wires embroidered into cotton clothing, with a wet salty bridge between them to interfere electrically.

Multiple tests of distance between the wires were made. An optimal distance was determined in order to keep the error rate of digital transmission from dropping below 50%.

There was great difficulty in achieving consistent results for the measurements as the digital transmission error rate was prone to multiple variables:

- distance between the wires – which we could consistently control.

- the amount of salty water present in the cotton cloth, as the liquid tend to drain and evaporate quite quickly, the measurement results changed radically after only 5 minutes.

- if the cloth bottom is stuck to a wet surface, in the case of the tests a ceramic plate which relates to a wet skin in the real world scenario.

- the mechanical strain upon the wires and upon the cloth.

- depending on the electrical power that travels the wires.

As a consequence, the below test scenarios were established in order to best reproduce at the best real world situations and problems. For all tests, trough one wire a 100 kHz 5V signal was transmitted, with a load in the circuit of 1kohm and a LED. The second wire transmitted serial data between two microcontrollers via hardware USART.

1. Two wires at 5 cm distance, a 4 cm wide bridge of salty water (1/100 concentration of salt). The transfer rate was 100%, see Fig. 13.

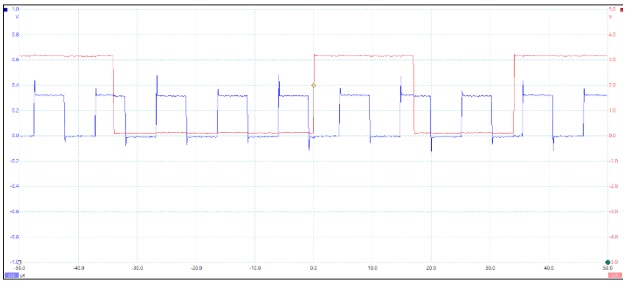

Fig. 13. Test 1 of scenario G, noise with load (blue) and digital serial signal (red).

2. Two wires at 5 cm distance, a 4 cm wide bridge of very salty water (2/100 concentration of salt). The transfer rate was 100%. We notice a tendency of the data signal to distort, see Fig. 14.

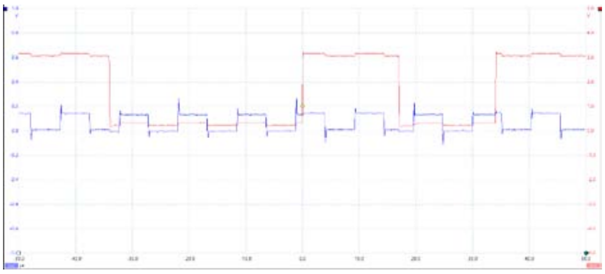

Fig. 14. Test 2 of scenario G, noise with load (blue) and digital serial signal (red).

3. Two wires at 2 cm distance, a 4.5 cm wide bridge of salty water (1/100 concentration of salt). The transfer rate was 100%. We notice a tendency of the data signal to distort, see Fig. 15.

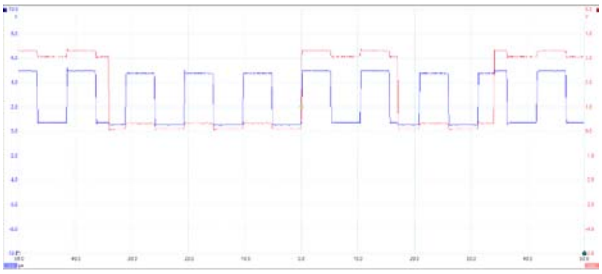

Fig. 15. Test 3 of scenario G, noise with load (blue) and digital serial signal (red).

4. Two wires at 6 mm distance, a 5 cm wide bridge of salty water (1/100 concentration of salt). The transfer rate was 100%. The data signal (red) is distorted, but this does not pose problems to the USART circuit as it is triggered by falling or rising edge around 2V, see Fig. 16.

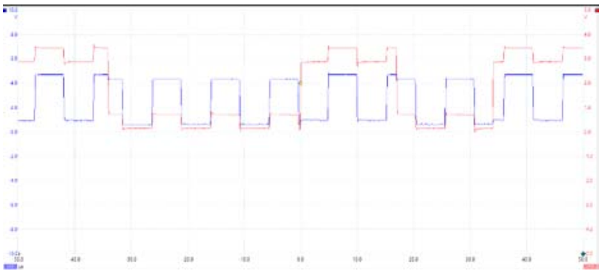

Fig. 16. Test 4 of scenario G, noise with load (blue) and digital serial signal (red).

5. Two wires at 6 mm distance, a 10 cm wide bridge of salty water (1/100 concentration of salt). The transfer rate dropped to 75.54%, see Fig. 17.

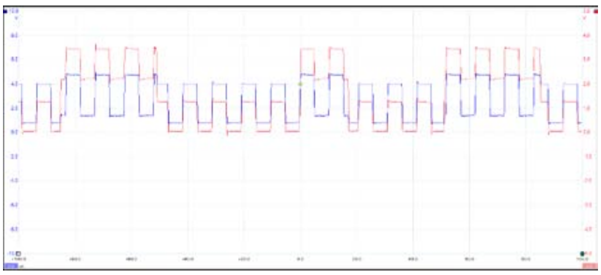

Fig. 17. Test 4 of scenario G, noise with load (blue) and digital serial signal (red).

6. Two wires at 6 mm distance, a 10 cm wide bridge

with excess of salty water (1/100 concentration of salt), the cloth stuck to the ceramic plate. The transfer rate was 99.98%.

7. Two wires at 6 mm distance, a 10 cm wide bridge with excess of salty water (1/100 concentration of salt), the cloth kept in the air without touching the ceramic plate. The transfer rate was 100%.

8. Two wires at 6 mm distance, a 10 cm wide bridge with excess of salty water (1/100 concentration of salt), the cloth kept in the air and stretched by hand in all directions, even folded so that the two wires touch and short-circuited (physical contact of the two adjacent wires) for very short (<100ms) moments. The transfer rate was 85.05%.

9. Two wires at 6 mm distance, a 10 cm wide bridge with excess of salty water (1/100 concentration of salt), the cloth kept in the air and touched shortly (<500 ms) with wet salty live human skin. The transfer rate was 100%. We noticed a slight discomfort (like soft pinching) on the skin because of the 5V signal.

10. Two wires at 6 mm distance, a 10 cm wide bridge with excess of salty water (1/100 concentration of salt), the cloth kept in the air and sheared in multiple directions as if trying to simulate an accidental fall or skid on the ground of the subject wearing the wet salty T-shirt. The transfer rate was 58.21%.

11. Two wires at 6 mm distance, a 10 cm wide bridge with excess of salty water (1/100 concentration of salt), the cloth kept in the air and a hand wash was mimicked. The transfer rate was 68.76%.

Results of the eleven tests of scenario G. are shown in Table 8.

Table 8. Error rate [%] for digital transmission for scenario G.

Results (point G.) Scenario:	Transmission rate
1	100%
2	100%
3	100%
4	100%
5	75.54%
6	99.98%
7	100%
8	85.05%
9	100%
10	58.21%
11	68.76%

V. CONCLUSION

The paper studies the feasibility of power transmission and digital signal trough stainless steel conductive thread embroidered into common clothing, like cotton T-shirt. Following the tests with the linear resistance in different mediums, as well as the digital transmission success in worst conditions simulated, we can conclude that 2 parallel wires at a distance of 6 mm, with a salty wet bridge long of 10 cm, in the most intense physical activities, would ensure more than 50% packet transmission rate between two devices. The data could be extrapolated in order to predict how the digital signal would behave with longer wire paths and various distances between the wires on cotton clothing, that is soaked in salty water, but because of the difficulties in correctly simulating the physical activities undergone by the human body in the laboratory, it is much better to leave this data more as guidelines for future integrators.

One particular note is around the very soft pinching felt on the skin because of the contact with the conductive uninsulated wires. Improvements could be made by integrating the wires at the exterior part of the T-shirt instead on embroidering them with common household techniques. Also, the reduction of the voltage from the tested 5V could easily be done to 3.3V, a common voltage for microcontrollers and other modern integrated circuits, which should improve slightly the discomfort caused by the running electrical current.

A valuable test, which this paper does not cover, is the electrical interference in severe conditions (salty water, high mechanical strain) of multiple parallel embroidered wires in the T-shirt, at close distances, and with long running lines, from an EKG sensor to the main unit which may be placed near the hip with a rechargeable battery.

VI. ACKNOWLEDGMENT

I would like to thank the Lexion Engineering SRL for the extensive contributions that made this research possible.

REFERENCES

[1] Banuleasa S., Munteanu Jr. R., Rusu A., Tont G., *IoT System for Monitoring Vital Signs of Elderly Population*, in Int. Conference and Exposition on Electrical and Power Engineering (EPE 2016), Iasi, 20-22 October,2016,pp. 59-64.

[2] A. Fleury, M. Sugar, T. Chau, *E-textiles in Clinical Rehabilitation: A Scoping Review*, in Electronics, vol. 4, iss. 1, 2015, pp. 173-203.

[3] S. Takamatsu, T. Lonjaret, D. Crisp, J.M. Badier, G.G. Malliaras, E. Ismailova, *Direct patterning of organicconductors on knitted textiles forlong-term electrocardiography*, in Scientific Reports, 08 October 2015.

[4] R. Fensli, E. Gunnarson, T. Gundersen,*A Wearable ECG-recording System for Continuous Arrhythmia Monitoring in a Wireless Tele-Home-Care Situation*, in Proc. IEEE CBMS, 2005, pp. 407-412.

[5] T. R. F. Fulford-Jones, G.-Y. Wei and M. Welsh., *Portable, Low-Power, Wireless Two-Lead EKG System*, in Proc. IEEE EMBS, San Francisco CA USA, 2004, vol. 1, pp. 2141-2144.

[6] Jerald Y., Long Y., Seulki L., Hyejung K., Hoi-Jun Y., *A Wearable ECG Acquisition System With Compact Planar-Fashionable Circuit Board-Based Shirt*, in IEEE TITB,vol. 13, no. 6, November 2009, pp. 897-902.

[7] Jussi M., Emmi P., *Flexible wire-component for weaving electronic textiles*, Proc. of IEEE 66th ECTC, 31 may-3 june,2016, pp. 1656-1663.

[8] C. M. Yang, T. L. Yang, C. C. Wu, S. H. Hung, M. H. Liao, M. J. Su, H. C. Hsieh, *Textile-based Capacitive Sensor for a Wireless Wearable Breath Monitoring System*, Proc. of IEEE ICCE,10-13 jan,2014, pp. 232-233.

[9] T. Linz, C. Kallmayer, R. Aschenbrenner and H. Reichl, Fully Integrated EKG Shirt based on Embroidered Electrical Interconnections with Conductive Yarn and

Miniaturized Flexible Electronics, n Proc. IWWI BSN, 2006, pp. 23-26.

[10] Min Ki Choi and Jooyong K., *Transmission Characteristics of Hybrid Structure Yarns for e-Textiles*, in IEEE ICPADS,16-19 Dec., 2014.

[11] Masahiro I., Yosuke I., Yasunori T., *Development of Bimodal Electrically Conductive Pastes with Ag Micro- and Nano-fillers for Printing Stretchable E-textile Systems*, in EMPC, Friedrichschafen, September 2015.

[12] S. Salehi, G. Bleser, N. Schmitz and D. Stricker, *A Low-cost and Light-weight Motion Tracking Suit*, Proc. of IEEE UIC/ATC, 18-21 Dec., 2013, pp. 474-479.

[13] Zhenqiang M., Yei H. J., Jung-Hun S., Tzu-Hsuan C., Sang J. C., Juhwan L., Huilong Z. and Weidong Z., *Materials and Design Considerations for Fast Flexible and Stretchable Electronics (Invited)*, Barcelona, July 15-17, 2009, pp. 255-260.