A Feasibility Analysis on the Use of Ultrasonic Multihop Communications for E-Health Applications

Laura Galluccio*, Sebastiano Milardo†, Elisabetta Sciacca*
*CNIT Research Unit at University of Catania, Catania, Italy
Email: {name.surname}@dieei.unict.it
†University of Palermo, Palermo, Italy
Email: {name.surname}@unipa.it

***Abstract*—Rise in population aging as well as diffusion of chronic diseases and health consciousness require constant monitoring of health conditions but also lead to increasing costs for the governments. Body Area Networks represent the next frontier in health care and are envisaged as the natural choice to provide detailed and updated information on health status to prevent health risks and diseases. However if, on the one hand, a large research effort has been devoted so far to the investigation of BAN communications on and around the body, on the other hand intra-BAN communications are still a scarcely explored area because of the difficulties and risks in successfully propagating signals inside the body where RF waves cannot be employed. In this paper we propose to use ultrasonic waves for intra-BANs and we investigate on the feasibility of supporting multihopping among different intra-body devices which communicate with a gateway node in charge of transmitting health information to a remote medical center. We discuss system implementation using Universal Software Radio Peripheral (USRP) nodes and test the feasibility of multihop transmissions across a body phantom enhanced with organic tissues. Our analysis shows that multihop transmission is feasible and can be effectively employed to support communications in next-generation E-Health applications.**

I. Introduction

E-Health expenditure represents today a remarkable cost in developed nations GDP. As an example it is foreseen that, due to the increase in aging, in 2022 the costs associated to healthcare in US will represent 22% of the GDP [1]. In the last 5 years this has lead to a technology shift towards the use of Body Area Networks (BANs) for monitoring purposes in order to allow constant patient control as requested by both emerging chronic diseases and prevention of health risks related to stress.

However, only few works have addressed intra-body communications [2], [3], [4] while the majority of them only consider out or around the body communications. The use of capillary intra-body organs and tissues monitoring is instead required to prevent serious pathologies such as hearth attacks or ischemias. To this purpose it is foreseen to have implanted or ingested pill-sized sensor devices deployed inside the body to perform continuous monitoring and periodically communicating with a remote medical center by way of a gateway node located on the body (e.g. a smart watch or phone [5]). Apart for the issues related to compatibility of materials to be used in devices deployed inside human organs and tissues, a relevant communication problem is posed either in terms of waves being used for communications, or in terms of support of multihop communications from a device to the gateway node. In fact, the human body is composed for more than 65% by water, a fluid through which RF waves scarcely propagate, while leading to high attenuation [6]. Moreover, traditional RF waves used in wireless transmission are ionizing waves which can cause overheating of tissues and consequent degeneration and damage of cells [7]. Accordingly, alternative solutions for communication have been recently proposed. In particular in the last 10 years body-coupled communications have been introduced [8], [9] along with ultrasonic communications [2], [10]. Body coupled communications employ either galvanic or capacitive coupling. In particular a pair of electrodes is used for transmitting and receiving. At the transmitter side a signal is applied between the electrodes and since the electrodes have a different capacitive coupling to the body, an electric field is induced to the human body and passes through the body. At the receiver side, either the two electrodes are at different distances from the body, or are located on the body which behaves as a conductor, so that it is thus possible to detect a differential signal between transmitter and receiver as a function of the varying electric potential of the person. As an alternative to the use of coupling, ultrasonic communications have been proposed [10]. They have been employed for screening purposes since the ’60s showing no side effects on human organs and tissues, either in case of prenatal diagnosis.

In this paper we still propose to use ultrasonic waves for intra-body communications, but we mainly focus on support of multihopping. In particular we explore the feasibility of using multihop communications inside the body. In fact, only few preliminary studies have appeared so far in the literature discussing the possibility to employ multihopping to communicate inside the body, e. g. [11], [12], but none of them either employs ultrasonic waves or provides experimental evidences of this feasibility. In this paper, instead, we explore for the first time the perspective of multihopping inside the body by using a real testbed developed using USRPs [13] and appropriate

978-1-4673-8999-0/17/$31.00 ©2017 IEEE

ultrasonic transducers and consisting of a transmission channel obtained by considering real organic tissues embedded inside a ballistic gel, mimicking human body tissues. To the best of our knowledge this is the first paper to provide such contributions to the scientific community.

The rest of this paper is organized as follows. In Section II we motivate the use of ultrasonic communications for realization of implanted BANs. In Section III we give an overview of the designed system. In Sections IV and V we describe the experimental testbed and the numerical results obtained through experiments. Finally, in Section VI conclusions are drawn as well as considerations on future evolutions of this work.

II. Ultrasonic Communications inside the body

Apart for underwater applications where ultrasonic communications have been successfully used since the World War II, ultrasonic waves are widely used for screening purposes in echocardiography (ECG) and for therapy in medical applications. Indeed it has been observed for more than half a century that these waves do not have counter-effects and do not cause damage to body tissues. Accordingly, in line with some recent literature in the field, in [2] we have proposed to employ ultrasonic waves for communication purposes in intra-body scenarios.

Ultrasonic waves are mechanical waves, working above the human-detectable frequency range, generated by vibrations of particles in elastic media, e.g. water. The vibration energy associated to particles' oscillations propagates through the material. The Helmhotz equation is used to describe pressure variations along the x, y and z dimensions in the propagating medium. In particular the Helmhotz equation can be formalized as $\bigtriangledown^2 P - \frac{1}{v^2}\frac{\partial^2 P}{\partial t^2} = 0$ being $P(x, y, z, t)$ the acoustic pressure scalar field in space and time and v the propagation speed in the medium under investigation. In particular it has been observed that upon propagating along the medium, the acoustic pressure decreases with the distance d according to an exponential law $P(d) = P_0 e^{-\alpha d}$ where α is the attenuation parameter in $[Np \cdot cm^{-1}]$ which gives an estimation of how the energy is dissipated by the ultrasonic beam as a function of tissue properties and operating frequency. Experimental evidences show that, the larger the distance d, the lower the needed operating frequency. However, this trend is antagonist to another relevant aspect related to the directivity of the used transducers. In fact, the beam spread is inversely proportional to the product between transducer diameter and operating frequency. Accordingly, in the view of having in the next decades small size transducers which can be implanted, it is advocated to figure out a tradeoff between the two above mentioned needs in the selection of the operating frequency range. In [2] we have identified a recommended operating frequency range not exceeding the 10 MHz, to allow coverage range around tens of cm to be compatible with the use of intra-body sensor devices distributed along the body in a reasonably not too capillary way and with a maximum tolerable attenuation of 100 dB which is a realistic value also accounting for conditions of scarce propagation.

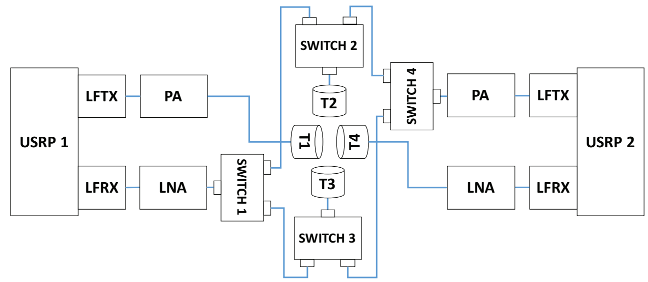


Fig. 1. Overview of the system.

III. System overview

We developed a physical testbed and a software solution to test the feasibility of using multihop communications in implanted body area networks.

The proposed system is based on the one described in [14] and the transmission medium consists of a cylinder of synthetic material, mimicking human body organs and tissues.

The system includes four Olympus V326-SU ultrasonic transducers [15]. These transducers operate around 6 MHz with a -6 dB bandwidth of about 4 MHz. Each transducer is connected to a single node in the network. The amplification and filtering devices, similarly to [14], are two Mini-Circuits Pulse Amplifier (PA) ZPUL-30P to amplify the signal in transmission, and two Low Noise Amplifiers (LNA) ZFL-1000LN+ to filter and amplify the received signal, respectively.

The A/D and D/A conversions are performed by two USRP N210 from Ettus Research [13], each of them incorporating a dual 100 MSPS 14-bit ADC and a dual 400 MSPS 16- bit DAC, and an FPGA unit (Spartan 3A-DSP 3400). Each USRP is equipped with two daughterboards (LFTX and LFRX) that operate from DC to 30 MHz. Observe that each daughterboard can work either as a receiver (LFRX) or as a transmitter (LFTX) only; therefore to use each transducer in both directions, we use four Minicircuit switches ZX80-DR230+ USRP driven, that alternatively connect the transducer to the appropriate daughterboard. An overview of the physical testbed is shown in shown in Figure 1. Each USRP is connected, via Gigabit Ethernet, to a PC running Ubuntu and the GNU Radio software development environment [16]. GNU Radio offers a rich library of tools to build software for USRP systems in a modular way. Each functional step of the signal processing is modeled by a so called *block* or *module* and new blocks can be added in Python or C++.

Leveraging such approach, we based our work on the modules developed in [17] to recreate a communication stack based on RIME [18], and we added new modules to manage the single hop and multihop communication scenarios.

The PHY layer of the proposed system consists of IEEE 802.15.4 modules working in the frequency range of a few

MHz. In the current configuration we employ a QPSK modulation. A snapshot of the GNU Radio modules involved in the system is reported, in case of a multihop transmission, in Figure 8.

The networking layer is provided by the RIME stack. Rime is a modular, lightweight networking stack, part of the Contiki [19] operating system, that is designed for constrained devices. Among its primitives it possible to find:

- unreliable unicast
- reliable unicast
- best effort broadcast
- reliable network flooding

In the proposed scheme we use best effort unicast communications (i.e. unreliable unicast) between all nodes. Our multihop management layer has been implemented on top of the described blocks and it allows to implement single hop and two hop communications.

a) Single Hop Scenario: In the single hop scenario, the message to be transmitted is created by a particular module called *Message Strobe*, that sends a message containing "Hello, World!" to the Rime and MAC modules of the first node; then it is sent at the PHY layer and finally it reaches the first USRP where it is transmitted by the transducer T1 (Figure 1). The message traverses the medium and is received by T4. At the receiver side the message traverses the communication stack up to the application layer. Finally, at the application layer, the message is received by the *Delay Estimator* block that logs the event. The Delay Estimator measures the transmission time of each message, by collecting two timestamps: one when the message is sent by the Message Strobe, and one when it is received by the Delay Estimator.

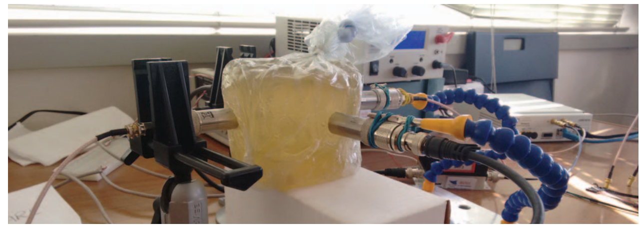
b) Two Hops Scenario: In the two hops scenario a message sent by USRP1 and received by the transducer T4 is not forwarded to the Delay Estimator, but it is retransmitted using an echo block. This block sends back the message along the protocol stack to T2 for retransmission. T3 then receives the message which is finally recorded by the Delay estimator at USRP1.

IV. Experimental Setting

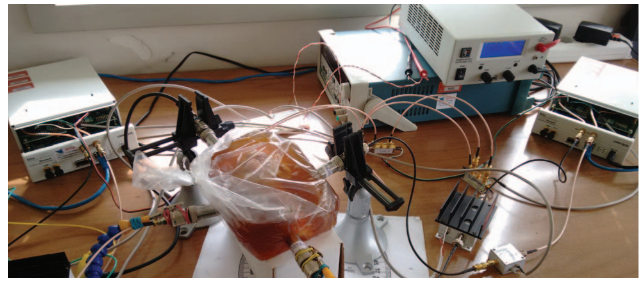
In this section we detail the experimental setting used to collect numerical results.

The transmission medium consists of a cylinder of ballistic gel, 8 cm of height and 78.5 cm^2 of section, which allows us to mimic the human body as the transmission medium. Ballistic gel is a solution consisting of gelatin powder in water. It simulates the density and viscosity on human muscle tissues and was developed by Martin Fackler in the field of wound ballistics [20]. In order to test a realistic scenario we also enhanced the ballistic gel by encapsulating inside organic tissues consisting of animals bones, muscles, skin and fat to mimic the heterogeneity of human tissues[1]. The ballistic gel enhanced with organic tissues has a parallelepiped shape with size 15x10x5 cm. The two scenarios addressed are shown in Figure 2. The above described experiments are labeled as Scenario 1 and 2, respectively, in the following. In our testbed we took into account different configurations of transducer positions in order to consider that, due to human movements and gestures, the relative position of nodes can change. In particular, transducers were first positioned on the same plane (Figure 3(a)). Then, transducers were put on parallel planes, 5 cm far apart in height (Figure 3(b)); finally transducers were put on two different planes 5 cm far apart and 45^o disaligned on the right (Figure 3(c)). Observe that for each configuration we investigated 4 different configurations starting from the ones illustrated in the plots, upon rotating the transducer position of 45^o counterclockwise up to 180^o.

[1]The research activity carried out in this work respects the European Commission Guidelines on scientific activity involving animals. In particular organic tissues have been obtained from those commercially available.



(a)



(b)

Fig. 2. a) Testbed configuration when using ballistic gel; b) testbed configuration when using ballistic gel with organic tissues embedded.

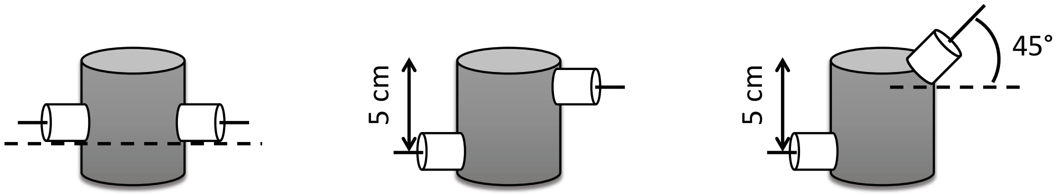
TABLE I
VALUES OF THE PER FOR THE DIFFERENT SCENARIOS AND WITH DIFFERENT TRANSMISSION MEDIA IN CASE OF A TRANSMISSION RATE OF 256 BYTES/S.

Scenario	Av. PER [%]	Confidence interval [%]
1 ballistic gel	5.2	0.4246
2 ballistic gel	15.76	2.2769
1 organic tissues	3.5	0.7664
2 organic tissues	12.62	1.1164

V. Numerical results

In our experimental campaigns we considered the 3 above cited scenarios and for each of them we investigated the following metrics:

- *Packet Error Probability* (PER) calculated as the ratio between the number of packets wrongly received and the number of packets transmitted;



(a) At the same level (b) Shifted (c) Shifted and not aligned

Fig. 3. Configurations with two ultrasonic transducers.

TABLE II
VALUES OF THE PER FOR THE DIFFERENT SCENARIOS AND WITH DIFFERENT TRANSMISSION MEDIA IN CASE OF A TRANSMISSION RATE OF 128 BYTES/S.

Scenario	Av. PER [%]	Confidence interval [%]
1 ballistic gel	4.74	0.3195
2 ballistic gel	16.02	0.5953
1 organic tissues	1.94	0.3373
2 organic tissues	2.38	0.3864

TABLE III
VALUES OF THE THROUGHPUT FOR THE DIFFERENT SCENARIOS AND WITH DIFFERENT TRANSMISSION MEDIA IN CASE OF A TRANSMISSION RATE OF 128 BYTES/S.

Scenario	Av. Thr. [kb/s]	Confidence interval [kb/s]
1 ballistic gel	2.95	9.89 x 10^{-3}
2 ballistic gel	2.60	18.44 x 10^{-3}
1 organic tissues	2.99	16.78 x 10^{-3}
2 organic tissues	2.70	34.57 x 10^{-3}

- *End-to-End Delay* (D) estimated as the difference between the time when the packet is received at the final destination and the time when it was transmitted by the source. To this purpose packets of size 16 bytes (payload) + 8 bytes (header) are issued;
- *Throughput* (T) calculated as the amount of bits per second received.

All the statistics have been obtained by collecting results in 5 campaigns of experiments for each setting and provide a confidence interval of 90%. During each campaign, 1000 packets are sent. In order to investigate the behavior of the system for different transmission data rates we carried out 2 sets of experiments upon varying the rate among 256 bytes/s and 128 bytes/s.

TABLE IV
VALUES OF THE THROUGHPUT FOR THE DIFFERENT SCENARIOS AND WITH DIFFERENT TRANSMISSION MEDIA IN CASE OF A TRANSMISSION RATE OF 256 BYTES/S.

Scenario	Av. Thr. [kb/s]	Confidence interval [kb/s]
1 ballistic gel	2.93	5.59 x 10^{-3}
2 ballistic gel	2.61	29.97 x 10^{-3}
1 organic tissues	3.04	10.45 x 10^{-3}
2 organic tissues	3.02	8.46 x 10^{-3}

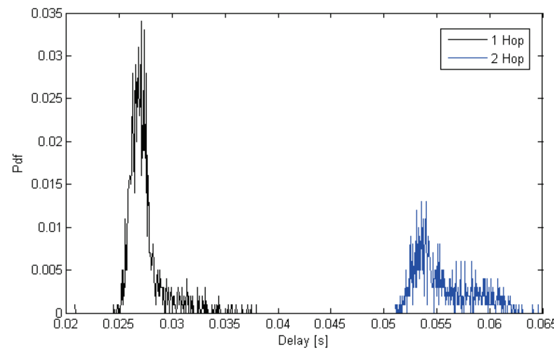


Fig. 4. Pdf for the case of Scenario 1 and Scenario 2 when transmission rate is equal to 256 bytes/s and pure ballistic gel is used.

TABLE V
VALUES OF THE PER AND THROUGHPUT FOR THE SCENARIO 1 IN CASE OF A TRANSMISSION RATE OF 256 BYTES/S AND BALLISTIC GEL.

Av. PER [%]	Conf. inter. [%]	Av. T [kb/s]	Conf. inter. [kb/s]
16.47	4.55	2.58	64.92 x 10^{-3}

a) PER: In Scenario 1 a single hop transmission is considered. We compared the results obtained by varying the position of the transducers as shown in Figure 3. In Table I we report the values of the packet error probability calculated for Scenario 1 when considering both the case of simple ballistic gel and gel with organic tissues embedded. Results have been provided considering a T-Student distribution and estimating the average PER as well as the size of the confidence interval. Observe that the PER is almost comparable in the two cases of pure ballistic gel and ballistic gel with organic tissues embedded but, due to the inhomogeneity in case of organic tissues, the PER is slightly reduced as well as the size of the confidence interval. In Table II we also report the values of the PER for a transmission rate of 128 bytes/s. Observe that, due to the increase in the energy per bit implied by the use of a lower bit rate, as expected, the error probability improves. However, in both cases the PER is significantly impacted by the processing at the intermediate node as witnessed by the fact that in the 2 hops case (Scenario 2) the impact of the transmission rate on the PER is negligible.

In Table I we report the average PER and the size of the confidence interval in case of Scenario 2 with both the

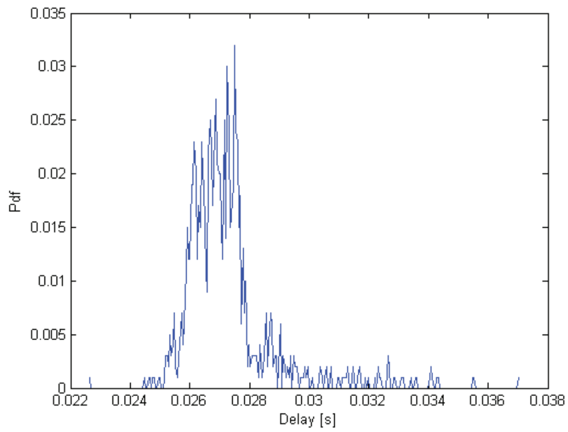


Fig. 5. Pdf for the case of Scenario 1 and transmission rate equal to 256 bytes/s for the case of ballistic gel embedded with organic tissues.

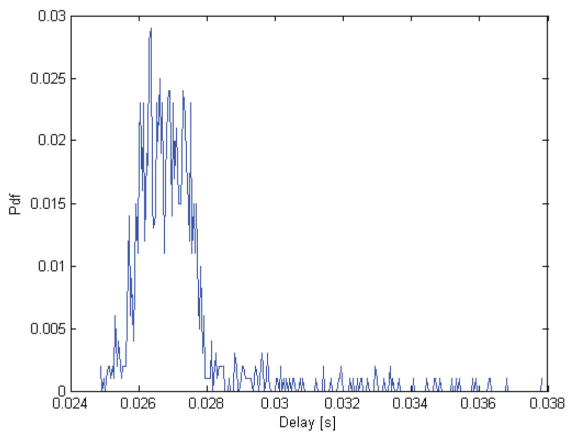


Fig. 6. Pdf for the case of Scenario 1 and transmission rate equal to 128 bytes/s for the case of ballistic gel embedded with organic tissues.

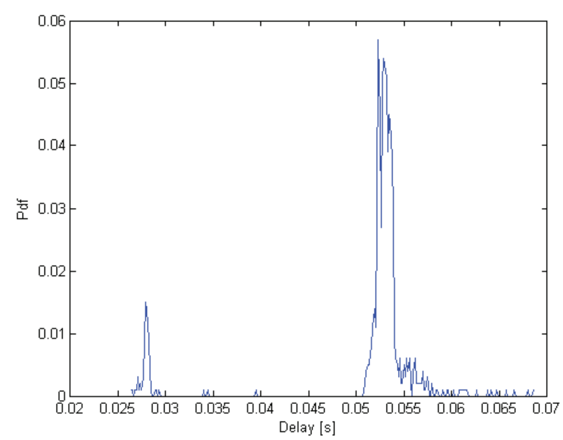


Fig. 7. Pdf for the case of Scenario 2 and transmission rate equal to 128 bytes/s for the case of ballistic gel embedded with organic tissues.

transmission media being used. Note that, as compared to the Scenario 1, also in this case the inhomogeneity of organic tissues decreases the PER as compared to the case of pure ballistic gel; however in the latter case the confidence interval size is smaller because of the lower variability. Similarly, in Table II we report the corresponding values for the transmission rate equal to 128 bytes/s.

b) Delay: In order to study the delay behavior, in Figure 4 we show the pdf of the delay between transmitter and receiver. In this figure we considered the ballistic gel without organic tissues embedded. Observe that the average delay in case of Scenario 1 is around 27 ms. In Figure 5 for worth of comparison, we illustrate the delay behavior in case organic tissues are added to the ballistic gel. Observe that, due to scatterers and reflections, while the average value of the delay is almost unchanged, the standard deviation increases significantly.

In the second scenario as shown in Figure 4 we estimated again the pdf of the delay when considering a configuration with 2 hops. Observe that the delay increases around 52 ms as expected by the occurrence of two hops. Moreover, due to an increase in the PER, the standard deviation of the delay increases remarkably as well. An interesting observation can be done in the case of 2 hops when employing ballistic gel with organic tissues embedded. In fact, in Figure 9 we see that in this case a fraction of packets can be delivered in just one hop, while a larger fraction of packets are delivered in 2 hops due to the unpredictable features of the inhomogeneous organic tissues. This problem was not encountered in case of simple ballistic gel because in that case the sample used for mimicking the transmission medium was more homogeneous in structure.

c) Throughput: We investigated also the throughput which can be obtained in the two scenarios considered in the paper and with the two settings of pure ballistic gel as well as the gel embedded. Observe that as a consequence of the increase in PER associated to the use of a higher transmission rate, the throughput decreases. However, note that a variation in the transmission rate does not lead to a remarkable change in the throughput. Also, the use of different ballistic gel configurations seems not to impact the throughput as well.

d) Interference: In order to have an estimation of the impact of interference, in Table V we also report the PER and Throughput when considering two separate pairs of nodes that communicate simultaneously. Observe that these results have been obtained in case of pure ballistic gel when the transmission rate is set to 256 bytes/s. Note that the impact of the interference is remarkable as it increases remarkably the PER as compared to the scenario without interference.

VI. Conclusions

In this paper we have investigated the feasibility of using multihop communications in intra-body area networks. In particular, in line with recent literature on the use of ultrasonic transmission to support implanted BANs, we designed and

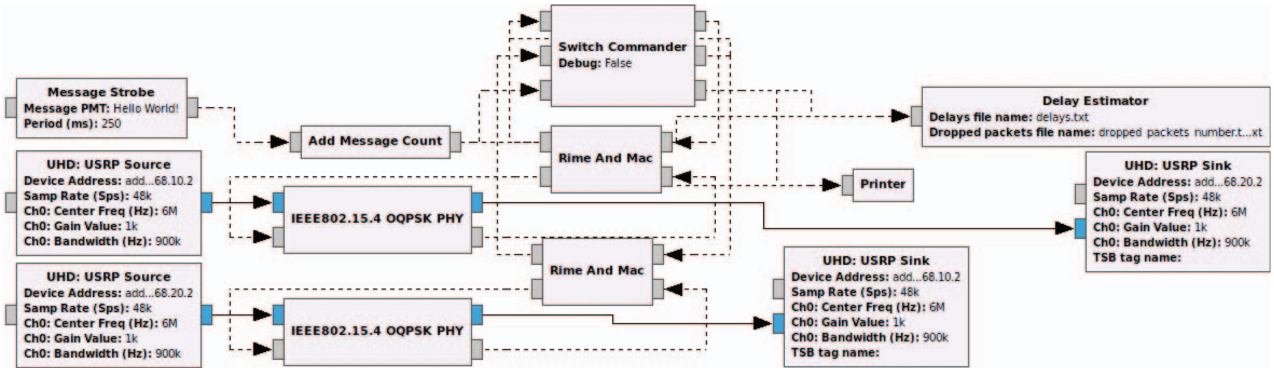


Fig. 8. Snapshot of GNU Radio modules in case of a 2 hops transmission.

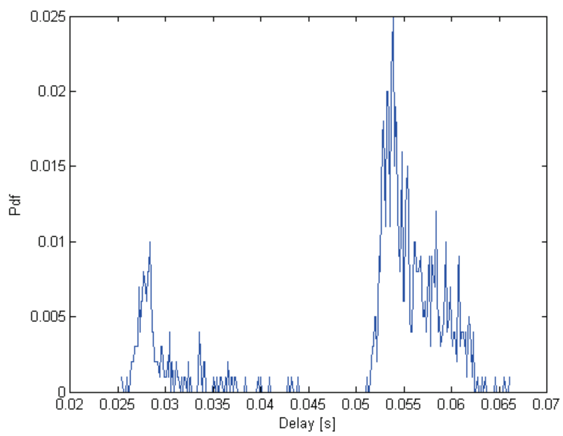


Fig. 9. Pdf for the case of Scenario 2 and transmission rate equal to 256 bytes/s for the case of ballistic gel with organic tissues embedded.

developed an experimental testbed including also a realistic transmission medium mimicking human body characteristics. To this purpose we considered both single hop and two hops scenarios and carried out measurements on a number of performance metrics by mimicking, with an increasing degree of precision, the propagation features of human body tissues. Results confirm that ultrasonic waves are a promising technology to be used, not only for screening purposes, as currently done in medicine, but also for communication purposes in next generation intra-body networks. Also multihop transmission is in principle feasible and this will allow to limit the amount of transmission power employed, so avoiding tissues overheating or the need for proximity between devices implanted inside the body and the gateway node used to communicate with the remote medical center. As a future work we plan to stress the issue of multihopping by also investigating on the feasibility of communicating on more than 2 hops. Moreover we would like to design and include into our testbed a thermal-aware routing mechanism which allows to adaptively tune the forwarding path so as to fairly balance the temperature on the tissues, thus avoiding human body overheating and cells damage.

VII. Acknowledgements

Authors would like to thank Marco Reno for his help in testbed set up. This work was partially supported by the Project PO FESR SICILIA 2007-2013 RILTUS (Rete Integrata dei Laboratori Tecnologici delle Universita' Siciliane).

References

[1] https://www.cms.gov

[2] G. E. Santagati, T. Melodia, L. Galluccio, S. Palazzo. Medium Access Control and Rate Adaptation for Ultrasonic Intra-Body Sensor Networks. *IEEE/ACM Trans. on Networking*. Vol. 23, No. 4. Aug. 2015.

[3] G. E. Santagati, T. Melodia. A Software-Defined Ultrasonic Networking Framework for Wearable Devices. *IEEE/ACM Trans. on Networking*. in press 2016.

[4] G. E. Santagati, T. Melodia. Experimental Evaluation of Impulsive Ultrasonic Intra-Body Communications for Implantable Biomedical Devices. *IEEE Trans. on Mobile Computing*. in press 2016.

[5] The Future of Healthcare: On Your Phone And On Your Body. [Online] *http://www.huffingtonpost.com/lisaserwinthefutureofhealthcare-_b_6804156.html*

[6] C. R. Hill. Ultrasonic attenuation and scattering by tissues. *John Wiley & Sons, Inc.,* . 1978.

[7] A. Y. Cheung and A. Neyzari. Deep local hyperthermia for cancer therapy: External electromagnetic and ultrasound techniques. *Cancer Res.*. Vol. 44, No. 9. Oct. 1984.

[8] G. S. Anderson, C. S. Sodini Body Coupled Communication: The Channel and Implantable Sensors. *Proc. of IEEE BSN*. 2013.

[9] T. C. W. Schenk, N. S. Mazloum, L. Tan, P. Rutten. Experimental characterization of the body-coupled communications channel. *Proc. of IEEE ISWCS*. Oct. 2008.

[10] T. Hogg and R. A. Freitas, Acoustic communication for medical nanorobots. *Nano Commun. Netw.* Vol. 3, No. 2. Jun. 2012.

[11] M. Nabi,T. Basten, M. Geilen, M. Blagojevic, T. Hendriks. A Robust Protocol Stack for Multi-hop Wireless Body Area Networks with Transmit Power Adaptation *Proc. of Bodynets*. Sep. 2010.

[12] B. Braem, B. Latre', I. Moerman, C. Blondia, and P. Demeester. The Wireless Autonomous Spanning tree Protocol for multihop wireless body area networks. *Proc. of First Intern. Workshop on Personalized Networks*. Apr. 2006.

[13] USRP N200/N210, Networked series. [Online] *https://www.ettus.com/content/files/07495_Ettus_N200-210_DS_Flyer_HR_1.pdf*.

[14] G. E. Santagati, T. Melodia. Sonar Inside Your Body: Prototyping Ultrasonic Intra-body Sensor Networks *Proc. of IEEE Infocom*. 2014.

[15] Olympus. Ultrasonic transducers technical notes [Online]: *http://www.olympusims.com/data/File/panametrics/UT-technotes.en.pdf*. 2006.

[16] GNU Radio - The free & open software radio ecosystem. [Online] *http://gnuradio.org*.

[17] B. Bloessl, C. Leitner, F. Dressler, C. Sommer. A GNU radio-based IEEE 802.15. 4 testbed *GI/ITG FACHGESPRÄCH SENSORNETZE*. Sept. 2013.

[18] A. Dunkels. Rime — a lightweight layered communication stack for sensor networks. *Proc. of EWSN* Jan. 2007.

[19] A. Dunkels, B. Gronvall, T. Voigt. Contiki - a lightweight and flexible operating system for tiny networked sensors *Proc. of IEEE LCN*. 2004.

[20] M. Fackler. Effects of small arms on the human body *Letterman Army Institute of Research*. Sept. 1988.