A Wearable Repeater Relay System for Interactive Real-time Wireless Capsule Endoscopy

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***Abstract*-Real-time wireless capsule endoscopy offers more flexibility and more precise screening options over commercially available passive endoscopy systems by allowing physicians to steer endoscopy capsules in real time. Yet, this requires reliable uninterrupted high frame-rate video streaming. In this contribution, we present a wearable repeater relay system that overcomes the impairments of the in-to-out body propagation channel and reliably relays implant data to a remote access point. The system consists of a set of wearable textile repeater nodes, exploiting receive diversity to provide a sufficiently large instantaneous carrier-to-noise ratio for live video streaming. Each wearable node, combining a dedicated receive antenna capturing the implant signal, an amplifier and an off-body transmit antenna, is fully implemented in textile materials, such that the comfort of the patient is not disturbed by the relay system. After outlining the design steps for the wearable relay node, in particular demonstrating stable robust antenna characteristics for the textile receive antenna oriented towards the body, we experimentally verify that a 6th-order diversity system provides the best compromise between user comfort and signal quality.**

I. INTRODUCTION

In the last decade, smart textile interactive fabric systems have shown great potential in health-care applications [1], enabling to remotely monitor patients in an unobtrusive and comfortable manner both in a hospital and home environment. Research on body-centric communication focused in particular on on-body [2], off-body [3] and in-body [4] wireless links, but only to a lesser extent on the in-to-out body wireless propagation channel. Yet, wireless communication with implants has recently gained increased attention thanks to the advent of Wireless Capsule Endoscopy (WCE) [5] and the advances made in the field of implanted antennas [6-8]. Setting up high data-rate wireless communication links between implants and remote base stations is hampered by the large attenuation of high-frequency signals inside the body, such that a trade-off must be made between link quality and available communication bandwidth. The lower frequency bands, such as the 402-405MHz Medical Implant Communication Services (MICS) band [9], offer low path loss at the expense of narrow communication bandwidth and large or inefficient antennas, whereas the higher frequency bands, such as the 2.45 GHz Industrial, Scientific and Medical (ISM) band [10] and the 3.4–4.8 GHz low-UWB band, provide large available bandwidth, achievable with smaller components, at the cost of excessive channel attenuation. Actively controlled capsules, however, require large bandwidths to support higher frame rates to provide real-time video feedback to the physician [11]. This enables real-time steering of the capsule's movement to interactively focus on diagnostically important features. Therefore, for these systems, the 2.45GHz ISM band might be the best option, provided the implant makes use of the maximum allowed transmit power of 20dBm and additional measures are taken to ensure the quality and reliability of the wireless in-to-out body communication channel.

In this paper, we present the design, implementation and experimental validation of a wearable repeater relay system for interactive real-time wireless capsule endoscopy. The textile multi-antenna relay system provides the diversity gain required to leverage the signal quality and reliability to sustain high-data communication between the implanted capsule and a remote access point. In the meanwhile, the comfort of the patient is guaranteed by fabricating each wearable repeater node fully based on textile materials, as described in Section II. The receive textile antenna of each repeater node, pointing towards the body to capture the implant's signals, exhibits robust and stable antenna characteristics when deployed on different parts of the body. The received signal is then amplified and relayed to a remote access point by means of a textile off-body antenna. Section III outlines how these nodes are distributed over a patient's body to achieve maximum diversity gain. In addition, the experimental setup is described that implements a two-step validation procedure of the system. The results of this experimental verification are detailed in Section IV. In the first phase, it is shown that a single wearable repeater indeed provides a significant increase in signal-to-noise ratio of the signal received at the remote access point. In the second phase, it is demonstrated that a 6th-order diversity system provides the best compromise between patient comfort, signal quality and link robustness.

II. TEXTILE REPEATER NODE

A. *System overview*

A general schematic overview of the textile repeater node is shown in Fig. 1, representing the repeater positioned on a human torso, consisting of a textile receive antenna RX_{rep}, capturing the signals emitted by the implant, an analog amplifier and a transmit antenna TX_{rep} that establishes the off-body wireless link with a remote access point. The receive RX_{rep} antenna's boresight, pointing along the y-axis, is directed towards the body, whereas the direction of main gain of the transmit antenna TX_{rep} is oriented along the negative y-axis. For the latter antenna TX_{rep}, we make use of the dual-polarized textile antenna described in [8], yielding a vertical linear polarization and 8.2 dBi gain when fed at one single terminal (with the other terminal, corresponding to horizontal polarization, correctly terminated by 50Ω). Although in this contribution only one single antenna terminal is used, the availability of a dual-polarized antenna offers the flexibility to later extend the functionality of the node by implementing transmit diversity at the transmit antenna TX_{rep} or by connecting a second receive antenna RX_{rep} to the other antenna terminal. An amplifier, with 43.8 dB gain at 2.45GHz, is used to amplify the signal received by RX_{rep}, which is then retransmitted by TX_{rep}. The textile ground planes provide sufficient shielding between RX_{rep} and TX_{rep}, as the isolation between the RX_{rep} and TX_{rep} antennas was measured to be 55 dB. More details about the system are found in [12].

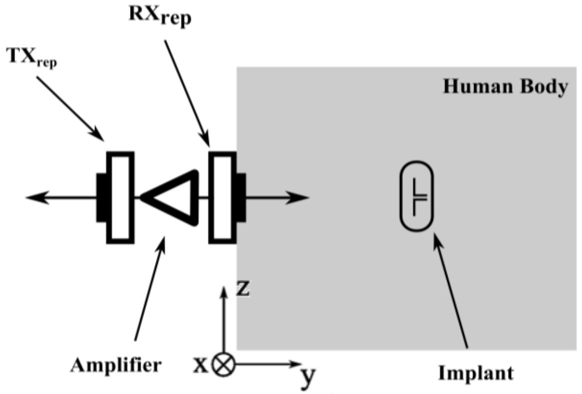


Figure 1. Schematic overview of the textile repeater node.

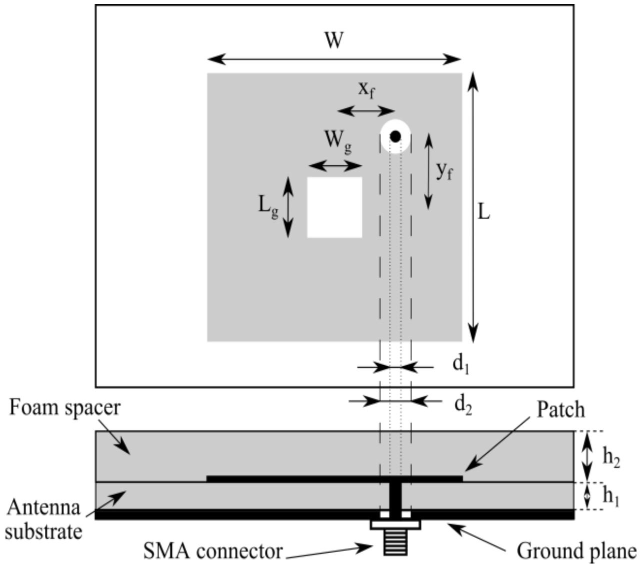


Figure 2. Repeater's receive antenna RX_{rep} (W=40.9mm, L=48.7mm, Wg=8.8mm, Lg=13.2mm, Xf=7.8mm, Yf=18.5mm, h1=3.94mm, h2=7.92mm, d1=1.3mm, d2=5.5mm)

B. *Textile receive antenna*

The wireless node's textile receive antenna RX_{rep}, shown in Fig. 2 with its dimensions specified in the caption of the figure, was specifically designed to exhibit optimal stable performance when deploying the antenna with its direction of main gain towards the body. To ensure robust 50Ω impedance matching when positioned at different locations on the body, a foam spacer with thickness 7.92 mm was placed on top of the antenna plane. Experimental verification shown in Fig. 3 indeed demonstrates that the return loss exceeds 10dB in the complete ISM band when positioning the antenna on the stomach back and sections of the body of an average test person.

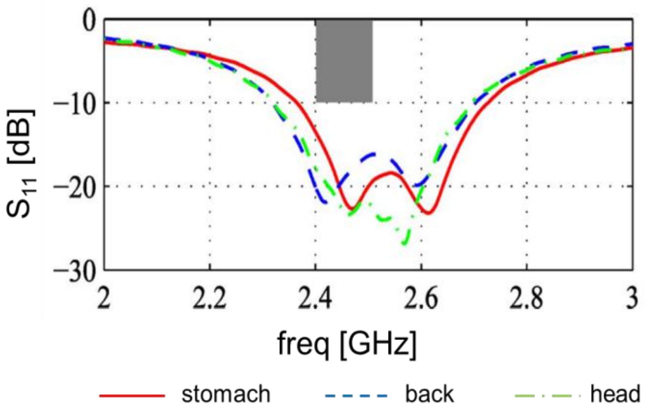


Figure 3. Reflection coefficient of receive antenna RX_{rep}, when deployed on stomach, back and head sections of an average person's body.

III. MULTI-ANTENNA DIVERSITY SYSTEM

In this section, we describe the practical deployment of the system and illustrate how reproducible validation of the system's figures of merit is performed.

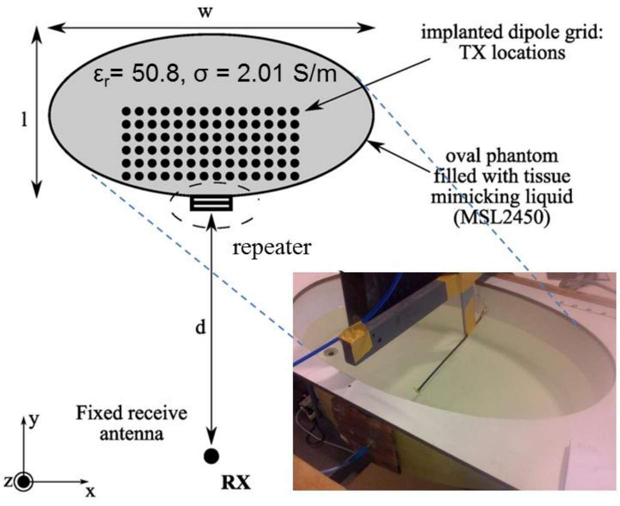


Figure 4. Wearable repeater on a standardized phantom, with w = 0.8 m, l = 0.5 m and h = 0.12 m, setting up a link between an implanted dipole antenna and a remote access point at d = 2m.

A. *Single-node standardized experimental setup*

Fig. 4 shows the flat phantom filled with tissue mimicking fluid MSL2450, used to emulate the torso of a patient and to yield reproducible measurements following the IEC 62209 standard. The wearable repeater is deployed on the side-wall of the phantom. This setup enables us to assess the data link quality between an implanted transmit antenna, being a half-wavelength dipole insulated by polytetrafluorethylene (ε_r =2.07) and resonating at 2.457 GHz, placed at various depths in the human body, and a remote receiver at d = 2m.

B. *Multi-node standardized experimental setup*

To exploit spatial receive diversity by improving the signal quality, by means of array gain, and the channel robustness, by means of diversity, we deploy multiple textile repeater nodes, distributed over the body for optimal coverage as shown in Fig. 5. Eight antennas are placed on the side and the back of the patient, such that they may be comfortably integrated into a garment. We concentrate on the improvement provided by the multi-antenna over a single-antenna setup by directly monitoring the signals at the output terminal of the receive antennas RX_{rep} at the different nodes using a Signalion wireless testbed. Again, a reproducible experimental setup is obtained by deploying the different wireless nodes on the wireless phantom with muscle-simulating fluid, as described in Section III.A. In the next section, the link improvement is studied as a function of the number of receive antennas. A more detailed description of the setup and its experimental validation is found in [13].

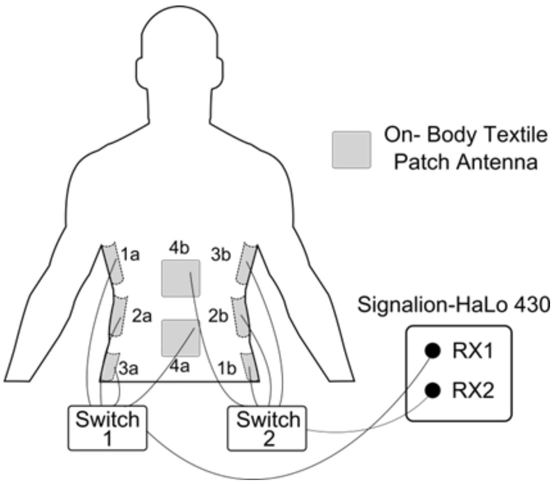
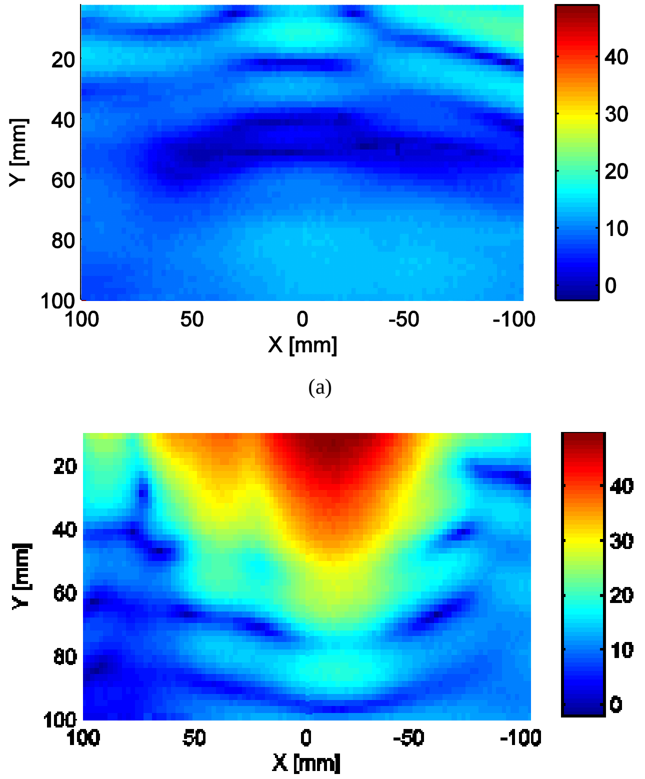


Figure 5. Multi-antenna repeater system, with 6 side (1a, 2a, 3a, 1b, 2b, 3b) and 2 back (4a, 4b) antennas, deployed on a patient, with the receive antenna outputs connected to the Signalion-HaLo 430 wireless testbed.

IV. EXPERIMENTAL VALIDATION

A. *Single-node setup*

To experimentally verify the benefits of the wearable repeater system, we compare the received signal level at the remote access point with and without the wearable repeater, for different implant (represented by the vertically placed dipole antenna, Section III.A) positions, varying from -10 cm to 10 cm along the x-axis with respect to the repeater's receiver placed at the origin, and depths, ranging from 1 cm to 10 cm (y-axis). The transmit power at the implant is set to 10 mW, which corresponds to about half the allowed SAR limit of 2 W/kg averaged over 10 g of tissue [IEC 62209-1]. The received SNR levels without repeater and with a repeater are displayed in Figs. 6a and 6b, respectively. The received SNR without repeater, averaged over the scanning grid, equals 8 dB, which only allows for low data rate communications. The SNR values achieved at remote terminal are significantly higher when using a repeater, with an average SNR of 33.0 dB.



(a)

(b)

Figure 6. Received SNR on RX, (a) without repeater, (b) with wearable repeater acting as a relay (Y-axis = TX depth in body; X-axis = position relative to RX_{rep} antenna's center).

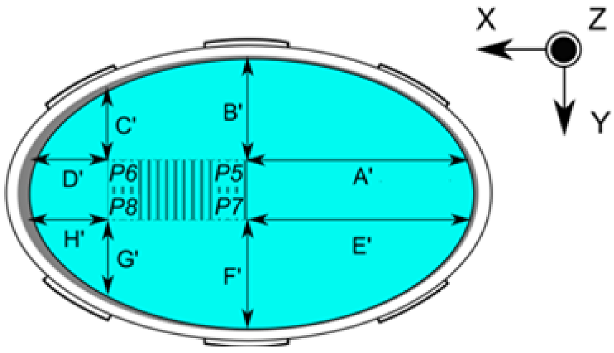


Figure 7. Scan area for the evaluation of the multi-node setup

B. *Multi-node setup*

We now consider a scan area deep inside the body phantom, between the points P5(192mm,105mm), P6(385mm,105mm), P7(192mm,150mm) and P8(385mm,150mm), as shown on Fig. 7. In Table I, the received signal-to-noise (SNR) ratios are compared for different orders of diversity. For dual-order diversity, antennas 4a and 4b are used, antennas 1a, 1b, 3a, 3b realize four-order diversity and all side antennas implement 6th-order diversity. We notice that making use of the antennas positioned on the back of the patient yields the highest signal levels. However, in Table 1 the most relevant figure in terms of links reliability is the minimum achieved SNR, which clearly increases for an increasing number of antennas. The 8th-order diversity setup guarantees a minimal received SNR of 10dB, which is required for highly reliable live wireless video streaming at a minimal bitrate of 3.5Mbit/s within a bandwidth of 1MHz. Yet, including the bottom antennas 4a and 4b in the 8th-order diversity scheme only yields marginal improvements in diversity gain, as they only partly cover the scan area. Therefore, a better tradeoff between link reliability and patient comfort might be obtained by using the 6th-order diversity scheme with a transmit power level of 20mW at the implant, which is still allowed by the SAR limits and which provides an additional 3dB margin in terms of SNR.

TABLE I
STATISTICAL PARAMETERS FOR VARYING NUMBER OF ANTENNAS, WHERE THE GAIN IS BASED ON THE 10% OUTAGE PROBABILITY LEVELS OF THE CDF

Number of Antennas	Max. (dB)	Min. (dB)	Mean (dB)	Median (dB)	Gain (dB)
8	27.99	10.85	16.89	17.32	9.25
6	11.83	8.74	10.25	10.16	7.65
4	10.97	6.87	8.69	8.56	6.15
2	27.92	3.34	14.40	16.34	2.45

V. CONCLUSION

A wearable textile repeater system was designed and deployed in a multi-antenna setup implementing receive diversity. Each repeater node consists of a receive antenna pointing towards to body to capture the signals of an implant, an analog amplifier and an off-body textile transmit antenna relaying the amplifying signal to a remote access point. A dedicated design procedure was outlined to ensure that the textile receive antenna exhibits excellent impedance matching when deployed at different locations on the body. Experimental validation by means of a standard setup relying on a body phantom filled with muscle-mimicking liquid demonstrated a significant increase in SNR. In addition, several nodes were deployed in a multi-antenna diversity reception configuration. It was shown that 6th-order diversity provides the ideal tradeoff between patient comfort and a link reliability that is sufficient to implement high frame-rate video transmission.

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