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In-body Communications Exploiting Light: A Proof-of-concept Study Using *ex vivo* Tissue Samples

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ABSTRACT This article presents a feasibility study on the transmission of information through the biological tissues exploiting light. The experimental results demonstrating the potentials of optical wireless communications through biological tissues (OCBT) are presented. The main application of the proposed technology is in-body communications, where wireless connectivity needs to be provided to implanted electronic devices, such as pacemakers, cardiac defibrillators, and smart pills, for instance. Traditionally, in-body communications are performed using radio and acoustic waves. However, light has several fundamental advantages making the proposed technology highly attractive for this purpose. In particular, optical communications are highly secure, private, safe, and in many cases, extremely simple with the potential of low-power implementation. In the experiments, near-infrared light was used, as the light propagation in biotissues is more favorable in this part of the spectrum. The amount of light exposure given to biotissues was controlled to keep it within the safety limits. Information transmission experiments were carried out with the temperature-controlled *ex vivo* samples of porcine tissue. The tissue temperature was found to be significantly affecting the light propagation process. Communication performance with respect to the biotissue thickness and light direction was assessed. The results showed that optical channels to and from the possible implant are nearly reciprocal. Communication links were established to the deepness of more than four centimeters, and the data rates of up to 100 Kbps were obtained. The encouraging results of this study allow us to anticipate the potential applications of the proposed light-based technology to communicate with the various electronic devices implanted at different depths in the human body.

INDEX TERMS Biological tissues, *ex vivo*, In-body communications, Implanted electronic devices Medical implants, Optical wireless communications, OCBT, Pacemaker.

I. INTRODUCTION

This article presents and discusses the initial experimental findings of an in-body communication system using near-infrared (NIR) light through samples of fresh porcine biotissues. The impressive technological advancements over the past decades have made possible not only to monitor health conditions but also to diagnose and quickly react to numerous onsets. Novel health-related technologies allow to enhance the quality of life and also to save lives during critical health conditions. Implantable electronic devices (IED) as well as different in-body sensors, play today a significant role in the medical information and communications technology (ICT) arena, and a great array of advanced devices already exist [1, 2]. Examples include cardiac pacemakers and defibrillators, implanted medicine dosifiers, brain implants, smart pills, and others. These implantable medical devices are generally programmed to perform designated tasks such as remote onset monitoring and providing defined responses to health conditions, etc. These devices can also be externally controlled, allowing medical staff to change configurations or operating modes, to control system functions and to add new medical profiles. Clearly, to perform remote monitoring or possible adjustment of the implant operation, a wireless communication link is needed.

Conventionally, a magnetic coupling mechanism was used to communicate with the implants. In 1999, a radio frequency (RF) spectrum named medical implant communication service (MICS) was introduced, communicating in the 402 - 405 MHz frequency range. MICS provides a flexibile wireless connection to the implant with a range of up to two meters. The allocated MICS RF spectrum is adopted for body area network (BAN) which allows the transportation of information to control both on-body and in-body sensors [3]. The spectrum allocation for MICS supports establishing interference-free communication with medical implants and on-body sensors in the presence of other medical devices also exploiting the RF spectrum. However, there are associated threats [4], when numerous BAN sensors sharing the same RF spectrum operate in close vicinity, interference issues may become a significant problem. As data integrity is a key requirement in medical ICT, any unwanted interference may result in loss of integrity. Moreover, the concern of vital RF signals being accessed by unintended parties or intentionally jammed needs to be taken seriously into account.

Commonly utilized implants such as pacemakers and defibrillators are implanted by cardiologists underneath the skin and chest muscles, meaning typically sub-centimeter communication ranges. In some cases, the implants are placed deep inside the body or swallowed e.g., gastrointestinal pills are swallowed to diagnose the diseases in intestinal tract. In order to communicate with these implants, a securer and reliable communicational link is necessary that could penetrate deeper inside the biological tissues. Biological tissues are complex turbid media, with inhomogeneous composition of blood, bones and tissues. The inhomogeneous composition restricts the propagation of electromagnetic waves, and the high amount of water content in the tissues effectively attenuates the propagation, limiting the attained communication range. Penetration depths under five centimeters through biological tissues have been reported for implanted devices that use the radio spectrum [5].

Ultrasonic waves can also propagate through biological tissues and ultrasound techniques have being used since 1940 to diagnose the onsets. The aftereffects of ultrasound on living beings are also well-known. While ultrasounds can penetrate deeper inside the biological tissues, penetration depth of ultrasonic communication is limited to about ten cm [6]. A much securer ultrasonic in-body communication has been presented in [7]. Since free-space is a poor dielectric, a major disadvantage of ultrasounds is found out to be their inability to propagate through free space, so mostly direct-contact (i.e., no free-space) wireless communication can be established with ultrasounds. Both RF and ultrasounds dissipate energy in tissues while propagating through, which means an increased amount of energy is absorbed by the biological tissues. Although the electromagnetic spectrum allocated for MICS and BAN uses ultra-low power, and the ultrasonic communication dissipate very low energy during propagation, excessive exposure is not considered safe.

Other modes for in-body communications include capacitive coupling and galvanic coupling. Capacitive coupling is subject to surrounding conditions, and it often needs additional dielectrics such as gels to support the capacitive properties. The changes in surrounding such as drying out of capacitive gel could result in poor link performance. On the other hand, the galvanic coupling can communicate up to 15 cm at higher data rates [8].

Optical wireless communication (OWC) has emerged as a future wireless communication in recent decades, though light as a data carrier has already been used in fiber optics. The free-space optical channels do support mostly line of sight (LOS) communication; in the non-line of sight communication (NLOS) the signal strength is significantly weak at the receiver, so the complexity of optimizing the channel conditions adds up when endeavoring to achieve a NLOS communication [9]. The electromagnetic light spectrum is divided into most widely referred visible, infrared and ultraviolet spectrums. The visible and infrared spectrum have been widely considered in wireless communications, either as stand-alone wireless communications technologies or as complementing radio communications. Broadband visible light communication (VLC) has become a highly discussed topic in the fifth generation (5G) as well as in the development of the sixth generation (6G) communication [10]. Wireless infrared communications have been used to transmit data to devices in close vicinity, first standardized by Infrared Data Association (IrDA) [11]. Traditionally, the infrared wireless link utilizes a 950 nm wavelength to transmit data within a range of one meter in LOS. IEEE 802.15.7 was one of the first published standards for OWC, back in 2011. The standard focuses on the visible light spectrum, later a target group (TG7r1) is formed which is still actively working on developing the OWC for different short-range applications. The aim of this group is to amend the IEEE 802.15.7-2011, and to widen the wavelength of operation from 190 nm to 10000 nm, covering the ultraviolet, visible light, and infrared regions too.

Prior to the IEEE standards, numerous vendors developed proprietary protocols for infrared communications, however, their devices were not interoperable. Infrared and visible wireless communication links can be established over ranges of up to ten meters.

Infrared light, particularly NIR, propagates relatively well in biological tissues. Indeed, NIR radiations are less affected by the strong absorption and scattering properties of biological tissues [12]. A great deal of research exists on exploiting NIR light to both diagnosis and therapy uses [13, 14]. Infrared spectroscopy is a well-known technique where infrared spectrum is utilized to study superficial and sensitive organs such as skin and eye [15]. The penetration depth in such cases is too limited i.e., up to some millimeters [16]. Another major application of light is in low level light therapies [17], that involve treating scars, lesions, etc. Light is also exploited in pulse oximetry [18], a well-know technique used to monitor blood pressure (BP), blood sugar, cardiac onsets, and other physiological parameters.

The potential of using light to transmit information through biological tissues has not been explored yet. Recently, NIR-based optical communications across biological tissues has been demonstrated using phantoms as the optical medium [19, 20]. In this paper, we extend our previous work considering OCBT, using a much more realistic communication medium, namely, fresh porcine biotissues are used as the optical communication channel. We demonstrate the feasibility of using NIR light for establishing communication links in realistic environments and very initial measurements of an OCBT network using porcine biotissues. We observe that ranges of up to four centimeters and data throughputs of several tens of Kbps can be attained. Such communications system could be used in a variety of practical use cases involving, for instance, pacemakers, defibrillators, insulin pumps, and others. The most significant advantages of using light for this type of communications include security and privacy, as optical links cannot be remotely accessed or disturbed by non-intended users or uncontrolled interference sources. Moreover, no exposure to radio is created.

This paper is organized as follows: Section 2 discusses the different in-body carriers, in Section 3 we discuss the light tissue interaction. In Section 4, we explain the typical requirements and environments related to implants. The implementation is explained in Section 5 and the feasibility results are explained in Section 6. Finally, the discussion and conclusion are presented in Sections 7 and 8, respectively.

II. IN-BODY CARRIERS

In this section, the key in-body carries are briefly introduced and compared. These are fundamental technologies needed to provide wireless access to the implants. The development of increasingly capable and sophisticated IED has progressively helped medicine science to deliver efficient therapy for life threatening diseases, largely improving quality of life and saving precious lives. A typical example of IED usage is in cardiac pace management where a pacemaker is implanted to administer the fading electrical activity of the heart that can cause, for instance, cardiac arrhythmia. Cardiac pace management has been used in practice since the last five decades [21] and the number of IED patients is increasing [22]. Failure or malfunctioning of the device is critical, and thus, reliability is one of the key requirements for IEDs. Since these IEDs are battery operated, extremely low-power solutions need to be exploited in the implementation and energy management of the devices. As IEDs need to be send and receive information, a wireless transceiver needs to be part of a device. Wireless communications provide a non-intrusive approach to connecting an IED, though the nature of the untethered link brings several challenges that need to be addressed, such as security, privacy, and safety. Radio, acoustic and optical communication technologies can be used to establish the wireless link to the IED, and each technology has its own strength ad drawbacks. Next, these approaches are briefly discussed.

A. RADIO FREQUENCY

RF is the dominant wireless carrier that has been used globally in almost every communication application. For IED, the RF spectrum from 402 to 405 MHz is allocated for communication. RF provides the flexibility of simply establishing an ultra-low-power wireless link of up to two-meter range. Since the IED are energy-limited, one of the key challenges is to design a wireless system with minimum power consumption. Due to limited battery life, the maximum current that a typical pacemaker can draw is somewhat between 10 μA and 20 μA. For an implant with a typical lifetime of seven years, the 15 % of total available energy is on average available for communications purposes, and the RF wireless link may require as low as 2 μA to 3μA [23]. MICS was extended as the medical device radio communication service (MedRadio), and it consists of an extended electromagnetic spectrum for radio communication which was previously allocated by MICS with an additional spectrum allocation for neural implants [24]. The rate of transfer required for medical applications is around 20 Kbps, and, in principle, the RF spectrum allocated in the ultra-wide band (UWB) can provide higher data rates at lower cost and complexity [25] than the minimum required for any application. The security and privacy of patient's data of an IED against malicious activities is of the greatest concern in wireless implants, and thus, authentication and secrecy of patients' information are vital requirements. Several techniques for authentication and blocking disrupting activities are available and can be applied, as in [26], such as cryptography, avoidance of jamming, detecting abnormalities through external devices, etc. Strong authentication techniques can reduce the chances of successful eavesdropping, cryptography keys based on physiological variations are also solutions to prevent the data from being accessed by non-intended parties. RF is still vulnerable to hacking and the radio link needs to be highly protected to provide security, privacy, and safety to the patient.

B. ACOUSTICS

Acoustic technology has been exploited in clinical application since decades and the most widely use cases of ultrasounds are in diagnostic imaging. Typical spectrum of ultrasonic communication lies between 2 MHz to 100 MHz. Ultrasounds can propagate through the biological tissues and are commonly used to diagnose myocardial onsets, pregnancies, etc. Ultrasound waves dissipate very low energy when propagating through biological tissues and can also propagate deeper inside these tissues. Ultrasound waves can be used to establish wireless communication links to communicate with implants, especially those which are place deeper inside the body or swallowed, e.g., gastrointestinal pills, brain implants etc. However, since the air is not an ideal dielectric medium for ultrasounds, a direct contact to the body is required. On the other hand, ultrasounds can propagate through water better than RF [27], since about 2/3 of human body consists of water, therefore ultrasounds can be a better solution for data transmission. An important consideration when using ultrasounds is the size of the transducer, ideally for an IED the transducer should be implemented at a miniaturized scale. Ultrasonic communication through beef meat samples is demonstrated in [6], employing a tiny two-mm transducer and achieving 340 Kbps. When communicating with an implant, the directivity of the transmitter is important. Omnidirectional transducers make the physical synchronization of a transmitter and receiver easier, whereas directional links increase the signal-to-noise ratio at the receiver, resulting in longer reachable ranges or higher data throughput support. Higher data rates can also be achieved with larger transducers, data transmission at 30 Mbps through pork meat samples is demonstrated in [28].

C. LIGHT

Light, electromagnetic radiation covering the infrared, visible, and ultraviolet part of the spectrum, can be used as a carrier to transmit information. The first application of data transmission over light is the invention of photophone [29]. Over the years, light has been used in fiber optics to transport information, for instance creating the backbone network for mobile and public data communication systems. Wireless communications exploiting light are often termed as optical wireless communications (OWC), and OWC have rapidly evolved in recent decades. Each part of the light spectrum, namely infrared, visible, and ultraviolet, can be used to transmit data [30]. Visible light communications (VLC) exploit white light-emitting diodes (LED), an immensely popular lighting source technology today. White LEDs can be used to simultaneously provide illumination and to transmit wireless data. Since light is modulated at a high rate, the human eye cannot perceive any flickering effects. Light-based wireless communication has unique advantages, such as inherent security, privacy, and safety, as well as low complexity and low power consumption in solutions requiring low- to moderate-rate. Some key operational characteristics and data rates for the in-body carriers discussed above are presented in Table I.

TABLE I
COMPARISON OF IN-BODY CARRIERS

	RF	Ultrasound	Light (initial results)
Bandwidth	402 – 405 MHz	2 – 100 MHz	100 – 384 THz
Depth	< 5 cm	< 15 cm	5 cm
Packaging	fully packaged	fully packaged	no
Data rate	< 1 Mbps	< 0.5 Mbps	100 Kbps
Security and privacy	low	high	very high

III. LIGHT-TISSUE INTERACTION

Light propagation in biological tissues is a complex process. During its propagation inside the biotissue, the light undergoes scattering, absorption, as well the reflection/refraction on the inner tissue interfaces. Most of the biotissues, such as skin, muscles, brain, etc., are spatially inhomogeneous multilayered structures. Due to this, from the optical point of view, the biotissues are often considered as a highly scattering media with relatively low absorption. The fundamental reason for the scattering is a mismatch in the refractive index of the tissue constituent on the micro and nano level [31]. The main scatterers of the biotissues are represented by cellular organelles such as membranes, nuclei, and mitochondria. The natural chromophores like hemoglobin, melanin, myoglobin, bilirubin, carotene are the main absorbers of tissues [31]. However, for the red and NIR light (650–950 nm) the absorption is rather low. This spectral band is often called a transparency window. The lower border of this window is determined by the blood absorption, while the upper border is limited by the peak in the water absorption spectrum. At the same time, the longer wavelengths from the second to fourth NIR transmission windows can also be used for deep tissue imaging: (II, 1,100–1,350 nm; III, 1,600–1,870 nm; and IV, centered at 2,200 nm) [32].

The main parameters describing the propagation of light inside the biotissue-like turbid media are the scattering coefficient $\mu_s(\lambda)$, absorption coefficient $\mu_a(\lambda)$, and the phase function of the scatterers composing the tissue [33]. The absorption coefficient is the reciprocal of the depth at which the light beam is attenuated due to the absorption in e times, whereas the scattering coefficient is determined by the length at which monochromatic, collimated light is attenuated in e times due to the scattering. The phase function describes the elementary act of scattering and represents the probability density function for the photon to be scattered into a particular direction characterized by the scattering angle θ [33]. Traditionally, Henyey-Greenstein, Gegenbauer Kernel, and Mie phase functions are the most used [34]. To describe the directionality (averaged direction) of the scattered light, the anisotropy factor g, defined as an average value of $\cos(\theta)$, is used. The possible values of g spans from -1 to 1. Here, $g = 0$ corresponds to the isotropic case (so-called Rayleigh scattering), $g = 1$ is for total forward scattering (Mie scattering). Typical values of the anisotropy factor for the biotissues lie in the range of 0.7–0.99 [31] that characterize them as highly anisotropic scattering media with dominating forward scattering.

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Several analytical and numerical models have been established to describe light propagation through the biotissues. In general, these models can be classified into two groups: deterministic and stochastic [33]. The deterministic methods include electromagnetic theory and radiative transfer theory (RTT) among others [35]. Due to the complex boundary conditions and multilayer structure of the biotissue, the direct solutions of the equations in the frame of the deterministic approach are limited by a small number of specific cases (e.g., plane-parallel configuration and isotropic scattering) [33]. In practice, the solutions of the equations are performed numerically or in the frame of the approximations such as diffuse or small-angle approximation [33]. The examples of stochastic methods are photon path-integral formalism and Monte Carlo method. Among these, the Monte Carlo approach is considered as a gold standard for simulating the photon transport in tissues [36]. The method relies on the multiple calculations of the random trajectories of a single photon and the statistical analysis of the obtained data. This approach can naturally account for complex boundary conditions (e.g., irregularly or randomly shaped borders or inclusions), arbitrarily assigned scattering phase function, and is not limited by the number of considered tissue layers.

IV. COMMUNICATIONS WITH IMPLANTED ELECTRONIC DEVICES

IEDs have been used to perform many critical medical functions for many decades, and nowadays, IEDs are also used for advanced diagnostic and therapeutic purposes, such as intestinal tract disease imaging, brain stimulation therapies etc. Wireless connectivity is a fundamental feature need to be implemented in an IED, and examples of these technologies where discussed in the previous section. In this section, we further discuss the communication requirements for an IED.

A. BASICS COMMUNICATION REQUIREMENTS OF TYPICAL IEDS

1) **Reliability:** Medical applications involving IED require ultra-reliable wireless connections. A reliable connection ensures the integrity of biological data which is vital for correct diagnostics and treatment. Since the implants are used for most critical operations nowadays, such as in cardiac pacing, defibrillation, etc., a reliable connection that overcome the impairments of the transmitted signal as it propagates through the biological tissue must be used. Furthermore, since interference-free communication is difficult when operating multiple devices in close vicinity and in an uncontrolled environment, the communication system must cope with possible interference.
2) **Security**: Multi-step authentication, cryptographic or encryptions are required to establish secure connections to IEDs. Security is utmost to avoid any eavesdropping and to keep the anonymity of the patient. The detection and rejection of malicious activities e.g., malware or any vicious attempt to alter the IED functionality is required from the security perspective.
3) **Throughput:** Data rates of up to 20 Kbps are considered enough for typical IED communications, and higher throughput is mandatory especially in tele-monitoring and applications involving transmission of medical imaging. Also, when uploading or downloading medical profiles or performance statistics of an IED, higher throughput might be required for in-time diagnostics.
4) **Energy:** IEDs are battery operated and for prolong battery life, the amount of current drawn by each component of an IED is carefully controlled. Chief applications such as pacing, defibrillation or glucose monitoring are allowed to draw a limited percentage of the allowable current. In turn, communication functionalities are allowed to use only a fraction of total current. Ultra-low power communication is required, for this reason the wakeup radio concept is necessary to keep the communication functionalities idle most of the time. Only after sensing a received wake-up signal, the communication system is fully activated, and data transfer can take place.
5) **Latency:** When IEDs perform telemonitoring, ultra-low latency communication is required. This is because the data is required in real-time for quick diagnostic and therapeutic purposes. Since most IED perform life-supporting and life-saving operations, ultra-low latent communication is utmost for timely treatments. For data offloading, the latency of the communication link can be compromised, since in those cases the diagnostic or treatment is performed in a scheduled time

B. TYPES OF ENVIRONMENT RELATED TO TYPICAL IEDS

Traditionally, IEDs have been used to perform a single designated task. In the case of pacemakers or defibrillators, these IEDs are mostly implanted in a pocket created by cardiologists, between the chest skin and flesh, which means sub-centimeter ranges from and to the IEDs. But nowadays, IEDs are also either implanted deeper inside the body or swallowed, and their applications may also include assisting telemonitoring, diagnosing onsets, perform therapies, etc. Sophisticated applications benefit patients in managing their disease and support healthcare personnel reducing their patient load. IEDs with wireless data transmission capability can work as a node of a wireless body area network (WBAN) and can, in principle, operate in both indoor and outdoor scenarios. Certain minimum requirements are mandatory to achieve when designing an IED capable of transmitting data wirelessly in different environments, as summarized in Table II. We consider four most distinctive daily environments in which an IED user can subject to. These include in inpatient care i.e., inside the hospital as well as outpatient both at home, on the move, and in public spaces.

TABLE II
TYPICAL ENVIRONMENT-RELATED REQUIREMENTS FOR IED.

	Reliability	Security	Latency	Data rate
Inpatient care	4-5	4-5	1-3	2-5
Outpatient care (on the move)	4-5	4-5	2-4	1-3
Outpatient care (at home)	4-5	4-5	2-4	1-3
Public spaces	4-5	5	1-3	3-4

5: very-high; 4: high; 3: moderate; 2: low; 1: very-low

High to very-high security is recommended in all environments, as safety of data and minimization of detrimental effects of eavesdroppers and malicious users must be guaranteed. The requirement of reliability of the data transmitted has the same high recommendations. The latency of transmission can be compromised since in 3 out of 4 cases the telemonitoring or diagnosis is performed remotely once the data is completely transferred, so the requirement of latency varies from low to high. The throughput in outpatient care can be moderate while in public space higher throughput might be required to establish a reliable connection (e.g., diversity is exploited). Similarly, inpatient care data rate can be low to very high, depending on the facility of the patient e.g., in intensive care or operation theatres very high data rate is typically required.

V. OPTICAL WIRELESS COMMUNICATIONS THROUGH BIOLOGICAL TISSUES (OCBT): SYSTEM DESCRITPION

The applications and sophistication of IEDs continue to grow as, due to the advance of chronic illness, the usage of implants is increasingly widespread. We designed and implemented an experimental testbed for OCBT, to evaluate the feasibility of in-body optical communications. The testing is performed on porcine biological tissues under controlled environmental conditions and the causal relation among variables influencing the optical communication is inspected. The basic concept of optical wireless communication is presented in Figure 1, where an optical communicational link is established, allowing the IEDs implanted at different depths to be wirelessly connected to an external (off-body) node. Health records and other medical information can be transmitted from IED, and conversely, data such as control information, user profiles, etc, can be also transmitted to the IED. Other use cases involve the intra-body communication in which an IED serves a relay for another device to communicate with a server, to pass on data or receive commands. In this study, we only considered the former case, and have used porcine biotissues of different thicknesses to characterize the achievable depth with the current testbed and associated limitations. The basic block diagram of the optical communication system, as well as its practical implementation, can be seen in Figure 2. A unidirectional communication link was established using equipment from different vendors.

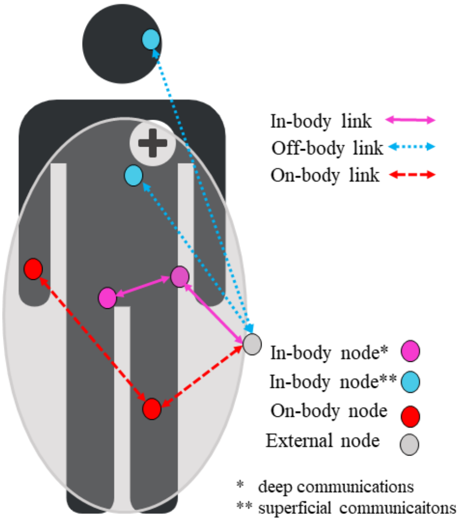

FIGURE 1. **Possible optical wireless communication links with implantable electronic devices.**

A fresh-meat porcine sample is exposed to a NIR optical signal modulated by the information to be transmitted. The transmitted light through *ex vivo* sample is received and processed to extract the relevant information to be stored into the IED. Next, the main components of the implemented OCBT testbed are described.

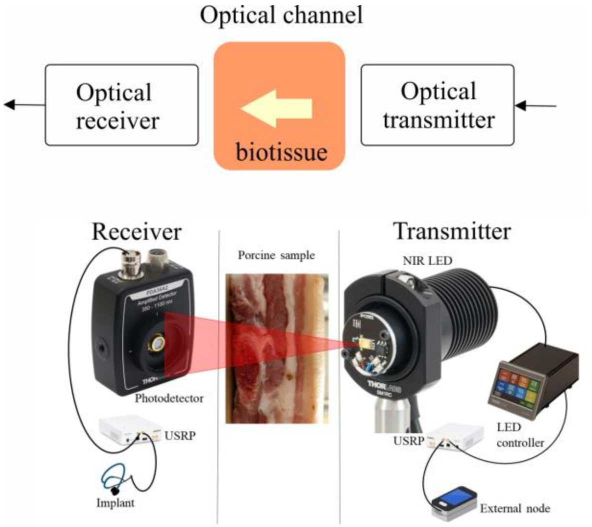

FIGURE 2. **Basic block diagram of the optical system (top) and an overview of testbed implementation (bottom).**

A. TRANSMITTER

The transmitter for OCBT is implemented mostly with off-the-shelf hardware and free to use software. The light source is an 810 nm NIR LED. In order to confine more power for some measurements, we also used a collimation lens. For the in-body communication, the optical signal is data modulated. A freeware GNU radio software and universal serial radio peripheral (USRP) were used to generate the modulated

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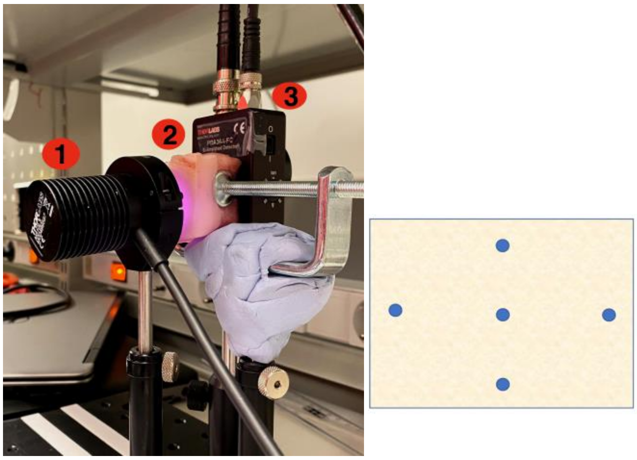
baseband signal. Then, this baseband modulated signal from the USRP containing the desired data is combined with voltage by passing it through a bias-T circuit and the resulting signal is finally fed to the LED driver. We used a DC2200 LED driver, another benefit of using the LED driver is the controlled modulation of LED. We tested different percentages of maximum input current for LED and inspected the variations in throughput. This is also important for tissue safety, since high optical power will increase SAR, and this could damage the tissue. Moreover, longer exposures could do the same damage to the tissues, so the exposure time needs also to be carefully controlled. In our case, we can reduce the amount of exposure through the LED driver for longer exposures.

B. RECEIVER

The data on the receiver side is gathered through an avalanche photodiode detector in light packets form, the equivalent current conversion of these packets is then fed to USRP connected to GNU radio software. The demodulated data is then stored in the receiver's memory. The range of the photodiode is selected so that it has peak at 800 nm and the overall range of the detector is between 400 nm to 1000 nm. The demodulation and other signal parameters are selected prior to receiving in GNU radio software. We selected GMSK modulation scheme for our implementation, GMSK is constant envelop scheme which performs better with LED which are slow and does not support sharp cut-off.

C. MEASUREMENT SET UP

A testbed implementation is presented in Figure 3.a. A unidirectional communication network is constructed for an in-body communication, where the transmitted light through a sample of fresh porcine biotissue is collected with a photodiode detector, placed on the other end of the sample. The incident power to biotissue is measured for each testing and compared with safe limits.



a)

b)

FIGURE 3. **a) Measurement setup for OCBT. 1 LED, 2. Porcine sample, and 3. Photodetector receiver. b) Locations at which detector is placed to record the measured optical power.**

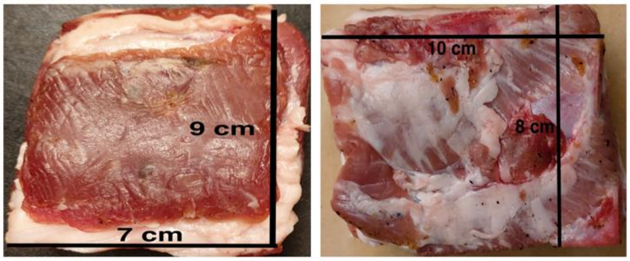
We tested porcine biotissues at two different temperatures i.e., once at room temperature and next at the normal body temperature of 37 ºC. The biotissue is kept in a heated box and the temperature of the box is set to 37 º C. We repeatedly measured the received optical power by placing the detector at five different locations, as depicted in Figure 3.b.

VI. SYSTEM EVALUATION

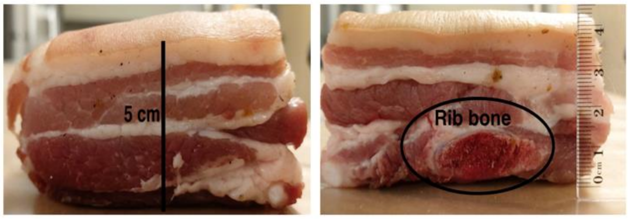
This study is the extension of our previous work [19, 20], where we tested in-body communication using biotissues-mimicking optical phantoms. In this section, we present the measurement parameters used in the evaluation and study the effect of thickness, direction and temperature on the performance if the OCBT system. In the tests, three high-resolution images were transmitted and successfully received on the receiving end.

A. THICKNESS

Thickness or maximum depth through which data can be transmitted is an important finding. Ultrasounds can propagate through 15 cm thick biotissues [6] in comparison to both RF [5] and OCBT [19], which makes ultrasounds superior for communication with IED placed deeper inside body. However, ultrasounds require direct contact with body, while both RF and OCBT can transmit wirelessly without such a precise contact. For our study, we used several thicknesses of fresh porcine biotissues taken from the belly with skin on it. We employed samples with different thicknesses in order to find the maximum range for OCBT. We found that data can be transmitted through up to around five centimeters thick biotissues with the current communication system. Figure 4 shows the porcine biotissues we used for testing. We used pieces of biotissues larger than 5 cm by 5 cm, since the light from the edges on smaller pieces of biotissue can escape, resulting in dubious outcomes.



a) Without rib bone b) With rib bone



c) Without rib bone d) With rib bone

FIGURE 4. **Porcine biotissue pieces of 5 cm thick without rib bone (a, c); porcine biotissue pieces of 4.5 cm thick each with rib bone (b, d).**

B. DIRECTION

The composition of the biological tissues associated with typical IEDs is layered and light will encounter a different order of layers depending on its direction, i.e., optical signal being transmitted or received by the IED. Skin, consisting of dead cells, is the outer layer, while the inner side is usually soft flesh. In our study, we tested optical communication in both directions, namely from outside of body to inside, and vice versa. The former case is realized by exposing the skin to light i.e., when optical transmission is facing skin first and then the light propagates through fat and flesh tissues. The latter case is performed by changing the biotissue direction i.e., exposing flesh first, which is similar to an in-body communication from inside of a living being. The light first propagates thorough flesh and then escapes through skin tissue. We measured the received optical power for both cases and received more optical power in former case, the results are presented in following section.

C. TEMPERATURE

The temperature of living human being is approximately 37 ºC, but the temperature of the experimented porcine biotissue was 18 ºC when purchased. To match the temperature to that of a living being, the biotissues was heated. For this purpose, a plexiglass box containing the controllable air heater was constructed. The air temperature inside the box was controlled using a controller, as shown in Figure 5. We observed a change in the amount of received optical power with heated biotissues, in comparison to cold biotissue. The results are presented in the next section.

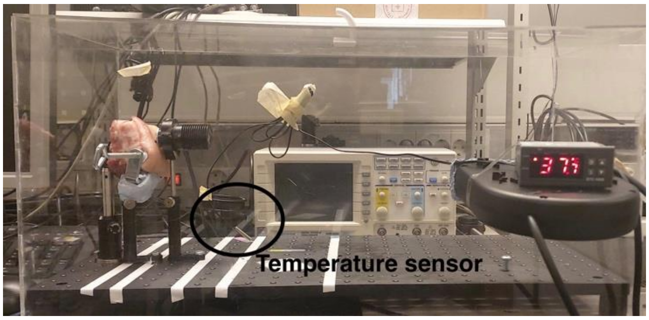


FIGURE 5. **Temperature control box.**

D. RESULTS

In this study, we transmitted several data files representing medical information payloads through samples of fresh porcine biological tissues. The files were successfully received and decoded by the receiving end. The link performance was estimated, and the throughput analysis is presented in Figure 6. An iPerf tool (available in Linux), which has been specifically designed to estimate the throughput performance, has been used. Reliability of the link is utmost when transmitting medical information, as any loss of information during data transmission could lead to a life-threatening situation. In order to test the reliability of the established optical wireless link, any loss of packets during transmission was estimated using the datagram protocol (UDP). 1470 bytes long datagrams were transmitted for 10 seconds duration, over the established optical link through *ex vivo* tissues. The throughput analysis shows that the network observes the packet loss once the offered load exceeds 0.7 Mbps, and the increase in throughput is not linear anymore with the load at this point to onwards. The network yields the maximum throughput of 95.5 Kbps. The repeated measurements revealed that a packet loss < 1% can be achieved during the operation. Additional use of redundancy can be used to increase reliability.

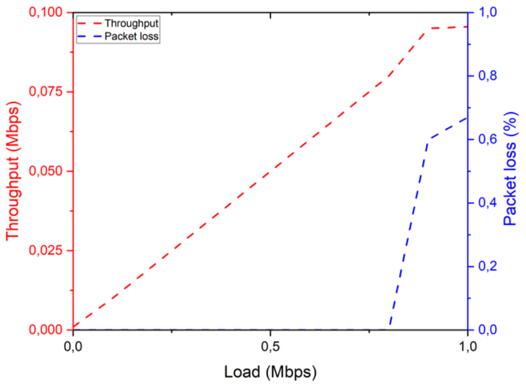


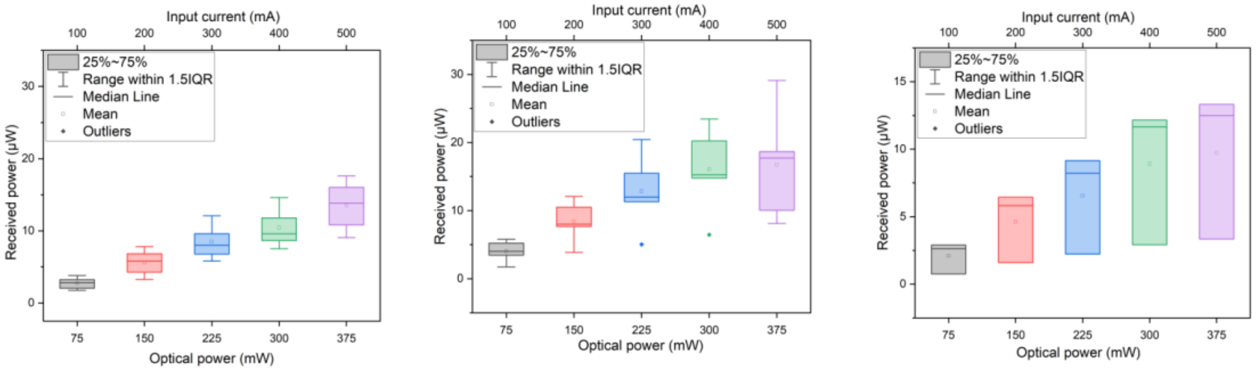
FIGURE 6. **Throughput analysis of the OWC link.**

The outcomes on the optical power versus the applied input current (input power) are also studied. The detector was placed at five different locations and the optical power was recorded at each involved location. Measurements were carried out to study the effect of the link range and the sample temperature on the quality of the link. We observed that an exposure of minimum of 20 % i.e., 75 mW of the maximum output power of LED which is 375 mW is required to transmit information through biological tissues. A comparison of an optical power applied versus the power received is presented in Figure 7. For both orientations i.e., skin-first and flesh-first, the received optical power is higher when the biotissues are heated (Figures 7b and 7e) in comparison to the case in which biotissues at kept at lower temperature (Figures 7a and 7d). This is because the heated biotissues are more transparent to light, which means that the light is less scattered when propagating though tissues, which have been heated in comparison to tissues, which are cold. Another comparison between the incident and received optical power is presented, in which the porcine sample is exposed again in two different orientations, namely flesh-first and skin-first. In this comparison, the difference in received and incident optical power is not huge. The received optical power in the skin-first orientation (Figures 7a and 7b) appears to be less than the received power measured in flesh-first orientation (Figures 7d and 7e). The possible reason for lower received power in skin-first setting is the reflection of light from the skin surface is relatively higher than in the case of the flesh. Thus, the communication from inside of the body to the outside is slightly more favorable, though the measurements support both directions. Finally, porcine samples were tested with and without bone. The received optical power measured in both skin-first (Figures 7a and 7c) and flesh-first (Figures 7d and 7f) orientations through 4.5 cm thick biotissues containing rib bone is lower than the power values obtained for the 5 cm thick sample, This is due to the presence of rib bone that attenuates the light more than flesh, skin or fat. These results suggest that communications can be established with IED placed deeper inside the body, i.e., hidden behind the bones. The *ex vivo* approach used in this study is in practice and extensively studied [37], the main changes between *in vivo* and *ex vivo* tissue are observed in the spectral regions dominated by hemoglobin and water (400-600 nm and 950-1500 nm respectively) [38]. This is explained by the change in the blood supply and loss of water associated with animal death. Our wavelength of 810 nm is out of these bands. Moreover, the utilized wavelength is close to the isosbestic point of 805 nm for oxy- and deoxyhemoglobin, which ensures the insensitivity of the obtained results to changes in blood oxygenation.

VII. DISCUSSION

In this proof of concept study, we focused on determining the feasibility of OWC in *ex vivo* tissue samples. After demonstrating that optical communication across fresh samples of porcine biotissues is feasible, we investigated the ranges and data throughputs that can be achieved through an *ex vivo* sample over an OWC link.

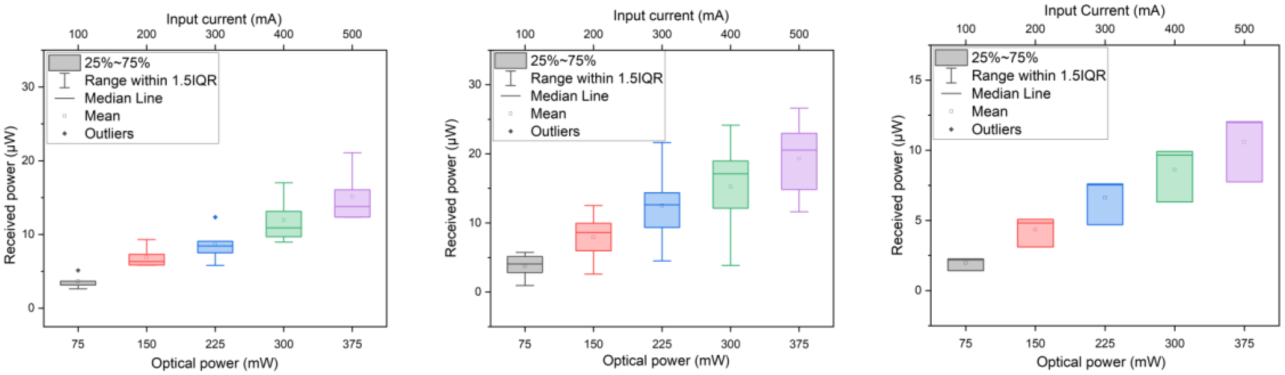
The wireless communication channels in the biotissues are different from those in free space due to, among others, the inhomogeneity of sample's composition. The inhomogeneity also hinders the propagation of optical carriers in in-body communication applications and thus, attaining a significant communication range is a challenge. Our initial results suggest that OWC delivers the signal to roughly the same depth as RF, with additional associated benefits of security and safety.



a) From outside to in (skin first) 5 cm thick meat piece at room temperature.

b) From outside to in (skin first) 5 cm thick meat piece when heated.

c) From outside to in (skin first) 4.5 cm thick with rib bone meat at room temperature.



d) From inside to out (flesh first) 5 cm thick meat piece at room temperature.

e) From inside to out (flesh first) 5 cm thick meat piece when heated.

f) From inside to out (flesh first) 4.5 cm with rib bone thick meat at room temperature.

FIGURE 7. **Optical link performance Comparison of received optical power versus applied input current to LED. The outcomes are from cold and heated porcine biotissues pieces and result from outside to inside and vice versa communications.**

Compared to ultrasound, OWC can operate in both contact (when LED is in contact with sample) and non-contact (when LED is placed away) modes. From the safety point of view, the applied optical power can be limited from the LED controller, while the OWC is inherently secure and well protected from eavesdropping and intentional attacks. The used *ex vivo* tissue samples used in the proof-of-concept setup came from an animal slaughtered roughly within 48 hours before the measurements.

The testbed shown above was implemented with mostly off-the-shelf equipment purchased from different vendors. A maximum data throughput of 95.5 Kbps was measured. However, the experimental limitations of the throughput were determined primarily by the maximum modulation frequency supported by the LED controller rather than by optical technology itself. Based on the optical power of the received signal, we expect that higher data rates can be attained. We utilized user datagram protocol (UDP) for testbed evaluation and found that packet drops lower than 1% can be accomplished, a promising Figure for OWC.

The demonstrated throughput is sufficient to communicate with implants placed even at nearly five centimeters depth. In practice, the communication system worked nearly similar in both directions of transmission, that is, when information is transmitted to or received from an EID.

OCBT has an excellent potential for future development and applications. Limitations in transmission rate and maximum penetration depth need to be studied extensively, and novel solutions to enhance the performance could be devised once the characteristics of the optical medium is well understood. Other areas for further studies include the use of other modulation schemes as well as multibeam transmission to increase the supported data rate. Pulsed communications could be used to increase the communication range. Also, diversity schemes can be used to increase the reliability of the optical link to the IEDs. The miniaturization of the OCBT to an implant-level is major leap that requires intention. The miniaturization involves discussing and finding practical solutions for many other key factors including overall device's power management, implant level optical front ends, encryption and so on.

VIII. CONCLUSION

In this paper, the feasibility of optical communications through the *ex vivo* biological tissues is experimentally demonstrated. Initial measurements of OCBT show promising results, indicating that distance exceeding four centimeters and data rate of at least 100 Kbps can be achieved. These Figures match the communications requirements of most of implantable electronic devices, with the additional advantage of high security, privacy and safety, features not necessarily present in RF communication systems. Based on the experiments, it is expected that, the communication performance can be further enhanced. OCBT technology lends itself to be miniaturized, a vital requirement needed for the communication system in order to be integrated into an IED. Finally, optical systems can be used in IEDs as a stand-alone communication technology or combined with other technologies (e.g., radio/acoustic) in order to create highly dependable systems.

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