Biodegradable Implant Antenna Utilized for Real-Time Sensing through Genetically Modified Bacteria

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***Abstract*—This work presents a wireless real-time sensing system. The sensing system consist of a bio-hybrid implant and a wearable reader antenna pair. The bio-hybrid implant has two parts: a biodegradable implant antenna and genetically modified bacteria. The biodegradable implant antenna operates as a passive reflector and genetically modified bacteria control the degradation speed according to the presence of a specific molecule of interest. As the implant antenna degrades, changes in its geometry shift its resonant frequency. This shift is tracked by the wearable reader antennas. Therefore, the presence of the molecule of interest can be wirelessly tracked in real-time from outside the body.**

***Index Terms*—implantable antennas, biodegradable antennas, real-time sensing, wireless sensing.**

I. INTRODUCTION

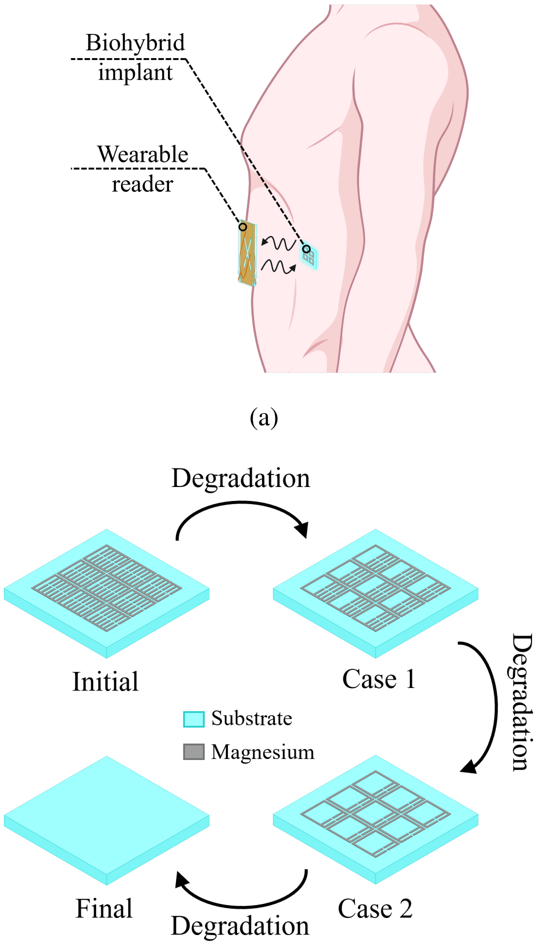
In the coming years, the rapid increase in the elderly population will lead to a demand for healthcare services that cannot be met. The solution to this problem is only possible through a revolution that will completely change the way we receive healthcare. For this technological revolution in healthcare to take place, it is necessary not only to transform our hospitals and homes but also our bodies. Constantly monitoring our well-being with various implant sensors, detecting health issues before symptoms arise constitutes a significant step in this technological revolution [1][2][3].

Taking a closer look at the sensors in the literature, we observe that these devices are used for monitoring, diagnosis, or treatment purposes [4][5]. Monitoring devices target various applications such as capsule endoscopy [6], brain-computer interfaces [7], glucose [8], pH [9], and intravascular pressure monitoring [10]. Most of these biomedical sensors have a limited lifespan due to their power requirements. The majority of these devices monitor non-specific physical parameters. For instance, real-time in-vivo sensors, such as electromagnetic wave-based glucose detection systems, have been proposed previously [11]. However, these sensors detect changes in the dielectric constant of tissue, which is a secondary effect of glucose concentration, meaning they do not provide molecule-specific detection. It is not possible to measure disease-specific biomarkers that may be needed for early diagnosis with the existing sensor technology. We have been working on utilizing engineered living cells to tackle this challenge [12]. Molecular-level detection has the potential to open entirely new doors for high-precision diagnostics [13]. Note that, electrochemical or nano-based biosensors with such molecular detection capabilities can be found in the literature [14]. However, these sensors are in-vitro sensors and, as they do not perform molecular detection in-vivo, they cannot provide real-time detection within the patient's body.

This paper proposes a wireless sensing platform for the detection of molecular biomarkers of diseases or the presence of any targeted molecule within the body. Synthetic biology has been revolutionizing healthcare with its capability of reprogramming living cells to be used as sensors [15]. The main challenge ahead for electronics engineers is to integrate the data these reprogrammed cells sense to our existing communications system. Here we demonstrate a novel method to how this integration can be achieved [16]. Escherichia coli, a widely used bacterium in synthetic biology, has been selected as the genetically modified bacteria for this demonstration. A bio-hybrid implant composed of genetically modified bacteria and a Mg-based biodegradable [17] passive antenna within the body is introduced along with a wearable antenna pair to monitor the the implant. From an electronic perspective, the implant is a passive reflector antenna that does not require a battery. From a biological perspective, it is composed of cells powered by ATP, our natural energy source within the body. The bio-hybrid implant concept had previously been published in [18] where the wireless link was based on the reflection coefficient of a single reader antenna. Here, we introduce a dual port wearable reader antenna pair and wirelessly track the bio-hybrid implant using the transmission coefficient between the reader antennas in order to increase the sensing depth.

The principle of operation for this proposal can be summarized briefly as follows: The presence of the molecule to be monitored within the body will trigger the genetically modified bacteria. The response of the triggered bacteria will change the degradation rate of the in-body passive antenna, and this change will be monitored by an external receiver-transmitter antenna pair. This study distinguishes itself from existing literature not just with its passive nature which eliminates the need for batteries, but also its biodegradability as well. The implant is going to disappear after completing its function. Note that the eradication of the engineered bacteria is another area of research which can be achieved through medication or thermal therapy. An overview of the proposed system can be seen in Fig. 1 (a).

In Section II, the sensing system and the electromagnetic



(a)

(b)

Fig. 1. (a) An overview of the system (b) the geometry of the implant antenna and the anticipated biodegradation pattern.

simulation setup are given. In Section III, the transmission coefficient between the wearable reader antennas is provided for various cases. Finally, the paper concludes in Section IV.

II. SYSTEM DESIGN

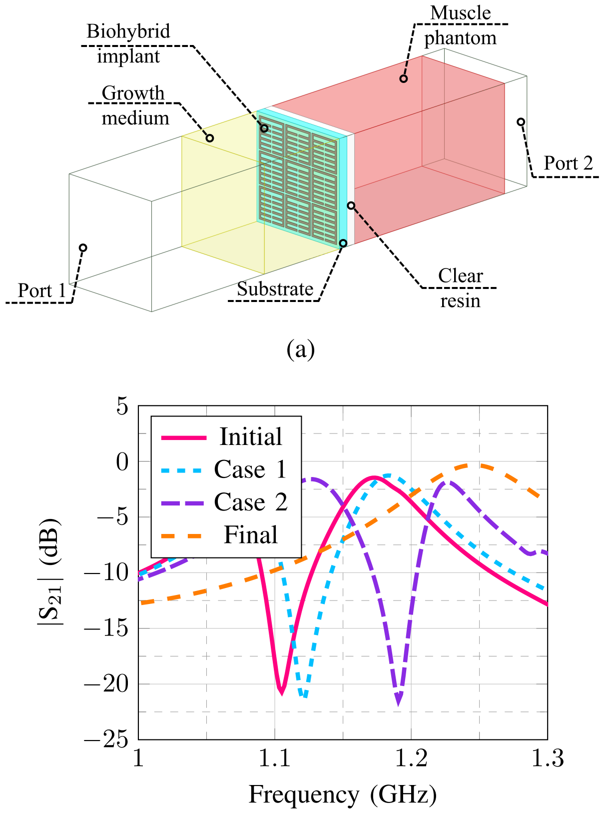
A. Wearable Reader Antennas

Since muscle tissue has a high dielectric constant, the electrical length between the implant and the reader antenna is much greater than its physical length. Therefore, even shallow implants such as subcutaneous implants, might fall outside of the near-field region of the wearable reader antennas operating in the GHz region. Although, in some cases, the changes in the implant antenna's resonance frequency might be tracked with the reflection coefficient of a wearable reader antenna, this solution limits the implant depth. Here, a pair of reader antennas, one serving as the transmitter and the other receiver, has been employed. By doing so, the tracking range is extended because now the change in the resonant frequency of the implant antenna is tracked using the transmission coefficient, which is sensitive to changes happening outside the near-field of the wearable antenna. On the other hand, the challenge in tracking with the transmission coefficient is that the conductivity of most tissues is high. The power level of the electromagnetic waves entering the body, reflecting off the implant, and reaching the receiver antenna is significantly lower compared to the direct coupling between the transmitter and receiver. Hence, using two orthogonal slot antennas has been preferred to reduce the direct coupling between the two. Finally, given that the electrical properties of body tissues can change over time and depending on where the wearable is located in the body, it is essential for the reader antenna to be broadband and capable of operating in the desired frequency range on various tissues with different permittivity values. Therefore, two wide slot microstrip patch antennas with orthogonal feeds have been employed. The detailed specifications of the reader antennas are provided in [19].

B. Implant Antenna

The implant antenna consists of an array of nested split-ring resonators (NSRR) as shown in Fig. 1 (b). An NSRR is a modified split ring resonator where the number of split gaps is raised to increase the capacitance and hence further miniaturize the structure [20]. Here the degradation takes place such that the number of split gaps are decreasing hence the operating frequency of the NSRR is increasing. To ensure the controlled degradation of the antenna, the rings of the NSRR structure shown in Case 1 in Fig. 1 (b) will be coated with Ti. It is expected that the coating will slow the degradation of Mg by limiting the attack for degradation to the sides. This design anticipates that the bottom rings will degrade earlier than the top rings. From now on, the states between the initial and the final states are called Case 1 and Case 2 where two rings and four rings degrades, respectively. Note that the implanted NSRRs cannot be accurately designed using analytical calculations due to the ambiguity in the effect of dielectric loading of the human tissues. Hence, to predict the resonant frequency of the implant antenna for each of its states, the implant antenna is located inside a waveguide loaded with the human muscle tissue phantom as seen in Figure 2 (a). The transmission coefficient between the two ports of the waveguide has the signature of the implant antenna. The waveguide simulations eliminate the effect of the reader antennas and provide good predictive values for the natural response of the implant antenna. Through these analyses, it is predicted that the implant antenna is going to have a resonant frequency between 1.1 GHz and 1.2 GHz as it degrades from its initial state to Case 2 as seen in Fig. 2 (b).

Subsequently, an experimental setup was designed to test the feasibility of tracking the implant's degradation with wearable reader antennas. The simulation model of the experimental setup is depicted in Fig. 3. The overall setup consists of a muscle phantom with electrical properties provided in the ANSYS material library, measuring $20 \times 20 \times 12$ cm^3 in size. Within the muscle phantom, a $4 \times 4 \times 5$ cm^3 bacterial culture medium has been defined, including the implant. The



(a)

(b)

Fig. 2. (a) The waveguide simulation setup to determine the resonance of the NSRR and (b) the transmission coefficient of the waveguide for different cases of the NSRR.

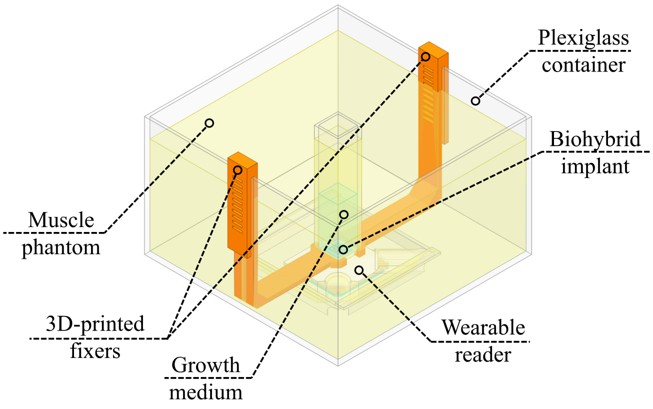


Fig. 3. The simulation model representing the set-up used to track the biodegradation in real-life applications

electrical properties of the culture medium were measured using SPEAG DAK 3.5, revealing a dielectric constant of 71 and conductivity of 2.9 S/m at 1.5 GHz. The implant is located at the base of the culture medium. The wearable reader antennas are located at the bottom of the muscle phantom. The distance between the reader antenna and the implant is set to 1 cm.

III. Results

Simulation results, mimicking the planned degradation stages of the implant, are shown in Fig. 4. It is observed that the implant's degradation can be monitored by examining the changes in the transmission coefficient between the ports of the wearable reader antenna. Fig. 4 (a) shows the magnitude of the transmission coefficient. The resonance of the initial state of the implant antenna is visible at 1.2 GHz. This resonance is shifting towards 1.3 GHz as the degradation occurs. Finally, the resonance is lost at the final stage where the implant completely degrades. Note that there is 100 MHz difference between the value predicted with waveguide simulations and the value observed in the overall setup. This is due to the existence of the culture medium container. Note that, differences are expected as the tissues and the location of the implant change. Hence, the wearable antenna is designed to operate at a large frequency band to mitigate these kind of obstacles. Fig. 4 (b) shows the phase of the transmission coefficient. A similar trend is observed in the phase plot as well, which can be used to support the results obtained from the magnitude plots.

The biodegradable implant antenna is prototyped with Mg which is a bio-compatible and biodegradable material. Due to the small feature size of the NSRRs, photo-lithography is required. The prototyping is being conducted in the clean room facilities of Bogazici University LifeSci. Note that the initial prototyping is being done on a borosilicate wafer. In the future, the prototyping is going to be done on a biodegradable substrate such as silk.

IV. Conclusion

In this study, a wireless sensing platform enabling real-time in-body molecular tracking has been presented. The platform consists of genetically modified bacteria and a biodegradable implant antenna used as a passive reflector. The presence of the molecule of interest triggers the genetically modified bacteria, which in turn alters the degradation rate of the implant antenna. The degradation rate of the implant antenna, hence the presence of the molecule, is monitored by wearable reader antennas. An array of NSRRs is modelled as the reflector implant antenna. The electromagnetic simulations have demonstrated that the degradation can be tracked at a depth of 1 cm within muscle tissue.

Acknowledgment

This work was supported by the Scientific and Technical Research Council of Turkey (TUBITAK) under Grant 120C131.

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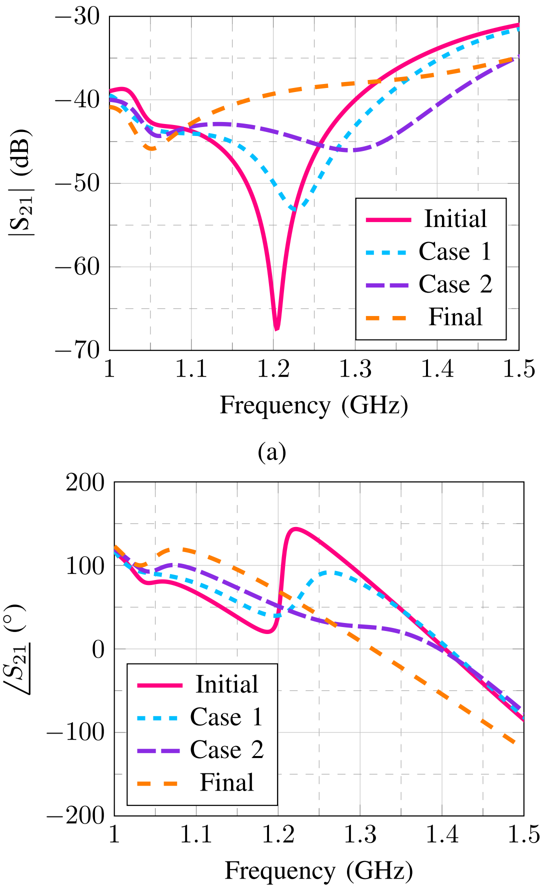

(a)

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Fig. 4. (a) Magnitude and (b) phase of the transmission coefficient between the wearable reader antennas as the implant antenna degrades.

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