A Repeater Antenna System Utilizing Genetically Modified Bacteria for Multiscale Communications

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***Abstract*— With the exponential advancements in communication technologies, synthetic biology, and nanotechnology, now it is time to aim high and design new generation of implants. To achieve this vision, this paper presents a novel sensing platform based on genetically engineered bacteria and a repeater antenna system, including a biodegradable in-body reflector antenna and on-body reader antenna. The biodegradation process is controlled by the engineered bacteria, which in the future will be utilized to sense a molecule of interest. The biodegradation, hence, the sensing can be wirelessly tracked. This paper presents the control of biodegradation experimentally by the engineered bacteria and show the wireless tracking numerically. The sensing at 2 cm implant depth in fat tissue in the 2.4 GHz ISM band is demonstrated.**

***Index Terms*—antennas, electromagnetics, propagation, measurements.**

I. Introduction

Over the years, there has been an increasing interest in wireless implants [1], [2]. These implants are aimed to be used for continuous monitoring of patients in real-time [2]. Early examples include capsule endoscopy, which does not require surgery for implantation, while a vast majority would do so for both insertion and removal. Biodegradable implants can partially tackle this problem by eliminating the need for a second surgery for removal [3], [4].

The biodegradable implants proposed in the literature are designed to degrade after fulfilling their function [5]. This proposal differentiates itself from state-of-the-art by taking advantage of the biodegradation process for the functioning of the implant while eliminating the need for removal surgery. To fulfil this goal, we genetically engineer bacteria to control the speed of biodegradation.

The implant is a hybrid device made up of a biodegradable in-body reflector antenna and a colony of engineered bacteria. Specifically, *Escherichia coli* (*E. coli*), a significant workhorse of synthetic biology is selected due to its ease of genetic manipulation and relatively well-understood gene-regulatory circuits [6].

In our set-up, it is envisaged that the bacterial degradation of the in-body reflector antenna is conditioned on the presence of the molecule of interest. This molecule could be an output of a biological process, or a chemical used in molecular communications. When the molecule of interest reaches to a certain threshold level in the medium, the engineered bacteria are triggered, and the in-body antenna biodegradation speed increases, which can be wirelessly tracked by an on-body antenna. Thus, the implant (in-body reflector antenna and colony of engineered bacteria) together with the on-body reader antenna, the antenna translates the molecular signal to a conventional wireless link.

In Section II, we introduce the details of the engineered *E. coli* bacteria. Section III discusses the in-body biodegradable reflector antenna and the wearable reader antenna, and the in-body link is numerically analyzed. Section IV concludes the work.

II. Genetically Modified *E. Coli* and Its Interaction with Magnesium

A. Design of Genetically Engineered Bacteria

Magnesium (Mg), iron (Fe), and zinc (Zn) are the most common types of biodegradable metals used for biomedical research. Of the three, Mg is the most extensively studied owing to its higher degradation rate *in vivo* compared to Fe and Zn [7]–[9]. Mg degradation *in vivo* involves a series of redox reactions. When Mg comes into contact with body fluids, it is oxidized to Mg cation and generates electrons. These electrons react with water to produce hydrogen gas along with hydroxide [10], [11]. Reacting with hydroxide, Mg forms a protective layer of $Mg(OH)_2$. This layer, however, erodes over time as chloride ions react with magnesium, forming $MgCl_2$ [11]. In later stages, accumulation of hydroxide in the vicinity of Mg implant alkalinizes the environment and leads to oversaturation of calcium and phosphate ions [10]. As a result, a calcium phosphate precipitate forms on the metal oxide layer, attracting cells to the site [10]. Aggregated cells produce more degradation products on the substrate surface, which leads to peeling off of larger chunks of metal and exposure of a fresh metal layer for a new round of degradation [10].

Bacteria of the genera Shewanella and Geobacter are naturally capable of reducing solid metal oxides [12]. These electrogenic bacteria use electron transfer to communicate with their surrounding [13]. By donating electrons to the electron acceptors, these bacteria may control the degradation rates of different types of metals [12]. We created an

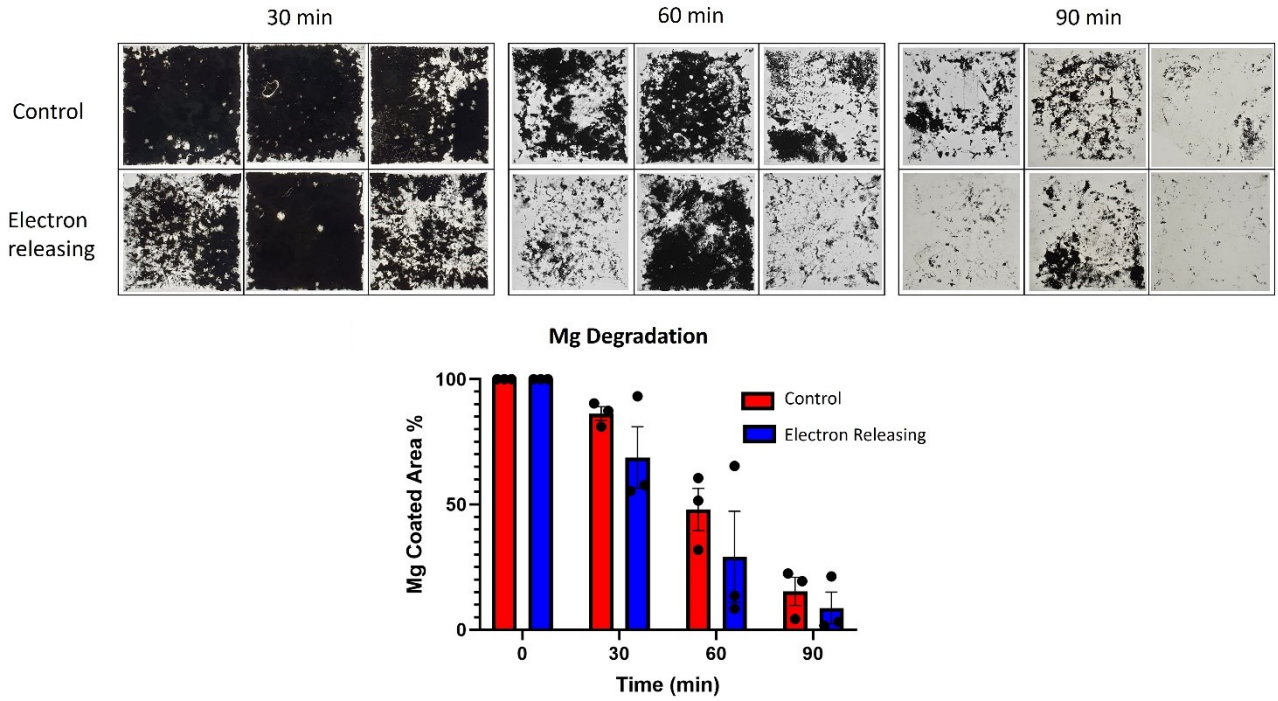

Fig. 1. Bacterial degradation of Mg-coated coverslips and graphical representation of decrease in Mg-coated area depict the decrease in Mg-coated area in. Mg biodegradation occurs faster with engineered bacteria expressing electron conduit proteins. According to the vision mapped here, the degradation speed will be linked to the arrival of the molecule of interest

electrogenic strain of Escherichia coli by transferring the electron conduit system of Shewanella. This strain established the starting point for our Mg biodegradation experiments. In later stages, we plan to integrate a metabolic sensor circuit into such electron releasing systems, thus creating a strain that conditionally releases electrons when the molecule of interest is present.

B. Degradation Experiments

To test the bacterial degradation of Mg, we first coated 20 mm x 20 mm glass coverslips with Mg using a magnetron sputtering system. We have grown electrogenic (electron releasing) and non-electrogenic (control) bacterial strains in Luria- Bertani medium supplemented with sodium sulfite at 37°C for 16 h. At the end of the incubation cycle, bacterial cultures were spun at 8000 rpm for 5min. Bacterial pellets were then resuspended in MOPS Minimal Medium containing 0.2% glucose and 0.03% sodium sulfite. Following a 30 min induction at 37°C, the bacteria-containing solutions were added on Mg-coated coverslips in 6-well plates (3 coverslips per bacterial strain). Over the course of a 1.5h long biodegradation experiment, coverslips were briefly removed from the wells every 30 min, placed on LED panels and photos were taken (Fig. 1a). Mg degradation was later analyzed on ImageJ by converting the coverslip image into a binary image, thresholding and counting black and white pixels (Fig. 1b). Analysis indicated Mg degradation occurs faster with electron-releasing bacteria.

III. WIRELESS TRACKING OF BIODEGRADATION

A. In-body Biodegradable Reflector Antenna

The reflection characteristics of the reader antenna are affected by the interaction between the in-body reflector antenna and the on-body reader antenna. As the in-body reflector antenna degrades, a shift in the resonant frequency of the reader antenna will be observed. Here, the in-body antenna is envisaged to be a meandered strip. Fig. 2 shows the initial form of the in-body antenna and its final form after complete degradation.

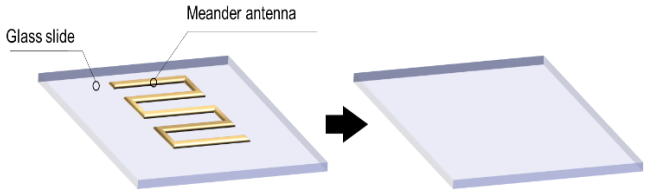

Fig. 2. Schematic representation of in-body reflector antenna before and after degradation.

The size of the initial form is calculated using (1) and (2) where ϵ_{eff} is the effective permittivity and λ_g is the guided wavelength at the frequency of operation of the antenna. The effective permittivity is a value between the relative permittivity of the 0.5 mm thick glass substrate ($\epsilon_{eff} = 6$) and the exposed tissue of fat ($\epsilon_{eff} = 5.2853,\ \sigma =$

0.10235 S/m). The width of the strip is taken to be 10 mm, while the non-meandered length is 6 cm. The final dimension of the implant is 10 mm x 13 mm.

$$l = \frac{\lambda_g}{2} \quad (1)$$

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}} \quad (2)$$

B. Wearable Reader Antenna

A meander slot antenna is designed to operate at the 2.4 GHz ISM band on 1.28 mm thick Rogers RO3010 substrate with a relative permittivity of 10.2. The ground is then directly located on the surface of a 10 cm x 10 cm x 4 cm fat block in which the in-body antenna is implanted. All design parameters are optimized by using ANSYS HFSS, and the final dimensions obtained can be seen in Fig. 3.

Due to the no magnetic losses of the tissues ($\mu'' = 0$), the high magnetic near fields are more resistant against dissipation in the human body [13]. Therefore, magnetic antennas are often preferred for implant communications. The circumference of the loop antenna can be calculated only if we know the filling factor (ff), hence effective permittivity and the meandering factor. Here we empirically found both values. First, a non-meandered loop antenna is matched at 2.45 GHz on fat tissue and the circumference hence λ_{guided} is found to be 51 mm. Using (3), effective permittivity is found to be 5.7, which corresponds to an ff value of 0.51 which is calculated using (4) [14]. Finally, the antenna is miniaturized through meandering, with a meandering factor of 0.86.

$$\lambda_{guided} = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}} \quad (3)$$

$$\epsilon_{eff} = \epsilon_R * ff + (1 - ff) \quad (4)$$

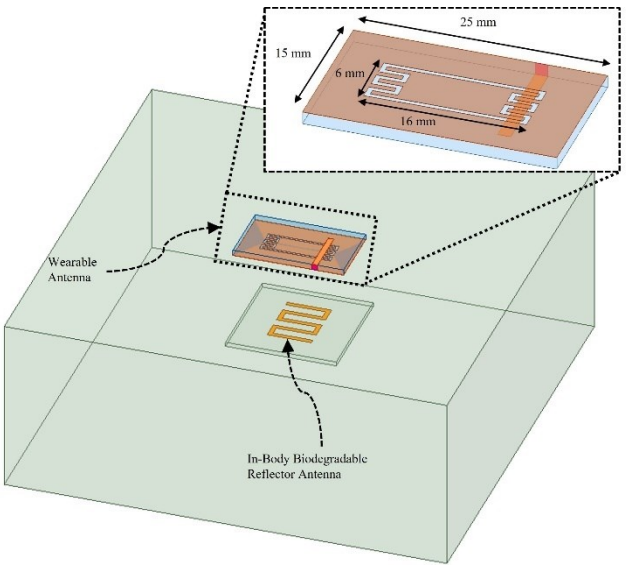

Fig. 3. HFSS model of the overall setup

C. Results

The tracking is numerically modelled and analyzed, as shown in Fig. 3. The in-body reflector antenna is implanted inside a fat block at a depth of 2 cm. The reader antenna is directly located on the fat block as described in Section III-B. The change in the reflection characteristics of the on-body reader antenna can be seen in Fig. 4 as the in-body antenna degrades.

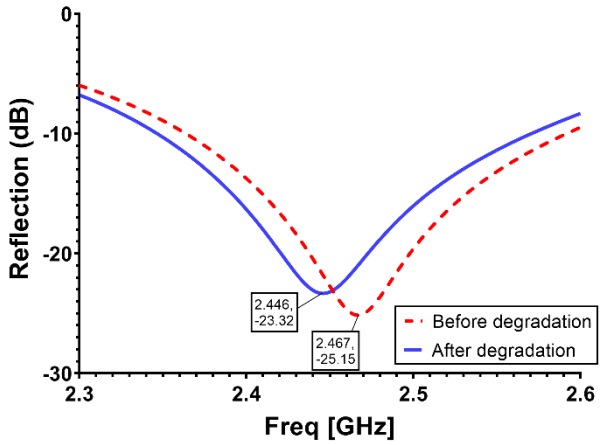

Fig. 4. The |S11| of the on-body reader antenna

IV. CONCLUSIONS

This study presents a novel sensing platform based on genetically engineered bacteria and a repeater antenna system. The repeater antenna is composed of an in-body biodegradable reflector antenna and a wearable on-body reader antenna. The bacteria are engineered to control the degradation speed. The degradation speed of the biodegradable reflector antenna is wirelessly tracked by the on-body reader antenna. To sum up, we benefit from the degradation process to proceed with the sensing task.

The bacteria used here are electrogenic strains that release free electrons to the environment. It has been shown via numerical analysis that the tracking is possible at an implant depth of 2 cm in fat tissue. Note that the presented work demonstrates the preliminary results.

The future work involves a repeater antenna system design for different depths and tissues, prototyping measurements, and optimizing the magnesium thickness and the overall degradation duration. Moreover, we intend to add a metabolic sensor circuit into these electrogenic bacteria for triggered electron release in response to the molecule of interest. The implant and wearable antenna designs can also be improved by selecting different resonating structures.

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