In-body Antenna Design for Wireless Hip Implants

Ahmet Bilir
Electrical and Electronics Engineering
Bogazici University
Istanbul, Turkey
ahmet.bilir@boun.edu.tr

Sema Dumanli
Electrical and Electronics Engineering
Bogazici University
Istanbul, Turkey
sema.dumanli@boun.edu.tr

***Abstract*—In this paper, an implant antenna to form a wireless link for a hip implant equipped with sensor technology to prevent mechanical overload is presented. The antenna is located in the ceramic head so that the integrity of the titanium femoral stem surface is protected and the antibacterial properties of the overall implant are maintained. The antenna is a conformal patch operating in the 2.4 GHz ISM band. The transmission coefficient between the implant antenna and an off-body antenna located 4 cm away from the human body surface is more than -65 dB where the implant depth is approximately 9 cm.**

***Index Terms*—implant antenna, in-body communications, orthopedic implants**

I. Introduction

Total hip replacement is a remarkably successful treatment method for patients suffering from severe hip joint diseases such as osteoarthritis [1]. The average cost of a primary total hip replacement in Europe was €5043 in 2008 [2] while around 3.1 million replacement surgeries were conducted in 2018 [3]. Due to aging population, more operations are anticipated to increase over the next decades . For instance, the number of primary total hip replacement has been estimated to grow by 134% from 2012 to 2030 in England and Wales [4], 29% from 2016 to 2040 in Germany [5], and %25 from 2010 to 2030 in Sweden [6].

Although total hip replacement is a highly effective treatment for reducing pain and restoring functional ability, many hip replacements require revision surgery. The primary cause for the revision of the replacements are infection, aseptic loosening, and dislocation [7]. Moreover, the success rate of subsequent revisions declines after the primary replacement fails. In [1], by using data obtained from National Joint Registry, it was found that approximately one fifth of the first, second, and third revisions were revised within 15, 7, and 3 years, respectively. If the initial revision is postponed by just a few years, the re-revision cycle could be avoided [8], which can be achieved by the advancements in the implant design.

A hip implant equipped with sensors monitoring the implant's performance continuously can detect the complications early on. Precautions may be taken to avoid these failures that can lead to revision surgeries. Hence, the life span of the implant might be increased and the life quality of the patient can be improved [9].

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Even though instrumented hip implants with wireless data transfer have been studied for in-vivo sensing of force and moments [10], temperature [11], vibration [12], [13], and infection [14], the studies investigating the wireless communication aspect of the implant are limited. The wireless communication link between a hip implant and the outside world plays an important role on the overall performance of the implant with a direct effect on the battery lifetime and reliability of the data. However, it is challenging to establish a wireless link between the implant antenna and the off-body reader antenna due to the high conductivity of the human body tissues [15]. Therefore, the implant antenna design is critical to increase the signal to noise ratio. The examples in the literature for this application is limited to [16], and [17]. In [16], the stripped coax monopoles operating at 433 MHz were used as the implant and external antennas. In [17], a cornered shallow cavity backed slot antenna operating at 2.4 GHz was utilised to evaluate the quality of the link. In addition, some techniques that use passive sensors have been proposed in the literature. As an example, in [18], a space-filling curve-based sensor based RFID transponder is used to detect micro-cracks over metallic hip implants.

In this paper, a conformal patch antenna operating in the 2.4 GHz ISM band to form a wireless link between a hip implant and the outside world is proposed. Section II explains the antenna design. The antenna performance are discussed in Section III. Lastly, the conclusion is given in Section IV.

II. Antenna Design

The orthopedic implant used in our design is an adult size titanium implant with a ceramic on metal head as seen in Fig. 1. The implant consists of a Ti-alloy femoral stem, a modular ceramic head, a PET insert, and a Ti-alloy acetabular cup. The antenna is located in the ceramic head since the closed conductive surface of the stem acts as a Faraday Cage for the electromagnetic transmission. Opening a slot on the stem surface is not acceptable due to bacterial growth concerns. The integrity of the stem surface should be protected.

A low-loss ceramic with a relative permittivity of 15 is used as the substrate for the patch antenna. The ceramic head is envisaged to be double layered to support both the ground and the radiating surfaces of the patch antenna.

The antenna design flow starts with a planar antenna design as seen in Fig. 2 (a). After the first optimization, the antenna

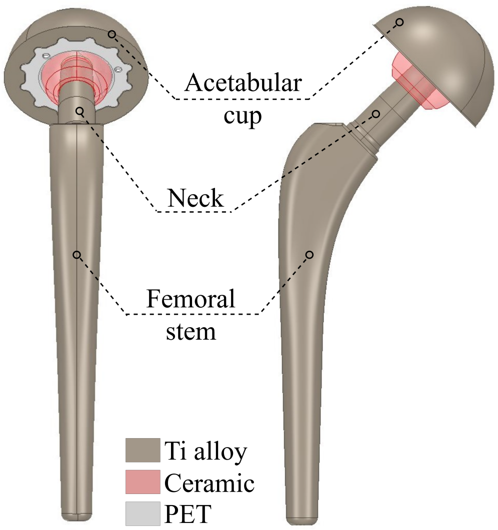


Fig. 1. The hip implant model.

is conformed to the spherical surface of the ceramic head as seen Fig. 2 (b). Finally, the antenna is moved into a realistic scenario as seen in Fig. 2 (c) and optimized for the last time. The final dimensions of the implant antenna can be seen in Fig. 3. The distance between the ground and the patch is 3.4 mm. The PET insert and titanium acetabular cup are hidden from the view for demonstration purposes. The acetabular cup work as a reflector, hence the wireless link between the implant and the reader antenna is improved.

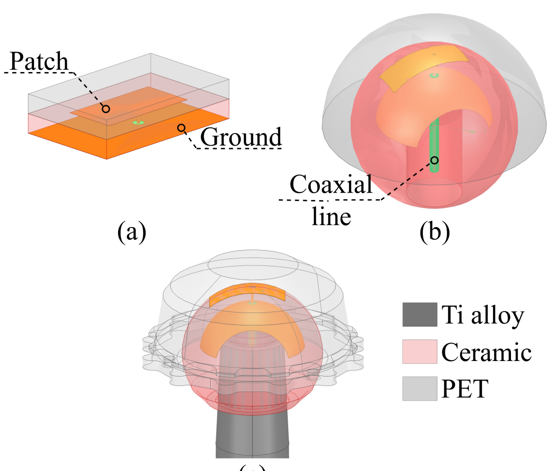


Fig. 2. The design steps of the implant antenna: (a) planar patch antenna with ceramic and PET as substrate and superstrate, (b) conformal patch antenna, and (c) final antenna design placed in the modular head of the hip implant. Ti-alloy acetabular cup is hidden for demonstration purposes.

The antenna and the hip implant are located inside the 2 mm accurate ANSYS Human Body Phantom consisting of two different frequency-dependent material definitions: human average and human bone cortical. The phantom is physically modified to decrease the computational cost of the simulation

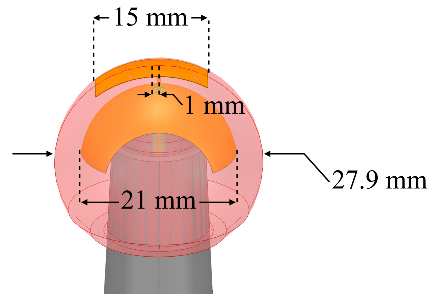


Fig. 3. The implant antenna geometry. (The PET insert and titanium acetabular cup are hidden from the view for demonstration purposes.)

as seen in Fig. 4. The transmission performance is analyzed using an off-body reader which is a conventional rectangular patch antenna located 4 cm away from the human body surface. The dimensions of the off-body reader antenna are 38 mm $\times$ 48 mm $\times$ 1.6 mm and the substrate is chosen as a high permittivity low-loss dielectric, RO3210 ($\varepsilon_r = 10.2$ and $\tan\delta = 0.003$), in order to minimize the off-body reader antenna's dimensions. The depth of the implant antenna is approximately 9 cm.

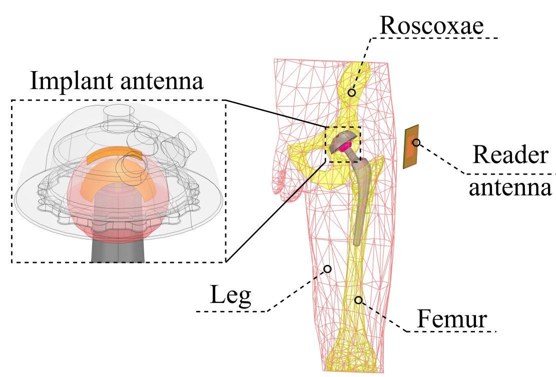


Fig. 4. The simulation model to test the transmission performance of the system.

III. Antenna Performance

The reflection coefficients of the implant and the off-body reader antennas are given in Fig. 5. Both antennas operate in the 2.4 GHz ISM band. Since the antenna is designed on high permittivity ceramic substrate, the bandwidth of the implant antenna is expected to be narrow. To mitigate this issue, the substrate thickness is increased by multiple-layer ceramic head design. For the dimensions given in Fig. 3, the bandwidth of the implant antenna is approximately 40 MHz. The communication can be established at the higher channels of the Bluetooth standard.

The transmission performance between the implant and the off-body reader antenna depends on the polarization matching of the antennas and their alignment. In order to test the transmission performance between the antennas, the model in Fig. 4 is simulated with various off-body reader antenna orientations as seen in Fig. 6. Note that the off-body antenna

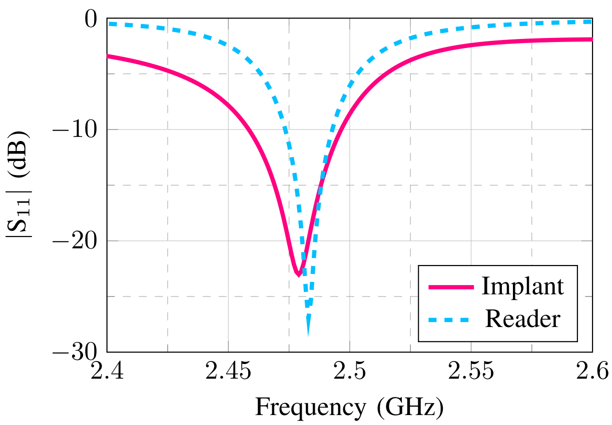
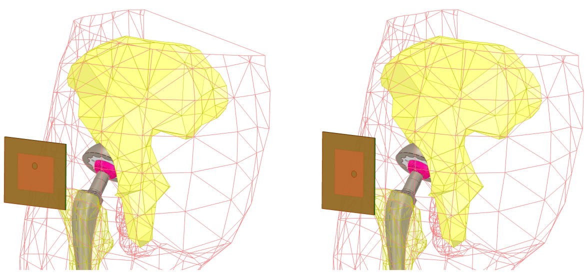


Fig. 5. The reflection coefficients of the implant and the reader antennas.



(a) (b)

Fig. 6. The simulation models to test the transmission coefficient performance for different reader antenna orientations, (a) 0° and (b) 90°.

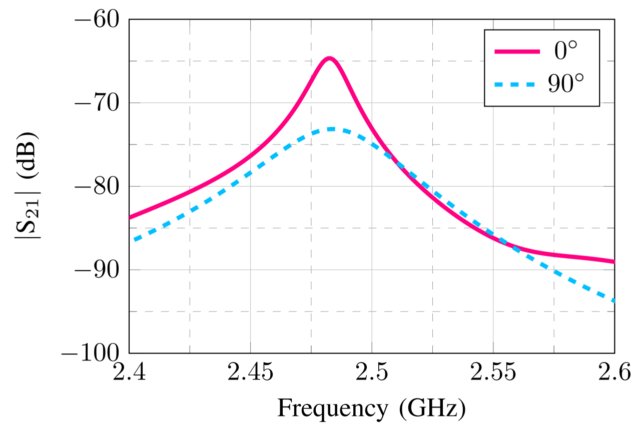


Fig. 7. The transmission coefficients between the implant and the reader antennas for the models given in Fig. 6.

is positioned according to the maximum radiation direction of the implant antenna.

The transmission coefficients for these cases are given in Fig. 7. Due to the polarization mismatch between the implant and the off-body reader antenna, the transmission performance for the 90° oriented case is worse than the 0° oriented one. For the 0° case, the transmission coefficient at 2.48 GHz is -64.6 dB. Also, since the radiation pattern of the implant antenna is directive due to the Ti-alloy acetabular cup reflector, the misalignment between the implant and the off-body reader antenna has a stronger effect on the transmission performance.

IV. Conclusion

In this paper, a conformal patch antenna used to form a wireless link for a hip implant equipped with sensors is proposed. The antenna is positioned in the modular ceramic head of the hip implant in order to maintain the antibacterial properties of the Ti-alloy femoral stem. The Ti-alloy acetabular cup is used as a reflector to improve the transmission performance of the implant antenna. The antenna operates in the 2.4 GHz ISM band and the transmission coefficient between the implant antenna at a depth of approximately 9 cm and an off-body reader antenna located 4 cm away from the human body is more than -65 dB.

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