Wireless Data Transmission from Smart Urinary Catheters Using Additively Manufactured Bluetooth® and NFC Antennas

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Abstract

Reusable "smart" urinary catheters have the potential to enable longitudinal urinary health monitoring through integrated sensing and wireless communication of biomarker data collected during catheterization. In this work, Bluetooth® and Near Field Communication (NFC) antennas were designed, additively fabricated, and characterized for integration within a "smart" catheter system capable of measuring bladder temperature and pressure. The antennas were fabricated on flexible PET substrates using aerosol jet printing with silver nanoflake ink. The experimental results of testing optimized antenna designs yielded a Bluetooth® antenna with a resonance maximum near 2.4 GHz and an NFC antenna with an inductance of approximately 4 μH near 13.56 MHz, in good agreement with electromagnetic simulations. The demonstrated performance validates additive printing as a suitable fabrication approach for compact flexible RF structures and establishes a pathway toward future Internet-of-Medical-Things (IoMT)-enabled urinary monitoring systems.

Key words

Wireless Data Transmission, Bluetooth® Antenna, Near Field Communication (NFC), Smart Catheter

I. Introduction

Urinary tract infections (UTIs) are among the most common bacterial infections worldwide and occur at high rates in individuals who undergo frequent catheterizations. Patients with spinal cord injury or disease (SCI/D) are particularly susceptible to catheter-associated urinary tract infections (CAUTIs) due to frequent catheter insertion, bacterial colonization, and impaired sensory feedback that often delays symptom recognition. Advanced infections frequently require clinical intervention and contribute significantly to healthcare costs, reduced quality of life, and increased hospitalization rates. As a result, there is growing interest in technologies that enable more frequent and/or continuous monitoring of urinary health markers in high-risk patient populations[1, 2].

Conventional urinary health assessment primarily relies on episodic clinical testing and laboratory urinalysis, which provide only isolated snapshots of a patient's physiologic condition. Such approaches are often insufficient for individuals requiring frequent catheterization because pathologic changes may occur rapidly between clinical visits. A promising solution is the development of reusable "smart" urinary catheters capable of acquiring, storing and transmitting clinically relevant data during routine catheterization procedures. Examples of relevant data include bladder temperature and pressure, urine pH, and leukocyte esterase concentration[3].

We previously demonstrated the proof-of-concept functionality of a reusable "smart" urinary catheter by integrating sensing modalities within a reuseable FDA-approved catheter design. This Flexible Hybrid Electronic (FHE) smart catheter system was designed for compatibility with repeated cleaning and disinfection cycles while operating within the dimensional constraints of a standard 14 Fr catheter design. The resulting prototypes established the feasibility of an intelligent urinary monitoring system for the longitudinal study of patients requiring frequent intermittent catheterizations[4].

Implementation of a fully integrated smart catheter requires not only on-catheter sensing, but also reliable wireless data transfer. During catheterization, physiologic data must first be acquired and temporarily stored in on-catheter electronics. Data is then transferred to external devices for storage, clinician access, and analysis. Discreet, wireless, off-loading of catheter-stored data is necessary because of the limited on-catheter space available for memory and computational hardware; the need to restrict patient access to sensitive information; minimization of patient involvement in the process; and the need for rapid access and remote monitoring capabilities for healthcare providers[5].

Wireless communication from urinary catheters presents significant packaging challenges due to the small catheter geometry, limited conductor routing area and antenna size requirements. Additive manufacturing methods, particularly aerosol jet printing (AJP), provide an efficient approach for fabricating high-resolution electronic circuits on flexible substrates. AJP enables easily customizable micro-scale circuit features deposition, multilayer interconnect formation, and conformal fabrication, on temperature-sensitive materials without requiring expensive, photolithographic and circuit plating or etching fabrication methods. In addition, silver nanoparticle and nanoflake conductive inks have demonstrated suitability for printed RF applications including antennas, transmission lines, and passive microwave components[6-10].

To enable wireless transfer of sensed data from the smart catheter to external networks, we designed and additively fabricated both Bluetooth® and Near Field Communication (NFC) antennas. Bluetooth® provides mid-range connectivity to smartphones and clinician-accessible platforms, whereas NFC enables low-power short-range communication for secure data transfer via range-limited device pairing.

In this work, we present the design, fabrication and characterization of Bluetooth® and NFC antennas specifically developed for integration into reusable smart urinary catheter systems. Both antennas were fabricated on 5-mil-thick polyethylene terephthalate (PET) substrates using aerosol jet printing with Novacentrix nanoflake silver ink. A 2.4 GHz inverted-F Bluetooth antenna and a 13.56 MHz square-loop NFC antenna were optimized to satisfy the dimensional constraints imposed by catheter packaging while maintaining robust wireless performance.

The remainder of this paper is organized as follows. Section II describes the design and optimization of the Bluetooth® and NFC antennas for smart catheter integration. Section III details the additive fabrication process using aerosol jet printing. Section IV presents the experimental characterization and wireless performance evaluation of the fabricated antennas. Section V concludes the paper.

II. Design and Simulation

Both antennas were designed for additive fabrication on 5-mil-thick PET substrates. PET was selected because it is flexible, inexpensive, chemically stable, thermally stable up to the temperatures required for ink and dielectric materials curing, biocompatible, and unaffected by repeated catheter cleaning and disinfection procedures. Also, PET exhibits favorable dielectric properties for printed RF devices while maintaining the flexibility required for conformal integration into our urinary catheter electronics module. The proposed location of the antenna on the electronics housing unit is shown in Figure 1

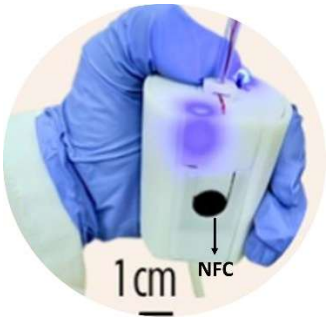


Figure 1: Proposed location on the electronics housing unit.

A. Bluetooth® Antenna Design

Among the candidate antenna topologies evaluated, the inverted-F antenna (IFA) architecture was selected due to its compact footprint, low-profile geometry and widespread use in miniaturized wireless devices. The folded conductor structure of the IFA enables resonant operation while reducing the overall antenna dimensions compared to conventional monopole designs, making it well suited for integration within the limited space available in the urinary catheter electronics housing. Also, the IFA provides acceptable impedance matching characteristics while maintaining compatibility with flexible fabrication methods. This antenna was implemented as a multilayer structure consisting of a 10 µm-thick printed silver ground plane, a 125 µm-thick PET dielectric layer and a 10 µm-thick silver radiating element. Electrical connection between the radiating element and ground plane was achieved using laser-drilled silver-filled vias. This multilayer architecture enabled compact integration while preserving the mechanical flexibility required for urinary catheter applications. Multiple antenna geometries were designed and iteratively optimized using full-wave electromagnetic simulations in Ansys HFSS. The design iterations were performed to maximize radiation efficiency near 2.4 GHz while maintaining compatibility with the dimensional constraints imposed by catheter integration. The resulting antenna exhibited a compact footprint of approximately 20 mm × 20 mm, making it suitable for integration within the smart catheter platform. Simulation results predicted

resonance within the 2.4 GHz ISM band with acceptable impedance matching and stable radiation characteristics, indicating the suitability of the antenna for wireless data transfer applications. Figure 2 shows the design and simulation for the proposed antenna.

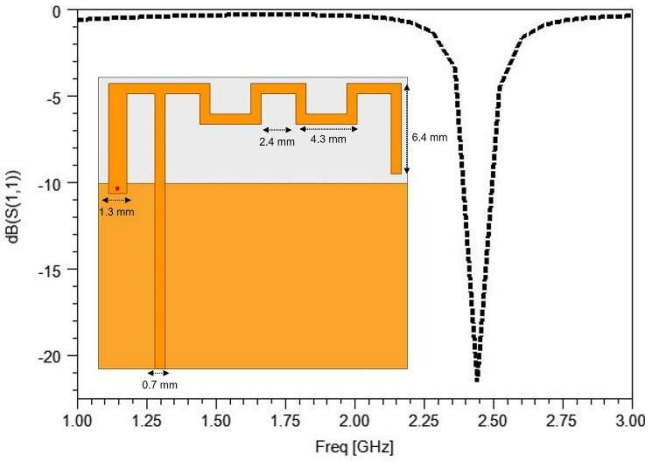


Figure 2: Design and simulation for the proposed antenna

B. NFC Antenna Design

NFC was introduced to provide short-range wireless communication for secure data retrieval and limited-range device pairing. NFC offers several advantages for medical devices, including low power consumption, rapid data exchange, and compatibility with commercially available smartphones and medical readers. These capabilities make NFC well suited for post-catheterization data transfer.

The NFC antenna was designed as a square-loop structure operating near 13.56 MHz. The antenna was implemented as a multilayer printed structure on PET consisting of a 10 µm-thick silver conductor layer, a 125 µm-thick PET substrate, and a dielectric bridge composed of approximately 200 µm thick NEA-121 dielectric material. The dielectric bridge enabled conductor crossovers while preserving electrical isolation and maintaining a compact layout.Multiple antenna geometries were designed and relative performances evaluated using electromagnetic simulations (modeling) to achieve the target inductance and resonant frequency required for NFC operation. Design iterations focused on optimizing loop dimensions, conductor widths and trace spacing to maximize magnetic coupling efficiency within the NFC operating range. Figure 3 shows the design and simulation for the proposed NFC antenna.

Antenna performance was then evaluated experimentally, and results were used to inform additional design revisions. The final antenna design incorporated a trace spacing of approximately 100 µm, enabling miniaturization while remaining dimensionally compatible with aerosol jet printing fabrication processes.

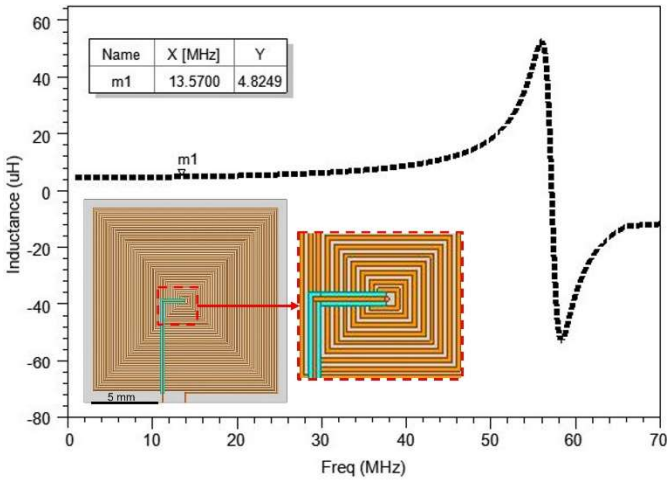


Figure 3: Design and simulation of the NFC antenna

III. Fabrication

The Bluetooth® and NFC antennas were fabricated using AJP which is an additive manufacturing technique (printing) capable of producing high-resolution conductive features on flexible substrates without requiring photolithography or subtractive processing. AJP offers several advantages for FHE circuit fabrication including micron-scale feature resolution, compatibility with a wide range of functional inks, and the ability to fabricate multilayer structures on temperature-sensitive substrates. These capabilities make AJP particularly well suited for wearable and biomedical devices where flexibility, miniaturization, and rapid prototyping are required. All antenna structures were fabricated using an Optomec AJP-3X system under ambient laboratory conditions. The printing process employed pneumatic atomization to generate aerosolized droplets of conductive or dielectric inks. The “jet” of ink droplets was then focused by a sheath gas surrounding the ink jet nozzle enabling the jet to pattern-print the conductor and dielectric features of the antenna circuit. The non-contact nature of AJP minimizes substrate damage and enables multilayer fabrication on thin polymer films, making it well suited for manufacturing electronics on flexible catheter-compatible substrates. Figure 4 gives an illustration of the AJP workflow.

Prior to printing, PET substrates were cleaned with isopropyl alcohol, air-dried and mounted on the heated platen of the Optomec AJP-3X system to improve adhesion and printing quality. Novacentrix Metalon® nanoflake silver ink was chosen to print the conductive traces and antenna elements due to its high conductivity, compatibility with AJP, and suitability for high-frequency applications. After curing, the ink provided excellent electrical performance while maintaining flexibility for device conformance. Multiple stacking print passes produced silver traces approximately

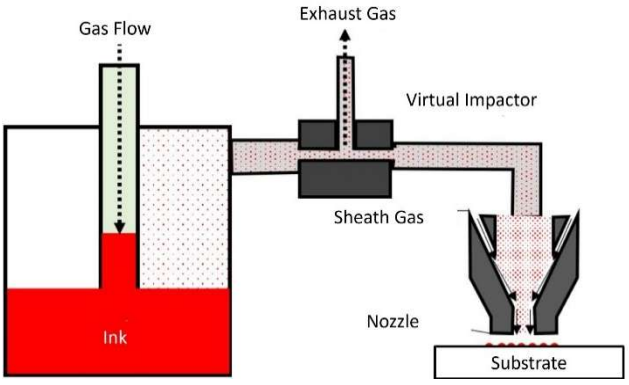


Figure 4: AJP Workflow illustration[11]

10 µm thick. For the NFC antenna, a multilayer conductor circuit was achieved by printing ~200 µm thick NEA-121, a UV-curable dielectric material, over a portion of the antenna circuit to form a dielectric bridge across the antenna which allowed an additional antenna circuit line to be printed across this bridge while remaining electrically isolated from the antenna circuit lines beneath the bridge. Both antennas were connected to the ground plane through low-resistance silver-filled vias This bridging approach eliminated the need for additional drilling or lamination, simplifying fabrication and enabling rapid prototyping. After printing, the silver structures were thermally cured to remove solvents and enhance particle sintering, improving conductivity. The fabricated antennas exhibited accurate geometries, strong substrate adhesion, and maintained flexibility under bending without cracking or delamination. Figure 5 and 6 show the fabricated both antenna samples Bluetooth and NFC.

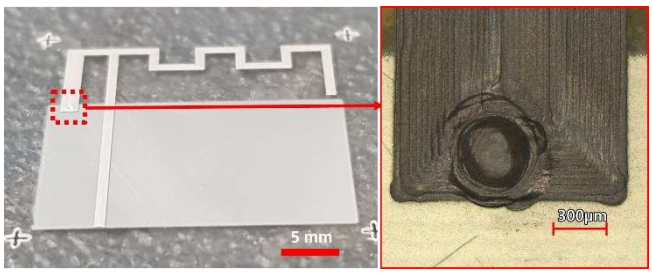


Figure 5: Fabricated Bluetooth Antenna with 300 umVia

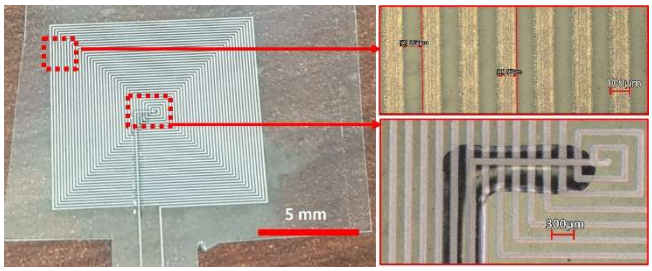


Figure 6: Fabricated NFC Antenna with dielectric bridge

IV. Tests and Results

RF measurements were performed on the fabricated devices to evaluate the resonant frequency of the Bluetooth® antenna and the inductance characteristics of the NFC antenna. Experimental measurements were compared with electromagnetic simulation results to assess the effectiveness of both the antenna designs and the additive manufacturing process.

A. Bluetooth® Antenna Characterization

The fabricated inverted-F Bluetooth® antenna was characterized using a vector network analyzer (VNA), where the input reflection coefficient (S11) was measured over a frequency range that included the target operating frequency. The measured response exhibited a strong resonance near 2.4 GHz, consistent with the design objectives and electromagnetic simulations. The close agreement between measured and simulated results indicates that the aerosol jet printing process maintained sufficient dimensional accuracy to approximate predicted RF performance. The observed resonance confirms the suitability of the printed antenna for Bluetooth® communication in catheter-based biomedical applications.

Minor differences between simulated and measured responses are attributed to fabrication tolerances inherent to additive manufacturing processes, including slight variations in printed trace width and the conductor thicknesses. Such effects have been previously observed in additively manufactured RF structures where small geometric variations can influence impedance matching and resonant frequency behavior. Figure 7 compares the measured and simulated S11 responses of the fabricated Bluetooth® antenna.

B. NFC Antenna Characterization

Because NFC systems rely primarily on inductive coupling rather than far-field radiation, NFC antenna characterization focused on measuring inductance properties using an impedance analyzer. Electrical measurements indicated that the fabricated square-loop antenna exhibited an inductance of approximately 4 µH while operating near 13.56 MHz as shown in figure 8. This inductance value falls within the range typically required for NFC communication and is consistent with electromagnetic simulation predictions shown previously in Figure 2.

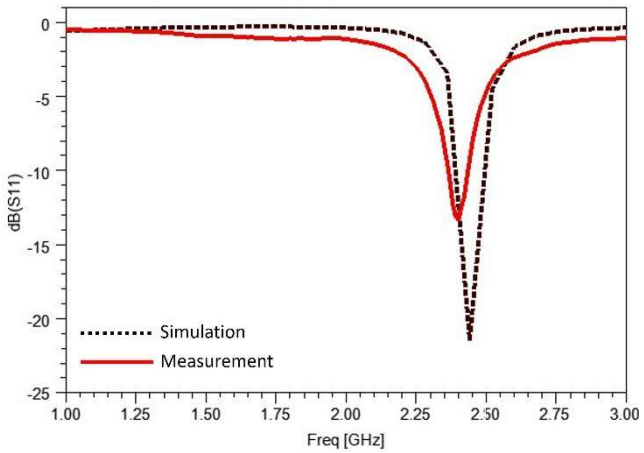


Figure 7: Bluetooth® antenna measurement vs simulation

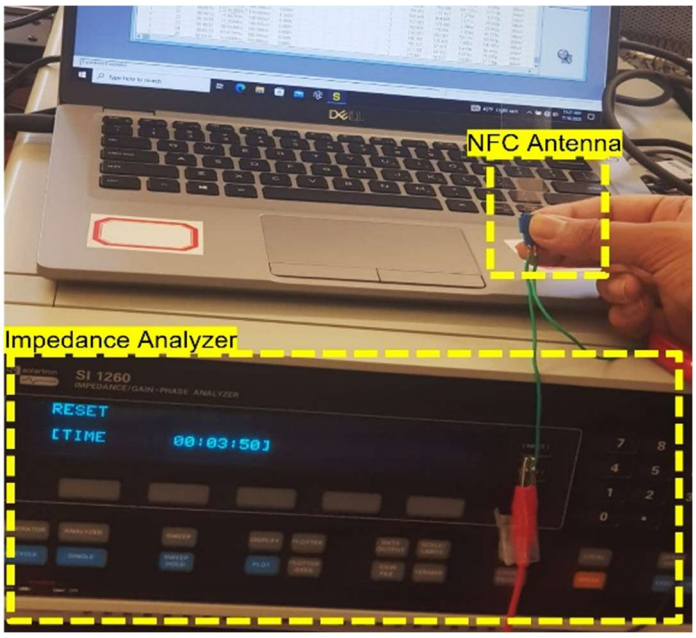


Figure 8: NFC antenna measurement and test setup. NFC antenna showed an inductance of 4 µH during 13.5 MHz operation

V. CONCLUSION

Bluetooth® and NFC antennas were successfully designed and fabricated using AJP on flexible PET substrates for integration within smart urinary catheter systems. Experimental characterization demonstrated Bluetooth® resonance near 2.4 GHz and NFC inductance of approximately 4 µH near 13.56 MHz, in good agreement with design simulation predictions. These results validate aerosol jet printing as a viable approach for fabricating flexible wireless components for future smart catheter and IoMT-enabled biomedical devices.

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