Wireless FracBot Nodes Design and Development of NFC with Inductive Coupled Systems

Shridevi.S

ECE Department

E.G.S Pillay Engineering College, Nagapattinam.

Sridevi.koolaiyar1997@gmail.com

Abstract—Near Field Communication is a short range wireless technology that enables data transfer between two NFC device. It is derived derived from Radio Frequency Identification Technology. It is very critical that the operation of NFC is well understood so that future application can make life easier for the users. The main purpose find out the parameters that can affect the optimal operation of passive NFC device. The NFC has created opportunities for different industries to design new application that could not easily developed with older technology. The NFC application can be regarded as a secure wireless technology due to its short-range of operation. The technology is based on the inductive coupling concept between the NFC initiator and target tag does not own power supply. Another mode operation is active mode whereby both initiator and target have their own supply.

Index Terms—Wireless underground sensor network (WUSN), Near field communication (NFC), magnetic induction (MI) communication, FracBot node, loop antenna coupling.

I. INTRODUCTION

Currently, there is a rapid demand for reliable energy supplies. 87% of the world's energy is extracted from fossil fuels. Renewable energy resources will not substitute the oil and gas fuel. 80% of the world's energy will still be provided from fossil fuels until 2030. However, the fuel sources in conventional reserves are shrinking at a quick pace. This big growth will require extracting more oil and gas from unconventional reservoirs [1]. To fulfill this challenge, optimal development of oil and gas fields is significant and necessitates real-time information such as pressure, temperature, and fluid composition. Thus, designing and developing a new technology is extremely necessary to monitor the oil reservoir in real time and extract more oil to satisfy the global demand. One of these technologies is FracBot technology that we are developing to monitor unconventional reservoirs, map hydraulic fractures and measure wellbore parameters. This technology is based on the concept of Wireless Underground Sensor Network (WUSN) [1]. In our previous work, we produce a novel prototype of NFC (MI)-based wireless sensor node (FracBot) to monitor hydraulic fractures, unconventional reservoirs and measure other oil and gas wellbore parameters.

Near Field Communication (NFC) is a wireless short-range interaction that enables simple half-duplex communication between inductive coupled systems via magnetic field induction when they are very close to each other within a few centimeters. It enables the communication between transmitting and receiving antennas when they are coupled via magnetic field induction at 13.56 MHz (ISM band). Accordingly, NFC occurs in MI near field not as the the electromagnetic (EM) far-field communication that happens through the radiation power in far field zone. NFC technology was established by Sony and Philips in 2004 a subset of the RFID technology [3]. NFC systems have a lot of advantages such as low propagation delay, high efficiency, very low cost and great capability to penetrate non-magnetic materials (water, concrete etc). In addition, it has unique features like no multipath fading and high immunity to interference with other RF systems operating out of the near-field systems ranges [4]. NFC technologies have been originally employed in many applications such as underwater communication, underground communication, contactless information transmission, health monitoring, wireless powered biomedical applications and real time localization [5]–[7].

To evaluate the performance of the NFC link, link budget and propagation have been extensively studied and many models have been generated [8]. A near field propagation model equivalent to Friis’s transmission law was proposed in [9]. Also, NFC propagation characteristics have been analyzed such as bandwidth, capacity channel, path loss, bit error rate for different applications such as wireless underground sensor networks and underwater communication [5], [8], [10]. In addition, the crucial-key performance for any communication link depends on both the bandwidth and received power according to Shannon’s law. Thus, the optimal link capacity entails a trade-off between the bandwidth and the received power [11].

For underground oil reservoir environment, NFC/MI techniques have been considered as an unconventional method to overcome the key challenge of inter-node communication for WUSN in the underground environment [5].
As an alternative of using big traditional antennas in a with electrical length of $\frac{Z}{4}$ which is not applicable in oil reservoir environment, the sensor nodes exploit a compact MI coil antenna to communicate through the magnetic coupling between the transmitter and receiver antennas. According to the characteristics of NFC, the MI field generated by the NFC coil antennas can penetrate a high-loss oil reservoir media and launch constant MI channel that enables wireless MI communication and energy harvesting inside the hydraulic fracture and oil reservoir environment [12]. While many intensive investigations have been theoretically conducted, slight efforts have been done so far to develop and evaluate a sensor node (FracBot) for underground environment that can confirm the theoretical outcomes. We make a comparison between our FracBot system with other similar applications that used NFC in underwater or healthcare fields, our FracBot is designed using off-the-shelf components to communicate in half duplex into underground environment (sand and water) with output power of 100 mW, 1.6 kbit/s and antenna size of 30x40 mm. It can reach 250 mm by only consuming 33µW harvested from radiated power to operate for 50 ms to transmit the data to next FracBot. In underwater application, one study used two smart-phones to communicate in underwater. It reached 10 mm. However, the smartphones require low power but the communication range is restricted to few centimeter [13]. In biomedical monitoring application, one study used NFC implantable devices with radius of 25.4 mm to measure the in-vivo body temperature through skin with thickness from few mm to a couple of cm [14]. From this comparison, there are few applications using NFC but no previous studies have a similar setup like our design. Our design is unique since it is self-powered node that needs to first harvest the energy then operate. In this paper, we evaluate our FracBot design published recently in [2]. The remainder of this paper is organized as follows. Section II introduces the design of NFC/MI-FracBot node and Section III describes perpetual powered sensor. Section IV presents NFC antenna design and Section V discusses the experimental measurements and analysis. Section VI summarizes the conclusions.

II. NFC/MI-BASED FRACBOT DESIGN OVERVIEW

The development and deployment of WUSN in harsh environments such as oil reservoirs and hydraulic fractures necessitate advanced electronic design that can endure the challenges posed by the environment and operate the required functions. The main feature of the advanced FracBot electronic design consists of an ultra high energy efficiency, an energy harvesting capability and a robust communication link. The harvesting energy capability is required due to the limitation of the FracBot size because of the environment restrictions. Moreover, the communication link cannot be established in underground environment using traditional wireless.

The analysis shows that the path loss is much higher than the terrestrial case due to the material absorption. The reliability of the communication link depends significantly on the composition of the soil and the operating frequency [12]. Since lower operating frequency achieves lower path loss but requires larger antenna size, we need to realize the underground link using suitable wireless communication technique such as NFC/MI-based technique. NFC can establish a communication link inside the oil reservoirs and the hydraulic fracture using MI coil antennas to penetrate a high-loss medium, provide reliable channel conditions and harvest the required energy to operate the FracBot. Based on these challenges and requirements, we design the underground FracBot node using NFC as a way of communication. In the following sections, we present the design requirements, the analysis on the FracBot components, and the experimental measurements to show the FracBot performance.

III. PERPETUAL POWERED FRACBOT NODE

Nowadays, the development of perpetual FracBot is based on the energy harvesting capability, the ultra-low power microcontrollers and transducers. Technologies as Ferromagnetic RAM (FRAM) enable the sensor nodes to operate in ultra low current and low voltage status as well as the memory can execute 100 trillion of read/write cycles. These properties are the key-role to facilitate the design and development of the FracBot. Figure 1 shows the FracBot block diagram with the main components and figure 2 shows the actual components. The main components are:

- PCB planar coil: It is a printed circuit board (PCB) antenna. It allows compact design and precise antenna characteristics. It is used as MI antenna to transmit and receive the MI signal.
- NFC communication interface with EEPROM Memory: It consists of two chips including transceiver chip (TRF7970A) and active tag chip (M24LR64). The transceiver enables the energy transmission and communication between the nodes in the communication range and the M24LR64 chip is a NFC wireless memory.
that establish a half duplex communication with the TRF7970A chip. The energy harvesting functionality of the M24LR64 chip allows the sensor node to collect the excessive energy transmitted by the TRF7970A chip and direct it to the energy management unit (EMU).

- Energy management unit (EMU): It is a nanopower energy harvesting controller chip (BQ25570) designed to work with ultra low power energy sources. With very high conversion efficiency of 95%, this chip is able to control the energy source draining without collapsing the energy source. This characteristic is named a Maximum Power Point Tracking (MPPT). In the FracBot design, this chip enables the energy harvesting without depending on the processing unit. The BQ25570 chip turns on the microcontroller only when minimum energy threshold is reached in the supercapacitor or Lithium ion battery.

- Ultra-low power microcontroller: The microcontroller technology is based on FRAM chip (MSP430FR5969). The extremely low energy demand and advanced watchdog time controller allow the microcontroller to optimize and adjust the ultra-low power mode in accordance with the energy availability. Also, the MCU can read/write data up to 100 trillion cycles.

- Ultra-low power temperature sensor: It has a high precision temperature sensing feature (TMP102). This temperature sensor can be configured to work independently or with the MCU and can wake-up the MCU from the sleep mode (Ultra low power mode). It works in a large temperature range with resolution of 0.0625°C.

IV. NFC ANTENNA DESIGN

In this section, we describe the FracBot main characteristics including antenna design, NFC antenna equivalent circuit and resonance frequency of the transmitter and receiver antennas.

A. Planar PCB Antenna Design

For optimal operation of the NFC systems, an efficient energy has to radiate by the transceiver (reader) to the tag (transponder). Thus, the antenna design of both transceiver and transponder needs to be tuned to the carrier frequency. Typically, the NFC antenna is designed in several geometric formats such as circular, square, hexagonal or octagonal spirals to build the coil antenna. The spiral square antennas of the NFC transmitter and NFC receiver have to match the chip requirements. Accordingly, we design the FracBot antennas using a PCB planar square antenna. We use Eq. (1) to design the antenna. The requirements of the NFC transceiver chip (TRF7970A) and the receiver chip (M24LR64) are to use antennas with inductance of 1.5 μH and 4.95 μH, respectively.

\[
L_{\text{ant}} = k_1 \mu_0 N^2 \frac{d}{1 + k_2 p}
\]

\[
d = \frac{(d_{\text{outer}} + d_{\text{inner}}) p}{2} = \frac{(d_{\text{outer}} + d_{\text{inner}})}{d_{\text{outer}} + d_{\text{inner}}}
\]

where \(k_1\) and \(k_2\) are format constants depending on the PCB layout (for square, \(k_1=2.34\) and \(k_2=2.75\)) [15]. \(L\) is the inductance in Henry, \(d\) is the antenna diameter (mm), \(c\) is the thickness of the winding (μm), \(N\) is the number of turns and \(\mu_0 = 4\pi \times 10^{-7} \text{ H/m}\).

A. NFC Antenna Equivalent Circuit

When designing a transponder antenna, the antenna must be tuned to operate in long-range, medium range or short range of resonance frequencies. Originally the NFC was designed to work in applications such as access control, electronic payment. However, the applicability of this technology opens new frontiers in health monitoring as well as wireless communication in underground environment or applications where EM can not propagate. The resonance frequency of the LC circuit determines the distance range required by the applications. Figure 3 shows the electrical model used to represent the NFC receiver.
Based on the electrical model shown in Figure 3, the resonance frequency is tuned to operate in accordance with the distance that the FracBot needs to cover. The resonance frequency can be configured to work in different ranges to optimize distance requirements [15]:

- Long-range (LR) operation mode: It is tuned between 13.6 MHz and 13.7 MHz.
- Standard short-range (SR) operation mode: It is tuned between 13.6 MHz and 13.9 MHz.
- Short-range operation mode: It is tuned between 14.5 MHz and 15 MHz.

Figure 4 presents the electronic schematic of the transponder. It shows the connection between the M24LR64 chip and the antenna coil. This chip can work as an energy harvesting system to absorb the excessive energy of the magnetic induction field. The energy output is configured using the energy harvesting registers. In the FracBot design, these registers are configured to operate with voltage output of 1.6V, current of 10mA and power of 16mW.

![Fig. 4: Schematic of Perpetual Powered FracBot Node](image)

**TABLE I: Transceiver and Transponder Antenna Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transceiver Antenna</th>
<th>Transponder antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Length (mm)</td>
<td>41</td>
<td>30</td>
</tr>
<tr>
<td>Antenna Width (mm)</td>
<td>65</td>
<td>40</td>
</tr>
<tr>
<td>Inductance (Lx) (µH)</td>
<td>1.5</td>
<td>4.89</td>
</tr>
<tr>
<td>Coil turns</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>Capacitance (Cx) (pF)</td>
<td>92.0</td>
<td>27.5</td>
</tr>
<tr>
<td>Resonance Frequency (MHz)</td>
<td>13.5</td>
<td>13.7</td>
</tr>
<tr>
<td>Resistance R Coil (Ohm)</td>
<td>0.8</td>
<td>2</td>
</tr>
</tbody>
</table>

**B. Transceiver and Receiver Resonance Frequency**

Table I shows the parameters used to design the antennas of the transceiver and the receiver including the matching capacitance and resonance frequencies. The antenna design for the TRF7970A and the M24LR64 chips requires antennas with calculated inductance of 1.5 µH and 4.95 µH, respectively. In our FracBot design, the antennas have actual inductance of 1.5 µH and 4.89 µH in addition to the parameters listed in Table I. Accordingly, we simulate the frequency response of the transceiver and receiver antennas. Figure 5 depicts the antenna response with normalized gain. The transceiver is tuned at 13.56 MHz and the transponder is tuned at 13.7 MHz. In accordance with the range standards, the FracBot is tuned to operate in long range mode with maximum gain in the resonance frequency interval of 13.5-13.7 MHz.

![Fig. 5: Resonance Frequency](image)

**V. EXPERIMENTAL MEASUREMENTS AND ANALYSIS**

MI is an alternative technique that be able to provide connectivity for WUSNs. However, the characterization and measurements for this physical layer are limited in controlled experiments at a laboratory level. In this section, we present the measurements for the MI propagation in 13.56 MHz. The analyses are based on received power measurements through the CXA Signal Analyzer N9000A (Agilent Technologies). The magnetic interaction is analyzed using our FracBot node.

![Fig. 6: FracBot Experimental Setup](image)

**A. FracBot Experimental Setup**

We measure and analyze the MI signal propagation in the air and the influence of the antenna orientation on the received power. Figure 6 presents the schematic of experimental setup. In this experimental case, we measure the MI interaction in distances between 0 and 25cm and angles of 0, 30°, 60° and 90°, respectively.
the MI-field. The transceiver (TRF7970A chip) can enable/disble the modulation control permitting to switch on and off the ASK 100%. Figure 9 presents the signal strength for the distances of 0–46cm. In this analysis, we compare the energy strength between the transceiver’s transmitting carrier and carrier with NFC modulation. When the FracBot operates in energy transfer mode (MI signal without modulation), the energy transfer improves by 2 dBm in air medium. On the other side, the signal attenuation in sand and stone media is 20 dB higher than that in air medium for distance lower than 8 cm. However, the energy transfer at distances more than 10 cm in the air and the sand media has the same amount of power.

**B. Modulation Effects**

The standard NFC communication operates at 13.56 MHz carrier with modulation of ASK 10%, ASK 100% and BPSK. Our previous results in [2] show that in underground environment the data transmission error for ASK 10% is over 70% while the ASK 100% reduces the error to 32%.

Although this modulation affects the power transfer, one feature of FracBot is only transmitting pure energy if no data is ready for transmitting via hop by hop fashion through

**C. Angular Analysis**

One of the problems in MI-based communication is the orientation and alignment between the transceiver and receiver of the FracBots. In the angular analysis, we conduct the measurements at the angles: 0°, 30°, 60° and 90°, respectively. The results between 6 and 25cm present a short variations when compared with distances under 6cm. Figure 10-A shows the power analysis considering the angular changes. For distances beyond 6 cm, the angle between the transceiver and the receiver antenna does not affect the received power that much, only lower than -2 dBm. Figure 10-B highlights the the signal strength between -45 and -60 dBm where the concentrated power occurs beyond 6cm in air. For the underground environment, the signal strength is between -50 and -75 dBm.
The FracBot MCU requires 50 ms to execute all reads which eventually degrade the MI and K. Ok, eshe and salt µs 25 cm, the received power will be less than 50 dBm to send data within a time-frame of 50 ms. It also observed that with MI signal strength higher than -50 dBm, FracBot can work at intermittent mode for RSSI of -70 dBm.

VI. CONCLUSION

This paper presented the evaluation of the FracBot node and the NFC/MI antenna in air, sand and stone media. One of the main results is that the mismatch between TX and RX antennas increases due to the effects of the sand or stone media. Thus, the adaptive-frequency feature or advance matching circuit design shall be incorporated in the optimized design of FracBot to overcome the mismatch due to inhomogeneous environment. This feature will allow an optimal energy transfer and a reliable communication link through sand and stone media. The minimum receiver sensitivity of the current MI system must be -70 dBm based on the experimental measurements. The sand and stone media affects the performance of the NFC antennas which eventually degrade the MI signal propagation and reduce the energy transfer. The experiments and testbed analyses demonstrated in this paper and in our previous work [2] help to determine the requirements in order to design an optimal MI system that can operate in ultra low energy requirements.

ACKNOWLEDGEMENT

This work is supported by EXPEC ARC/ Saudi Aramco, Dhahran, Saudi Arabia.

REFERENCES