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Design and Analysis of a Metal-Backed RFID Tag Antenna for Oil Mining

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***Abstract*—in this paper, an improved metal-backed RFID tag antenna is presented. The proposed antenna is designed to operate at 915 MHz with MONZA3 RFID chip. Ground material effect is studied for different material cases. The designed antenna achieves very good radiation characteristics with directive main lobe, and good impedance matching, which makes it suitable for metal-objects RFID applications. Then testing the antenna with seven different soil samples taken from Riyadh city following results show the different electrical properties of seven different soil samples taken from Riyadh city. Moreover, the results illustrate the effect of the water content effect on the soil properties. The measurements are done using DAK kit provided by SPEAG Company. The measurements are done over two frequency bands, the first from 850 MHz to 950 MHz, while the second one from 1 GHz to 5 GHz.**

***Index Terms*— RFID, Antenna, Radio-Frequency Identification, CSTMWS, Modelling and Simulation.**

I. INTRODUCTION

In this paper, the applicants are investigating a novel approach that will address the application of Radio Frequency Identification (RFID) technology to several areas of importance to the Kingdom of Saudi Arabia. RFID technology has a very high potential application in different sectors of oil and mining industry including exploration and management of resources. The proposed research will focus on several challenging issues related to RFID technology and its implementation with focus on both device development and design and improving their RF range. It presents the theory of electromagnetic waves propagation through sands, soils, rocks, etc. Our focus is on evaluating and selecting RFID systems for harsh environments with emphasis on the design and testing of different novel reader and tag antennas and investigating their performance and improving read ranges of low-frequency RFID systems. Prototyping and testing of RFID reader are also planned together with investigating its properties through software simulation and measurements in harsh environments, like performing the tests in dusty atmosphere, very high operating temperature leaving the device for extended periods of time in this environment and repeating the test.

The project is of strategic interest to the Kingdom because of the importance of oil and mining service industry and utility companies and the potential of RFID technology. In addition, results of this project are applicable to any other area where it is necessary to detect and locate buried objects, or "to see" tagged objects through media such as concrete.

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II. LITERATURE REVIEW

A. Review Stage

Radio Frequency Identification (RFID) technology is an emerging technology for a broad spectrum of applications including managing goods, tracking the movement of tools, equipment, people, animals or even anti-counterfeiting [1]-[7]. The use of RFID technology improves safety in a variety of applications such as tracking location of miners and in personal protective equipment. RFID retrieves data stored on a tag wirelessly. It comprises of a tag, a reader, and a host computer with data management software [8]-[10]. A full RFID system consists of three major components [3]

a) RFID tags (transponders),
b) RFID readers (transceivers),
c) Application software (Data processing subsystem).

Tags are attached to the objects so that every RFID enabled object has its own unique identification (ID) number. Object identification is performed by information exchange between tag and reader via radio transmissions at low/high/ultra-high frequencies (LF/HF/UHF). The tags can be either passive or active based on their power mechanism. Passive tag harvests the energy from the reader antenna radiating near field and responds to reader query by modulating the backscattered signal. They are cheap and long life as compared to active tags that use internal batteries as source of power. However, active tags can operate at longer ranges and typically have a larger capacity, higher data transfer speeds and increased read/write capability [3]. RFID enabled sites will monitor activities and inventory in real time.

Ultra-high frequency (UHF) and microwave based RFID systems have been developed to be operated at relatively longer ranges using radiating fields between reader and tag antennas [11]-[12]. Use of higher frequencies has several advantages like high speeds and comparatively longer ranges. However, their performance gets severely hampered by the presence of dielectric or metallic materials present in the propagation channel. UHF RFID systems found applications in item-level tagging in retailing industry and other applications including short range wireless communication, material characterization, and various modulated scattering probe techniques [13]-[14].

The Kingdom of Saudi Arabia's oil and mining sectors are of "strategic importance" to the Kingdom economy. Around the world, oil and mining industries are taking advantage of the quick expansion of computers and microelectronics in many development activities including exploration methods, through production, and marketing [15]. RFID is a very powerful and useful technology to improve production, operational and financial results of both oil and mining industries, while continuing to meet the expected demand for energy. The use of RFID in the Oil and mining industries is very well accepted in the transportation and distribution network [16]. Considering the harsh environment in the oil and mining fields, RFID tags have the advantage of withstanding harsh conditions, can work in extreme weather conditions, and remain operable long after bar codes would have been washed or worn away. It is expected that operators of planned new oil fields in the Kingdom will make use of the RFID technology to adhere to inspection protocols of critical components and follow safety and security guidelines and codes. These two sectors and related petrochemical industries, for example SABIC and other Corporations, are the main sources of prosperity for Saudi's families [17]. As well, the manufacturing sector, the high tech industries and utilities are all dependent, in some way, on the oil, mining and related industries.

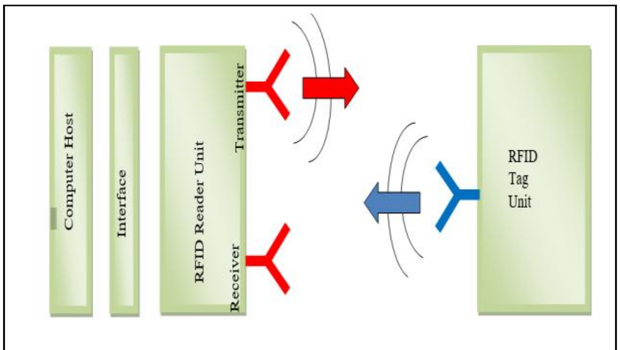

Fig. 1: A passive RFID system

RuBee RFID technology works at low frequencies, in 100KHz range, using long wave magnetic induction coupling mechanism between the reader and tag.[21-22]. RuBee standard enables full-duplex communications and can be used to form a network of sensors. Majority of energy radiated from reader to the tag lies in magnetic field [21]. This allows reading around metals and liquids, as well as through rocks because they are non-magnetic materials. As a matter of fact, magnetic materials are rare in nature. Longer battery life is achieved due to the use of slower clocks at the tags. Longer read-range is related to the performance of the reader's antenna [22]. A RuBee tag contains a battery, integrated circuit with associated memory, crystal for timing and an antenna. The tag's antenna depends on the application as well as operating frequency.

The effectiveness of an RFID system in oil and mining sectors applications is limited in general by its maximum effective range in the medium of interest. This is determined both by the propagation path loss and by propagation loss in the soil. It is necessary to assess the influence of soil properties on the quality of the RFID signal. In ideal free space, the tag received power can be calculated using the Friis formula [23]:

$$P_T = P_i * G_T * \left(\frac{\lambda}{4\pi R^2}\right)^2 * \zeta * p_T * \left[1 - \Gamma_T^2\right] \tag{1}$$

Where Pi is the reader radiated power, GT is the gain of tag antenna, λ is the wavelength, R is the propagation distance, ζ is the polarization mismatch factor and ΓT is the reflection coefficient at the tag antenna. A minimum PT is typically required to turn on the tag and to allow data transmission through a backscatter wave. The corresponding backscattered received power at the reader can be expressed in the form

$$P_R = P_i * G_R * G_T^2 * \left(\frac{\lambda}{4\pi R^2}\right)^4 * \zeta^2 * p_T * \left[1 - \Gamma_R^2\right] \tag{2}$$

Where GR is the gain of reader antenna and ΓR is the reflection coefficient at the reader antenna.

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \tag{3}$$

The investigation of EM wave propagation, attenuation, radiation, and scattering in soil is more complicated. It is well known that soil electrical properties affect the EM wave's propagation properties and thus the radiation and backscattering characteristics of an RFID system. For oil and mining sectors, there are many factors that should be included for a reliable estimate of an RFID system performance. These include electromagnetic waves propagation in soil instead of free space (soil frequency-dependent electrical conductivity (σ) and soil moisture, distance of propagation (R), etc), potential interferences and degradation due to real environmental conditions. We will develop a realistic model in the frequency domain to investigate EM wave's propagation and its attenuation in infinite half-space soil medium. If a plane wave approximation is used for the attenuation, the depth of penetration into the materials is known as skin depth. The skin depth depends on the frequency of the RFID reader antenna used to transmit EM energy into soil and soil properties. It is given by the following formula:

$$\alpha = \omega\sqrt{\varepsilon\mu}\sqrt{\frac{1}{2}\left(\sqrt{1+\left[\frac{\sigma}{\omega\varepsilon}\right]^2}\ -1\right)} \tag{4}$$

III. Research Challenges and Description of Research Approach

RFID technology presents several advantages that can significantly enhance detection of buried objects but there are also major weaknesses associated with using current

RFID technology in the mining and oil industry. Most of the weaknesses are due to the harsh environment and limitation of reading ranges [24]. Another barrier to RFID implementation is the antenna performance degradation due to soil conditions that will limit the reading range and may cause anon-reliable wireless communication link. The applicants will consider some of these problems and analyze several proposed solutions to improve the overall performance.

1. *Study of the propagation properties into soils*

The attenuation properties, associated with equations (3) and (4), in media like cement-concrete, soil, rock, mud, sand at frequencies of LF-UHF ranges are not well understood and publications that describe EM wave propagations underground, under rocks or under cement concrete are rare. Attenuation and scattering are some of the properties that determine limitations of low-frequency RFID systems. Ground's properties can be described in terms of its permittivity and permeability. For soil and rocks, the permittivity is dominantly controlled by the distribution and content of water. The permeability is dominantly controlled by the distribution and content of iron. These parameters can greatly impact signal propagation and attenuation. One of the challenges will be to accurately simulate, model and test the propagation through different environments such as soil, rock, mud, and cement concrete.

The first step is to study the attenuation properties and parameters that affect, attenuate or enhance the propagation of electromagnetic signals into soils at LF and UHF frequencies. This part also includes numerical and experimental characterizations of the EM field propagation underground, under sands, rocks and concrete with embedded metallic frames which will enable us to better understand the conditions that affect signal propagation.

2. *Antennas for RFID applications in Mining, Oil and/or Utility Industries*

We focus on the development of different antennas for both RFID tags and readers including range measurement techniques, and concentrated on application to mining, oil and utility industries and analyze various practical aspects such as its sensitivity to fabrication process and packaging. A main task of our investigation will concentrate on studying the range distance and its effect on the selection, design, shape and geometrical parameters of reader antennas. To improve read orientation sensitivity, we will consider design tags with multiple antennas as well looking into the effect of polarization diversity to minimize such limitation issues. The following tasks will be carried out first through simulation and once optimized will be fabricated and tested. The analysis will be extended to active tags [3] and tags operating at other frequencies.

3. Testing the exiting RFID systems in a harsh environment

In this part of the project, the applicants will test the existing low-frequency RFID devices in harsh environments, like performing the tests in dusty atmosphere, very high operating temperature leaving the device for extended periods of time in this environment and repeating the test. The applicants will test the RFID devices in a normal environment, then compare and analyze it with the performance in a harsh environment. In this part of the project, we will use a number of RFID readers that will be purchased and investigate techniques to improve their accuracy to minimize readings error, such as duplicate or miss reads.

4. Building the reader antenna

A series of antennas (to be used as reader antenna) with different shapes and sizes will be designed and tested to understand their behaviors in terms of transmitting signals and power levels over the horizontal and vertical directions. Furthermore, exhaustive comparison with existing regulations and standards should be performed to avoid any potential accident while activating tags on detonators. This part includes theoretical examination of designs of very efficient and electrically small-size reader antennas for a 125/134 kHz frequency range and other RFID frequency bands investigating and optimizing a number of their characteristics including data transfer rate, cost, radiation efficiency, and side-lobe level to reduce interference. Simulations of radiation pattern, input impedance, and antenna power coupling of the reader antenna will also be performed and compared with available data. Due to the constraints of frequency of operation as well as the desire to have the smallest size as possible, the designed antenna must typically be a physically large but electrically small antenna. An optimal reader antenna type and size will be determined based on EM simulation and following analytical expressions. The built antenna radiation pattern will be measured in the lab and compared to the analytical expressions and numerical simulations. Another challenge will be to determine the size of the reader's antenna. Low frequency signals «150 kHz) can propagate, under some conditions, through large distance of soil and rock, but require a very large antenna (hundreds of meters). The advantage of using, for example, a loop antenna is that it covers a much larger surface area. The disadvantage is that the large antenna is not practical to be built and tested. A more practical approach is to build a smaller antenna which has diameter of less than 10 meters. If the antenna is placed at a large distance from the reader, instead of direct connection to the reader IC, a transmission line should be used and losses must be accounted for.

6. *Regulations and standards*

In order to use RFID technology to detect detonators, strict regulations must be applied and rigorous procedures followed to avoid any accident [25]. Therefore, the applicants must define precisely the levels of powers to be applied to tags fixed on detonators, regardless of the reading distance. The applicants plan to work closely with The Saudi Geological Survey (SGS): http://www.sgs.org.sa/ and other government agencies on these issues.

7. *Detection of buried objects*

One important aspect of this project is to detect tags before the blast as well as to detect tags attached to misfired detonators after the blast. The applications of that system include detection of not only explosive devices and materials buried underground but also objects buried under various materials such as mud, water, snow, cement concrete with embedded metallic frames, rocks, etc.

8. *Proposed tag antenna structure*

The schematic diagram of the proposed antenna is shown in Fig. 1. The antenna, basically, consists of two elliptical patches printed on a 0.635-mm-thick semi-flexible substrate RT6010® with relative permittivity “ε_r=10.2”. Multiple slits and two smaller elliptical cuts are introduced in the patches to adjust the input impedance the differential port connecting the two patches. In addition, two tuning stubs are placed over the port for more precise adjustment of the imaginary part value of the antenna impedance. The overall dimensions of the substrate are (32.47mm×45.5 mm). A ground plane of (100 mm×100 mm) is placed under the substrate to emulate the effect of the metallic object. The optimized dimensions of the proposed design are listed in Table I.

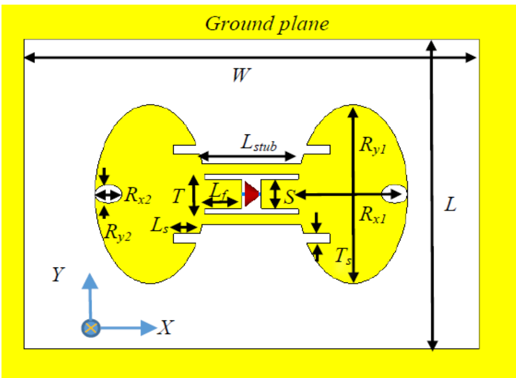

Fig. 2. Schematic diagram for the proposed tag antenna

TABLE I. THE PROPOSED ANTENNA DIMENSIONS IN (MM).

Parameter	*L*	*W*	R_{x1}	R_{x2}	R_{y1}	R_{y2}
Value	*32.47*	*45.5*	*11.02*	*2.64*	*18.76*	*1.98*
Parameter	*T*	*S*	L_s	L_f	L_{stub}	T_s
Value	*4.15*	*3*	*2.61*	*3.68*	*9.85*	*0.99*

The input impedance of the proposed tag antenna is shown in Fig. 3. The differential port of the antenna is intended to be connected to MONZA3 chip [6], which has an input impedance of (32-j216) ohm. The design parameters of the antenna are optimized using CSTMWS in order to have an impedance close to the complex conjugate of the chip impedance. The simulated impedance of the antenna is found to be around (40+j216) ohm. The reflection coefficient of the proposed antenna (S11) is calculated using the formula shown in Eq.1 [3]. To investigate the impact of different metallic-object materials on the antenna performance, three different ground planes (annealed copper, aluminum, and iron) are considered in the simulations. As illustrated in Fig. 3, there are some deterioration in the antenna matching of using aluminum and iron instead of copper. The former behavior can be accounted to the conductivity reduction of the ground plane.

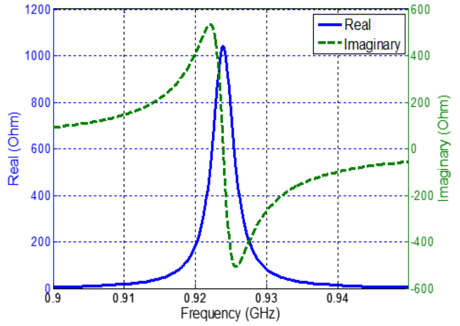

Fig. 3. Input impedance of the proposed antenna (real and imaginary).

$$S_{11} = 20.\log_{10}\left(abs\left(\frac{Z_{chip} - Z^*_{antenna}}{Z_{chip} + Z_{atenna}}\right)\right) \quad (5)$$

The proposed antenna exhibits an impedance bandwidth of 3 MHz starts from 913 MHz to 916 MHz with a center frequency of 915 MHz (in case of copper ground plane).

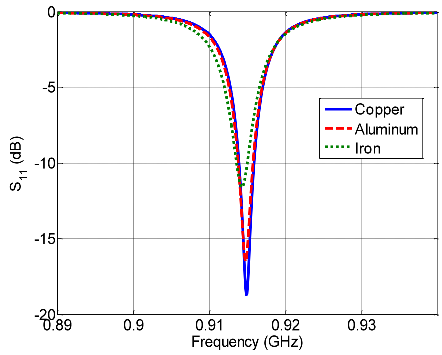

Fig. 4. Reflection coefficient (S11) of the tag antenna over different ground plane materials

Both 2D E (X-Z) and H-plane (Y-Z) radiation patterns at 915 MHz are introduced in Fig. 4. The proposed antenna exhibits a broadside directional pattern, with a directivity of 4.89 dBi as shown in Fig. 5. The electrical field distribution over the antenna at 915 MHz is presented in Fig. 6. It can be noticed that there are fast variation of the electrical fields near the edges of the elliptical patches, which are responsible for radiating behavior.

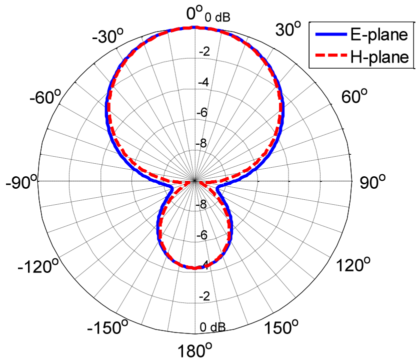

Fig. 5. 2D E, and H-plane radiation patterns at 915 MHz

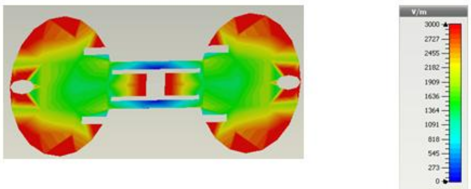

Fig. 6. Electrical field distribution over the antenna at 915 MHz

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