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Wireless system with RFID tag antenna for infrastructure health monitoring

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ABSTRACT: In this paper, a wireless system with radio frequency identification (RFID) tags is proposed for infrastructure health monitoring. In the process of developing sensor integrated RFID tags, a novel tag antenna is designed and its electromagnetic performance has been investigated when it is mounted on selected concrete and metal blocks. Read range analysis of RF section of the system is carried out for the above cases. The optimized RF section with the designed RFID tag antenna has shown desired performance in complex physical environment. It has the potential to be used in mountable sensor integrated RFID tag wireless systems.

1 INTRODUCTION

Infrastructure health monitoring is a vital aspect of modern civil and structural engineering. It provides important status information of the civil structures to identify fault conditions. This helps to plan timely refurbishment work which ensures the integrity of the infrastructure throughout the expected life time. In the process of collecting measurement data for infrastructure health monitoring, several methods have already been tried including human oriented conventional methods (e.g., visual inspection and tap testing) and wired sensor systems. However, conventional methods have inherent operational difficulties. Wired sensor systems also have installation difficulties and expensive installation costs. Therefore, wireless sensor systems are being investigated for infrastructure health monitoring concentrating on economical low power wireless sensors.

Implemented wireless sensor systems for infrastructure health monitoring mostly consist of active wireless sensor nodes. Usage of sensor attached wireless nodes for infrastructure health monitoring has been studied for different structures in Zimmerman et al. (2008), Cho et al. (2010) and Ledeczi et al. (2009). However some scenarios such as crack detection or fault identification require detailed information about the structure which can only be generated with an installation of dense population of sensors. The common practice is to use a lesser number of wireless nodes and wire multiple sensors for each of them as it is not economical to use wireless nodes at every sensor point. Therefore, development of wireless sensor systems with low power, low cost wireless sensors is essential for large scale infrastructure health monitoring.

RFID technology is pervasive in the areas of inventory control, logistics and managing store databases. RFID uses passive backscatter communication which has been identified as a low power technique and it has been studied for wireless sensor development related to structural measurements in Capdevila et al. (2012), Occuhiuzzi et al. (2011) and Bhattacharyya et al. (2009). However structural environments with different orientations tend to affect signal strength and cause difficulties in implementation of these types of sensors which rely on indirect measurements. The recently developed new generation ultra-high frequency (UHF) RFID hardware which complies with Generation 2 RFID air interface provides the advantage of direct sensor interface and passive backscatter communication which prompted further development of RFID-based sensors. Sensor prototypes have been investigated for environmental monitoring in De Donno et al. (2014a). Performance of battery-less sensors is investigated in De Donno et al (2014b). However, investigations of RFID-based sensor development methods for infrastructure health monitoring are limited.

In the process of infrastructure health monitoring, the structural members made out of concrete and metal in the vicinity is unavoidable. This becomes an issue for antennas as studied in Salama et al. (2013).When developing an RFID-based sensor system, the performance parameters such as the read range (maximum distance at which the RFID reader can detect backscattered signal from the tag) and backscatter signal power are adversely affected due to tag antenna detuning in the vicinity of material elements. Especially, commercially available dipole-like RFID tags have this effect according to investigations in Manzi et al. (2008) and Dobkin et al. (2005). Therefore, investigations into an RFID tag antenna which has considerable performance in the vicinity of material like concrete and metal are needed for practical implementation of RFID-based wireless infrastructure health monitoring system.

This paper introduces the proposed RFID-based wireless sensor system for infrastructure health monitoring. An RFID tag antenna has been designed and investigated to be used to develop sensor integrated RFID tag. Performance results of the designed RFID tag antenna mounted on selected blocks of concrete and metal are presented along with an analysis of possible read ranges.

2 PROPOSED WIRELESS INFRASTRUCTURE HEALTH MONITORING SYSTEM

2.1 System description

The block diagram of the proposed wireless infrastructure health monitoring system is shown in Fig. 1. The RFID reader integrated commercial wireless node can interrogate multiple sensor integrated RFID tags mounted on structural members. The same node can operate in a wireless network which covers different sections of a large scale infrastructure. A webserver which is connected with same wireless network can collect the sensor data and make them available to be accessed via the internet for remote monitoring stations.

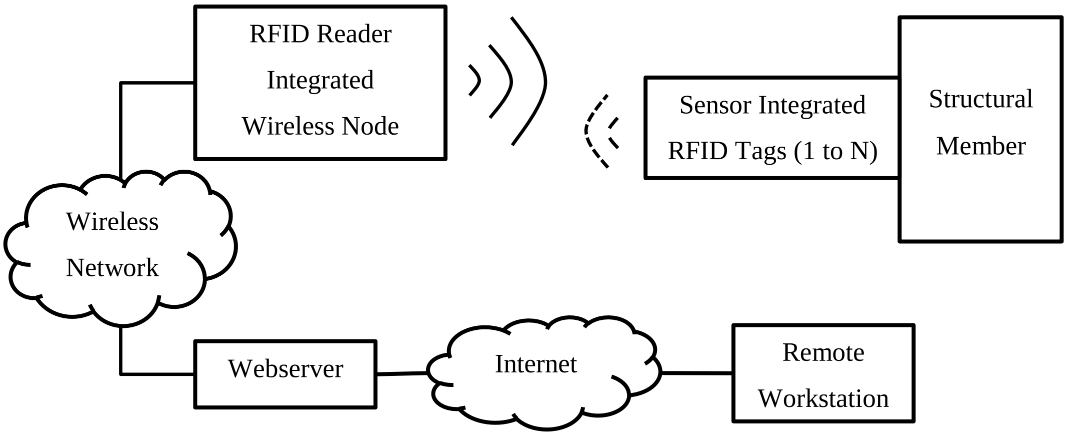

Figure 1. Proposed wireless infrastructure health monitoring system.

2.2 *Practical implementation*

The practical implementation of the system depends upon the type of infrastructure health monitoring needed. In a scenario of monitoring large scale infrastructure the proposed RFID-based system with maximized read range in RFID link can be implemented to monitor locations which are difficult to access. Since these low-power sensors communicate through passive backscattering, the frequent servicing of sensors is not required. Using proposed RFID reader integrated wireless nodes which can operate in a higher level wireless network, can combine number of these vital monitoring locations in to a large infrastructure health monitoring system. Additionally, in scenarios such as fault detection which needs detail information, demands dense population of sensor installations. This can be economically achieved by implementing the proposed system which contains low-cost RFID hardware and less number of wireless nodes compared to general wireless system implementations for infrastructure health monitoring. Furthermore, the low-power implementation provided by RFID at the sensor end of the proposed system makes it viable to enhance the system with extended life-time embeddable sensors for infrastructure health monitoring (e.g., sensors embedded in concrete members). However, the achievable read range of the RFID link of the system will generally determine the number of RFID reader integrated wireless nodes of the entire system.

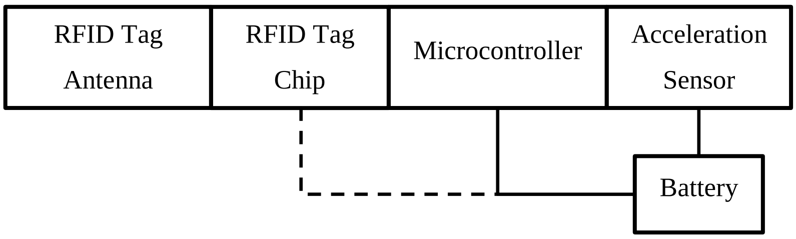

Figure 2. Block diagram of the sensor integrated RFID tag.

3 RFID TAG ANTENNA DESIGN AND SIMULATION RESULTS

3.1 *Tag antenna design*

Fig. 2 shows the block diagram of the sensor integrated RFID tag. As already discussed, the antenna is a vital part of the development of this sensor which will be mounted on structural members. A novel patch antenna is designed using CST Microwave Studio to be used as RFID tag antenna in Australian UHF RFID frequency band (920 – 926 MHz). Fig. 3 shows the geometry of the designed RFID tag antenna. The patch has symmetrical 1 mm slits along its length, bilateral to the *xz* plane. Rogers 5880, which has relative dielectric constant $\varepsilon_r = 2.2$ and loss tangent $\tan\delta = 0.0009$ is used as the substrate material. It has a height of 3.2 mm. The RFID tag antenna is designed to be near conjugate matched with Impinj® Monza® X-8K Dura RFID tag chip which has a chip impedance $Z_c = 18.37 - j170.45\ \Omega$ at the center frequency of the Australian UHF RFID frequency band (923 MHz /$\lambda = 0.325$ m). CST Design Studio is used to acquire the conjugate impedance matching between the RFID tag antenna and the RFID tag chip which is selected for the sensor integrated RFID tag development.

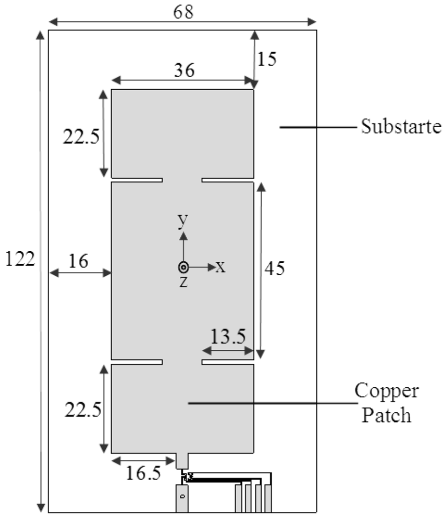

Figure 3. Designed tag antenna (all dimensions are in mm).

3.2 *Performance of RFID tag antenna in free space and mounted on selected concrete and metal blocks*

CST Microwave Studio is used to simulate the electromagnetic performance of the designed RFID tag antenna employing a discrete port to excite it. Some selected simulation results are presented when RFID tag antenna is placed in free space and mounted on selected concrete and metal blocks. As shown in Fig. 4, it has a maximum far-field gain of 4.07 dBi in the *xz* plane at 0° when operating at 923 MHz in free space. The gain becomes 2.86 dBi and 4.3 dBi when mounted on concrete and metal blocks, respectively. Selected concrete and metal blocks have the dimensions of 3.25 by 3.25 by 0.25 m^3 where the length and width are selected to be $\sim 10\lambda$ to model the large scale civil structural member background. The simulations are conducted by placing the RFID tag antenna on the middle of the 3.25 by 3.25 m^2 surface of the structural blocks. Concrete material (dry concrete) has the dielectric properties of $\varepsilon_r = 4.75$ and $\tan\delta = 0.0081$ at 923 MHz while copper is selected to simulate the metal block. The antenna is directional in the far-field gain pattern and has highest gain when mounted on metal block. The maximum far-field gains are oriented in the desired direction in which RFID reader integrated wireless node will be interrogating. Fig. 5 shows how the effective tag antenna impedance is affected by the influence of concrete and metal. The effective tag antenna impedance is affected slightly when it is mounted on concrete while the impedance is reduced more when it is mounted on metal at the desired 923 MHz frequency when compared with free space impedance.

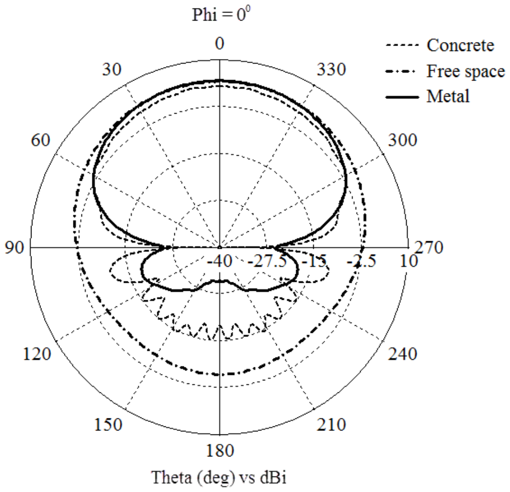

Figure 4. Far-field gain pattern of RFID tag antenna at 923 MHz on *xz* plane.

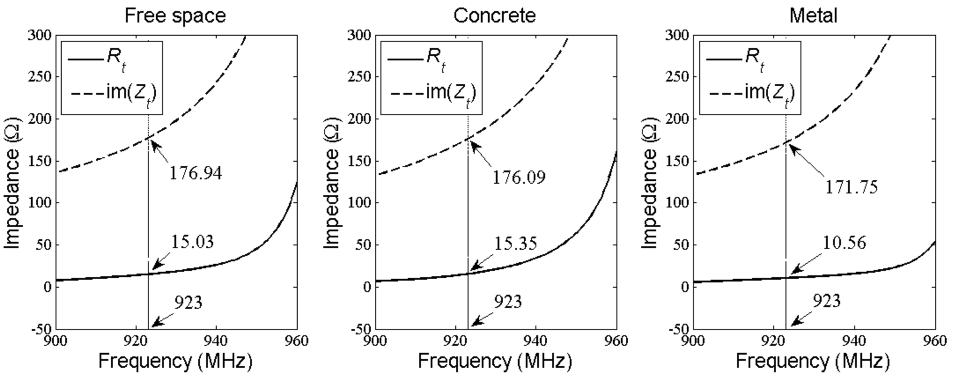

Figure 5. Effective tag antenna impedance in free space and mounted on concrete and metal blocks.

4 READ RANGE ANALYSIS OF THE TAG ANTENNA

The read range of the RFID tag antenna is a vital performance parameter in the design as it determines the maximum distance from which the RFID reader integrated wireless nodes can interrogate the sensor integrated RFID tags mounted on structural members.

4.1 *RFID link budget*

For the purpose of analyzing the achievable read range of the RFID tag antenna, following RFID link budget equations are used:

$$G_t = P_{tc} - P_r - G_r + 20log_{10}\left(\frac{4\pi}{\lambda}\right) + 20log_{10}(r) - 10log_{10}(\tau) \tag{1}$$

The forward RFID link budget with assumed polarization match is given by (1) as in Rao et al. (2005) where G_t (dBi) and G_r (dBi) are gains of RFID tag and reader antennas, P_{tc} (dBm) is the sensitivity of the RFID tag chip, P_r (dBm) is the power transmit capability of the RFID reader chip, λ (m) is the wavelength and r (m) is the read range. τ is the power transmission coefficient between the RFID tag antenna and the RFID tag chip which is given by,

$$\tau = \frac{4R_tR_c}{|Z_t+Z_c|^2}\ .$$

Here, the Z_t (Ω) and Z_c (Ω) represent the complex impedances of the RFID tag antenna and RFID tag chip while R_t (Ω) and R_c (Ω) denotes the resistances of the same. The RFID backscatter link budget which is governed by RFID reader chip sensitivity P_{rc} (dBm) is given by (2) as in Nikitin et al. (2006).

$$P_{rc} = P_r + 2G_r + 10log_{10}\left(\frac{\sigma}{4\pi}\right) - 20log_{10}\left(\frac{4\pi}{\lambda}\right) - 40log_{10}(r) \tag{2}$$

σ represents the radar cross-section offered by the RFID tag antenna in reader interrogation which is given by,

$$\sigma = \frac{\lambda^2R_t^2G_t^2}{\pi|Z_t+G_t|^2}\ .$$

4.2 *Achievable read range*

The selected RFID tag chip has two sensitivity modes. It has sensitivity $P_{tc} = -12$ dBm as passive mode (P) and $P_{tc} = -24$ dBm as battery assisted passive mode (BAP) where the tag chip has to be supplied with battery power according to the data sheet. Consequently, the analysis is done using both (1) and (2). Fig. 6 shows the analysis according to (1) using 28.6 dBm ($P_r + G_r$) effective isotropic radiated power which is under the allowable maximum of ~36 dBm of the Australian UHF RFID frequency band. Performance variations of the RFID tag antenna are shown in Fig. 6 in terms of gain and power transmission coefficient. According to Fig.6, a read range of 5 m is not achievable in the P mode for any of the cases considered for the tag antenna while it is achievable for the BAP mode with a good margin. However, the analysis with BAP option has to be done using (2) which includes the capabilities of RFID reader ($P_{rc} = -65$ dBm/ Impinj® Indy® RS500 reader development kit) since it is an enhanced sensitivity option for the RFID tag chip. The calculated theoretical maximum read ranges are given in Table 1.

Table 1. Theoretical maximum read ranges of the tag antenna

Case	Read Range (m)	
	P	BAP
Free Space	4.32	11.73
Concrete	3.78	10.28
Metal	4.37	10.94

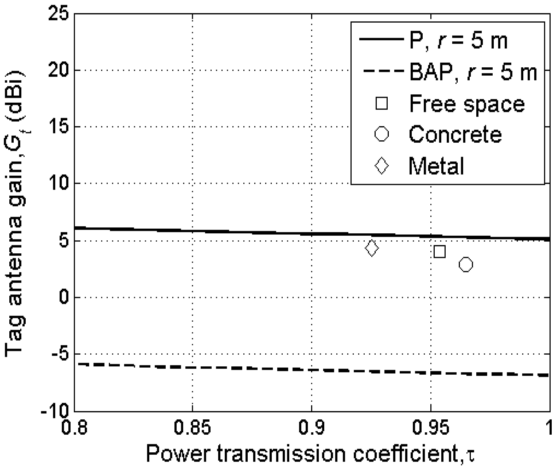

Figure 6. Gain (dBi) vs power transmission coefficient for the forward RF link.

5 CONCLUSION

Wireless systems with RFID tag antennas have great potential to incorporate low power, low cost nature of RFID technology in the area of wireless infrastructure health monitoring. This paper introduced an RFID-based wireless system which includes mountable sensor integrated RFID tags. A novel RFID tag antenna was designed and analysed according to the scenarios as it is a vital component which determines the performance of a sensor integrated RFID tags in infrastructure environments where structural members made out of concrete and metal are ubiquitous. Investigation results have shown that it has satisfactory far-field gains in the desired direction for the cases of tag antenna in free space, mounted on concrete and metal blocks. Maximum gain was shown for the case of tag antenna mounted on metal. The read range analysis of the RFID section of the system with designed tag antenna and selected RFID hardware has shown promising results with minimum deviations for the investigated cases. Hence, the tag antenna has shown tolerance to the environment in the vicinity. Therefore the proposed system with integrated tag antenna can be effectively used for wireless infrastructure health monitoring.

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