Improving Passive RFID Tag Performance: Application to Rotorcraft Dynamic Component Tracking

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Abstract

Researchers at Missouri University of Science and Technology and Technical Data Analysis, Inc. (TDA), have been working to address problems associated with part tracking of rotorcraft dynamic components using Radio Frequency Identification (RFID) systems. The position and placement of the passive RFID tags has a significant impact on their performance, both in terms of energy harvesting from the RF signal and communication reliability. The main objective of this research is to increase the read range and efficiency of multi-tag readability in the metal-rich environment of a rotor hub. This paper discusses our current research work on improving the passive tag readability in a complex metal-rich environment by boosting the back-scatter signal from passive tags through beamforming and impedance matching techniques.

Keywords: RFID, rotorcraft dynamic component tracking, beamforming, impedance matching, mutual coupling,

Introduction

Tracking dynamic components of rotorcraft is crucial to component life assessment and overall fleet management. It is also necessary to assure flight safety and to maximize asset usage while minimizing fleet actions. The United States Navy (USN) recognizes the importance of enhanced rotorcraft health assessment capability by focusing on serialization and tracking of fatigue life limited flight critical safety items (CSI).

TDA has been working for the past three years to address problems associated with part tracking of rotorcraft dynamic components [1,2]. As part of the solution to the rotorcraft part and life tracking, TDA envisioned a framework called **HeloTrack** in which component information is collected via a RFID system, rotorcraft usage data (such as HUMS) is processed to make reliable life predictions, and right information is made available to different stake holders to make appropriate decisions for fleet management. Component information as gleaned from the tags will support rotorcraft configuration management, maintenance, and repair and overhaul shop optimization and life-limited parts monitoring. Consequently, the fast maintenance turnaround facilitated by RFID can translate into improved aircraft availability.

Figure 1 below shows a TDA's notional passive RFID (pRFID) network to be used for component tracking. It consists of pRFID tags, a gateway node and pRFID readers.

Fig. 1: Notional on-board RFID architecture

Passive RFID Assessment for Rotorcraft Dynamic Component Tracking

TDA investigated several metal-mountable passive tags. There are several metal-mountable tags in the market; however not all were suitable because of their power requirements, tag readability, and form factor for use on rotorcraft. The form factor for metal-mountable passive tags are generally far greater than the passive tags generally marketed for other applications. The passive tags were of different sizes, smallest being 1in long x 0.25in wide and 0.25 in thick. When we contrast this t o the dimensions of the name plate affixed on the components, we find that the tag size is a significant issue.

Detection in Metal Rich Environment - In the case of metal rich environment, detection of passive tags becomes difficult because of radio interference and back reflection. Even metal-mountable tags claimed to work on metals need to be tested on a case-by-case basis. TDA tested several tags from various vendors and identified only two tags that performed better: Confidex IronSide Tag and Universal RFID Asset Tag

Effect of Object Quantity – The performance of tag readability changes depending upon the number of objects stacked together since multiple objects affect the average detection probability. Multi-readers and multi-tagging on objects may become part of the solution in pRFID implementation based on the studies conducted so far.

Environment - Tag detectability reduces due to many environment factors such as ambient radio noise, temperature and humidity.

Tag Orientation – It was found that tag orientation with respect to the reader is an important factor. Ideal orientation may not be achieved with one reader/one tag combination, and may need two tags with orthogonal orientation with respect to the reader.

Tag Variability –RFID tags with different chip manufacturers and antenna geometries have different detectability/receptivity properties. No two chips are truly identical due to inherent VLSI manufacturing variations. TDA's work was primarily with Alien's antennas (both circular and linear polarized). However, tests using Motorola antenna which has the same 6dB gain showed that its performance was poorer in certain conditions.

Reader Variability - Due to differences in tag detection algorithms used and antenna size, readers procured from two different vendors may perform differently.

Antenna Design –Detection probabilities for circular antennas higher than for linear. However, average object detection probabilities decrease more rapidly for circular than for linear antennas, as a function of decreasing antenna power. Section 3 describes the performances of these antennas in more detail.

Lessons Learned

From the above observations and TDA's off- and on-aircraft tests as described in Reference [2], the basic requirements of any passive RFID system for use on in tracking rotorcraft dynamic components near rotor hub are:

a. **Small form factor for both tag and reader-antennas** - This is important for application in fleet aircraft. The active tags suffer from the bulkiness because of the batteries. Semi-passive tags that use batteries are also bulky because of the batteries.
b. **Good read range and received signal strength** – Important significantly for the metal-mountable passive tags that have no batteries.

With the above points in mind, any implementation on rotorcraft or metal rich-environments, the tag sizes have to be kept small while boosting the back-scatter. In light of this, our team started investigation on passive RFID tag performance improvements by boosting the back-scatter signal from passive tags through beam forming and impedance matching techniques, which is described below.

Problem Description

A passive scattering based wireless communication is an attractive alternative to the traditional, active transmission systems. The main benefits are a low power, inexpensive, and often battery-less design since the device requires less power to operate and can be implemented as a system-on-a-chip (SOC). However, due to path loss and signal fading in wireless links, the communication range of passive systems is limited to no more than several tens of feet. Furthermore, such passive devices often harvest energy from the original RF signal transmitted by the reader/base station. There is a minimal amount of RF power required to wake and power such a passive device up. Consequently, in presence of fading channel, for example due to shadowing and multipath propagation, a passive device is often unable to receive sufficient energy to operate and successfully communicate. This limits the usage of backscatter-based communication to short-range wireless applications. There are dedicated designs of tags to operate in a metal-rich environment. However, such systems typically employ the low frequency, inductive type tags, which offer limited communication/reading range (max. few inches).

In practical deployment, however, the placement of the passive tags has a significant impact on their performance, both in terms of energy harvesting from the RF signal and communication reliability. Specifically in rotorcraft application, the devices are often attached to a large surface. Moreover, those surfaces often contain metallic and dielectric components that can affect the performance of the passive device in two major ways:

1. Antenna radiation pattern changes – the attached object alters the propagation of the RF signal around the device. The antenna becomes more directional (most signal is radiated perpendicularly to the object's surface).

2. Impedance between antenna and chip becomes mismatched – due to mutual coupling effect the tag's impedance changes; this leads to reduced signal strength and quality (i.e. gain is reduced, signal is distorted).

There is little on the tag that can be done to correct the radiation pattern. Typical approach is the past is to increase separation between the object and the antenna to minimize these effects. Alternatively, the reader antennas can be carefully positioned to mitigate the negative effect [3]. With regards to the impedance mismatch, our work on adaptive RF frontend for the RFID tags suggest that by changing chip impedance (i.e. adding, removing capacitance/resistance) the mismatch can be corrected [4].

Moreover, multiple adjacent tags can be configured such that the negative effects are minimized. Typically, when multiple tags are placed in a close proximity they interfere with each other. Also, the mutual coupling effect among the passive tags leads to the impedance mismatch. Overall, it leads to signal distortion and low read-rate. In contrast, our work aims at introducing special tags with modified impedance to mitigate the negative effects of mutual coupling.

Our team discovered that by introducing such a modified tag (modified chip impedance) the read-rate and read-range improves, as shown in subsequent sections. The additional, low cost, passive tag(s) will be deployed in carefully selected locations to improve the RF-based energy harvesting and passive communication with the target tags. Moreover, these additional tags alter directionality of the reader antenna. In the future work, a dynamic beamforming scheme can be implemented [4,5] to extend the benefit to a random and mobile deployment scenarios. In the subsequent sections of this paper, we provide our solution approach to improve the pRFID performance.

First, the background of the pRFID systems is provided. Then, the considered passive device-based distributed beamforming is explained. Next, the antennas radiation patterns and mutual coupling effects are presented. Finally, the preliminary results are shown for scenario with the additional, modified tags are introduced around the reader antenna. The latter demonstrate, the improvement in read-range and rate with the proposed approach. Also, we present a sensing-capable, pRFID tag design that our team employed in the past to develop a passive, battery-less, wireless sensor.

Proposed Methodology

Several works studied the issue of interference and mutual coupling effects in the RFID systems with passive tags [5-8]. Since a typical deployment of RFID system includes a large number of pRFID tags, this creates severe fading environment with number of nulls where tags cannot be read. The existing works focus on static design improvements, for example a tag's antenna redesign, or experimentally test the performance in different system configuration, e.g. antenna types and placement. In contrast, the proposed work aims at dynamically adjust the scattering properties of the multiple tags to improve the received signal and improve effective communication range.

Several approaches have been proposed in the literature to extend the range of communication in wireless networks including an active beam forming, a relaying network, and the RAKE receivers [9-12]. However, these works are not suitable for passive, backscatter-based systems since they often require active-transmission devices and precise synchronization. For instance, in a non-regenerative relaying network, the relay nodes scale the signal received from a source, and retransmit it to destination. However, passive devices are not capable of retransmitting an amplified signal due to power limitation; thus making the non-regenerative relaying approach unsuitable. Another approaches present in the literature include a RAKE receiver and an active beamforming. In general those relay on time-synchronization of the signal replicas such that they can be coherently combined together. For example, RAKE receiver collects and coherently adds time-delayed replicas of the received signal. While it could be implemented at a capable, advanced reader/base station, the passive devices have neither sufficient energy nor time resolution capabilities to implement such a RAKE receiver. Similarly, antenna-array based beamforming cannot be implemented at the passive devices. Moreover, a distributed beamforming require significant time synchronization among the transmitters to achieve coherent signal at the receiver. The inexpensive and energy-constrained design of passive devices, for example RFID tags, makes such beamforming approaches impractical. The main reason is that such passive, backscattering transceivers are unable to perform complex signal processing operations and computations.

In the past, the authors have proposed a passive beamforming method to improve SNR in a backscattering network [5]. This preliminary study employed a brute force (B-F), Taguchi-based, and Learning Automata (LA) based beamforming algorithms. It is assumed that the intermediate passive devices could be set to operate in one of two modes: *scattering* and *inhibition* where the device either scatters the reader's signal or minimizes the scattering. The proposed approach selects the states of intermediate devices such that the received signal strength and quality is maximized. In contrast to the preliminary results in [5], this paper revises the proposed approach and introduces two novel beamforming methods: a Taguchi- and LA-based, which increases SNR in a passive RFID network under realistic, large-scale scenarios with random topologies. Also, the selection of the scheme's design parameters is studied here. The exhaustive search of the brute force (B-F) method, while impractical for more than few tags, provides a reference, optimal selection of scattering tags.

Beam Forming using Passive Tags

The concept of a distributed beam forming using a scattering network is shown in Figure 2. We consider a communication link between the transmitter, , and the receiver, . In between there are N scattering devices, which are assumed to be passive components whose scattering properties can be varied. Notably, such passive devices, for example the RFID passive tags, are small and inexpensive since they have simple, integrated design, and require *no batteries* to operate. When the transmitter, , interrogates a target device, , the intermediate devices will generate scattered copies of the signal. The N non-unisonous signals interfere with the

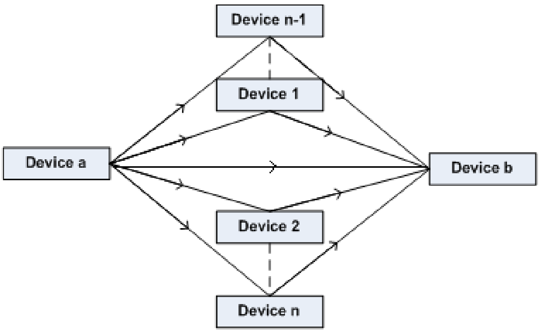

Fig 2: Distributed beamforming using a scattering network

LOS signal at the receiver, . These signals arrive with variable delays, or offsets, depending on their position and scattering property, i.e. the antenna and chip impedance. Such a scattering based multipath propagation contributes to the already existing channel fading and lowers overall signal quality. Potentially, **the combined signal at the destination will become stronger** when the phase shifts align. However, in a random topology the effect is often negative due to phase mismatch among the signals. Generally, variation of phase occurs due to three factors: (a) *distance*: scattered signals propagate through a different-length paths thus introducing phase variation; (b) *medium*: channel properties variation may also cause phase shift; and (c) *reflection/scattering:* the reflecting/scattering object may cause a phase shift due to electric properties. It is well understood that when an electromagnetic field encounters an object, transmitted and reflected fields will be produced:

(1)

(2)

where E_i , E_r and E_t are respectively incident, reflected, and transmitted fields, and Γ is reflection coefficient. A simplified model of the internal circuits of a RFID tag is depicted in Fig. 2; where Z_a is the complex impedance of tag's antenna and Z_L is the complex impedance of chip of the tag. The reflection coefficient Γ is equal to:

$$\Gamma = \text{———} \qquad (3)$$

Two modes of operations are expected from a RFID tag: *scattering* and *inhibition*. In scattering mode, the tag switches to acting as a reflecting object. In reflection coefficient will be $\Gamma=1$, giving no amplitude or phase shift to the reflecting signal. In inhibition mode, the scattered energy should be minimized by setting its impedance . Overall, the reflected signal energy and its phase shift is modeled as:

$$\text{———} \qquad (4)$$

Mutual Coupling of RFID Tags

In contrast, mutual coupling among the antennas of RFID tag is a phenomenon in the near field of antennas. It changes the current distribution of antennas because of the scattered electric filed from other antennas in its vicinity. A changed current distribution will result in changed input impedance to RFID tag ( ), which consequently results in a non-optimum power transfer from antenna to tag IC. As a result, the energy harvesting from environment may not be enough for a tag to power up its internal circuits and respond to the reader. The mutual coupling effect is described through a set of Z-parameters. The corresponding circuit model [13] is expressed as:

(5)

where and are the input impedances of antenna 1 and 2 respectively. Further, and are defined as the induced impedances in the circuit of antenna 1 from antenna 2 and of antenna 2 from antenna 1 respectively.

Experimental validation of mutual coupling in RFID systems

In this section, the mutual coupling is both simulated and experimentally validated for two side-by-side Alien 9640 Squiggle Inlay RFID tags. It is shown in the results, that the mentioned RFID tag has a similar pattern to a half wave dipole. For comparison purpose, two half-wave dipoles are studied. The mutual impedance between half wave dipoles is well known [13] thus providing a good benchmark result. The two half wave dipole antennas were constructed for a *f=1GHz* as shown in Figure 3. The dipole length is 15 cm and is fed by a short (~1” long) coaxial cable. The RFID tags were mounted onto a piece of cardboard slightly bigger than the antenna size for structural support as shown in Figure 4. The microchip was replaced with an SMA connector for measurements.

Fig 3: Constructed dipoles

Fig 4: Prepared Alien 9640 Squiggle Inlay RFID tag

Experimental setup

Figure 5 shows the experimental setup for measuring the mutual coupling between two antennas. The antennas were placed in a small anechoic chamber and connected to an Agilent 8753E vector network analyzer (VNA). The VNA was calibrated such that the measurements are referenced to the input of the antennas. The VNA measures the S-parameters (i.e, transmission and reflection coefficients) of the set up. The S-parameters are then transformed to Z parameters using:

(6)

where U is unit matrix. These measurements were conducted with varying distance between the antennas for up to 45 cm separation.

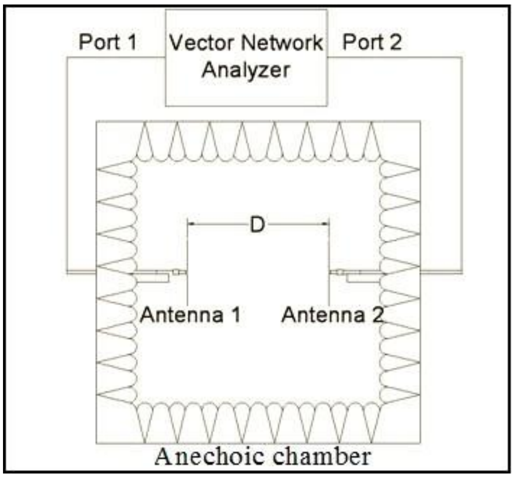

Fig 5: The architecture for the experiment

Simulating Mutual Coupling

The same set up of the experiment was simulated in CST Microwave Studio (numerical electromagnetic simulation tool) for both dipoles and the Alien tag, as shown in Figure 6. The simulation produced S-parameters and then these S-parameters were converted to Z-parameters as before. The S and Z matrices were recorded and compared to the measured results. Figure 7 shows the radiation pattern of the RFID tag, which is similar to a dipole. Therefore one would expect similar mutual coupling behavior in between the Alien tags as in between dipoles.

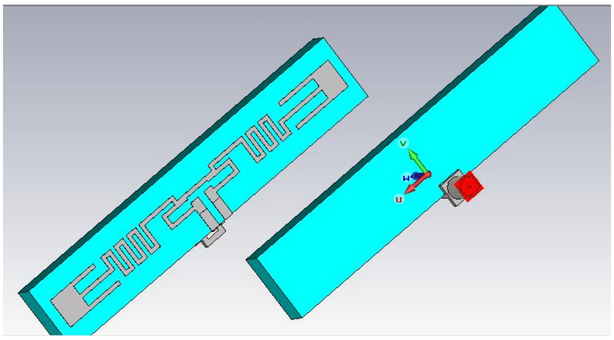

Fig 6: Simulated RFID tag in CST Studio

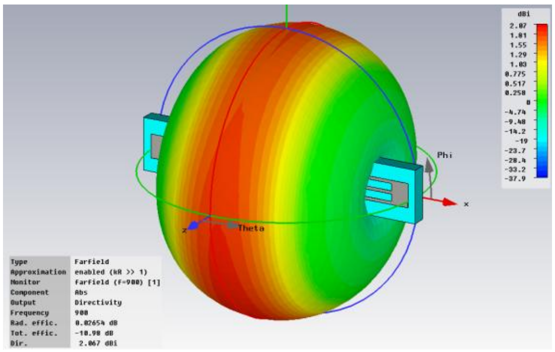

Fig 7: Antenna pattern of an Alien 9640 Squiggle Inlay RFID tag with coaxial connector

Impact of an additional tag on read-rate in a passive RFID system

Our previous results [3-5] indicate that there is an increase in signal strength if an intermediate tag is placed closed to the reader. At such a distance the intermediate tag is within a near-field range. The intermediate tag will enter a far-field when its distance, d, to the reader's antenna is greater than $\geq(2D^2)/\lambda$; where D is the largest dimension of reader antenna.

For practical experiments, the largest dimension of the reader's antenna is equal to 16cms. Hence, the far-field starts at about 15cm away from the reader antenna. The experimental results show that the signal strength increases the most when the intermediate tag is placed at that distance (i.e. 15cm) from the reader antenna. Consequently, a static beamforming is obtained by placing such tags at the specific locations, which would increase the effective reading range.

Figure 8 shows the effective read range for the desired direction. The reader power is set to 12dBm and the target tag is moved along this direction of the passive beam (x-axis). For the standalone target tag, the maximum effective read range has been determined to be equal to 26cm. Nulls are observed in the region 26-30cm with intermittent connectivity at the 30-36cm distance from the reader. Next, the unmodified (i.e. with matching impedance) and modified (i.e. with 1.5pF chip impedance) tags are interchangeably placed at 12cm from reader. Their effect on the target tag read rate is measured and shown at the lower part of Figure 8. The experimental results confirm that by placing an additional tag at specific positions, nulls can be avoided thus increasing the read-range. The best results are observed when two modified, intermediate tags are placed at 12cm and 15cm from reader. It avoids the nulls and increases reading range by 40cm.

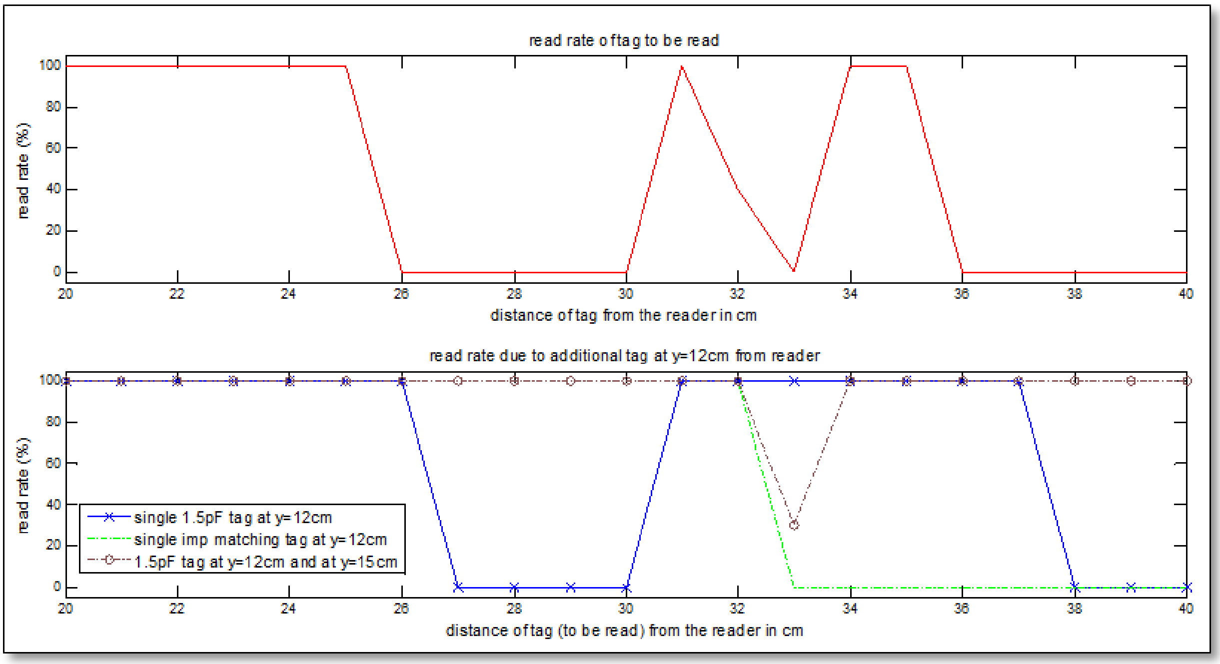

Fig 8: Static beamforming result for 12dBm reader power

Figure 9 shows the read rate for the scenario with a higher transmission power, i.e. 20dBm. Consequently, the effective read-range increases by 90cm when two modified tags are placed at 12cm and 15cm from the reader. Also, the nulls do not change thus indicating correlation with the environment and the RF frequency and not the reader power. In summary, the preliminary results demonstrate that introduction of the modified tags at specific locations improves RFID performance.

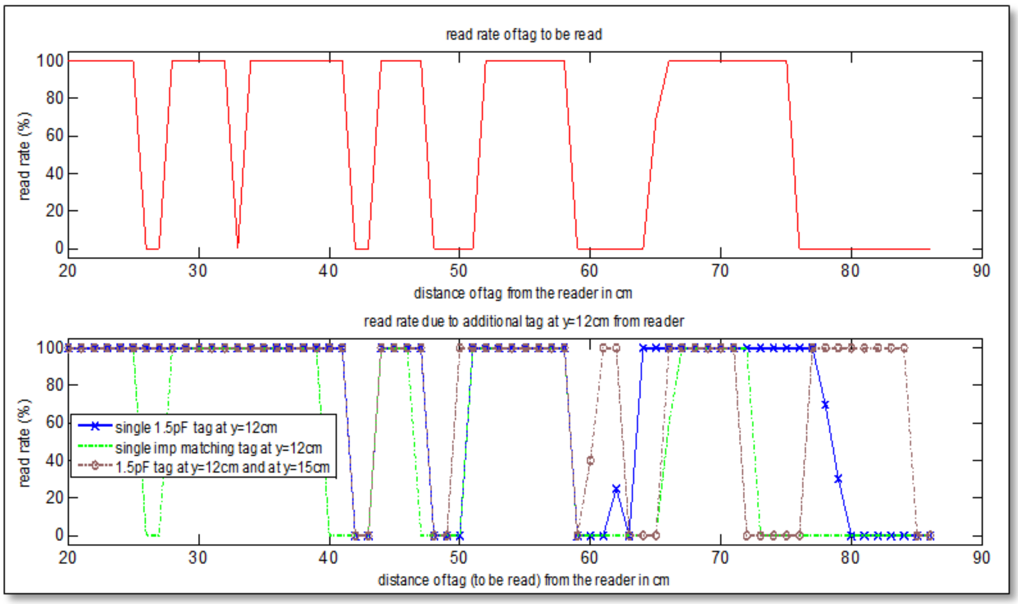

Fig 9: Static beamforming result for 20dBm reader power

Conclusions and Future Work

We have demonstrated that introduction of special tags with modified chip impedance at specific locations improves passive RFID performance in read rate and read ranges. We are building upon these concepts of beamforming and impedance matching methods towards a design of a suitable placement and configuration of the RFID readers and passive tags such that the tags deployed in the designated rotorcraft area are reliably read. Our current focus areas are:

1. Study of the tags propagation and radiation pattern when deployed on or near metallic surfaces of the rotorcraft. The acquired propagation patterns will be used in subsequent steps to develop the deployment strategy – placement and type of passive tags and reader antennas.

2. Identify the placement of the reader, the monitoring tags, and the dedicated reflecting tags such that the best communication reliability is achieved. The additional tags will be placed and configured (e.g. impedance selection) such that the read-rate and read-range are improved to cover the desired deployment area. Prototype and demonstrate the tags reading on the rotorcraft parts in the laboratory setup are planned.

3. Study and design of the adaptive beamforming for passive tags. The participating tags will modify their impedance to ensure the full coverage in dynamic environment. The impedance switching will be demonstrated in a realistic deployment scenario.

We foresee that passive RFID system can be implemented to track rotorcraft components with improvements in design and implementation of system as described in this paper.

References

1. N. Iyyer, D. Algera, N. Phan, et al, “Architecture for Dynamic Component Life Tracking in an Advanced HUMS, RFID, and Direct Load Sensor Environment”; 13th Australian International Aerospace Congress; Melbourne, Australia, Mar 2009.

2. D. Algera, N. Iyyer, N. Phan, et al, “Testing of Passive RFID Systems on Rotorcraft for Tracking Dynamic Components”; Ft. Worth, TX, May 2012.

3. A. Soylemezoglu, M. Zawodniok, S. Jagannathan, "RFID-based Smart Freezer," IEEE Transactions on Industrial Electronics, vol.56, no.7, pp.2347-2356, July 2009.

4. Pratim M. Shah, “Experimental Feasibility Study of a Passive RFID-based Distributed Beamforming Framework and RF Tag Design for Achieved Dynamic Beamforming”, Master dissertation, Missouri University of Science and Technology, 2011.

5. Surendra, Vikram Reddy; Zawodniok, Maciej; “Distributed Beamforming Using a Scattering Network “, Communication Networks and Services Research Conference (CNSR), May 2010, Page(s): 116 – 123.

6. Beiwei Zhang Kunyuan Hu Yunlong Zhu “Network architecture and energy analysis of the integration of RFID and Wireless Sensor Network”, Control and Decision Conference (CCDC), May 2010, Page(s): 1379 – 1382

7. Oka A, Lampe, L, Distributed target tracking using signal strength measurements by a wireless sensor network, Selected Areas in Communications, IEEE Journal, September 2010, Volume 28 , Issue:7 , Page(s): 1006 – 1015

8. Jaekyu Cho, Yoonbo Shim, Taekyoung Kwon, Yanghee Choi, “SARIF: A novel framework for integrating wireless sensor and RFID networks”, IEEE Wireless Communications , December 2007 , Volume : 14 , Issue:6 , Page(s): 50 – 56.

9. C. U¨ nsal, “Intelligent Navigation of Autonomous Vehicles in an Automated Highway System: Learning Methods and Interacting Vehicles Approach,” Ph.D. dissertation, Virginia Tech., Blacksburg, 1997

10. Ubaidulla P, Chockalingam A, “Robust distributed beamforming for wireless relay networks” Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium, Sept. 2009, Page(s): 2345 – 2349

11. Antonis Kalis, Athanasios, G. Kanatas, George P. Efthymoglou , “A co-operative beamforming solution for eliminating multi-hop communications in wireless sensor networks”, IEEE Journal on Selected Areas in Communications - Special issue on simple wireless sensor networking solutions archive, Volume 28 Issue 7, September 2010

12. Tao Cui, Tellambura, C. , “Analysis and optimization of pilot symbol-assisted Rake receivers for DS-CDMA systems”, Vehicular Technology, IEEE Transactions, July 2006, Volume : 55 , Issue:4 , Page(s): 1159 – 1170.

13. Constantin A. Blanis, Antenna Theory, Wiley 2005