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Experimental feasibility study of a passive radio frequency identification-based distributed beamforming framework and radio frequency tag design for achieving dynamic beamforming

Pratim Shah

EXPERIMENTAL FEASIBILITY STUDY OF A PASSIVE RADIO FREQUENCY IDENTIFICATION-BASED DISTRIBUTED BEAMFORMING FRAMEWORK AND RADIO FREQUENCY TAG DESIGN FOR ACHIEVING DYNAMIC BEAMFORMING

by

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This thesis is composed of the following two papers which were reformatted in the style used by the university.

The first paper presented in pages 5-46 titled “EXPERIMENTAL FEASIBILITY STUDY OF A PASSIVE RFID-BASED DISTRIBUTED BEAMFORMING FRAMEWORK” is intended for submission to IEEE Transactions on Instrumentation and Measurements, 2012.

The second paper presented in pages 47-65 titled “RF TAG DESIGN FOR ACHIEVING DYNAMIC BEAMFORMING IN RFID” is intended for submission to IEEE RFID, 2012.

ABSTRACT

Passive UHF RFID tags works on the principle of backscattering mechanism. In realistic environment, there are multiple objects and tags that create complex, multipath propagation scenarios with numerous null-points, reduced read range and read rate.

In general, the RF frontend of tags could be controlled such that the negative effects of multipath propagation are reduced or even inverted thus implementing a virtual beamforming. The theoretical framework of beamforming in RFID system, using additional tags as virtual antenna arrays, has been discussed before. The presented study evaluates the feasibility of such beamforming in passive RFID systems. Moreover, it synthesizes an appropriate propagation model that explains the experimental results and will aid in refining the beamforming scheme. Number of practical experiments has been carried out to validate the propagation models that were employed during the scheme design phase. The experimental results are presented and discussed.

Although above method achieved increase in signal strength at certain locations, it had negative effect at remaining locations. Thus, a more dynamic beamforming would be required to achieve consistent increase in signal strength at all locations. Hence, above beamforming method is further extended to achieve dynamic beamforming. Method of dynamic beamforming is simulated and its results are discussed. Also, aspects of designing RF tag for achieving dynamic beamforming has been discussed.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

PAPER I

PAPER II

LIST OF TABLES

PAPER I

1. INTRODUCTION

1.1 OBJECTIVE

The main objective of this work is to study the feasibility of achieving beamforming in Radio Frequency Identification. The goal was to address the inconsistent reading in RFID due to interference from additional tags. These additional tags also lead to dead spots/nulls and decrease the reading range of the RFID system. Firstly, feasibility of using additional tags as virtual antenna arrays to achieve beamforming is studied, so as to address the above problems. Then, RF tag is designed which would incorporate the beamforming aspect.

1.2 BACKGROUND

In the last decade, there has been a lot of research in RFID due to its wide industry applications. RFID is used to track, locate and identify objects and offers a whole new approach to asset management and traceability, in addition to the opportunity to assign individual identification numbers to each product thereby lending itself to item level traceability. To date RFID technology has been successfully incorporated into the transportation, retail, library services, waste management, mining industries, construction, aviation, automobile, animal identification, food and health industries.

However despite all the claims, RFID has not lived to its true potential. There are number of challenges in RFID and the primary reason which has hampered the adoption of RFID is its inconsistent reading of the RFID tags. This inconsistency arises due to the effect on antenna electric field because of different materials. UHF electromagnetic wave gets attenuated and scattered in the presence of substances such as water and metal, which may cause sub-optimal performance or even total failure [2, 3]. Metal acts as a reflector and water acts as absorber which deteriorates with increase in frequency. Thus, RFID tag antennas experience RF coupling with tagged packages and it degrades the radiation pattern.

Inconsistency in reading rates also arises due to additional tags in the proximity. This tags might interfere constructively or destructively with the incident signal at the tag end (tag to be read), depending on its position with respect to the tag to be read. Also, this interference due to additional tags is not restricted to line of sight. Depending on the number of additional tags and its position, RFID read range and signal strength gets affected [12-15]. Thus, presence of additional tags has significant and unpredictable consequences to RFID system.

Interference due to different materials has been addressed by changing the RFID tag antenna design, especially due to metal and water [4, 5]. Though there has been considerable research to study the impact of additional tags [12-15], there has not been any solution for negating those effects, apart from [16]. In [16] a method has been proposed for addressing the additional/multiple tag scenario. It shows how these additional tags can be effectively used to increase the signal strength and performance of RFID. However, its feasibility and practical implementation is yet to be determined.

1.3 FEASIBILITY STUDY AND TAG DESIGN

In this thesis, feasibility and practical implementation of the proposed method in [16] is studied experimentally. The impact of additional tag has already been studied.

However, there has is lack of knowledge about how and in what way do this additional tags impact. Thus, initially experiments have been carried out to understand the change in signal strength due to single additional tag, depending on its position. [16] proposes that by suitably changing the chip impedance of the additional tag, signal strength can be improved. Hence, experiments are performed to observe the variation in signal strength due to different chip impedances, with respect to its antenna impedance, of the additional tag. Depending on the experimental results and using the theoretical background, optimal chip impedance is selected. Thus, whenever the tag is not read by the reader, it will switch to this additional impedance. Further experiments are carried out using two types of tag: type 1 is without additional impedance (current scenario) and type 2 is with additional impedance (proposed method). Experiments are performed to compare the performance of the RFID system using both the types of tags. Read rate and signal strength are the parameters used for comparison.

The above experiments were carried out using single additional tag. Now, multiple tags are placed to observe the signal strength and read rate. Again, both the types of tag are used to observe their impact. A new method is proposed which increases the reading range of the RFID system in certain directions using static beamforming.

Additional chip impedance does increase the signal strength and reading rate but only at certain locations. Thus, if additional tag has option of switching to multiple impedances then consistent increase in the signal strength can be achieved and dynamic beamforming can be performed. Additional tag must switch it to different impedance depending on its location with respect to the tag to be read. However, the selection of these additional impedances is important. Also, different tag design aspects are considered having the capability of dynamically switching to the appropriate impedance.

1.4 CONTRIBUTIONS

Paper I

- Detailed analysis about interference from additional tag
- Variation in signal strength due to additional tag at different locations
- Selection of additional impedance
- Solution for improving read rate in the presence of multiple tags
- Increase in reading range using static beamforming

Paper II

- Achieving dynamic beamforming
- Selection criteria for selecting different chip impedances

1.5 FUTURE WORK

Detailed study about mutual coupling between multiple antennas is required. This would help evaluating impedance value more accurately. To achieve dynamic beamforming, it is important to understand when to switch the chip impedance and to what value. Also, more specific models for near-field and far-field needs to be considered for selecting the appropriate chip impedances. Change in chip impedance would change the signal quality at both tag and reader end which needs to be addressed. Further study is required to obtain a more detailed calculation for choosing the different chip impedance’s to achieve dynamic beamforming.

PAPER

I. EXPERIMENTAL FEASIBILITY STUDY OF A PASSIVE RFID-BASED DISTRIBUTED BEAMFORMING FRAMEWORK

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Abstract

Passive UHF RFID tags works on the principle of backscattering mechanism. In realistic environment, there are multiple objects and tags that create complex, multipath propagation scenarios with numerous null-points, reduced read range and read rate. In general, the RF frontend of tags could be controlled such that the negative effects of multipath propagation are reduced or even inverted thus implementing a virtual beamforming. The theoretical framework of beamforming in RFID system, using additional tags as virtual antenna arrays, has been discussed in [16]. The presented study evaluates the feasibility of such beamforming in passive RFID systems. Moreover, it synthesizes an appropriate propagation model that explains the experimental results and will aid in refining the beamforming scheme [16]. Number of practical experiments has been carried out to validate the propagation models that were employed during the scheme design phase. The experimental results are presented and discussed.

Keywords - Radio Frequency Identification (RFID), backscattering, RCS, beamforming.

1. INTRODUCTION

Traditionally, the radio frequency identification (RFID) systems are applied in logistics and retail operations to track individual palettes, boxes, and even items. In contrast to a barcode technology, the RFID offers unique identification of each tagged item and allows reading the tag without a need for having clear line of sight between reader and the tag. Moreover, the newer RFID tags can provide information beyond the unique id number including expiration time for perishable items, localization information, temperature, etc. The RFID, in-particular passive UHF RFID, has been used in variety of applications including access control systems, a supply chain management, a library item tracking, homeland security applications, toll collection solutions, and network enabled manufacturing.

Consequently, the RFID had been proclaimed by many to be the next generation barcode. However, critical challenges including security, privacy, read rate, read range, and reliability have hindered the universal adoption of the RFID systems. These challenges have been discussed and summarized in several publications [2][3]. The lack of reliable and consistent read rate has been singled out as the fundamental, technological limitation of the real world deployment of RFID systems. Past works proposed different approaches to improving the read rate performance [4-5]. Read rate impairments due to presence of various materials (e.g. metal, water) have been studied in [7-11]. Papers [4-5] propose new RFID tag antenna designs such that those negative effects are minimized. In an ideal scenario, the read rate should not be affected by the tag orientation. However, typical tag antennas have a non-omnidirectional radiation patters thus resulting in inconsistent read performance in random deployment. Additionally, the antennas experience RF coupling with tagged packages and their contents [10], thus further distorting radiation pattern. In [10-11], it has been observed experimentally that change in the antenna orientation by as little as 30 degrees can result in lack of communication with the tag due to creation of a null. While it is often impossible to change the orientation of a tag antenna, or enforce the particular antenna orientation, it is important to understand the implications of tag orientation.

Over the years, analyses have been carried out for scenarios with a standalone RFID tag. However, in the real world environment there are multiple tags deployed within the RFID reader's range. Several experimental studies and trial deployments demonstrated that presence of multiple tags has significant and unpredictable consequences to the RFID system performance [12-14]. For instance, in one experiment [12] a single, reference RFID tag was placed at a maximum read range. Next, multiple tags were placed on a direct path between the reader and the RFID tag resulting in unsuccessful reading of the reference tag. Other experiments in [12] demonstrated that the presence of tags away from the line of sight (LOS) also affected the read rate of nearby tags. The observer performance changes were correlated with changes to the signal strength at both the reference tag and the reader. Overall, from [12-15] it can be concluded that the presence of adjacent tags, their number and locations affects the RFID read range and signal strength when compared with the single-tag scenario. Moreover, on a random basis the effect is typically negative for a multiple tag scenario.

These studies demonstrate that the multiple tags affect each other's communication performance; however, there is lack of comprehensive understanding of the propagation in such multi-tag scenarios. While the individual, fundamental phenomena, for example mutual coupling between adjacent antennas and multipath propagation, are well known; there is a lack of predictable model for multi-tag scenarios in RFID systems.

Real world environments will have multiple tags and its effects cannot be nullified. Instead, [16] shows how a multiple-tag scenario can be effectively used to increase the signal strength and performance of the RFID. In [16], concept of beamforming is applied to multipath reflections. In this paper, concept of RFID tag-based beamforming will be practically validated and its feasibility studied. Changing the impedance of the additional tag is the basic principle used in achieving beamforming. By changing the impedance of additional tags, amount of backscattered energy and its phase can be controlled. So by changing the phase of reflected signal, from the additional tags, beamforming can be achieved. Also, degree of mutual coupling between the neighboring tags affects impedance of nearby tags and the array pattern. Thus, by changing the impedance helps controlling mutual coupling between the tags which changes the array pattern.

The main contributions of this paper are: (1) analysis of communication with an interrogated tag in the presence of additional tags with various design parameters, (2) modeling the impact of an additional tag on signal strength as a function of a position, (3) study the effect of distributed beamforming using the additional tags, (4) and a new method of extending the range of the backscatter communication through careful positioning of special tags.

First, the backscattering mechanism and mutual coupling is explained. Next, the proposed method for improving read rate and signal strength is presented using the concept of beamforming. Then, the experimental setup and scenarios are described. Finally, the experimental results are presented, discussed, and conclusions are given.

2. BACKSCATTERING MECHANISM

Passive RFID tags do not use an active radio transmitter. Instead, communication link between the tag and the reader is based on the backscattering phenomenon. Passive tags do not have battery. Instead, they harvest energy from the reader's signal to power up internal circuitry. Then, it modulates the reflected RF signal by altering impedance of the antenna's matching network, as shown in Fig 2.1.

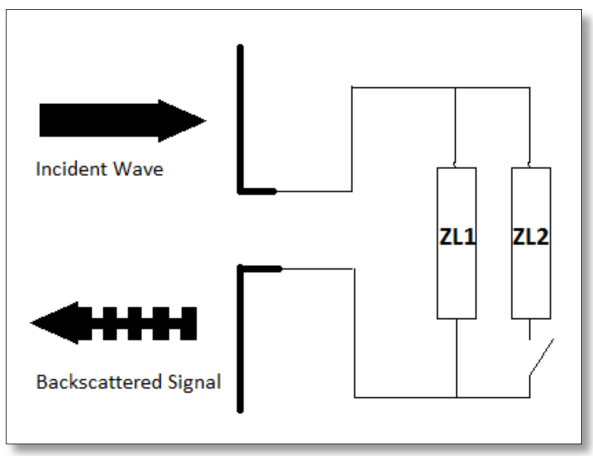


Fig 2.1: Passive RFID tag architecture overview [18]

The part of the incident wave on the tag gets reflected, while the rest of wave's energy is absorbed and stored in a capacitor. The amount of signal being reflected by the tag depends on the load impedance of the tag, i.e. ZL1 and ZL2 [17]. If the impedance is the short circuit, maximum power gets reflected, whereas if the impedance is conjugate matching with that of the antenna impedance than half the power gets reflected and half the power is transferred to the chip [19]. Thus, tag switches between the two impedance states, which results in modulated backscattered signal. For each impedance state, RFID tag presents a certain radar cross-section (RCS). The RCS defines the ability of an object to interact with radio waves. The re-radiated power level varies with RCS thus enabling amplitude or phase modulation. As the tag switches between such two impedance states, it generates differential RCS, also called the delta RCS. It can be modeled using following equation [17]:

$$\Delta RCS = |\sigma_1 - \sigma_0| = \sigma_{match} . \left||1 - \Gamma_1|^2 - |1 - \Gamma_0|^2\right| \qquad (1)$$

where $\sigma_{match} = \left(\frac{\lambda^2}{4\pi}\right) G^2$ represents RCS of the tag when its polarization and impedances are matched with antenna. Antenna reflects maximum energy when its impedance is short-circuited. However for complex load impedance, the RCS is maximum and equal to $4 * \sigma_{match}$ when $X_c = -X_a$ and when $R_c = 0$ which is typically the case of UHF RFID tags.

Thus by changing the impedance of the additional/surrounding tags, backscattered energy can be varied and desired beamforming at the tag end (tag to be read) can be achieved. This is further explained in section 3.

3. MUTUAL COUPLING

In typical applications, there will be multiple tags deployed in a given area. Due to proximity, a mutual coupling occurs among them thus modifying their impedance. Consequently, the antenna element's radiation patterns and input impedances change resulting in uncertain communication. When two antennas are in proximity and one is transmitting, the second one will receive some of the transmitted energy, with the amount dependent on their separation and orientation. Even if both antennas are transmitting, they will simultaneously receive part of each other's transmitted energy. Furthermore, antennas rescatter a portion of any incident wave and thus act like small transmitters. This interchange of energy is known as mutual coupling.

Mutual coupling effect varies with the center impedances of these elements (i.e. tags). By appropriately changing the center impedances, the backscattered energy of that tag and more importantly that of its surrounding tags can also be controlled [33]. Carefully tuning impedances of individual tags may result in formation of a virtual antenna array. Moreover, it is possible to dynamically steer the beam in any desired direction, thus achieving an adaptive, distributed beamforming [20-27].

Consider a case where there is a single extra tag in-between the RFID reader and the read tag. The induced current can be calculated from equation (2):

$$V_{N\times1} = Z_{N\times N} \times I_{N\times1} \qquad (2)$$

where N is a number of elements, V denotes voltage levels at each node, Z is pair-wise impedance matrix for all nodes, and I is the vector of current levels at each node.

Let’s consider the case with three nodes: (1) reader, (2) additional tag, and (3) target tag. The voltage vector, V, has all zeros except for the source element, i.e. the RFID reader. Hence, $V = [V_{reader\ power}\ 0\ 0]^T$). The impedance matrix assumes form:

$$Z=\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix}$$

where $Z_{11}, Z_{22}\ and\ Z_{33}$ are known self-impedances, and $Z_{12} = Z_{21}$, $Z_{13} = Z_{31}$ and $Z_{23} = Z_{32}$ are pair-wise mutual impedances between the reader, the additional tag, and the intended tag. These impedances can be calculated as given in [28].

Assuming that the impedances and voltages are known, the induced current at each tag can be calculated as:

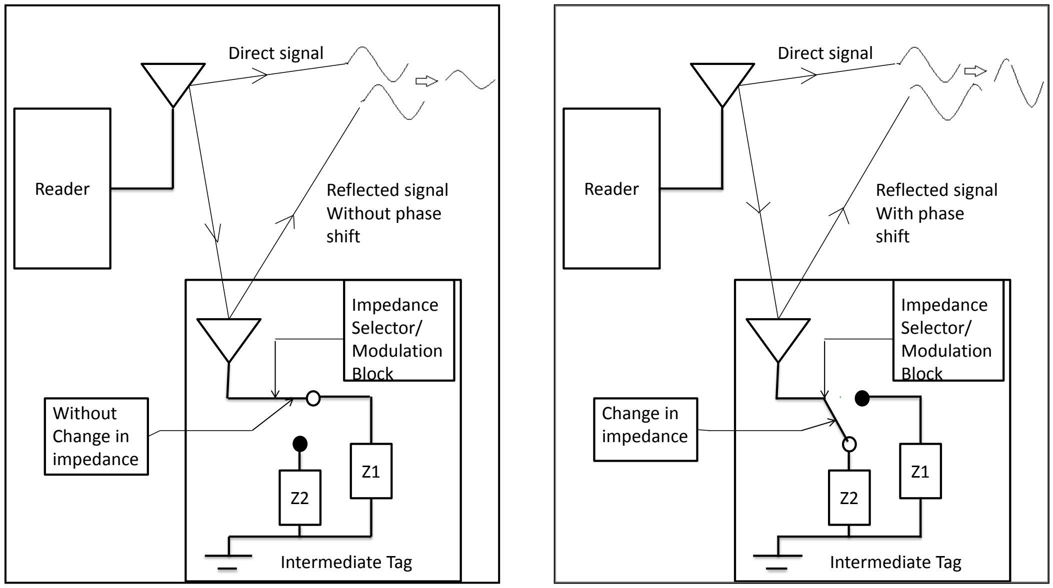
$$I = [I_{reader}\ I_{intermediate\ tag}\ I_{intended\ tag}\ ]^T$$

When the center impedance of the additional tag (Z_{22}) is changed, then the mutual impedance changes thus altering the induced current. Consequently, the amount of backscattered energy can be controlled through the impedance of additional tag.

4. INTRODUCTION TO BEAMFORMING

Wireless communication systems have to operate in presence in multipath fading, polarization mismatch, and interference. Furthermore, power constraints increase the difficulty of addressing those challenges in backscatter-based devices. Beamforming takes the advantage of the multiple copies of the signal by creating a pattern of constructive interference in the wavefront. Traditionally, the beamforming is achieved by injecting a carefully selected, synchronized delay to each copy of the signal at the antenna components. It improves the signal strength and mitigates the multipath fading by combining the weak signals from multiple antennas into one coherent and strong signal. Typically, beamforming is achieved using an active antenna array, either transmitting or receiving ones. Each antenna elements injects a carefully selected delay to the RF signal such that the multiple copies interfere constructively at the receiver.

In contrast, this paper considers the beamforming where the multiple signal copies are reflected by randomly located, additional tags. The main difference from the traditional distributed beamforming is that the additional tags are passive devices that can switch among a set of fixed impedance networks to alter the scattering characteristics including phase shift, signal strength, and mutual coupling effect. These parameters vary with the antenna and tag impedance matching and relative position of the additional tags. Hence, in order to perform beamforming, the system has to select a suitable impedance to be applied at the additional tags. They should either maximize strength of combined signal or minimize destructive interference.



(a) (b)

Fig 4.1: Received signal construction (a) without change in impedance and (b) with change in impedance

Fig 4.1 illustrates a basic scenario of the considered beamforming. Copies of the original signal arrive at the receiver's antenna delayed with respect to the line-of-sight (LOS) signal. This delay includes the propagation time difference and a phase shift introduced by the additional tags impedance, as shown in Fig 4.1(a). When the additional tags have undesirable impedance, e.g. Z1, the reflected signal becomes interference to the LOS signal due to phase mismatch. In contrast, the proposed approach would switch the impedance of additional tags as to compensate for the difference in propagation time among the signal copies, as shown in Fig 4.1(b). If the arriving signals are perfectly aligned, then the received power is a sum of the individual signal powers.

Additionally, the “corrected” reflections will no longer contribute to the interference, thus increasing signal to interference ratio and the performance of the communication.

In general scenario, there can be a large number of additional tags involved. The additional tags reflect the backscattered signal thus becoming virtual sources of the distributed beamforming. Their position and scattering properties determine whether the multiple copies interfere constructively or destructively at the destination. Hence, it is important to study the propagation of a scattering signal [29,30]. Unlike in a traditional distributed beamforming, these “virtual course” tags are not synchronized. However, the potential gains from the proposed approach [16] are substantial. Also, it can be concluded from [29] that even with phase errors on the order of 60^0, it is possible to achieve SNR gains of up to 70%.

5. VALIDATION EXPERIMENTS OF THE BEAMFORMING IN RIFD

The proposed distributed beamforming [16] when applied could improve the reliability and quality of communication, or in case of RFID improve read-rate. The simulations carried out previously [16] had made some assumptions about the propagation and channel models. Hence, this paper aims at validating those assumptions and evaluates the feasibility of the proposed beamforming.

The presented results and studies aim at validating several aspects of the proposed beamforming:

- Vary location of the additional tag or tags to understand how the received power and read rate changes
- Vary the impedance of matching network at the additional tags to understand its impact on performance, and to identify the desirable impedance value.
- Verify the positive impact of the specifically located tag types (with selected impedance) on performance and maximum communication distance.

5.1 EXPERIMENTAL SETUP

The experiments are performed with Skyetek M9 UHF RFID reader/writer, Avery's squiggle tags, and U3772 Advantest Spectrum Analyzer. The tags are placed on a 4ft x 4ft wooden board. Fig 5.1illustrates the experimental setup. It shows the positions of the RFID reader antenna, the target tag (T) and additional tag. Placement of additional tag is shown along X-Y axis with tag (T) at the origin (0,0). The RFID reader is set to operate without frequency hopping, and with transmission power 27dBm.

Antenna impedance of squiggle tag is Z_a= 12 + j133. From the discussion in section 2, it was seen that tag's maximum RCS is when $X_c = -X_a$ and $R_c = 0$ and hence, we replace chip of the additional tag with capacitor of the value 1.2pF. Such a type of tag is referenced as additional tag. These additional tags are placed at different x-y coordinates on the board and change in power level on the spectrum analyzer is noted.

Four types of experiments are conducted:

1. Study the impact of neighboring tag impedance on signal strength at a receiver.
2. Study the position of the additional tags on signal strength and quality.
3. Modeling the impact of the additional tags position on the received signal strength.
4. Finally, the evaluation of improvement in read rate performance when the additional tag is introduced in the optimal position.

All the experiments performed replicate the real world environment and hence, tag may not behave ideally. For instance, ideally tag power should decrease as a function of distance but in real world due to reflections power might increase at some point even if distance is increased.

5.2 TAG DESIGN CONSIDERATION

The effect of changing the impedance of the additional tag has been discussed. Thus, the purpose of this experiment is to verify its impact on signal strength. The results are discussed in context of additional tag's impedance values which increases the signal strength and minimize the destructive interference.

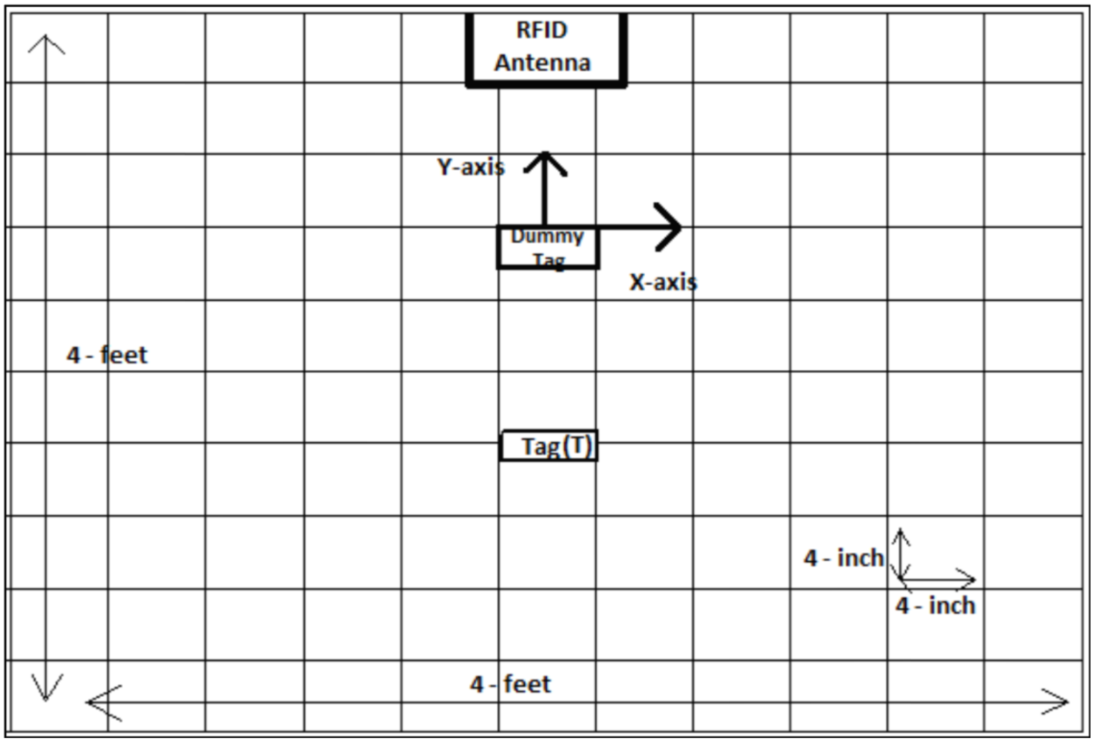
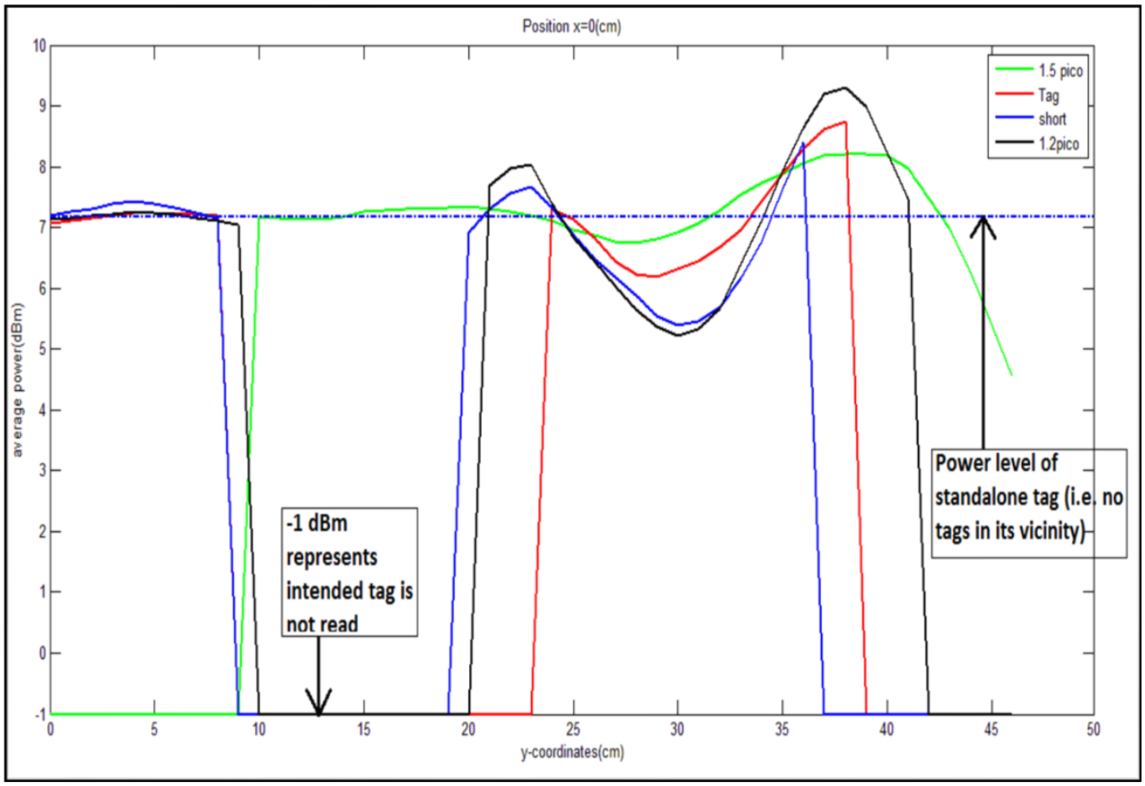


Fig 5.1: Basic experimental setup

Position of the RFID antenna and tag is fixed for this scenario. The power level at receiver is observed while the additional tag is placed at different x-y coordinates. For this experiment, 4 types of additional tags are used with different impedances: (1) max RCS i.e. 1.2pF, (2) zero impedance i.e. short, (3) 1.5pF, and (4) an ordinary, unmodified, squiggle tag with its matching impedance.

Impedance of 1.5pF is selected since it advances the phase of the signal incident on it, to compensate for the additional distance it has traveled. Hence, it is selected for the purpose of achieving beamforming.



NOTE: Power level equal to -1dBm indicates that the tag is not detected.

Fig 5.2: Tag power with different additional tags

Fig 5.2 illustrates the signal power at receiver with varying y-coordinate position of the additional tag. The measured power varies with both the additional tag's impedance and position. The additional tag with the maximum RCS (i.e. with impedance of 1.2pF and zero impedance) causes maximum power variation. If placed in few, selected locations it results in the highest power. However, for 60% of cases it interferes such that the intended tag is not being read. The negative effect of mutual coupling and reduced power prevent successful decoding of the signal at the target tag.

Unmodified additional tag with its chip on can achieve the second highest power in specific locations, but also can be read for only 25% of cases. Hence, it results in the worst read-rate performance among the various tags. This result matches earlier findings [12] that read rate suffers when high number of tags is present.

The additional tag with 1.5pF impedance shows the least power variations while resulting in the highest and most resilient read-rate equal to 85%. The main reason for such a high read rate is the lowest absorption of RF energy by such an additional tag. Hence, this particular design offers the benefit of the best performance for a random topology. However, when tags are close to each over, this tag type results in missed communication, that if for y-coordinates between 0-10cm (from the target tag). This can be attributed to a negative effect of mutual coupling between the tags.

Moreover, the maximum power level for all the type of additional tag is observed when the additional tag is 12 cm from the reader, which corresponds to y-coordinate equal to 38cm. Further analysis explains that this corresponds to the maximum mutual coupling case between the reader and additional tag antennas.

The received signal variation is the largest for the additional tag with maximum RCS. The beamforming scheme would benefit from setting such impedance for tag at the maximum-power locations. Conversely, it will significantly reduce read-rate when the additional tag is positioned in the minima. Hence, it is not the best solution when the impedance cannot be dynamically adjusted to the particular random topology. In contrast, an additional tag with 1.5pF impedance resulted in more consistent read-rate regardless of the position since it has the least impact on the received signal. Hence, such impedance is a preferred solution for a random topology scenario with static tag's impedance. In general, the tags should switch to the 1.5pF impedance once they complete communication, thus reducing their negative impact on the read rate of other tags.

Table 5.1 shows the tabulated results for the above scenario. It includes the read-rate for each tag type and position. There is no direct correlation between the power level and the read-rate. For example, the additional tag with 1.2pF at positions y=41-47cm achieves high power value while providing read rate at only 55%. Further analysis indicates that the phase shift introduced by the additional tag distorts the signal thus preventing its correct decoding.

Subsequent experiments will consider two types of tags: (a) type 1 – an unmodified tag with the original chip (i.e. the squiggle tag) and (b) type 2 – the tag with its chip replaced by 1.5pF impedance.

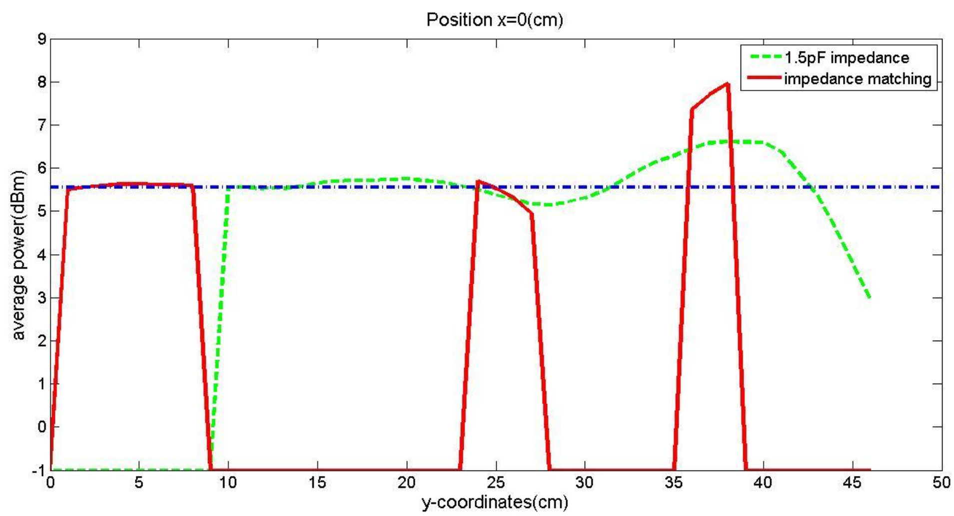
Table 5.1: Power values from Fig 5.2

Benchmark Power Level: 7.17 dBm								
Distance (cm.)	**Tag type 1 (1.5pF)**		**Tag type 2 (original)**		**Additional tag – (short)**		**Additional tag 1.2pF**	
	Power (dBm)	Read rate (%)	Power (dBm)	Read rate (%)	power (dBm)	Read rate (%)	power (dBm)	Read rate (%)
1-5	NR	0	7.07-7.23	100	7.2 - 7.44	60	7.14 - 7.27	100
6-10	NR	0	7.24-7.2	80	7.4 - 7.16	80	7.25 - 7.04	80
11-14	7.15-7.13	80	NR	0	NR	0	NR	0
15-21	7.17-7.35	100	NR	0	6.91	70	NR	0
22-26	7.3 - 6.97	100	7.3 - 7.13	70	7.31-6.88	100	7.7 - 6.83	90
27-29	6.88 - 6.75	100	6.83 - 6.23	100	6.49-5.88	100	6.45 - 5.64	100
30-35	6.82 - 7.74	100	6.19 - 7.44	100	5.54-6.77	85	5.37 - 7.12	100
36-40	7.89 - 8.21	100	7.89 - 8.74	80	7.62 - 8.4	60	7.93 - 8.99	100
41-47	8.2 - 4.55	70	NR	0	NR	0	8.23 - 7.47	55

NOTE: Power level equal to -1dBm indicates that the tag is not detected

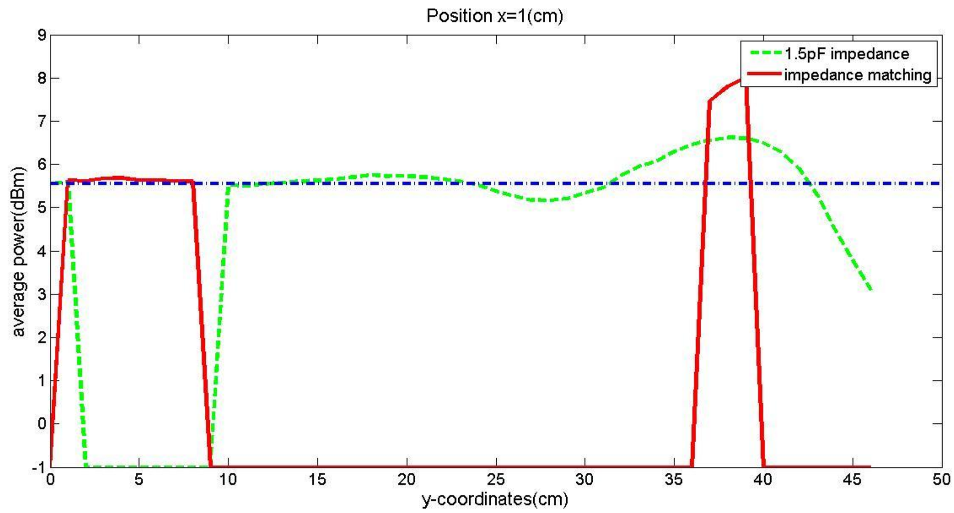
5.3 VARYING POSITION OF THE ADDITIONAL TAG

The aim of these experiments is to study the power variations as the additional tag is moved away from line-of-sight (LOS) between the reader and the intended tag. The performance is compared for both type 1 and 2 additional tags.

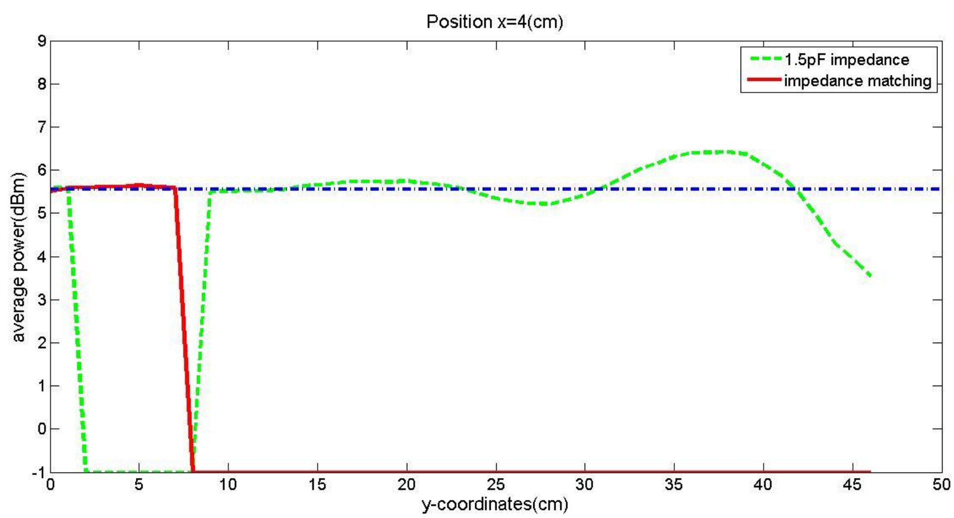


(a) x = 0cm

Fig 5.3: Power at reader for varying additional tag distance

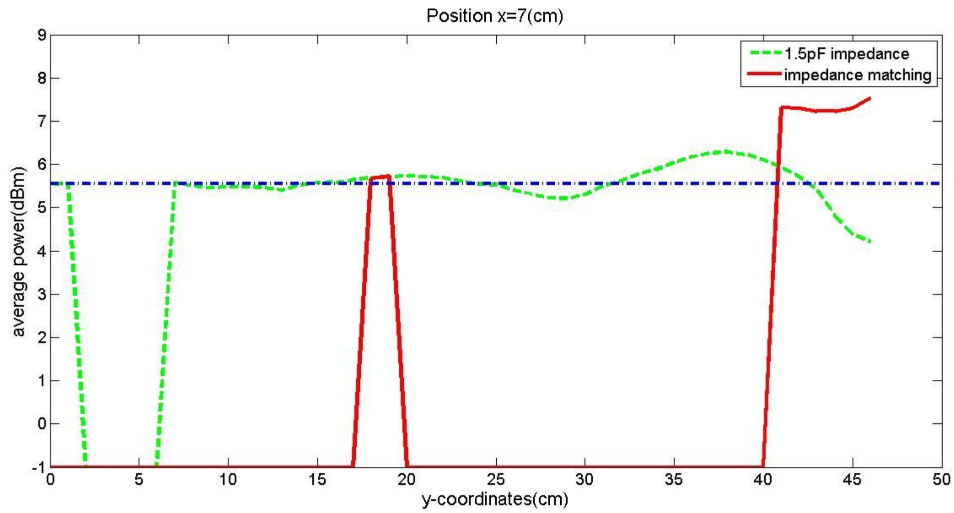


(b) x = 1cm

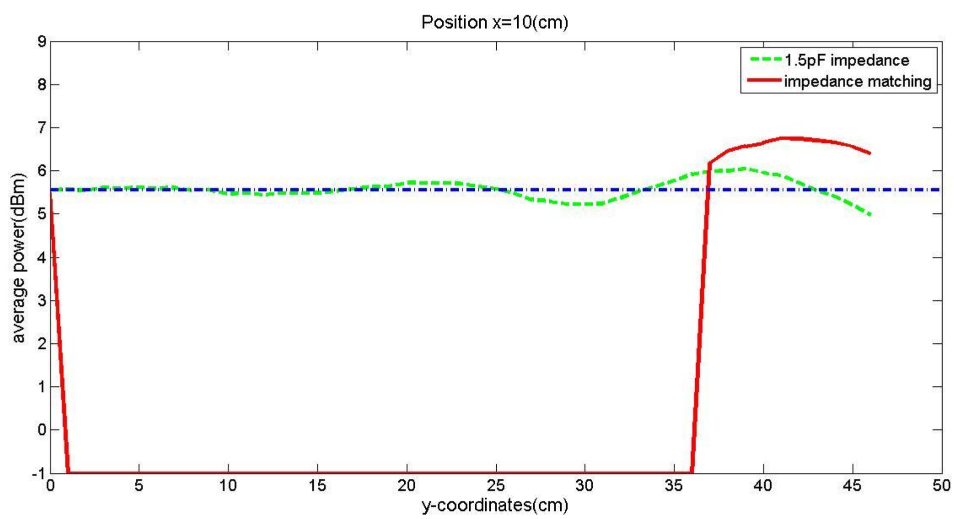


(c) x = 4cm

Fig 5.3: (Continued) Power at reader for varying additional tag distance

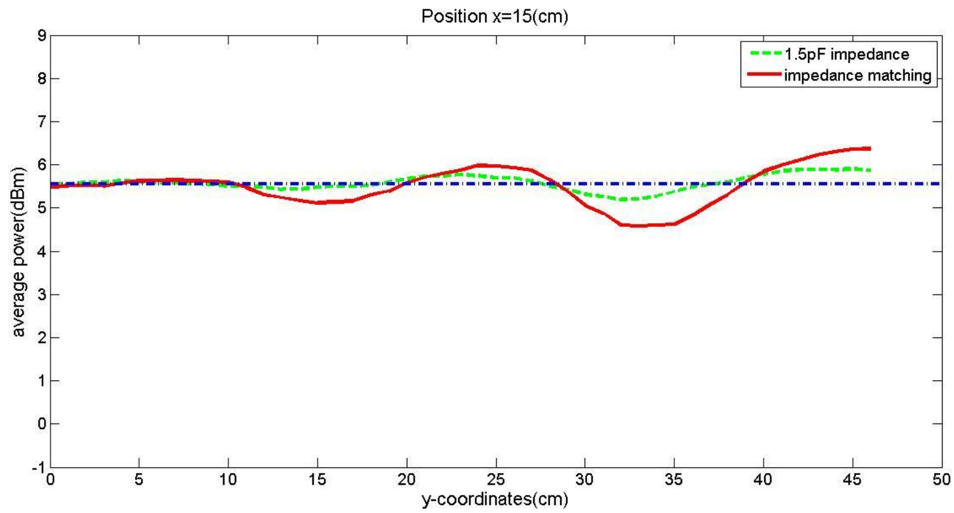


(d) x = 7cm

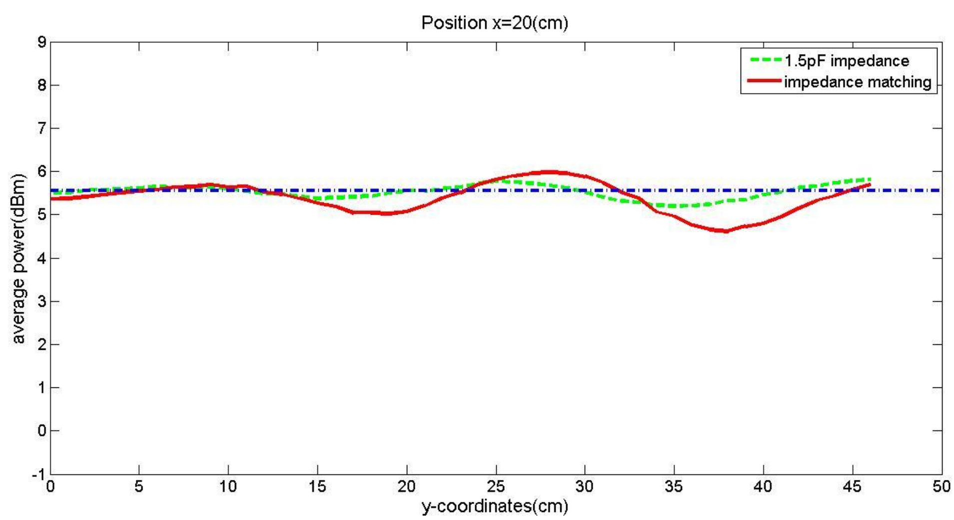


(e) x = 10cm

Fig 5.3: (Continued) Power at reader for varying additional tag distance



(f) x = 15cm



(g) x = 20cm

Fig 5.3: (Continued) Power at reader for varying additional tag distance

Fig 5.3 illustrates power level in dBm versus the distance (y-coordinate) of the additional tag in centimeters (cm), with the target tag T at origin (0,0). The red curve denotes the power variations for the additional tag type 1 (i.e. impedance matching scenario) whereas green curve is for the tag type 2 (i.e. 1.5pF impedance.) Blue, dashed line denotes the power level for the standalone tag – i.e. when only the target tag, T, is present. The mutual coupling among the antennas is visible as a dumped sinusoidal variation of signal power level. Furthermore, the Section 5.5 presents a comparative study that validates the considered mutual coupling model against the experimental results.

The type 1 additional tag (with a chip) produces the largest power variation. It significantly increases the power level at certain locations while preventing reading of the target tag, T, at many locations. The impedance of the chip is matched with antenna thus resulting in largest mutual coupling effect. In contrast, the additional tag type 2 has mismatched impedance. Hence, it reduces the impact of the additional tag through mutual coupling. Three key observations from the above results are:

1. Influence of the additional tags reduces as it moves away from the line of sight of the reader and the tag (i.e. as x increases.) Hence, the maxima and minima power level produced by either of the additional tags decreases. This corresponds to positions x = 15cm and x=20cm.

   Analysis: Considering the mutual coupling for the side-by-side (x=0cm) and parallel-in-echeleon (x>10cm) configurations [28], the latter results in weaker coupling effect and thus smaller power variations.

2. The additional tag type 2 enhances read rate at most positions except when it is close to the target tag. In fact, the additional tag 1 (original) outperforms the tag type 2 at those locations. Thus, the decision of switching the impedance by the additional tags should depend on its position. The dynamic impedance selection schemes [16] can be used to make the appropriate selection.

3. The additional tag type 2 results in a small phase shift due to the selection of its impedance. When the tag is close to line-of-sight (LOS), this results in a constructive interference. Moreover, the mutual coupling effect is the strongest around the LOS, as explained in Section 3. Consequently, it can deliver the largest improvement when the beamforming approach [16] is employed. In contrast, a destructive interference occurs when the additional tag moves away from the LOS. At the same time, its magnitude decreases thus reducing the negative impact.

5.4 VARYING DISTANCE BETWEEN THE TAG AND THE READER

Next, the distance of the target tag (T) to reader is varied to observe, if the beamforming approach could improve the read-rate, signal strength, and maximum communication distance.

Comparing received power among Fig 5.4 - Fig 5.6, we observe that the effect of mutual coupling decreases with distance between the reader and the tag (T). Hence, the tag can be read more consistently independent of the type of additional tag.

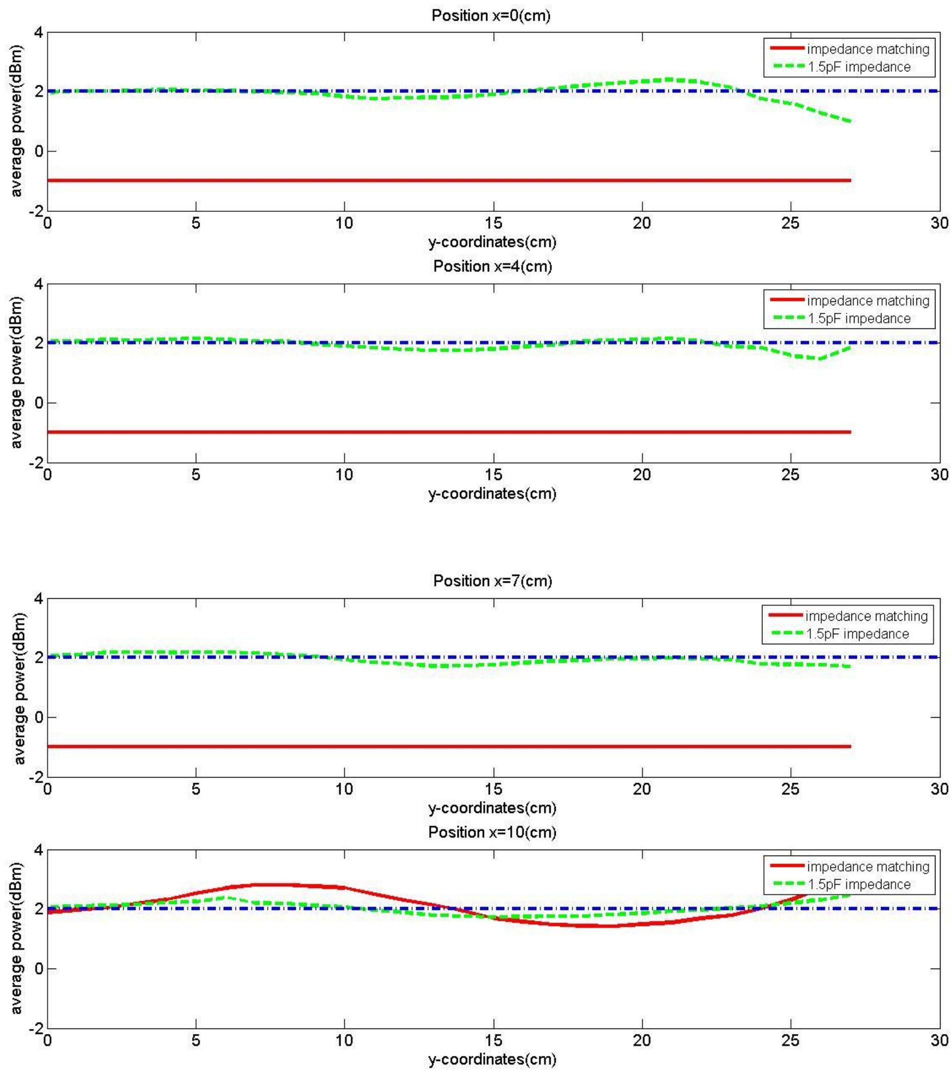


Fig 5.4: Power at reader for varying additional tag distance when tag T=30cm

Specifically, Fig 5.4 shows that the tag type 1 with impedance matching prevents the successful transmission for the distance of 30cm. In contrast, when the target tag is placed at distance equal to 80cm from reader, it can be read at almost all positions despite the presence of the additional tag type 1.

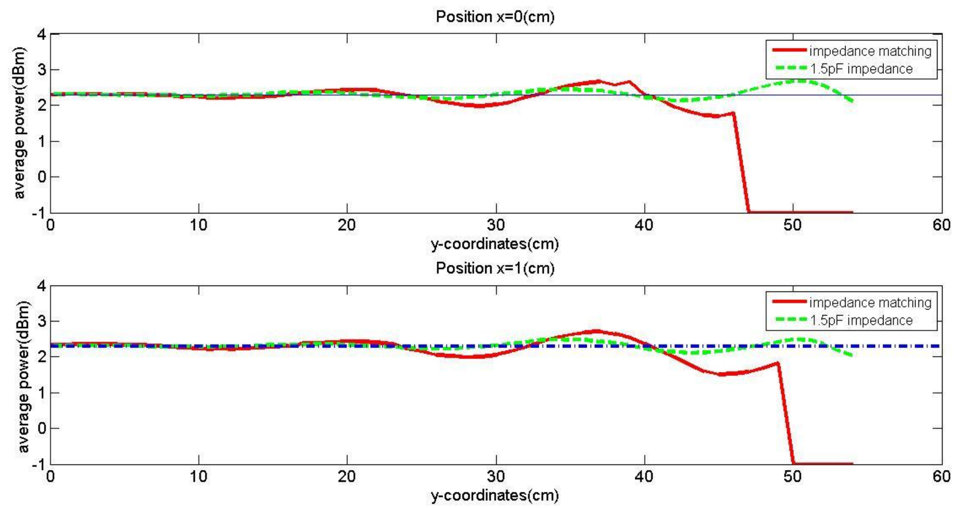


Fig 5.5: Power at reader for varying additional tag distance when tag T=60cm

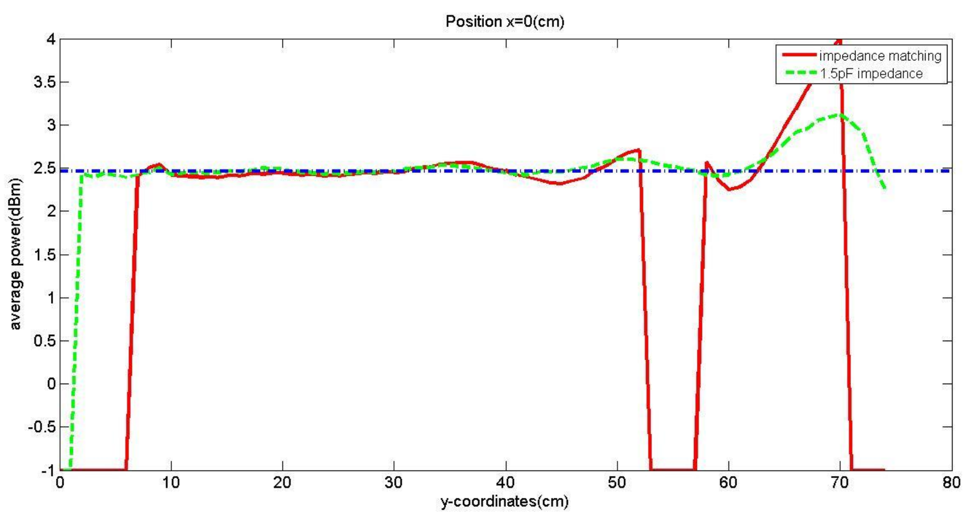


Fig 5.6: Power at reader for varying additional tag distance when tag T=80cm

Also, it is noticed that as the distance between the tag and the reader varies the sine wave period remains constant at about 16cm. This corresponds to the half wavelength of the reader's frequency (915MHz with no hopping – wavelength λ=32.78cm). Hence, the power levels of the reader/tag due to additional tag 2 (i.e. 1.5pF impedance) can be modeled as:

$$P_{reader,tag} = a(x,y)\, sin\left(\frac{\left(y+\left(\frac{x}{2}\right)\right)\pi}{8}\right) + b \qquad (2)$$

where x is horizontal distance of the additional tag from the line-of-sight of the reader and the tag (T), y is a vertical distance of the additional tag from the tag (T), a is the signal attenuation function of distance, and b is a system and topology specific gain. Value of the attenuation function, $a(x,y)$, decreases with the distance from the reader (increases when moving away from the target tag). For movement along the line-of-sight, a=0.5 for 1st sine cycle, a=1.2 for 2nd sine cycle. Value of b is equal to the baseline power level (i.e. power level of a stand-alone tag). Further study is presented in subsequent section where mutual coupling is attributed to the variation.

Remark: The empirical model (2) matches the mutual coupling formulation [28]. Hence, it can be inferred that the mutual coupling has the biggest impact on the propagation in the presented scenarios. Moreover, the beamforming approach [16] has to consider it as a major contributor to received RF signal modeling.

5.5 EXPERIMENTS WITH MULTIPLE ADDITIONAL TAGS

As in the real world environment there are multiple tags, this experiment is carried out for observing reading capabilities when there are more than one additional tag.

Following notations will be used:

Tag type 1 – additional tag with impedance matching scenario

Tag type 2 – additional tag with 1.5pF impedance scenario

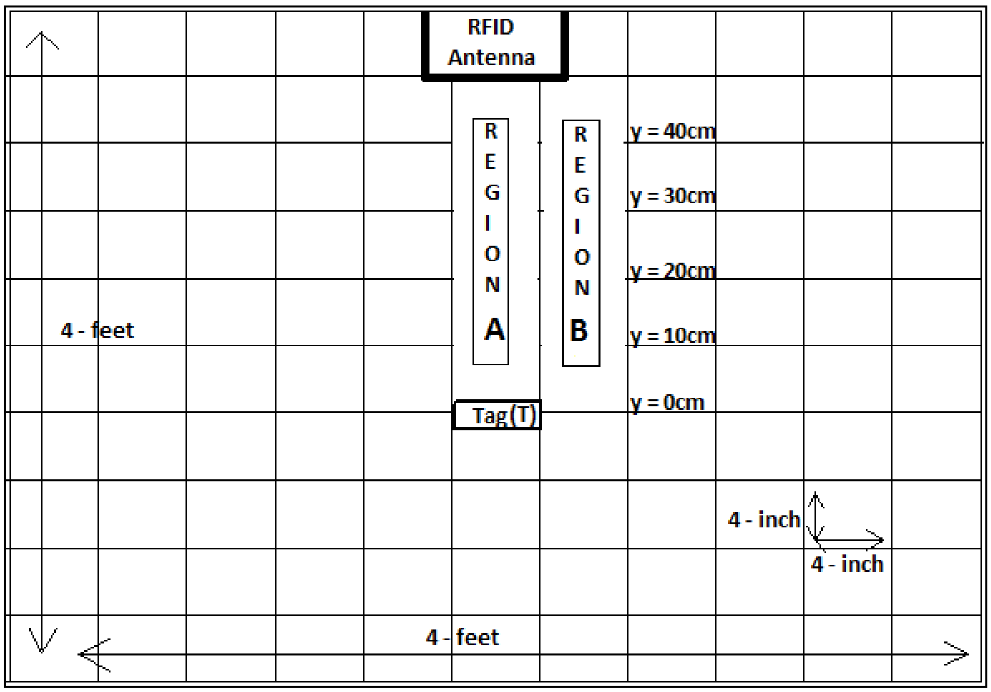


Fig 5.7: Topology overview for multi-tag scenarios

Fig 5.7 illustrates the placement of reader, target and additional tags during experiments. Region A denotes line of sight (i.e. x=0cm) whereas region B denotes away from line of sight at x=10cm. Y-coordinate increases as we move from intended tag (T) towards the reader antenna.

First experiment is carried out with 3 additional tags, 5cm apart from each other, along the line of sight of the reader and the tag (i.e. for x=0cm, region A). Table 5.2 summarizes the read rate and the received power measurements at the target tag, T. The read rate for tag type 2 is much better as compared to type 1 in almost all cases.

Again 3 additional tags are used, but now one of them is placed along the region A (i.e. for x=0cm) and other two in region B (i.e. for x =10cm), each 5 cm apart.

Next, four (4) additional tags are placed as 2m x 2m matrixes between the reader and the tag. Two additional tags, 5cm apart, are placed in region A (i.e. x=0cm) and the other two, 5cm apart, in region B (x=10cm). The position of the additional tags is varied and the measured power levels are shown in Table 5.3.

Overall, following observations can be drawn from the results (including the tables in appendix):

1. The power level increases for most locations with number of the type 2 tags since these tags create virtually larger (higher gain) antenna through the mutual coupling effect.

2. Even if there is a single tag in the region 40-50 cm, irrespective of the position of the other tags, the power level decreases significantly. Though when tag type 2 is used in this region, its read rate is 100%

3. When there is a tag in the region 30-35cm, the power level increases significantly irrespective of the position of the other tags. Though read rate for both type of tags is less than 100%. The special case is when tags are in the 40-50 cm region as described above. In such a case, the effects cancel each other.

4. Tag type 2 performs better than tag type 1 in terms of read rate and average power.

5. Read rate is negatively affected when a tag type 1 is close to either the target tag or the reader antenna.

6. Presence of a tag type 2 in a particular location might decrease the power level. However, an introduction of another additional tag at about 10-15cm from the reader will compensate for the negative impact of the first tag. As a result, the overall power level increases when compared with the standalone tag case (i.e. the benchmark power level.). Tables 1.2 and 1.3 for *y* in between 45-50cm illustrate this conclusion.

Thus, it can be concluded that if the power level is to be increased, then a (any type) tag should be placed at around 35cm. Whereas, if 100% read rate is to be achieved then the tag type B should be placed close to the reader antenna. The latter conclusion leads us to development of the improved reader antenna design shown in Section 6. Also, it is noticed that with increase in number of tag type B, read rate and power level is increased. Whereas for tag type A, read rate certainly decreases with increase in number of its tag type.

Table 5.2: Read rate with 3 additional tags

Distance of additional tag 1	Distance of additional tag 2	Distance of additional tag 3	Read Rate (%)		Power (dBm) Benchmark Power level = -16.7dBm	
x = 0 y in cm	x = 0 y in cm	x = 0 y in cm	Tag Type 1	Tag Type 2	Tag Type 1	Tag Type 2
5	10	15	0	100	-1	-16.45
10	15	20	0	100	-1	-17.1
15	20	25	0	100	-1	-17
20	25	30	0	100	-1	-17.33
25	30	35	100	100	-17.7	-18.4
30	35	40	0	100	-1	-18.1
35	40	45	0	100	-1	-18.15

Table 5.3: Experimental values using 4 additional tags

Y-Region Co-ordinates In cms	Case-I X-Region Co-ordinates =(25,30), for tag type 1			Case-II X-Region Co-ordinates =(25,30), for tag type 2		
	Power Px	Diff Px-Pavg	Diff Px-P	Power Px	Diff Px-Pavg	Diff Px-P
(5,10)	-16.15	-0.24	-0.55	-15.3	-0.56	1.4
(10,15)	-16.1	-0.29	-0.6	-15.65	-0.21	1.05
(15,20)	-16.3	-0.09	-0.4	-15.77	-0.09	0.93
(20,25)	-16.4	0.01	-0.3	-15.91	0.05	0.79
(25,30)	-16.2	-0.19	-0.5	-15.72	-0.14	0.98
(30,35)	NA	NA	NA	-15.69	-0.17	1.01
(35,40)	-17.2	0.81	0.5	-16.98	1.12	-0.28
(40,45)	-19.7	3.31	3	-20.5	4.64	-3.8
Average Power (Pavg)	**-16.39**			**-15.86**		

*P is standalone tag power i.e. -16.7dBm

Table 5.3 represents power variations when two tags in A-region are at 25cm and 30cm (in reference to origin at the target tag location). The position of the other two tags in B-region is varied. Difference between observed power level and its average is calculated. Also, difference is calculated between observed power level and standalone tag power. These statistical values gives specific trend when two tags are constant and other two are varied. This trend of decreasing power level (Px-P), till the mid-point, when additional tags are moved from tag towards the reader and then drastically decreasing as it approaches reader after slight improvement is observed to be more or less the same for all possible cases.

5.6 EXPERIMENTAL VALIDATION OF PROPAGATION MODEL

This section presents the comparison of experimental and theoretical results of the propagation model with additional tag. The simulations are performed based on the theory and equations discussed in the Section 3.

Simulations are carried out replicating the practical experiments scenario like gain of the RFID reader antenna, power from the reader, distances between tags and reader etc. We can observe that simulation results are in a good match with practical results. Also, it can be observed that simulated average power available at the reader is more when impedance of the additional tag is changed. Thus, the initial claim of increasing the power level by changing the impedance of the additional tag is verified, which also matches with practical experiments.

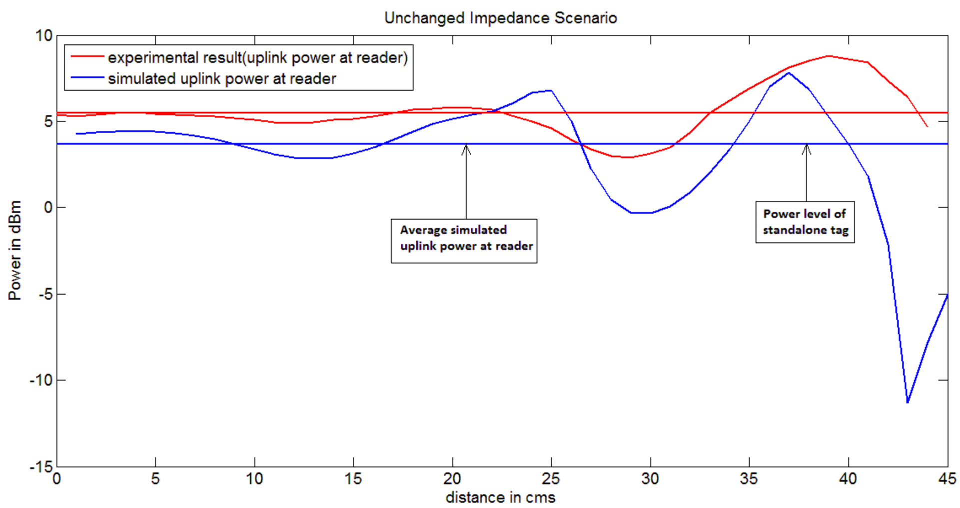


Fig 5.8: Simulation and practical results for unchanged impedance scenario

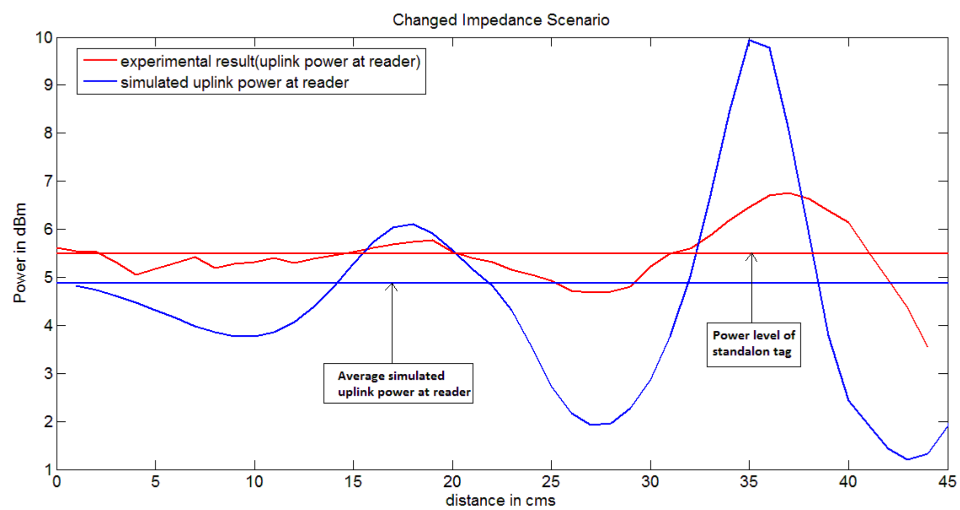


Fig 5.9: Simulation and practical results for changed impedance scenario

6. PROPOSED DESIGN OF READER ANTENNA FOR IMPROVED COMMUNICATION RANGE

From all the previous experiments, it is seen that there is an increase in signal strength if an additional tag is placed closed to the reader. This distance is the region when additional tag switches from near-field to far-field from the reader's range. For additional tag to be in far-field,

$$Dist \geq \frac{2D^2}{\lambda}$$; where D is the largest dimension of reader antenna

For practical experiments, readers antenna's largest dimension was 16cms and hence the additional tag will be in far-field if its atleast 15cms away from the reader antenna. Hence from the practical experiments and simulation results, improvement in signal strength was observed if an additional tag was around the 15cm region from the reader antenna.

Thus, we could increase the read range of the tag to be read by placing these additional tags in those regions. Hence, static beamforming in particular direction can be obtained by placing the tags at specific locations which would increase the reading range in that direction.

Fig 6.1 shows the result for achieving increased read range in particular direction. For this experiment, reader power is set to 12dBm and tag (to be read) is moved away from the reader till its maximum read range (which is 36cm). Nulls are observed in the region 26-30cm. Unmodified tag (imp matching) and modified tag (with 1.5pF chip impedance) is placed at 12cm from reader and its effects are observed.

Above result shows that by placing an additional tag at a particular position, nulls can be avoided and reading range can be increased. The best results are observed when 2 modified tags are placed at 12 and 15cm from reader. It avoids the nulls and increases reading range by 4cm.

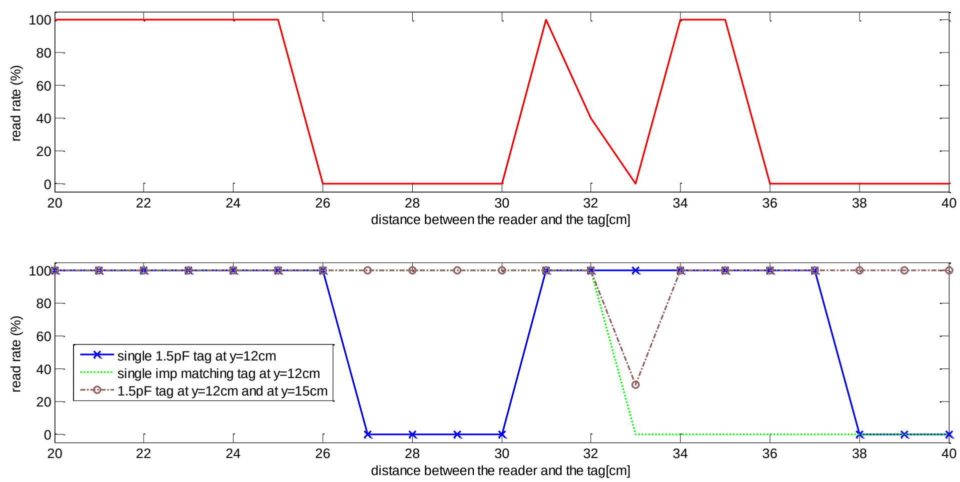


Fig 6.1: Static Beamforming Result for 12dBm reader power

Similarly can be observed in Fig 6.2, where reading range this time increases by 9cm when 2 modified tags are placed at 12cm and 15cm from reader.

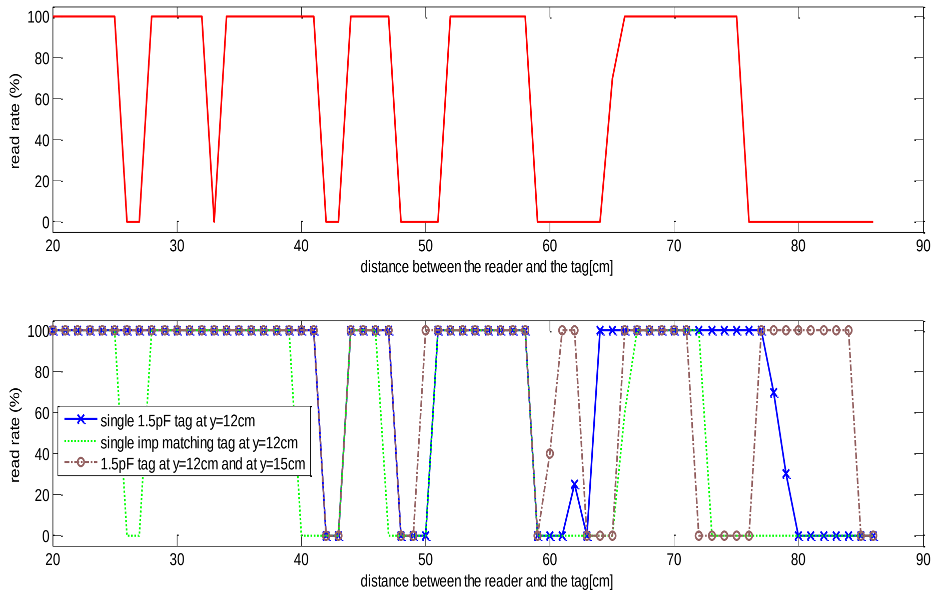


Fig 6.2: Static Beamforming Result for 20dBm reader power

7. TAG DESIGN CONSIDERATION

To implement the proposed beam forming approach in realistic scenario, the tag has to be expanded to allow switching between multiple impedances. Selection of this impedance is important and the details will be presented in future work. The criteria for selecting the impedance are that it should be slightly mismatched (from its maximum RCS). Maximum RCS for a typical UHF RFID tag is when its $X_c = -X_a$ and $R_c = 0$ [17]. Hence, the preferred impedance would consist of a capacitor with its value near that of the chip's capacitance. In real time applications, when the reader communicates with a particular tag, remaining tag in its vicinity will change its present impedance (i.e. conjugate matched) to the above value for a time period equal to the one when impedance is changed during modulation. For precautionary measures, whenever tag gets powered up, it can switch to its conjugate matched impedance.

8. CONCLUSION

The experiments and their analysis demonstrated that the proposed distributed beamforming [16] is feasible. The results demonstrate that the best results are achieved for the additional tag type 2, which has a capacitance 1.5pF, connected to the antenna. Furthermore, it has been demonstrated that the beamforming can increase received signal strength by up to 2.35dBm with single tag, and by 3.3dBm for 4 tags. Also, the read rate of the tag has been shown to improve by 52% when the additional tags of type 2 are introduced at the desired locations. Moreover, an empirical model has been derived that can be utilized to design a static beamforming setup. Also, the model will be used in future work to design a new beamforming scheme that outperforms [16]. Moreover, future work will include analysis of the signal quality (distortions and fading) that will provide more detailed understanding of the propagation issues and explains the read-rate variation. Finally, a detailed design of a new tag will be created to facilitate the beamforming scheme.

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II. RF TAG DESIGN FOR ACHIEVING DYNAMIC BEAMFORMING IN RFID

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Abstract

In practical scenario, RFID tag to be read is surrounded by additional RFID tags. Although these tags are passive, they reflect reader's incident signal which affects the power level at the tag end which is to be read. Null spots are created if these reflected signals interfere destructively at the tag end. Additional tags also change the antenna impedance of the tags due to mutual coupling between them. Thus, tags are no more in a matched condition and hence, require more power to achieve same reading range. This has been the primary reason for inconsistent reading of the tags. If certain property of these additional tags can be changed such that they always interfere constructively, then beamforming can be achieved at the tag end. This concept has been already discussed in the previous paper, but higher power level due to beamforming was achieved only at certain locations. In this paper, method to achieve higher power level consistently and at all locations is presented. This would eliminate null spots and also increase the reading range of the RFID tag.

Keywords – RFID, Mutal Coupling, backscattering, beamforming

1. INTRODUCTION

A typical RFID system consists of a reader/interrogator and one or more tags/transponders. RFID tags are used for purpose of identifying and tracking objects. RFID tags can be classified into active tag, semi-passive tag and passive tag depending on their source of electrical power. Depending on the application, one of the above tag types is chosen. When the objects are expensive, the cost of the tags is of little importance, and tags performance and its lifetime is more important. When objects are cheap, tags must be cheaper. These are the basic fundamentals in choosing the tag type.

When tags are intended to last for years and give better performance, active tags are chosen which have their own radio transmitter and receiver, powered by a local battery. Whereas passive tags has no local power source to use for transmitting and processing, and require all the power to come from reader. Hence, passive tags are cheaper than active tags and used for identifying inexpensive objects. Considering the advantages in terms of low cost and small size, passive tag is a good choice for RFID application. Hence there has been a lot of on-going research and development in passive RFID systems.

Passive tag converts reader's signal into DC voltage to power up its circuitry and it also depends on reader's signal to communicate back by switching its chip impedance. Designing passive tag is a challenge and has many design considerations. Traditionally, a lot of emphasis has been given on designing rectifier, regulator and backscattering circuitry [2-8]. Rectifier generates power supply voltage for frontend circuits and for whole chip from the reader signal, regulator maintains power supply to a certain minimum level and backscattering circuitry ensures proper communication with the reader. So, designing a good rectifier and regulator ensures power in the tag for its operation and backscattering circuitry ensures reliable communication with the reader. These blocks are very important for basic operation of a passive tag and hence, lot of emphasis has been given on its design.

Also, impedance matching between the antenna impedance and chip impedance of a tag is important which determines the maximum tag read range, given by [9]

$$r_{tag} = \frac{\frac{\lambda}{4\pi}\sqrt{P_t G_t G p \Gamma}}{\sqrt{P_{th}}} \qquad (1)$$

where λ is wavelength, P_t is the output power of the RFID reader, G_t is the gain of the reader, G is gain of the tag antenna, p is polarization mismatch and Γ is impedance matching coefficient between chip and the tag antenna given by:

$$\Gamma = \frac{4R_c R_a}{|Z_c + Z_a|^2} \qquad \{0 \leq \Gamma \leq 1\} \qquad (2)$$

where $Z_a = R_a + jX_a$ is the complex antenna impedance and $Z_c = R_c + jX_c$ is complex chip impedance. Thus any change in impedance matching coefficient directly affects the maximum reading range of the tag and when $Z_a\ and\ Z_c$ are conjugate matched Γ is equal to 1.

Variation in antenna impedance of the tag is observed due to mutual coupling between the surrounding tags. [9] shows that even 3-dB variation in impedance matching can change tag range by about 40%. Thus, there is decrease in the reading range of the tag and dead spots/ nulls are observed due to additional tags in proximity. The effect on read rate due to nearby tags has been discussed in [10-14]. Hence, it can be said that antenna impedance changes due to mutual coupling between the tags which in-turn changes the amount of power available to the tag's chip. This would affect the maximum reading range and create null spots. Mutual coupling effect and interference from the nearby tags has been studied but there has been no solution to mitigate this problem. In previous paper, change in power level due to interfering tag as a function of distance was derived. It was also demonstrated that by changing the chip impedance of the additional tags, beamforming at certain locations can be achieved.

However, it would be beneficial to increase power level at all locations. So in this paper, a method is proposed to achieve dynamic beamforming using additional tags as array antennas. This can be achieved by suitably changing the chip impedance of the additional tags to different impedances such that beamforming at all times is achieved.

Firstly, different factors' affecting the backscattered power is studied. Then, variation in antenna impedance due to mutual coupling from the surrounding tag is revised. Later, method for deriving impedance values is discussed along with the simulation results.

2. RFID SYSTEM MODEL

From [11], power available to the chip is given by

$$P_e = \left(\frac{\lambda}{4\pi r}\right)^2 P_r G_r G_t \left(\frac{4R_c R_a}{(R_c+R_a)^2+(X_c+X_a)^2}\right) \quad (3)$$

where λ is wavelength, P_r is the received power from the reader, G_r and G_t are the gains of the reader and the tag respectively, r is the distance between the reader and the tag, R's and X's are the impedances which have been already explained. P_e should be above a threshold value so that tag can power up its circuitry.

Passive RFID system can be considered as radar systems because the backward communication link i.e. from tag to reader is purely scattering. Thus applying radar equations to passive RFID system gives [15],

$$P_{backscattered} = SA_e \quad (4)$$

where $P_{backscattered}$ is the backscattered power by the tag antenna, S is the incident power density on the tag and A_e is the effective aperture of the tag antenna.

$$\text{with } S = \frac{P_r G_r G_t}{4\pi r^2} \text{ and } A_e = \frac{\lambda^2 G_t}{4\pi} K \quad (5)$$

where factor K is given by [16]

$$K = |1 + \Gamma^*|^2 \quad (6)$$

Γ^* is modified power reflection coefficient which is different from equation (2)

$$\Gamma^* = \frac{Z_a^* - Z_c}{Z_a + Z_c} \quad (7)$$

with Z_a and Z_c as defined earlier in equation (2)

$$\text{Finally, } K = \frac{4R_a^2}{|Z_a+Z_c|^2} \qquad 0 < K \leq 4 \quad (8)$$

3. DYNAMIC BEAMFORMING METHOD

In typical RFID applications, there are number of RFID tags in close proximity to one another. Even though these additional tags do not transmit any signal (or energy), part of the incident energy from the reader and intended tag (i.e. tag communicating with the reader) gets coupled with its antenna. This incident energy causes current flow in the antenna which reradiates some of the received energy. Part of this reradiated energy again couples with other additional tags and so on. This effect is called mutual coupling. Mutual coupling changes the antenna impedance of each RFID tag and causes not only power reflected, but also an undesired phase and amplitude distribution among the tags [17]. These phenomena may degrade the signal at the tag end and at the reader end.

From equation (3) and (4), it can be seen that change in chip impedance or antenna impedance affects both P_e and $P_{backscattered}$ differently. Due to mutual coupling, there is change in antenna impedance which will incur power loss at the tag end as antenna impedance and chip impedance are no more conjugate matched. So, more power would be required at the tag end to achieve the same reading range. Also, backscattered signal (reradiated energy) from the additional tags might interfere destructively at the tag end creating null spots.

One way to mitigate mutual coupling effect is to achieve beamforming at the tag end by using the additional tags as virtual arrays. If these additional tags are at right positions, beamforming at the tag end is achieved. But additional tags cannot always be at the right positions or cannot be manually placed at the right positions. So to achieve beamforming consistently without physically changing the position of additional tags, phase of the backscattered signal from additional tag needs to be appropriately changed.

From equation (4) and (5), it can be seen that K is the only factor which can change the backscattered signal, assuming transmitted power and gains are constant. But K is a factor dependent on antenna and chip impedance of a tag; of which antenna impedance cannot be changed by choice. So, chip impedance is the only factor by which backscattered signal can be controlled/varied.

From equation (8), maximum value of K=4 when $X_C = -X_a$ and $R_C = 0$ (short circuited) which means that tag re-radiates four times as much power as compared when matched antenna i.e. when K=1. But due to mutual coupling there is a variation in antenna impedance which means $X_c \neq -X_a$. Due to this, reflected signal from the additional tags undergoes phase shift which might interfere constructively or destructively at the tag end. So, the chip impedance must be varied such that it compensates these phase changes introduced due to mutual coupling. Also, phase change due to additional distance traveled by the reflected signal must also be compensated. Thus, additional tag will vary its chip impedance appropriately depending upon its position with respect to the tag. Also, K>1 to re-radiate maximum energy back.

Hence from equation (8), $\frac{4R_a^2}{|(R_a+R_c)+j(X_a-X_c)|^2} \geq 1$ for K>1

It can be seen that when $R_C = 0$, most of the energy is re-radiated back. So, for $R_C = 0$ we get

$$abs(X_a - X_c) \leq \sqrt{3}R_a \qquad (9)$$

If $X_a - X_c$ is positive, signal will lead the phase with respect to original signal whereas if it is negative then there will be phase lag.

To achieve beamforming, reflected signal must lead the phase so as to compensate the phase introduced due to additional distance traveled and also compensating mutual coupling effect. Thus, equation (9) gives us the bound for how much X_c can be varied given that X_a can be estimated with the mutual coupling effect for K to be greater than 1.

4. SIMULATION SCENARIO

Fig 4.1 replicates simulation scenario where reader and the tag (T) are at fixed distance (i.e. 60cms) and reader is taken as a reference point. Additional tag is moved along x-direction i.e. from reader towards the tag (T) and in y-direction i.e. away from the line of sight.

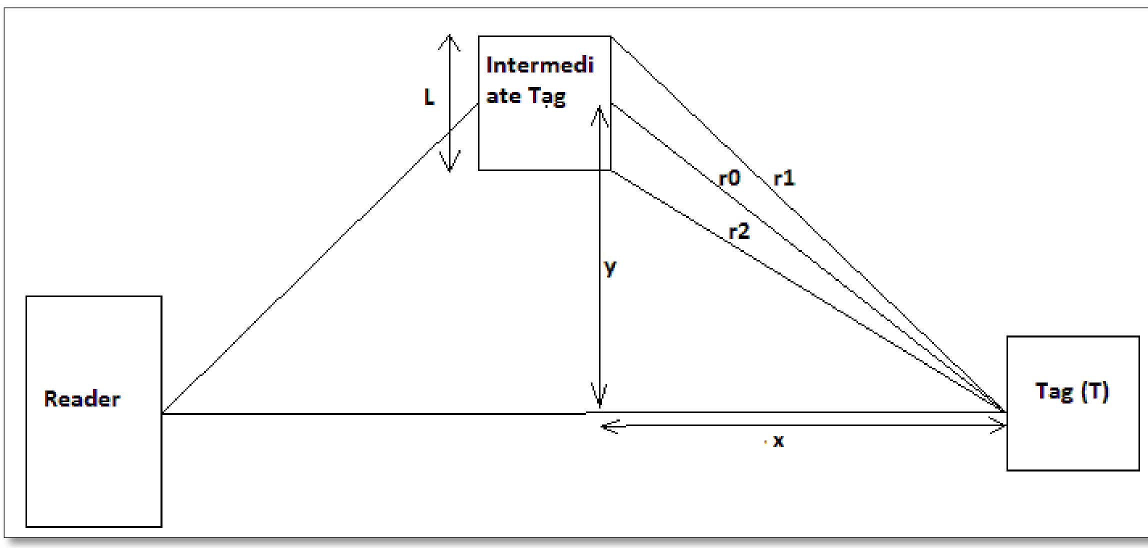

Fig 4.1: Simulation Scenario

Simulations are carried out to observe the power available at the tag (T) end due to incident energy from the reader and reflected energy from the tag. Depending upon the position of the additional tag, reflected signal will interfere constructively or destructively with the incident signal and available power at the tag (T) end will vary.

Both tags are identical and are considered as dipole. This is a valid assumption as most of the UHF RFID tags are similar to dipole. E_{inc} is the incident electric field at tag (T) from the reader and $E_{reflected}$ is the backscattered electric field from the additional tag. Thus, power at tag (T) is the addition of E_{inc} and $E_{reflected}$. An expression for the reflected electric field from the dipole can be written in the following manner [19]

$$E_{reflected} = \frac{j30E_{reader}}{(Z_c + Z_a)\beta \cos^2\left(\frac{\beta L}{4}\right)} \left[\frac{e^{-j\beta r_1}}{r_1} + \frac{e^{-j\beta r_2}}{r_2} - \frac{2\cos\left(\frac{\beta L}{2}\right)e^{-j\beta r_0}}{r_0}\right] \quad (10)$$

where $\beta = \frac{2\pi}{\lambda}$, $r_0 = r$ (distance between additional tag and tag (T)), $r_1 = r + \frac{L}{2}$ and $r_2 = r - \frac{L}{2}$, L being the length of the tag and E_{reader} is the incident electric field on the additional tag from the reader. Thus by changing Z_c, electric field from additional tag can be changed which would change electric field at tag (T). Also, phase change due to additional distance traveled from the additional tag is also considered. For simulations, mutual coupling between the reader and the tag (T) is neglected as reader is assumed to be far-off from the tag.

It is important to note that Z_a, antenna impedance, changes due mutual coupling effect from nearby tags. From [18], it can be seen that mutual impedance varies as a distance between the two antennas. Thus antenna impedance is dependent upon x and y w.r.t tag (T) to be read.

From the Fig 4.1, it can be seen that r_1, r_2 and r_0 are also dependent on x and y. So to obtain chip impedance, following are the steps:

1. $E_{reflected}$ is integrated over x and y i.e. $E_{avg} = \iint_0^{x,y} E_{reflected}\, dxdy$
2. $E_{avg} = \frac{dE_{avg}}{dZ_c} = 0$ which will give maximum value for chip impedance

Thus, chip impedance can be calculated using above steps when its location w.r.t tag (T) is known.

5. SIMULATION RESULTS

Initially, simulation is performed to observe the difference in the power available at the tag (T) end due to the mutual coupling effects. P_{th} is the minimum power required at the tag (T) to power up its circuitry assuming tag's (T) chip impedance is conjugate matched with antenna impedance. Assume that the incident power at tag (T), when there are no additional tags, is P_{th}. Thus if the power level is below P_{th} then tag (T) will not operate.

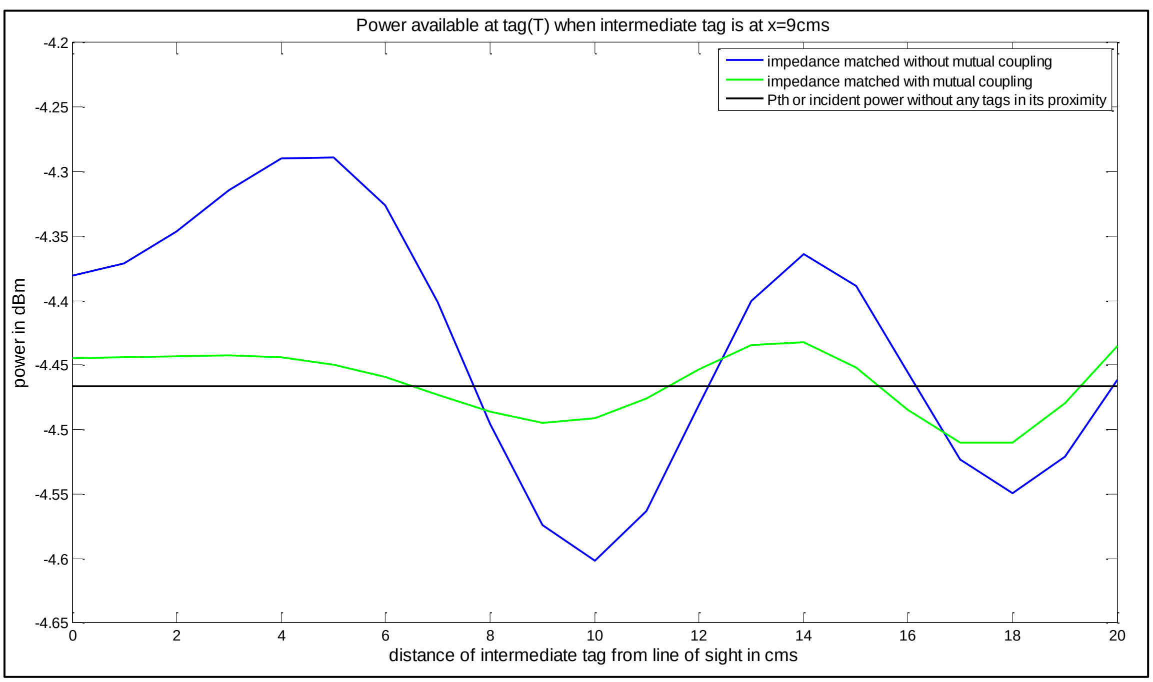

Fig 5.1: Additional tag with impedance matching

Now, additional tag is placed at 9cms from the reader and is moved away from the line of sight. For this part of the simulation, chip impedance of the additional tag is not switched. Considering that P_{th} is the minimum/threshold power required by the tag (T) for its operation, it can be seen from Fig 5.1 that for approximately half the time tag (T) would not operate due to additional tag. As mentioned previously, that mutual coupling changes the antenna impedance of the antenna, as explained. Hence, tag (T) is no more conjugate matched and more power will be required to power up its circuitry i.e. P_{th} increases. This would mean that tag (T) will not at all operate for green line.

Change in antenna impedance due to mutual coupling depending upon the configuration and position is given in [18] which are used during simulations.

From here on, all the simulations will be carried out considering the effects of mutual coupling. To counter the effect of mutual coupling and to increase the power level at the tag (T), chip impedance of the additional tag is changed to Xc1. This value is chosen by taking into consideration the maximum deviation in impedance(X) due to mutual coupling. From [18] it can be seen that maximum deviation due to mutual coupling in X is ± 40. Thus, Xc1 is taken as +40.

It can be observed that by switching the chip impedance of the additional tag to Xc1, there is an increase in power level at certain locations. But it also decreases the power level at remaining locations. Thus, it is desirable to switch the impedance of the additional tag to a different value, when Xc1 decreases the power level. For instance in Fig 5.2, if the additional tag is switched to another impedance, say Xc2, at locations 9 and 14cm and after 18cm, then improvement in power level at those locations can also be obtained. Xc2 is selected to be -40, based on the previous explanation.

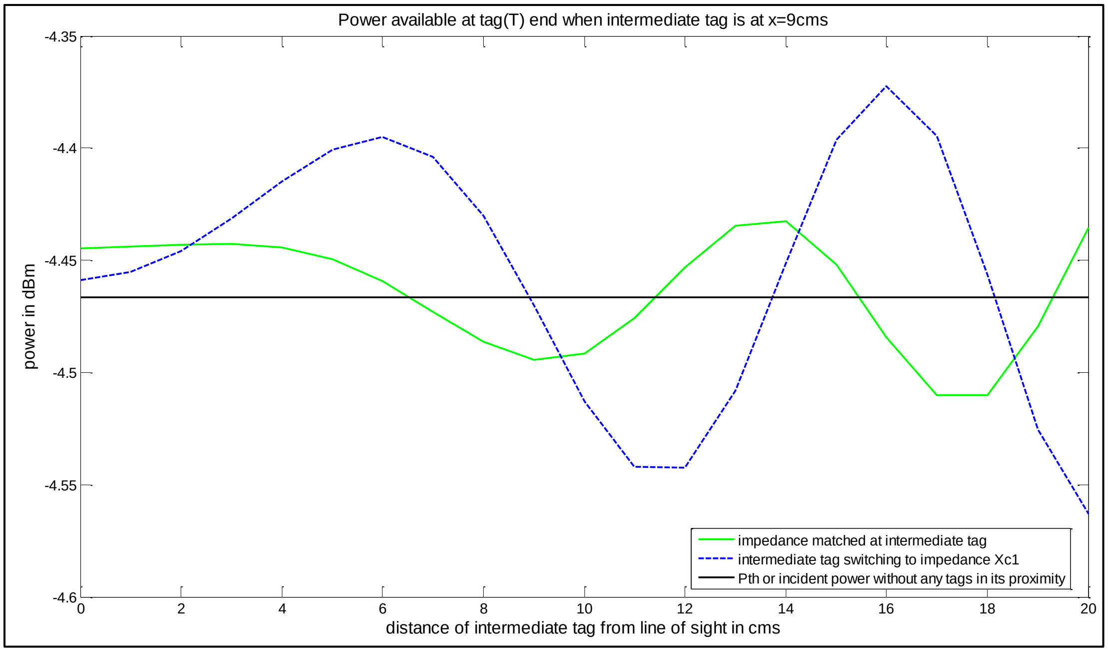

Fig 5.2: Additional tag switching to impedance Xc1

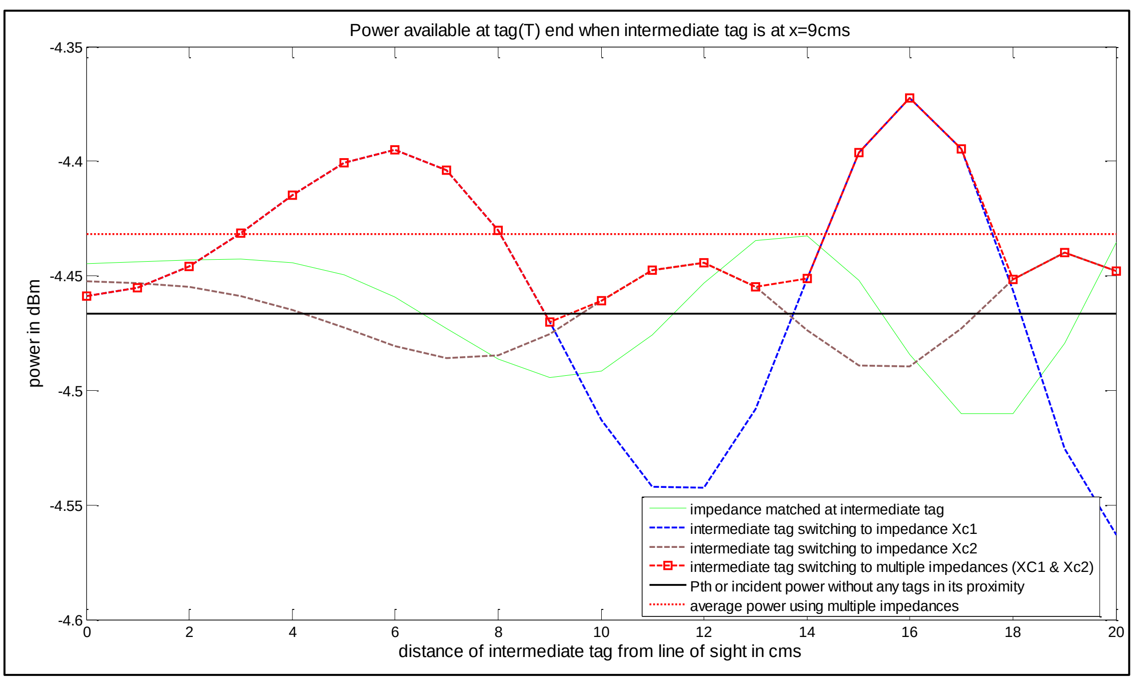

Fig 5.3: Additional tag switching to different impedances when it is at x=9cms

From Fig 5.3, it can be seen that by switching chip impedance of additional tag to Xc1 and Xc2 depending upon its position, higher power levels can be achieved consistently. Thus, we get a higher average power as compared to the incident power when chip impedance of the additional tag is varied suitably. However, decision of switching to particular impedance will depend upon its location with respect to tag (T).

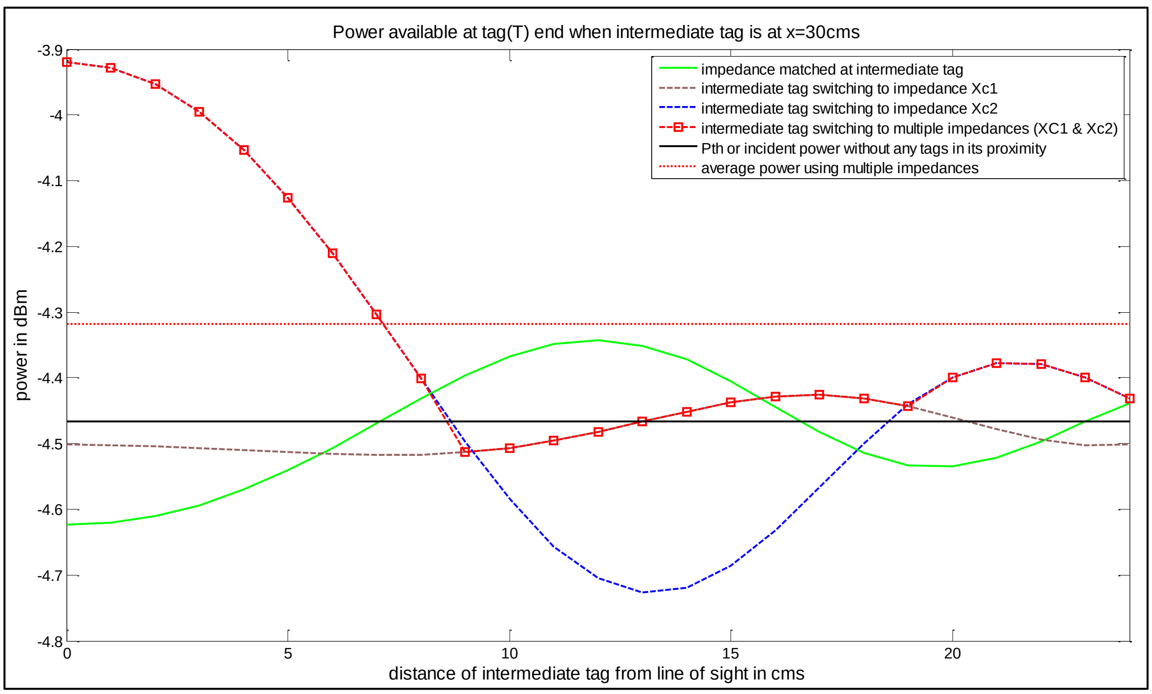

Fig 5.4: Additional tag switching to multiple impedances when it is at x=30cm

For Fig 5.4, distance between additional tag and reader is changed to 30cm. For this particular situation, impedance must be switched at 9 and 19cms. In fact in this case, it would be best if additional tag switches between Xc2 and to impedance matching. Thus, the decision of switching to which impedance and at what location will vary depending upon the location of the additional tag with respect to tag (T). Hence, it is important for additional tag's to have prior information about when and to which impedance it must be switched.

6. CONCLUSION

For achieving consistent beamforming, it is necessary for a tag to switch to different chip impedance’s. Method for obtaining the values of chip impedance is described. By using additional tags and suitably switching chip impedance’s, considerably higher power can be achieved at the intended tag end. This would not only avoid the null spots but will also increase the reading range of the RFID tag. However it is necessary to have prior knowledge about when to switch and to what impedance. This would be addressed in future work and also, further study about mutual coupling aspects between multiple antennas is required to achieve the desired beamforming.

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2. CONCLUSION

It is evident that RFID tag antennas scatter incident radiation and have significant effects on neighboring tags. Thus, additional tags limit the reading range to shorter distances than expected for an isolated tag design. It also affects the reading rate. Decrease in reading range and reading rate occurs due to interference and mutual coupling from surrounding tags. So, either interference from surrounding tags has to be reduced or use these additional tags to achieve beamforming by using them as virtual antenna arrays. To start with, chip impedance of additional tags is changed to fixed impedance which helps reducing interference and achieves increase in power level at certain locations. This is seen from the practical experiments carried out and verified using simulation results. Then, chip impedance of the additional tags is suitably varied to different impedances so that increase in power level at all locations can be achieved. Thus, beamforming is achieved. Also, a new method is proposed for increasing the range of RFID tag and shown by carrying out practical experiments. Thus, by suitably changing the chip impedance of additional tags – reading range, read rate and power level can be increased. Hence, it can be concluded that the proposed method is successful.

VITA

Pratim Mukesh Shah was born in Mumbai-Maharashtra, India, on January 30, 1986. In July 2008, he received his Bachelor of Engineering in Electronics and Telecommunications Engineering from Pune University. He joined Global Sourcing Group in December 2008 as a Telecom Analyst and worked in the field of Telecommunications for 11 months. He started his Master of Science program in Electrical Engineering at Missouri University of Science and Technology in January 2010. He worked as a research assistant under the guidance of Dr. Maciej Zawodniok from January 2010 to December 2011. He graduated in May 2012.