# An Overview of Near Field UHF RFID

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***Abstract*— In this paper, an overview of near field UHF RFID is presented. This technology recently received attention because of its possible use for item-level tagging where LF/HF RFID has traditionally been used. We review the relevant literature, discuss basic theory of near and far field antenna coupling in application to RFID, and present some experimental measurements.**

## I. Introduction

RADIO frequency identification (RFID) [1] is an automatic wireless data collection technology with a long history [2]. In a passive RFID system, the reader transmits a modulated RF signal to the tag consisting of an antenna and an integrated circuit chip. The chip receives power from the antenna and responds by varying its input impedance and thus modulating the backscattered signal. First functional passive RFID systems with a range of several meters appeared in early 1970's [3]. Since then, RFID has significantly advanced [4-7] and experienced a tremendous growth.

Low frequency (LF, 125-134 KHz) and high frequency (HF, 13.56 MHz) RFID systems are short range systems based on inductive coupling between the reader and the tag antennas through a magnetic field. Ultra-high frequency (UHF, 860-960 MHz) and microwave (2.4 GHz and 5.8 GHz) RFID systems are long-range systems which use electromagnetic waves propagating between reader and tag antennas. UHF RFID systems have several advantages compared to LF/HF systems but their performance in general is more susceptible to the presence of various dielectric and conducting objects in the tag vicinity. Currently, near field UHF RFID receives a lot of attention as a possible solution for item level tagging (ILT) in pharmaceutical and retailing industry [8-12].

Near field antenna concept is well established technical area with existing standards [13, 14], measurement techniques [15-17], and companies which specialize in design and testing [18]. Near field coupling is already being used in such areas of UHF RFID as printer coupler [19] and conveyor belt applications [20]. Other near field HF, UHF, and microwave applications, to name a few, include short range wireless communication, also known as near field communication (NFC) [21-27], hyperthermia treatment [28-31], MRI imaging [32-35], detection of buried objects [36], measuring material properties [37], and various modulated scattering probe techniques [38]. In current article, we discuss basic theory of near and far field antenna coupling in application to RFID and present some experimental measurements with emphasis on physical tag performance.

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## II. Theory

### A. Antenna Field Regions

The space around the reader antenna can be divided into two main regions as illustrated in Figure 1: far field and near field. In the far field, electric and magnetic fields propagate outward as an electromagnetic wave and are perpendicular to each other and to the direction of propagation. The angular field distribution does not depend on the distance from the antenna. The fields are uniquely related to each other via free-space impedance and decay as $1/r$. In the near field, the field components have different angular and radial dependence (e.g. $1/r^3$). The near field region includes two sub-regions: radiating, where the angular field distribution is dependent on the distance, and reactive, where the energy is stored but not radiated.

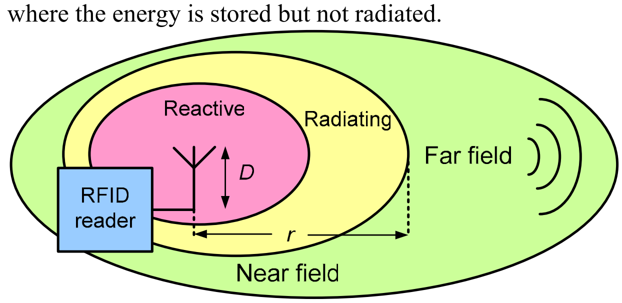


Fig. 1. Antenna near and far field regions.

For antennas whose size is comparable to wavelength (used in UHF RFID), the approximate boundary between the far field and the near field region is commonly given as $r = 2D^2/\lambda$ where $D$ is the maximum antenna dimension and is the wavelength. For electrically small antennas (used in LF/HF RFID), the radiating near field region is small and the boundary between the far field and the near field regions is commonly given as $r = \lambda / 2\pi$. An excellent overview of near and far field regions can be found in [39] while more detailed analysis can be found in [38, 40, 41]. It is important to remember that reference point of antenna structure (also referred as phase center of antenna) depends on antenna geometry and its electrical size [42].

*B. General Antenna Coupling*

In general, the power $P_{chip}$ absorbed by the RFID tag chip can be expressed as

$$P_{chip} = P_{reader}\ \rho\ C\ \tau\ , \qquad (1)$$

where $P_{reader}$ is the output power of the reader, $\rho$ is the impedance matching coefficient between the reader and its antenna, $C$ is the coupling coefficient (the power transmission loss) between the two arbitrarily oriented reader and tag antennas, and $\tau$ is the impedance matching coefficient between the tag chip and its antenna. Impedance matching coefficients can be expressed as [43]:

$$\rho = \frac{4R_r R_t}{\left|Z_r + Z_t\right|^2}\ ,\ \tau = \frac{4R_c R_a}{\left|Z_c + Z_a\right|^2}, \qquad (2)$$

where $Z_r = R_r + jX_r$ is the reader output impedance (typically 50 Ohm), $Z_t = R_t + jX_t$ is the transmitting antenna impedance, $Z_a = R_a + jX_a$ is the tag antenna impedance, and $Z_c = R_c + jX_c$ is the chip impedance. For example, when the chip is directly connected to the reader output (conducted tag) and perfectly matched, the coupling coefficient is $C = 1$. Main factors which affect coupling coefficient are:

- Reader and tag antenna geometries;
- Relative position of antennas (distance and orientation);
- Environment, including any objects near antennas.

The signal transmission between the antennas, including above effects, can be represented with a well known linear two-port network shown in Figure 2 where the coupling coefficient is the transmission loss between two ports.

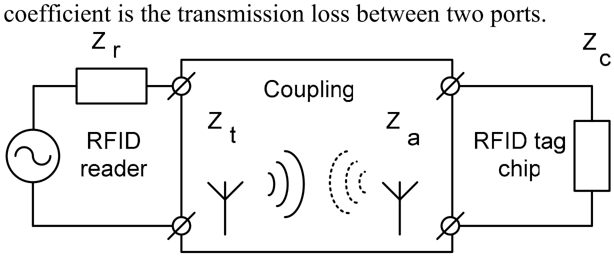


Fig. 2. Antenna coupling in general RFID system.

Other equivalent models for coupling are discussed in antenna literature [38, 40] and have been extensively used in analysis of LF/HF RFID systems [44-50] and inductive biomedical telemetry systems [51, 52].

*C. Far Field Coupling*

When the tag antenna is located in the far field of the reader antenna, the mutual effect of antennas is minimal and the antenna performance parameters (gain and impedance) can be specified independently from each other. The coupling coefficient can be written as:

$$C = G_t L_{path}\, G_r\ p\ , \qquad (3)$$

where $G_t$ is the gain of the transmitting reader antenna, $L_{path}$ is the propagation path loss, $G_r$ is the gain of the receiving tag antenna, and $p$ is the polarization mismatch loss between the reader and the tag antennas. Path loss strongly depends on propagation environment [53, 54] including other tags in the vicinity [55, 56] and the object the tag is placed on [57-59]. In free space, the path loss is given by well known Friis equation [60]:

$$L_{path} = \left(\frac{\lambda}{4\pi d}\right)^2, \qquad (4)$$

where $d$ is the distance to the tag.

When the tag antenna is located in the near field of the reader antenna, the coupling between the antennas affects the impedance of both antennas and the field distribution around them. The equivalent antenna performance parameters (gain and impedance) can no longer be specified independently from each other and become position and orientation-dependent [61-63]. In general, to calculate the power received by the tag in such situation, one needs to perform a three-dimensional electromagnetic simulation of the near field problem [64] except for some simple cases where analytical solution is possible [65] or when the tag is small and does not perturb the field of the reader antenna.

The near field of a reader antenna can have several tangential and radial electric and magnetic field components which can all contribute to coupling. Two ultimate cases are magnetic (inductive) coupling and electric (capacitive) coupling. In magnetic RFID system, both reader and tag antennas are coils inductively coupled to each other like in a transformer. If the tag antenna is small, the magnetic field created by the reader antenna is not perturbed by the tag, and the coupling coefficient is proportional to [44, 45]:

$$C \propto f^2 N^2 S^2 B^2\ \alpha\ , \qquad (5)$$

where $f$ is the frequency , $N$ is the number of turns in tag antenna coil, $S$ is the cross-section area of the coil, $B$ is magnetic field at the tag location created by the reader antenna, and $\alpha$ is the coil misalignment loss.

*D. Material Penetration*

The depth of penetration of harmonic time-varying electric and magnetic fields into materials is known as skin depth and is given by the following formula [66]:

$$\delta = \sqrt{\frac{1}{\pi\,\mu\,\sigma\,f}}, \qquad (6)$$

where $\sigma$ is the electrical conductivity and $\mu$ is the magnetic permeability. Time-varying electric and magnetic fields are related to each other via Maxwell's equations and penetrate any given material to the equal extent. For aluminum (nonmagnetic material, $\sigma = 3.77\cdot 10^7\, S/m$), the skin depth is 0.23 mm at 125 KHz (LF), 22.3 um at 13.5 MHz (HF), and 2.7 um at 900 MHz (UHF).

## III. NEAR-FIELD UHF RFID SYSTEMS

The basic near field UHF RFID concept is to make UHF RFID system work at short distances and on different objects as reliably as LF/HF RFID [8]. Below we describe several approaches to implementing near field UHF RFID systems using existing reader modules and tag ICs.

1. First, and most obvious, approach is to use an existing UHF RFID system with full reader output power and standard (far-field) reader antennas and tags. It can be expected that in most cases the UHF RFID tag which can operate in the far field should receive more than adequate power to operate when brought closer to RFID reader antenna into the near field. However, some applications require only short range reading zone. Since the field region is not localized, such system may unintentionally see some other (long range) tags present in far field region.

2. Second approach is to use low reader output power mode in an existing UHF RFID system, with standard (far-field) reader antennas and tags. Such system has lowest cost (no new special reader antennas or tags are required). However, because of lower reader output power, high performance (long range, material insensitive) tags must be selected to provide adequate read performance on RF non-friendly objects.

3. Third approach is to use short range tags in an existing UHF RFID system, with standard (far-field) reader antenna operated in full reader output power mode. The tags can either use magnetic antennas or be standard tags intentionally mismatched by tuning so that they respond only to strong fields in the vicinity of the reader antenna. Such system does not require special reader antennas but, like in the first approach, the field region is not localized and unintentional tag reads from far field zone are possible.

4. Finally, one can use special near-field reader antennas and tags. Such system will have the best performance but highest cost (new special reader antennas and tags will be required) and can be designed similarly to existing LF/HF RFID systems which use inductive reader coil antennas to create strong localized magnetic field region. For UHF, the antenna coil sizes must be appropriately resized (scaled down with frequency).

The primary coupling mechanism in near field UHF RFID can be either magnetic (inductive) or electric (capacitive). Depending on particular reader antenna and its environment, the field distribution in RFID system can be affected by the presence of various objects. Inductive coupling systems, where most reactive energy is stored in magnetic field, are mostly affected only by objects with high magnetic permeability. Such objects are not common in everyday life, which is why this coupling is used in LF/HF RFID systems that are able to operate in close proximity to metals and liquids. On the other hand, capacitive coupling systems, where most reactive energy is stored in electric field, are affected by objects with high dielectric permittivity and loss. Simple examples of antenna structures for near field inductive and capacitive coupling are solenoid coil and parallel plate capacitor [44, 67].

Inductive and capacitive coupling can be associated with different regions of reader antenna impedance which are illustrated in Figure 3 for a dipole antenna case. When radiation resistance is low, the energy is not radiated and contained in the near field (non-radiative region) which can be inductive or capacitive. At low frequencies (significantly lower than antenna resonant frequency), dipole antennas become highly capacitive (in contrast with coil antennas, used in LF/HF RFID, which become highly inductive). When radiation resistance is high (radiative region), antenna radiates and the near field region can be either inductive or capacitive, depending on the particular driving frequency.

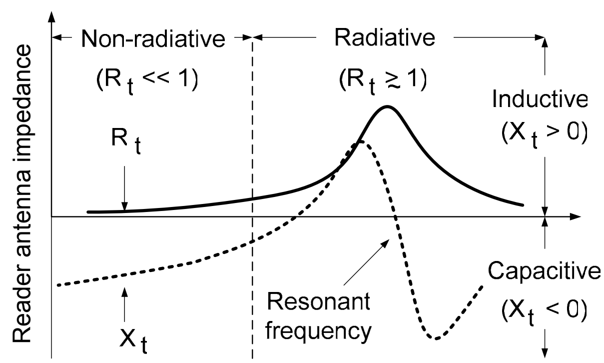


Fig. 3. Different regions of reader antenna impedance (shown for a typical dipole antenna).

The tag antennas for near-field UHF can be made very small [68-71] and sensitive to either electric or magnetic field similar to field probes [72-75]. Properties and limitations of such electrically small antennas are well known [76-80]. Typically, such antennas are poor radiators, well suitable for near field applications. For example, the radiation resistance of a small loop of diameter $a$ given by

$$R_r = 20\pi^6 \left(\frac{a}{\lambda}\right)^4 , \quad (7)$$

is only 0.016 Ohm at 900 MHz for $a = 1$ cm.

Currently several companies have some versions of near-field UHF RFID tags for item level tagging [81-90]. Most of these tags use small loop-like structures which may also be coupled (e.g. via inductive feed [91-93]) to dipole-like structures for better sensitivity in far field region. UHF near field antennas are also the subject of recent interest in UWB short-range communications where the antenna design task is even more challenging because of the bandwidth requirements [94, 95]. In near field, detailed analysis is important for each particular reader and tag antennas combination and their environment. Such analysis can be carried using various electromagnetic simulation tools which are already being used in RFID for modeling [96-101].

## IV. MEASUREMENTS

To illustrate some of the approaches to implementing a near field UHF RFID system described in the previous section, we characterized the performance of standard UHF RFID tag in the near field using experimental setup shown in Figure 4. The tag was placed at different distances from the reader antenna, spanning both near and far field regions. The measurement equipment functioned as an RFID reader with variable frequency and output power which was increased until the tag response was detected. This allowed us to determine the minimum reader output power needed for tag to respond as a function of frequency.

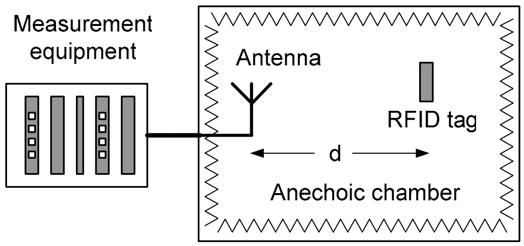


Fig. 4. Measurement setup.

The block diagram and the photograph of the measurement equipment block diagram are shown in Figure 5 and Figure 6. The equipment was the same as described in [102]. It was built on a National Instruments modular PXI hardware platform and consisted of RF signal generator, RF signal analyzer, a computer controller running LabVIEW, a power amplifier, and a circulator.

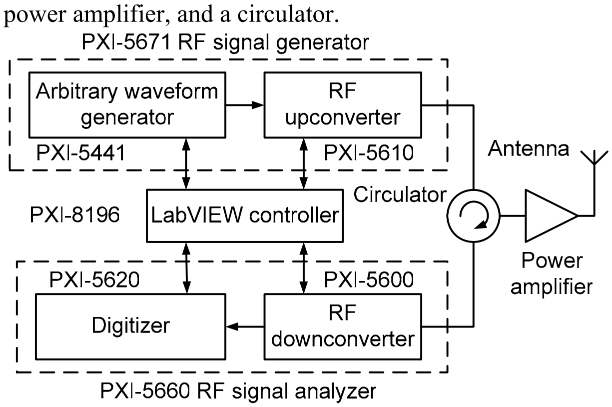


Fig.5. Measurement equipment block diagram.

We used a standard UHF RFID reader antenna made by Sinclair Technologies [103] and shown in Figure 7. The antenna was linearly polarized, with 6 dBi gain in 800-1000 MHz band. The tag used in measurements is shown in Figure 8. The tag was standard silver ink EPC Gen2 UHF RFID inlay made by Texas Instruments [104]. The loop-like center structure serves for impedance matching and good tag sensitivity to magnetic field while the triangular dipole-like structure provides necessary antenna gain and bandwidth. The photograph of the actual measurement setup is shown in Figure 9. The tag was located on bore sight line and oriented to match reader antenna polarization in far field.

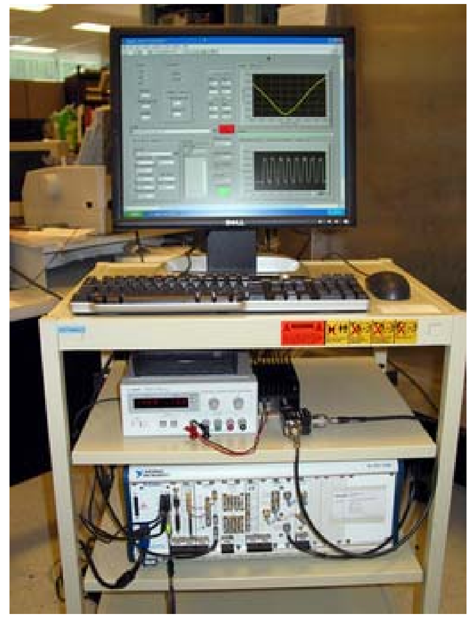

Fig. 6. Photograph of the measurement equipment.

Fig. 7. UHF RFID reader antenna used in measurements.

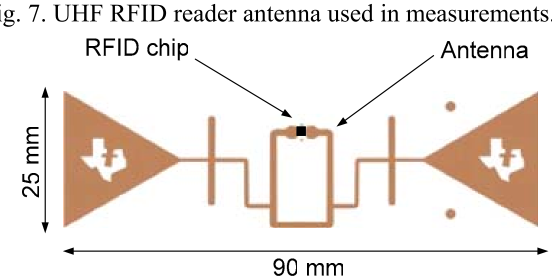


Fig. 8. UHF RFID tag used in measurements.

Fig. 9. Photograph of the measurement setup in anechoic chamber.

The measurement results are presented in Figures 10 - 12. Figure 10 shows the minimum power necessary for tag to respond as a function frequency for various distances between the tag and the reader antenna (measured from approximate antenna phase center). The minimum power values at 900 MHz for distances $d$=24 in. and $d$=12 in. differ by 6.9 dB which is close to the 6 dB difference expected from (4) in free-space far-field region when the distance is reduced by a factor of two. Near field effect becomes noticeable for distance $d$=6 in. where the resonant frequency of the tag starts shifting down. This distance corresponds to the tag being in direct contact with the antenna plastic housing body. The minimum power required to read the tag in this position is approximately -6 dBm which, assuming the chip sensitivity of -12 dBm, corresponds to the coupling coefficient being $C$ = -18 dB.

The threshold tag sensitivity to electric field in far field is readily found from minimum power measurements as

$$E_{th} = \frac{\sqrt{30 P_{t\min} G_t}}{d} \qquad (9)$$

and can be calculated to be 4.24 V/m (133 dBuV/m) at 960 MHz (tag resonant frequency in free space). The tag range (maximum distance at which RFID reader can either read or write information to the tag) for any given value of *EIRP* (Equivalent Isotropic Radiated Power) can also be easily found from minimum power measurements as shown in [13]:

$$r_{\max} = d\sqrt{\frac{EIRP}{P_{t\min} G_t}} \quad . \ (10)$$

Figure 11 shows tag range vs. frequency (calculated from minimum power measured at $d$=24 in.) for two different values of reader transmitted *EIRP*. One can see that reducing the *EIRP* can make a long range tag act as a short range tag, effectively implementing a simple near field UHF RFID system (see the second approach described in the previous section). Note that EIRP of 0.04 W in conjunction with 6 dBi antenna gain corresponds to 10 mW reader output power.

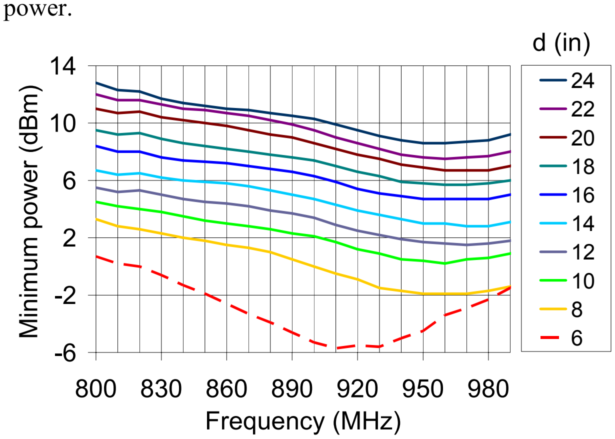


Fig. 10. Minimum power vs. frequency for various distances between the tag and the reader antenna.

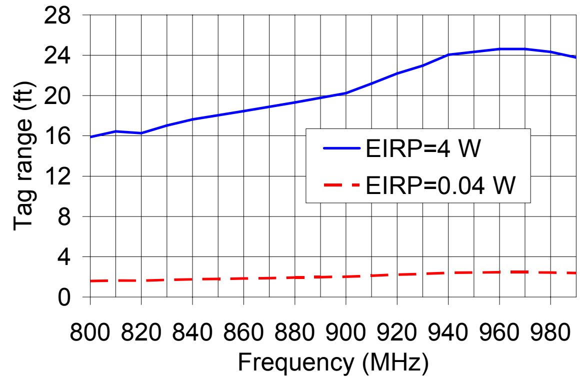


Fig. 11. Tag range vs. frequency for different EIRP values.

Another way to observe the near field boundary is to plot the measured minimum power as a function of distance as shown in Figure 12. The theoretical curve for far-field region was calculated from $1/r^2$ dependence using the power at a distance $d$=24 in. as a reference point. One can see that at a distance of approximately 8 in. (20 cm) the measured minimum power starts deviating from the far field curve. This boundary is close to the value of 19 cm obtained from $2D^2/\lambda$ formula for $D$=19 cm. (size of antenna used in measurements) and $\lambda$ =33 cm (900 MHz frequency).

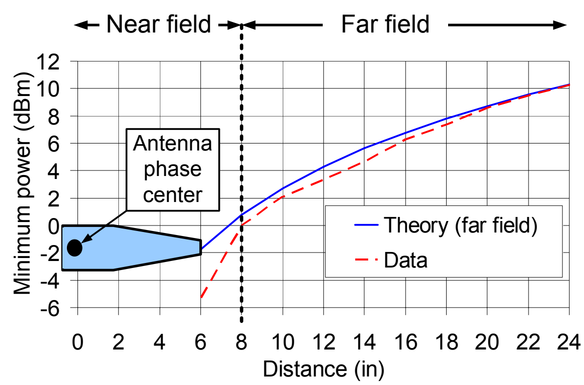


Fig. 12. Minimum power vs. distance at 900 MHz.

In the near field of the reader antenna the field intensity is much stronger compared to far field and thus less minimum power is required to activate the tag. This means that tags can work in RF non-friendly scenarios, especially when magnetic coupling is used. For example, it has been demonstrated [9] that special near field UHF RFID tags can be read even when immersed into the water which absorbs RF field.

Indeed, in our experiments, we observed that even the standard tag (shown in Figure 8) could be successfully read with the standard reader antenna (shown in Figure 7) when the tag was immersed inside the plastic bottle of sports drink (conducting liquid) as shown in Figure 13. This was possible partially because the radial electric field in the vicinity of the reader antenna was very strong.

Fig. 13. Gen2 UHF RFID tag inside the bottle of sports drink being read using standard far-field UHF RFID antenna.

The minimum power required to read the tag in such scenario was approximately 24 dBm (250 mW) at 890 MHz as shown in Figure 14. Assuming the tag chip sensitivity of -12 dBm, this corresponds to the coupling coefficient of $C$ = -36 dB between the reader and the tag antennas.

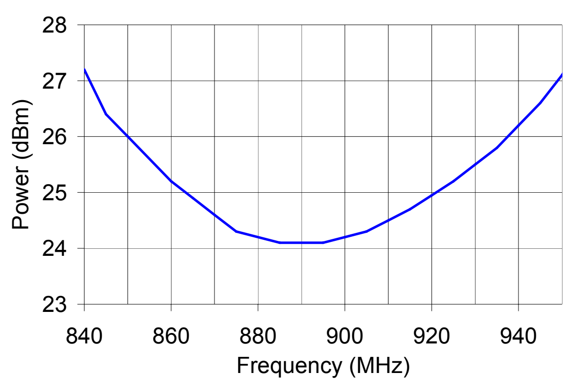


Fig. 14. Minimum reader output power vs. frequency necessary to read the tag in the scenario shown in Fig. 12.

Although the tag was severely detuned in the liquid (the resonant frequency of the tag shifted from 960 MHz to 890 MHz), the received tag signal was clear and easily decodable as shown in Figure 15.

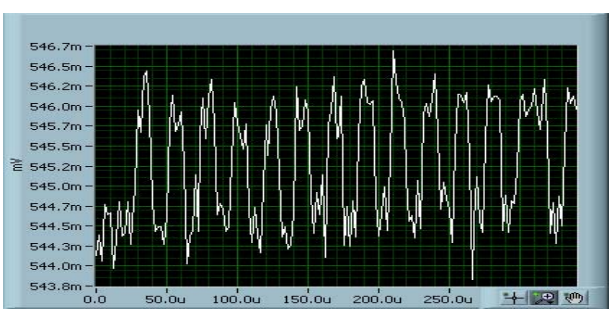


Fig. 15. Portion of the received tag response at 890 MHz with the reader output power of 24 dBm in the scenario shown in Fig. 13.

## V. Conclusion

Equations (1), (3), and (5), which describe the coupling between the reader and the tag antennas are valid for any frequencies (LF, HF, or UHF) but appropriate antenna realization in terms of size and performance strongly depends on the frequency band. For example, because of stronger inductive coupling at higher frequencies, magnetic UHF tags can employ single loops which are simpler and cheaper compared to LF/HF multi-turn coils with jumpers. At the same time, at UHF frequencies the skin effect becomes more pronounced which may create challenges for some tag application scenarios. All in all, while near field UHF RFID has many technical challenges to overcome, it is definitely a promising route for item-level tagging. Some interesting recent developments in this area include RFID tags with dual HF/UHF functionality [105] and organic printed technology developed by several companies [106-108] which is currently making its way into HF RFID [109-115] and may one day reach the UHF band and be used in near field for item level tagging.

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