High-Q, Over-Coupled Tuning for Near-Field RFID Systems

Mohsen Shahmohammadi, Matt Chabalko, and Alanson P. Sample
Disney Research
Pittsburgh, PA 15213
Email: mohsen.shahmoh@disneyresearch.com
Email: matt.chabalko@disneyresearch.com Email: alanson.sample@disneyresearch.com

***Abstract*—Commonly, near field RFID is used in situations where a tag is brought close to some device that is to read the identity of the tag thereby enabling some action: unlocking a door, reading payment information at a merchant's register, or sharing social information between enabled devices. In all these cases, the ergonomics of the physical reading process can be hindered if read range requires a user to awkwardly maneuver the tag near the reader until a read is achieved. One way to facilitate an extended and reliable read range borrows on knowledge from the wireless power transfer community where it is known that increasing the Quality factor of the reader or tag coil will increase power transfer. However, RFID engineers have typically limited maximum coil Q factor to about 10–20 due to the need for maintaining a system bandwidth that is broad enough to support the necessary communication data rates. To meet this challenge, this paper introduces a method of impedance matching high Q reader coils to the source known as "over-coupling" the source to the system input. On one hand, the use of high Q coils extends the range where the tag receives sufficient power to turn on, while it is over-coupling that slightly damps the system resonance, producing an effective *system* Q factor that simultaneously supports a bandwidth wide enough to accommodate necessary data rates. This work will show both theoretically and through experimentation that using high Q coils in the over-coupled regime supports extension of read range in near field RFID systems by 81% or more compared to the next best impedance matching strategies.**

I. Introduction

Recent advances in wireless power transfer (WPT) utilizing magnetic coupled resonance has shown significant improvements in range compared to traditional inductive coupling using high-Q, resonant coils operating in the low megahertz frequency range. Applications typically focusing on power consumer electronics [1], [2], medical implants [3], [4], robotics [5], [6], and electric vehicle charging [7], [8].

One of the key advantages of magnetic coupled resonance is that, given proper tuning techniques, it is possible to achieve near constant power transfer efficiency as a function of distance and orientation for transmitter to receiver separation up to approximately one coil diameter [9]. This increase in performance is largely due to the fact that these high-Q systems operate in the over-coupled regime, meaning that the two inductive coils share more magnetic flux than is needed to support the load. This results in frequency splitting and multiple modes of operation.

Since many wireless power systems based on magnetic coupled resonance operate on the same physical layer as near-field RFID (i.e. the 13.56MHz ISM band) there is the opportunity to apply these techniques to RFID reader and tag coil designs; thereby increasing read range, ease of use, and overall system reliability. However, near-field RFID antenna designers face an inherent tradeoff between increasing coil quality factor (to improve range) verses maintaining the bandwidth needed for communication. Conventional wisdom from industry states that tag and reader coils should have a Quality factor no greater then 10 or 20 in order to have enough bandwidth for communication [10]–[13].

While traditional techniques focus on ensuring there is a conjugate impedance match between the RFID reader and antenna in order to maximize power transfer (i.e. ensuring that they are critically coupled). This paper draws upon the lessons learned from the wireless power community and employs a novel tuning method based on over-coupling the RFID reader to the coil. This method allows the antenna designer to simultaneously increase the coil quality factor (> 125) while maintaining the bandwidth necessary for communication, thus resulting in longer read ranges.

Section II provides background information and shows how increasing the coil quality factor can increase the range at which an RFID tag can be powered and also describes the effect of increased Q on bandwidth. Section III describes how this bandwidth limitation can be over come via over-coupled tuning. In addition, a mathematical model is presented that shows how to optimize the systems read range as a function of both reader coil Q factor and over-coupling ratio. Section IV presents measured results showing that a Texas Instruments TRF7970A RFID reader development board can be modified to improve the read range of commercial stock RFID tags by 19% to 77%, simply by changing the impedance matching network such that the antenna is over-coupled and its Q is 125. While the primary focus of this paper is on improving the reader range by modifying the reader coil; section V presents measured results showing the improvements that can be achieved by applying the high-Q and over-coupled tuning techniques to both the reader and tag coils. Finally concluding remarks are discussed in section VI.

II. Overview of RFID Coupling Strategies

This section will describe how read range of near field RFID systems can be increased using coils with high Q-factors. Conventional near field RFID designs will be discussed first, with

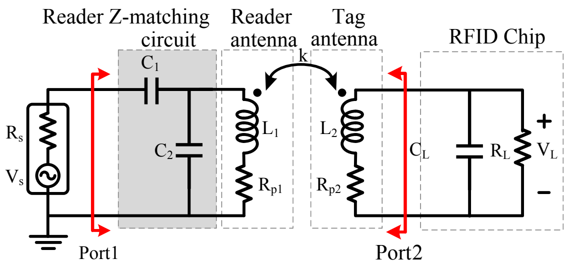

Fig. 1. Circuit schematic showing tuning circuit for reader and tag antennas and also the RFID chip lumped model

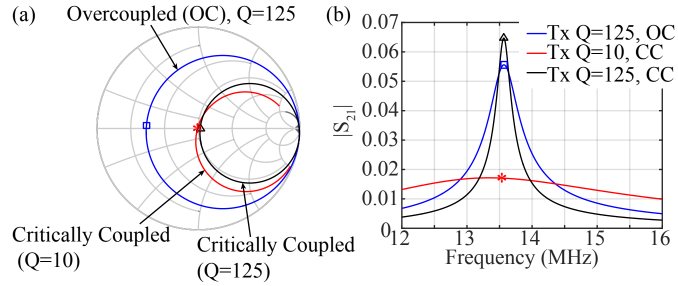

Fig. 2. (a) Smith chart illustrating impedance variation over frequency for OC and CC resonators, with high and low Q values.(b) Magnitude of the transmission coefficient, $|S_{21}|$ corresponding to the impedances plotted in panel (a). In this example, the coupling coefficient, $k = 0.005$. The blue square, red asterisk (*), and black triangle indicate the frequency at which f =13.56 MHz on each curve for the $Q = 125$ OC, $Q = 10$ CC, and $Q = 125$ CC cases, respectively.

a focus on how traditional systems are impedance matched for maximal read range. Then, an alternative impedance matched strategy using over-coupling (OC) on the reader side will be introduced that shows how high Q coils used in this regime can simultaneously allow for greater wireless power transfer to the tag, while maintaining sufficient bandwidth for communication. Taken together these two elements ultimately yield extended read range.

A. Background on Near Field RFID Impedance Matching

The circuit model for a typical near field RFID system, and the one to be analyzed throughout this section is shown in Fig. 1. It is a pair of coupled coils with transmitter (Port 1, reader) inductance and self-resistance, L_1 and R_1, respectively, and a receiver (Port 2, tag) inductance and self resistance of L_2 and R_2. Their coupling is captured through the coupling coefficient, k, where k is related to the mutual inductance, M, of the coils by $M = k\sqrt{L_1 L_2}$. The transmitter has a source resistance of $R_s = 50\Omega$. The capacitors C_1, C_2, are used in impedance matching the source to the network input. On the tag (load) side, resonance results from the parallel combination of the parasitic capacitance of the chip, C_L, and the RFID coil inductor, L_2.

In near field RFID, to maximize read range, a major concern is ensuring that enough power reaches the RFID chip for operation. It is well known in the WPT and circuit communities that maximum power transfer is achieved between the source and the load by ensuring a conjugate match is achieved on the transmitter (and optimally also receiver) end(s) of the system [14]–[16]. This statement is likewise true in near-field HF RFID applications.

Thus, in a standard near field RFID system, the approach is to match the input impedance of the reader coil (as seen at Port 1), to the source impedance, R_s, when is isolated from the tag. This is known as critical coupling (CC) which maximizes the amount of the power leaving the reader. When the tag coil is brought from very far away, closer and closer to the reader coil, k goes from effectively 0 (completely decoupled) to very small values (e.g. $k = 0.005$). Fig. 2(a) shows a plot of the system input impedance for two CC coils (red and black curves) when $k = 0.005$. Note that for small k the red and black curves meet the center of the smith chart, indicating that they are impedance matched to the source and minimal power is lost to input reflections.

Since small k represents distances at which the reader coil and tag coil are farthest apart, the result is that, for the CC regime, the system is optimized for best efficiency at large separations.

In near field RFID applications, however, it is not sufficient to only optimize for maximum WPT. Another consideration is ensuring that the system bandwidth is sufficient to support the transfer of data between reader and the tag. The conventional view of near-field RFID systems places a limit on the *maximum* Q-factor of the reader antenna of about 10–20 [10]–[13]. Higher Q-resonators have smaller bandwidth since the Q-factor is related to the bandwidth by $Q = f_c/\Delta f$, where f_c is the center frequency, and Δf is the bandwidth. Thus, the Q-factor cannot be increased indefinitely without making the system such an effective filter such that the transmission coefficient (we use S-parameters in this work, and thus the transmission coefficient is S_{21}) rejects all frequencies outside of a very small band around the center frequency.

On the other hand, as the next subsection will show, coils with larger Q-factors can provide more power at longer distances than coils with low Q. What follows will address how higher Q coils can be used to increase the power received by the tag without sacrificing bandwidth.

B. Impedance Matching Approaches

In this work, impedance matching is implemented in one of two regimes: either the input of the system (Port 1) is critically coupled (CC) to the source at 13.56 MHz, or Port 1 is overcoupled (OC) to the source at 13.56 MHz. It is the latter OC case that will be shown to be beneficial in increasing near-field RFID read range. This is in contrast to the traditional CC case of the last subsection. Figure 2 shows a typical smith chart plot illustrating how the impedances of the OC and CC cases vary with frequency. Note the CC case has zero reflection coefficient at resonance, but the OC case has a non-zero reflection coefficient in the same frequency range.

As alluded to, WPT is increased for coils with higher Q since the figure of merit for maximum power transfer of a system is proportional to $k^2 Q_1 Q_2$ [17], where Q_1 and Q_2 are the quality factors of the transmitter and the receiver

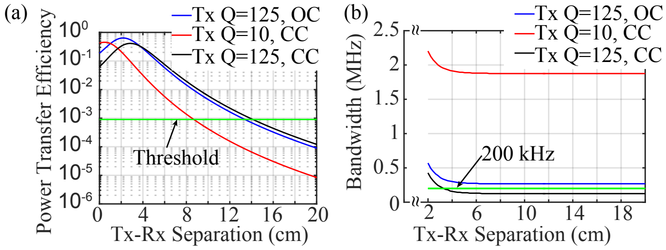

Fig. 3. (a) Power transfer efficiency for the circuit of Fig. 1 as the distance between transmitter and receiver is varied for an OC transmitter with Q = 125, a CC transmitter with Q=10, and a CC transmitter with Q=125.(b) Bandwidth versus reader to tag coil separation for same Q and OC/CC combinations of panel (a).

coils, respectively. While higher Q does increase WPT, it is simultaneously necessary to ensure that the bandwidth of the system is sufficient to support communication. To boost WPT while meeting bandwidth constraints, this work proposes using a reader coil with higher Q-factor that is over-coupled to the source. This is because over-coupling damps the resonance of the high Q resonator, thus broadening bandwidth, but not to such a degree that WPT efficiency is sacrificed. The next subsection will elaborate on this via an example.

To enable quantitative comparison, this work uses a parameter to distinguish between over-coupled (OC) and critically coupled (CC) circuits. This will be especially relevant in later experimental sections. Thus, an "overcoupling coefficient", g, will be used as defined in [18]: $g = Q/Q_e$, where Q is the unloaded quality factor of the RLC tank, and Q_e is the external quality factor of the resonator ($R \rightarrow R_s$). Defining g this way yields 3 cases: 1) $g < 1$, for the under-coupled case, 2) $g = 1$, for the CC case, and 3) $g > 1$ for the OC case.

C. Model and Results

Here, an example of increasing read range via OC high Q coils is lastly introduced. Figure 3 shows the calculated WPT efficiency to the load ($R_L = 1000\Omega$, $C_L = 17$ pF; this approximates a commercial tag) for the circuit of Fig. 1 at the center frequency f_c= 13.56 MHz for three cases: a CC transmitter with $Q = 10$, a CC resonator with $Q = 125$, and an OC resonator with $Q = 125$. The results are for reader to tag coil separations of 0 to 20 cm. [1] Also shown is a black line indicating the minimum efficiency necessary to turn the tag on, assuming a 200 mW input, as in this work. All other circuit parameters for these three cases are shown in Table I. Note the choice of C_1 and C_2 are the mechanism by which OC or CC are achieved. It is clear that the transmitter coils with larger Q factor can meet the minimum required power threshold at greater distances than the low Q factor transmitter. Also important is that the OC and CC resonators meet this threshold at about the same transmitter to receiver separation. For OC resonators, this phenomenon appears often

[1] These distances mirror those of the experimental data of later sections. Computation of k at each distance was done using a numerical algorithm that solves the field equations of a coupled coil system and generates mutual inductance via extraction of the coupled flux.

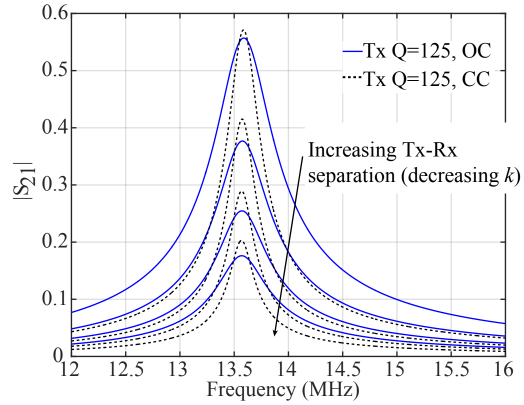

Fig. 4. $|S_{21}|$, between the transmitter and load (RFID chip), for varied separations between transmitter and receiver from 3.8 to 6.8 cm. Note that, due to overcoupling, the resonance of the OC case is damped compared to the CC case, yielding a desirably larger bandwidth.

throughout the literature on WPT [2], [19], and designs are often optimized using OC topologies.

Figure 3(a) shows that either the $Q = 125$, CC or OC can increase read range if only considering power received by the tag. However, bandwidth must also be considered. Fig. 3(b) shows the bandwidth vs. separation for the same circuit and setup as in (a). This bandwidth is computed as the full width half maximum (FWHM) bandwidth of the transmission coefficient, $|S_{21}|$. The figure also shows the minimum required forward link bandwidth (load modulation bandwidth will be discussed later on) of 212 kHz (green line) for the tags used in this work, which are 14443 type A standard and have a bit rate of 106 kb/s. The low Q (Q=10) CC transmitter has the largest bandwidth at all distances, but it is much larger than what is necessary. The high Q resonators have similar bandwidths versus transmitter to receiver separation, but of the two, it is only the OC resonator that maintains sufficient bandwidth across all separations.

The reason for the above effect on system bandwidth can be seen in Fig. 4. Shown here is a plot of $|S_{21}|$ versus frequency for several example reader to tag coil separations. It can be seen that for the same separations, the over-coupled (OC) transmitter maintains a broader transmission spectrum than in the critically coupled (CC) case. This is due to the fact that OC the system effectively damps the resonance increasing the FWHM bandwidth; the system behaves effectively as one with lower quality factor. If it were not for the fact that the overcoupling of the source in isolation leads to a damped resonance, then, as seen in the CC case of Fig. 3(b), the read range would be limited to about 3.3 cm due to insufficient

TABLE I
READER PARAMETERS FOR SIMULATION

Parameters	Low Q Tx, CC	High Q Tx, CC	High Q Tx, OC
L_1	1.5 μH	1.5 μH	1.5 μH
Q	10	125	125
C_1	51 pF	13 pF	23 pF
C_2	45 pF	79 pF	69 pF
OC coeff. (g)	1.01	0.98	3.12

bandwidth at greater distances, even though the chip receives more power than required at these distances, Fig. 3(a). Thus, via this example it has been demonstrated how using higher Q coils can increase read range due to increased WPT, without limiting read range due to insufficient bandwidth.

III. Effects of Increasing Q-factor and Overcoupling on System Performance

The following analysis investigates the effects of using high Q-factor coils and over-coupling on the reverse link modulation (tag to the reader), the forward link data transmission (reader to tag) and the read range. First, it is discussed that the main limitation on increasing the Q-factor of the reader is the forward link budget. This restriction is relaxed by leveraging over-coupled tuning. Then, the key limitations imposed by reader and tag are combined to derive the read range as a function of over-coupling coefficient and Q-factor.

A. The Reverse Link Bandwidth

Typically, increasing the Q-factor results in narrower system bandwidth. To have a better understanding of this effect, a typical HF RFID spectrum is shown in Fig. 5. The reader command is carried in the sidebands of the carrier and the load modulation is carried in the sidebands of the two subcarriers shown in the blue triangles. The green line shows the magnitude of the scattering parameter ($|S_{21}|$) for a low Q reader and the pink line shows $|S_{21}|$ corresponding to a high Q-factor reader. It can be seen that with increasing Q-factor, bandwidth shrinks and the result is more attenuation at the subcarrier frequencies. In other words, if the received carrier power remains the same, the return signal will become smaller due to increased attenuation. This raises the concern that despite activating the tag, the return signal will be smaller than the reader sensitivity and the reader cannot decode the load modulation.

To evaluate the impact of the bandwidth on the reverse link with more scrutiny, the return signal power must be computed based on the circuit model introduced in Fig. 1. First, the power delivered to the tag is calculated using

$$P_d = P_{av}\ G_T(f_c) \tag{1}$$

where $G_T(f_c)$ and P_{av} are the transducer gain (which is the same as actual received power) at the carrier frequency and the available power of the reader, respectively. G_T is defined based on the Z-parameters of the circuit diagram in Fig. 1 as

$$G_T = \frac{4\ R_S\ R_L |Z_{21}|^2}{|(Z_{11}+Z_S)(Z_{22}+Z_L) - Z_{21}Z_{12}|^2} \tag{2}$$

where Z_S and Z_L are the impedance of source and load respectively, and R_S and R_L are their real parts. Second, the power of the signal modulated with the subcarrier is computed. The load modulation power is equal to $P_m = \frac{m^2}{4}\ P_d$ [20]. Finally, the modulated signal will return to the reader at the subcarrier frequency and the returned power received at the reader is equal to

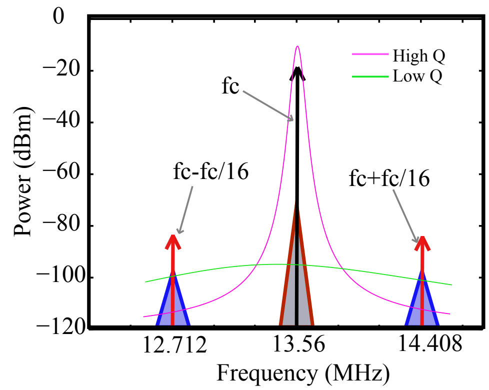

Fig. 5. A typical spectrum of an HF RFID system illustrating the reader command and the load modulation. The impact of increasing the reader Q-factor on the bandwidth and the load modulation is shown.

$$P_{bs} = P_m\ G_T(f_{sub}) \tag{3}$$

where $G_T(f_{sub})$ is the transducer gain at the subcarrier frequency. Equations (1)-(3) are used to calculate the return power from the load ($R_L = 1000\Omega$, $C_L = 17$ pF for a typical HF RFID chip) to the source ($R_S = 50\Omega$) for the circuit of Fig. 1. The computed return signal is plotted in Fig. 6. The reader and the tag coils are tuned to resonate at the center frequency f_c= 13.56 MHz. The Q-factor of the reader coils is varied from 10 to 300 while the Q-factor of the tag coil is fixed at 30. Then, the frequency is swept from 12 MHz to 15 MHz and the return signal power of the subcarrier frequency $f_{sub} = 14.04\ MHz$ is computed from Eqs. (1)-(3) for a number of values of the overcoupling coefficient ($g = Q/Q_e$). It shows that for a given overcoupling coefficient by increasing Q-factor, the return signal power that reaches the reader increases. In other words, if the reader can detect and resolve the return signals for low Q-factor coils, it will be able to resolve the load modulation for higher Q-factor coils as well. Typically, the return signal can be detected if it lies above 110 dB below the level of the transmitter carrier signal [13]. This figure also shows that by increasing the over-coupling coefficient of the reader coil, the return signal gets stronger due to the increased bandwidth and after a certain point by increasing the overcoupling coefficient, the the return signal gets smaller which is due to increased input power reflection at the reader.

Another important interpretation of Fig. 6 is that the bandwidth of high Q-factor HF RFID systems is not limited by the reverse link. In other words, the required bandwidth is defined mainly by the limitation on the forward link. Therefore, to find the Q-factor upper bound on the reader coil, the bandwidth required by the forward link must be taken into account.

B. The Forward Link Bandwidth

It is necessary to understand the relationship between increasing Q-factor and the forward link bandwidth before discussing the impact of overcoupling on the bandwidth. As

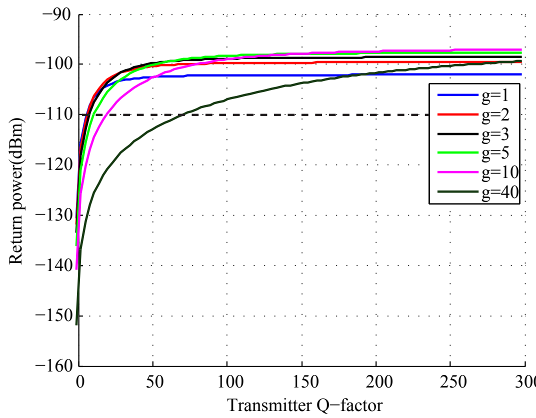

Fig. 6. The calculated return power vs. transmitter Q-factor for various over-coupling ratios (g), for $Qrx = 20$, and $k = 0.01$). It shows that increasing the Q-factor increases the load modulation power that reaches the reader. The dashed line shows a typical value for the sensitivity of the reader chip.

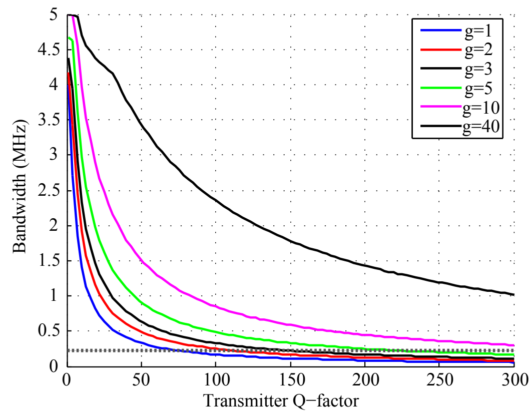

Fig. 7. The calculated bandwidth vs. reader Q-factor for various over-coupling coefficients (g) for $Qrx = 20$, and $k = 0.01$. The grey dotted-line shows the minimum bandwidth required for a 14443 type A with 106 kb/s bit rate discussed earlier as an example. Over-coupled tuning increases the bandwidth and enables use of higher Q reader antennas.

shown in Fig. 5, the link from the reader to the tag is a bandpass filter and the reader command is modulated at the center frequency of this filter, f_c. The 3 dB bandwidth of this filter decreases with increasing reader Q-factor. As long as, this 3 dB bandwidth covers the the forward link data, shown in gray in Fig. 5, the tag will be able to decode the command, provided that the tag is turned on. In other words, the minimum bandwidth of the HF RFID system is equal to the bandwidth of the forward link.

The bandwidth of the forward link is the bandwidth of the modulation sidebands of the carrier and is dependent on the modulation scheme used by the reader. Typically, HF RFID readers use amplitude-shift keying (ASK) as the modulation scheme. The signal bandwidth for ASK modulation is estimated by $B = 1/T_b$ where T_b is the effective bit length [13], [20]. For instance, the bit length for 106 kb/s 14443 type A protocol is equal to a pulse width of up to 3 μs and therefore the effective bandwidth is approximately 330 kHz [20].

As described in the overview section, over-coupled readers enjoy higher bandwidth because over-coupling damps the resonance. Fig. 7 shows that the calculated bandwidth increases with over-coupling coefficient. The circuit model in Fig. 1 is tuned for a number of values of over-coupling coefficient at 13.56 MHz and the resultant bandwidth is calculated when the Q-factor of the reader is swept from 10 to 300; the reader is coupled to a typical RFID chip load as in Section II. C, for $k = 0.01$. It is important to note that with increasing Q-factor, the reader must be more over-coupled to the source in order to provide enough bandwidth for the forward link. In other words, for higher Q-factor readers, the distance between the reader and the tag must be decreased to have enough bandwidth. This is an important insight because it shows the effect of the bandwidth on the range of the RFID reader. In the next subsection, we will combine this effect with the minimum power for activation of the tag to calculate read range.

C. Read Range

The tag read range is the most prominent performance characteristic of an RFID system. The read range is dependent on many parameters, mainly, the sensitivity of the tag, the bandwidth of the system and the sensitivity of the reader. Generally, the read range is not limited by the reader sensitivity for RFID systems [21]. This leads to two conditions based on the tag sensitivity and the bandwidth as follows

$$P_d = P_{av}\ G_T(f_c) \geq P_{th} \tag{4}$$

$$BW \geq 1/T_b \tag{5}$$

Where P_{th} is the tag sensitivity and is defined as the minimum received power at the tag to activate the RFID chip. As discussed earlier, T_b is the effective bit length. The circuit model in Fig. 1 is simulated for a typical HF RFID chip load ($R_L = 1000\Omega$, $C_L = 17$ pF) over a wide range of values for the Q-factor of the transmitter, over-coupling coefficient (g) and distance (i.e. the coupling factor, k). For each set of values for Q_{Tx}, g, and d, the Z-parameter of the circuit is calculated and then the delivered power to the tag is computed using eq. (1) and eq. (2) and then the conditions of Eq. (4) and (5) are checked to be true for $P_{th} = -7$ dBm (a typical RFID chip sensitivity) and minimum bandwidth of 300 kHz (this is an example for 106 kb/s, as in 14443 type A tags). Then the maximum reading distance (d_{max}) is extracted for each pair of (Q_{Tx}, g), and the resulting surface is plotted in Fig. 8.

From Fig. 8, it can be seen that for a given over-coupling coefficient, e.g. $g = 1$ [the blue line in Fig. 9(a)], the read range increases as the Q-factor increases up to the point where the bandwidth becomes smaller than the minimum required bandwidth of the forward link [Eq.(5)], the point where read range starts shrinking with increasing the Q-factor. At this point, by increasing the over-coupling of the reader to the source, the Q-factor increment still can lead to read range

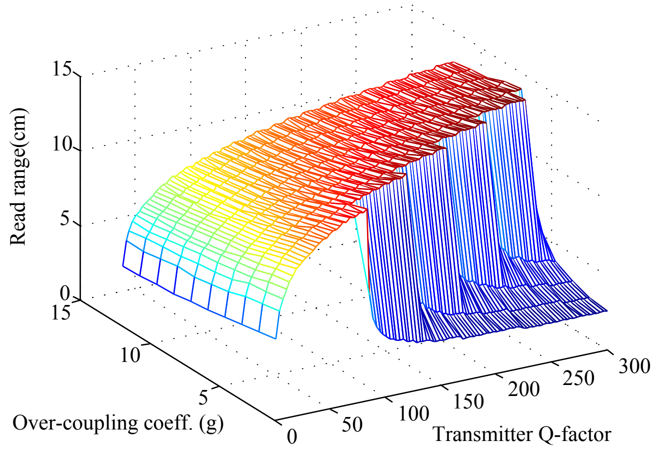

Fig. 8. The maximum reading distance vs. Q-factor of transmitter for varied over-coupling coefficients (g).

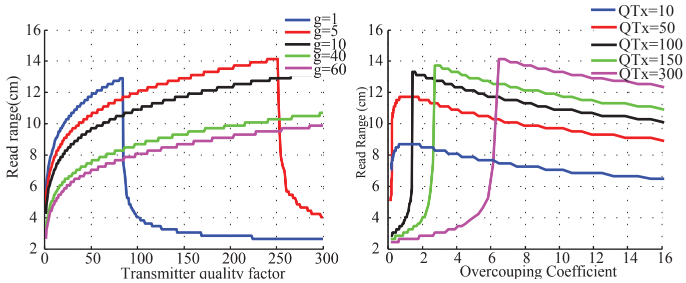

Fig. 9. (a) Shows the impact of increasing Q-factor for given values of g (b) Shows the value of g_{min} for certain values of Q-factor of of transmitter.

improvement. To observe this effect clearly, the read range is depicted vs. Q-factor of the transmitter for different values of g in Fig. 9(a). The read range vs. over-coupling coefficient for different transmitter Q-factors is shown in Fig. 9(b). It shows that for a certain Q-factor of reader, there is a minimum value of over-coupling coefficient, g_{min}, to ensure enough bandwidth for the forward link is provided. However, for over-coupling coefficients larger than g_{min}, due to increased power lost to reflections at the input port, the read range decreases.

IV. Experimental Results for Over-coupled Reader

Fig. 10 shows the experimental setup used to validate the effectiveness of over-coupling for high-Q coils in improving the read range. In this work, TRF797A development kit is used as the RFID reader. The reader consists of a 4-turn 55 $mm \times$ 39 mm printed circuit rectangular coil with trace width of 1.3 mm and spacing of 0.5 mm. The inductance and self-resistance of the reader coil are $1.5\mu H$ and 1 Ω as measured by a vector network analyzer (VNA). The reader position is fixed while the tag is mounted on a plastic pole on a positioning stage with an accuracy of 0.076 mm.

The tuning circuit shown in Fig. 11 (a) is implemented on the TRF7970a board using the parameter values of Table I for three cases: a CC with $Q = 10$, a CC with $Q = 125$, and OC

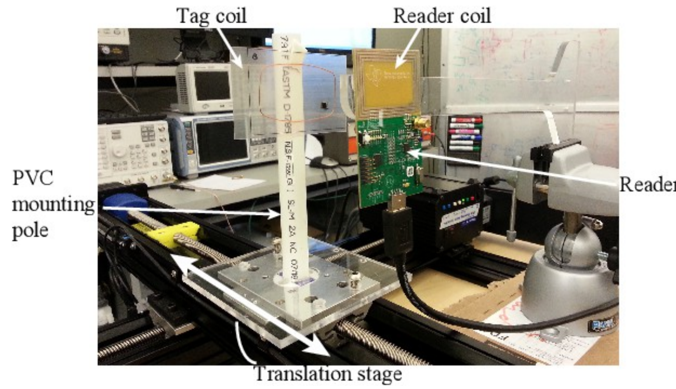

Fig. 10. Photograph of the experimental setup for measuring the read range. The RFID reader is TRF7070 A development kit.

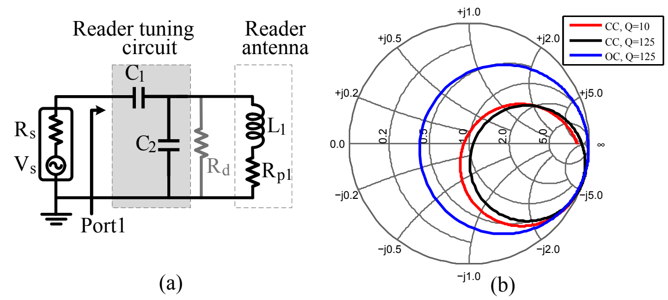

Fig. 11. (a) Circuit diagram of the antenna and tuning circuit (b) The Smith chart shows the measured S_{11} for 3 design cases considered in this work: CC, Q=10; CC, Q=125; and OC, Q=125.

with $Q = 125$. To bring the Q-factor of the reader down to $Q = 10$ for first case, TRF7970A stock configuration uses a resistor parallel to the reader coil, $R_d = 1.2$ kΩ. This resistor is removed from the board for the high-Q cases. All readers are tuned to resonate at f_c=13.56 MHz. Fig. 11(b) shows the measured reflection coefficient (S_{11}) when looking into Port 1 when the reader is in isolation (i.e. no reader to tag coupling.)

The designed readers are tested by 9 off-the-shelf commercial proximity and vicinity tags. 14443 and 15693 standard tags are used in this work as they are the most common tags used in HF RFID applications. The measured read ranges for all of the tags are summarised in Table II. The read range is increased by using High-Q over-coupling tuning technique for all the cases. The read range is improved from 18% to 81% for these tags. The reason for the variation of the improvement percentage is that the readers are not designed for a specific tag. Note that the read range is dependent on the Q-factor and also the size of the tags. The Q-factor of these tags are typically low and the size of tag coils and number of turns are generally determined by the application form-factor restriction as well as RFID chip parasitic capacitance. In addition, the loaded Q-factor of the tags are normally less than 10 due to the loading effect of the RFID chip (assuming $R_L = 1$ kΩ). To better represent the tag Q-factors, the unloaded Q-factor of the tags are measured by magnetically coupling into the tags using the method described in [22]. The results show that with increasing the Q-factor of the tag, the read range increases for all the readers. To show the power of the over-coupled

TABLE II
READ RANGE OF ANTENNAS USING COMMERCIAL TAGS

Standard	MFG PN	Bit rate	Tag coil size	Unloaded Q-tag	LQ-CC	HQ-CC	HQ-OC
14443A	NA	106 kbp/s	$7 \times 4.1cm$	53	9.3 cm	10.6 cm	11.6 cm (+24%)
14443A	NA	106 kbp/s	$7.2 \times 3.9cm$	32	7.2 cm	7.8 cm	8.6 cm (+19%)
14443A	NA	106 kbp/s	$6.5 \times 2.4cm$	23	4.4 cm	7.1 cm	7.8 cm (+77%)
14443A	MN63Y3212N4	106 kbp/s	$3 \times 3cm$	30	4 cm	6 cm	7 cm (+75%)
14443A	MIKROE-1475	106 kbp/s	$2 \times 2cm$	28	4.8 cm	6.8 cm	8 cm (+66%)
14443A	MF0MOA4U10	106 kbp/s	$7 \times 4.1cm$	53	4.8 cm	7.2 cm	8.7 cm (+81%)
15693	RI-I02-114B-01	1.66 kbp/s	$7.6 \times 4.5cm$	38	11.3 cm	13.8 cm	15.2 cm (+34%)
15693	RI-I11-114A-01	1.66 kbp/s	$4.5 \times 4.5cm$	33	10 cm	11.8 cm	13.2 cm (+32%)
15693	RI-I03-114A-01	1.66 kbp/s	$3.8 \times 2.25cm$	28	7.2 cm	8.8 cm	9.9 cm (+37%)

tuning for high Q coils, in the next section, the over-coupled impedance matching method is used on a high Q *tag* coil as well as on the reader coil.

V. High-Q Over-coupled Tuned Reader and Tag

To increase the read range farther, it is desirable to implement a tuning circuit before the RFID chip thereby *also* tuning the tag coil to operate in the over-coupled regime. To apply over-coupled tuning method for the tag coil, a printed circuit 6-turn spiral coil with outer diameter of 39 mm, inside diameter of 16 mm, and trace width of 1.3 mm with 1 mm spacing between the traces is fabricated on FR4 material. Fig. 12 (b) shows the designed tag coil with an SMA connector on it. For the read range measurement, a 14443 type A chip is soldered to an SMA connector and is mounted on the tag coil.

Fig. 12 (a) shows the diagram of the tuning circuit used to over-couple the tag coil. The way that the tuning circuit works is by reducing the voltage drop across the load using a capacitive voltage divider. If the impedances of the capacitors, C_3 and $C_4 + C_L$, are less than R_L at the resonance frequency, the ratio between the voltage across the tag coil and the load, $n = V_L/V_{coil}$, will be

$$n = \frac{C_3}{C_3 + C_4 + C_L} \tag{6}$$

Normally, capacitors have very high Q-factors on the order of 1000 at NFC operating frequency, i.e. 13.56 MHz, and can be considered to be lossless. Therefore, the capacitive voltage divider simplifies to a voltage transformer. The capacitors can be used to create resonance with the coil inductance at f_c =13.56 MHz by using

$$f_c = \frac{1}{2\pi\sqrt{L_2\frac{C_3(C_4+C_L)}{C_3+C_4+C_L}}} \tag{7}$$

In this case, the impedance seen through port 2 will then be equal to

$$R_{in} = n^2(1 + Q_2^2)R_{p2} \tag{8}$$

where Q_2 is the Q-factor of the coil. At resonance, the over-coupling coefficient g reduces to $g = R_L/R_{in}$ [18] and is thus a function of the ratio n. By decreasing n, R_{in} decreases and the coil is more over-coupled to the load (i.e. g increases).

The spiral coil tag shown in Fig. 12 (b) was tuned for 4 different over-coupling ratios, g, by varying n from 0.3 to 1 (from critically coupled, $g = 1$, to highly over-coupled, $g =$ 10). The read range is reported in Table III. The fourth column of this table shows that even for Low Q (LQ), CC transmitters, the read range is extended when the tag $g \sim$ 2-3. Thus, over-coupling the tag has benefits itself. However, looking at the last column, which is for high Q (HQ) OC reader coils, the benefits are even more dramatic than using an OC tag alone where read range is improved by up to 88%. This improvement is between the conventional near field tuning approach (shaded in gray in the fourth column) where no tuning is done on the tag and the reader is a low Q, CC coil, and the case where both the tag and reader are over-coupled to a near optimal degree (this case is also shaded in gray in the sixth/last column). For those cases in Table III with two values, the reader is not able to read the tag at distances closer than the smaller of the two values due to the frequency splitting effect [2], and cannot read at distances farther than the large of the two values due to insufficient power transfer.

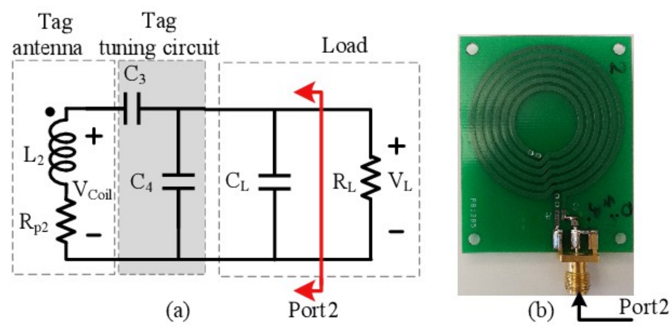

Fig. 12. (a) Shows the circuit diagram of the receiver side b) shows the receiver antenna and tuning circuit (Chip is soldered to an SMA connector to be attached to antenna)

The red asterisks in Fig. 13 show the measured read range in Table III, plotted together with the calculated read range, blue circles, using the model presented in Section III. C. The blue line shows the read range estimate for the case when the reader and the tag coils have the same Q-factors, as Q-factor varies from 1 to 300. Fig. 13 shows a good agreement between

TABLE III
READ RANGE FOR VARIED n OF TAG Z-MATCHING CIRCUIT

n	g	Tag Q_{loaded}	LQ-CC Tx (cm)	HQ-CC Tx (cm)	HQ-OC Tx (cm)
0.99	10	11	6	6.5	9.6
0.5	2.9	36	7.2	1.6-9.4	11.3
0.4	1.8	55	7.3	2.2-9.9	1.9-11.5
0.3	1	65	6.9	2.8-9.4	2.1-10.8

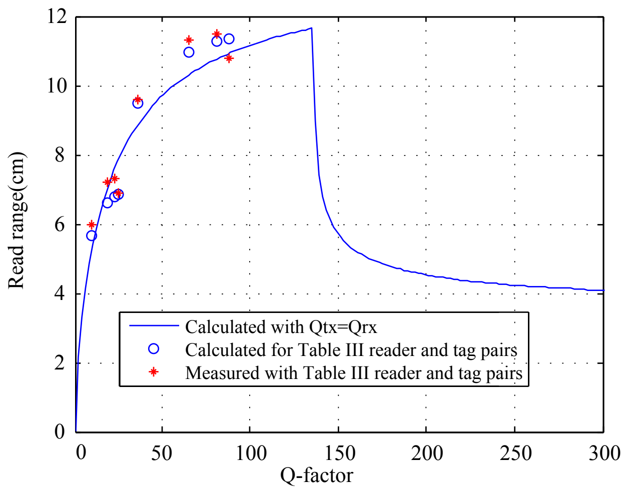

Fig. 13. Maximum reading distance versus quality factor. For $Q_{tx} \neq Q_{rx}$, Q is defined as the geometric mean of Q_{rx} and Q_{tx}. Measurement is the actual reading range using TRF7970A development kit.

the measured and calculated read range, illustrating the utility of the model to predict the read range and aid in optimizing NFC RFID systems.

VI. Conclusion

This work has shown how to achieve increased read range and increased read reliability in near field RFID systems via the introduction of high Q coils that extend the distances over which the tag receives adequate power to tun on, while over-coupling is used to maintain sufficient system bandwidth. This OC topology has been contrasted with traditional impedance matching strategies in near-field RFID where standard practices require critically coupling the source to the input.

Additionally, it has been shown experimentally and theoretically how the Q factor of transmitter antennas need not be strictly limited to values of 10–20, but that by leveraging the overcoupled tuning technique, higher Q coils can be successfully used. The results presented here show that high Q OC reader antennas can outperform low Q, CC antennas by almost a factor of 2 in some instances. Even when comparing high Q coils with critical coupling to high Q coils in the over-coupled regime, the improvements are considerable. The focus of this work has been on 106kb/s 14443A, and 15693 standard RFID tags. Note that much more significant improvements are achievable for higher bit-rates where restrictions on Q-factor are tighter. This strategy of over-coupling is straightforward and can be implemented quite easily into many existing near field RFID systems, and so the benefits of this approach can be immediately reaped without extensive system re-engineering, ultimately leading to systems with increased range and reliability that is noticeable to a real world user.

References

[1] Z. N. Low, R. Chinga, R. Tseng, and J. Lin, "Design and test of a high-power high-efficiency loosely coupled planar wireless power transfer system," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 5, pp. 1801–1812, May 2009.

[2] A. Sample, D. Meyer, and J. Smith, "Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer," *Industrial Electronics, IEEE Transactions on*, vol. 58, no. 2, pp. 544–554, Feb 2011.

[3] B. Waters, A. Sample, P. Bonde, and J. Smith, "Powering a ventricular assist device (vad) with the free-range resonant electrical energy delivery (free-d) system," *Proceedings of the IEEE*, vol. 100, no. 1, pp. 138–149, Jan 2012.

[4] A. RamRakhyani, S. Mirabbasi, and M. Chiao, "Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants," *Biomedical Circuits and Systems, IEEE Transactions on*, vol. 5, no. 1, pp. 48–63, Feb 2011.

[5] T. Deyle and M. Reynolds, "Surface based wireless power transmission and bidirectional communication for autonomous robot swarms," in *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, May 2008, pp. 1036–1041.

[6] M. Karpelson, B. Waters, B. Goldberg, B. Mahoney, O. Ozcan, A. Baisch, P.-M. Meyitang, J. Smith, and R. Wood, "A wirelessly powered, biologically inspired ambulatory microrobot," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, May 2014, pp. 2384–2391.

[7] C. Qiu, K. T. Chau, C. Liu, W. Li, and F. Lin, "Quantitative comparison of dynamic flux distribution of magnetic couplers for roadway electric vehicle wireless charging system," *Journal of Applied Physics*, vol. 115, no. 17, 2014.

[8] J. Shin, S. Shin, Y. Kim, S. Ahn, S. Lee, G. Jung, S.-J. Jeon, and D.-H. Cho, "Design and implementation of shaped magnetic-resonance-based wireless power transfer system for roadway-powered moving electric vehicles," *Industrial Electronics, IEEE Transactions on*, vol. 61, no. 3, pp. 1179–1192, March 2014.

[9] A. Sample, B. Waters, S. Wisdom, and J. Smith, "Enabling seamless wireless power delivery in dynamic environments," *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1343–1358, June 2013.

[10] J. Schillinger, "Antenna matching for the trf7960 rfid reader," Texas Instrument Inc., Texas Instruments, Post Office Box 655303, Dallas, Texas 75265, Application Report SLOA135A, sep 2013, q=6.78.

[11] Melexis, "13.56 mhz rfid systems and antennas design guide," Melexis: Microelectronic Integrated Systems, The Corporate Vitlage Da Vincitaan 9 - Box E. Elsinore Buitding B-1935 Zaventem, Application Report 390119012107, mar 2004, q:9-16.

[12] Y. Lee, "Antenna circuit design for rfid applications," Microchip Technology Inc., 2355 West Chandler Blvd. Chandler, AZ 85224-6199, Application Report DS00710C, 2003.

[13] K. Finkenzeller, *RFID Handbook: Radio-frequency identification fundamentals and applications*. Wiley, 1999.

[14] D. S. Ricketts, M. J. Chabalko, and A. Hillenius, "Experimental demonstration of the equivalence of inductive and strongly coupled magnetic resonance wireless power transfer," *Applied Physics Letters*, vol. 102, no. 5, 2013. [Online]. Available: http://scitation.aip.org/content/aip/journal/apl/102/5/10.1063/1.4788748

[15] M. Chabalko, E. Alarcon, E. Bou, and D. S. Ricketts, "Optimization of wpt efficiency using a conjugate load in non-impedance matched systems." in *Antennas and Propagation Society International Symposium (APSURSI), 2014 IEEE*. IEEE, 2014, pp. 645–646.

[16] D. Ricketts and M. Chabalko, "On the efficient wireless power transfer in resonant multi-receiver systems," in *Circuits and Systems (ISCAS), 2013 IEEE International Symposium on*, May 2013, pp. 2779–2782.

[17] M. Zargham and P. Gulak, "Maximum achievable efficiency in near-field coupled power-transfer systems," *Biomedical Circuits and Systems, IEEE Transactions on*, vol. 6, no. 3, pp. 228–245, June 2012.

[18] D. M. Pozar, *Microwave engineering*. John Wiley & Sons, 2009.

[19] D. Ahn and S. Hong, "A study on magnetic field repeater in wireless power transfer," *Industrial Electronics, IEEE Transactions on*, vol. 60, no. 1, pp. 360–371, Jan 2013.

[20] F. Pfeiffer, K. Finkenzeller, and E. Biebl, "Theoretical limits of iso/iec 14443 type a rfid eavesdropping attacks," in *Smart Objects, Systems and Technologies (SmartSysTech), Proceedings of 2012 European Conference on*, June 2012, pp. 1–9.

[21] P. Nikitin and K. Rao, "Performance limitations of passive uhf rfid systems," in *Antennas and Propagation Society International Symposium 2006, IEEE*, July 2006, pp. 1011–1014.

[22] D. Kajfez and E. Hwan, "Q-factor measurement with network analyzer," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 32, no. 7, pp. 666–670, Jul 1984.