Revisiting RFID Link Budgets for Technology Scaling: Range Maximization of RFID Tags

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***Abstract*—Passive RFID tags are traditionally assumed to be downlink limited since typical tag sensitivity is considerably poorer than reader sensitivity, due to stringent power limitations. On the other hand, semi-passive tags are generally uplink limited since tag and reader sensitivity are comparable. In this paper, it is demonstrated that judicious choice and use of IC impedance for backscatter modulation will be needed to simultaneously maximize tag read and write ranges as passive tag designs improve. Optimal backscatter modulation indices for amplitude-shift-keying are derived for range maximization of next generation low-power RFID tags.**

I. Introduction

Passive RFID tags are (strongly) power limited and depend on rectification of downlink signal from the reader to operate their circuitry. It has long been held that availability of power for tag IC operation is the system limiter, as opposed to the detector sensitivity for decoding of queries; i.e., passive tag systems are downlink (range) limited [1]. On the other hand, semi-passive tags that are battery-assisted [1] incorporate a power source (e.g. a coin cell) in the tag IC, but still use backscattered communication on the uplink. As a result, sensitivity of semi-passive tags (whose operation is not limited by power considerations) approach that of the reader detector; thus, RFID systems based on semi-passive tags are uplink (and not downlink) limited, with the backscattered power at the reader constituting the limit.

Given the extreme constraints on available power for passive tags, whether they are able to respond at all to reader query depends on the ability of the reader to transfer sufficient power on the downlink to support particular circuit functions such as the backscatter modulation on the uplink. This induces a maximum distance for reliable reader-to-tag communication that is denoted as the 'write' (downlink) range. For passive tags, the write range is limited *not* by the sensitivity to decoding the tag query signal, but by the power requirement for tag ICs. On the uplink, the 'read' (uplink) range is determined by the reader detectability of the tag data and the received backscattered power. Clearly, the smaller of these two ranges determines system performance and passive RFID systems have historically been downlink limited [1]. The above highlights an important facet of RFID systems that appears to have been under-appreciated in the existing literature - the fundamental *asymmetry* of the uplink and downlink ranges at which information may be reliably communicated. Thus, a system design objective is to improve the write range for passive tags to match the read range. With continuing advancements in IC technology, RFID tags that consume much less power than their predecessors [2–4] are being designed, that directly contributes to this. For example, [5] proposed a novel RFID tag that consumes only 2.7 μW, significantly lower than the 25 μW in [6] or the 16.7 μW in [3].

This paper examines the problem of optimizing the range for amplitude-shift-keying (ASK) modulation on the uplink. ASK requires two impedance states for the tag IC to achieve backscatter modulation [2–4]. Each modulation is characterized by an index that, in turn, determines the power backscattered to the reader. As tag IC power thresholds decrease, a link budget analysis shows that a cross-over between uplink and downlink range emerges. In other words, future passive tags with improved sensitivity may be read range limited.

A recent work [7] proposes optimal ON/OFF resistance for the ASK modulated passive RFID system. This scheme maximizes the harvestable power for the tag IC in order to enhance identification range between the tag and the reader. Range estimation has not been undertaken in [7] to highlight the actual improvement in range brought about by the proposed optimal configuration. It is shown that the effective backscattered power deteriorates under antenna mismatch conditions. However, as outlined in this paper, a trade-off emerges between uplink and downlink ranges because of technology scaling in the absence of mismatch as well. Thus, future passive RFID tags may become read range limited even when tag antenna is matched. The aforementioned trade-off is exploited in range maximization of RFID tags.

The organization of the paper is as follows. Sections II and III outline link budget analysis based downlink and uplink range estimation for ASK modulation. Section IV then discusses concurrent maximization of both read and write ranges and Section V offers observations and concluding remarks.

II. Downlink Range Estimation

Figure 1 depicts the equivalent circuit model for the RFID tag. The tag IC is modeled as a complex impedance Z_{IC} consisting of a resistance and a capacitance such that

$$Z_{IC} = R_{IC} - \frac{j}{\omega C_{IC}} \tag{1}$$

The Thevenin equivalent model for the antenna consists of a

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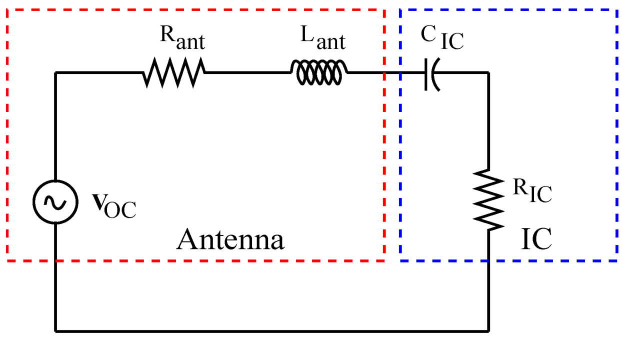

Fig. 1. Equivalent circuit model for RFID tag showing tag antenna and IC.

voltage source V_{OC} in series with a complex impedance Z_{ant} where

$$Z_{ant} = R_{ant} + j\omega L_{ant} \tag{2}$$

and R_{ant} combines the radiation and ohmic loss resistances. When possible, to ensure maximum power transfer to the tag, the antenna is designed for $Z_{ant} = Z_{IC}^{*}$. Otherwise, a power-matching network is placed between the antenna and tag to accomplish conjugate match [4]. Thus, $R_{ant} = R_{IC}$ in the absence of any modulation.

Figure 2 provides a simple model for backscatter modulation by insertion of a modulating resistance in either series or parallel with the IC. The IC capacitance and antenna inductance cancel each other at the frequency of operation and are not shown in Fig. 2. Series or parallel modulation alters the tag IC resistance to $R_{IC,eq} = mR_{ant}$, where m is the 'impedance modulation index'. Placement of a series modulating resistance ensures $m > 1$ while parallel placement ensures $0 < m < 1$. Thus, the series and parallel modulating resistances are respectively

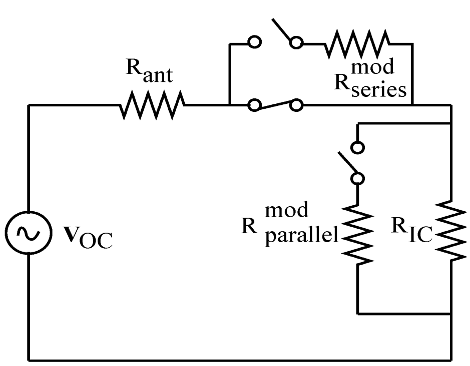

Fig. 2. A switching mechanism depicting series and parallel resistive modulation of R_{IC}. Only one switch is closed at a time.

$$R_{series}^{mod} = (m-1)\,R_{ant} \tag{3a}$$

$$R_{parallel}^{mod} = \left(\frac{m}{1-m}\right) R_{ant} \tag{3b}$$

The peak current I_{pk} flowing through the tag IC can be computed as

$$I_{pk} = \frac{V_{OC}}{Z_{ant} + Z_{IC}} = \frac{V_{OC}}{(1+m)R_{ant}} \tag{4}$$

and the corresponding total power supplied is

$$P_{total,IC} = \frac{1}{2}|I_{pk}|^2 R_{IC,eq} = \frac{|V_{OC}|^2}{2R_{ant}} \frac{m}{(1+m)^2} \tag{5}$$

However, part of this power is dissipated in the modulation resistor and only the remaining is available to supply the IC. For parallel modulation ($0 < m < 1$), the actual usable power delivered to the IC is

$$P_{usable,IC}^{parallel} = mP_{total,IC} = \frac{|V_{OC}|^2}{2R_{ant}} M_{parallel} \tag{6}$$

where

$$M_{parallel} = \left(\frac{m}{1+m}\right)^2 \tag{7}$$

For series modulation ($m > 1$), the actual usable power delivered to the IC is

$$P_{usable,IC}^{series} = \frac{P_{total,IC}}{m} = \frac{|V_{OC}|^2}{2R_{ant}} M_{series} \tag{8}$$

where

$$M_{series} = \left(\frac{1}{1+m}\right)^2 \tag{9}$$

In equations (7) and (9), $M_{parallel}$ and M_{series} are respective power scaling factor (PSF) as a function of impedance modulation index m. Thus, the combined PSF for usable power supply to tag IC M_{IC} is

$$M_{IC} = \begin{cases} \left(\frac{m}{1+m}\right)^2, & \text{for } 0 \le m \le 1 \\ \left(\frac{1}{1+m}\right)^2, & \text{for } m > 1 \end{cases} \tag{10}$$

For a more general analysis, it is assumed that the tag IC resides in two impedance states $state1$ and $state2$ for backscatter modulation where the impedances are, respectively,

$$Z_{IC}^{state1} = m_1 R_{ant} - j\omega L_{ant} \tag{11a}$$

$$Z_{IC}^{state2} = m_2 R_{ant} - j\omega L_{ant} \tag{11b}$$

The tag IC impedances in equation (11) may be the result of (a) parallel modulation in both states, (b) series modulation in both states, (c) parallel modulation in one state and series in the other. While only parallel or series modulation are intuitive, it may also be possible to operate with a mismatch in both states by alternating between parallel and series modulation when the tag antenna has been designed for $Z_{ant} = Z_{IC}^{*}$.

Assuming that the tag encodes backscattered data as FM0 baseband, the IC resides in each of its two impedance states an equal amount of time [3], and the time-average power delivered to the tag IC for rectification is

$$P_{tag}^{parallel} = 0.5 * \frac{|V_{OC}|^2}{2R_{ant}} \left[\left(\frac{m_1}{1+m_1} \right)^2 + \left(\frac{m_2}{1+m_2} \right)^2 \right] \quad (12)$$

for parallel modulation in both states, while it is

$$P_{tag}^{series} = 0.5 * \frac{|V_{OC}|^2}{2R_{ant}} \left[\left(\frac{1}{1+m_1} \right)^2 + \left(\frac{1}{1+m_2} \right)^2 \right] \quad (13)$$

for series modulation in both states, and finally, it is

$$P_{tag}^{mixed} = 0.5 * \frac{|V_{OC}|^2}{2R_{ant}} \left[\left(\frac{m_1}{1+m_1} \right)^2 + \left(\frac{1}{1+m_2} \right)^2 \right] \quad (14)$$

for parallel modulation in *state1* and series modulation in *state2*.

In general, the RFID reader can be assumed to reside in the far-field of the tag. In compliance with FCC regulations for unlicensed transmitters, the reader is assumed to emit 1 W of power with a transmit antenna gain G_{tx} of 6 dBi [1]. This translates to an effective isotropic radiated power (EIRP) P_{eirp} of 4 W. The reader antenna considered in this work is circularly polarized with 0 dB axial ratio.

For reader-tag downlink distance r_{write}, the impinging power density P_{den} at the tag is given by

$$P_{den} = \frac{P_{eirp}}{4\pi r_{write}^2} \quad (15)$$

Thus, the peak value of the incident electric field E_{inc} along the tag axis is

$$E_{inc} = \sqrt{Z_0 \eta P_{den}} = \frac{1}{2r_{write}} \left(\frac{Z_0 \eta P_{eirp}}{\pi} \right)^{1/2} \quad (16)$$

where Z_0 is free-space impedance and the factor η accounts for the polarization mismatch loss due to the linearly polarized tag antenna.

The induced open-circuit port voltage V_{OC} at the tag antenna is proportional to E_{inc} and is denoted as

$$V_{OC} = \alpha_{tag} E_{inc} = \frac{\alpha_{tag}}{2r_{write}} \left(\frac{Z_0 \eta P_{eirp}}{\pi} \right)^{1/2} \quad (17)$$

where the vector effective length α_{tag} is dependent on of the geometrical layout of the tag antenna [8, 9]. Thus, α_{tag} is a function of θ and ϕ only.

Thus, if the tag sensitivity is P_{tag}^0, then based on the selected modulation scheme, the write (downlink) range may be

$$D_{write}^{parallel} = \left[\frac{|\alpha_{tag}|}{4} \right] \left(\frac{Z_0 \eta P_{eirp}}{\pi R_{ant} P_{tag}^0} \right)^{1/2} \sqrt{\left[\left(\frac{m_1}{1+m_1} \right)^2 + \left(\frac{m_2}{1+m_2} \right)^2 \right]} \quad (18)$$

or,

$$D_{write}^{series} = \left[\frac{|\alpha_{tag}|}{4} \right] \left(\frac{Z_0 \eta P_{eirp}}{\pi R_{ant} P_{tag}^0} \right)^{1/2} \sqrt{\left[\left(\frac{1}{1+m_1} \right)^2 + \left(\frac{1}{1+m_2} \right)^2 \right]} \quad (19)$$

or,

$$D_{write}^{mixed} = \left[\frac{|\alpha_{tag}|}{4} \right] \left(\frac{Z_0 \eta P_{eirp}}{\pi R_{ant} P_{tag}^0} \right)^{1/2} \sqrt{\left[\left(\frac{m_1}{1+m_1} \right)^2 + \left(\frac{1}{1+m_2} \right)^2 \right]} \quad (20)$$

III. Uplink Range Estimation

The power reflection coefficients ρ_1 and ρ_2 for modulated tag impedances [3] are given, respectively, as

$$\rho_1 = \frac{Z_{IC}^{state1} - Z_{ant}^*}{Z_{IC}^{state1} + Z_{ant}} = \frac{m_1 - 1}{m_1 + 1} \quad (21a)$$

$$\rho_2 = \frac{Z_{IC}^{state2} - Z_{ant}^*}{Z_{IC}^{state2} + Z_{ant}} = \frac{m_2 - 1}{m_2 + 1} \quad (21b)$$

for the two states of the tag IC impedance.

If I_{state1} and I_{state2} denote the currents induced at the tag antenna terminals in *state1* and *state2* respectively, then for tag-reader uplink distance r_{read}, the *modulated* backscattered electric fields at the reader are given, respectively, as

$$E_{bs}^{state1} = I_{state1} \frac{E_a}{I_a} = I_{match}(1 - \rho_1) \frac{E_a}{I_a} \quad (22a)$$

$$E_{bs}^{state2} = I_{state2} \frac{E_a}{I_a} = I_{match}(1 - \rho_2) \frac{E_a}{I_a} \quad (22b)$$

where I_{match} denotes the current induced at the tag antenna terminals for a conjugate match between the tag antenna and its load [10], and is given by

$$I_{match} = \frac{V_{OC}}{2R_{ant}} \quad (23)$$

Also, for the set of equations in equation (22), E_a denotes the field radiated by the tag antenna when the current at its terminals is I_a [8] and no external excitation is applied to it. For free-space propagation, the ratio $|E_a/I_a|$ is given by

$$\left| \frac{E_a}{I_a} \right| = \frac{Z_0 |\alpha_{tag}|}{2\lambda r_{read}} \quad (24)$$

Assuming (a) no polarization mismatch at the reader antenna, and (b) conjugate match between the reader antenna and its load, the induced open-circuit voltages V_1 and V_2 at the reader antenna are given, respectively, as

$$V_1 = \alpha_{rd} E_{bs}^{state1} = \alpha_{rd} I_{match}(1 - \rho_1) \frac{E_a}{I_a} \quad (25a)$$

$$V_2 = \alpha_{rd} E_{bs}^{state2} = \alpha_{rd} I_{match}(1 - \rho_2) \frac{E_a}{I_a} \quad (25b)$$

Since the vector effective lengths α_{tag} and α_{rd} are proportional to the square root of their respective antenna gains in a specific direction [8], their relationship can be expressed as

$$\frac{\alpha_{rd}}{\alpha_{tag}} = \sqrt{\frac{G_{rx}}{G_{tag}}} \tag{26}$$

with G_{rx} representing the reader receive antenna gain in a specific direction, and G_{tag} denoting the tag antenna gain in the same direction.

A. Uplink Range

The uplink performance is determined by the reader's ability to decode the tag data which depends on the received backscattered signal power at the reader. In turn, the latter determines the achievable bit error rate (BER) for the specific modulation on the uplink [11].

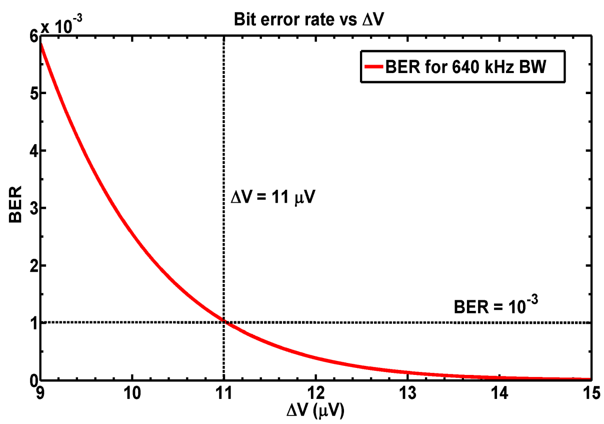

Fig. 3. Bit error rate vs. ΔV for 640 kHz tag bandwidth.

Since the typical RFID reader is monostatic (one RF chain for both transmit and receive as shown in Fig. 4) - it continues to transmit an unmodulated carrier on the downlink while simultaneously listening to the modulated tag response on the uplink. There is always some leakage from transmit to receiver chain consisting of both the (a) downlink CW signal component as well as (b) the transmit LO phase noise [1]. For a reader transmitting 30 dBm CW on downlink, the signal leakage is typically 15 dB below the transmitted signal, i.e., around 15 dBm. Thus for any decoding of the tag backscatter modulated signal, this CW component must be removed, which is achieved by dc blocking in the reader. *

The primary performance limiter on the uplink is the LO phase noise leaking from the transmit chain which overshadows the thermal noise component. Per [1], the phase noise power spectral density is typically around -115 dBc/Hz relative to the CW signal power at 640 kHz offset. Thus, for 640 (40) kHz tag signal bandwidth, the total LO noise power is (-115+59) = -56 (-68) dBc relative to the CW signal. Hence, for a CW signal component of 15 dBm, the phase noise power is approximately (15-56) = -41 dBm (-53 dBm).

*Any CW component at the center frequency appears as a dc shift after demodulation in the reader.

For BER determination, this phase noise needs to be converted into a voltage in the baseband receiver. The antenna reflection is not in phase with the local oscillator signal as it has to travel down cables to the antenna and back as shown in Fig. 4. The total delay for the transmit signal to reach the antenna, get reflected and finally reach the mixer, depicted in Fig. 4 as τ ns, introduces variation in the absolute phase of the reflected signal. This phase variation, in turn, affects the output voltage of the mixer that is fed by the local oscillator. In this paper, in accordance with the analysis in [1], it is estimated that the phase noise is reduced by a factor of 50 dB in being converted to amplitude noise. Thus, the equivalent amplitude noise at the receiver is (-41-50) = -91 dBm (-103 dBm). If the leakage power is $P_{leak} = -91$ dBm, then the BER is

$$BER = \frac{1}{2} erfc\left(\frac{|V_1 - V_2|/2}{2\sqrt{2}\sqrt{P_{leak}}}\right) \tag{27}$$

with erfc(.) denoting the complementary error function and P_{leak} expressed in Watts.

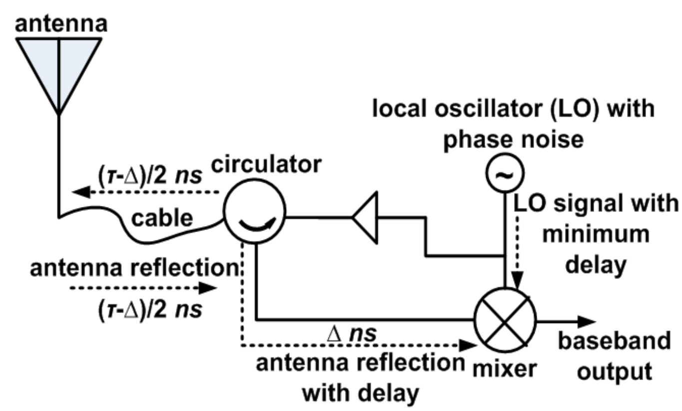

Fig. 4. Delayed antenna reflection depicting phase noise conversion to equivalent amplitude noise. All delay measurements are in nanoseconds (ns).

Often, an operating BER threshold value is $BER_{th} = 10^{-3}$ at $T = 300$ K [12]. If $\Delta V = |V_1 - V_2|$, then Fig. 3 depicts the necessary $\Delta V = 11$ μV to achieve the desired BER of 10^{-3} for $BW = 640$ kHz. For $BW = 40$ kHz, $\Delta V = 2.75$ μV. Note that 640 - 40 kHz denotes the range of the uplink signal, corresponding to binary modulation at rates of 640 (max) - 40 (min) Kbps as specified in the EPC Global standard [13].

The uplink range estimation is undertaken based on the necessary ΔV for a specific tag bandwidth. By employing equations (21), (23), (24) and (25), it can be derived that

$$\Delta V = \frac{Z_0 |V_{OC}||\alpha_{rd}||\alpha_{tag}||m_1 - m_2|}{2R_{ant}\lambda r_{read}(1+m_1)(1+m_2)} \tag{28}$$

In equation (28), V_{OC} should be replaced with

$$V_{OC} = \frac{\alpha_{tag}}{2r_{read}}\left(\frac{Z_0 \eta P_{eirp}}{\pi}\right)^{1/2} \tag{29}$$

yielding

$$\Delta V = \frac{Z_0|\alpha_{rd}||\alpha_{tag}|^2|m_1 - m_2|}{4\lambda R_{ant} r_{read}^2 (1+m_1)(1+m_2)} \left(\frac{Z_0 \eta P_{eirp}}{\pi}\right)^{1/2} \tag{30}$$

Thus, based on the BER requirement, the read (uplink) range D_{read} is

$$D_{read} = \frac{|\alpha_{tag}|}{2} \sqrt{\frac{Z_0|\alpha_{rd}||m_1 - m_2|}{\lambda \Delta V R_{ant}(1+m_1)(1+m_2)}} \left(\frac{Z_0 \eta P_{eirp}}{\pi}\right)^{1/4} \tag{31}$$

IV. Range Maximization

A link budget analysis is undertaken to characterize the read range D_{read} and write range D_{write} for an RFID system operating at 915 MHz with 640 kHz tag bandwidth. Specifically, an analytical expression for the optimal impedance modulation indices m_1 and m_2 that concurrently maximize both D_{read} and D_{write} is derived. The maximum reader-tag distance is $D_{range} = min.\{D_{read}, D_{write}\}$. Thus, range maximization of RFID tags is commensurate with (a) first equalizing D_{read} and D_{write}, and (b) then maximizing this common range.

A. Equalization of Read and Write Ranges

Three different situations arise based on the chosen modulation scheme - (a) parallel only, (b) series only, and (c) alternate parallel and series (mixed). The corresponding write ranges are defined as $D_{write}^{parallel}$, D_{write}^{series} and D_{write}^{mixed} in equations (18), (19) and (20) respectively.

1) Parallel Modulation: Equating $D_{write}^{parallel}$ from equation (18) and D_{read} from equation (31), the following equation may be used to select m_2 for a chosen value of m_1 in the range $0 < m_1 \leq 1$ such that $m_2 < m_1$

$$m_2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{32}$$

where

$$\begin{aligned} A &= F + 2m_1F + 2m_1^2F + 1 + m_1 & (33a)\\ B &= 2m_1^2F - m_1^2 + 1 & (33b)\\ C &= m_1^2F - m_1 - m_1^2 & (33c) \end{aligned}$$

and

$$F = \frac{\lambda \Delta V}{4P_{tag}^0|\alpha_{rd}|}\left(\frac{\eta P_{eirp}}{\pi Z_0}\right)^{1/2} \tag{34}$$

Though equation (32) may yield two possible values of m_2, the correct value is chosen such that $m_2 > 0$ and $m_2 < m_1$. It is also possible to select $m_1 < m_2$, and owing to symmetry in the relationship between m_1 and m_2, their values just need to be interchanged.

2) Series Modulation: Equating D_{write}^{series} from equation (19) and D_{read} from equation (31), the following equation may be used to select m_1 for a chosen value of m_2 in the range $m_2 \geq 1$ such that $m_1 > m_2$

$$m_1 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{35}$$

where

$$\begin{aligned} A &= F - 1 - m_2 & (36a)\\ B &= 2F + m_2^2 - 1 & (36b)\\ C &= 2F + m_2^2F + 2m_2F + m_2 + m_2^2 & (36c) \end{aligned}$$

and F is defined in equation (34).

Again, equation (35) may yield two possible values of m_1, and the correct value is chosen such that $m_1 > 1$ and $m_1 > m_2$. It is also possible to select $m_1 < m_2$, and symmetry in the relationship between m_1 and m_2 may be directly exploited to interchange values.

3) Alternate Parallel and Series Modulation: Equating D_{write}^{mixed} from equation (20) and D_{read} from equation (31), the following equation may be used to select m_1 for a chosen value of m_2 in the range $m_2 \geq 1$ such that $m_1 < m_2$ and $0 < m_1 < 1$

$$m_1 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{37}$$

where

$$\begin{aligned} A &= 2F + 2m_2F + m_2^2F + 1 + m_2 & (38a)\\ B &= 2F - m_2^2 + 1 & (38b)\\ C &= F - m_2 - m_2^2 & (38c) \end{aligned}$$

and F is defined in equation (34).

Even though equation (36) may yield two possible values of m_1, and the correct value is chosen such that $0 < m_1 < 1$ and $m_1 < m_2$. It is also possible to select $m_1 > m_2$, and symmetry in the relationship between m_1 and m_2 may be directly exploited to interchange values. This interchange implies series modulation in *state1* and parallel modulation in *state2*.

B. Range Maximization

The range maximization problem is essentially a constrained optimization problem that aims to maximize read (or write) range and simultaneously equate read and write ranges. Sequential quadratic programming within the Matlab environment is used for optimization. Let D_{write} be a generic reference to $D_{write}^{parallel}$, D_{write}^{series} or D_{write}^{mixed}. It must be noted that both D_{read} and D_{write} are functions of m_1 and m_2, and are explicitly referred to as $f^{(read)}(m_1, m_2)$ and $f^{(write)}(m_1, m_2)$ for a complete mathematical description of the problem as

$$\begin{gathered} Maximize\ f^{(read)}(m_1, m_2) \\ subject\ to \\ f^{(read)}(m_1, m_2) - f^{(write)}(m_1, m_2) = 0 \end{gathered}$$

Since $f^{(read)}(m_1, m_2)$ and $f^{(write)}(m_1, m_2)$ are estimated during the optimization procedure with only m_1 and m_2 as variables of interest, it is necessary to discuss the fixed values assumed by Z_0, P_{eirp}, η, λ, ΔV, R_{ant}, $|\alpha_{tag}|$, $|\alpha_{rd}|$ and P_{tag}^0 in equations (18), (19), (20) and (31). The first four terms are $Z_0 = 377\ \Omega$, $P_{eirp} = 4$ W, $\eta = 0.5$ (reader antenna assumed to have 0 dB axial ratio) and $\lambda = 0.32$ meters at 915 MHz operation frequency. For $BW = 640$ kHz, $\Delta V = 11\ \mu$V.

The magnitude of the vector effective length of the tag antenna for a given system geometry (i.e. as a function of reader position (r,θ,ϕ)), and antenna resistance are best estimated by use of electromagnetic (EM) simulation. In this work, the 3D EM full-wave field solver that measures these terms is $PhysWAVE^{©}$ [14]. Thus, $|\alpha_{tag}|$ is measured as 0.1 for a half-wavelength dipole employed as the tag antenna, with the reader positioned in its broadside direction. For the same tag antenna at 915 MHz, $R_{ant} \approx 76\ \Omega$. Once $|\alpha_{tag}|$ is measured, equation (26) is employed to calculate $|\alpha_{rd}|$ for the reader antenna. Since the reader has been positioned in the broadside direction of the tag with $G_{tag} = 2$ dBi, $|\alpha_{rd}| = 0.12$ with an effective receive antenna gain of 3 dBi after accounting for polarization mismatch on the uplink. The optimal solution is determined for a chosen tag sensitivity, P_{tag}^0.

The maximization of read range is subject to the nonlinear equality constraint equating read and write ranges. Thus, if the optimal values are $m_1^\star$ and $m_2^\star$, then the maximum operable reader-tag distance D_{range} is

$$D_{range} = \frac{|\alpha_{tag}|}{2}\sqrt{\frac{Z_0|\alpha_{rd}||m_1^\star - m_2^\star|}{\lambda \Delta V R_{ant}(1+m_1^\star)(1+m_2^\star)}} \left(\frac{Z_0 \eta P_{eirp}}{\pi}\right)^{1/4} \tag{39}$$

The ranges of values of m_1 and m_2 within which $m_1^\star$ and $m_2^\star$ will lie depend on the chosen modulation scheme and are enumerated as

- <u>Parallel modulation</u>: $0 \leq m_1 \leq 1$ and $0 \leq m_2 < 1$
- <u>Series modulation</u>: $m_1 \geq 1$ and $m_2 > 1$
- <u>Mixed modulation</u>: $0 \leq m_1 \leq 1$ and $m_2 > 1$

The question now arises - are these ranges of m_1 and m_2 attainable for any choice of tag sensitivity? Based on equations (32)-(38), it becomes obvious that the factor F in equation (34) is inversely proportional to tag sensitivity P_{tag}^0, while all other contributing factors including ΔV ($BER_{th} = 10^{-3}$) remain constant. Since F has a direct impact on the discriminant of the quadratic equations (32), (35) and (37), the appropriate ranges of m_1 and m_2 will depend exclusively on tag sensitivity.

The approximate ranges of m_1 and m_2 for parallel modulation are depicted in Table I along with the corresponding tag sensitivity measure. The ranges are interchangeable based on symmetry.

For series modulation, the ranges of m_1 and m_2 are both [1,∞], and remain unaffected by tag sensitivity.

However, as depicted in Table II, these ranges undergo drastic changes for mixed parallel and series modulation as tag sensitivity improves. Interchangeability of ranges remains a viable option.

TABLE I
POSSIBLE RANGES OF m_1 AND m_2 FOR PARALLEL MODULATION

Tag sensitivity	Range of m_1	Range of m_2
0 dBm	[0,1]	[0,0.999]
-10 dBm	[0,1]	[0,0.994]
-25 dBm	[0,1]	[0,0.829]
-35 dBm	[0,1]	[0,0.254]

C. Impact of Technology Scaling

The improvement in reader-tag operable distance, D_{range}, can be attributed to technology scaling that improves tag sensitivity [5]. A comprehensive overview of tag sensitivity is provided in [2]. Table III outlines the dependence of optimal impedance modulation indices for either parallel or series modulation on tag sensitivity. No modulation is necessary when either $m_1^\star = 1$ or $m_2^\star = 1$, and the entry corresponding to the modulating resistance in this state is omitted from the table. The important observations from Table III are:

TABLE II
POSSIBLE RANGES OF m_1 AND m_2 FOR MIXED MODULATION

Tag sensitivity	Range of m_1	Range of m_2
0 dBm	0.999	1
-10 dBm	[0.993,0.999]	[1,1.007]
-25 dBm	[0.813,0.993]	[1,1.23]
-35 dBm	[0.243,0.999]	[1,4.12]

- Irrespective of the choice of modulation, one optimal index is always $m_1^\star = 1$ (or, alternatively, $m_2^\star = 1$ from symmetry). The explanation lies in the fact that the tag write range is maximized for conjugate match. Hence, equalization of read and write ranges for $m_1^\star = 1$ is the obvious choice, with $m_2^\star$ based on uplink and downlink range trade-off.
- If $m_2^\star$ is denoted by $m_2^{\star^{parallel}}$ for parallel modulation and $m_2^{\star^{series}}$ for series modulation, then their relationship may be defined as $m_2^{\star^{series}} = 1/m_2^{\star^{parallel}}$. It must be mentioned that the choice of $m_2^\star$ for parallel and series modulation equalize power supplied to the tag IC as well as backscattered power to the reader between them only when $m_1^\star = 1$. If m_2 is replaced by $1/m_2$ (with $m_1 = 1$) in equations (20) and (31) for D_{write}^{series} and D_{read} respectively, then the former transforms into $D_{write}^{parallel}$ while D_{read} remains unchanged. Thus, range maximization may be achieved using *either* parallel or series modulation. Design consideration such as ease of realization of on-chip modulating resistance $R_{m_2^\star}^{mod}$ may eventually dictate the choice of the modulation scheme.
- Mixed modulation simply reduces to parallel modulation for range maximization. An equal mismatch condition for ASK does not maximize range.
- The choices of (a) $m_1 = 1$ and $m_2 = 0$ for parallel modulation [3, 15], or (b) equal mismatch such that $m_1 = 1/m_2$ ($\rho_1 = -\rho_2$) for mixed modulation are always sub-optimal for range maximization. This important issue has been consistently overlooked in the literature on RFID system deployment. As a baseline comparison, Table IV depicts the achievable D_{range} for choice (a). A D_{range}

TABLE III
IMPACT OF TECHNOLOGY SCALING

P^0_{tag}	Parallel Modulation			Series Modulation			Mixed Modulation			D_{range}
	$m_1^\star$	$m_2^\star$	$R^{mod}_{m_2^\star}$	$m_1^\star$	$m_2^\star$	$R^{mod}_{m_2^\star}$	$m_1^\star$	$m_2^\star$	$R^{mod}_{m_1^\star}$	
-10 dBm	1	0.994	11.7 kΩ	1	1.007	0.5 Ω	0.994	1	11.7 kΩ	**3.14 meters**
-25 dBm	1	0.829	370 Ω	1	1.206	15.6 Ω	0.829	1	370 Ω	**16.86 meters**
-35 dBm	1	0.254	25.84 Ω	1	3.936	223.5 Ω	0.254	1	25.84 Ω	**42.6 meters**

of 12.49 meters for $P^0_{tag} = -25$ dBm in Table IV closely matches the 12 meters achieved in [5] for 4 W EIRP.

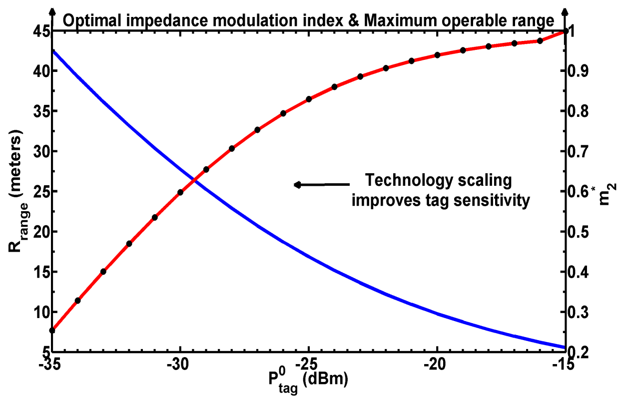

Fig. 5. Optimal impedance modulation index $m_2^\star(= m_2^{parallel})$ and maximum operable range D_{range} each as a function of tag sensitivity.

Figure 5 outlines both D_{range} and $m_2^\star(= m_2^{parallel})$ as a function of tag sensitivity. Thus, range improvement is empowered by technology scaling.

With further improvement in tag sensitivity ($P^0_{tag} < -35$ dBm), the tag becomes uplink limited. Semi-passive tags have sensitivities around -40 dBm [16]. Thus, for semi-passive tags, the maximum range is simply the read range, D_{read}, for $m_1 = 1$ and $m_2 = 0$. This choice of m_1 and m_2 maximizes backscattered power, and involves a conjugate match in *state1* in conjunction with shorted IC resistance in *state2*.

TABLE IV
MAXIMUM RANGE FOR PARALLEL MODULATION

Tag sensitivity	m_1	m_2	D_{range}
-10 dBm	1	0	2.22 meters
-25 dBm	1	0	12.49 meters
-35 dBm	1	0	39.5 meters

V. REFLECTIONS AND CONCLUSIONS

Figure 5 emphasizes the fact that for fixed reader sensitivity, an enhancement in tag sensitivity improves D_{range} for RFID tags. Are any other degrees of freedom available to designers to further improve D_{range}?

The key to improving D_{range} lies in careful design of the tag antenna and IC. Typically, the goal of tag antenna design is to conjugate match it to the IC impedance [1]. A marginally better tag design is proposed when $P^0_{tag} = -35$ dBm and parallel modulation is employed for backscatter. It is assumed that the antenna resistance and nominal IC resistance are intentionally mismatched such that $R_{ant} \neq R_{IC}$.

The tag IC resides in two impedance states $state1$ and $state2$ where the impedances are, respectively,

$$Z_{IC}^{state1} = m_1 R_{ant} - j\omega L_{ant} \tag{40a}$$
$$Z_{IC}^{state2} = m_2 R_{ant} - j\omega L_{ant} \tag{40b}$$

with $m_2 < m_1$ for parallel modulation. In this case, however, Z_{IC}^{state1} is the nominal IC impedance and Z_{IC}^{state2} is the modulated impedance. Thus, the parallel modulating resistance that transforms Z_{IC}^{state1} to Z_{IC}^{state2} is

$$R^{mod}_{parallel} = \left(\frac{m_1 m_2}{m_1 - m_2}\right) R_{ant} \tag{41}$$

The actual usable power delivered to the tag IC in $state1$ and $state2$ are, respectively,

$$P^{state1}_{usable,IC} = \frac{|V_{OC}|^2}{2R_{ant}} \frac{m_1}{(1+m_1)^2} \tag{42a}$$
$$P^{state2}_{usable,IC} = \frac{|V_{OC}|^2}{2R_{ant}} \frac{m_2^2}{m_1(1+m_2)^2} \tag{42b}$$

Thus, the write range is

$$D^{parallel}_{write} = \left[\frac{|\alpha_{tag}|}{4}\right]\left(\frac{Z_0 \eta P_{eirp}}{\pi R_{ant} P^0_{tag}}\right)^{1/2} \sqrt{\left[\frac{m_1}{(1+m_1)^2} + \frac{1}{m_1}\left(\frac{m_2}{1+m_2}\right)^2\right]} \tag{43}$$

The read range estimation is still based on equation (31). The optimal indices turn out to be $m_1^\star = 1.41$ and $m_2^\star = 0.39$, and the maximum achievable range is 43.16 meters. The optimal solution, $m_1^\star$, implies that the tag should be designed for $R_{IC} \approx 107\ \Omega$. However, D_{range} improves by only 0.6 meters for $P^0_{tag} = -35$ dBm. Introducing an intentional mismatch between R_{ant} and R_{IC} yields range improvement, but the overall gain in RFID performance should justify tag re-design. In the aforementioned case, tag re-design is not necessary since it offers negligible range improvement. It must be noted that $m_1^\star \neq 1/m_2^\star$ ($\rho_1 \neq -\rho_2$), and this implies that an equal mismatch condition [3, 4] is sub-optimal for range maximization.

The magnitude of the vector effective lengths α_{tag} and α_{rd} associated with tag and reader antennas improve with an increase in their respective antenna gains, G_{tag} and G_{rx}. This improves both write and read ranges. A different antenna type such as a patch antenna may yield a higher gain [1] than the typical dipole considered in this paper. Thus, designers have flexibility in improving D_{range} based on aforementioned design choices.

This work demonstrates the need to consider the impact of impedance modulation indices on the read/write range for passive RFID tags. Using a link budget analysis leveraged by EM simulation, this paper investigates the choice of ASK impedance modulation indices that maximize the operating range as a function of key system parameters - notably the tag sensitivity and bit error rate at the reader. Technology scaling will continue to improve tag sensitivity, implying that existing values of impedance modulation indices must be modified. The analysis put forth in this paper suggests how on-chip parallel or series modulating resistances may be used to achieve optimum reader-tag distances.

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