Self-Interference Noise Limitations of RFID Readers

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***Abstract*—In this contribution we compute the read range limits of RFID readers also modelling the often ignored self-interference and leakage cancellation effects. The forward link limit is defined by the sensitivity of the tag, while the reverse link limit depends on the ability of the reader to decode the tag message. We will express the reverse link limit and the receiver Signal to Noise Ratio (SNR), whose dominating expression is the self-interference noise. Further, we will introduce two Figures Of Merits (FOMs) relevant for the reverse link limit. In a broad range of these FOMs, the receiver SNR is independent of the transmit power and reader noise figure. Further, we calculate the average suppression gain of leakage cancellers which enables us to upper-bound the noise effective cancellation gain which directly relates with the reverse link limit.**

I. INTRODUCTION

Ultra High Frequency (UHF) and microwave Radio Frequency IDentification (RFID) systems use radio waves to remotely detect and identify objects that carry so called RFID tags. The device which communicates with the tags is called RFID reader. The block diagram of a generic dual-antenna reader is shown in Fig. 1. On the top, the transmitter creates a signal which is emitted from the Transmitter (TX) antenna. This signal is either modulated to communicate with the tags, or it constitutes an unmodulated Continuous Wave (CW) signal to facilitate tag to reader communications. The tag signal is picked up by the Receiver (RX) antenna and further processed in the receiver hardware. The signal is then fed to a baseband processor which covers signal processing, protocol handling and hardware control.

Passive and semi-passive RFID systems use backscatter modulation to transmit data from an RFID tag to a reader. This technique relies on the fact that the amplitude and phase of the waves scattered from an antenna depend on its termination impedance. Thus, the tag chip sends data to the reader by modulating the impedance presented to the antenna terminals [1], [2]. While this backscattering technique enables remotely powered communication, it necessitates a constant CW signal to be transmitted from the RFID reader during tag to reader data transfer [3]–[5]. This CW signal poses a challenge for RFID reader designs, since it interferes with the received backscattered tag-response and dominates the required dynamic range at the reader's receiver. To reduce this dynamic range demand, Leaking Carrier Cancellers (LCCs) may be used. To cancel the interference, these devices inject a signal of opposite phase and equal amplitude at the receiver.

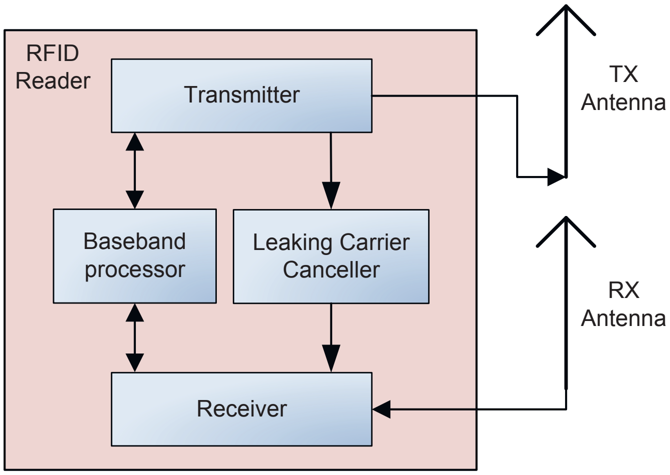

Fig. 1. Block Diagram of an RFID reader.

This paper deals with the limitations on read range and SNR due to leaking transmit noise. There are several publications which deal with the link budget and noise analysis of RFID systems [6]–[9], but the noise aspect of self-interference is either ignored, or treated in a very implementation oriented fashion, notably exceptions being [10], [11]. These contributions analyse the effects of moduation schemes on bit error probabilities and bit rates in the presence of leakage noise, but do not capture the effects of a reader hardware employing a leakage canceller. In this paper we will compute the receive SNR at the reader taking the transmitter SNR and leakage cancellation into account. The purely theoretic analysis we present in this contribution is validated by measurements presented in [12], which corroborates that the receiver SNR depends on the TX–RX isolation and the LCC isolation gain.

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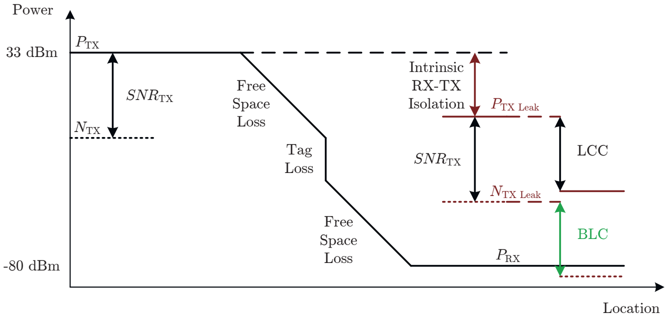

Fig. 2. RFID link budget chart focusing on carrier cancellation and transmit noise.

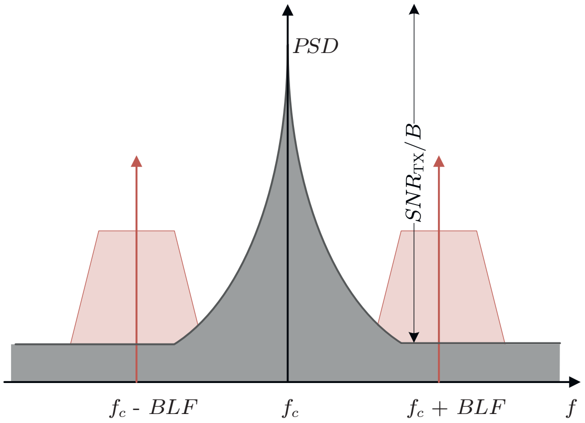

Fig. 3. Power spectral density of RFID reader received signals.

II. Self-Interference Noise and Cancellation

To illustrate the issue of self-interference noise, we start with an example [13] illustrated in a schematic link budget, see Fig. 2. On the left side a typical transmit power of $P_{\mathrm{TX}} = 33\,\mathrm{dBm}$ is plotted. Going from left to right, the free space loss, tag loss (antenna gain, modulation and matching losses) and second free space loss in the reverse direction reduce the power at the receiver to a exemplary power of $P_{\mathrm{RX}} = -80\,\mathrm{dBm}$. This is a realistic value for long distance reader to tag communications [14] using state of the art tags which have a sensitivity of $P_{\mathrm{Tag_{min}}} = -21.5\,\mathrm{dBm}$ [15]. Additionally, the transmit SNR is plotted on the left side and the transmitted noise power N_{TX} is shown. This reader transmit SNR is the ratio between the power of the transmitted CW signal, and the unintentionally transmitted noise power, assuming white noise in our bandwidth of interest. Of course the transmit noise in practise is not white but usually increases for spectral components closer to the intended CW frequency. An example is plotted in Fig. 3. Besides this coloured carrier phase noise there are other noise components from the transmitter stages and the transmitter baseband. For our analysis, the relevant spectral noise components are those centred around the Backscatter Link Frequency (BLF) of the tag response. In our model we consider the transmit noise in this region as white and use the transmit SNR as the ratio between the transmit carrier power and the white noise level integrated in the relevant bandwidth B.

On the right side of Fig. 2, the intrinsic TX to RX isolation is recorded. This isolation applies to the transmitted CW signal as well as to the TX noise component. Therefore, by redrawing the transmit SNR we see the leaking transmit noise power $N_{\mathrm{TX\ Leak}}$. In our example it is larger than the received tag signal power P_{RX}, and the receiver SNR is negative.

The situation is relaxed when leakage cancellation is used. An LCC is part of the Radio Frequency (RF) section of an RFID reader (see Fig. 1) and injects a phase and amplitude adjusted sample of the transmit signal at the receiver input [14], [16]. The conventional approach to characterize LCCs in RFID systems is to measure the attenuation realized at the reader's carrier frequency only. But this approach is insufficient in many cases. For conventional passive RFID systems which only transmit a CW signal during tag to reader communications, a narrowband canceller is adequate to suppress this sine wave. But since the power levels in RFID are extremely diverse, we already argued that the broadband transmit noise is an issue, too.

Without any leakage cancellation, the dynamic range of the reader RX needs to be at least $P_{\mathrm{TX\ Leak}}/P_{\mathrm{RX}}$, which possibly is in the order of $90\,\mathrm{dB}$. To reduce these RX demands, the LCC suppresses the leakage signal, as indicated by the corresponding arrow on the far right side. But the broadband TX noise component is not suppressed, and so the receive SNR is dominated by the leaking TX noise power $N_{\mathrm{TX\ Leak}}$, being negative in the example plotted in Fig. 2. A Broadband Leakage Canceller (BLC) on the other hand does also suppress the noise component, so while the necessary dynamic range remains unchanged when compared to the LCC, the received SNR is improved. In fact, a very narrow band LCC even enhances the noise level, since the leaking signal and the cancellation signal will interfere constructively at some frequencies [14].

III. RFID Link Budget Limitations

Passive RFID systems have two fundamental link limits corresponding to the required communication links: The forward link limitation describes the situation, when the received RF power at the tag is too small to generate sufficient Direct Current (DC) power to supply the tag electronics. The reverse link limitation describes the effect when the received backscatter-modulated tag signal in comparison to the receiver noise is too weak to successfully decode the data [17, Chapter 2]. We will now formulate the two limits for a dual-antenna RFID system, which can easily be reduced to a single antenna system by setting $G_{\mathrm{TX}} = G_{\mathrm{RX}} = G_{\mathrm{TRX}}$.

A. Forward Link Limit

The received RF power at the perfectly matched tag is given by

$$P_{\mathrm{Tag}} = \frac{P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{Tag}}}{FSPL} = \frac{EIRP \cdot G_{\mathrm{Tag}}}{FSPL}, \tag{1}$$

where P_{TX} is the reader transmit power, G_{TX} is the gain of the reader antenna used for transmitting, G_{Tag} is the tag antenna gain, and the Free SPace Loss (FSPL) describes the thinning of the transmit power due to the distance between reader and tag. Since the transmit Equivalent Isotropically Radiated Power (EIRP) is subject to legal limits[1], only the tag antenna gain is a means to increase the read range for a given tag with minimum received power. Quasi-omnidirectional tag antennas with low gains are usually used, since the orientation of tags is naturally unspecified, unpredictable, or changing. Therefore, the forward link limit for maximum read range or channel loss is solely defined by the technologically defined minimum required tag power $P_{\mathrm{Tag_{min}}}$, which is called tag sensitivity.

B. Reverse Link Limit

The received power at the reader is given by:

$$P_{\mathrm{RX}} = \frac{P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{RX}}}{FSPL^2} G^2_{\mathrm{Tag}} \eta_{\mathrm{Mod}}, \tag{2}$$

where η_{Mod} is the modulation efficiency of the tag, which depends on the tag antenna matching [17, (2.14)] and the tag impedance shift that occurs during modulation. The modulation efficiency also depends on the tag's input power [18], but since this paper deals with the limitations of readers and not tags is considered constant here.

The noise at the reader is composed of two parts. First, the thermal noise $N_{\mathrm{th}} = kTB$, where k is the Boltzmann constant, enhanced by the receiver noise figure F, and the leaking transmit noise of the reader:

$$P_{\mathrm{N}} = N_{\mathrm{th}} F + \frac{P_{\mathrm{TX}}}{SNR_{\mathrm{TX}} IS \cdot G_{\mathrm{I}}}, \tag{3}$$

where SNR_{TX} is the SNR of the transmitter, IS is the intrinsic TX–RX isolation of the reader, and G_{I} is the isolation gain of an LCC defined as:

$$G_{\mathrm{I}} = \frac{|H_{\mathrm{L}}|^2}{|H_{\mathrm{L}} + H_{\mathrm{LCC}}|^2}, \tag{4}$$

where H_{L} is the TX–RX leakage channel and H_{LCC} is the transfer function of the LCC. Since both channels are in general frequency dependent, G_{I} is strictly speaking also frequency dependent. For now, we assume G_{I} to be constant, this topic is further treated in Section IV. If no LCC is used G_{I}=1, if it is misadjusted or not optimized for broadband operation values of $G_{\mathrm{I}} < 1$ are probable [19].

Using (2) and (3) and $EIRP = P_{\mathrm{TX}} G_{\mathrm{TX}}$ we compute the receiver SNR:

$$SNR_{\mathrm{RX}} = \frac{EIRP\, G_{\mathrm{RX}} FOM_{\mathrm{R}} FOM_{\mathrm{Ant}} G^2_{\mathrm{Tag}} \eta_{\mathrm{Mod}}}{FSPL^2 \left(EIRP\, G_{\mathrm{RX}} + N_{\mathrm{th}} F\, FOM_{\mathrm{R}} FOM_{\mathrm{Ant}} \right)}, \tag{5}$$

where we defined two Figure Of Merits (FOMs): The reader FOM:

$$FOM_{\mathrm{R}} = SNR_{\mathrm{TX}} G_{\mathrm{I}}, \tag{6}$$

TABLE I
MODEL TAG PARAMETERS

Sensitivity $P_{\mathrm{Tag_{min}}}$	–21.5	dBm
Antenna Gain G_{Tag}	0	dB
Modulation Efficiency η_{Mod}	–10	dB
Maximum Read Range at 2 W ERP	18.76	m

TABLE II
READER PARAMETERS

Frequency f	866	MHz
Bandwidth B	1	MHz
Noise Figure F	0	dB
Required SNR I	18	dB
Required SNR II	5	dB

and the antenna FOM:

$$FOM_{\mathrm{Ant}} = G_{\mathrm{TX}} G_{\mathrm{RX}} IS. \tag{7}$$

The first FOM represents the hardware capabilities of the reader: A high number corresponds to a clean transmit signal (high transmit SNR) and an effective LCC (high isolation gain). The second figure represents the reader antennas: For dual-antenna scenarios besides the obvious antenna gains the intrinsic TX-RX isolation depends on the antenna patterns and geometrical arrangement. For a single-antenna system and a perfect TX-RX decoupling in the reader this number reduces to $FOM_{\mathrm{Ant}} = G^2_{\mathrm{TRX}}/|S_{11}|^2$, where $|S_{11}|$ is the return loss of the antenna.

To gain insight in the receive SNR we differentiate two cases to simplify the denominator in (5): for $EIRP\, G_{\mathrm{RX}} \ll N_{\mathrm{th}} F\, FOM_{\mathrm{R}} FOM_{\mathrm{Ant}}$ we neglect the first denominator term and compute

$$SNR_{\mathrm{RX_{th}}} = \frac{EIRP\, G_{\mathrm{RX}} G^2_{\mathrm{Tag}} \eta_{\mathrm{Mod}}}{FSPL^2 N_{\mathrm{th}} F}, \tag{8}$$

which is the SNR assuming only thermal noise components. For conventional RFID systems operating at the legal transmit limit the only ways to enhance $SNR_{\mathrm{RX_{th}}}$ is to increase the reader antenna gain and lower the receiver noise figure. However, the SNR obtained for the opposite self-interference dominated case where $EIRP\, G_{\mathrm{RX}} \gg N_{\mathrm{th}} F\, FOM_{\mathrm{R}} FOM_{\mathrm{Ant}}$ may be more relevant in practice:

$$SNR_{\mathrm{RX_{SI}}} = \frac{FOM_{\mathrm{R}} FOM_{\mathrm{Ant}} G^2_{\mathrm{Tag}} \eta_{\mathrm{Mod}}}{FSPL^2}. \tag{9}$$

Interestingly, this SNR limit does not depend on the reader transmit power, but solely on reader and antenna FOMs — assuming that we do not change the tag parameters, especially its modulation efficiency. In practise this means that it is easy to verify if the reader is currently noise or self-interference limited: If the SNR does increase if the transmit power is increased, the reader operates noise limited. If the receiver SNR is independent of the transmit power, the the self-interference limitation kicks in. (A decreasing SNR with increasing transmit power indicates a reduction in tag

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[1] In Europe the maximum transmit Equivalent Radiated Power (ERP) of an RFID system is 2 W, which corresponds to an EIRP of 35.2 dBm, using the gain of a half wave dipole $G_{\mathrm{D}} \approx 2.2\,\mathrm{dBi}$.

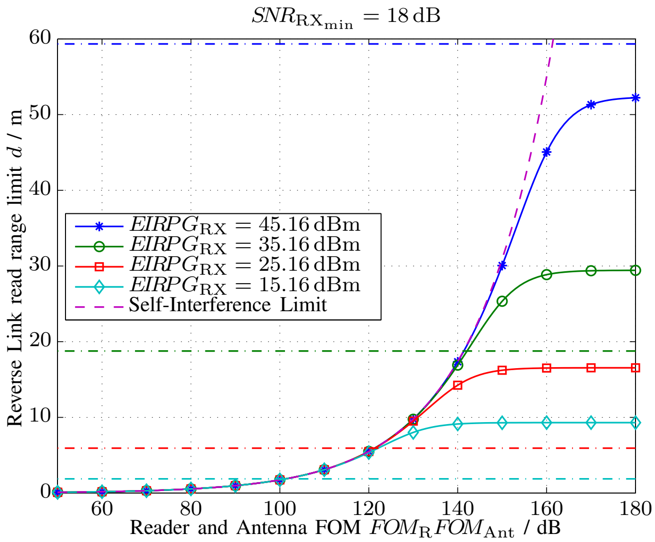

Fig. 4. Reverse link read range limit d for different FOM values, $SNR_{\mathrm{RX}_{\min}} = 18\,\mathrm{dB}$. The horizontal chain dotted lines correspond to the forward link limits of our model tag.

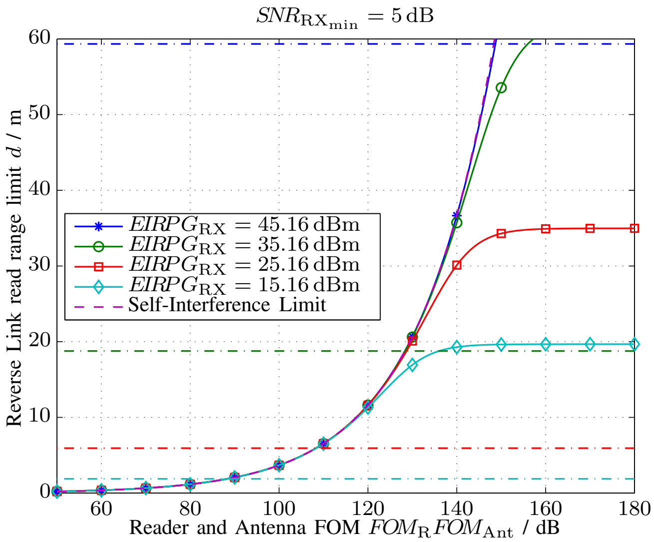

Fig. 5. Reverse link read range limit d for different FOM values, $SNR_{\mathrm{RX}_{\min}} = 5\,\mathrm{dB}$. The horizontal chain dotted lines correspond to the forward link limits of our model tag.

modulation efficiency due to the tag's shunt voltage regulator behaviour.)

To illustrate the reader's self-interference limitation, we compute the read range limit d based on (5) and $FSPL = \left(\frac{4\pi d}{\lambda}\right)^2$. For all following simulation results we use the model tag parameters summarized in Table I, where the sensitivity of a state of the art tag [15] is adopted. Note that we use a rather conservative tag antenna gain of one, but on the other hand do not include any polarization mismatch which creates an extra 6 dB penalty for RFID systems operating circular polarized antennas and linear polarized tags. For the reader parameters summarized in Table II we achieve the reverse link limits presented in Fig. 4 for a minimum SNR of 18 dB corresponding to the values reported in [20]. Using sophisticated synchronization and timing recovery methods, necessary SNR values drop to 5 dB [21], this value is used in Fig. 5.

The four solid lines correspond to the reverse link read range limits for different products of transmit EIRP and receiver antenna gain. For high FOM values the thermal noise dominates according to Equation 8. For low FOM values, the self-interference term limits the read range, and it becomes independent on transmit power or receiver antenna gain (for constant antenna FOM). In this region using (9) the self-interference reverse link limit is found to be

$$d_{\max_{\mathrm{SI}}} = \frac{\lambda}{4\pi} \sqrt[4]{\frac{FOM_{\mathrm{R}} FOM_{\mathrm{Ant}} G_{\mathrm{Tag}}^2 \eta_{\mathrm{Mod}}}{SNR_{\mathrm{RX}}}}, \tag{10}$$

which is indicated in Fig. 4 and Fig. 5 by the dashed line. Additionally, the forward link limits for different EIRP values corresponding to the labelled numbers and $G_{\mathrm{RX}} = 1$ are plotted as horizontal chain dotted lines. The regions below the curves is reachable, so we see in Fig. 5 that exploitation of the legal forward link limit of our model tag of 18.76 m requires a FOM product of at least 130 dB — and this is for readers employing very good decoders at $SNR_{\mathrm{RX}_{\min}} = 5\,\mathrm{dB}$. For readers requiring a higher SNR for detection we see from Fig. 4 that the FOM demand is increased to more than 140 dB, but thermal noise is still not the limiting factor for reasonable reader antenna gains and the legal transmit limits. The situation also does not change when a noise figure is added, e.g. a noise figure $F = 10\,\mathrm{dB}$ and a receiver antenna gain $G_{\mathrm{RX}} = 10\,\mathrm{dB}$ cancel each other in (8) and for the European legal limit of 2 W ERP the resulting curve ($EIRP G_{\mathrm{RX}} = 35.16\,\mathrm{dBm}$) is still enabling read ranges of $d = 29\,\mathrm{m}$, if the FOM product allows it.

C. Dependent Reverse Link SNR

In the previous section, we computed the received SNR subject to the distance or FSPL. But since in passive RFID systems only powered tags respond, it makes sense to condition the SNR on tags operating at the forward link limit — so the worst case scenario.

The minimum received power at the reader occurs for a tag operated at its sensitivity limit[2] (1). In this case the maximum FSPL occurs:

$$FSPL_{\max} = \frac{EIRP G_{\mathrm{Tag}}}{P_{\mathrm{Tag}_{\min}}}. \tag{11}$$

The received SNR for this case is computed by inserting (11) into (5):

$$SNR_{\mathrm{RX}} = \frac{G_{\mathrm{RX}} FOM_{\mathrm{R}} FOM_{\mathrm{Ant}} P_{\mathrm{Tag}_{\min}}^2 \eta_{\mathrm{Mod}}}{EIRP \left(EIRP G_{\mathrm{RX}} + N_{\mathrm{th}} F \, FOM_{\mathrm{R}} FOM_{\mathrm{Ant}} \right)}. \tag{12}$$

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[2] Again this only holds for the assumption of a tag with constant modulation efficiency η_{Mod}. There might be tag implementations where the modulation efficiency severely degrades for high tag input powers and the minimum received power at the reader occurs for a tag very close to the reader. But then the limiting factor is the tag and not the reader.

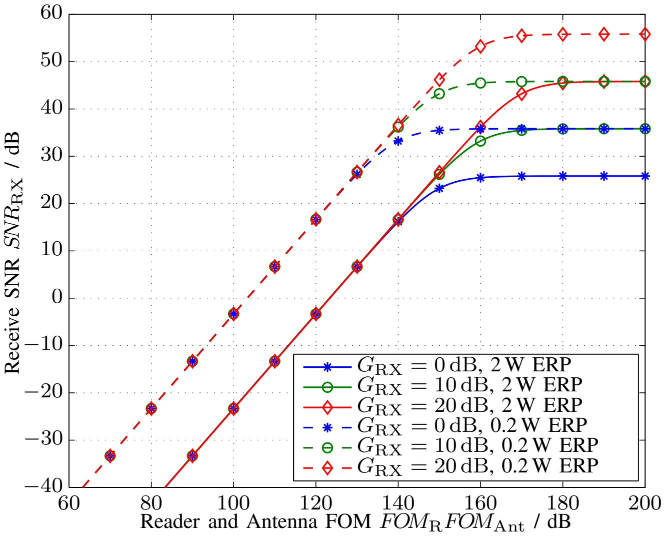

Fig. 6. Receiver SNR for tag operated in forward link limit, parameters according to Table I and Table II.

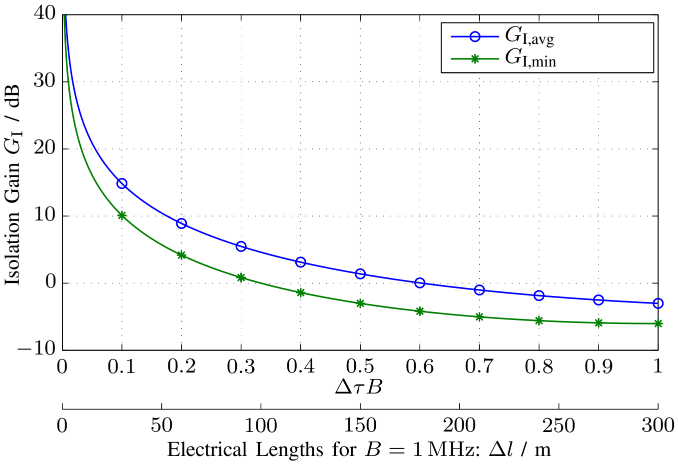

Fig. 7. Average isolation gain for single tap LCC and white noise.

We see that the conditioned SNR is independent of the tag antenna gain, but instead is increased for low sensitivity tags, since they only support shorter read ranges. Equation (12) is plotted in Fig. 6 for different RX antenna gains and ERP values. At the legal transmit limit a product FOM of 124 dB is required for positive RX SNR values. In our example, the receiver SNR is entirely dominated by the self-interference up to a FOM product of 140 dB.

Fig. 6 also gives a hint what to do when the required FOM is not achieved for a certain hardware. Reducing the transmitted EIRP reduces the forward link limited range, and therefore improves the SNR of the tags operated at that distance. For closer tags, this reduction has no direct effect (Fig. 4). However, the receiver noise figure for any receiver incorporating an Automatic Gain Control (AGC) depends on the input power level. Since the leakage signal is usually the strongest received signal, the noise figure F in practise is not constant, but depends on the transmit power and LCC isolation gain. So lowering the transmit EIRP to a value where the receiver SNR is still not dominated by the thermal noise, effectively yields an improvement in receive SNR and reader power consumption without any negative effect on the read range.

IV. ISOLATION GAINS FOR LCCS

We have seen in the previous section that the reader FOM is an important parameter for the reverse link performance of RFID readers. It is the product of the transmit SNR and the isolation gain of an LCC. When realistic antenna FOM values of 40 dB are considered, the reader FOM should be in the 100 dB range to ensure a forward link limited RFID system with state of the art tags. A transmit SNR of 100 dB is difficult to reach, but an LCC may lower these demands.

In this section we further explore the isolation gain G_{I} for LCCs. Remember, that the LCC extracts a part of the transmit signal, adjusts it in amplitude and phase and injects this modified signal at the receiver, introducing an additional delay. To calculate the noise effective average isolation gain for arbitrary LCCs and BLCs [22] requires specific knowledge of the leakage and cancellation channels. However, for the simplified model of a single tap leakage channel [13], the minimum isolation gain for an LCC is computed in [14] depending on the delay offset $\Delta\tau$ of leakage and cancellation path. This therefore is a lower bound of the isolation gain in the interesting region centred around the BLF (see Fig. 3). We will now compute the average isolation gain assuming white transmitter noise and a baseband filter centred around the carrier frequency f_{c} with bandwidth B.

With slight modification of the notation given in [14] the standardized power spectral density of the direct TX-RX channel including leakage and cancellation is given by

$$|H(j\omega)|^2 = 2\left(1 - \cos\Delta\tau(\omega - \omega_0)\right), \tag{13}$$

where ω_0 is the centre adjustment frequency of the LCC. Using the white noise assumption, the average isolation gain is found as the reciprocal value of the average centred around ω_0:

$$\frac{1}{G_{\mathrm{I,avg}}} = \frac{1}{2\pi B}\int_{\omega_0-\pi B}^{\omega_0+\pi B} |H(j\omega)|^2 \,\mathrm{d}\omega, \tag{14}$$

from which we compute

$$G_{\mathrm{I,avg}} = \frac{1}{2 - \frac{2\sin(\pi\Delta\tau B)}{\pi\Delta\tau B}}. \tag{15}$$

Fig. 7 shows the comparison of this average gain and the minimum gain [14, equ. (7)]

$$G_{\mathrm{I,min}} = \begin{cases} \frac{1}{2-2\cos(\pi\Delta\tau B)} & \text{for } |\Delta\tau B| < 1, \\ \frac{1}{4} & \text{for } |\Delta\tau B| \geq 1. \end{cases} \tag{16}$$

Note that for large time-bandwidth products greater one the minimum isolation gain is constant and −6 dB, while the average isolation gain for large products converges to −3 dB. This is intuitively clear, since for the minimum gain case, the signals with same amplitude but different delays will add up at certain frequencies producing a leakage signal of twice the original amplitude, hence 6 dB larger. For the average gain, if the delay becomes large enough the leakage and cancellation signals are completely uncorrelated and the noise powers add. While the minimum gain is clearly a lower bound for the obtainable isolation gain in a practical scenario, the average gain is likewise an upper bound, since the gain obtained very close to the carrier frequency is also taken into account. This gain close to the centre frequency is in practise irrelevant for the backscatter sidebands centred around the BLF when proper filtering is applied. So we have bounded the noise effective isolation gain assuming a dominant single tap leakage path.

V. CONCLUSION

In the RFID community the myth about an always dominating forward link limitation of RFID systems is still well spread [9]. This myth is based on the belief that the main noise source in RFID systems is thermal receiver noise, which is wrong for various scenarios.

In this contribution we present a simple analytic description of the receiver SNR of an RFID reader including self-interference effects. This is accomplished by introducing a transmit SNR and two figures of merit, namely a reader FOM and a reader antenna FOM. To reach the forward link limit set by state of the art RFID tags, the product of the FOMs must exceed 130 dB for an RFID reader which requires a receive SNR of 5 dB. In this region the reader receiver is limited by the self-interference reverse link limit derived in this paper. It is independent of the transmit power or noise figure of the reader, but solely depends on the product FOM, the tag antenna gain, the tag modulation efficiency and the required SNR at the receiver.

Further, an upper bound for the effective isolation gain of single-tap leaking carrier cancellers is derived. Greater than unity gains demand for a path-delay bandwidth product smaller than 0.6. For an average isolation gain of 30 dB the electrical length difference may not exceed 5.1 m for 1 MHz bandwidth.

The dependent reverse link SNR computed in this paper provides a tool to set the optimum transmit power of an RFID reader, such that all tags which overcome the forward link limit are read with the required SNR while at the same time the interference and power requirements of the reader are reduced.

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