Limitations of Range of Operation and Data Rate for 13.56 MHz Load-Modulation Systems

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***Abstract*: The paper presents an analysis of the achievable range of operation and data rate for passive 13.56 MHz load modulation communication. With increasing data rates and lower transponder energy requirements, reading ranges are primarily limited by background/man-made noise as well as power amplifier noise, as is documented by experimental results.**

***Keywords*: HF-RFID, 13.56 MHz, Load Modulation**

I. Introduction

The free ISM-band (industrial, scientific, medical) in the range of 13.56 MHz has become very popular for Radio Frequency Identification systems. Despite the wide-spread usage, little information is available in literature on the limitations of such systems with respect to their range of operation and the achievable data rates.

A basic block diagram of a load modulation High Frequency Radio Frequency Identification (HF-RFID) system is shown in Figure 1. A corresponding equivalent circuit can be found in Figure 2. For data transmission, the transponder, which is mainly inductively coupled to the reader, alters its impedance. This impedance change alters currents and voltages at the reader antenna and thus the signal can be detected [1]. It is also common that a RFID reader uses separate antennas for the transmitter and the receiver path.

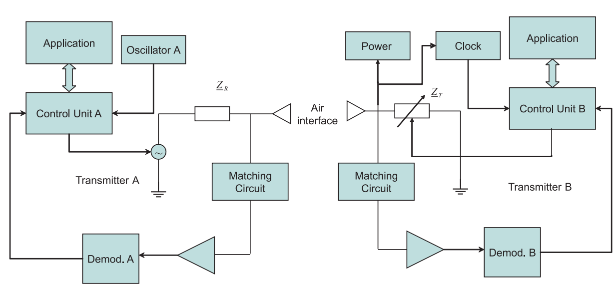

Figure 1. Block diagram of a load modulation RFID system. Both the reader on the left and the transponder on the right can receive and transmit data. However, the transponder has to obtain the power supply and typically the clock signal from the air link. Furthermore, it does not act as an active transmitter but communicates by modulation of the transponder impedance $\underline{Z}_T$.

II. Modulation and Demodulation

For a load modulation system, the transmission power associated with the passive device is governed by the field strength at the transponder location generated by the active device and the impedance variation in the antenna circuit of the passive device (transponder). Therefore, the achievable bit energy depends on the duration of the corresponding symbol only and is thus independent of the bandwidth of

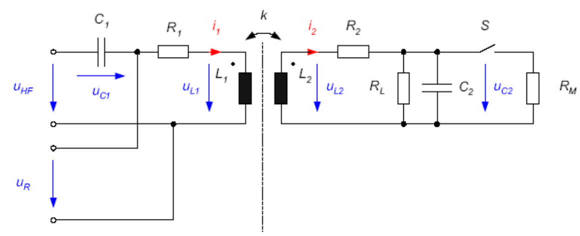

Figure 2. Equivalent circuit of a load modulation system: The reader antenna is part of a resonance circuit and inductively coupled with the transponder coil, which is also part of a resonance circuit in order to provide a sufficient voltage to power the electronic circuitry of the transponder. Typically, binary modulation by means of switching the impedance of the resonance loop is used [1].

the load modulated signal, i.e. load modulation can be considered as a power limited system where frequency shift keying is a good choice for the modulation [2]. In contrast, On-Off keying spoils 50 percent of the available bit energy. Consequently, the range or data rate for equivalent geometry and transmitter power levels will be significantly reduced compared to FSK.

The most common modulation schemes for RFID communication are Amplitude Shift Keying (ASK), Phase Shift Keying (PSK) and Frequency Shift Keying (FSK) and are binary only (i.e. the alphabet uses the symbols 0 and 1). On-Off Keying (OOK) and binary PSK can be considered as a special cases of ASK whereas binary orthogonal FSK can be considered as a combination of two complementary ASK signals. In the following we will focus on FSK as an example.

The probability of bit error for binary orthogonal FSK (and for On-Off keying) with coherent detection is given by

$$P_B = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{E_b/N_0}}^{\infty} e^{-\frac{u^2}{2}} du = Q(\sqrt{E_b/N_0}) \qquad (1)$$

where E_b is the energy per bit, N_0 the spectral noise density and $Q(.)$ the co-error function [2].

For non-coherent detection the probability of bit error for binary orthogonal FSK is determined by

$$P_B = \frac{1}{2} e^{-\frac{E_b}{2N_0}} \qquad (2)$$

The bit error rates for coherent and non-coherent detection are compared in Figure 3. For coherent detection reasonable bit error rates can be obtained with an $E_b/N_0 >$ 10 dB.

III. Powering Range

For the 13.56 MHz ISM band (13.56 MHz $\pm$ 7 kHz) the permitted magnetic field strength in a distance of 10

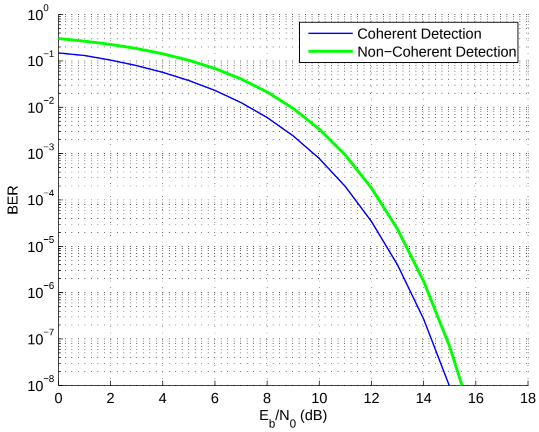

Figure 3. Probability of bit error (BER) for coherent and non-coherent detection of a binary orthogonal FSK signal for different bit energy to spectral noise density (E_b/N_0) values. Reasonable error rates for coherent detection can be achieved with an E_b/N_0 of more than 10 dB.

meters from a device amounts to 60 dBμA/m (1 mA/m) [3]. Please note that starting at above 8 meters the coplanar field strength exceeds the coaxial field strength. The definition of the terms ”coaxial” and ”coplanar” is given in Figure 4. Therefore, the field strength in coplanar orienta-

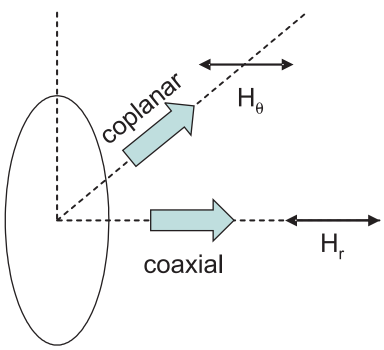

Figure 4. Definition of the terms ”coplanar” and ”coaxial” according to [4].

tion must not exceed 60 dBμA/m in a distance of 10 m [3] (compare Figure 5).

The magnitude of the magnetic field in coplanar orientation is given by

$$|H_r| = \frac{2m_0}{4\pi\mu}\sqrt{\left(\frac{1}{r^3}\right)^2 + \left(\frac{\omega}{cr^2}\right)^2} \tag{3}$$

and the magnitude of the magnetic field in coaxial orientation is determined by

$$|H_\theta| = \frac{2m_0}{4\pi\mu}\sqrt{\left(\frac{1}{r^3} - \frac{\omega^2}{rc^2}\right)^2 + \left(\frac{\omega}{cr^2}\right)^2} \tag{4}$$

where r is the distance between the source and the observer, A the antenna area and m_0 represents the magnetic dipole moment, given by

$$m_0 = \mu I_{Ant} A \tag{5}$$

for a circular loop antenna [5].

The ISO 15693 standard [6] requires that transponders operate at a field strength of 150 mA/m (103.5 dBμA/m). Taking the field strength limit above into account, this corresponds to a powering range of approximately 1.3 meters for the given transmitter antenna (Figure 5). However, with

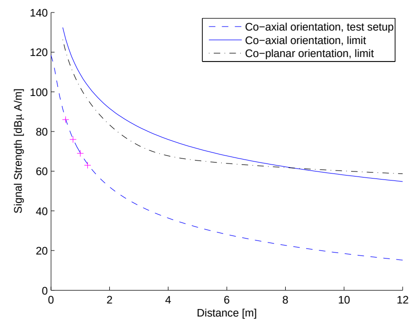

Figure 5. Powering range: The lower line indicates the field strength provided by the test setup, the ”+”-symbols indicate experimental results. The upper solid line depicts the limit when a maximum field strength of 60 dBμA/m in a distance of 10 meters is permitted. The ISO 15693 standard requires operation at a field strength of 103.5 dBμA/m, corresponding to a theoretic powering range of approximately 1.3 meters with a 25 cm x 25 cm transmitter antenna.

lower field strength requirements of the transponders the range may be extended, e.g. for a transponder with only 10 mA/m field strength requirement[1] the powering range would extend to 3.3 meters. The ranges not only depend on the permitted field strength in a certain distance but also on the geometry of the antenna. [1] provides a detailed description of the relations.

An example for a signal obtained with a transponder resonant loop antenna is shown in Figure 6. A voltage signal of more than 6 Volts is achieved for a field strength of only 75 dBμA/m, which can be achieved at a distance of about 4 meters from the transmitter antenna without exceeding the 60 dBμA/m in 10 meters limit.

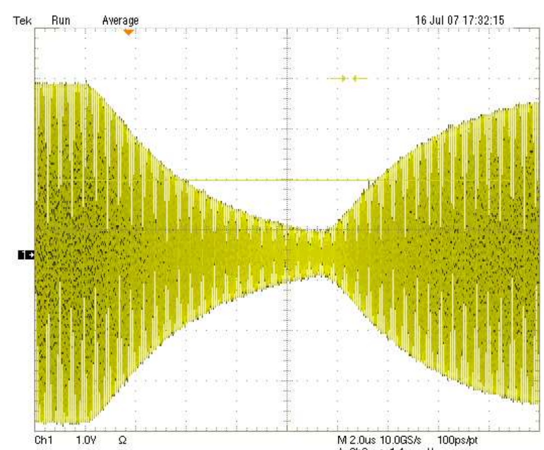

Figure 6. Voltage measurement on a high Q resonance loop antenna (r=3.5 cm, L=2μH, N=3) at a field strength of 75 dBμA/m (5.6 mA/m). Although the quality factor Q is high in order to achieve a sufficient voltage ($U_{pp} = 6.7\ V$), the current (I=13.9 mA) can still be significantly modulated with 10 μs pulses thus permitting data rates of 100 kilobit/s.

IV. Receiving Range

In order to provide some numeric examples, a passive communication with 6.67 kilobit per second and an effec-

[1] This can be achieved with a low power transponder or a larger antenna.

tive transponder antenna current of I_{Ant}=120 mA are assumed. This is the equivalent current associated to the load modulation. Furthermore, we assume a transponder with a circular loop antenna with a radius of 2 cm.

The resulting magnetic field components for a passive transponder with a data rate of 6.67 kilobit per second are plotted in Figure 7, scaled such that noise levels from [4] can be applied directly (dBμA/m in 2700 Hz). Please note that separate transmitter and receiver antennas were used for the experiments because the used power amplifier/antenna system could not provide the permitted magnetic field strength at the desired distance and also power amplifier noise can be suppressed. However, the receiving range will depend on the field strength at the transponder location, regardless of the location of the source of the magnetic field. For a noise level of 0 dBμA/m, the signal could be demodulated over a distance of only 1.1 meters. An increase of the data rate by a factor of 10 would reduce this range to 0.7 meters. However, in a low noise environment, such as solid buildings, significant range extensions should be possible. Our experimental results show that a receiving range of 3 meters between the reader and state of the art transponders (ID-card size) at a noise level of -25 dBμA/m can be achieved. Therefore, for the given data rate and power requirements, the system is limited by the powering range. This will change when the data rate is further increased or the field strength requirement of the transponder is further reduced.

Experimental results obtained in our laboratory environment are shown in Figure 8. A standard ISO 15693 communication with a data rate of 6.67 kB/s was used. The field strength at the location of the transponder was 101 dBμA/m. Please note that only one side band is shown on the spectrum analyzer, thus only one fourth of the bit energy is depicted. Therefore, the total bit energy is 12 dB higher.

For a single loop antenna and direct measurement of the induced antenna noise signal (assuming the noise sources at infinite distance), the induced spectral noise signal U_{ind} can be approximated by

$$U_{ind} = A\omega\mu * E_n/Z_0 \tag{6}$$

where A is the area of the antenna, ω the frequency, E_n the spectral noise density of the electric field and Z_0 the impedance of the free space.

Based on (7) the required antenna size (single loop, no resonance) for a certain spectral background noise field strength E_n and a certain amplifier noise e_n should be

$$A > \frac{e_n Z_0}{\omega\mu * E_n} \tag{7}$$

in order to ensure that the amplifier noise is negligible. For an environment of E_N=0 dBμV/m in 2700 Hz and a (receiver) amplifier noise of e_n=1 nV/$\sqrt{Hz}$ a required area of $A > 0.18$ m^2 (corresponding to a radius of 13 cm) is obtained, not taking into account the gain due to resonance which will also be effective to a certain extend at the sideband frequency. Provided that the size of the antenna exceeds this value, no significant performance improvement can be achieved through an increase of the antenna dimensions. However, when the power amplifier noise becomes

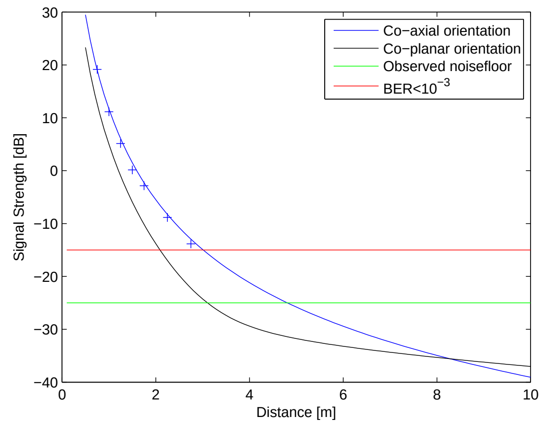

Figure 7. Received sideband signal for 13.56 MHz load modulation communication. The blue and black lines indicate the field strength associated with the load modulation for a standard transponder (field strength@transponder location 100 dBμA/m) with a data rate of 6.67 kilobit per second. The red line represents the detection limit (bit error rate $< 10^{-3}$) for the observed noise level, the green line the corresponding noise level. The "+"-symbols indicate experimental results. Note that only one sideband of one auxiliary carrier is shown in the figure, the actual bit energy is four times as high. Consequently, the data rate could be four times as high when all four sideband signals are considered. For a further increase of the data rate a lower noise level or a higher modulation of the transponder would be required, which is also feasible (compare Figure 6).

dominant, larger antennas can be useful. Besides resonance, the required antenna size could also be reduced using a higher number of windings. The number of windings is limited by the increasing impedance of the antenna and the coupling capacitance between the layers as undesired gains and suppressions may occur. For our experiments a resonance loop antenna with r =3.5 cm and $N = 3$ was sufficient that the environmental noise significantly exceeded the receiver amplifier noise.

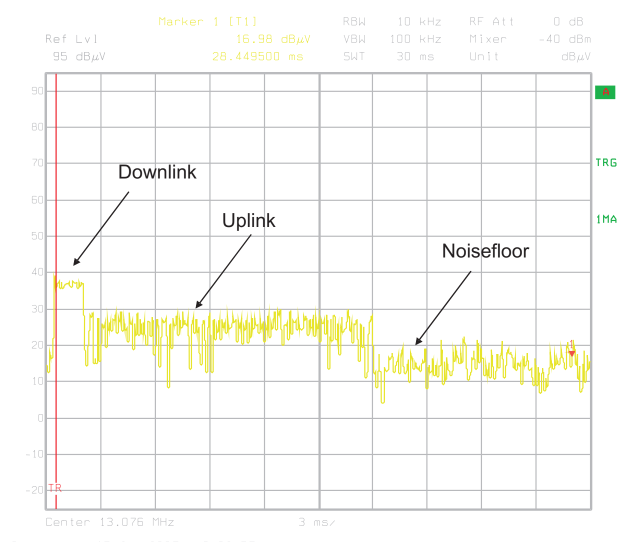

Figure 8. Sideband measurement of an ISO 15693 communication (field strength@transponder location 101 dBμA/m) measured with a receiver antenna (r=3.5 cm) in a distance of 3.5 m.

V. Intrinsic Limitations

A reader comprises the following components:

- Low Noise Power Amplifier

- Resonance Loop Antenna
- Carrier Suppression
- Demodulation
- Detection

In particular single antenna readers have high demands on these components. In order to achieve the receiving ranges presented in the section IV it would be required that the noise from the power amplifier remains below the received noise. However, this is not easily achieved considering the high power levels and the power amplifier will be of major importance for the performance of an actual HF-RFID reader.

Resonance loop antennas are usually used because they can generate high magnetic field strength while the load for the amplifier remains comparatively low. However, circuits with high quality factors also have drawbacks. They do not only affect the transmitted signal but also the received signals, which are actually suppressed by the resonance circuit. Furthermore, antennas are usually tuned to an impedance of 50 Ω in order to permit easy exchange of antennas and variable cable length. As a resonance antenna will be tuned to a certain impedance for the resonance frequency but not for the side band frequencies, the impedance at the side bands will be significantly different. This can lead to a reflection of power amplifier noise into the receiver circuitry, for instance through a directional coupler.

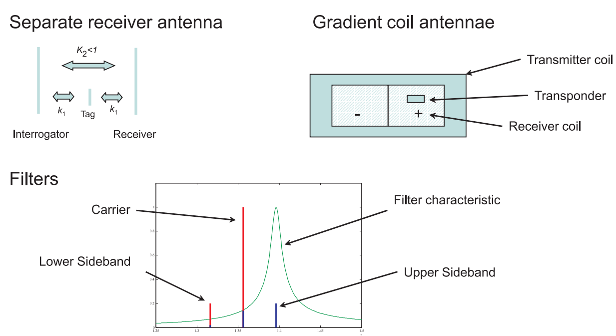

Figure 9. Carrier suppression methods: The simplest method is the use of separate transmitter and receiver antennas, as we did for our investigations. Gradient coil (differential) antennas are also a simple yet effective suppression method, which also reduces carrier noise. However, it has limited applicability for long ranges. Filters may also be used, typically separate filters (with separate demodulation chains) for the upper and lower sideband are applied, which may also be useful for suppression of narrow-band disturbers. Combinations of these methods may bring further improvements.

Assuming a power of 8 Watt applied to a 50 Ω antenna, the signal at the tapping point would be approximately 20 volts (compare Fig. 1). Even with a 10 Bit analog to digital converter with a sampling rate of 30 MS/s the quantization noise would amount to approximately 4 μV/$\sqrt{Hz}$. As a typical low noise amplifier can achieve an equivalent input noise of 1 nV/$\sqrt{Hz}$ or lower, it is obvious that a carrier suppression in the analog domain is needed before the received signal can be processed. Another desirable effect of carrier suppression, e.g. with differential antennas (compare Figure 9), is the suppression of carrier associated noise thus lessening the requirements for the power amplifier. Besides differential antennas, other typical choices are directional couplers and high quality factor filters (which do not remove carrier associated noise). Both methods are sensitive to changes of component values, therefore it is necessary to automatically tune the antenna circuit, which is usually done by means of switched capacitors or by means of tuneable inductors [7]. Another simple method to eliminate the carrier is rectification, which will not only suppress the carrier but also shift the signal to the base band. A disadvantage of this approach is that it is only sensitive to amplitude modulation but not to phase modulation, whereas load modulation is usually a combination of both. However, it is possible to achieve an in-phase/quadrature demodulation using a modulation mode conversion and two rectifier circuits. Other demodulation approaches include synchronous demodulation or analog sampling. Both methods also suppress the carrier and may be applied together with filters and couplers.

Once the signal is demodulated, standard techniques for the detection can be applied, such as matched filters and maximum ratio combining when more than one channel is available [8].

VI. Conclusion

The paper presents an analysis of the limitations of range and data rate of HF-RFID systems. Based on standard models and typical parameters (such as field strength requirements and man-made noise) the reading range for a given data range is determined and verified experimentally with state of the art transponders. The results indicate that operating ranges of 3 m @ 100 kilobit per second are feasible for HF-RFID systems with ID-card sized transponders within the permitted field strength levels in low noise environments.

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