INTEGRATION WIRELESS **DOCUMENTATION**

IA ISM-AN2

Antenna Development Guide for the IA4220 and IA4320 ISM Band FSK Transmitter/Receiver Chipset

Application Note

Version 1.0 - PRELIMINARY

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ABOUT THIS GUIDE

The Antenna Development Guide for the IA4220 and IA4320 ISM Band FSK Transmitter/Receiver Chipset is designed to give additional information to product designers about the IA4220 Transmitter(TX) and IA4320 Receiver(RX) chipset. Through this guide, product designers can engage in custom antenna designs.

Designers looking for existing less custom design may refer to the **Antenna Selection Guide: IA ISM-AN1.**

For further information on the devices used in this publication, see the following datasheets:

IA4220 Universal ISM Band Transmitter datasheet: IA4220-DS

IA4320 Universal ISM Band Receiver datasheet: IA4320-DS

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INTRODUCTION

DESCRIPTION

This document describes the basic RF properties of the universal four-band (315 MHz, 434 MHz, 868 MHz, 915 MHz) IA4220 type transmitter (TX) and IA4320 type receiver (RX). Also available is additional information and design hints regarding high impedance, printed antennas as presented in the *Antenna Selection Guide: IA ISM-AN1,* and the RF link properties applying those antennas. The advantages of the high impedance configuration and details of the automatic antenna tuning circuitry applied in the IA 4220 TX chip are also presented. The outline of the document is as follows:

Chapter 1 provides the r.m.s. electric field strength required by the IA4320 receiver to obtain a specified BER value in the case of varying RX antenna types, which are also presented in the *IA ISM-AN1*. BER values are given for 10^{-2}, 10^{-3}, 10^{-4}, and 10^{-5}. The method and setup of sensitivity measurement is given in Appendix C of *IA ISM-AN1*. This chapter is useful to RF engineers estimating ranges of custom-designed TX antennas.

Chapter 2 provides the 'typical range vs. BER' curves with different TX and RX antenna pairs for 9,600 and 57,470 bit/sec bit rate. Also presented in *IA ISM-AN1* are antenna layouts, the EIRP with the given TX antennas, and the method of range calculation.

Chapter 3.1 analyzes the high Q configuration, comprising of the TX and the antenna. Chapter 3.2 provides further detailed information regarding the applied antenna types available.

Chapter 4 demonstrates the high efficiency and low power consumption of the high Q configurations comprising of the TX and the antenna in low power short range applications.

Chapter 5 provides further information regarding the RF properties of a high impedance transmitter and describes the special features (automatic antenna tuning, variable output current) necessary for optimum operation.

Chapter 6 describes the basic RF properties of the receiver.

For the detailed antenna layouts and dimensions, please visit our website:
http://www.integration.com and download the ***Antenna Selection Guide: IA ISM-AN1.***

1. RECEIVER SENSITIVITY AT DIFFERENT BER VALUES

The IA4320 receiver (RX) sensitivities covered in this document were measured in the presence of strong GSM interference. Further details of this interference can be found in the Appendix D of *IA ISM-AN1*. To evaluate the possible TX-RX range values, it is useful to define the minimum necessary field strength at the RX antenna, which provides a given received quality. The r.m.s. electric field strength of the RX antennas with several BER values are given for the 915, 868, 434, and 315 MHz bands in Tables 1.1, 1.2, 1.3, and 1.4, respectively.

915 MHz BAND RECEIVER ANTENNA CONSTRUCTIONS

In our designs, to accommodate the various requirements of many possible applications in the U.S. 915 MHz band, a cross tapped loop antenna (given in Fig. 2.5 in *IA ISM-AN1*) and a so-called back inverted-F (BIFA) antenna (given in Fig. 2.6 in *IA ISM-AN1*) were designed for the IA4320 chip (detailed description of the antenna types is given in Chapter 3).

E_{min} [mV/m]$_{r.m.s.}$ *915 MHz*	RX Antenna type			
	Loop		Back IFA	
BER	**9600 bps**	**57470 bps**	**9600 bps**	**57470 bps**
10^{-2}	0.24	0.44	0.06	0.09
10^{-3}	0.31	0.65	0.07	0.13
10^{-4}	0.37	0.91	0.08	0.17
10^{-5}	0.42	1.25	0.09	0.2

Table 1.1. Required r.m.s. electric field strength [mV/m] for the RX chip with various antennas at 915 MHz to achieve different BER values in the case of strong interference

868 MHz BAND RECEIVER ANTENNA CONSTRUCTIONS

In our designs for the European 868 MHz band using the IA4320 RX chip, a cross tapped loop antenna (given in Fig. 2.13 of *IA ISM-AN1*) and a so-called back inverted-F (BIFA) antenna (given in Fig 2.14 in *IA ISM-AN1*) was designed (detailed description of the antenna types is given in Chapter 3)

E_{min} [mV/m]$_{r.m.s.}$ *868 MHz*	RX Antenna type			
	Loop		Back IFA	
BER	**9600 bps**	**57470 bps**	**9600 bps**	**57470 bps**
10^{-2}	0.16	0.28	0.05	0.07
10^{-3}	0.2	0.41	0.06	0.09
10^{-4}	0.24	0.57	0.07	0.11
10^{-5}	0.29	0.84	0.08	0.13

Table 1.2. Required r.m.s. electric field strength [mV/m] for the RX chip with various antennas at 868 MHz to achieve different BER values in the case of strong interference

1. RECEIVER SENSITIVITY AT DIFFERENT BER VALUES

434 MHz BAND RECEIVER ANTENNA CONSTRUCTIONS

In our designs for the 434 MHz band, which allows for non-licensed products both in the U.S. and Europe, a cross tapped loop antenna (given in Fig. 2.8 in *IA ISM-AN1*) was designed for the IA4320 RX chip, (a detailed description of the antenna types is given in Chapter 3)

E_{min} [mV/m]$_{r.m.s.}$ *434 MHz*	RX Antenna type	
	Loop	
BER	**9600 bps**	**57470 bps**
10^{-2}	0.48	0.9
10^{-3}	0.64	1.2
10^{-4}	0.72	1.6
10^{-5}	0.8	1.9

Table 1.3. Required r.m.s. electric field strength [mV/m] for the RX chip with cross tapped loop at 434 MHz to achieve different BER values in the case of strong interference

315 MHz BAND RECEIVER ANTENNA CONSTRUCTIONS

In our designs for the U.S. 315 MHz band, a cross tapped loop antenna (given in Fig. 2.10 in *IA ISM-AN1*) is designed for the IA4320 RX chip (a detailed description of the antenna types is given in Chapter 3)

E_{min} [mV/m]$_{r.m.s.}$ *315 MHz*	RX Antenna type	
	Loop	
BER	**9600 bps**	**57470 bps**
10^{-2}	0.29	0.7
10^{-3}	0.37	0.9
10^{-4}	0.47	1
10^{-5}	0.62	1.4

Table 1.4. Required r.m.s. electric field strength [mV/m] for the RX chip with cross tapped loop antenna at 315 MHz to achieve different BER values in the case of strong interference

2. ANTENNAS AND RANGES

GENERAL CONDITIONS

The *free space* range is estimated from the required r.m.s. electrical field strength at the RX antenna as given in the previous chapter and by the measured EIRP (Equivalent Isotropic Radiated Power) of the TX with different antennas as given in the Antenna Selection Guide: *IA ISM-AN1*. The range calculation method is also presented in Appendix B of *IA ISM-AN1.*

Briefly, the EIRP of the TX-antenna configuration is the power level, which would generate the identical field strength using a perfectly matched isotropic antenna. The radiated power of the TX-antenna configuration can be described by the so-called ERP (Equivalent Radiated Power) as well. The ERP is the power level, which would generate the identical field strength at the direction of maximum using a perfectly matched half wavelength dipole. Due to the gain of the dipole, it can be observed that ERP[dBm]=EIRP[dBm]-2.14[dB]. The European ETSI (Note 1) standard applies the ERP to describe the radiation power. The U.S. FCC regulation (Note 2) gives restrictions to the maximum, or r.m.s. field strength, at a distance of 3 meters. As the EIRP can be easily calculated from the ERP, the two descriptions are equivalent i.e. the ERP can be converted to field strength and vice versa. For the conversions, equation 1 and equation 2 from Appendix B of *IA ISM-AN1* can be used.

As the RX sensitivity measurements at several BER values were performed for the case of 9600 bps and 57470 bps data rates, the ranges are also calculated for these two bit rates. During the measurements, a one sided FSK deviation of 60 KHz and 90 KHz was applied at 9600 bps and 57470 bps data rates, respectively. The RX baseband filter bandwidth was adjusted to 135 KHz.

The RX sensitivities were measured in the presence of strong interference (further details can be found in Appendix D of *IA ISM-AN1*). In the case of an *interference free environment,* the receiver sensitivity is *6-8 dB better* and the *range available is about 2 times higher*.

Under certain regulations, given either in ERP, EIRP, or field strength limitation by the U.S. FCC (Note 1) or European ETSI (Note 2) standards, the allowed radiation power is lower than the available maximum power from the transmitter. In those cases, the range corresponding to the allowed ERP is given together with the necessary power reduction.

As the impedance of the loop antennas are much higher compared to that of the IFA antennas, the output current of the TX with loop antennas must be reduced not to exceed the maximum allowed differential voltage swing (4 Vpp) on the outputs. The given ranges with loop TX antennas correspond to the appropriately reduced currents.

The given ranges are ideal free space ranges. Ranges for realistic non-ideal propagation conditions, can be calculated from the free space range by using the method presented in Appendix E of IA ISM-AN1.

Note 1: For further details on FCC part 15, see "Understanding the FCC Regulations for Low-Power, Non-Licensed Transmitters," by the Federal Communications Commission, available through the FCC Web site, **http://www.fcc.gov**, or via Integration's Design Resources page at **http://www.integration.com**.

Note 2: For further details on ERC/REC devices, see "Relating to the Use of Short Range Devices," available through the European Radio Communications Office website, **http://www.ero.dk** or via Integration's Design Resources page at **http://www.integration.com**.

2. ANTENNAS AND RANGES

US REGULATIONS: 915 MHz LINK

At the U.S. 915 MHz band, the allowed r.m.s. electric field strength at 3 m is 50 mV/m, which corresponds to –1 dBm EIRP. For spread spectrum transmissions, the maximum allowed TX power is 1 W, which can be achieved only with an external amplifier stage. (Note 1, previous page)

In our designs with the IA4220 TX chip, a small normal loop (given in Fig. 2.1 in *IA ISM-AN1*), a cross tapped loop (given in Fig. 2.2 in *IA ISM-AN1*) and two so-called BIFA antennas (given in Fig. 2.3 and Fig. 2.4 in *IA ISM-AN1*) are designed. (See Chapter 3 for further information about BIFA antennas)

The loop antenna has a fairly high input impedance (~4 KOhm). To avoid saturation, the TX output current should be 3 dB lower than the maximum. Due to the very small dimensions (aperture), the resulting EIRP of the IA4220 TX chip with a small loop antenna at the -3 dB power state is –15 dBm. With this antenna, small and compact transmitters can be designed.

The cross tapped loop has a lower quality factor (Q) compared to the normal loop antenna and therefore, it can be driven by maximum TX driver current. In addition, the aperture size is also bigger. Thus, the resulted EIRP is -9.5 dBm.

The BIFA antennas have significantly lower Q than the loop antennas. BIFA antennas can be driven by the full power of the TX chip. In addition, the radiation efficiency of the BIFA antenna is fairly high due to its large dimensions.

The antenna given in Fig 2.3 of *IA ISM-AN1* is applied in the IAI RF link demoboard and denoted by IA ISM-DARFT. To highlight the antenna design, we have referred to it as BIFA_IA_ISM_DARFT1 within this application note. This design has a maximum EIRP of approximately -1 dBm. The antenna given in Fig 2.4 of *IA ISM-AN1* is applied in the IAI TX development board denoted by IA4220-DKDB2. To highlight the antenna design, we have referred to it as BIFA_IA4220_DKDB2 within this application note. This design has a maximum EIRP of 4.4 dBm. At 6 dB reduced power state, the EIRP of the BIFA_IA4220_DKDB2 antenna is -1.3 dBm.

EIRP [dBm] **915 MHz U.S.**	**TX Antenna type**			
	Loop	**Tapped loop**	**BIFA_IA_ISM_DARFT1**	**BIFA_IA4220_DKDB2**
	-15.3 (-3dB state)	-9.5	-1.2	4.4 (spread spectrum TX) -1.3 (CW TX (-6 dB state)

Table 2.1

The EIRP of the different TX antennas at 915 MHz is summarized in Table 2.1.

For the IA4320 RX chip, a cross tapped loop (given in Fig. 2.5a in *IA ISM-AN1*) and a BIFA (given in Fig. 2.6 in *IA ISM-AN1* and used for IA4320-DKDB4 development boards) antenna is designed.

The BER of the 'RF link vs. Range' at the U.S. 915 MHz band is shown in Figure 1 at 9600 and 57470 bps data rates. In this link setup, a cross tapped RX and a small loop TX antenna is applied. In Figure 2, the same parameters are given for a BIFA RX and a small loop TX antenna.
In Figure 3, the case of a cross tapped RX and a cross tapped TX antenna is given.
In Figure 4, the case of a BIFA RX and a cross tapped TX antenna is given.
In Figure 5, the case of a cross tapped RX and a BIFA_IA_ISM_DARFT1 TX antenna is given and in Figure 6, the case of a BIFA RX and a BIFA_IA_ISM_DARFT1 TX antenna is given.
In Figure 7, the case of a cross tapped RX and a BIFA_IA4220_DKDB2 TX antenna is given.
In Figure 8, the case of a BIFA RX and a BIFA_IA4220_DKDB2 TX antenna is given. In the case of Figure 7 and Figure 8, full power TX operation (~4 dBm EIRP) is assumed. If the power is reduced by 6 dB, the ranges available with the BIFA_IA4220_DKDB2 TX antenna is very close to the ranges given in Figure 5 and Figure 6.

2. ANTENNAS AND RANGES

US REGULATIONS: 915 MHz LINK (continued)

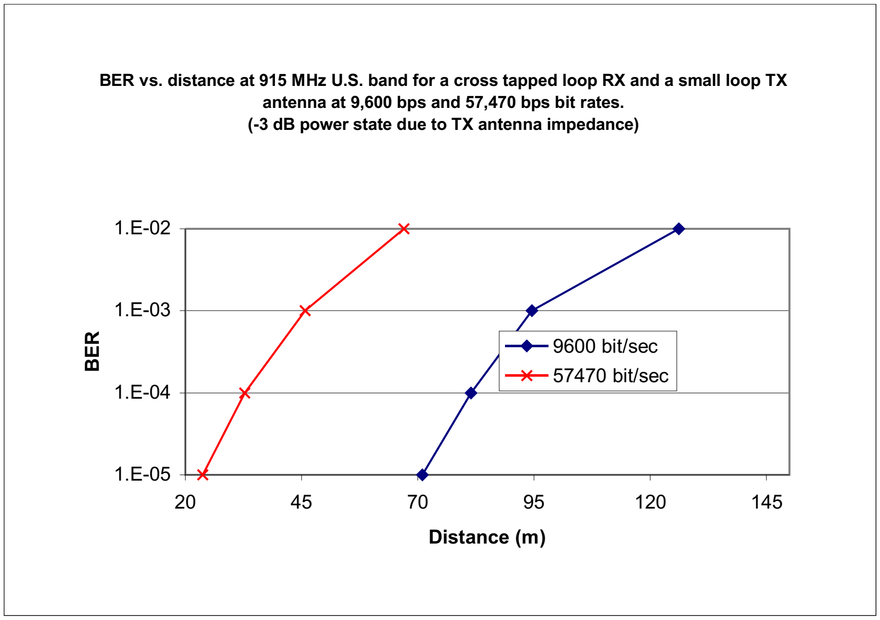

Fig. 1

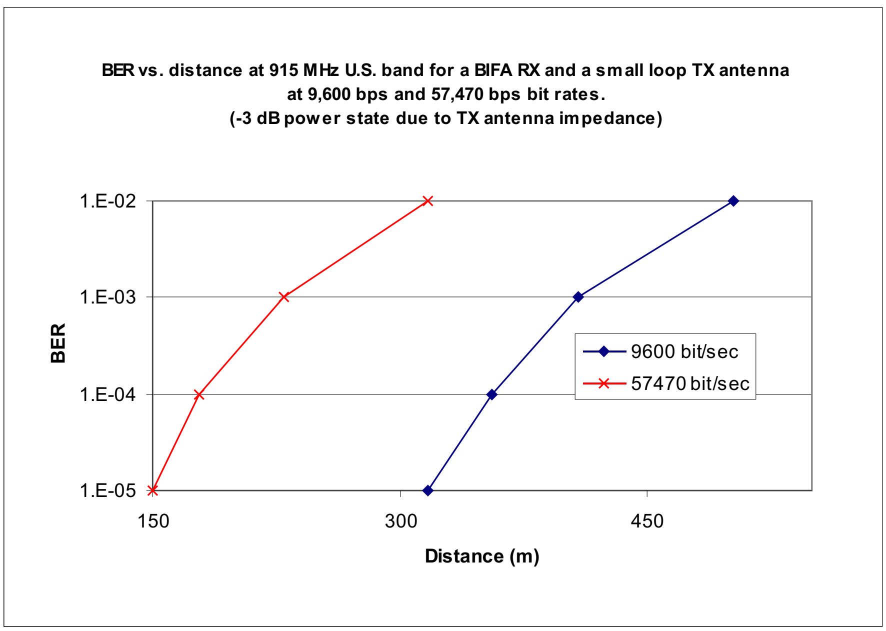

Fig. 2

2. ANTENNAS AND RANGES

US REGULATIONS: 915 MHz LINK (continued)

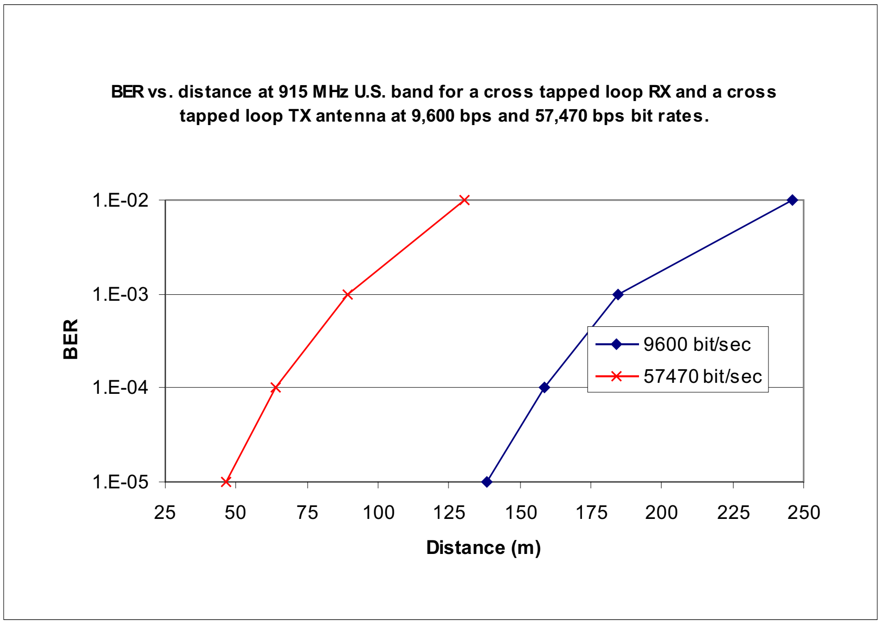

Fig. 3

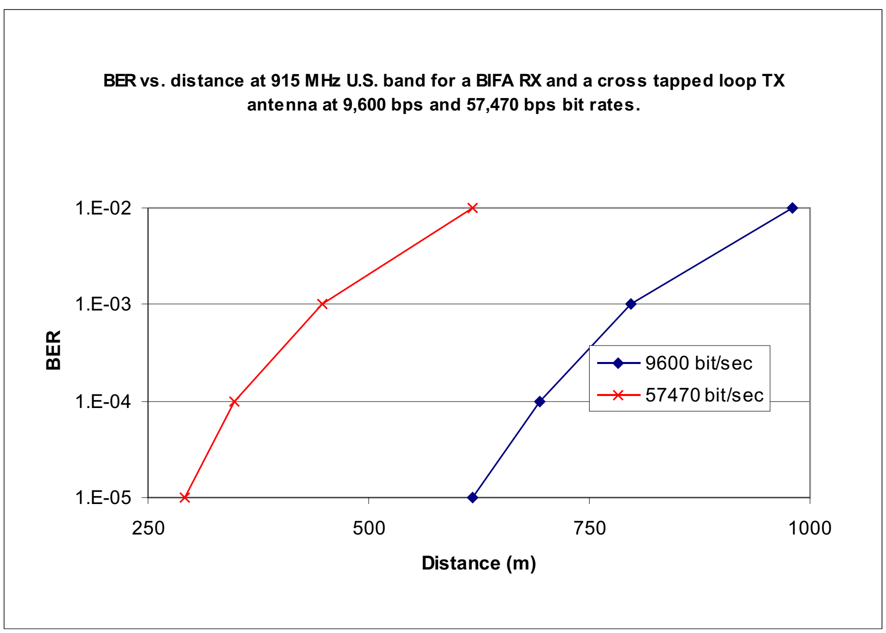

Fig. 4

915 MHz LINK (continued)

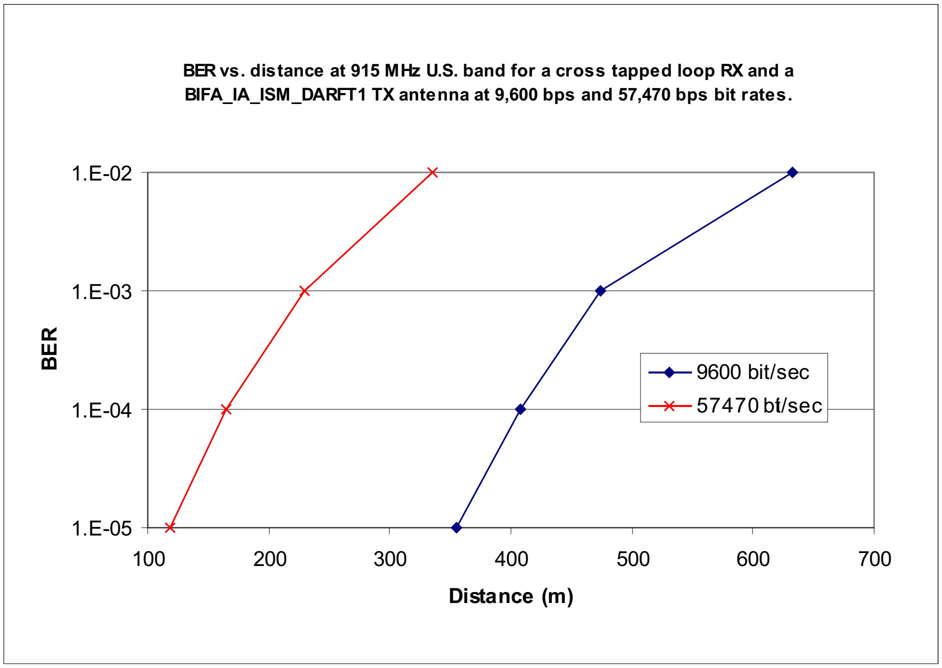

Fig. 5

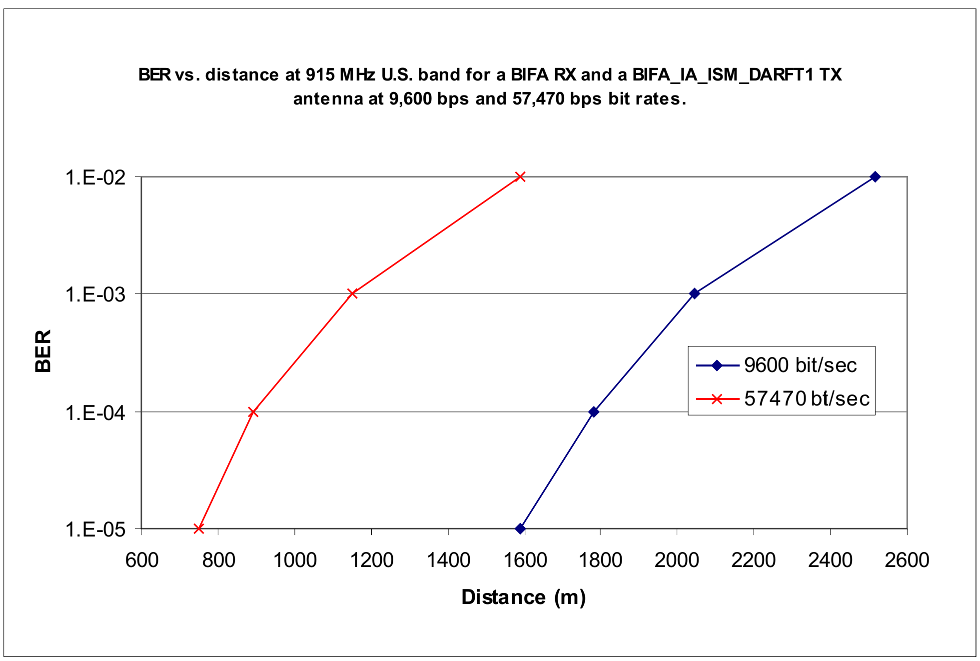

Fig. 6

2. ANTENNAS AND RANGES

915 MHz LINK (continued)

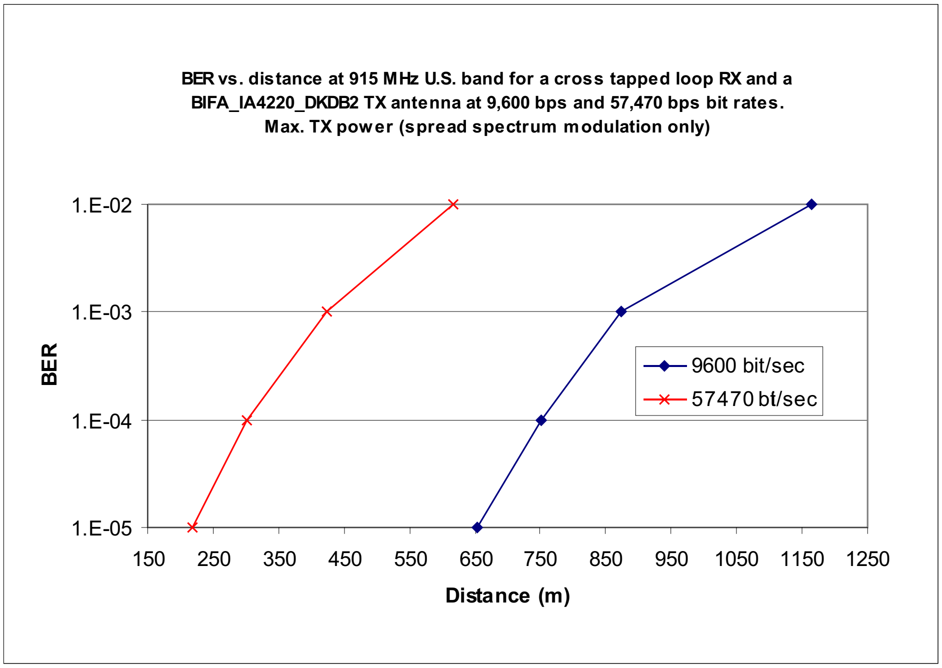

Fig. 7

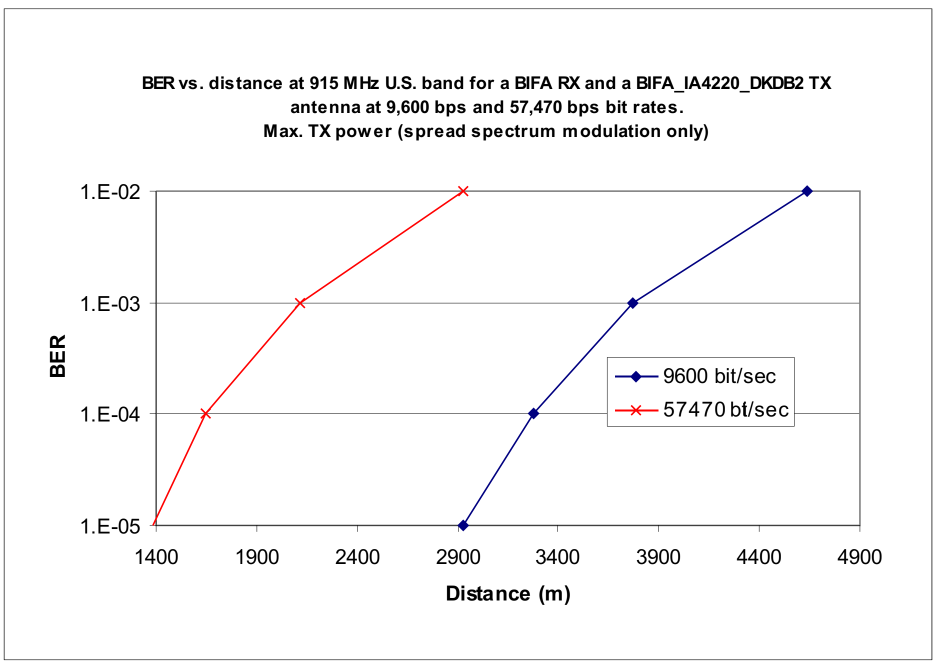

Fig. 8

2. ANTENNAS AND RANGES

US REGULATIONS: 434 MHz LINK

In the U.S. 434 MHz band, the allowed r.m.s. electric field strength at 3 m is 11 mV/m, which corresponds to –15 dBm EIRP.

In our designs for the IA4220 TX chip, a normal loop antenna (given in Fig. 2.7 in *IA ISM-AN1*) is designed.
Due to the high impedance of the loop antenna, to avoid saturation the output current of the TX driver should be reduced by 6 dB. A radiation power (EIRP) of –18 dBm is achieved at that reduced power state.

For the IA4320 RX chip a cross tapped loop (given in Fig. 2.8a in *IA ISM-AN1*) antenna is designed.

The BER of the 'RF link vs. Range' at the U.S. 434 MHz band is shown in Figure 9 at 9600 and 57470 bps data rates. In this link setup the cross tapped RX and loop TX antenna are applied.

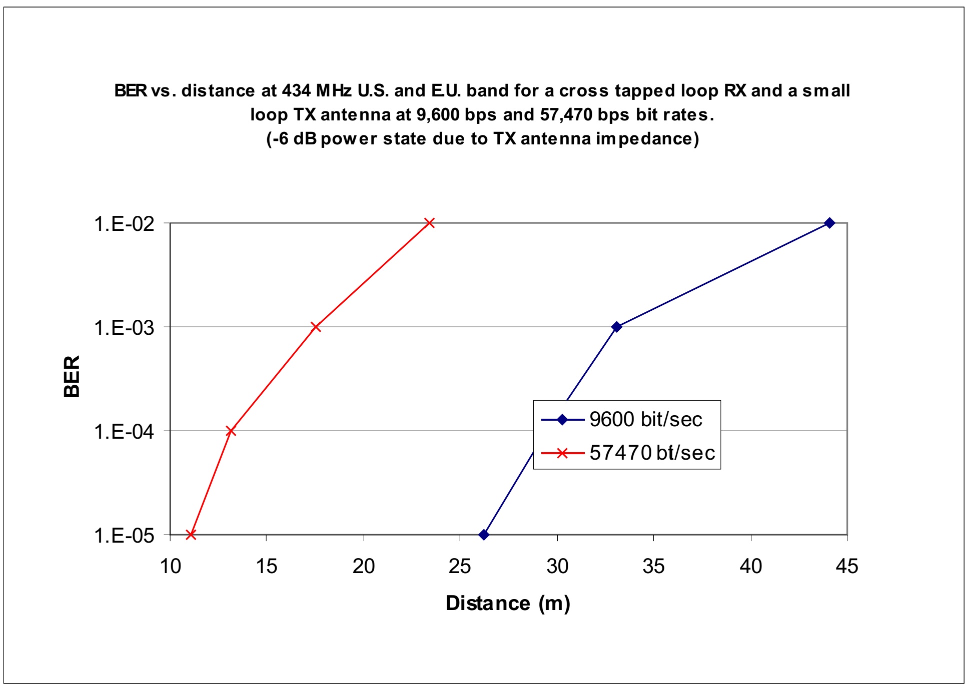

Fig. 9

2. ANTENNAS AND RANGES

US REGULATIONS: 315 MHz LINK

In the U.S. 315 MHz band, the allowed r.m.s. electric field strength at 3 m is 6 mV/m, which corresponds to –19.5 dBm EIRP.

In our designs for the IA4220 TX chip, a normal loop antenna (given in Fig. 2.9 in *IA ISM-AN1*) is designed.
Due to the high impedance of the loop antenna, to avoid saturation the output current of the TX driver should be reduced by 6 dB. A radiation power (EIRP) of –20 dBm is achieved at that reduced power state.

For the IA4320 RX chip a cross tapped loop (given in Fig. 2.10a in *IA ISM-AN1*) antenna is designed.

The BER of the 'RF link vs. Range' at the U.S. 315 MHz band is shown in Figure 10 at 9600 and 57470 bps data rates. In this link setup, the cross tapped RX and loop TX antenna are applied.

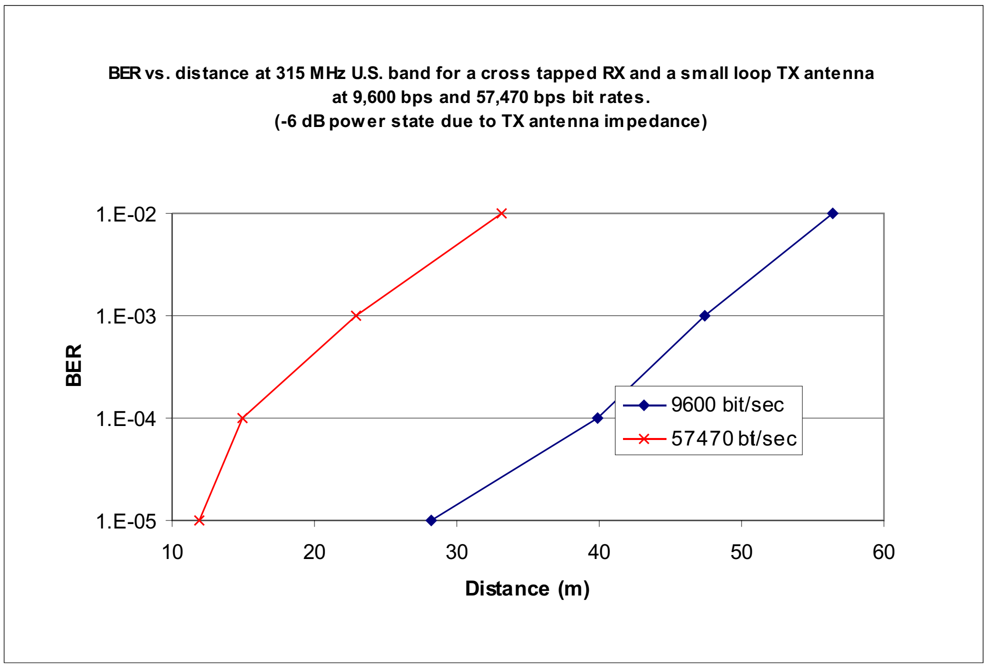

Fig. 10

2. ANTENNAS AND RANGES

EUROPEAN REGULATIONS: 434 MHz LINK

In the European 434 MHz band, the allowed ERP is 10 dBm, which corresponds to 12.14 dBm EIRP.

In our designs for the IA4220 TX chip, a normal loop antenna (given in Fig. 2.7 in *IA ISM-AN1*) is designed.
Due to the high impedance of the loop antenna, to avoid saturation the output current of the TX driver should be reduced by 6 dB. A radiation power (EIRP) of –18 dBm is achieved at that reduced power state.

To achieve higher radiated power a tapped loop TX antenna or a BIFA antenna is necessary as they have higher aperture size and lower Q. The higher aperture size yields better radiation efficiency whereas the lower Q allows higher driver output current. However, due to the larger wavelength, the dimensions of an antenna with good radiation efficiency would become uneconomically large.

For the IA4320 RX chip a cross tapped loop (given in Fig. 2.8a in *IA ISM-AN1*) antenna is designed.

The BER of the 'RF link vs. Range' at the European 434 MHz band is shown in Figure 11 at 9600 and 57470 bps data rates. In this link setup the above given cross tapped RX and loop TX antenna are applied.

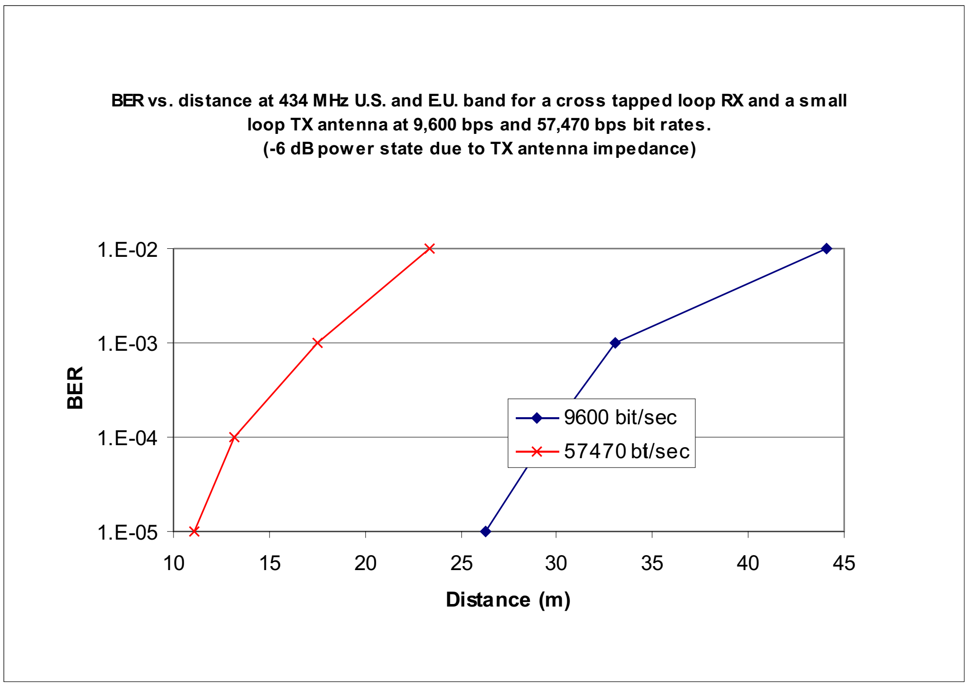

Fig. 11

2. ANTENNAS AND RANGES

EUROPEAN REGULATIONS: 868 MHz LINK

In the European 868 MHz band, the allowed ERP is between 7 and 27 dBm, depending on the sub-channel frequency.

In our designs using the IA4220 TX chip, a small normal loop identical to the antenna used in the 915 MHz band (given in Fig. 2.1 in *IA ISM-AN1*), a cross tapped loop identical to the antenna used in the 915 MHz band (given in Fig. 2.2 in *IA ISM-AN1*), and two so-called BIFA antennas (given in Fig. 2.11 and Fig. 2.12 in *IA ISM-AN1*) are designed (See Chapter 3 for further information about BIFA antennas).
Multiband operation of loop antennas is possible due to the automatic antenna tuning circuitry (See chapter 5) implemented by the IA4220 chip.

The loop antenna has a fairly high input impedance (~4 KOhm). To avoid saturation the TX output current should be 3 dB lower than the maximum. Due to the very small dimensions (aperture), the resulting EIRP of the IA4220 TX chip with small loop antenna at the -3 db power state is approximately -20 dBm. With this antenna, compact transmitter designs are possible.

The cross tapped loop has lower quality factor (Q) and can be driven by maximum TX driver current. Thus, the resulting EIRP is -11 dBm.

The BIFA antennas has a significantly lower Q than loop antennas. Thus BIFA antennas can also be driven by the full power of the IA4220 TX chip. In addition, the radiation efficiency of the BIFA antenna is fairly high due to its larger dimensions.

The antenna given in Fig 2.11 of *IA ISM-AN1* is applied in the IAI RF link demoboard and denoted by IA ISM-DRAFT2. It is referred to as BIFA_ISM_DARFT2 as follows and has a maximum EIRP of -1.6 dBm. The antenna given in Fig 2.12 of *IA ISM-AN1* is applied in the IAI TX development board and denoted by IA4220_DKDB3. To highlight the antenna design, we have referred to it as BIFA_IA4220_DKDB3 in this application note, which has a maximum EIRP of 3.9 dBm.

EIRP [dBm] **868 MHz E.U.**	**TX Antenna type**			
	Loop	**Tapped loop**	**BIFA_IA_ISM_DARFT2**	**BIFA_IA4220_DKDB3**
	-20 (-3dB state)	-11	-1.6	3.9

Table 2.2

The EIRP of the different TX antennas at 868 MHz are summarized in Table 2.2.

For the IA4320 receiver chip, a cross tapped loop antenna (given in Fig. 2.13a in *IA ISM-AN1*), and a BIFA antenna (given in Fig. 2.14 in *IA ISM-AN1* and used for IAI development boards, IA4320-DKDB5) is designed.

The BER of the 'RF link vs. Range' at the European 868 MHz band is shown in Figure 12 at 9600 and 57470 bps data rates. In this link setup, a cross tapped RX and a small loop TX antenna are applied. In Figure 13, the same curves are given for a BIFA RX and a small loop TX antenna.
In Figure 14, the case of cross tapped RX and cross tapped TX antenna is given. In Figure 15, the case of BIFA RX and cross tapped TX antenna is given.
In Figure 16, the case of cross tapped RX and BIFA_IA_ISM_DARFT2 TX antenna is given. In Figure 17, the case of BIFA RX and BIFA_IA_ISM_DARFT2 TX antenna is given.
In Figure 18, the case of cross tapped RX and BIFA_IA4220_DKDB3 TX antenna is given. In Figure 19, the case of BIFA RX and BIFA_IA4220_DKDB3 TX antenna is given.

2. ANTENNAS AND RANGES

EUROPEAN REGULATIONS: 868 MHz LINK (continued)

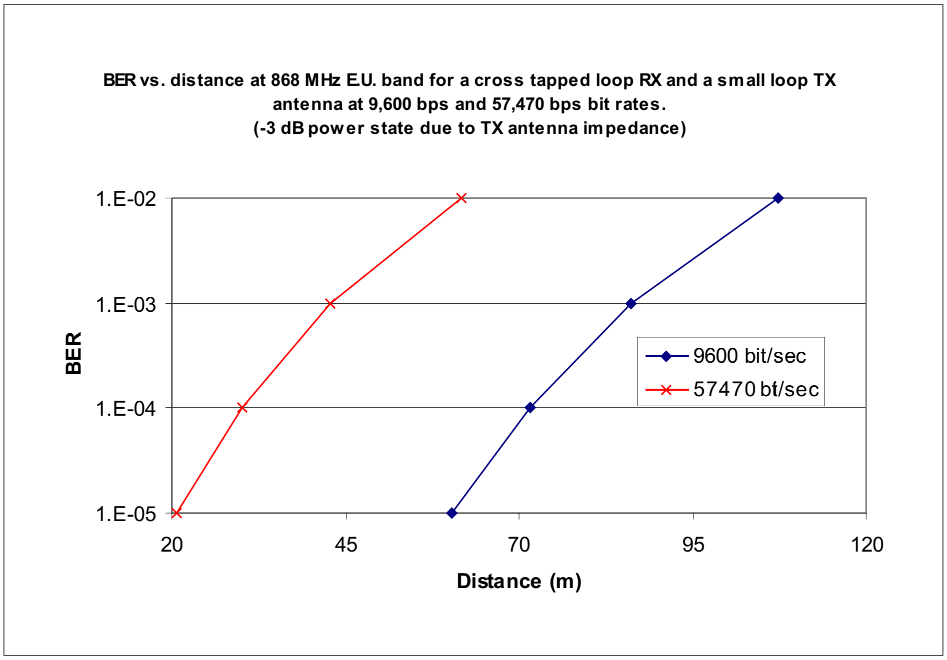

Fig. 12

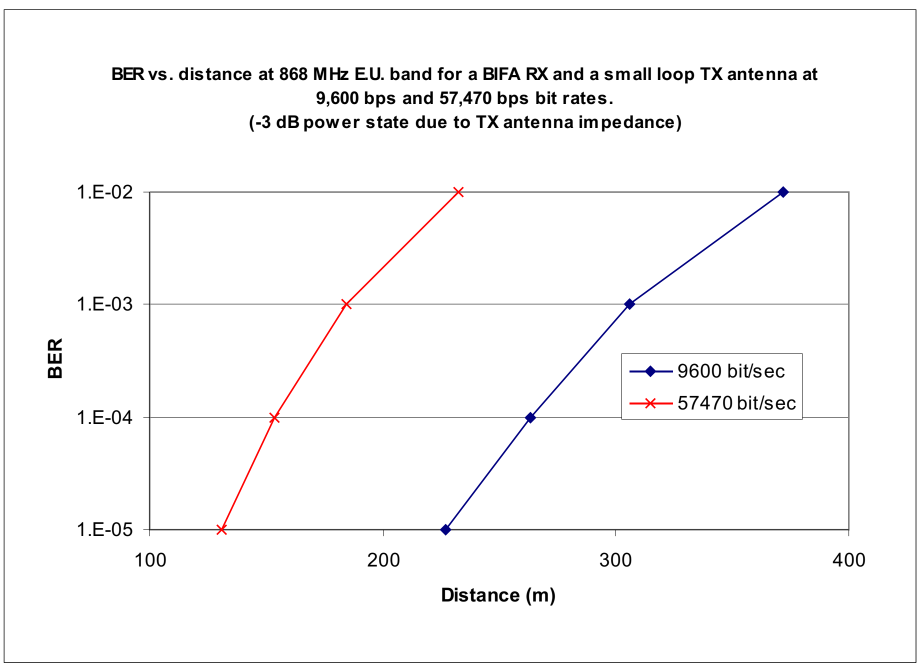

Fig. 13

EUROPEAN REGULATIONS: 868 MHz LINK (continued)

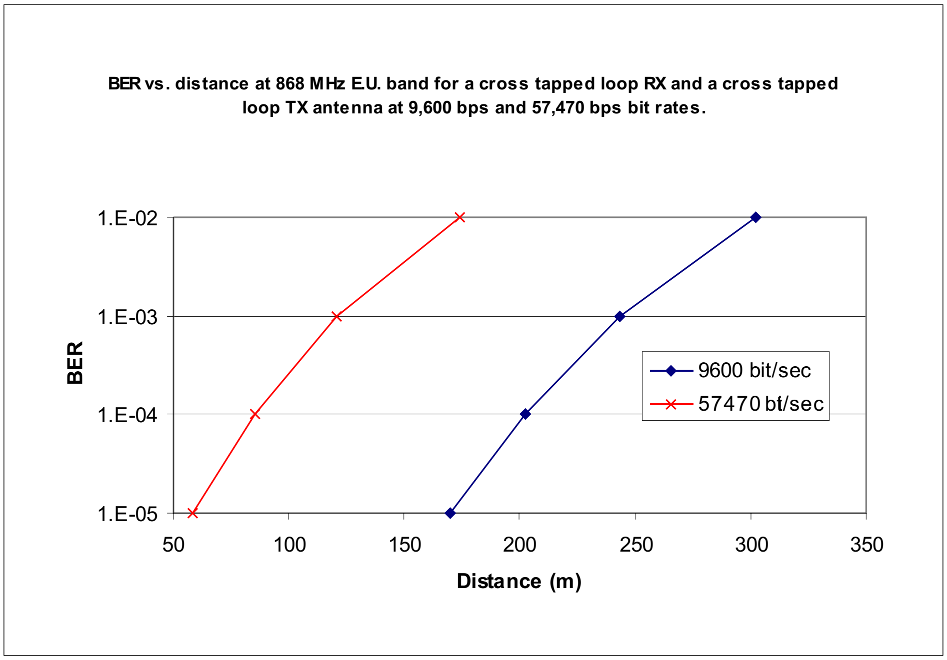

Fig. 14

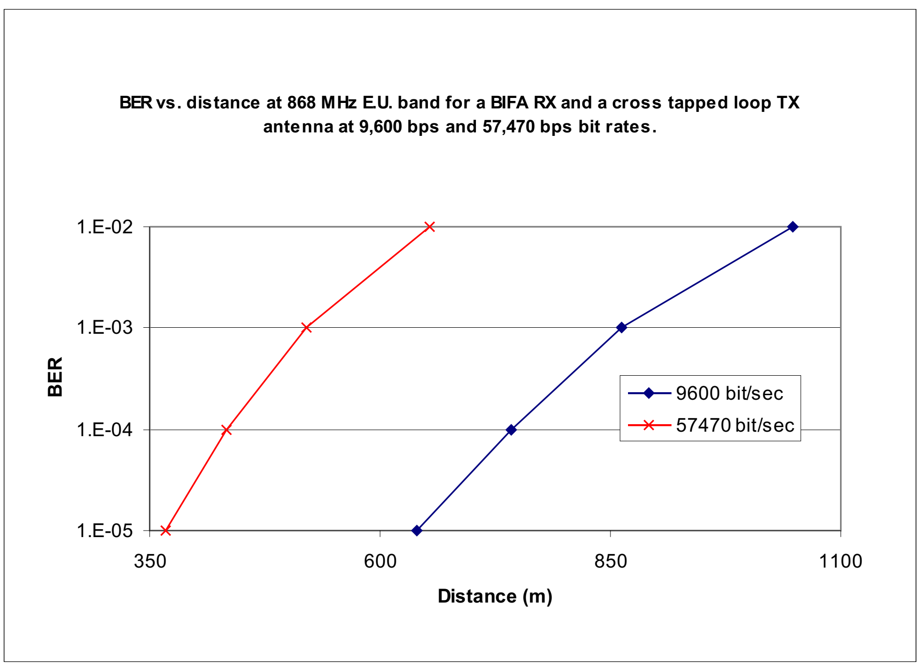

Fig. 15

2. ANTENNAS AND RANGES

EUROPEAN REGULATIONS: 868 MHz LINK (continued)

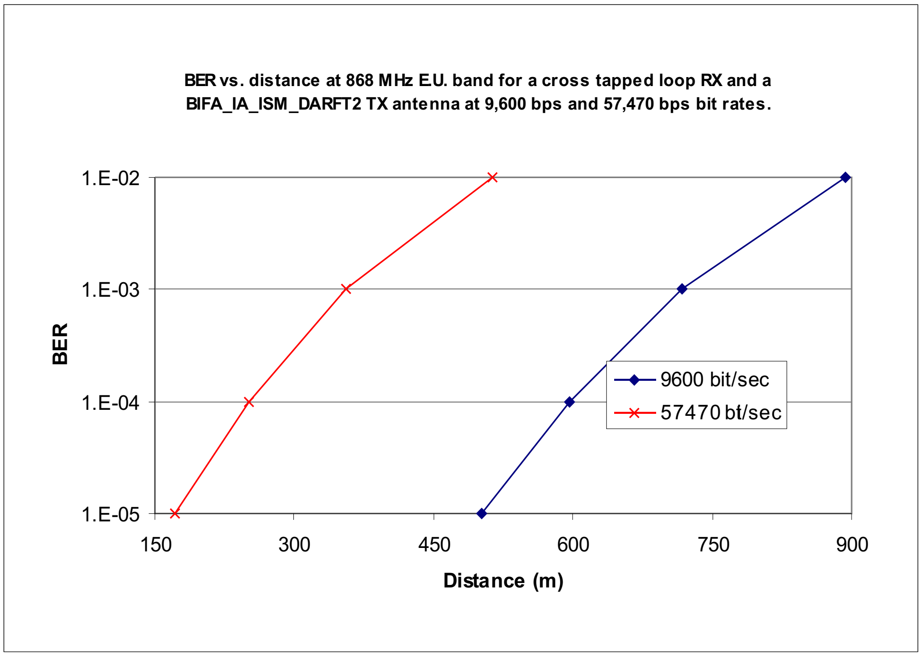

Fig. 16

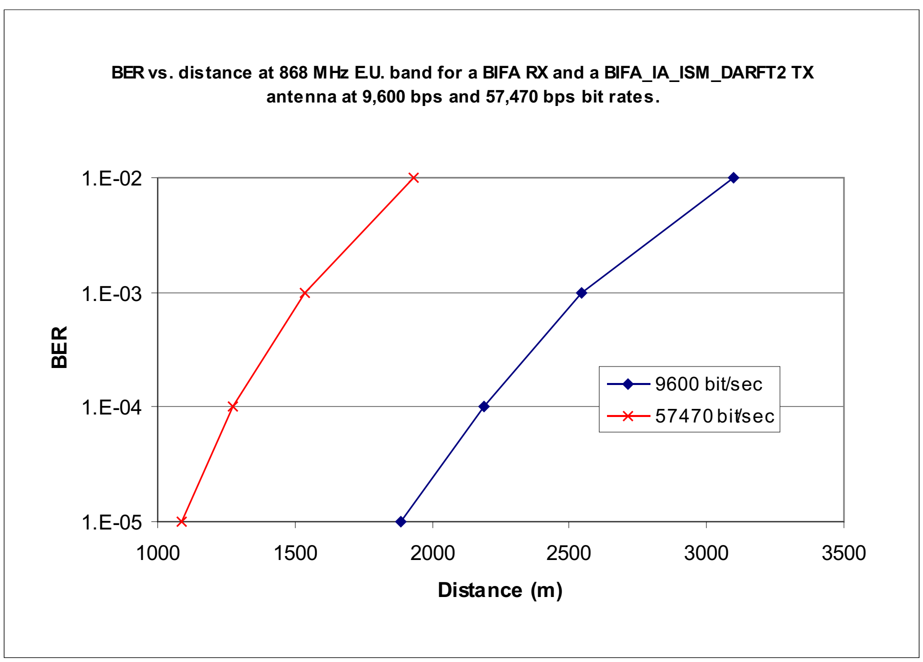

Fig. 17

2. ANTENNAS AND RANGES

EUROPEAN REGULATIONS: 868 MHz LINK (continued)

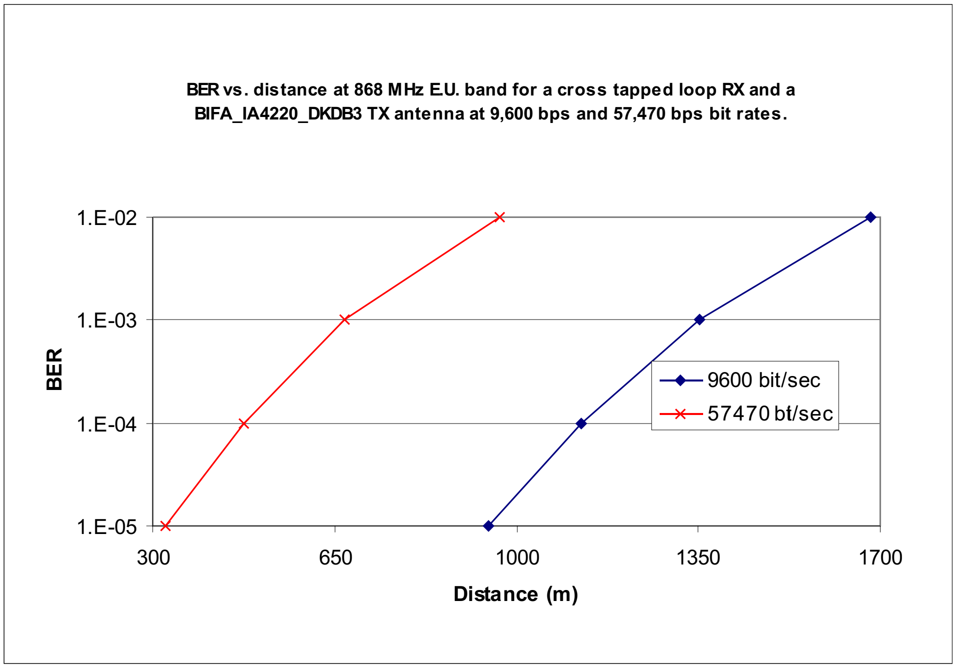

Fig. 18

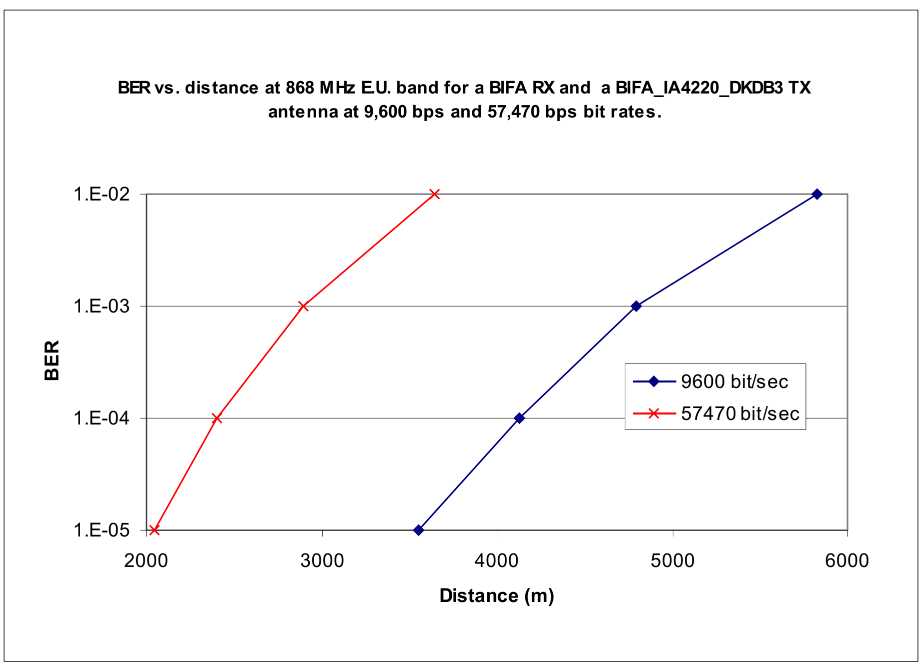

Fig. 19

3.1 HIGH Q TX ANTENNA CONFIGURATION ANALYSIS

The differential output impedance of the IA4220 TX chip can be modeled by a series R-C equivalent circuit. The loss (R) of this equivalent circuit is referred to as the Equivalent Series Resistance (ESR) of the chip capacitance.

The general model of an inductive, high impedance antenna is a series L-R circuit. The resistive part of the antenna model consists of the ohmic losses and the so-called radiation resistance, which represents the radiated power.

The general model of the TX together with the antenna is given in the left side of Fig. 20. At a given frequency the series equivalent circuit elements can be converted to parallel equivalent circuit elements. The resulting parallel resonant structure is shown at the right side of Fig. 20. The parallel resonant equivalent circuit is important as the TX-antenna configuration is used at its resonance frequency, where the remaining real part of the admittance defines the load for the transmitter. In this case, the output voltage magnitude, the radiated power and thus the efficiency of the whole configuration can be easily calculated.

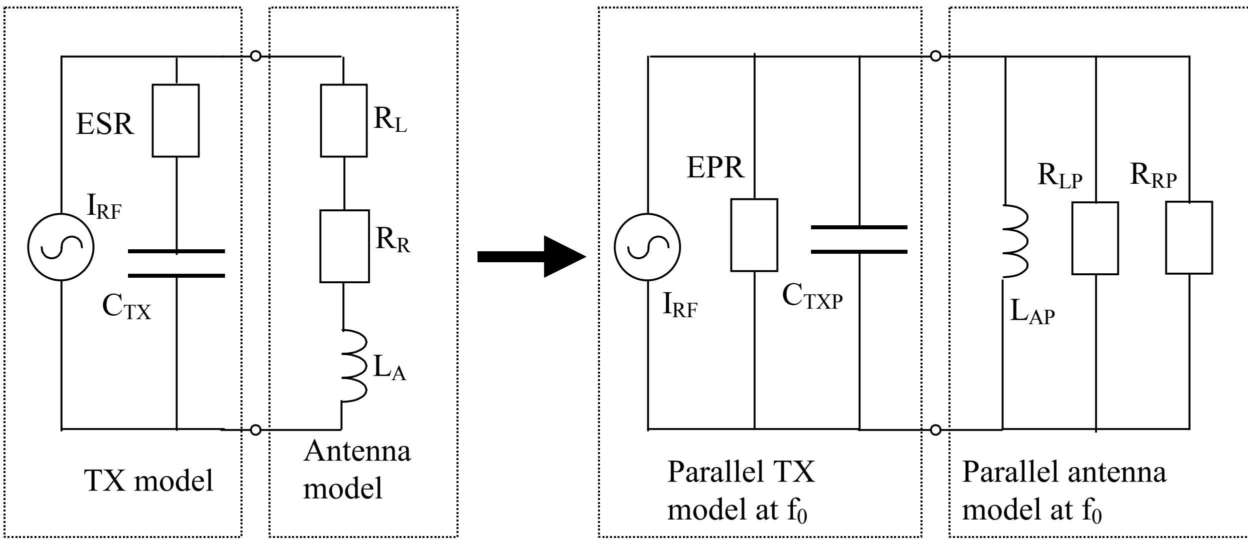

Fig. 20

The element values of the parallel R-C equivalent circuit of the TX at any f_0 frequency -this frequency can be even the parallel resonant frequency of the whole TX-antenna configuration- can be calculated from the series R-C circuit elements using the condition that the impedances must be equal:

$$ERP = \left(Q_{TX}^2 + 1\right)ESR \qquad 1.$$

$$C_{TXP} = \left(\frac{Q_{TX}^2}{Q_{TX}^2 + 1}\right)C_{TX} \qquad 2.$$

where Q_{TX} is the TX quality factor at f_0, which equal both for the series and parallel equivalent circuit:

$$Q_{TX} = \frac{1}{ESR\,\omega_0\,C_{TX}} = EPR\,\omega_0\,C_{TXP} \qquad 3.$$

One can observe that in case of high Q (~20) C_{TX}~C_{TXP} and EPR>>ESR.

3.1 HIGH Q TX ANTENNA CONFIGURATION ANALYSIS

The same method can be applied to the series R-L equivalent circuit of the antenna to get the parallel equivalent circuit at f_0. The corresponding equations are as follows:

$$L_{AP} = L_A\left(\frac{1+Q_A^2}{Q_A^2}\right) \qquad 4.$$

$$\frac{R_{LP}R_{RP}}{R_{LP}+R_{RP}} = \left(R_R + R_L\right)\left(1+Q_A^2\right) \qquad 5.$$

where Q_A is the antenna quality factor at f_0, which equal both for the series and parallel equivalent circuit:

$$Q_A = \frac{\omega_0 L_A}{\left(R_R+R_L\right)} = \frac{R_{RP}R_{LP}}{R_{RP}+R_{LP}}\frac{1}{\omega_0 L_{AP}} \qquad 6.$$

One can observe that in case of high Q (~20) L_A~L_{AP} and:

$$\frac{R_{LP}R_{RP}}{R_{LP}+R_{RP}} >> \left(R_R+R_L\right) \qquad 6.b$$

The efficiency is the ratio of the radiated power to the total consumed power. It can be calculated easily from the parallel equivalent circuit:

$$\eta = \frac{P_R}{P_R+P_L+P_{ESR}} = \frac{\frac{1}{R_{RP}}}{\frac{1}{R_{RP}}+\frac{1}{R_{LP}}+\frac{1}{EPR}} \qquad 7.$$

Substituting Equ. 1. and Equ. 5 into the denominator, and after some algebraic steps one can derive:

$$\eta = \frac{\frac{1}{R_{RP}}\left(R_R+R_L\right)\left(1+Q_A^2\right)}{1+\frac{\left(R_R+R_L\right)\left(1+Q_A^2\right)}{ESR\left(1+Q_{TX}^2\right)}} \qquad 8.$$

It also can be stated that the ratio of the radiation loss to the total antenna loss (radiation + ohmic loss) is the same for both the series and parallel equivalent circuits i.e.:

$$\frac{\frac{1}{R_{RP}}}{\frac{1}{R_{LP}}+\frac{1}{R_{RP}}} = \frac{R_R}{R_R+R_L} \qquad 9.$$

3.1 HIGH Q TX ANTENNA CONFIGURATION ANALYSIS

By rearranging Equ. 9 and substituting Equ. 5, one can derive:

$$\frac{1}{R_{RP}} = \left(\frac{1}{R_{LP}} + \frac{1}{R_{RP}}\right)\frac{R_R}{R_R + R_L} = \frac{R_R}{\left(R_R + R_L\right)^2\left(1 + Q_A^2\right)} \qquad 10.$$

By substituting the right side of Equ. 10 into Equ. 8 for a higher Q, a new formula for efficiency is yielded:

$$\eta = \frac{R_R}{\left(R_R + R_L\right) + \frac{\left(R_R + R_L\right)^2\left(1 + Q_A^2\right)}{ESR\left(1 + Q_{TX}^2\right)}} \approx \frac{R_R}{\left(R_R + R_L\right) + \frac{\left(R_R + R_L\right)^2 Q_A^2}{ESR\, Q_{TX}^2}} \qquad 11.$$

Substituting the middle part (series elements) of Equ. 3 and Equ. 6 into Q_{TX} and Q_A, respectively, and taking into account that at resonant frequency $C_{TX} L_A \approx \omega_0^2 = C_{TXP} L_{AP}$ if the Q is high, one can get the generally applied approximate (valid only in the case of high Q) expression for the efficiency, which uses only the losses of the well measurable series equivalent circuit.

$$\eta = \frac{R_R}{R_R + R_L + ESR} \qquad 12.$$

It must be noted that besides the above defined efficiency, the efficiency of the output driver also has a large influence on the total power consumption. In order to achieve high driver efficiency, the output voltage swing (i.e. swing on the TX-antenna configuration) should be close to the allowed maximum, which is approximately 4 Vpp for a supply voltage of 2.2 V. See Chapter 4 and 5 for more details.

3.2 HIGH IMPEDANCE ANTENNA TYPES

The aim of this chapter is to provide an overview of the various TX and RX antenna types presented by Integration. The dimension, cost, and efficiency is investigated. Detailed antenna analysis along with design formulas are given in Reference 1 and 2. The final sophisticated design can be performed by the use of electromagnetic CAD tools.

SMALL LOOP ANTENNA

Due to the small dimensions and high impedance of small loop antennas, it is suitable for very low power applications, where size is important. The loop antenna has a small size, a high *Q* (20-60 depending on size and frequency), and a moderate radiation gain (G=-10 dB) dependent on the size. Its input impedance is inductive and along with the chip outputs, the small loop antenna forms a high impedance parallel resonant circuit with fairly good harmonic suppression. Due to the very high impedance (4-8 K at resonance), the loop antenna requires small supply current and is well matched to the output impedance of the TX chip at low bands (315, 434 MHz).
The loop antenna is fairly insensitive to the vicinity of the human body, i.e. capacitance issues, such as the hand effect. The small loop antenna is ideal for short range, battery powered applications, such as remote controls.
Due to its high Q, the loop antenna is sensitive to any detuning caused either by technological spreading , vicinity of metallic objects or temperature variations. A common solution to resolve the detuning issue is the reduction of Q through a resistor connected parallel with the antenna. The resistor has a typical value of several hundred ohms. However, as the resistor value is much lower than the antenna impedance, most of the output power of the TX chip is dissipated by the resistor instead of being radiated by the antenna. Another unfortunate side effect of the additional resistor is the extra bill of materials.

Using the IA4220 where an automatic antenna tuning circuitry is applied, the detuning effects are automatically resolved and hence the maximum radiated power is maintained without an external resistor. Due to the maximized Q, the necessary driver current to achieve the same radiation power is much smaller, which enables longer battery life.

A typical loop antenna layout is shown in Figure 21.

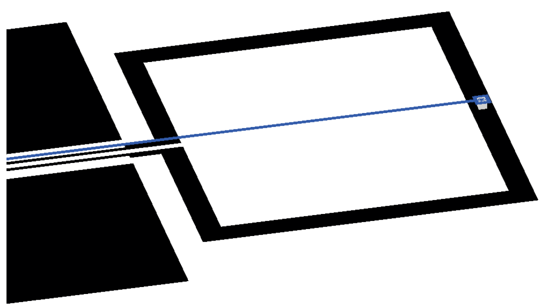

FIg. 21 Small loop antenna layout

The narrow wire at the symmetrical axis, connected through a via to the antenna, is for the DC biasing of the TX open collector outputs.
The conventional loop antenna can be modeled by a lossy inductance. The antenna inductance consists of the inductance of the loop and the wire. The former usually gives 80-90% of the total antenna inductance and it is proportional to the logarithm (ln) of the loop area:

$$L = \frac{\mu}{2\pi} l \ln\left[\frac{8A}{lw}\right] \qquad 13.$$

where

- μ is the permeability which is usually equals to that of the air (4πE-7 [H/m]) for the most dielectric type substrates.
- *l* is the total perimeter of the antenna trace (at the center of the trace) [m]
- w is the width of the trace [m]
- A is the loop area [m^2] inside the trace center

3.2 HIGH IMPEDANCE ANTENNA TYPES

SMALL LOOP ANTENNA (continued)

Balanis [2] gives a more accurate expression for the case of rectangular loop antennas:

$$L_{loop} = 2\mu_0 \frac{\sqrt{A}}{\pi}\left(\ln\left(\frac{\sqrt{A}}{b} \right) - 0.774 \right) \qquad 14.$$

where

- $b = (0.35h + 0.24w) / 1000$ 15.
- *h* is the thickness of the metallization [m]
- m_0 is the permeability of the air (4pE-7 [H/m])

The inductance of the wire, which is only a small part of the total inductance is given by Equ. 16.

$$L_W = \mu_0 \frac{\sqrt{A}}{2} \qquad 16.$$

As it can be observed from the above equations, the area of the normal loop antenna is determined by the required antenna inductance value. The optimum antenna inductance values for the IA4220 TX chip are given in Table 5.1 for the four different bands. With these optimum inductance values, the resonant frequencies are at the band centers if the capacitance bank of the automatic tuning circuitry is in the middle state (7). More details are given in Chapter 5.

The real part of the antenna impedance represents the effect of the ohmic loss and the radiation. For good radiation efficiency, the value of the radiation resistance must be dominant. The radiation resistance is proportional to the square of the aperture size (area) and inversely proportional to the square of the wavelength (λ), i.e.:

$$R_R = 320\pi^4 \frac{A^2}{\lambda^2} \qquad 17.$$

For better radiation efficiency a bigger aperture size is necessary. As the antenna inductance is proportional to the square of the aperture size (see equation 15 and 16), usually it is best to design the antenna inductance higher than the previously mentioned optimum value. In this case, the tuning circuitry tunes the antenna to resonance by decreasing the capacitance. It is practical to increase the antenna inductance such a way, that the resonance is achieved at capacitance bank state 3 or higher, resulting in a margin for the compensation of the previously mentioned detuning effects. According to Equation 25 (Chapter 5) this method (higher antenna inductance and lower chip capacitance) results in an increase of the equivalent parallel resistance at resonance, and thus a higher voltage swing with the same driver current. This is advantageous if the antenna *Q* is lower than the optimum (see Chapter 5) for the targeted power level. Usually, this is not the case for loop antennas. Fortunately, an increase in size increases the radiation efficiency, i.e. increases the radiation resistance (loss) in the series equivalent circuit of the antenna. It also causes a decrease of the antenna impedance at the parallel resonance. This effect works against the previously mentioned antenna impedance increase caused by the higher antenna inductance. Due to these reasons, a larger, more efficient loop antenna with approximately the same resonant impedance can be designed.

The ohmic loss can be calculated by taking into account the hand effect:

$$R_L = \frac{l\sqrt{\frac{\pi f \mu_0}{\sigma}}}{2w} \qquad 18.$$

where:

- *l* is the total perimeter at the trace center [m]
- *w* width of the trace [m]
- *s* is the copper conductivity (5.8E7 [S/m])
- *f* is the frequency [Hz]

3.2 HIGH IMPEDANCE ANTENNA TYPES

TAPPED LOOP ANTENNA

The high impedance of the loop antenna can be reduced by the so-called tapping technique. The tapped loop antenna has a lower input impedance compared to a normal loop antenna due to the impedance transformation caused by the tapping. As the antenna inductance is reduced, an antenna with a larger aperture size can be in resonance with the same chip output capacitance at the required frequency, resulting in a better radiation efficiency. Using tapping, the larger radiation resistance causes a further reduction of the antenna impedance at resonance.
As mentioned earlier, the Q of a normal loop antenna is usually higher than the Q of an IC because of the generic losses in the I/O pads especially at high bands (868 and 915 MHz). Because of this, most TX driver current flows into the chip's internal loss and only a small fraction goes to the antenna, resulting in poor overall efficiency.
For low impedance tapped loop antennas, the efficiency is higher. It is also possible to match the antenna impedance to the chip impedance, so that maximum power can be delivered to the antenna. The radiated power with this matched antenna can still be lower than the maximum allowed by the regulations, and it cannot be increased further by the increase of the driver current as the voltage swing would exceed the available maximum (4 Vpp). If this is the case, an antenna with lower impedance is practical to use, which allows higher driver current. The antenna impedance is determined by the condition that the required power should be achieved with maximum available voltage swing. This also determines the necessary driver current. This problem is discussed in further detail in Chapter 5.
The greatest advantage of the tapped antenna is the possible variation of the tapping point. The antenna impedance can be tuned to the power requirements. Good efficiency can be maintained through this design as its lower impedance means a larger portion of the driver current flows through the antenna.
The tapping can be either a capacitive or an inductive type.

Capacitive tapping of loop antennas

The capacitive tapping is shown in Fig. 22.

For high Q antenna (Q_A>>1) and high Q TX (QTX>>1), the resonant frequency can be given by Equ. 19.

$$\omega_0 \approx \sqrt{\frac{C_{ST}+C_{PT}+C_{TX}}{C_{ST}\left(C_{PT}+C_{TX}\right)L_{AP}}} \approx \sqrt{\frac{C_{ST}+C_{PT}+C_{TX}}{C_{ST}\left(C_{PT}+C_{TX}\right)L_{A}}} \qquad 19.$$

The transformed impedance at resonance is given by Equ. 20.

$$R_{TP} = \left(\frac{C_{ST}}{C_{ST}+C_{PT}+C_{TX}}\right)^2 \frac{R_{LP}R_{RP}}{R_{LP}+R_{RP}} \qquad 20.$$

Using Equ. 5 and Equ. 6 and taking into account that Q_A>>1, at resonant frequency Equ. 20 can be simplified:

$$R_{TP} \approx \left(\frac{C_{ST}}{C_{ST}+C_{PT}+C_{TX}}\right)^2 Q_A^2\left(R_R+R_L\right) = \frac{C_{ST}L_A}{\left(C_{ST}+C_{PT}+C_{TX}\right)\left(C_{PT}+C_{TX}\right)\left(R_R+R_L\right)} \qquad 21.$$

3.2 HIGH IMPEDANCE ANTENNA TYPES

TAPPED LOOP ANTENNA (continued)

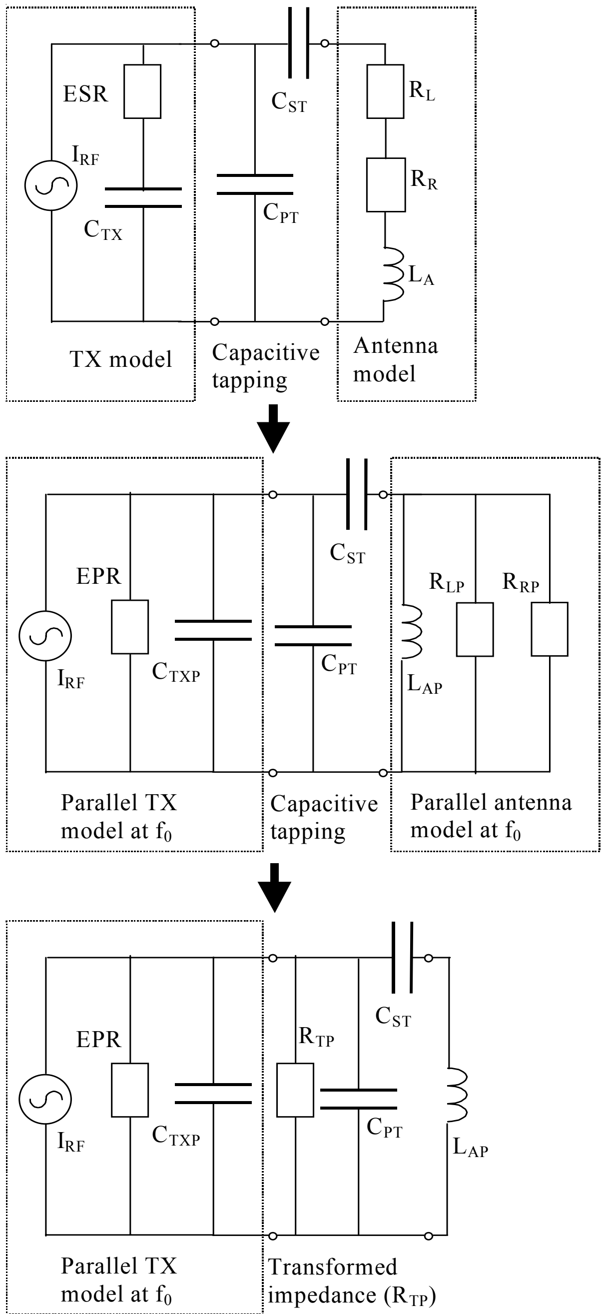

Fig. 22 Capacitive tapping of loop antenna

3.2 HIGH IMPEDANCE ANTENNA TYPES

TAPPED LOOP ANTENNA (continued)

If $C_{ST} << (C_{PT}+C_{TX})$, then the resonant frequency is determined by C_{ST}, and the impedance is determined by $C_{PT} + C_{TX}$. Although capacitive tapping has many advantages, there are several issues to be addressed:

- The C_{ST} and C_{PT} are usually external SMD capacitors which increases the bill of materials.
- If C_{ST} is a small printed capacitor (~0.1..0.3pF), the resonant frequency will become sensitive to the dielectric constant variation of the PCB. This variation is difficult to compensate for by the change of C_{TX}.
- The open collector outputs of the IA4220 TX chip require a DC path to the supply. With a series connected C_{ST} this can be difficult to create.

Due to these characteristics, the capacitive tapping technique is not suggested for transmitter and receiver designs using the IA4220 and IA4320.

Inductive tapping of loop antennas

A symmetrical inductive tapped antenna is shown in Fig. 23.

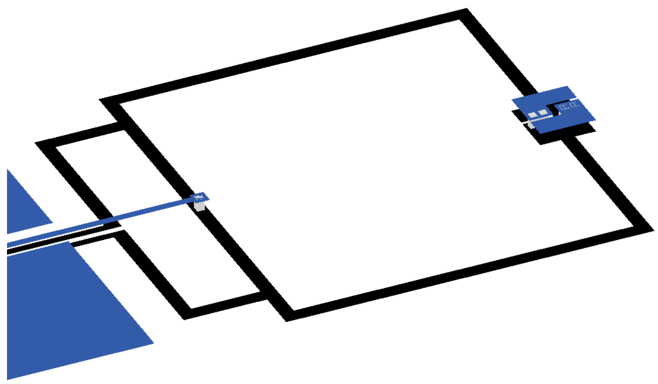

Fig. 23 Inductively tapped loop antenna layout

The main loop contains a printed or a discrete series capacitance. In our example, a symmetrical printed capacitor is used. (See IA ISM-AN1 document for detailed capacitor drawings.) The impedance transformation depends on the position of the tapping point.

A simplified equivalent circuit is shown in Fig. 24. This figure shows the loss (ESR) of the capacitor, however, it does not contain the inductance of the small loop being formed by the leads of the antenna input to the tapping points. The ratio of L_{A1} and L_{A2} and the value of M depends on the position of the tapping (tapping ratio)

TAPPED LOOP ANTENNA (continued)

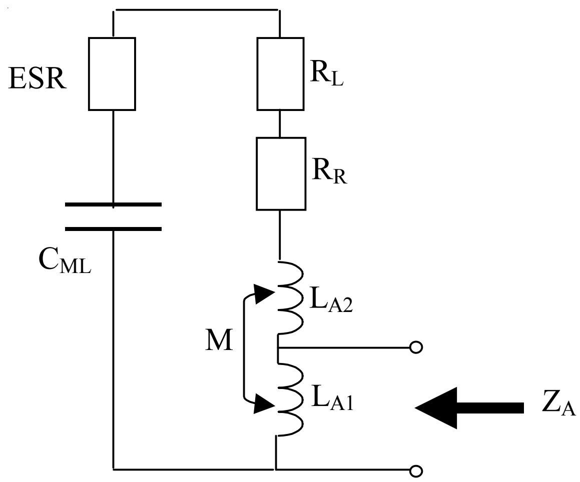

Fig. 24 Equivalent circuit of an inductively tapped loop

The antenna admittance is given by Equ. 22. if the reactive impedances are assumed to be much higher than the resistive impedances [1]. i.e. a high Q antenna is used.

$$Y_A = \frac{\omega^2 \left(R_R + R_L + ESR\right)\left(L_{A1} + M\right)^2}{\left[\omega^2 \left(L_{A1} + M\right)^2 + \omega L_{A1}\left(\omega L_{AT} - \frac{1}{\omega C_{ML}}\right)\right]^2} + $$

$$+ j \frac{\omega L_{AT} - \frac{1}{\omega C_{ML}}}{\omega^2 \left(L_{A1} + M\right)^2 + \omega L_{A1}\left(\omega L_{AT} - \frac{1}{\omega C_{ML}}\right)} \qquad 22.$$

where $L_{AT}=L_{A1}+L_{A2}+2M$. Here M is the mutual inductance between L_{A1} and L_{A2}.

The antenna impedance depends on L_{A1}, L_{AT}, and M (i.e. on the tapping ratio) and on C_{ML} as well. The antenna inherently has a high impedance parallel resonance. At the resonant frequency:

$$\omega L_{AT} = \frac{1}{\omega C_{ML}} \qquad 23.$$

the antenna impedance is real, given by Equ. 24:

$$Z_A\Big|_{\omega=\frac{1}{\sqrt{C_{ML}L_{AT}}}} = \frac{\left(L_{A1} + M\right)^2}{\left(R_R + R_L + ESR\right) C_{ML} L_{AT}} \qquad 24.$$

3.2 HIGH IMPEDANCE ANTENNA TYPES

TAPPED LOOP ANTENNA (continued)

According to Equ. 24, L_{A1}, and the tapping ratio has a strong influence to the impedance at resonance.
At the operating frequency, the antenna should be inductive to be in resonance with the output (or input) capacitance of the IA4220 (or IA4320). The above defined self resonant frequency should be higher than the operating frequency.

To determine the resistive elements of the equivalent circuit, the formulas used by the normal loop antennas (Equ. 17 and 18) can be applied. The determination of L_{A1}, L_{A2}, and M is more difficult and usually done by CAD tools. Besides that, the equivalent circuit of a realistic tapped antenna (which is shown in Fig. 23) is more complicated as it includes the inductance of the small loop formed by the leads at the antenna input to the tapping point and the additional inductive coupling between this small loop and the main loop.
Analysis of this realistic equivalent circuit is too complex. Numerial analysis can easily be done through the use of circuit simulation tools.

Due to the printed capacitance used in the main loop, the input impedance is sensitive to the dielectric constant and to the variations of the PCB thickness. In addition, the antenna is less 'tunable' by the variations of the impedance at its input (chip capacitance) due to the tapping. Therefore, a larger change of the IA4220 TX chip capacitance is necessary by the automatic tuning to compensate for the PCB technological spreading and hand effect.

Multiple resonances can cause further problems. Referring to Figure 23, it is possible to understand that each loop will have its own resonance, each at a different frequency. These resonant frequencies need to be far apart (>20%) in order to ensure that the resulting phase characteristics allow the automatic antenna tuning to function correctly. Strong magnetic coupling between the main loop and small loop makes this difficult to achieve. The coupling between the main loop and small loop can be reduced by the so-called cross tapped structure, which is shown in Figure 25.

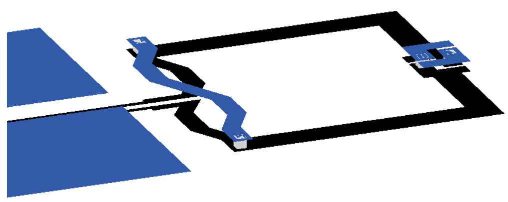

Fig. 25 Cross tapped structure

3.2 HIGH IMPEDANCE ANTENNA TYPES

TAPPED LOOP ANTENNA (continued)

In the 315 and 434 MHz European bands, the dimensions of the normal loop antennas are large. Their aperture sizes cannot be increased further by tapping as the dimensions would become unacceptably high for typical applications. Tapped antennas of the same sizes can be designed by increasing the capacitance value in the main loop, though radiation efficiency may be reduced when compared to the normal loop antenna. Using this technique however, the antenna impedance is lower and the output current (i.e. the power) of the TX chip can be increased. The allowed radiation power is higher in the 434 MHz band.
The tapped antennas are a good choices of antennas for the IA4320 RX chip, as they have well-matched input impedance (approximately 300 Ohm at resonance) and have a higher radiation efficiency.

DIFFERENTIAL INVERTED-F (IFA) ANTENNA

The differential Inverted-F (IFA) antenna is derived from the asymmetrical IFA antenna by mirroring it to the ground plane. It is shown in Figure 26.

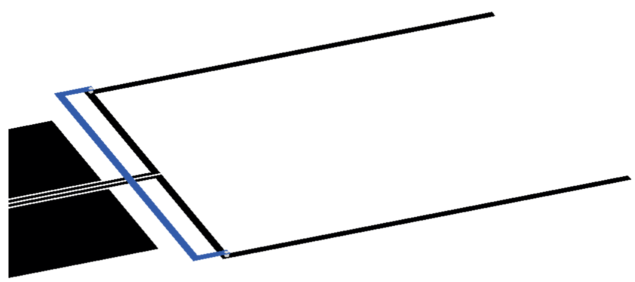

Fig. 26 Differential IFA antenna

The differential IFA also has a high impedance parallel, self- resonance. With correct geometry, inductive input impedance and thus resonance with the transmitter's output capacitance can be achieved at the desired frequency. The radiation efficiency is much higher compared to the loop antenna and comparable to that of the quarter wave monopole. Its *Q* is lower than the Q of the loop antenna. The impedance is 300 Ohm at resonance with the typical transmitter's output capacitance value (2.2 pF). Due to the lower *Q*, the antenna is less sensitive to detuning. Also higher output current can be applied at a given supply voltage and therefore a higher output power can be achieved. However, as it was mentioned above in the case of short range (~10m) applications, where the required radiated power is very low (~ -20 dBm ERP), the efficiency of the driver with a higher impedance antenna is better. This driver efficiency degradation is compensated by the better radiation gain (G=0...1 dB) and efficiency (compared to the conventional loop antenna) especially at high bands, where the overall performance (ERP/DC current consumption) of the IFA is approximately 10 dB better. Due to the inherent resonance of this kind of antenna at the operation frequency, its harmonic suppression is very good. (5..10 dB better compared to the loop antenna.)
However, one of the main disadvantages of this antenna type is the large dimension compared to the small loop antenna. In conclusion, the IFA antenna is the correct choice for 868 and 915 MHz applications, where the lower wavelength results in good efficiency with acceptable antenna sizes.

3.2 HIGH IMPEDANCE ANTENNA TYPES

MODIFIED DIFFERENTIAL IFA ANTENNA

In low power applications or in bands where only low output power is required, the efficiency of the TX could be improved by increasing the input impedance of the IFA antenna. Only a slight increase of the back IFA impedance can be achieved by reducing the dimensions of the loop.
As it was mentioned earlier, designers will get better results if an antenna with a higher inductance is designed, which is in resonance with the chip outputs at a lower capacitance bank state of the automatic antenna tuning. (See Chapter 5.) As the *Q* of the antenna is approximately the same (radiation is the same), according to Equation 25 (Chapter 5), the resulting impedance at resonance will be higher.
Design dimensions can be effectively reduced by bending the horizontal arms around the circuit , as highlighted by the black square in Figure 27. The application circuit of the PCB can be considered as a large ground plane, therefore shorter arms are enough for impedance tuning. This antenna type is called the back IFA antenna and is presented in Figure 27. The input impedance of the antenna is sensitive to the length of the arms.

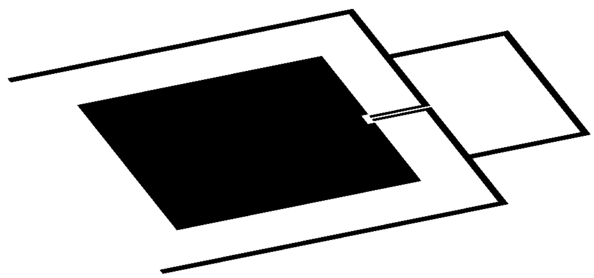

Fig. 27 Back IFA antenna

4. CHOOSING HIGH OR LOW IMPEDANCE ANTENNAS

The transmitter efficiency is dependent on three variables: the efficiency of the driver, the internal loss of the chip, and the radiation efficiency of the antenna. As will be demonstrated, the best overall transmitter efficiency is achieved by the BIFA antenna driven by a high Q output stage. The overall efficiency of the loop is significantly lower, but it is the ideal choice for applications where the small sizes are important.

In conventional circuit solutions, the lowest operating DC voltage is 2.2 V per the datesheet, allowing a certain level of maximum differential voltage swing on the output depending on the structure. A lower voltage swing will result in poor driver efficiency.

For example, in the case of low ERP power requirements (0-20 dBm), the voltage swing on a 50 Ohm antenna will be small in comparison to the maximum available from a 2.2 V supply. In Figure 28, the properties of an ideal low impedance, single-ended, emitter follower output is shown. The available voltage swing is 1 Vpp. Assuming a 50 Ohm antenna at the output, the necessary current magnitude to obtain 0.5 mW power at the antenna is 4.5 mA, which yields approximately 10 mW DC power consumption.

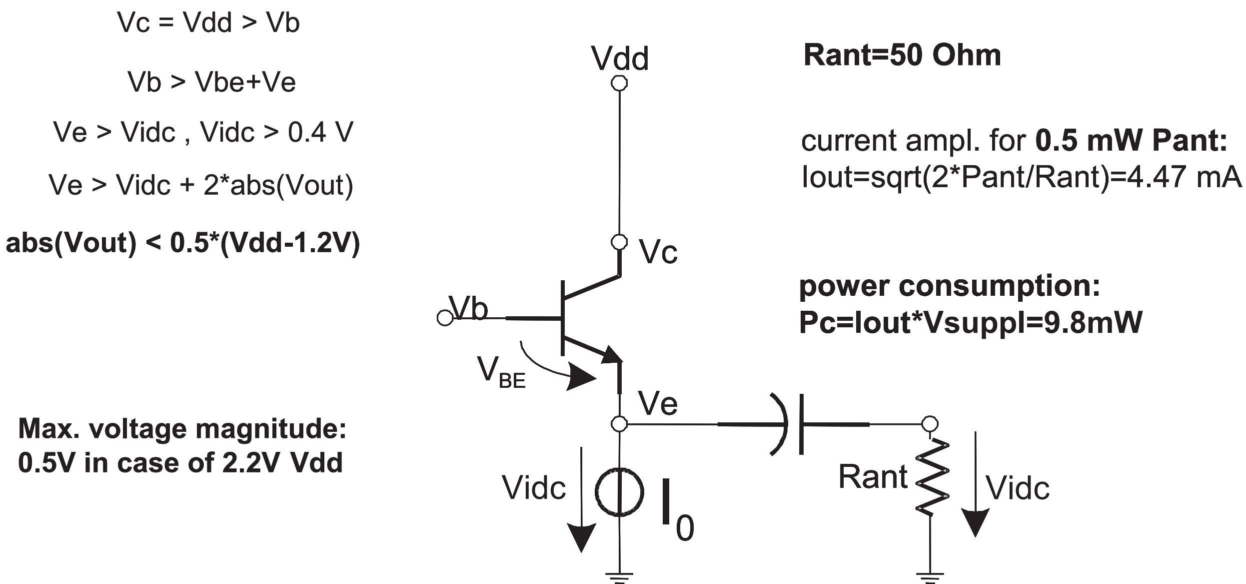

Fig. 28

4. CHOOSING HIGH OR LOW IMPEDANCE ANTENNAS

In the case of a high impedance antenna, the voltage swing is close to the maximum, giving a highly efficient driver. Figure 29 demonstrates an open collector driver structure, whose properties are ideal, differential, and has high impedance. The load is represented by the antenna equivalent circuit. The available differential voltage magnitude is 2 V in the case of a 2.2 V supply voltage. Assuming a 4 kOhms antenna impedance at resonance, the maximum power to the antenna is 0.5 mW, which requires a 1 mA tail current. The total DC power consumption is 2.2 mW.

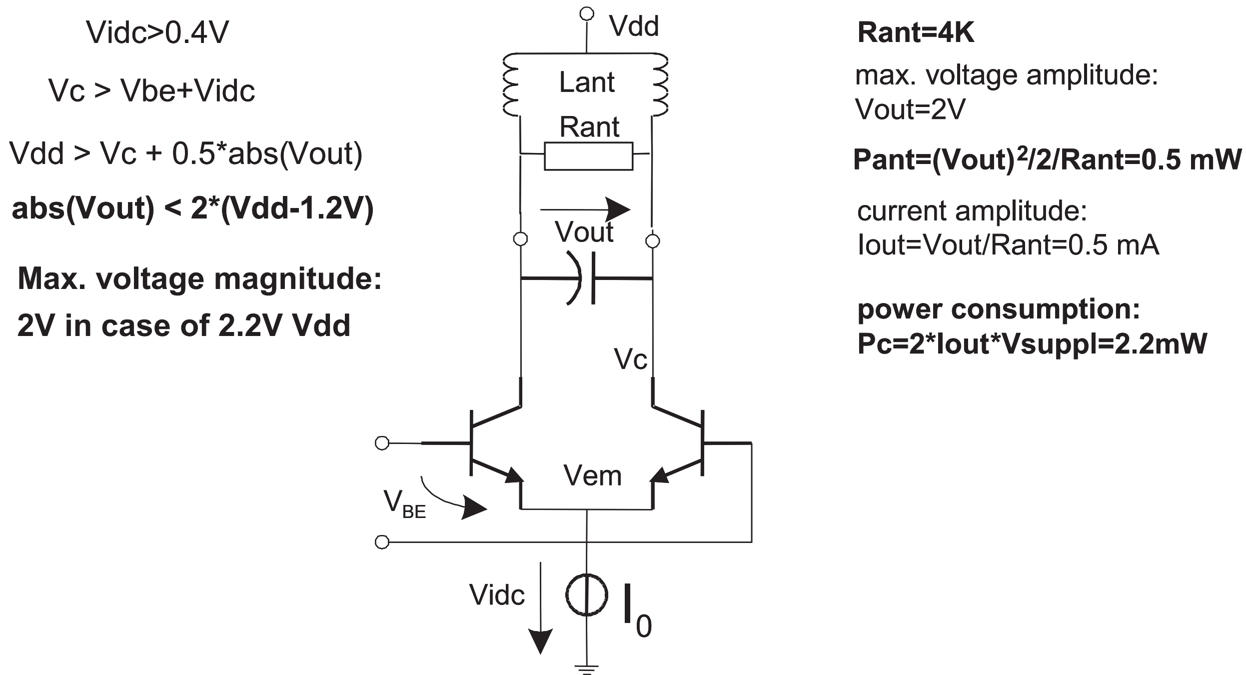

Fig. 29

By comparing the two examples, it can be seen that the low impedance configuration uses 4 times the DC power consumption, yet delivers only the same power to the antenna. As such, a low impedance antenna should only be used for high power (above +10 dBm) applications, where voltage swing is large enough to create good efficiency. In contrast to this, the high impedance antenna is appropriate for low power levels.

In practice, an ideal generator cannot be created. TX impedance is limited by the applied technology. (See Table 5.1 in Chapter 5.) So in addition to the high voltage swing, for good efficiency it is also important that only a small portion of the driver current flows through the internal loss of the TX chip. In theory, if the maximum voltage swing is obtained with a smaller antenna impedance, the overall efficiency is better due to smaller internal losses. In the case of a low impedance antenna, more current is needed to achieve the maximum available voltage swing. Accordingly, higher power is radiated.

4. CHOOSING HIGH OR LOW IMPEDANCE ANTENNAS

In Table 4.1, a comparison between a quarter wavelength monopole, a small loop, and a back IFA antenna is shown at 868 MHz for the case of lossy generators and typical antenna efficiencies.

	Quarter wave monopole	*Printed small loop*	*Printed back IFA*
Antenna gain [dB] (ideal generators)	~1.7 (90% efficiency, above small ground)	~ -13 (27 mm^2 @ 868 MHz)	~1 (~60 by 60 mm including the circuitry)
Antenna gain [dB] (lossy generators)	~ -1.3	~ -19 (normal loop) ~ -12 (tapped loop)	~ 0
Size, cost	Large, expensive	Very small, cheap	Small, cheap
Antenna impedance	Resistive	Inductive	Inductive
Necessary matching reactance (generator)	Not needed	Capacitive (2.2 pF with automatic tuning)	Capacitive (2.2 pF with automatic tuning)
Real part antenna impedance in case of resonance **(Ohm)**	~28	4k...8k or 1k..3k (tapped loop)	~300-500
Necessary current to achieve – 20 dBm EIRP [mA]	~0.98	~2.3 (normal loop) ~1.3 (1.5 k tapped loop)	~0.5
Required power to achieve –20 dBm EIRP (Vcc=3V) **[mW]**	~3	~6.9 ~4.5	~1.5
Required power to achieve 0 dBm EIRP (Vcc=3V) **[mW]**	~30	Cannot be achieved with loop ~39 (1.5 k tapped loop)	~15

Table 4.1

The assumed generator impedance for a quarter wave monopole is 28 Ohm and for high *Q* antennas, such as the printed small loop or IFA, 1.4 kOhm.

The lossy emitter follower behaves like a non-ideal voltage generator, therefore half of the output voltage swing appears on the antenna.

The lossy open collector output has a finite output impedance. Therefore only a reduced portion of the output current flows to the antenna. If the antenna impedance is much lower in comparison to the generator impedance, then the loss is small. This is the case with BIFA antennas. If the antenna impedance is comparable or higher than the generator impedance, then the loss is high. This is the case with loop antennas.

As mentioned in Chapter 3.2, the radiation efficiency of a loop is low with a gain of only -13 dB. By comparison to the monopole, the loop is only slightly less efficient overall because of the higher voltage swing at the typical power ranges compensating for the poor radiation efficiency and high internal loss. At the low bands, not referenced in Table 4.1, the output impedance of the TX chip is 2-3 times higher, making the loss only ~3 dB, therefore, the overall efficiency of the loop can be considered comparable with the monopole.

In addition to this, the loop is small, simple, and very affordable because it is printed directly on the PCB and does not have any connectors and it is not an extra component. It is also insensitive to hand effect at all bands.

The tapped antenna has approximately 7-9 dB better overall efficiency compared to that of the normal loop antenna, if the maximum available voltage swing is achieved. This is due to the better radiation efficiency caused by the bigger aperture size, and due to the lower loss caused by the lower antenna input impedance. For the maximum swing, the tapped loop requires higher drive current.

As it can be observed, the overall efficiency of the tapped loop is only slightly worse than the monopole at high bands (868, 915 MHz). At low bands, where the generator (TX chip) impedance is much higher, the efficiency of the tapped loop is better.

5. RF PROPERTIES OF THE IA4220

AUTOMATIC TUNING

The high impedance capacitive output of a TX chip coupled with an inductive high *Q* antenna forms a high *Q* parallel resonant circuit, as described in Chapters 3.1 and 3.2. Hence, the high impedance configuration is sensitive to the detuning caused either by the hand effect or technological spreading. To overcome this problem, an automatic tuning circuit is integrated into the output stage of the TX, which tunes the value of the output capacitance to have resonance at the carrier frequency with the given antenna. The block diagram of the automatic antenna tuning circuitry is given in Figure 30.

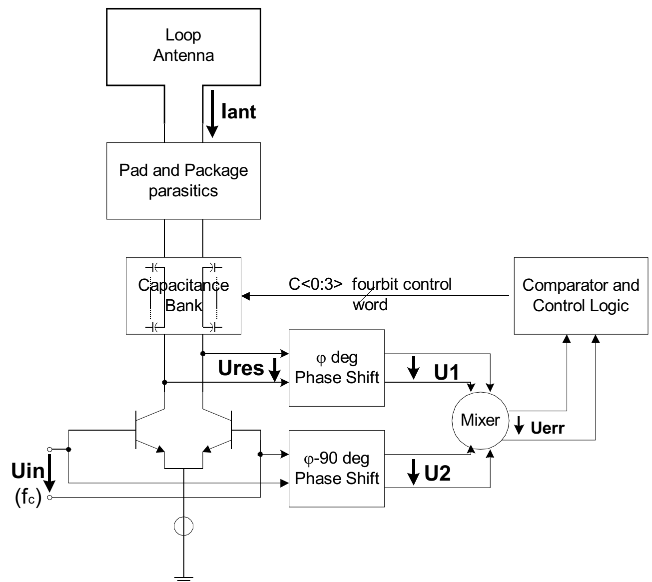

Fig. 30 Block diagram of the automatic tuning circuitry

The output block consisting of a loop antenna, capacitance bank, package and bonding pad parasitics, circuit parasitics (driver output, phase shifter input) can be modeled by a parallel RLC resonant circuit. At resonance, a 180º phase shift occurs between the driver's collector current and the differential voltage over the output collectors. As the phase shift between the collector current and base voltage is constant, the phase of the later is compared to the phase of the collector voltage. The phase shifters are adjusted to have a 90º phase difference in their phase characteristics over a wide band (300-1000 MHz). The DC term of the error voltage at the mixer output is monitored by a comparator and the state of the four-bit control word for the capacitance bank is varied in order to reduce the error voltage. This process takes 6.4 μs and operates continuously to correct environmental changes in real time (hand effect etc.).

At every turn on or reset event, the counter of the capacitance bank is adjusted to state 7. The phase shifter connected to the amplifier's collectors contain a limiter at the input to eliminate error voltage variations due to the output voltage level changes caused either by an intentional change in RF power or by detuning. If the output voltage swing is less than ~80 mV, the automatic tuning is switched off and the capacitance bank is set to state 7, as the signal level is not enough for reliable operation.

The automatic antenna tuning circuitry monitors the phase change around the parallel resonance. Hence, if the phase change is rapid (e.g. in case of a high impedance normal loop antenna), the error voltage at the output of the mixer will be high even for a slight mistuning. Several steps may be necessary for the counter of the control logic to adjust the capacitance bank to the right state in order to compensate for the mistuning.

In contrast, if the antenna Q is low, the phase change is low and so the error voltage is small, even in case of significant deviation between the operation and resonant frequencies. Finally, the change of the capacitance bank has only slight influence to the error voltage, and several capacitance bank states will be found to be correct by the tuning circuitry. This hysteresis-like phenomenon is not a problem, as the change in the amplitude is also small in case of lower Q antennas.

5. RF PROPERTIES OF THE IA4220

ADJUSTABLE OUTPUT CURRENT

To be able to maintain the voltage swing and the driver efficiency close to the maximum available at various antenna impedances, the output current of the transmitter must be properly adjusted. As the output of a transmitter behaves as a non-ideal lossy current generator, its output impedance must be taken into account during all calculations. Assuming parallel resonance (reactive parts are eliminated), the necessary differential output current magnitude to achieve *4* V_{pp} differential voltage swing is given by Equation 25:

$$I_{out} = \frac{U_{\max}}{R_0} = 2\left(G_{TXP} + G_{AP}\right) = 2\left[\omega_0 \frac{C_{TXP}}{Q_{TX}} + \frac{1}{\omega_0 L_{AP} Q_A}\right] = 2\sqrt{\frac{C_{TXP}}{L_{AP}}}\left[\frac{1}{Q_{TX}} + \frac{1}{Q_A}\right] \qquad 25$$

where R_0 is the impedance at resonance (pure real);
G_{AP}, L_{AP} and Q_A are the equivalent parallel conductance, inductance, and the quality factor of the antenna at the resonance frequency, respectively. G_{AP} is the reciproc of the total parallel loss of the antenna given in Figure 20.
G_{TXP}, C_{TXP} and Q_{TX} are the equivalent parallel output conductance, capacitance, and the quality factor of the chip at the resonant frequency, respectively. G_{TXP} is the reciproc of EPR given in Figure 20 in Chapter 3.1.

As it can be observed from Equation 25, at a given Q_A *and* Q_{TX} *value, the* R_0 *is lower if the chip capacitance is higher (with a lower antenna inductance to keep the resonance frequency).*
The optimum tail current (Figure 29) value of the driver stage is $2I_{OUT}$. In this case, highest current magnitude (I_{OUT}) can be applied to the antenna without exceeding the voltage swing limit. It results in the highest driver efficiency and the maximum power for the antenna. If the tail current is lower, the power to the antenna will be reduced by the square of the current reduction. Table 5.1 shows the typical output admittance, Q_{TX} and $1/G_{TXP}$ of the TX chip at capacitance bank state 7. The last column shows the required L_{AP} value to resonate out the chip capacitance.

Frequency [MHz]	Yout=G_{TXP}+jωC_{TXP} [S]	Q_{TX}	1/G_{TXP} [kΩ]	L_{AP} [nH]
315	2.5e-4+j4.5e-3	18	4	112
434	3.1e-4+j6.25e-3	20	3.2	58.7
868	6.9e-4+j1.2e-2	17.4	1.45	15.3
915	7.3e-4+j1.25e-2	17	1.37	13.9

Table 5.1

5. RF PROPERTIES OF THE IA4220

ADJUSTABLE OUTPUT CURRENT

The admittances given in Table 5.1 correspond to approximately 3.5 kOhm and 1.4 kOhm parallel equivalent resistances at low (315 and 343 MHz) and high (868 and 915 MHz) bands, respectively. The parallel equivalent capacitance is approximately 2.3 pF and 2.2 pF at the given bands at capacitance bank state 7.
In order to keep the voltage swing close to the maximum available at various antenna impedances or to reduce the output power if necessary, the tail current of the transmitter can be varied in 8 steps, each giving a power change of approximately 3 dB for the same antenna impedance.
Assuming a maximum voltage swing held at a constant level, the output power to the antenna is inversely proportional to the antenna impedance (proportional to the G_{AP}):

$$P_{out\,\max} = U_{\max}^2 \frac{G_{AP}}{2} \qquad 26.$$

where U_{max} is the magnitude

Due to the internal loss (i.e. G_{TXP} is not zero), $1/G_{TXP}$ is the upper limit for R_0 (if G_{AP} is zero, i.e. an antenna with infinite Q_A is assumed). Due to the existence of the upper limit of R_0, a lower limit for the tail current ($2I_{OUT}$) also exists. If the tail current is lower than this limit the maximum voltage swing cannot be achieved even when a very high impedance antenna is used.

In the case of low tail currents, it is not suitable to use high Q antennas in order to approach the upper limit of R_0. If the antenna impedance is high when compared to the TX impedance, only a small fraction of the driver current will flow to the antenna, which will result in low overall efficiency. An antenna can have high Q only if its losses are low. But in this case, the radiation loss, i.e. the radiation efficiency, must be also low. It can be concluded that the application of a very high Q antenna results poor overall efficiency (in practice, antennas with a G_{AP} lower than 1.24E-4 [S], have unacceptably low radiation efficiency).

Instead, an antenna perfectly matched to the chip output impedance gives the highest overall power and efficiency, even if the maximum voltage swing is not available.

In a given design, there is a driver current which provides a maximum available voltage swing for a matched antenna. According to equation 25, it is achieved if I_{OUT} equals $4G_{TXP}$ (this special current value is denoted by I_{out}^m in the followings.

An increase of I_{out} beyond I_{out}^m will require a decrease in the antenna impedance to avoid going beyond the maximum voltage swing available. Exceeding the maximum voltage swing would cause unnecessary harmonic distortion. Due to the lower antenna impedance, the internal loss is lower, resulting in higher overall efficiency.

Thus, it can be concluded that if I_{out} is lower than $4G_{TXP}$ (i.e. the required G_A to achieve the maximum 4 V_{pp} voltage swing, would be lower than G_{TXP}), the matched antennas give the best efficiency. Whereas at high current levels, where $I_{out} > I_{out}^m$, a G_{AP} corresponding to the maximum voltage swing results the highest power and overall efficiency.

On the following page, Table 5.2a shows the available output current magnitude (I_{out}) values of the IA4220 chip. The R_0 required to achieve a 4 V_{pp} voltage swing with these current values is also given. In addition, the table presents the required input admittance of the antenna, Y_A, needed to achieve resonance with the previously given R_0. The maximum output power for the 315 MHz antenna designs is shown in 5.2a, as well. Tables 5.2b, 5.2c, and 5.2d show these quantities at 434, 868, and 915 MHz bands, respectively.

If the I_{out} is lower than I_{out}^m, then the given maximum output power levels, denoted by ^{M} in the P_{outmax} column in Table 5.2a, b, c, d, correspond to the matched antenna. In this case, R_0, Y_A, $1/G_{AP}$ and the power value in brackets are denoted by ^{R} and correspond to the maximum available swing. If the actual I_{out} value is so small that the maximum available swing can not be obtained, even with the minimum G_{AP} value of *1.25e-4 [S]*, then R_0, Y_A, $1/G_{AP}$, and the power values in the brackets are denoted by ^{LR} and correspond to the minimum G_{AP}.

5. RF PROPERTIES OF THE IA4220

315 MHz ***I_{out} [mA]***	***R_0 [$k\Omega$]***	***$Y_A=G_A-j1/\omega L_A$ [S]***	***$1/G_A$ [$k\Omega$]***	***P_{outmax} [dBm]***
2.2	0.9	8.5e-4-j4.5e-3	1.2	2.3
1.5	1.33	5e-4-j4.5e-3	2	0
1.11	1.8	3.1e-4-j4.5e-3	3.2	-2.1
0.81	2.48^{R}	$1.5e\text{-}4\text{-}j4.5e\text{-}3^{R}$	6.7^{R}	-4.9^{M} ,(-5.2^{R})
0.54	2.67^{LR}	$1.25e\text{-}4\text{-}j4.5e\text{-}3^{LR}$	8^{LR}	-8.4^{M},(-8.9^{LR})
0.38	2.67^{LR}	$1.25e\text{-}4\text{-}j4.5e\text{-}3^{LR}$	8^{LR}	-11.3^{M}, (-11.8^{LR})
0.27	2.67^{LR}	$1.25e\text{-}4\text{-}j4.5e\text{-}3^{LR}$	8^{LR}	-14.5^{M}, (-15^{LR})
0.2	2.67^{LR}	$1.25e\text{-}4\text{-}j4.5e\text{-}3^{LR}$	8^{LR}	-17.2^{M}, (-17.7^{LR})

Table 5.2a

434 MHz ***I_{out} [mA]***	***R_0 [$k\Omega$]***	***$Y_A=G_A-j1/\omega L_A$ [S]***	***$1/G_A$ [$k\Omega$]***	***P_{outmax} [dBm]***
2.2	0.9	7.9e-4-j6.25e-3	1.3	2
1.5	1.33	4.4e-4-j6.25e-3	2.3	-0.6
1.11	1.8^{R}	$2.4e\text{-}4\text{-}j6.25e\text{-}3^{R}$	4.2^{R}	-3^{M}, (-3.2^{R})
0.81	2.3^{LR}	$1.25e\text{-}4\text{-}j6.25e\text{-}3^{LR}$	8^{LR}	-5.8^{M}, (-6.7^{LR})
0.54	2.3^{LR}	$1.25e\text{-}4\text{-}j6.25e\text{-}3^{LR}$	8^{LR}	-9.3^{M}, (-10.2^{LR})
0.38	2.3^{LR}	$1.25e\text{-}4\text{-}j6.25e\text{-}3^{LR}$	8^{LR}	-12.2^{M}, (-13.1^{LR})
0.27	2.3^{LR}	$1.25e\text{-}4\text{-}j6.25e\text{-}3^{LR}$	8^{LR}	-15.4^{M}, (-16.3^{LR})
0.2	2.3^{LR}	$1.25e\text{-}4\text{-}j6.25e\text{-}3^{LR}$	8^{LR}	-18.1^{M}, (-19^{LR})

Table 5.2b

Note: Shaded area corresponds to maximum available voltage swing. In the case of the non-shaded area, the matched antenna gives the best efficiency.

5. RF PROPERTIES OF THE IA4220

868 MHz / I_{out} *[mA]*	R_0 *[kΩ]*	$Y_A=G_A-j1/\omega L_A$ *[S]*	$1/G_A$ *[kΩ]*	P_{outmax} *[dBm]*
2.95	0.68	7.81e-4-j1.2e-2	1.28	1.9
2.2	0.9^{R}	$4.1e\text{-}4\text{-}j1.2e\text{-}2^{R}$	2.44^{R}	-0.6^{M}, (-0.9^{R})
1.6	1.23^{LR}	$1.25e\text{-}4\text{-}j1.2e\text{-}2^{LR}$	8^{LR}	-3.3^{M}, (-6.2^{LR})
1.1	1.23^{LR}	$1.25e\text{-}4\text{-}j1.2e\text{-}2^{LR}$	8^{LR}	-6.6^{M}, (-9.5^{LR})
0.8	1.23^{LR}	$1.25e\text{-}4\text{-}j1.2e\text{-}2^{LR}$	8^{LR}	-9.3^{M}, (-12.2^{LR})
0.58	1.23^{LR}	$1.25e\text{-}4\text{-}j1.2e\text{-}2^{LR}$	8^{LR}	-12.2^{M}, (-15.1^{LR})
0.42	1.23^{LR}	$1.25e\text{-}4\text{-}j1.2e\text{-}2^{LR}$	8^{LR}	-15^{M}, (-17.9^{LR})
0.3	1.23^{LR}	$1.25e\text{-}4\text{-}j1.2e\text{-}2^{LR}$	8^{LR}	-17.8^{M}, (-20.7^{LR})

Table 5.2c

915 MHz / I_{out} *[mA]*	R_0 *[kΩ]*	$Y_A=G_A-j1/\omega L_A$ *[S]*	$1/G_A$ *[kΩ]*	P_{outmax} *[dBm]*
2.95	0.68	7.3e-4-j1.25e-2	1.35	1.6
2.2	0.9^{R}	$3.7e\text{-}4\text{-}j1.25e\text{-}2^{R}$	2.7^{R}	-0.8^{M}, (-1.3^{R})
1.6	1.17^{LR}	$1.25e\text{-}4\text{-}j1.25e\text{-}2^{LR}$	8^{LR}	-3.6^{M}, (-6.6^{LR})
1.1	1.17^{LR}	$1.25e\text{-}4\text{-}j1.25e\text{-}2^{LR}$	8^{LR}	-6.9^{M}, (-9.9^{LR})
0.8	1.17^{LR}	$1.25e\text{-}4\text{-}j1.25e\text{-}2^{LR}$	8^{LR}	-9.6^{M}, (-12.6^{LR})
0.58	1.17^{LR}	$1.25e\text{-}4\text{-}j1.25e\text{-}2^{LR}$	8^{LR}	-12.5^{M}, (-15.5^{LR})
0.42	1.17^{LR}	$1.25e\text{-}4\text{-}j1.25e\text{-}2^{LR}$	8^{LR}	-15.3^{M}, (-18.3^{LR})
0.3	1.17^{LR}	$1.25e\text{-}4\text{-}j1.25e\text{-}2^{LR}$	8^{LR}	-18.1^{M}, (-21.1^{LR})

Table 5.2d

Note: Shaded area corresponds to maximum available voltage swing. In the case of the non-shaded area, the matched antenna gives the best efficiency.

6. RF PROPERTIES OF THE IA4320

The *Q* and the equivalent parallel input capacitance of the receiver is much lower compared to that of the transmitter. The equivalent parallel input resistance is approximately 310 Ohm and the capacitance is approximately 0.75 pF. According to this, receiver antennas with a lower *Q* (back IFA, tapped loop) have more advantages.
The input admittance, quality factor (Q_{RX}), equivalent parallel resistance ($1/G_{RXP}$), and the necessary inductance to get resonance of the IA4320 RX chip is given in Table 6.1.

Frequency [MHz]	*Yout=G_{RXP}+jωC_{RXP} [S]*	*Q_{RX}*	*1/G_{RXP} [Ω]*	*L_{AP} [nH]*
315	3.5e-3+j1.6e-3	0.45	285	316
434	3.4e-3+j2.1e-3	0.62	294	175
868	3e-3+j3.5e-3	1.1	330	52
915	2.95e-3+j3.7e-3	1.25	338	47

Table 6.1.

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APPENDIX

TABLE OF ABBREVIATIONS

BER	Bit Error Rate
BIFA	Back Inverted-F Antenna
EIRP	Equivalent Isotropic Radiated Power
ESR	Equivalent Series Resistance
ERP	Equivalent Radiated Power
EPR	Equivalent Parallel Resistance
FSK	Frequency Shift Keying
IFA	Inverted-F Antenna
Q	Quality Factor
RX	Receiver
TX	Transmitter

NOTES

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