RESEARCH REPORT

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# Inductively Coupled Wireless Power Supply

Authors: Niko Niskala

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Summary

This document is a part of ALMA-project. In this paper is presented basics of inductive coupled power links. A document presents inductive link basic theory, inductive link parameters and theoretical efficiency calculations. After that there is simulated and measured one antenna coil setup in Ponsse's control joystick. There is also documented a simple way how to do the inductive power link (transmitter and receiver circuit). Operating frequency is 13.56 MHz.

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| Confidentiality | Public |

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| Written by | Reviewed by | Accepted by |
|---|---|---|
| Niko Niskala, Researcher | Timo Lehikoinen, Site Manager | {Clarification of signature, position} |

VTT's contact address
Kehräämöntie 7, Kajaani, PL 126, FI-87401 Kajaani, Finland

Distribution (customer and VTT)

# LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| ISM | industrial-scientific-medical |
| RFID | radio frequency identification |
| IPT | inductive power transfer |
| EMC | electromagnetic compatibility |
| EMF | electromotive force |
| CAN | controller–area network |
| PA | power amplifier |
| NFC | near field communication |

| | |
|---|---|
| $A$ | area |
| $B$ | magnetic field |
| $D$ | electric displacement field |
| $E$ | electric field |
| $f$ | frequency |
| $H$ | magnetizing field |
| $J$ | total current density |
| $k$ | coupling coefficient |
| L | inductance |
| $M$ | mutual inductance |
| $Q_1$ | quality factor |
| $Q_2$ | quality factor |
| $Q(V)$ | net unbalanced electric charge in the interior of an arbitrary closed surface S |
| $R$ | resistance |

| | |
|---|---|
| $\Phi$ | magnetic flux |
| $\Psi$ | flux linkage |
| $\lambda$ | wave length |

## Contents

# 1 Introduction

This document describes wireless power supply technology. Wireless power supply can be used in very short range communication and powering links. In automotive and heavy vehicle's it can be used in for example powering controlling joysticks or transfer data and power over a small air-gap.

This document explains basic theory of inductive coupled power links, explains how nearby conductive materials affects to link efficiency. This document also explains how inductive link antenna coils can be simulated and measured, and how to estimate inductive link efficiency in theory. At the end of the document there is also presented simple circuit model of inductive power link.

Nowadays inductive powering systems are growing rapidly. Electric toothbrushes have been for a long time on the market. Electric toothbrush uses inductive coupled charging system. Now it's coming on to the markets charging tables [1] and floors [2]

Inductive power transfer can also be in use in automotive systems. It's is a good way to take of power and signal cables in joints, rotators, control user interfaces etc. There is also on the market some inductive coupled power and data links for automotive use. Those devices can transfer power and data across a small air-gap without mechanical contact. [3]

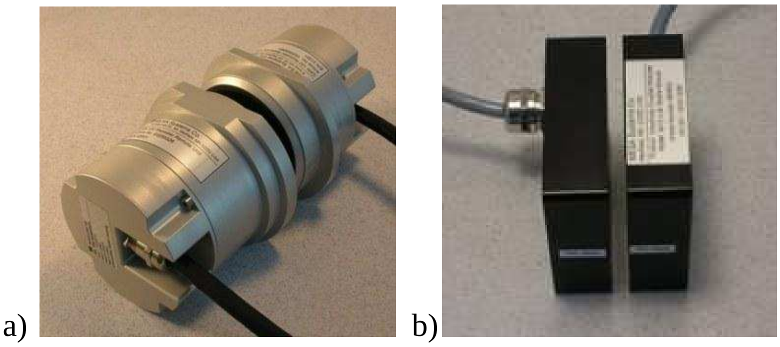

a) b)

*Figure 1. a) CAN120 120 Watts @ 12 V dc and CAN bus repeater b) 3-Channel 12 V DC Power Coupler [lähde sama ku ylempänä tekstissä]*

# 2 Goal

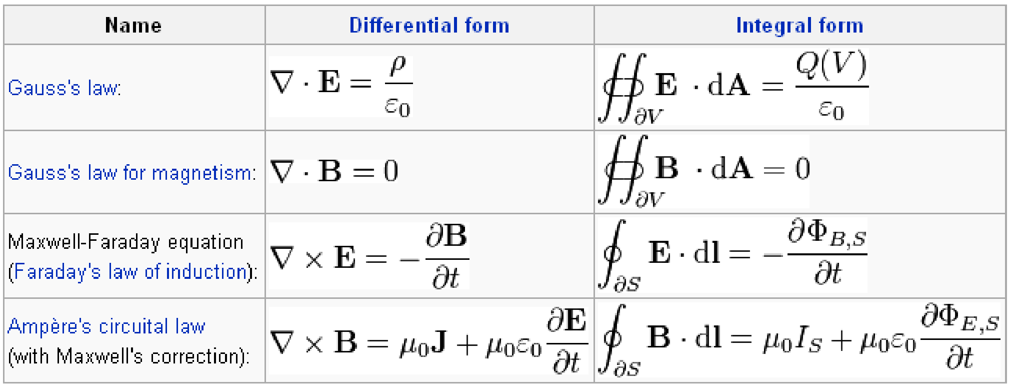
This report explains inductive powering link theory and presents one easy made circuit to demonstrate the inductive powering in the Ponsse forest harvester controlling joystick. This document is not taking care of EMC and other regulations.

# 3 Methods

This document's theory sections are based on literature review. The example circuitry is simulated with Orcad pspice and antenna structure is simulated with FastHenry. The powering link is build and then measured with impedance analyzer. Whole link efficiency is measured. Finally the powering link is powering RF-radio and microcontroller module (read more from document ALMA_DataLink_300709.doc).

# 4 Basics of Inductive Coupled Power Links

This chapter describes the basics of inductive power links. Michael Faraday discovered electromagnetic induction in 1831 at the same time with Joseph Henry. Faraday's of induction describes a basics law of electromagnetism. In Maxwell's equations there is a set of four partial differential equations. These four equations with Lorentz force law describe classical electromagnetism. Induction law is one of these laws. [4]



| Name | Differential form | Integral form |
|---|---|---|
| Gauss's law: | $\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$ | $\oint\!\!\!\oint_{\partial V} \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q(V)}{\varepsilon_0}$ |
| Gauss's law for magnetism: | $\nabla \cdot \mathbf{B} = 0$ | $\oint\!\!\!\oint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0$ |
| Maxwell-Faraday equation (Faraday's law of induction): | $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ | $\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$ |
| Ampère's circuital law (with Maxwell's correction): | $\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$ | $\oint_{\partial S} \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_{E,S}}{\partial t}$ |

*Figure 2. Maxwell's laws in differential and integral form [wiki]*

Maxwell's laws and especially Faraday's law are basics of inductive coupled systems. In this document we are not going more deeply in to those laws. It's only important to know what are the laws which are we working with when talking about inductive coupled links. [4]

Inductive powering links are based on two inductive coupled coils. These coils are placed in near field. Near field can be calculated by next equation (Maxwell's criterion). [4]

$$d = \frac{\lambda}{2\pi} \quad , \qquad (1)$$

where

*d* is distance from antenna and
$\lambda$ is wave length.

Next table presents wave lengths and the border of near field calculated by Maxwell criterion.

*Table 1. Wave length and near field by Maxwell criterion*

| Frequency | Wave length | Near Field (Maxwell criterion) |
|---|---|---|
| 125 kHz | 2398.34 m | 381.71 m |
| 5 MHz | 59.96 m | 9.54 m |
| 10 MHz | 29.98 m | 4.77 m |
| 13.56 MHz | 22.11 m | 3.52 m |
| 27 MHz | 11.10 m | 1.77 m |
| 40 MHz | 7.50 m | 1.19 m |

Typically inductively coupled power link works 0 to 10 cm range. The range is about the size of the bigger antenna coil diameter.

## 4.1 Basic idea of inductive power link

### 4.1.1 System overview

Main idea of inductive power transfer is presented in the following figure. There is a transmitter side (left side) and receiver side (right side). Transmitter side consist of power amplifier (PA) circuit and an antenna coil $L_1$. The transmitter antenna coil is tuned to resonance with tuning capacitor $C_1$. Receiver side consist of an antenna coil $L_2$, a tuning capacitor C2 and rectifier and regulator part.

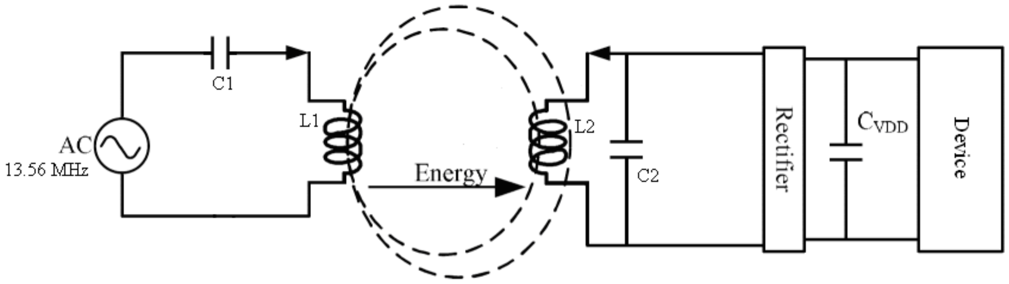


*Figure 3. Basic idea of inductive coupled powering system*

### 4.1.2 Transmitter

Figure 4 presents simplified transmitter circuit.

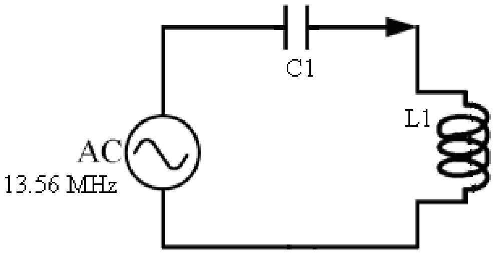


*Figure 4. Transmitter circuit.*

Transmitter tuning capacitor $C_1$ can be calculated by formula (2).

$$C_1 = \frac{1}{\omega^2 L_1}, \qquad (2)$$

where $C_1$ is tungin capasitor,
$L_1$ is antenna coil one inductance and
$\omega$ is $2\pi f$.

Power amplifier circuit can be made for example from B- or E- class PA circuits. Next figure represents two ways to do class B PA. The first is typical class B circuit that amplifies only the half of the input wave cycle (figure 2 a). Figure 2 b represents how to amplify both halves of the input signal. The maximum theoretical efficiency is 78.5 %. [5]

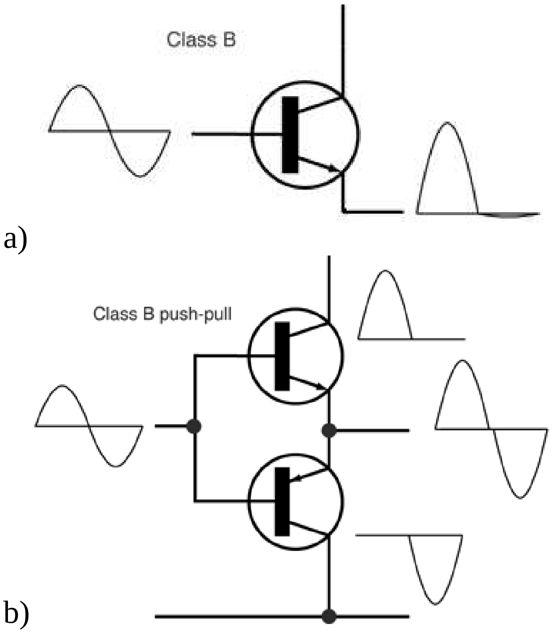


*Figure 5. a) Class B amplifier b) Class B push-pull amplifier*

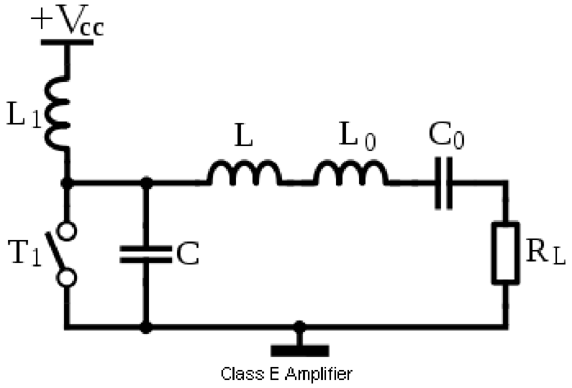


*Figure 6. Class E amplifier*

In the figure 6 is presented class E amplifier circuit. More about Class E power amplifiers can be read for example from application note 1954 [5].

### 4.1.3 Receiver

The receiver’s ability to efficiently draw energy from the reader field is based on the well known electrical resonance effect. Antenna element has to be designed to resonate at system operating frequency. Receiver circuit is presented on figure 7.

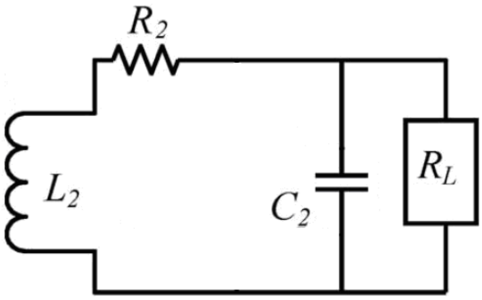


*Figure 7. Inductive power link receiver.*

Tuning capacitor $C_2$ can be calculated by formula (3).

$$C_2 = \frac{1}{\omega^2 L_2}, \tag{3}$$

where $C_2$ is tuning capacitor and
$L_2$ is antenna coil two inductance.

Formula (2) is not optimal. The optimal $C_2$ value can be calculated by formula (4). Optimal $C_2$ value depends on coupling coefficient between antenna coils. Quality factors $Q_1$ and $Q_2$ also have impact to $C_2$ optimal value.[VTT]

$$C_2 = \frac{1}{\omega^2 L_2 \left(1 + \frac{1}{Q_2^2} + k^2 \frac{Q_1}{Q_2}\right)}, \tag{4}$$

where $Q_1$ is quality factor for coil one,
$Q_2$ is quality factor for coil two and
$k$ is coupling coefficient.

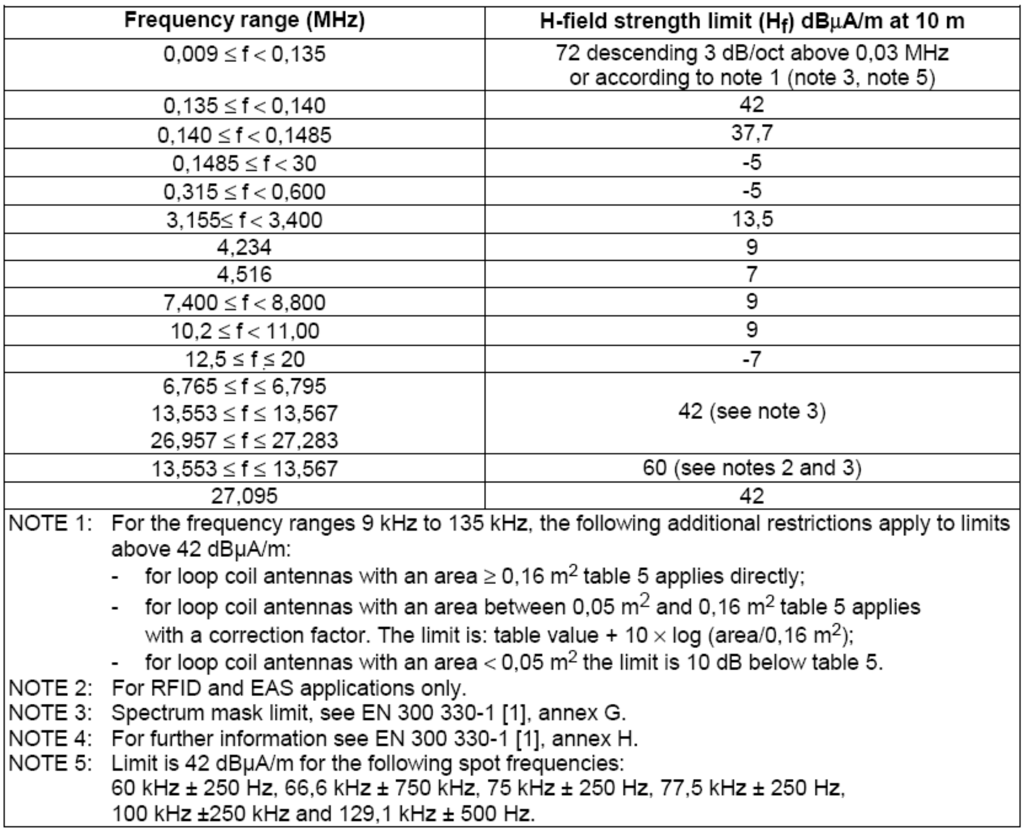
The load resistance $R_L$ also should be optimized to get the best efficiency for the powering link. Optimal load can be calculated by formula (5). [VTT]

$$R_L = R_2 \frac{Q_2^2 + 1 + k^2 Q_1 Q_2}{\sqrt{1 + k^2 Q_1 Q_2}}, \tag{5}$$

where $R_L$ is load resistance.

### 4.1.4 Frequency Ranges and Magnetic Field Limitations

Inductive power link works in ISM (industrial, scientific, medical) radio frequency ranges. These frequencies can be freely used for industrial, scientific and medical (ISM) applications. ISM frequencies are classified worldwide. The most used frequency ranges for RFID (Radio frequency identification) and IPT (inductive power transfer) systems are 0-135 kHz, 6.78 MHz, 13.56 MHz, 27.125 MHz, 40.68 MHz. [ETSI]



| Frequency range (MHz) | H-field strength limit ($H_f$) dBµA/m at 10 m |
|---|---|
| 0,009 ≤ f < 0,135 | 72 descending 3 dB/oct above 0,03 MHz<br>or according to note 1 (note 3, note 5) |
| 0,135 ≤ f < 0,140 | 42 |
| 0,140 ≤ f < 0,1485 | 37,7 |
| 0,1485 ≤ f < 30 | -5 |
| 0,315 ≤ f < 0,600 | -5 |
| 3,155≤ f < 3,400 | 13,5 |
| 4,234 | 9 |
| 4,516 | 7 |
| 7,400 ≤ f < 8,800 | 9 |
| 10,2 ≤ f < 11,00 | 9 |
| 12,5 ≤ f ≤ 20 | -7 |
| 6,765 ≤ f ≤ 6,795<br>13,553 ≤ f ≤ 13,567<br>26,957 ≤ f ≤ 27,283 | 42 (see note 3) |
| 13,553 ≤ f ≤ 13,567 | 60 (see notes 2 and 3) |
| 27,095 | 42 |

NOTE 1: For the frequency ranges 9 kHz to 135 kHz, the following additional restrictions apply to limits above 42 dBµA/m:
- for loop coil antennas with an area ≥ 0,16 $m^2$ table 5 applies directly;
- for loop coil antennas with an area between 0,05 $m^2$ and 0,16 $m^2$ table 5 applies with a correction factor. The limit is: table value + 10 × log (area/0,16 $m^2$);
- for loop coil antennas with an area < 0,05 $m^2$ the limit is 10 dB below table 5.

NOTE 2: For RFID and EAS applications only.
NOTE 3: Spectrum mask limit, see EN 300 330-1 [1], annex G.
NOTE 4: For further information see EN 300 330-1 [1], annex H.
NOTE 5: Limit is 42 dBµA/m for the following spot frequencies:
60 kHz ± 250 Hz, 66,6 kHz ± 750 kHz, 75 kHz ± 250 Hz, 77,5 kHz ± 250 Hz,
100 kHz ±250 kHz and 129,1 kHz ± 500 Hz.

*Figure 8. H-field limits at 10 m. [5]*

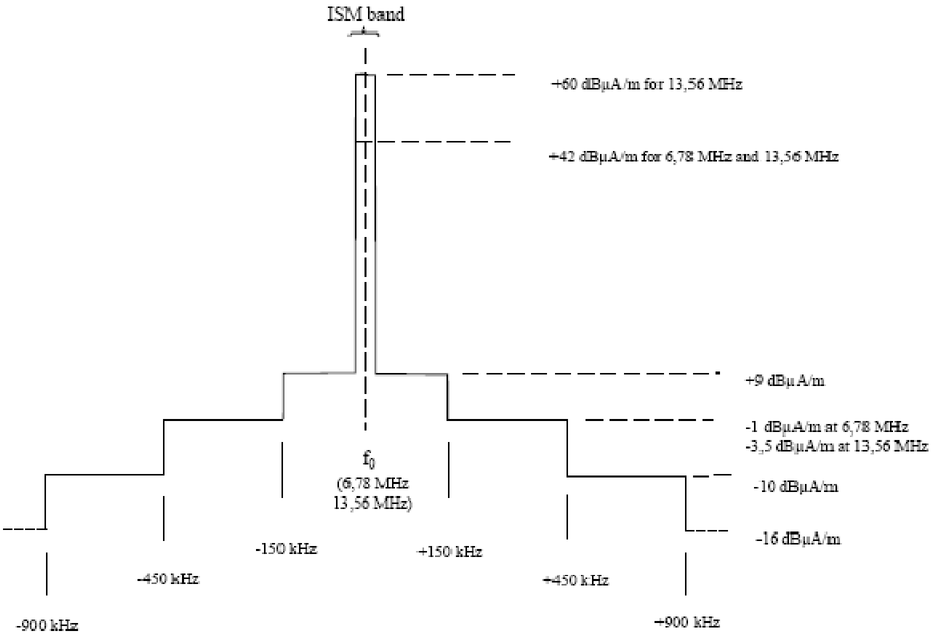


*Figure 9. Spectrum mask limit for RFIDs and EAS in the 6,78 MHz and 13,56 MHz range (annex G).*

## 4.2 Inductive Link Parameters

### 4.2.1 Inductance

The term inductance was coined by Oliver Heaviside in 1886. In an electrical circuit where the current flowing through circuit induces an EMF (electromotive force) that opposes the change in current. [4]

### 4.2.2 Self-inductance *L* of conductor loop

Coils have parameter that we call self-inductance (*L*). Self-inductance is the ratio of the magnetic flux to the current. Self-inductance depends totally upon the material properties of the space that the flux flows through and the geometry of the layout. In a literature there is a lot of formulas for calculating inductances of various coil structures. One good set can be found from Microchips application note AN710. It is also possible to model a coil structure and then simulate the inductance of the coil. Later in this document it is shown how to model and simulate coil systems with FastHenry. [4]

$$L = N\frac{\Phi}{I} = \frac{\Psi}{I} = N^{2}\Lambda, \tag{6}$$

| | |
|---|---|
| $L$ | is coil inductance, |
| $\Phi$ | is magnetic flux and |
| $\Psi$ | is flux linkage. |

### 4.2.3 Mutual inductance M and coupling factor k

If we have two conductor loops in the vicinity each other there is a mutual inductance between the loops. Because of this the change in current in conductor loop 1 induces a voltage in conductor loop 2. Mutual inductance is always present between two electric circuits. Its dimension and unit are the same as for inductance. Mutual inductance is defined mathematically by next formula (formula 7). [4]

$$M_{21} = \frac{\psi_{21}(I_1)}{I_1} = \oint_{A2} \frac{B_2(I_1)}{I_1} \cdot dA_2 \tag{7}$$

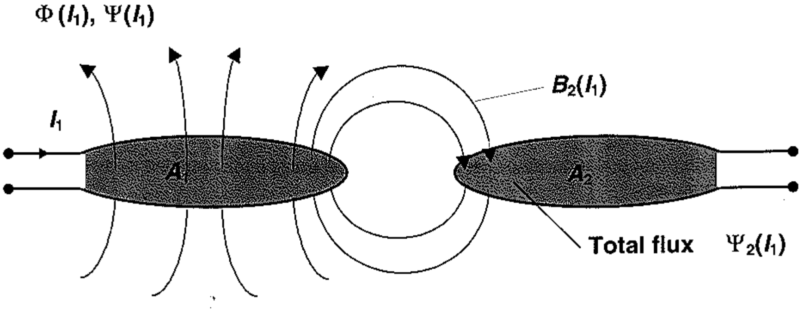


**Figure 4.8:** The definition of mutual inductance $M_{21}$ by the coupling of two coils via a partial magnetic flow

*Figure 10. Mutual inductance $M_{21}$ between two coils [4]*

It's important to notice that the following relationship applies (formula 8).

$$M = M_{12} = M_{21} \tag{8}$$

A previous formula means that there is exactly same mutual inductance between the coils if we are looking the system from a coil 2 to coil 1.

The coupling coefficient describes how good the coupling between coils is. The coupling coefficient always varies between 0≤k≤1. k=0 means that there is no coupling between coils. k=1 means that there is total coupling between coils. In the transformers the coupling coefficient is almost 1. In inductive coupled power links the coupling coefficient is typically something between 0 and 0.5. Inductive links can be though as poorly coupled transformer. [4]

How the orientation between coils affects to mutual inductance or coupling coefficient? Affect of orientation depends of the angle between coils. When the coils are at the same orientation (angle is 0 degrees) coupling reaches maximum, whereas when the angel is 90 degrees coupling is zero. Following figure 11 and formula (9) shows how orientation affects to the coupling coefficient between coils. [4]

$$k(x) \approx \frac{r_T^2 \cdot r_R^2 \cdot \cos(\alpha)}{\sqrt{r_T r_R} \cdot \left(\sqrt{x^2 + r_R^2}\right)^3}, \tag{9}$$

| | | |
|---|---|---|
| where | $r_T$ | is coil one radius, |
| | $r_R$ | is coil two radius and |
| | $x$ | is distance between coils. |

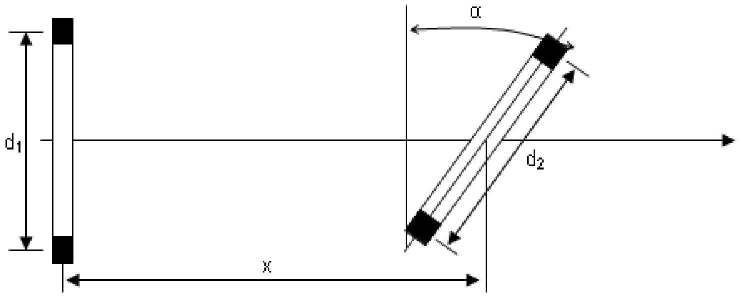


*Figure 11. Orientation between coils changes.*

### 4.2.4 Quality Factor Q and Bandwidth BW

Quality factor Q defines how well the resonating circuit absorbs power over it's relatively narrow resonance band. The coil Q is usually calculated (without taking into account additional parasitic interwinding capacitance losses) according to equation 10.

$$Q = \frac{\omega L}{R}, \tag{10}$$

Usually in IPT antenna Q should be made as high as environmental detuning consideration will allow. Environmental detuning is big problem in high Q values.[4]

## 5 Inductive Link Efficiency Calculations

In optimum case inductively coupled link efficiency can be calculated by following formula.

$$\eta_{opt} = \frac{P_L}{P_{IN}} = \frac{k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k^2 Q_1 Q_2}\right)^2} \tag{11}$$

From formula 11 we can easily see, that only coupling coefficient k, and quality factors $Q_1$ and $Q_2$ affects to inductive link efficiency. This formula applies only in optimal case. Optimal case means that link is tuned and matched perfectly.[4]

When we are thinking the whole inductive powering system we have to take into consideration oscillator circuit, power amplifier circuit and rectifier circuit. Then we can get the whole system efficiency.

$$\eta_{LINK} = \eta_{osc} \cdot \eta_{PA} \cdot \eta_{link'} \cdot \eta_{rect} \tag{12}$$

VTT have developed inductive link optimization tool. With the tool you can optimize inductive link components, like coil inductances and tuning capacitors. It takes into consideration influence of transmitter and receiver circuit (antenna detuning effect).

# 6 Circuit Example and Simulations (Ponsse demo case)

In this ALMA project we demonstrate IPT on Ponsse's controlling joystick. The demo is integrated inside the joystick like in real end product. We are powering microprocessor and RF module by inductive coupled power link. Button data is send over RF link.

RF module and microprocessor needs maximum about 40 mW power when sending data. In this case the radio link distance is only few centimetres so we don't need maximum transmitting power.

This case we have built quite simple IPT power link. Power link needs only few components. Next is presented the parts of inductive powering system.

## 6.1 Transmitter Circuit

### 6.1.1 Crystal Oscillator Circuit

Next is presented, how to calculate component values of oscillator circuit. In figure 12 we can see resistors $R_{xf}$ and $R_{x1}$. $R_{xf}$ provides negative feedback and sets the bias point of the inverter. Typical value of this resistor is in the range of 500kΩ – 2MΩ. $R_{x1}$ is the drive limiting resistor. The primary function of this resistor is to limit the output of the inverter so that the crystal is not overdriven. "$R_1$ and $C_1$ form a voltage dividing circuit, the values of these components are chosen in such a way that the output of the inverter goes close to rail-to-rail and the input to the crystal is 60% of rail-to-rail, usual practice is to make resistance of R1 and reactance of $C_1$ equal at the operating frequency, i.e. $R_1 \gg X_{C1}$. This makes the input to the crystal half that of the inverter output. Always make sure that the power dissipated by the crystal is with-in the crystal manufacturer's specifications. Over-driving the crystal may damage the crystal. Please refer to the crystal manufacturer's recommendations." First calculate capacitances $C_{x1}$ and $C_{x2}$ ($C_{x1} = C_{x2}$). [16]

$$C_L = \frac{C_1 \cdot C_2}{C_1 + C_2} + C_S \ , \tag{13}$$

where $C_L$ is the optimum load capacitance for a given crystal (specified by the crystal manufacturer) and
$C_S$ is stray capacitance of the printed circuit board (typically 5pf can be used for calculation)

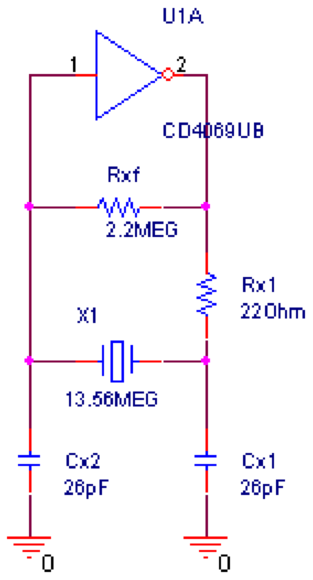


*Figure 12. Crystal oscillator circuit*

### 6.1.2 Power Amplifier Circuit

The Power amplifier is made by two MOS-FETs (N-channel and P-channel). So it is class B push pull –type, so both sides of input signal is droved to load (antenna coil).

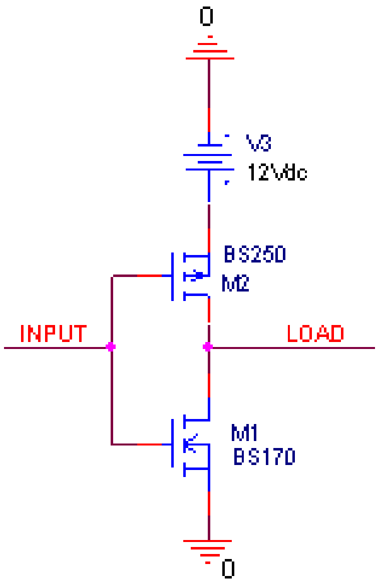


*Figure 13. Power Amplifier circuit*

### 6.1.3 Matching Circuit

Next figure (figure 14) represents a simple way to do impedance matching circuit. Formulas 14, 15 and 16 represent how to calculate the matching circuit component values. [6]

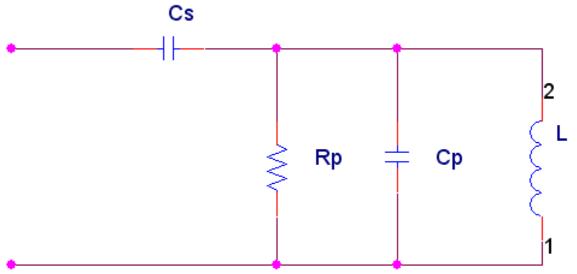


*Figure 14. Matching circuit*

$$R_p = \frac{(L \cdot \omega)^2}{R_S}, \tag{14}$$

where ω is $2 \cdot \pi \cdot f$,
$L$ is coil self inductance and
$R_S$ is coil resistance at operating frequency.

$$C_s = \frac{1}{\sqrt{Z \cdot R_p} \cdot \omega}, \tag{15}$$

where Z is matching impedance (typically 50Ω).

$$C_P = \frac{1}{L \cdot \omega^2} - C_S \tag{16}$$

### 6.1.4 Whole transmitter circuit

Next is presented the whole transmitter circuit. The circuit consist the parts that are presented earlier (Crystal Oscillator Circuit, Power Amplifier Circuit and Matching Circuit).

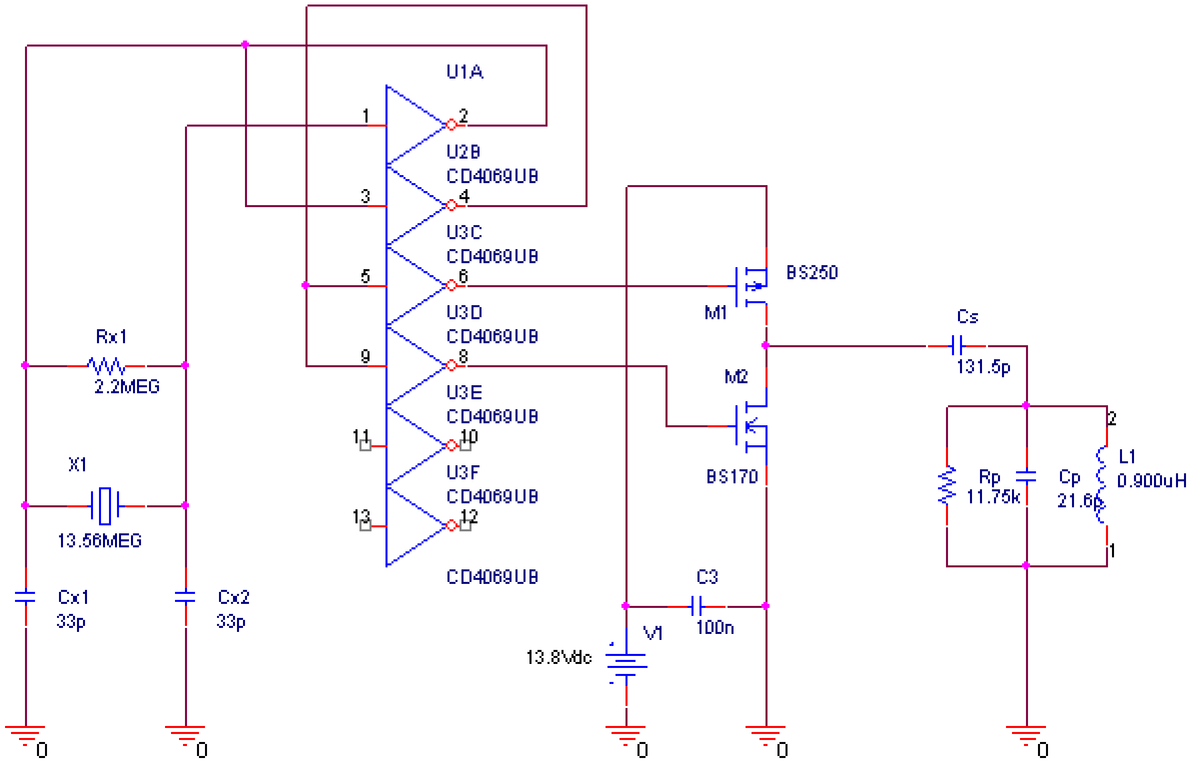


*Figure 15. Inductive power link transmitter circuit*

## 6.2 Receiver Circuit

The receiver circuit consists of parallel resonance circuit. The circuit is tuned in resonance at 13.56 MHz. The tuning can be calculated with equation 17.

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{17}$$

and the tuning capacitor can calculated by next equation

$$C_2 = \frac{1}{\omega^2 L_2} \tag{18}$$

After the resonance tuning there is a rectifier and regulator part. The part is sized for 3.3v output voltage. The whole system looks like the next figure (Figure 16).

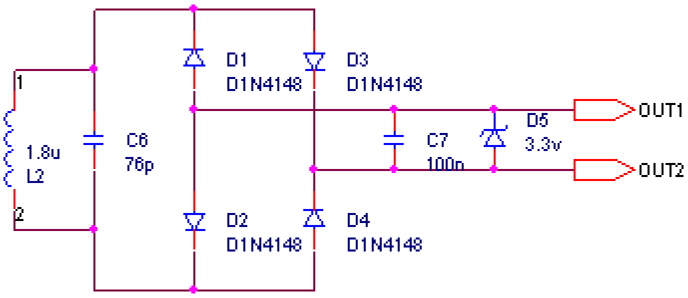


*Figure 16. Inductive link receiver circuit*

# 7 Measurement Equipments and Methods

## 7.1 What to measure?

We are interested in measuring inductive link antenna coil electrical parameters. These parameters are coil self-inductance, resistance, mutual inductance between antenna coils and *Q* value and bandwidth. All the measurements should be done at the correct frequency. It is also important to measure tuned system resonance frequency and matching impedance.

## 7.2 Measuring equipments

To measure parameters above it is possible to use several measuring equipments. The easiest way is to measure with network analyzer or impedance analyzer. Other measurement equipments are RF LCR meter and it is also possible to measure with signal generator and oscilloscope.

*Figure 17. Measuring equipments*

## 7.3 How to measure

Inductive link can be measured just like transformers. Easiest way is to use network analyzer or impedance analyzer. Measurement system consist measurement instrument, cable/adapter, test fixture and DUT. Before measurement it is important to remember to do compensation. Typically compensation is open, short and load (50 Ω) compensation. [11, 12]

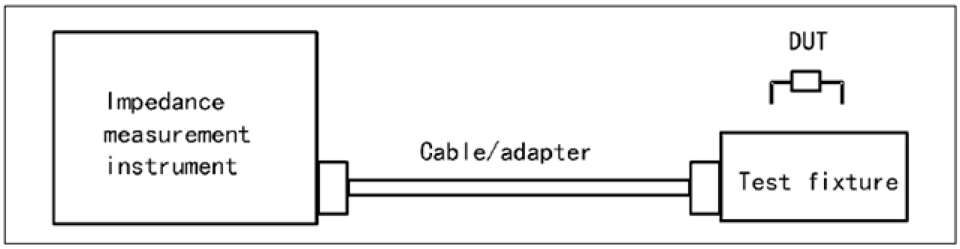


*Figure 18.* System configuration for impedance measurement.

### 7.3.1 Self inductance and resistance measurement

Measuring equipment typically gives resistance and reactance at measuring frequency. Self inductance can be calculated from reactance with the following formula. [10]

$$L = \frac{X}{\omega} = \frac{X}{2\pi F}\ , \tag{19}$$

where $X$ is reactance.

Connection to measurement equipment is simply to connect in port one ($S_{11}$)

*Figure 19. Connection when measuring self inductance and resistance*

### 7.3.2 Mutual inductance measurement

To determine mutual inductance between two coils you have to connect coils in series in two ways and then measure inductance $L_{ab}$ and $L_{cd}$. Then you get two inductance values and you can calculate mutual inductance by formula 20. [10]

$$L = \frac{L_{ab} - L_{cd}}{4} \tag{20}$$

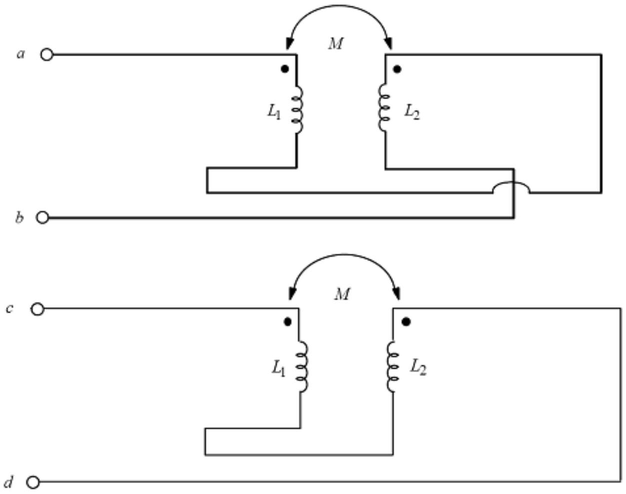


*Figure 20. Wiring when measuring mutual inductance between coils.*

### 7.3.3 Resonance frequency measurement

When using network analyzer or impedance analyzer the resonance frequency can be found when phase shift is 0° or/and impedance reaches minimum value.

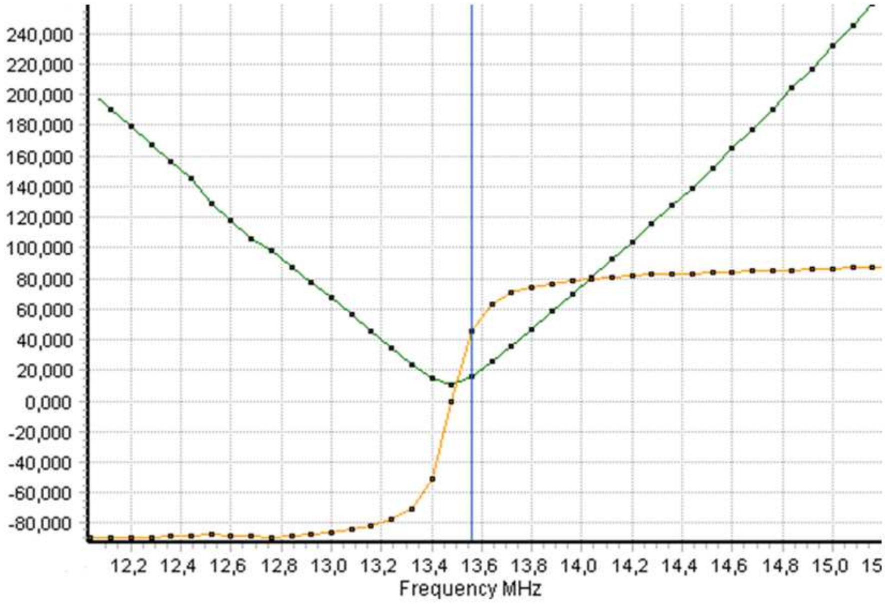


*Figure 21. Determine resonance frequency from impedance and phase plot*

### 7.3.4 *Q* value and bandwidth measurement

*Q* value and bandwidth can also determine from $S_{21}$ plot window. It is also possible to determine *Q* value and bandwidth from $S_{11}$ plot window. Next figure presents one plot measured $S_{21}$ method. [10, 11]

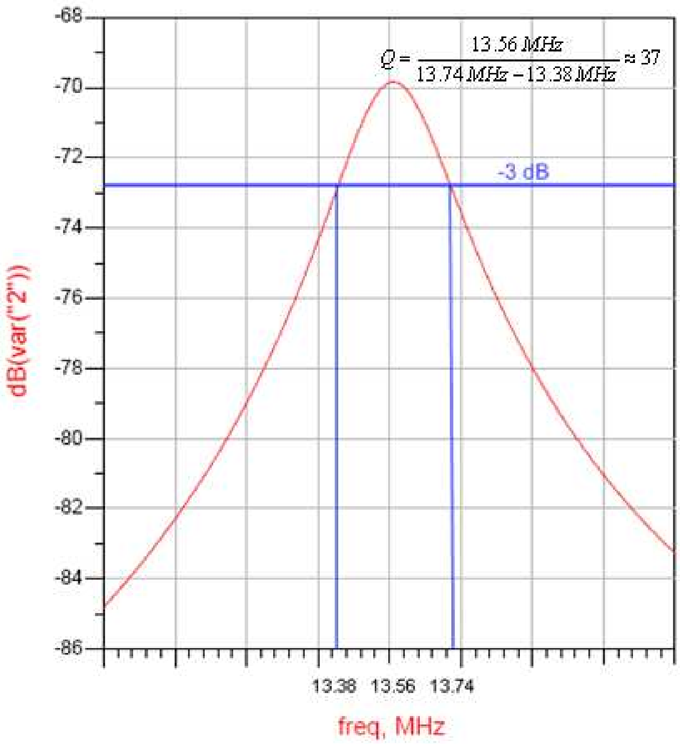


*Figure 22. Determine Q value and bandwidth from* $S_{21}$ *plot.*

Q value can be calculated directly from resistance and reactance (formula 21). But it is also possible to use formula 22

.

$$Q = \frac{X}{R} \tag{21}$$

$$Q = \frac{f_{res}}{f_{res-3dB_{low}} - f_{res-3dB_{high}}} \tag{22}$$

Then we can calculate bandwidth with formula 23.

$$BW = \frac{f_{res}}{Q} \tag{23}$$

Bandwidth can also be determined from frequencies between -3dB from resonance frequency (formula 24)

$$BW = f_{res-3dB_{low}} - f_{res-3dB_{high}} \tag{24}$$

.

# 8 Antenna Coil Simulations with FastHenry

The inductive link coils have been simulated with FastHenry software [8]. With FastHenry we can determine the antenna coil self-inductance, self resistance and mutual inductance between coils. It is also possible to determine how the environment and another coil effects to the coils inductances, resistances and mutual inductance.

The simulations have been made with two simulation models. The first simulation model is in free space and the second model is in the actual place. The second model is not perfect model of Ponsse’s controlling joystick; it is only rough simplified model of the metallic parts of joystick. The coils are exactly same in the two models. In the figure 23 is presented the simulation models. Left side is model one and right side is model two.

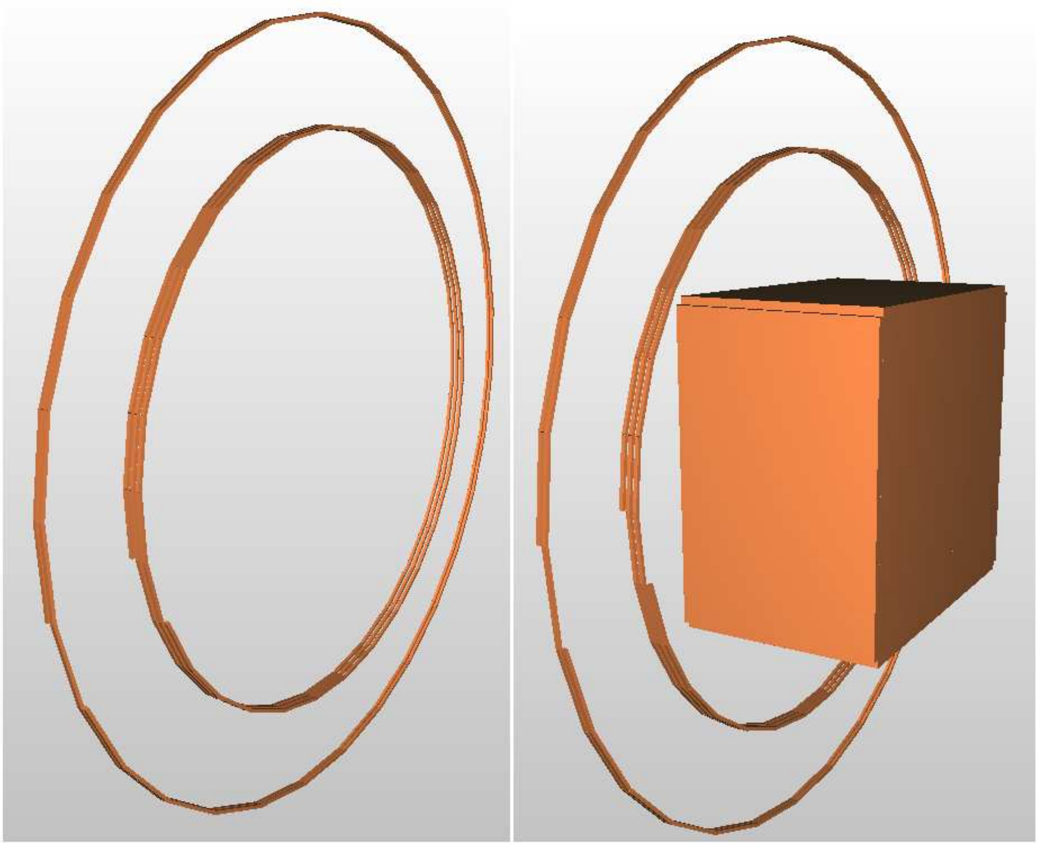


*Figure 23. Simulation model one in free space (left) and simulation model two with environment model (right).*

Both simulation models have exactly same sized coils. Coils mechanical dimensions can be found from table 2.

*Table 2 Coil mechanical properties.*

| | Wire Ø [mm] | d [mm] | N | l [mm] |
|---|---|---|---|---|
| Coil 1 | 0.7 | 155 | 2 | 2 |
| Coil 2 | 0.7 | 116 | 3 | 4 |

The simulation is made with FastHenry2 and it gives the following results. In the table 3 there are also measured values. As we can see that there is little difference between simulated and measured values. The difference can be caused by accuracy of measurement equipment or/and by the difference of the simulation model and the real system.

*Table 3 Simulated and measured values of the system.*

| | Simulated | | Measured | |
|---|---|---|---|---|
| | model 1 | model 2 | model 1 | model 2 |
| $L_1$ [µH] | 1,82 | 1.77 | na | 1,86 |
| $L_2$ [µH] | 2,60 | 2.38 | na | 2,73 |
| $R_1$ [Ω] | 0.49 | 0.49 | na | 0.90 |
| $R_2$ [Ω] | 0.59 | 0.57 | na | 0,60 |
| M [µH] | 0.67 | 0.56 | na | 0,71 |

# 9 Validation of Results

The documented, simulated and measured inductive power system has been build and tested. The system works like expected. The receiver side can be loaded 20mA@3.5v. The whole system efficiency is about 15%. That is not very good, but in this case efficiency is not in a big role.

# 10 Inductive Power and Data link

Next step in this case will be to do inductively coupled power and data link. So now we know that power link works well. To do inductively coupled data link we have to add some functional parts to reader and transponder side. The block diagram in figure 21 describes a digital communication system. Inductively coupled power and data transfer system also requires three main functional blocks. These are: signal coding, and the modulator in the transmitter, the transmission channel and the demodulator and signal decoding in the transponder (receiver) [4]

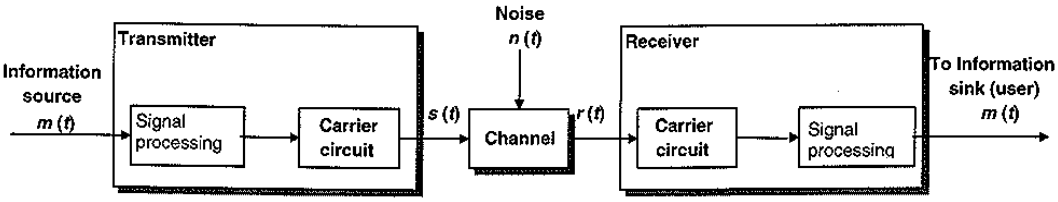


*Figure 24. Signal and data flow in a digital communications system*

So to the reader and transponder side we need to add microcontroller. Microcontroller sends and receives transmitted data. In this case transponder only send data and reader only read what transponder side have sent. [4]

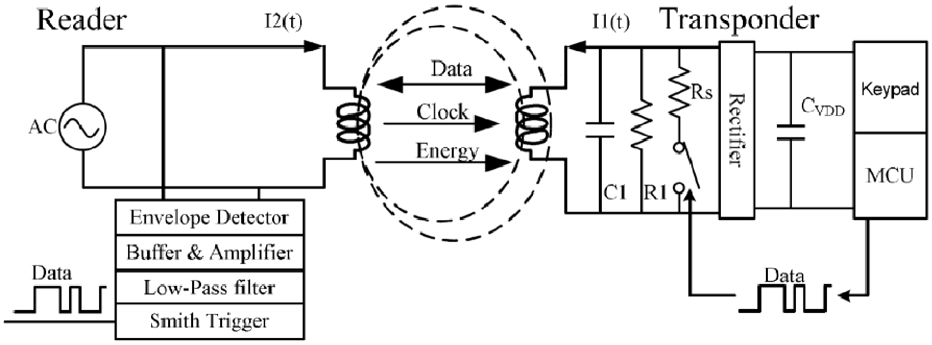


*Figure 25*. Inductively coupled data and power link.

## 10.1 Modulation

Three main variables of electromagnetic wave are amplitude, frequency and phase. By these variables we can use three different modulations: amplitude modulation (AM), frequency modulation (FM) and phase modulation (PM). All other modulation procedures are derived from one of these three types. Inductive coupled systems uses digital modulation procedures like ASK (amplitude shift keying) FSK (frequency shift keying) and PSK (phase shift keying) (figure 26). [4]

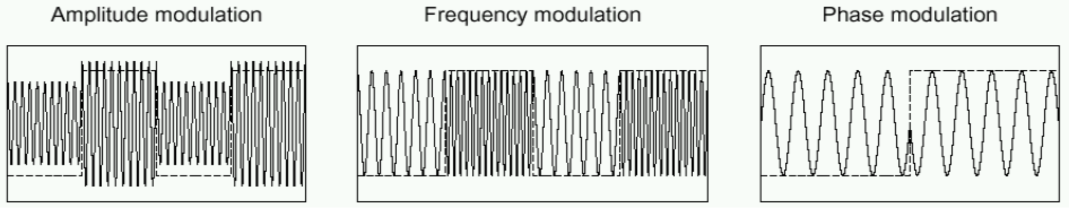


*Figure 26*. Modulations.

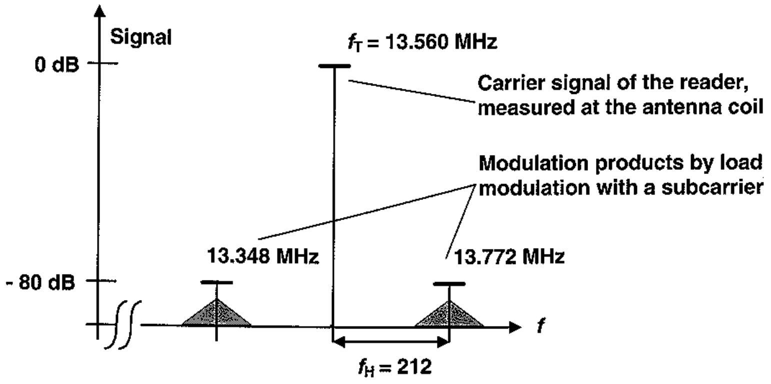


**Figure 6.13:** Modulation products using load modulation with a subcarrier

*Figure 27.* Modulation products using load modulation with a subcarrier.

## 10.2 Coding

Bits (ones and zeros) can be represented in various line codes. An inductively coupled system typically uses some of next methods: NRZ, Manchester, Unipolar RZ, DBP (differential bi-phase), Miller. Differential coding and PP coding (Figure 28). [4]

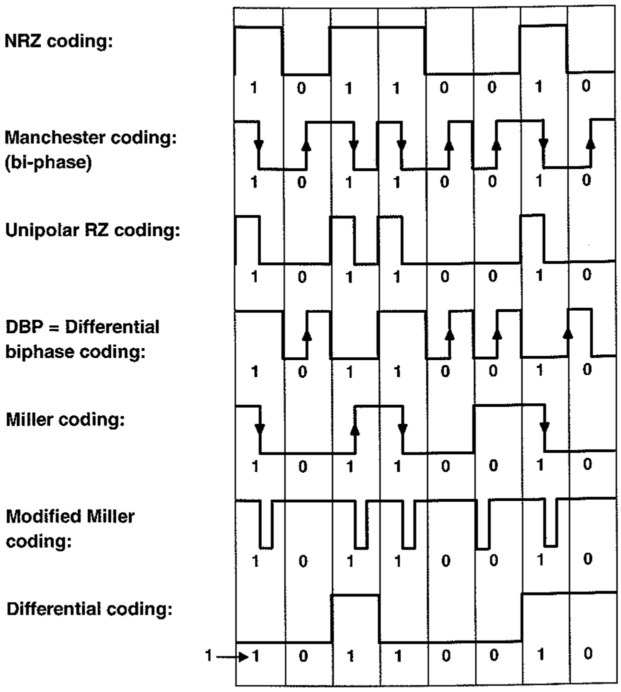


*Figure 28.* Signal coding by frequently changing line codes in inductively coupled systems.

### 10.3 Data Security

Modern authentication protocols can be used. Like we know the working range in inductively coupled systems is quite short. Hence it is not easy to access to the system or generate fault functions. For example RFID payment systems have high data security. [4]

## 11 Inductive power and data link risk analysis

Inductive coupled power link reliability is better than inductive coupled data link. When the power can be delivered, it is not sure that the data link will also work fine.

The inductive coupled power and data link risks are following:

- External materials
    - detunes link
    - coupling coefficient decreases

- Eddy currents (near conductive plates)
    - Magnetic field decreases

- Misalignment decreases efficiency
    - Lateral misalignment
    - Angular misalignment

- External magnetic fields
    - other RFID & NFC devices
    - Frequency range 13.56 MHz is freely available ISM-band. Nowadays not much in use, but maybe in future there will be more use, when RFID/NFC comes more public.
- Power supply
    - no power supply
    - too low
    - too high
    - disturbance

- Temperature, humidity, vibration, ageing etc.
    - Oscillator creep
    - Out of resonance frequency

- Modulation problems

Risks in inductively coupled links are quite minimal. The biggest problems are external materials which can come too near the link when the link is in use. When we are building the system we can take care of the mechanical conditions and tune the link. But if the mechanical condition changes it is possible that problems will occur, because the link is not anymore in resonance frequency. If external material is conductive it can also cause eddy current. Eddy currents decrease magnetic field because these fields are opposite to the original magnetic field. If there is an external conductive material between the antenna coils the link will not work at all (usually not possible case).

If coils can go to some misalignment state the link efficiency decreases dramatically and finally the link will not work at all. The possibility that antennas can go to misalignment state is absolutely minimal if the system is designed to work at the worst case.

In theory it is possible that near the inductively coupled link can be some high magnetic fields. These fields can affect problems to inductive link.

One risk might be frequency range 13.56 MHz that is on freely available ISM-band. Nowadays the frequency is not much in use, but maybe in future there will be more use, when RFID/NFC comes more public, like in mobile phones.

Finally the basic electronic problems, like temperature, humidity, vibration etc are one risk. Alternating temperature drives oscillator circuit out of the designed frequency and link efficiency fall down. Humidity and vibration breaks circuit boards solder joints etc. Vibration also affects to crystal what affects to frequency.

## 12 13.56 MHz system advantages13.56 MHz

- Frequency band available worldwide as an ISM frequency
- ISO 15693 and ISO 14443 and HF ePC standardisation for the air interface
- Robust reader-to-tag communication
- Excellent immunity to environmental noise and electrical interference
- Well defined and localised label interrogation zones
- Minimal shielding effects from adjacent objects and the human body
- Water’s damping effects relatively small, field penetrates dense materials
- Freedom from environmental reflections that can plague UHF and microwave systems
- Good data transfer rate
- High clock frequency and synchronous subcarrier
- On-chip capacitors for tuning transponder coil can be easily realised
- Cheap IC’s, disposable tags
- Cost effective antenna coil manufacturing
- Low RF power transmission so EM regulation compliance cause no problems
- No user licenses for reader systems required (ISM band)
- Possible to use the systems in industrial and in hazardous environments with potential for explosive substances

[13, 14]

## 13 Comparing key RFID parameters to other wireless standards

Table 4 compares inductively coupled links to other wireless standards. [15]

Table 4 Comparing key RFID parameters to other wireless standards.

| | Inductive | Zigbee | Bluetooth | 802.11b | 802.11a | GSM/GPRS | IS2000 |
|---|---|---|---|---|---|---|---|
| Multiple Acces | FHSS/TDMA | CDMA/CA | FHSS/TDMA | FDM/CSMA/CA | FDM/CSMA/CA | FDMA/TDMA | CDMA |
| Frequency Band | 125 kHz – 2.5 GHz | 868 MHz, 915 MHz, 2,4 GHz | 2402-2484 MHz | 2402-2484 MHz | 5,2-5,8 GHz | 800-2000 MHz | 1885-2200 MHz |
| Data Rate | 0,12 kB/s-25 kB/s | 20 kB/s – 250 kB/s | 122 kB/s | 122-1343 kB/s | 122-6592 kB/s | 1-14 kB/s | 12207-244140 kB/s |
| RF Modulation | ASK, mFKS, mPSK | BPSK, QPSK | FSK | DQPSK | nPSK/QAM-n OFDM | GMSK | QPSK (DL) BPSK (UL) |
| Transmission Power | 1 mW-4W | 1 mW | 1 mW-100mW | 100 mW | 2 W | 2 W | 600 mW |
| Typical Range | 50 cm (passive), 10 m (active) | 10 m | 1-30 m | 120 m | 60 m | 30 km | 20 km |

SWOT analysis of the Inductive Link Standard is described in the table 5

Table 5 SWOT analysis of inductive link.

| | ***Helpful*** | ***Harmful*** |
|---|---|---|
| ***Internal Origin*** | **Strengths**<br>• Free frequency band<br>• Power and data can be delivered<br>• Cheap parts<br>• Excellent immunity to environmental noise and electrical interference | **Weaknesses**<br>• Short working range<br>• Low data rate |
| ***External Origin*** | **Opportunities**<br>• Minimal shielding effects from adjacent objects and the human body<br>• Security applications | **Threats**<br>• Changing environmental conditions<br>• Frequency range use in future? |

## References

[1] Powerkiss In the Media, Powerkiss (luettu 23.3..2009) URL: http://www.digipaper.fi/powerkiss/30641/

[2] Lukkari J. Korealainen sähköbussi lataa akkunsa tiestä (luettu 12.7.2009) URL: http://www.tekniikkatalous.fi/duuniauto/article292309.ece?s=r&wtm=-28052009

[3] http://www.mesasystemsco.com/category.php?cat=2

[4] Klaus Finkenzeller (2003) RFID Handbook: Radio-Frequency Identification Fundamentals and Applications John Wiley & Son, LTD

[5] European Telecommunications Standards Institute (2009) EN 300 330.2 Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment in the frequency range 9 kHz to 25 MHz and inductive loop systems in the frequency range 9 kHz to 30 MHz; Part 2: Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive, France

[6] http://www.st.com/stonline/products/literature/an/10429.pdf

[7] Youbok Lee (2003) Antenna Circuit Design for RFID Applications, Microchip Technology Inc. URL: http://ww1.microchip.com/downloads/en/ AppNotes/00710c.pdf.

[8] Mattan Kamon, Smithhisler C. White J. (1996) FastHenry USRE'S GUIDE, Research Laboratory of Electronics Department of Electrical Engineering and Computer Science Massachusetts Institute of Technology Cambridge, USA

[9] Kamon M., Smithhisler C. White J. (1996) FastHenry USRE'S GUIDE, Research Laboratory of Electronics Department of Electrical Engineering and Computer Science Massachusetts Institute of Technology Cambridge, USA

[10] Agilent Technologies Inc.(luettu 12.7.2009) Impedance Measurement Handbook URL: http://cp.literature.agilent.com/litweb/pdf/5950-3000.pdf

[11] AEA Wireless: Operating Manual (2003). Vector Impedance Analyzer – 100kHz to 200 MHz, California

[12] Silvonen K. (luettu 1.8.2009) Piirianalysaattori, kalibrointi ja sirontaparametrit. URL: http://www.aplac.hut.fi/books/elektroniikka/piirianalysaattori.pdf

[13] UPM raflatac (2003) Tutorial overview of inductively coupled RFID Systems URL: http://www.mobiusconsulting.com/papers/rfidsystems.pdf.

[14] Rata M., Rata G., Graur A. & Popa V.(2007) The influence of dirrerent materials in 13.56 RFID system, RFID EURASIA, s.1-3

[16] Crystal Oscillator Circuit Design (1997),URL: http://www.google.fi/url?sa=t&source=web&ct=res&cd=1&url=http%3A%2F%2Fwww.eetkorea.com%2FARTICLES%2F2001SEP%2F2001SEP06_AMD_AN.PDF&ei=dQqWSv6cA56OnAOQ26jYCg&rct=j&q=Crystal+Oscillator+Circuit+Design&usg=AFQjCNGAQRkFb7X75ncJ0mZW4NhnJQn4-A

[15] Hande A., Bridgelall R., Bhatia D. (2009) Chapter 18: Energy Harvesting for Active RF Sensors and ID Tags In: Priya S., Inman D.J. (eds.), Energy Harvesting Technologies, Blacksburg.

[16] http://www.datasheetcatalog.org/datasheet/CML/mXyyzquy.pdf