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Evaluation of a Tyre Pressure Monitoring System and Radio-Frequency Identification Application

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Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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Kurzfassung

Der Einbau eines Reifendruckkontrollsystems (TPMS) in das Rad eines Kraftfahrzeuges eröffnet neue messtechnische Möglichkeiten. Diese Masterarbeit befasst sich mit der Möglichkeit, ein TPMS zur Identifikation eines batterielosen UHF RFID Tags, der auf die Innenseite eines Reifens aufgebracht ist, zu verwenden. Um die nötige RFID Funktionalität zu gewährleisten, wird das TPMS um einen energiesparenden RFID Reader erweitert. Hierbei werden verschiedene Einbaupositionen und Antennenarten näher untersucht. Das Ergebnis dieser Arbeit ist ein funktionierender Prototyp, der die Machbarkeit demonstriert und auf seine Praxistauglichkeit untersucht wird.

Der erste Teil der Masterarbeit befasst sich mit dem Design und der Implementierung der Hard- und Software des Prototypen, wobei das TPMS um einen UHF RFID Reader erweitert wird. Der zweite Teil befasst sich mit der Verifikation und Evaluierung des Systems, wobei der Fokus auf dem RFID Teil des Systems liegt. Die darauffolgende Schlussfolgerung vervollständigt die Masterarbeit mit einem Fazit und gibt einen Ausblick auf mögliche Anschlussprojekte.

Abstract

The installation of a Tyre Pressure Monitoring System (TPMS) into the wheels of a car opens up new opportunities of measurement. This master thesis investigates the possibility of identifying a battery-free Ultra High Frequency (UHF) Radio Frequency Identification (RFID) tagged tyre mounted on the wheel using a TPMS. To achieve the necessary RFID functionality the TPMS is expanded with a low power UHF RFID reader. Several mounting positions as well as antenna types are evaluated. The outcome of this work is a demo board which demonstrates the feasibility of this system and is used to evaluate its usability.

The first part of this thesis describes the design and implementation of the hard- and software to build the demo board whereby the board extends the TPMS functionality with an UHF RFID reader. The second part covers the verification and evaluation of the system, whereby the main focus lies on the RFID part. The following conclusion completes the thesis with a summary of the acquired knowledge and gives an outlook on possible future projects.

Acknowledgement

First I would like to thank Ass.Prof. Dipl.-Ing. Dr.techn. Peter Söser from the Institute of Electronics at the Graz University of Technology for his support and for keeping me on track when I lost my focus during this thesis.

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List of Abbreviations

ASK	Amplitude Shift Keying
dBm	Decibel-Milliwatts
D-FF	Delay Flip Flop
EPC	Electronic Product Code
EOM	End Of Message
FIFO	First In, First Out
FSK	Frequency Shift Keying
GPIO	General Purpose Input / Output
IO	Input / Output
IC	Integrated Circuit
JTAG	Joint Test Action Group (program and debug interface)
LSB	Least Significant Bit
MCU	Micro Controller Unit
MSB	Most Significant Bit
PA	Power Amplifier
PC	Protocol Control
PLL	Phase-Locked Loop
POR	Power-On Reset
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SPI	Serial Peripheral Interface
SFR	Special Function Registers
SMA	Sub-Miniature-A
SMT	Sub-Miniature-T
TPMS	Tyre Pressure Monitoring System
TPMiS	Tyre Pressure Monitoring and Identification System
UART	Universal Asynchronous Receiver Transmitter

Chapter 1

Introduction

This master thesis is a collaboration between Infineon Technologies Austria AG, Department of Contactless and Radio Frequency Exploration (CRE) at the Design Center in Graz and the Technical University of Graz. The thesis discusses the construction of a system and is divided into a literature research, the design of the system, its implementation, verification and evaluation. In the end an outlook for further projects is given.
The first Chapter outlines the main goals of this project, beginning with the topic of this work, followed by a state of the art literature review which explains the currently used technologies. Furthermore, this Chapter gives additional information about the system components used in this master thesis.

1.1 Topic of this Work

The topic of this project is the design and implementation of an extension to an already existing Tyre Pressure Monitoring System (TPMS) with an 868 MHz Ultra High Frequency (UHF) Radio Frequency Identification (RFID) system, followed by its verification and evaluation. The overall demo system called TPMiS should be able to obtain information from a tag located in the tyre of a wheel and send this information to a central unit in the car where further processing can be done. There are two basic use cases for the TPMiS in this thesis:

TPMiS on Rim: This first scenario is currently the most common method to position TPMSs on the wheels of passenger cars. Here the TPMS is located on the rim, more precisely on the air valve of the wheel. The transponder (tag) is located at the inside of the rolling surface of the tyre. This scenario is hereafter referred to as the „TPMiS on rim scenario“.

TPMiS on Tyre: This is a more prospective scenario. A TPMiS module is placed at the inside of the rolling surface of a tyre, directly above a tag which is permanently fixed on or in the tyre. This scenario is derived from the idea of harvesting the deformation energy of the tyre to power the TPMS module. Hereafter, this application is referred to as the „TPMiS on tyre scenario“.

Figure 1.1 gives an overview of the system. In this case the TPMiS module is fixed directly onto the tyre. The figure also shows the communication paths between the different sub systems which are the tag in the tyre, the TPMiS module and the central unit in the car. Figure 1.1 shows the arrangement of these subsystems.
As shown in the figure, the TPMiS module is located on the tyre, directly over the tag (2) which is fixed to the tyre. The central receiving unit (3) is mounted inside the car. The TPMiS module identifies (1) the UHF RFID tag by getting its Electronic Product Code (EPC). The tag is battery less and must therefore be powered by the interrogator's RF field during this communication. The obtained data is then forwarded to the central unit.

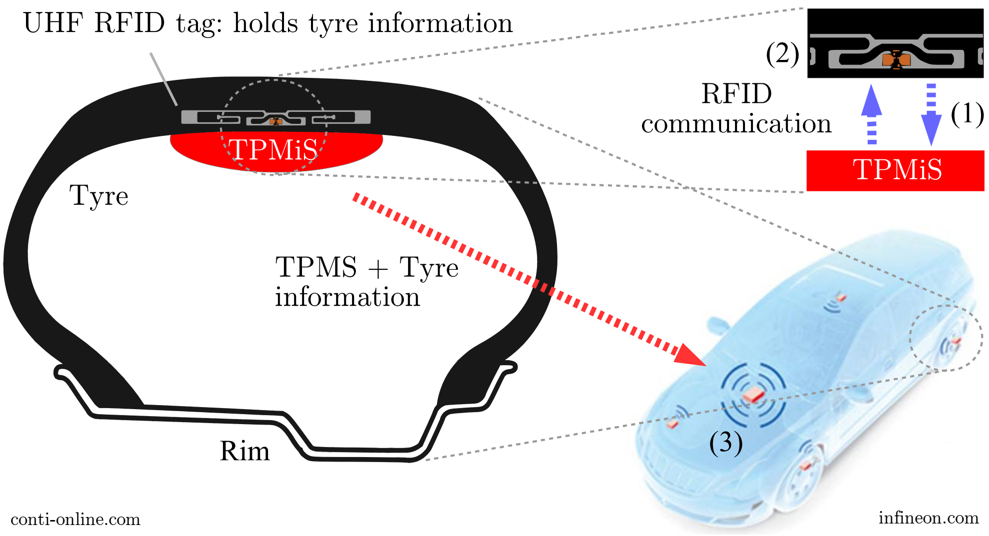

Figure 1.1: Overview of the TPMiS system in a wheel

Besides the functional requirements the system must also fulfill limiting factors and adaptations as follows. The RFID Interrogator should be able to communicate to the tag with a maximum RF power of 5 dBm. This requirement is necessary for a future system configuration. The power management should save energy to ensure a long battery life. The antennas for the 868 MHz UHF RFID and the 434 MHz TPMS parts need to be adapted for this special TPMiS application. One of the mayor issue for this antennas is the correct function inside the wheel of a car, where the whole system is surrounded by the rim and the metal structures inside the tyre.

1.2 State of the Art

This section gives an overview of the current technologies which relate to this master thesis. This thesis deals with the fundamental topics of TPMS, TPMS installed on a tyre, UHF RFID, low power RFID and tagged tyres. These functional parts are well researched, but the combination of these technologies to create a TPMiS is not yet known in technical literature.

1.2.1 TPMS

„Proper tire inflation pressure improves fuel economy, reduces braking distance, improves handling, and increases tire life, while underinflation creates overheating and can lead to accidents. Approximately 3/4 of all automobiles operate with at least one underinflated tire“ [VG07].
Most people do not check tyre pressure on a regular basis. The Tyre Pressure Monitoring System (TPMS) warns the driver when tyre pressure drops below a certain pressure limit. For that reason tyre pressure monitoring is becoming more and more interesting for drivers. The pressure measurement can be performed with a direct or an indirect pressure measuring system. The indirect tyre pressure measurement is performed through differential speed measurement of the wheels of a car. When the tyre pressure decreases, the weight of the vehicle causes the tyre to rotate at a different rate than the other tyres. According to Velupillai [VG07], this difference can be used to detect underinflated wheels. Another possibility is the use of a direct TPMS, which can measure pressure deviations as low as 0.1 bar [VG07]. A direct TPMS can also measure the pressure faster then the indirect system. Known direct TPMSs allow the measurement of temperature and acceleration in addition to the pressure measurement. This technology constitutes the basis of this master thesis project.

Energy Harvesting on Battery-free TPMS

Currently most TPMS modules are mounted on the rim of a car. Current, commercially available TPMSs are battery powered. These TPMSs are able to react faster to an event than battery-free versions, can transmit measurement results with a higher power and are able to power energy intensive subsystems. The installed batteries limit the lifetime of the TPMS modules and increases their weight. For those reasons a lot of research has been done into battery less TPMSs. The energy harvesting is mostly realized through the use of the acceleration energy of the wheel in several different forms. One of the ideas is to use the gravity of the earth in combination with the rotation of the wheel [RT13]. According to this article, this form of harvesting is capable of directly powering an RF transmission every minute while the vehicle is travelling at speeds ranging from 10 to 150 kph. Another example is the use of a 13.56 MHz transmitter, mounted near the wheels of a car to wirelessly power the TPMS [WZY+12].

In trucks, the TPMS modules are mostly mounted directly on the inside of the rolling surface of the tyre. Most of these modules are still battery powered, but this construction makes it possible to use the deformation energy of the rubber tyre for energy harvesting. The weight of the car decreases the radius of the tyre above the road contact area. Every time the TPMS module enters or leaves the road contact area of the wheel, it achieves a acceleration change. This change of acceleration can be used to harvest energy [WdEH11].

1.2.2 UHF RFID

Radio Frequency Identification (RFID) is a contactless communication technology. RFID systems consist of the following main parts: a transceiver, an antenna and a transponder (also called tag) which contains a small data memory. Currently, common tags are available in three different frequency classes: the Low Frequency (LF) tags, working at 125 kHz, High Frequency (HF) tags at 13.56 MHz and Ultra High Frequency (UHF) tags working at a frequency ranging from 860 MHz to 960 MHz. LF systems are used in low range applications where very small data packages are transmitted. These systems are slow but due to its low frequency are insensitive to organic tissue and are therefore used in applications such as animal identification. HF systems can transmit with much higher data rates then low frequency systems and are used for fast identification systems. UHF tags are mainly used in the logistic sector. They have a high communication data rate and are used for wide range identification. [SS05]
Another defining feature of tags is the type of power supply. The so-called active tags have their own battery. These tags have a wider operating range and bigger memory. They are also larger and more expensive than passive tags. Passive tags are powered by the reader's RF field and cannot be active outside this field. Another disadvantage is the shorter operating range [AT07]. According to Sabesan [SCPW13] the communication range of these increasingly important passive tags can be increased using antenna diversity combined with phase and frequency hopping.

UHF RFID Tag in tyre

The idea to place an UHF RFID tag inside of a tyre has been around for several years. But the use of this technology is currently restricted to logistic purposes, where it is used for tracking. Due to the higher frequency of UHF systems, the systems can achieve a larger detection range than HF or LF RFID systems. According to Basat [BLK$^+$05], tags installed on tyres are often placed on the face of the tyre. The face contains less metal structures than the rolling surface of the tyre and is therefore better suited for positioning the tag. Unfortunately for energy harvesting purposes a tag positioning on the rolling surface of the tyre is preferable which leads to further problems.

1.2.3 UHF RFID Antennas

The design of the antenna has a big influence on the communication range of RFID systems. In this project, the antenna environment contains a lot of metal structures which interfere with UHF RFID communications. These metal structure changes the impedance of the UHF antennas of reader and tag so dramatically, that the reading distance is reduced to a fraction of the expected range. There are however a couple of techniques to reduce the impact of these metal structures on reading range.
There are several applications where an UHF RFID tag has to be placed on a metallic object which calls for specialized antenna design. An example of such an antenna is a label-type patch adhering to a flexible polyvinyl chloride (PVC) substrate. This antenna reaches a high reading range and is flexible. [SJC12]
An other antenna suited to place on a metallic object is the looped-bowtie antenna. This antenna structure consists of two non connected load bars and two bowtie patches electrically connected through four pairs of vias to a conducting backplane to form a looped-bowtie RFID tag antenna that is suitable for mounting on metallic objects. [LCM12]

1.3 EPCglobal Generation 2 Standard

The 2^{nd} generation EPCglobal standard defines the physical and logical requirements for an interrogator-talks-first (ITF) RFID system operating at a frequency ranging from 860 MHz to 960 MHz. The system is comprised of an interrogator (reader) and one or more tags. [EPC04]
This standard describes Class-1 identify tags, which are passive and must be powered via the interrogator's RF field. The interrogator transmits data to the tag by modulating the signal onto the RF waveform. The tag transmits data to the interrogator by backscattering information on the RF field of the interrogator. This is done by modulating the reflection coefficient of its antenna, which influences the RF waveform of the interrogator. [EPC04]
The communication via the 2^{nd} generation EPCglobal standard is divided into tree basic operations. The operations and the individual commands are shown in Table 1.1.

Operation	**Select**	**Inventory**	**Access**
Command	Select	Query Query-Rep ACK	Req_RN Read Write Kill Lock Access BlockWrite BlockErase

Table 1.1: EPCglobal operation commands overview [EPC04]

The next sections are going into more detail and describe the UHF RFID communication between the reader and a tag which is located in the RF field of the reader. Both the reader and the tag use the EPCglobal Gen2 standard for their communication, which consists of the ASK modulated transmission from the reader to the tag and the backscatter signal for the tag answer.
To make these next sections more illustrative a test setup has been created to provide oscilloscope graphs of the different transmission stages. This setup is composed of the RFID reader, a tag and an oscilloscope with an adapted measurement antenna. The distance between the reader and the tag should be small so that the tag can better influence the reader field during backscatter signal transmission. The measuring antenna is positioned at a distance to the two communication participants to prevent an influence on the communication.
The sequence of communication patterns needed to acquire the EPC of an RFID tag is called an inventory round. This EPC could afterwards be used to access an RFID tag. Since the tags EPC is the only information needed by the TPMiS an inventory round represents a complete UHF RFID cycle of the TPMiS. Figure 1.2 shows an example of an inventory round with its different communication patterns.

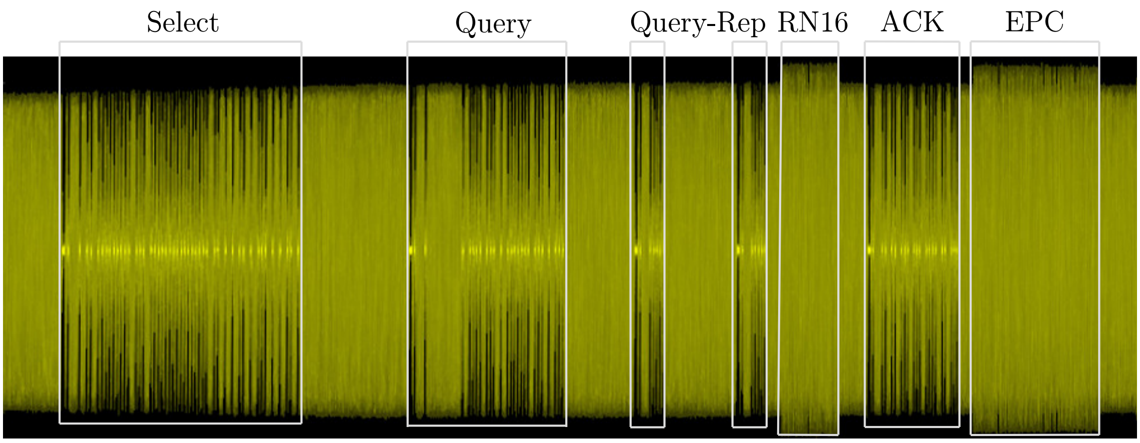

Figure 1.2: UHF RFID EPCglobal inventory round communication

An inventory round starts with the select command which is used to select a specific group of tags to participate in this inventory round. The following query command configures the selected tags for further communication. The query reply command and the RN16 are parts of the collision avoidance mechanism used during the inventory round. The query reply command needs to be repeated until either an RN16 answer has been received or the maximum number of repetitions has been reached. Figure 1.2 shows an example of two replies being needed to receive an answer. This mechanism is explained in more detail in the following sections. As the name suggests the ACK command acknowledges the correct reception of the RN16 and causes the tag to send its EPC to the reader.

1.3.1 Select Pattern

As previously mentioned the select command selects a population of tags for the following inventory round. The select command is optional and not directly part of the inventory round. To select a population of tags, the select command selects a part of the tags memory. The select command sends a pointer to a specific area of the tags memory and a bitmask to compare this area to. If the specified memory of a tag corresponds to the bitmask sent, the tag applies the inventory and selection flag options also sent by the select command. In summary the select command brings a population of tags to a specified state.

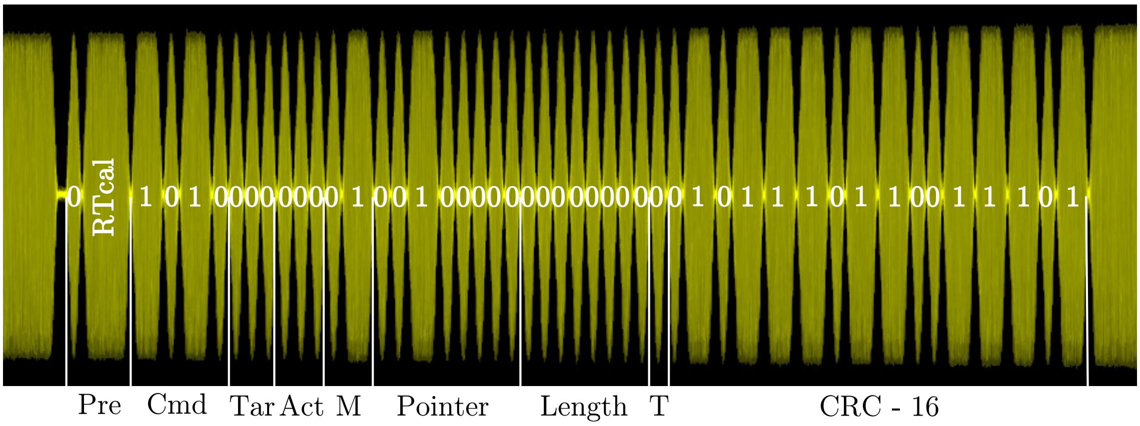

Figure 1.3: EPCglobal inventory select command

Figure 1.3 shows a select command which selects all tags located in the RF field of the reader. The following table describes the options of the select pattern shown in the figure.

Command	Target	Action	Mem bank	Pointer	Length	Truncate	CRC-16
1010	inv. S0	sel. A	EPC	+32 bits	0	disabled	

Table 1.2: Options of the select pattern

To select all tags in the readers RF field the length field of the select command is set to zero. This also means that the mask field can be omitted in the pattern, which would normally hold the data mask to select a specific population of tags.

The target and action fields set the tags inventory flags to inventoried S0 and the selection flags to target state „A“. The memory bank and pointer fields define that the EPC memory block should be compared starting on the 32^{nd} bit. The truncate flag is disabled which means that the tag should answer with the whole EPC memory content to an ACK command. Finally a CRC-16 checksum is transmitted.

1.3.2 Query Pattern

The query command is used to configure the tags for further communication in the inventory round. To configure the correct tags the same inventory and selection flags used by the select command have to be used. The preamble of the query command differs from the preamble of the other commands. In addition to the usual preamble a TRcal sequence is also sent as part of the preamble.

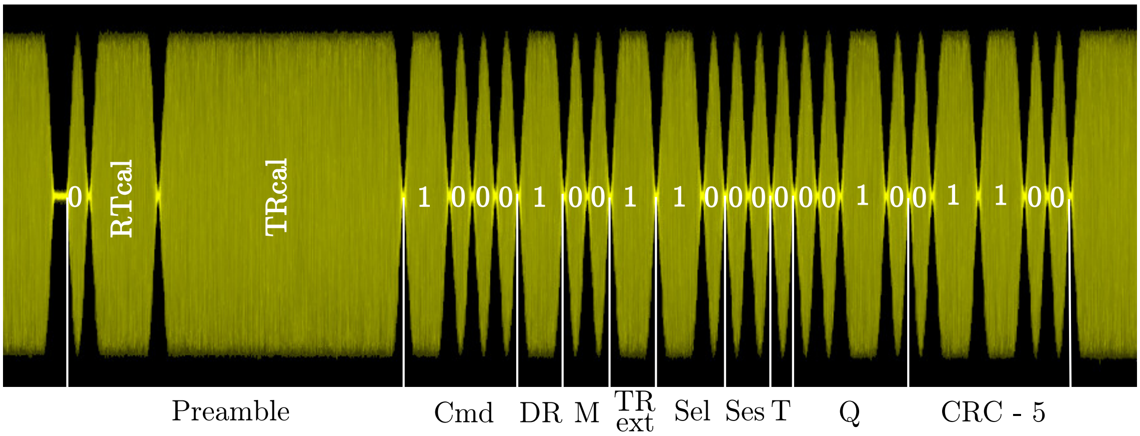

Figure 1.4: EPCglobal inventory query command

Figure 1.4 shows a query command pattern. The TRcal and the DR fields define the backscatter link frequency for the tag. The duration of one bit in the backscatter is calculated by dividing the duration of TRcal by the value of DR. The following table shows the options selected in the above signal.

Command	DR	M	TRext	Sel	Session	Target	Q	CRC-5
1000	64/3	FM0	pilote tone	inv. SL	S0	A	2	

Table 1.3: Options of the query pattern

Option M defines the backscatter encoding type which in this case has been set to FM0 (bi-phase space encoding), the shortest possible bit encoding type. To configure the tag population selected with the previous select command (see Section 1.3.1) the Sel, Session and Target options have to be set to inv. SL, S0 and A respectively. Option Q is part of the collision avoidance mechanism of the EPCglobal Gen2 standard. In this case Q is set to 2. This means that the tag should calculate an internal random slot count number which can range from zero to a maximum value of $2^Q = 4$. This is important for the following selection procedure described in the next section.

1.3.3 Query Reply Pattern and RN16

The query reply command is part of the collision avoidance mechanism of the EPCglobal Gen2 standard. The maximum number of repetitions of the query reply pattern is depended on the Q value specified by the query command. After receiving a query command the tag calculates a random slot count number. This slot count number is decremented by one each time a query reply command is received by the tag. If a tags slot count number reaches zero, the tag answers with a random 16 bit number (RN16). This transmitted RN16 number initiates a communication with this specific tag.
The slot count can already be zero after the first query command. It is therefore possible that a tag answers after the first query. In the worst case the query reply must be repeated 2^Q times until a tag has decremented its slot count to zero. Q is an indicator for the level of collision avoidance. The higher the value of Q the less collisions are going to occur.
Should more than one tag reach a slot count of zero at the same time a collision occurs. This can either be solved by sending another query reply or by deeming the inventory round unsuccessful and repeating it.

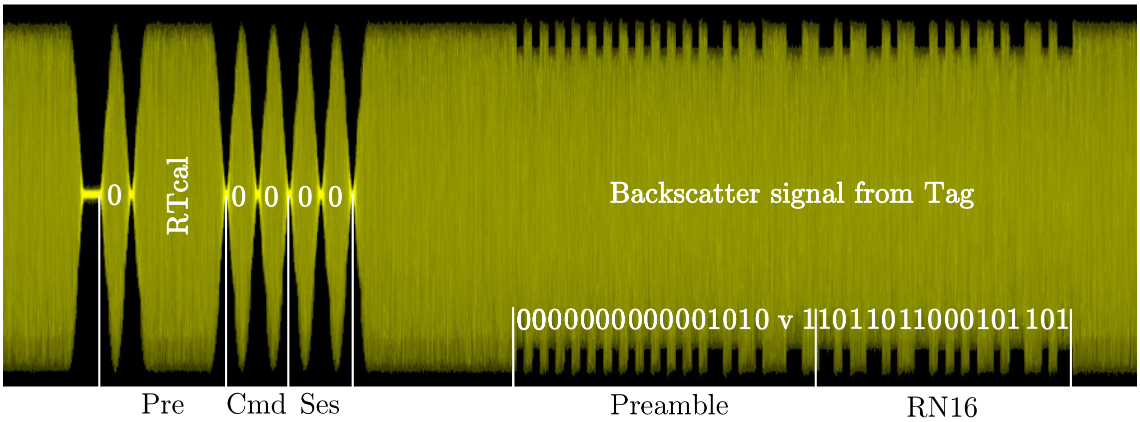

Figure 1.5: EPCglobal Gen2 inventory query rep command and backscattered RN16

Figure 1.5 shows a query reply command which is followed by the backscattered answer of a tag which has reached a slot count of zero. The query reply is a short command with the command code „00“. The only option of this command is the session. In this case the session is 0 (S0). If a tag receives a query reply whose session number is different from the tags session number, the command is ignored.
The backscattered signals preamble used by the tag is dependent on the TRext flag of the query command. In this case the long preamble is used. The preamble consists of 12 leading „0“ followed by „1010“, an FM0 encoding violation „v“ and an other „1“. The FM0 violation is achieved by omitting the required level change at the beginning of the „v“ bit. The preamble is followed by the RN16.

1.3.4 Acknowledge Pattern and Tag Response

If the reader receives an RN16 it answers with an ACK command which contains the same RN16 to acknowledge the correct reception of this number. Figure 1.6 shows the transmission of the ACK command in response to the RN16 shown in Figure 1.5.

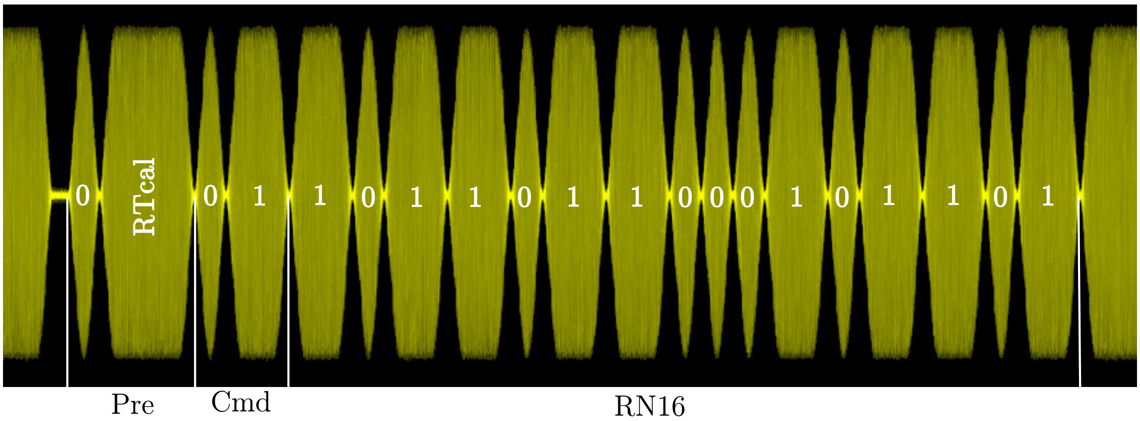

Figure 1.6: EPCglobal inventory ACK command

If the ACK command is sent back correctly, the tag answers with the data specified in the select command. This can either be the whole EPC memory content or just a specific part of its memory content.

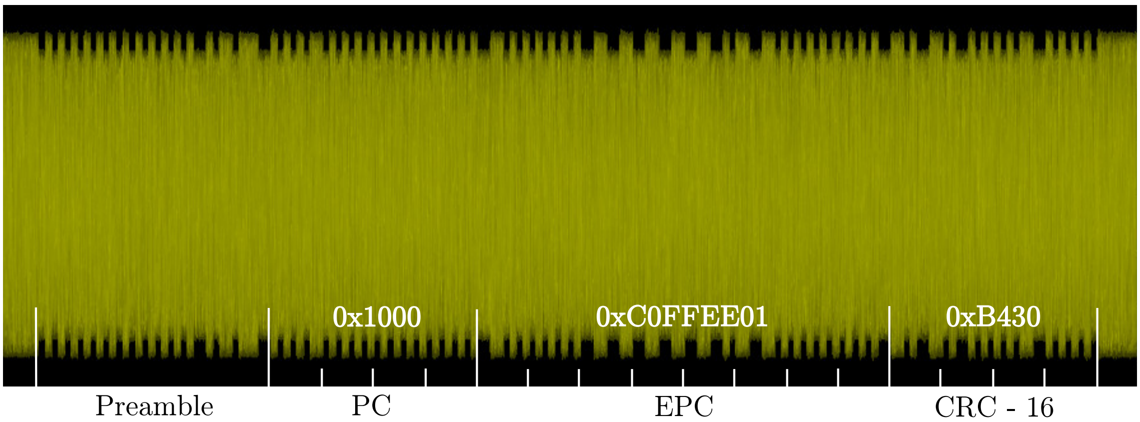

Figure 1.7: EPCglobal inventory: Tag backscatters its EPC memory content

Figure 1.7 shows the backscattered EPC memory content followed by a CRC-16. In this case the EPC memory contains a 16 bit protocol control word (PC) as well as the tags electronic product code (EPC). The PC contains information about the length of the EPC.

1.4 Components

The two main components of a TPMiS are the UHF RFID reader and the TPMS. The UHF RFID reader is needed to communicate with tags embedded in the tyre. The TPMS transmits the obtained RFID tag data to the central unit in the car as well as providing pressure monitoring functionality. The TPMS's Micro Controller Unit (MCU) is used to configure and control the UHF RFID reader. The first step of development is the implementation of communication functionality between the MCU and the reader IC using the Serial Peripheral Interface (SPI). The next step is the configuration of the contactless communication between the reader and the UHF RFID tag. These key functions will be developed on an UHF RFID development board. It contains the UHF RFID reader and a micro controller to control the reader. As soon as the communication between this controller and the reader is running the functions will be ported from the micro controller situated on the UHF RFID development board to the TPMS's MCU which runs on its own development board. Then the TPMS should be able to control the UHF RFID Reader on the UHF RFID development board via a few control lines which interconnects the development boards. Based on this test setup a Printed Circuit Board (PCB) containing both the TPMS and the reader IC is then developed.

1.4.1 The TPMS Chip

There are two different types of pressure monitoring systems. Passive TPMSs detect deflated tyres by measuring the difference in rotational speed of the wheels of a car. Active TPMSs use a pressure sensor to directly detect underinflated tyres.

This work uses an active TPMS which in addition to pressure monitoring also allows the monitoring of serveral other parameters. Being an active system it is faster at detecting underinflated tyres then passive systems. The TPMS Chip is an integral part of a system to measure the air pressure of the tyres on a car. Currently most TPMSs are located on the rim of a car and are battery powered. After a certain event or time interval, the TPMS transmits the measured data to a central receiving unit located inside the car.

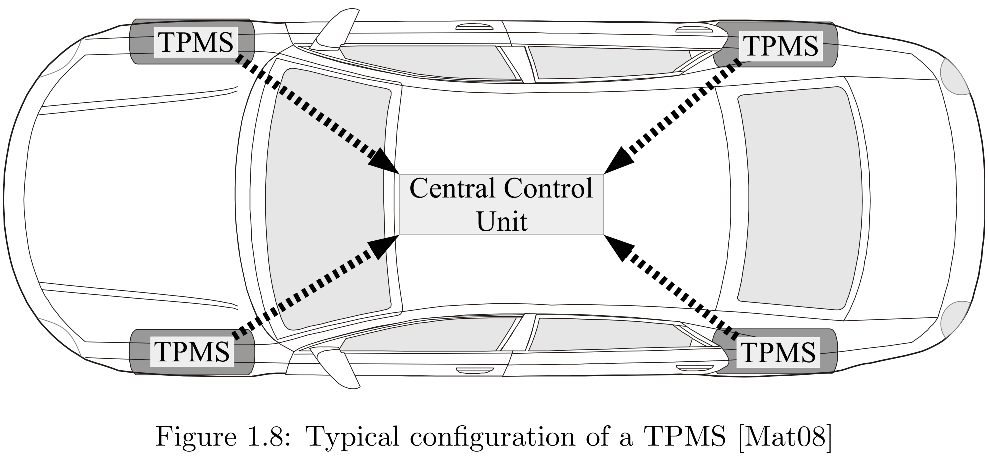

Figure 1.8: Typical configuration of a TPMS [Mat08]

Figure 1.8 shows a typical system structure of an active TPMS. The TPMS used consists of a Micro Electro Mechanical System (MEMS), a low power wireless amplitude / frequency shift keyed (ASK/FSK) UHF transmitter, a Low frequency (LF) receiver and an embedded extra small micro controller. The TPMS is usually mounted on the air valve on the rim of a car wheel. A battery supplies the System for its whole lifetime. Tyre pressure, acceleration, temperature and battery voltage can be measured on-chip. The embedded micro controller is a 8051 architecture compatible 8 bit controller. Thus it is possible to create own programs to control the measurements and wireless communication. The RF transmitter can transmit on either 315 MHz or 434 MHz and only needs 5 dBm to transmit the measured data to the central unit in the car. The 125 kHz LF receiver provides system wake-up from power down mode. For an on-board wired communication the TPMS IC provides four General Purpose IOs (GPIOs) (see [Inf13]). These GPIOs are an important communication interface in this TPMiS project and are used to communicate with the UHF RFID reader.

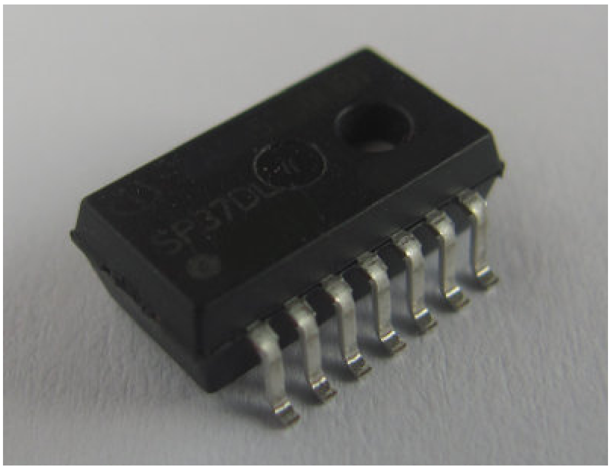

Figure 1.9: The TPMS IC from Infineon

1.4.2 The RFID UHF Reader Chip

The UHF RFID Reader AS3992 used in this thesis is manufactured by AMS AG. According to [Aus10] it provides ISO18000-6 (EPC Gen2) full protocol support (see EPC Gen2 data sheet) and comes in a small QFN64 Package. The on-board voltage controlled oscillator (VCO) and phase-locked loop (PLL) covers the complete RFID frequency range of 840 MHz to 960 MHz. A parallel or serial interface can be selected for communication with the MCU. The RFID transmitter can output with a power up to 20 dBm into a 50 Ω load. The transmission system includes automatic generation of frame synchronisation, preamble sending and CRC calculation. The receiver system offers automatic gain control and selectable signal bandwidth to cover the tag's range of input link frequency. Via the integrated Received Signal Strength Indication (RSSI) the signal strength of AM and PM modulation can be measured. The reader IC can be configured with several parameters. Inter-chip communication can be implemented via SPI or an 8 bit parallel interface in addition to the other signal lines like chip enable or interrupt output. The communication signal level can be defined via a special control voltage input pin. It is therefore possible to set the communication signal level voltage to a value lower than the 5 V used as the reader ICs power supply. This is important for communication with the TPMS, which can only work with a maximum voltage of 3.6 V (see [Inf13]). The configuration and communication with the reader IC is register based. The registers can be accessed via their address followed by their values. Most of these registers are used for configuration, the others for reading out received data or the status of the IC.

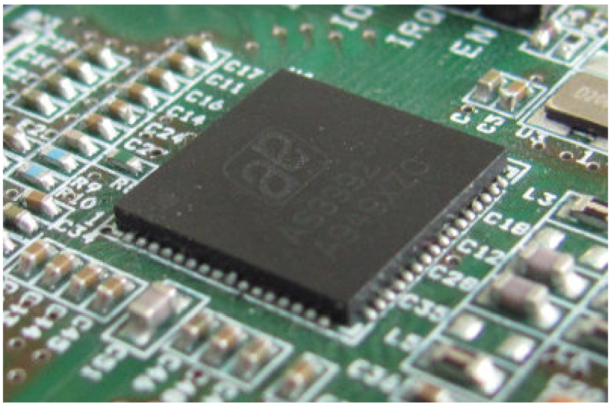

Figure 1.10: The UHF RFID Reader IC
AS3992 from AMS AG

Some special EPC Gen2 commands, such as the query command are already implemented on the reader. CRC checking of incoming data and on-chip storage of protocol specific data is also possible. The receiver part of the IC ID comprised of two input mixers followed by a gain stage and several configurable filter stages. A more detailed documentation is available in the data sheet [Aus10].

1.4.3 The first UHF RFID Reader Demo Board

The first system design steps for this thesis were made on the AS3992 LEO UHF RFID Demo Board by Austria Micro Systems AG. In essence the functional parts on it are the C8051F340 8 bit micro controller from Silicon Labs which controls the demo board, the UHF RFID reader and an UHF analog part which consists of the matching network for the antenna, filter stages and a directional coupler. Communication between the two IC's can be configured as either serial SPI or parallel interface mode. The signal lines available on the PCB are able to support both types of communication. The reader can output a differential UHF signal up to a power of 20 dBm. This signal needs to be converted via a so-called „Balun“ to a single-ended signal. A low pass filter connected directly after the Balun filters out the second and higher order harmonics. To separate the receiver from the transmitter path a directional coupler is used.

On maximum RF output power, the UHF reader IC has a high power consumption while sending out the carrier wave for several milliseconds. To provide this energy a back-up capacitor is used on the development board. The reader IC provides a special 3.3 V supply output which is used to power the micro controller which controls the reader IC. This power supply stays active, even if the reader IC is disabled via the enable line „EN“. Therefore it is not necessary to provide a specialized power source for the micro controller. For debugging purpose the Universal Asynchronous Receiver Transmitter (UART) interface of the micro controller is routed to connector pins. The communication signals between the MCU and the reader are also routed to a connector. These connectors allow for easy measurements of the communication signal patterns.

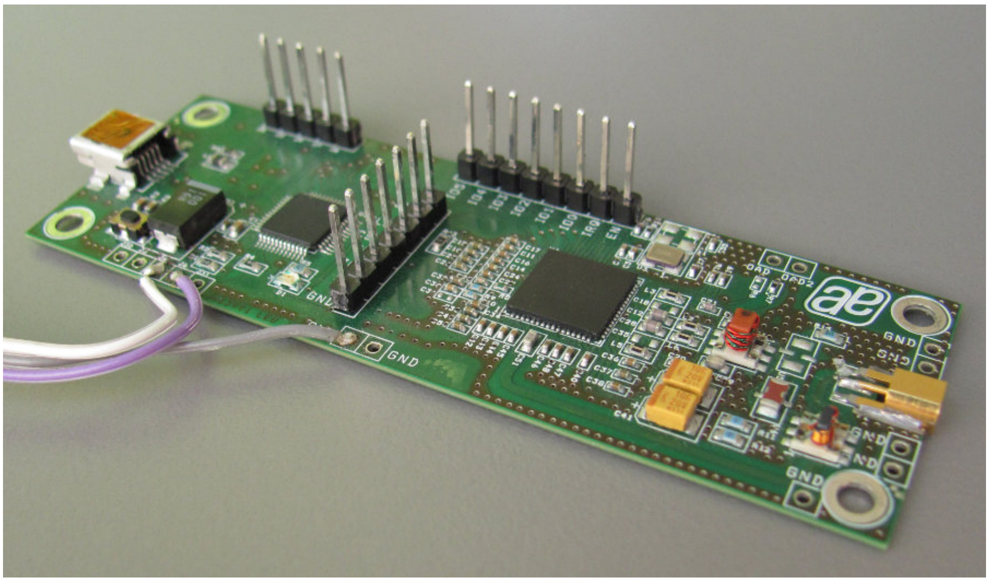

Figure 1.11: The LEO Demo Board used for software developement

Figure 1.11 shows the demo board. The leftmost part pictured is a Mini USB Port for communication with the host PC. It is followed by the big back-up capacitor and the micro controller. The next, bigger chip is the reader chip with the matching network for the RFID UHF interface on its right. The three cables soldered to the board are used to flash the program onto the micro controller.

1.4.4 The UHF RFID Tag

An RFID tag is a small memory that can be accessed via wireless communication. A tag can either be passive and is powered by the continuous wave field transmitted by the RFID reader or active and powered by its own battery. A semi active tag is a hybrid, which uses its own battery as well as the RF field of the reader as power supply. The active tags have a longer transmission range but are larger and more expensive then passive tags. Passive tags have a shorter transmission range (a few meters), but are smaller and cheaper. The TPMiS treated in this thesis uses passive 868 MHz UHF RFID tags, compatible with EPC generation 2 standard (see [EPC04]). The higher frequency (UHF) allows a higher transmission range and higher data rate then HF tags which work at a frequency of 13.65 MHz. Figure 1.12 shows an EPC generation 2 868 MHz UHF RFID tag. The cut-out shows the tiny tag itself as well as the pads connecting it to the antenna.

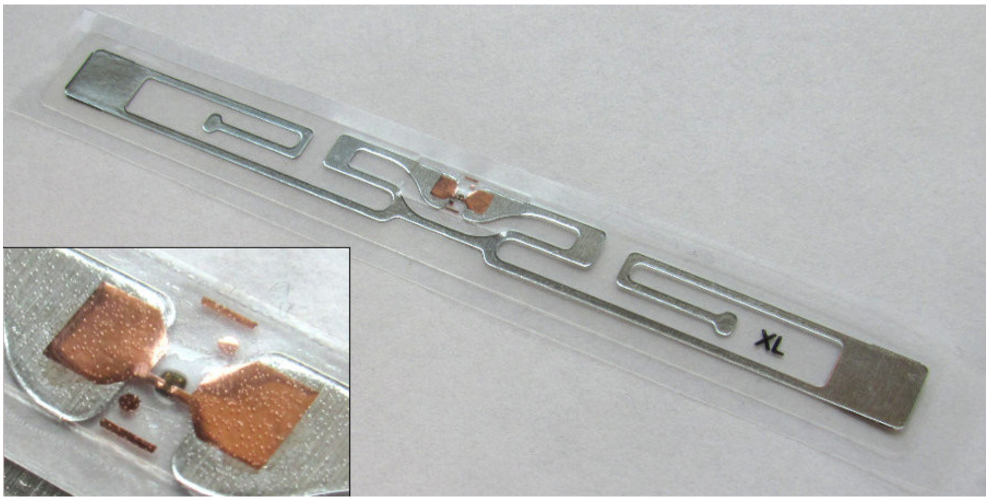

Figure 1.12: A common UHF RFID tag

The tag receives its messages via information modulated onto the supply field. Figure 1.13 shows an Amplitude Shift Keyed (ASK) modulated signal on the continuous wave of the RFID reader. The passive tag does not have enough power to transmit data to the reader via a self generated electromagnetic field. Therefore the tag uses the reader field to backscatter its data to the reader by switching between two different impedances in the reader field. This causes an attenuation of the reader field which can be detected by the reader. Figure 1.13 shows an example of this backscatter signal.

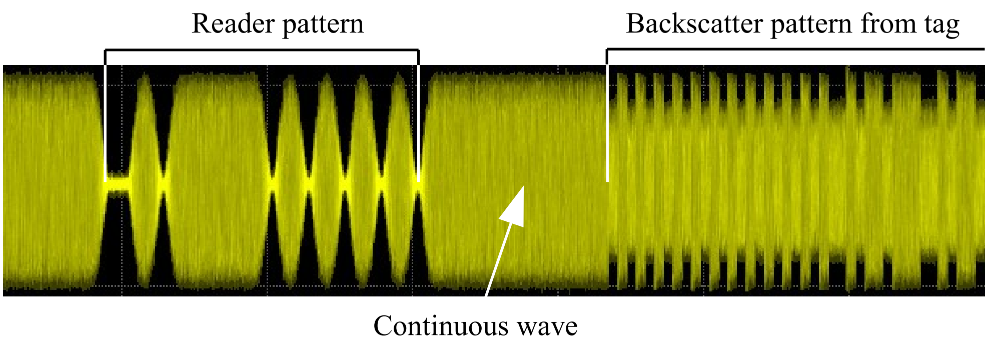

Figure 1.13: UHF RFID communication pattern

As previously mentioned this project uses EPC Gen2 standard conforming tags. More details on this communication can be found in the EPC Global data sheet as well as in Section 1.3. There the whole UHF RFID communication between the reader and the tag during an inventory round is presented and explained.

Chapter 2

System Design

2.1 The TPMiS Demo System

The practical aim of this work is the construction of a system wherein all of the parts mentioned in Chapter 1 are combined. The next sections give an overview of this system which is called TPMiS (Tyre Pressure Monitoring and Identification System). The „i“ in TPMiS denotes the additional RF Identification part compared to a conventional TPMS system.

2.1.1 General Requirements of the System

The idea was to create a system with TPMS features and RFID reader functionality that can be mounted on the rim or the tyre of a vehicle. It should be possible to read an RFID tag inside of a tyre and transmit its information to the central unit in the vehicle. This system should be powered by a single battery for its complete lifetime. Therefore the system has to be designed with minimal power consumption. The TPMS IC is already highly optimized to save power. However, the UHF RFID reader is not designed for these requirements and must be adapted.

When fully charged, the battery used to power the TPMiS has a load-free voltage of 3 V. The TPMS IC works in a voltage range from a minimum of 1.6 V to a maximum of 3.6 V (see [Inf13]). During RF transmission a minimum voltage of 1.7 V is needed. The UHF RFID reader needs a minimum voltage of 4.1 V. Therefore it is necessary to increase the voltage for the RFID part of the TPMiS. Another issue which plays an important role is the high power consumption of the reader while sending the carrier wave (see [Aus10]). Since the battery also imposes severe restrictions on the system, it is necessary to include a sophisticated power management into the TPMiS.

The TPMS includes a micro controller which controls the RFID reader via software. The inter-chip communication has to be solved via SPI, because the RFID reader only supports SPI for serial communication. Additionally the inter-chip-logic has to be able to perform control functions such as chip enable or interrupt request. For debugging purposes the system needs an interface to send information to the development PC. All this communi-

cation has to be handled by the 4 available General Purpose IO (GPIO) ports (see [Inf13]). It is therefore necessary to interpose an inter chip communication logic between the TPMS and the reader IC.
The TPMiS needs two antenna matching networks. One for 434 MHz UHF communication with the central unit in the vehicle and another for 868 MHz UHF RFID communication with the tag in the tyre. The communication with the central unit is unidirectional: it is only possible to transmit data from the wheel to the central unit. The communication with the UHF RFID tag is bidirectional as required by the RFID UHF Gen2 Standard communication protocol [EPC04]. For this purpose, the hardware of the RFID part of the system is more complex. Figure 2.1 shows an overview of the TPMiS.

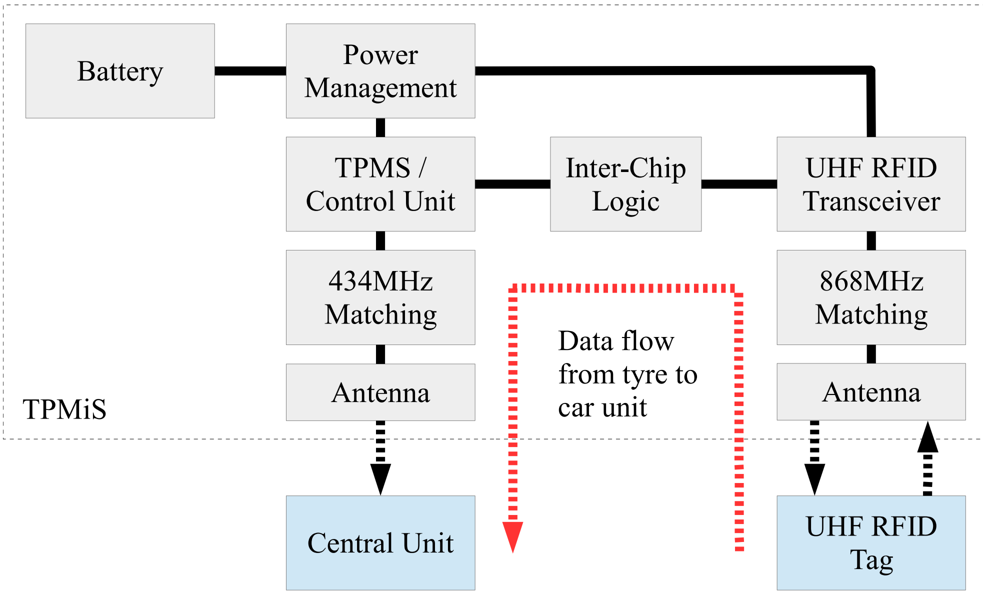

Figure 2.1: Overview of the TPMiS components

All these system parts including the battery need to be combined on a small PCB. This board should be constructed as a demo board with a debug interface and possibilities to measure certain signals such as the SPI communication. It should also be possible to power the board from an external power supply in case the system is not connected to the battery. The possibility to program the micro controller in the TPMS chip should also be retained.

2.2 Inter-Chip Communication and Debug Control Logic

The inter-chip logic handles the communication between the TPMS GPIO port and the AS3992 UHF RFID reader control interface. It includes, among SPI, other functions such as UART debugging, TPMS programming and some functions to perform „chip enable“ and interrupt signal.

2.2.1 TPMS Ports and AS3992 UHF RFID Reader Communication Interface

The communication interface to the AS3992 UHF RFID reader form AMS can be configured as a parallel 10 bit bus or a serial SPI interface. To select the SPI communication mode the reader IC pin IO0 must be at digital low and the IO1 at digital high. If the enable pin „EN“ then changes from digital low to digital high (power-up) the reader switches to SPI communication mode (see [Aus10]).

Regardless of the communication modes there are 2 different operating modes on the AS3992 reader IC: The easy to use so-called „normal“ mode and the more complex „direct“ mode in which the whole communication protocol has to be handled externally. In direct mode the reader therefore only works as a simple modulator with its higher functions disabled.

This project uses normal operating mode, in which most of the protocol handling is done by the reader. Table 2.1 describes the pin assignments for the serial SPI communication mode. Unused pins are not needed for this project.

Pin	**Description**
CLK	SCLK from master
IO7	MOSI (data in)
IO6	MISO (data out)
IO5	*unused*
IO4	SS (slave select)
IO3	*unused*
IO2	*unused*
IO1	hard wired to V_{DD}
IO0	hard wired to GND
IRQ	interrupt wire

Table 2.1: AS3992 communication port assignment of the serial interface

The TPMS IC only has 4 GPIO's to communicate with its peripherals. As shown in Table 2.1 the SPI itself needs 4 lines for communication. In addition to the SPI an interrupt request signal (IRQ), chip enable signal (EN) and an UART interface for debugging purposes also need to be handled by this port. Finally, the micro controller in the TPMS must also be programmed via the same 4 available GPIOs. In summary the GPIOs have to handle 5 different types of communication on different interfaces. For this reason an inter-chip logic is needed. Fortunately, the 5 V powered reader chip has an adaptable communication interface for signal voltages less than 5 V. So there is no need for an external level shifter to adapt the TPMS's GPIO signal voltage level to the readers signal level. Figure 2.5 shows the overview of this logic. The whole inter-chip-logic is described in detail in Chapter 2.2.5.

2.2.2 SPI Communication

SPI is a serial communication protocol. In this case a „4 wire“ communication model is used, whereby the send and receive signals are on separate lines called „Master Out Slave In“ (MOSI) and „Master In Slave Out“ (MISO). The SPI slave device is selected by a low level on the slave select signal (SS). The SPI transceiver of the reader IC accepts data on MOSI or gets data on MISO on the falling edge of the SPI communication clock signal (CLK). Figure 2.2 shows a SPI signal pattern example.

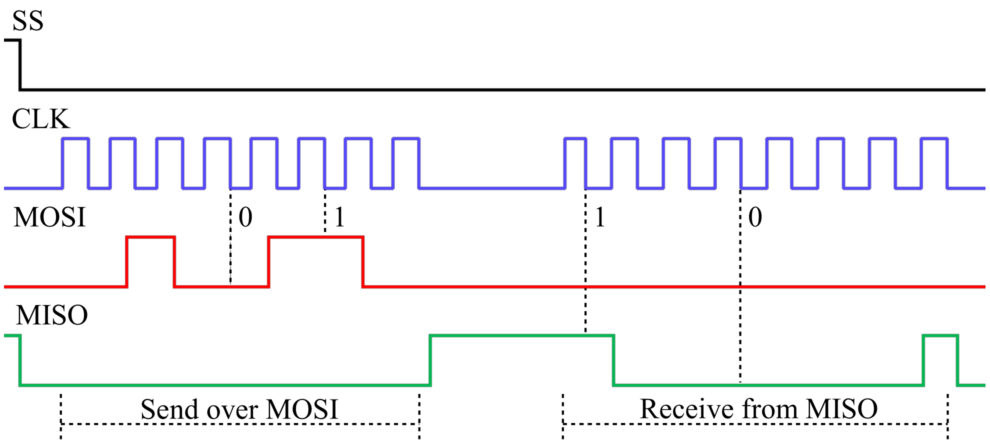

Figure 2.2: SPI communication example

The SPI communication interface on the TPMS is implemented in software, because there is no integrated hardware SPI module. The SPI interface on the AS3992 reader IC has certain timing constraints. These constraints are explained in the data sheet of the reader IC (see [Aus10]). The software SPI used in the TPMSs MCU is slower than hardware integrated SPI modules. Therefore the software SPI can be run on maximum performance, without breaking the timing constrains of the SPI communication interface of the reader IC. On the other hand the speed needed to handle UHF RFID Gen2 (see [EPC04]) standard communication can be difficult to achieve when using software SPI. This is especially true for the micro controller on the TPMS which has a relatively slow instruction cycle. For this reason the SPI software interface is coded in assembler with highest possible performance.

```
MOV    A, tx_byte        ; write transmit byte to A

RLC    A                 ; rotate A left to write MSBit to C bit
SETB   spi_sck           ; set clock signal to high
MOV    spi_mosi, C       ; write value of C to MOSI pin
CLR    spi_sck           ; clear clock signal(data on MOSI will be valid)
```

Listing 2.1: Code fragment from assembler SPI send function

Listing 2.1 shows a fragment of the assembler code. The final four code lines of this listing represent the transmission of one bit. A whole byte is transmitted if these four lines are repeated eight times. On a system clock of 12 MHz the TPMS has an instruction cycle duration of 500 ns for most of its instructions. Therefore the system runs at an instruction cycle speed of 2 MHz which implies that one instruction cycle is equal to six clock cycles. Hence the duration of one SPI clock cycle is equal to four instruction cycles which equals to 2 μs and the send frequency is therefore 500 kHz.

The GPIOs of the TPMS are bit addressable for writing operations. Therefore the pin can be directly accessed from code within one instruction cycle. Unfortunately an internal read of the GPIOs can only be performed by reading the whole GPIO port (see [Inf13]). This means that the port byte must first be loaded from the byte addressable space to a bit addressable space. For this reason the SPI receive function is slower than the transmit function. The following Listing 2.2 shows the receive function for one data bit.

```
CLR   spi_sck        ; clear clock
MOV   B, in_port     ; get the whole pin port to bit addressable space
SETB  spi_sck        ; set clock (slave can now send next bit)
MOV   C, B.2         ; write the right bit from input port to C bit
MOV   ACC.6, C       ; write this bit to the right position in ACC

CLR   spi_sck        ; next bit
MOV   B, in_port     ; get next port
```

Listing 2.2: Code part of the assembler SPI receive function

The received data byte will be collected bitwise in the accumulator register A. After eight repetitions of the code in Listing 2.2 the value of register A will be returned from the receive function to the calling code.

The receive function needs 2.5 μs to get one bit. This is 25% more time then the 2 μs required for the transmission of one data bit. This time difference needs to be taken into consideration when designing the software SPI. Since RFID communication is controlled by the SPI and is timing critical, the software needs to compensate for the time difference.

2.2.3 UART Debug Interface

The UART interface is an interface to transmit and receive data via two separate serial transmit and receive lines. This type of interface works without a clock signal. Therefore both transceivers must be configured with the same settings. The defined idle signal is at high level on the communication line and the communication starts if the start bit (falling signal edge on the same line) is transmitted. After the start bit the data byte will be transmitted, starting with the Least Significant Bit (LSB). After the transmission of the data byte an odd parity bit and the stop bit are sent (see Figure 2.3). The stop bit is always at high level and returns the line to its idle level.

As mentioned in section 2.2.2, the SPI interface uses all 4 available GPIO's of the TPMS. So all of the available pins are already in use. The SPI communication channel is active while the slave select (SS) signal is at a low level. While SS signal is set to high the MOSI and MISO pins are available for different uses. In case of the TPMiS the MOSI will act as UART transmit (TX) and MISO as UART receive (RX) while SPI is not active. The clock wire CLK is not in use while UART transmission or reception is active. Table 2.2 shows the usage of the GPIO port in both cases.

Pin	**Port Direction**	**SPI mode (SS = low)**	**UART mode (SS = high)**
PP1	OUT	CLK	–
PP2	IN	MISO	RX
PP3	OUT	MOSI	TX

Table 2.2: TPMS GPIO usage for SPI and UART depending on PP0 (SS)

The inter-chip logic hardware should therefore be able to switch between these two communication protocols or interfaces. This is achieved by using a multiplexer in the MOSI / TX signal path and a demultiplexer in the MISO / RX path.

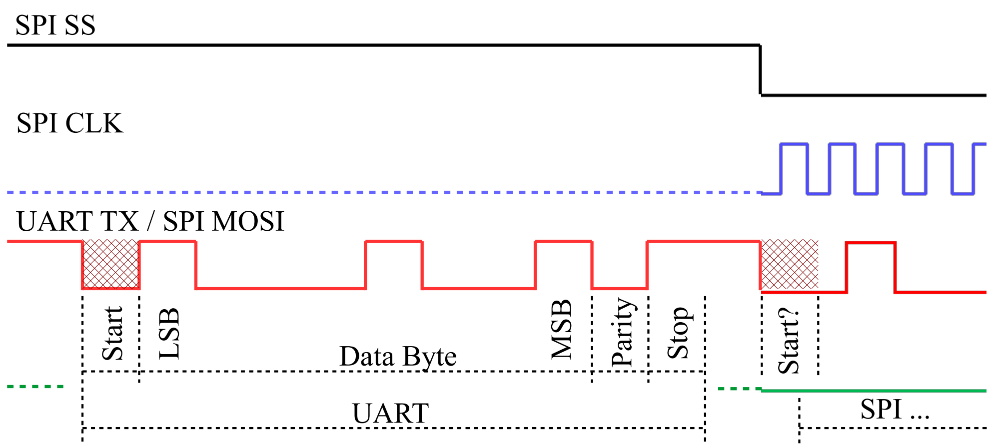

Figure 2.3: UART communication example and conflict with SPI communication

Figure 2.3 shows an UART communication example. The transmission starts with the falling edge on the TX line (the start bit). The following eight bits are the transmitted data byte. After the data byte an odd parity bit is sent to detect transmission errors. Finally a stop bit is send. After the stop bit the next UART transmission can be started. The figure also shows the beginning of an SPI sequence starting right after the UART sequence is finished. While the idle signal level for the UART communication on TX and RX is high, the idle level for the SPI communication is low on MOSI and MISO. This causes a falling edge on the UART TX line when the communication switches from UART to SPI as can be seen in the Figure. This falling edge is interpreted as start bit for a

UART sequence (see Figure). To prevent this behaviour, the UART communication can be inverted on signal level, which means that the idle state of SPI and UART on MOSI / TX and MISO / RX are equal and at a low level. To regain a standard UART sequence, this inverted UART signal must then again be inverted by an external hardware logic.

2.2.4 Chip Enable, Interrupt Signal and Program Interface

Chip Enable

Even in its idle state the AS3992 UHF RFID reader IC has a high power consumption. In this idle state the reader needs a current of a few mA. If the IC is disabled via „chip enable“ (EN), the current drops to a few μA. Since the battery can not continuously deliver the current needed for the IC, the system needs to be able to disable the reader if it's not needed.
The SPI and UART interface are already using the 4 GPIO pins. Using the Slave Select (SS) pin, the GPIO port of the TPMS IC can be switched between SPI and UART communication. The SPI uses all 4 ports while the UART interface does not use the clock (CLK) line. The idle state of the CLK signal during SS = high is at a low level. Therefore the SS and the CLK signal can be used to activate chip enable mode. If both are set to high chip enable mode is active and the MOSI / TX pin can be used to enable or disable the reader IC. Figure 2.4 shows the signal patterns to enable or disable the reader IC.

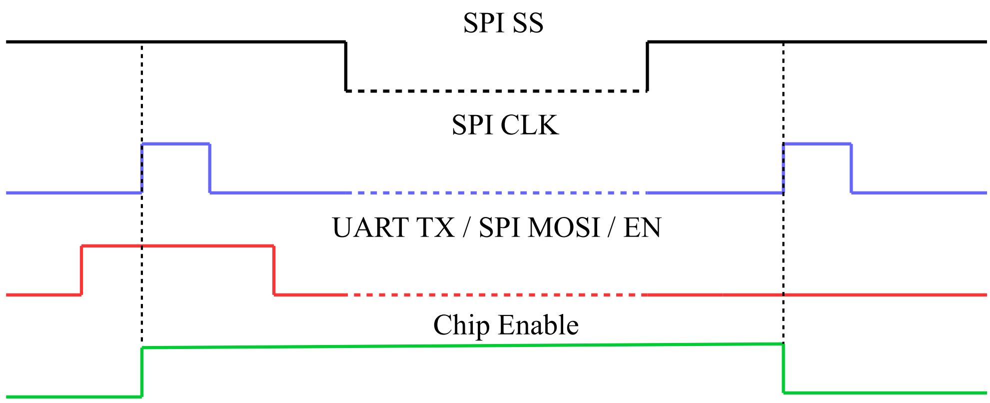

Figure 2.4: Chip enable and disable signal pattern

Interrupt Signal handling

Communication between the TPMS and the reader is bidirectional. This communication is mostly handled by the SPI. The TPMS sends the configuration and data to the reader and the reader answers with a status word or data word. But in addition to the SPI communication the reader also uses an interrupt signal to inform the MCU about newly received data or other events on the RFID channel. This interrupt signal must also be handled by the inter-chip-logic.

These interrupts only happen when the SPI communication is not active i.e. SS is at a high level. This can be used to inform the MCU of an interrupt request (IRQ).
The IRQ and the UART communication are now simultaneously active (SS = high). The interrupt signal is a pulse on the MISO / RX line. The falling edge of this pulse is interpreted as a start bit by the UART interface. To avoid the accidental reception of a symbol by the UART, the communication on the UART TX channel must be prevented by keeping it at a low level for the duration of the UART transmission time for one byte. The receiver notices the absence of the odd parity bit, detects the transmission error and interprets this as an IRQ.

TPMS Program Interface

The micro controller on the TPMS can be programmed via the first two GPIO pins PP0 and PP1. After a Power-On Reset (POR) the TPMS waits for a specific time interval during which programming mode can be started via I^2C commands. If the TPMS does not receive any I^2C commands during this interval, it powers on normally.
Since POR can be used to flash the MCU of the TPMS the reader chip is disabled via „chip enable“ (EN) during POR. This is necessary so that the flash procedure which is using SPI SS and SPI CLK pins does not affect the reader IC.

2.2.5 Overview of the Inter-Chip-Logic

As a summary of the previously described functional system parts, Figure 2.5 shows the complete logical construction of the inter-chip-logic.

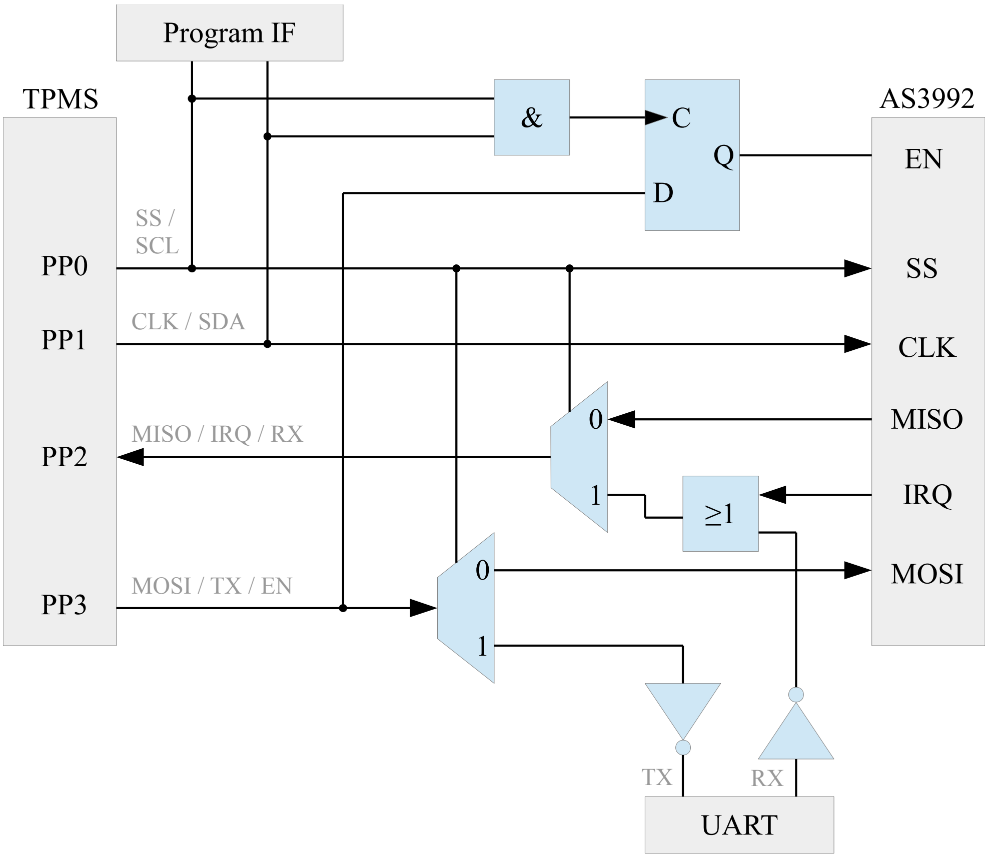

Figure 2.5: Overview of the TPMiS inter-chip logic

The program interface is directly connected to the I^2C interface of the TPMS IC (PP0 / PP1). Chip Enable reacts to signals on PP3 on a rising edge on the output of the logic AND combination of PP0 and PP1. PP0 and PP1 are directly connected to SS and CLK on the AS3992 for SPI communication. The signal on PP0 activates SPI mode by switching to a low level. In this mode PP2 and PP3 are connected to the MISO and MOSI pins of the reader IC. If PP0 switches to a high level, PP2 and PP3 have other functionalities: the demultiplexer switches PP2 to listen to the interrupt request (IRQ) and the UART RX signal. The multiplexer switches PP3 to control either the UART TX signal or the Chip Enable signal. The physical UART signal level is inverted to avoid the conflict between UART and SPI communication (see Figure 2.3 in Section 2.2.3).

2.3 Contactless Tag Communication

The TPMiS should be able to get information about a tyre by reading the tag embedded in this tyre. The communication between the TPMiS and the tag is handled via UHF RFID communication. In this project passive 868MHz UHF RFID tags, compatible to EPC generation 2 standard are used (see [EPC04]). The next sections describes the communication via this standard.

2.3.1 Reader to Tag Communication

The RFID reader has two functions. Firstly the reader must power the tag through its continuous reader field. Furthermore it has to control the communication with the tag. The communication can be handled via different types of ASK modulation. Figure 2.6 shows a reader to tag communication via a Phase Reversal ASK (PR-ASK) pulse interval encoding (PIE).

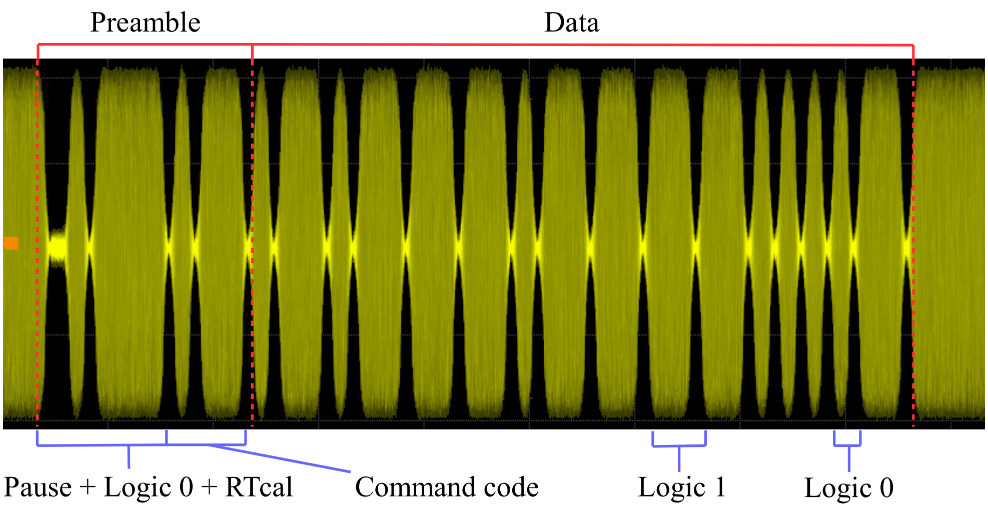

Figure 2.6: An UHF RFID reader to tag communication of EPC Gen2 standard

Communication begins with a pause in the continuous wave, which is called delimiter. It is followed by a logic „0“ symbol and a reader-tag calibration sequence (RTcal) with a specific length. Next up is the command code which defines the kind of command. Finally the data will be transmitted. In this case 16 data bits are transmitted.

Communication Configuration

According to the EPC Gen2 data sheet communication is extensively configurable. As previously mentioned ASK is used in combination with PIE.

As a first step the reference time interval for the reader to tag communication must be defined: the so-called Tari value is the duration of a logic „0“ in PIE and can range from

6.25 μs to 25 μs. The length of a logical „1“ is between 1.5 and 2 times of the duration of Tari. The pulse width (PW) is also configurable. The pulse width defines the duration of the attenuated RF field and can range from 0.265 Tari to 0.525 Tari. Figure 2.7 shows these configuration possibilities for reader to tag communication (see [EPC04]).

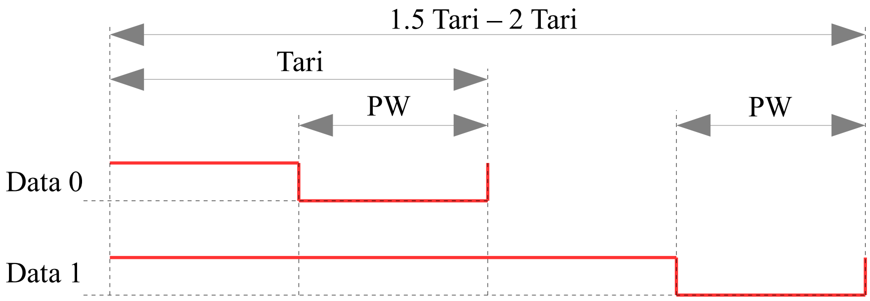

Figure 2.7: Configuration possibilities for the reader to tag communication [EPC04]

For this work, the logical „1“ is set to 2 Tari and the PW is set to 0.5 Tari. Tari itself should remain variable.

Communication Preamble

With one exception, the UHF RFID communication preamble is comprised of a fixed-length start delimiter, a logical „0“ and the RTcal sequence. RTcal is used to calibrate the tag to understand the readers commands. The length of this RTcal is the length of a logical „0“ plus the length of logical „1“. The tag divides this RTcal value by 2 to compute a pivot. All symbols transmitted from the reader which are shorter then this pivot are interpreted as logical „0“. Longer symbols are interpreted as logical „1“. If the transmitted symbol is longer than $4 \cdot$ RTcal, the data is interpreted as bad data [EPC04]. In addition to the preamble the so-called query command also contains a TRcal sequence. The length of TRcal sequence is used by the tag to calculate the backscatter link frequency (LF). This calculation also needs a divide ratio (DR). This divide ratio is transmitted to the tag via the query command. Equation 2.1 shows the dependencies [EPC04].

$$\mathrm{LF} = \frac{\mathrm{DR}}{\mathrm{TRcal}} \tag{2.1}$$

2.3.2 Tag to Reader Communication

As previously mentioned in Section 1.4.4, the tags used in this project are passive and therefore powered by the readers RF field. This method of power transmission is inefficient. Therefore the tag can not transmit its own RF field and has to use backscattering of the readers field to transmit data. This is done by switching between two different impedances of the tag antenna in the reader field. This causes an attenuation of the reader field which can be detected by the reader. Figure 2.8 shows such a backscatter signal encoded with ASK.

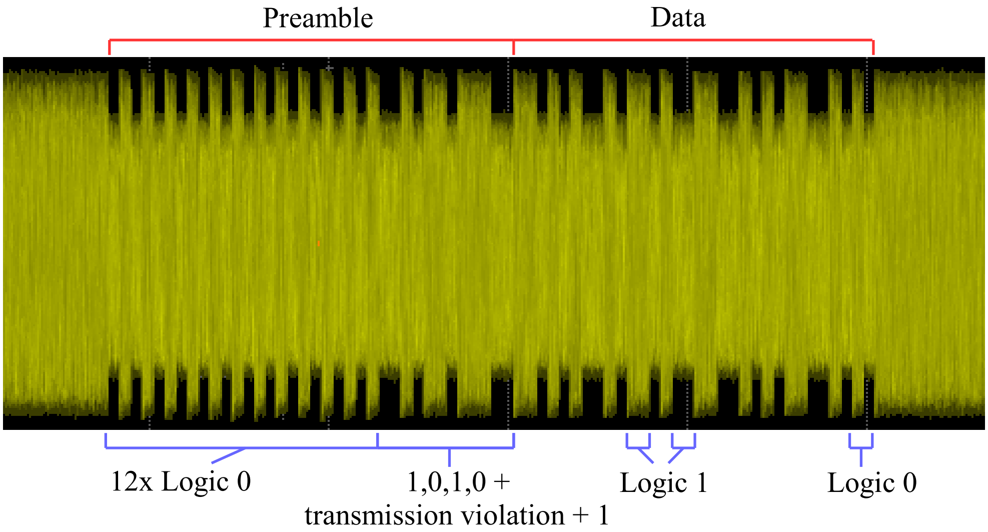

Figure 2.8: EPC Gen2 UHF RFID tag to reader communication

The EPC Gen2 standard defines 4 different ASK backscatter encodings, which are mentioned in the next section. The figure above shows the simplest and most power saving encoding method FM0. The data transmission from the tag to the reader starts with a special preamble followed by data and an optional Cyclic Redundancy Check (CRC).

Communication Configuration

The tag to reader communication configuration is handled by the query command, which is transmitted from the reader at the beginning of an EPC inventory round. Amongst other parameters, the encoding type, the preamble and the backscatter link frequency are configured. FM0 baseband, Miller 2, Miller 4 and Miller 8 can be selected as transmission encoding.

Communication Preamble

Every encoding type has its own preamble. Each encoding type also offers a choice of two different preamble lengths. The FM0 encoding used in this project, is the simplest and fastest choice. Since it offers better synchronisation between the tag and the reader the extended preamble is used in this project. This preamble is shown in Figure 2.8 as well as in Figure 2.9.

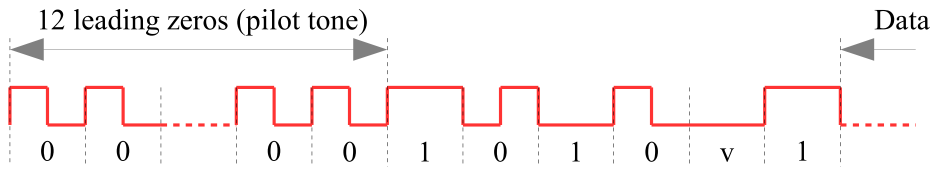

Figure 2.9: Extended preamble of the FM0 encoding [EPC04]

The preamble starts with 12 leading „0“s, the so called pilot tone. Afterwards a short sequence of „1“s and „0“s is sent. The „v“ in the figure indicates an FM0 violation: after the prior „0“ a phase inversion should have occurred but did not happen. This violation is part of the preamble.

2.4 Power Management

The TPMiS should be powered by a relatively small battery with a load-free voltage of 3 V. The TPMS can be directly supplied with this voltage level, but the UHF RFID reader needs a voltage of about 5 V to function properly. This is done by using a suitable power management system.
The next sections describes the battery, the power supply for the TPMS plus the communication logic and the power supply of the UHF RFID reader which works on a higher voltage.

2.4.1 The Battery

To ensure a long lifetime for the TPMiS a battery has to be chosen that is able to power the system during its whole lifetime. During active sending the UHF RFID reader needs a high current that the battery needs to be able to supply. Thus the main requirements for the battery are: a high capacity, a stable voltage during its discharge cycle, a high power output, very low self-discharge and a small size to fit on the compact TPMiS.
The best choice for this project is a 3 V lithium button battery which is also used to supply commercial TPMSs. This type of battery complies with the major requirements, except for the necessary high power output. Specifically the CR2450N 3 V lithium button battery by Renata Batteries was chosen for its high constant continuous current of 3 mA [Ren]. Most comparable models are only able to deliver 1 mA continuous current or less.

2.4.2 TPMS and Communication Supply Line

The TPMS is a low power system and is designed to work for many years with the same battery. The TPMS IC works in a voltage range from a minimum of 1.6 V to a maximum of 3.6 V (see [Inf13]). During RF transmission a minimum voltage of 1.7 V is needed. In run state, in which the micro controller is executing code, the whole TPMS IC needs a current of up to a maximum of 1.25 mA. The supply current needed during RF transmission is up to 7 mA [Inf13].

Therefore the TPMS requires 1.25 mA for code execution time and subsequently 7 mA during the RF data transmission. The communication between the micro controller in the TPMS and the UHF RFID reader also requires a relatively high current. Figure 2.10 shows power supply voltage during the active time of the TPMiS taken from the test setup with the TPMS development board and the AMS AS3992 UHF RFID reader demo board which is explained in Section 1.4.3.

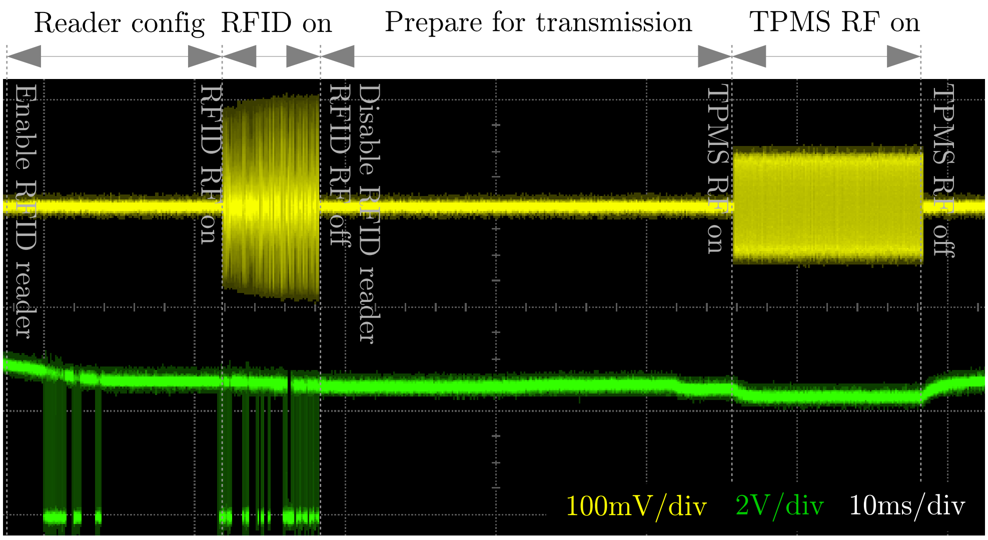

Figure 2.10: Power supply voltage during the active time of the TPMiS

The yellow signal is measured with an antenna and shows the RFID and TPMS protocol transmission sequences. The green signal is the Slave Select signal of the SPI communication. The beginning of the SPI communication also marks the start of the UHF RFID reader configuration via SPI. After the end of RFID communication, the supply voltage increases slowly, but this can barely be seen in the Figure 2.10. During this time, the micro controller located in the TPMS IC prepares the payload and configures the TPMS transmitter for the TPMS protocol.

The power consumption on the 3 V line is very low with the exception of the TPMS RF transmission. The voltage drop during this transmission is caused by the TPMS. After this transmission, the TPMS holds and waits until the next timer wake up where the whole communication will be repeated.

As Figure 2.10 shows the voltage already drops at the beginning of reader configuration. This voltage drop is caused by a battery drain, caused by the high power consumption of the UHF RFID reader. To avoid a negative influence of this voltage drop on the TPMS, its power supply voltage needs to be stabilized via the circuitry shown in Figure 2.11.

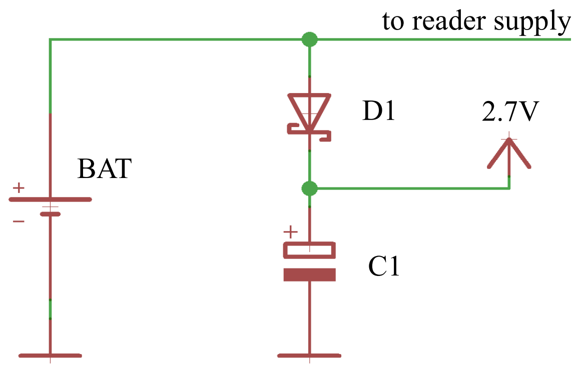

Figure 2.11: Circuit to avoid the voltage drop on TPMS supply line

The required electrical energy to power the TPMS IC is stored in the capacitor $C1$. The Schottky diode $D1$ prevents the discharge of this capacitor while the reader is enabled, but also causes a voltage drop of 0.3 V so that the TPMS supply voltage drops from 3 V to 2.7 V. As previously mentioned, the minimum voltage for the TPMS is 1.7 V. Therefore the voltage drop at the battery can be up to a maximum of 1 V when using a fully charged battery.
If the battery voltage drops below the required minimum of 2 V due to discharge or load, the system will no longer work.

2.4.3 UHF RFID Reader Supply Line

According to the data sheet [Aus10], the UHF RFID reader IC can be supplied with a voltage ranging from 4.1 V to a maximum of 5.5 V. The reader can be configured to work at a voltage between 5.3 V to 5.5 V or for a lower supply voltage ranging from 4.1 V to 5.3 V. Since the lower voltage range provides more flexibility for the supply voltage, it's used in this project.
The battery delivers a voltage of about 3 V. To bring the supply voltage for the UHF RFID reader to about 5 V a charge pump is used. To be able to chose a suitable charge pump and its external components several parameters of the battery and the UHF RFID reader need to be taken into consideration.
According to the data sheet of the selected battery the maximum continuous discharge current is 3 mA [Ren]. On the other hand the UHF RFID reader needs a maximum current of 120 mA while its RF field is active, which corresponds to the maximum RF

output power of 20 dBm (see [Aus10]). This is much more power than can be constantly supplied by the battery.
To figure out how much power the battery can deliver at peak load, the internal battery resistance must be measured. The battery is therefore short-circuited via an ampere meter and the short circuit current measured to be 480 mA. Since the load-free voltage of the battery is 3.1 V, the internal resistance can be calculated to 6.46 Ω. It should be noted, that these values are measured using a fully charged battery. A partly discharged battery has a higher internal resistance.
Since a voltage drop of 0.3 V at the battery is acceptable for the purposes of this project, the maximum allowable current can be calculated to approximately 50 mA. Based on theses parameters the „Maxim MAX1595“ charge pump was chosen. It can deliver a maximum output current of 125 mA. The regulated output voltage is 5 $V \pm 3\%$. The switching frequency is 1 MHz which is important when choosing the external components of the charge pump. Furthermore this charge pump requires only 3 external capacitors to work correctly, which helps to keep the system compact [Max11]. Figure 2.12 shows the charge pump which supplies the UHF RFID reader IC.

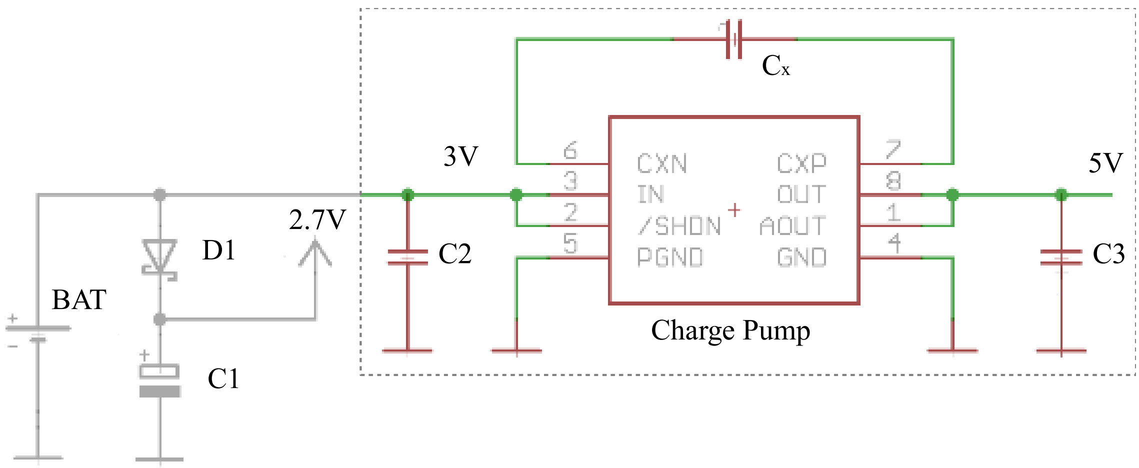

Figure 2.12: UHF RFID reader supply charge pump

Simply put a charge pump works by charging a capacitor and then switching it in line with the power supply to create a higher voltage. This is done at a high frequency to achieve a nearly constant power supply. The current flow through the charge pump, can be limited via this switched capacitor C_X. At the 1 MHz switching frequency of the chosen charge pump the capacitor gets charged for 0.5 μs and discharged for another 0.5 μs. Since the energy stored in the capacitor is available at output for 0.5 μs at a time the capacitor C_X can be used as a limiter for the current flowing through the charge pump. Using the the 50 mA current limit, the capacity of the C_X can be calculated to:

$$C_X = \frac{\Delta Q}{\Delta U} = \frac{50mA * 0.5\mu s}{5V - 3V} = 15.5nF \tag{2.2}$$

Limiting the maximum input current to 50 mA leads to a maximum output current of 30 mA. Since this is less then the current required by the UHF RFID reader IC large buffer capacitors are used after the charge pump to provide the neccessary current. To determine the energy needed by the UHF RFID reader for a complete operation cycle the current flow through the UHF RFID reader is measured by using a 1.1 Ω shunt resistor. Results can be seen in Figure 2.13.

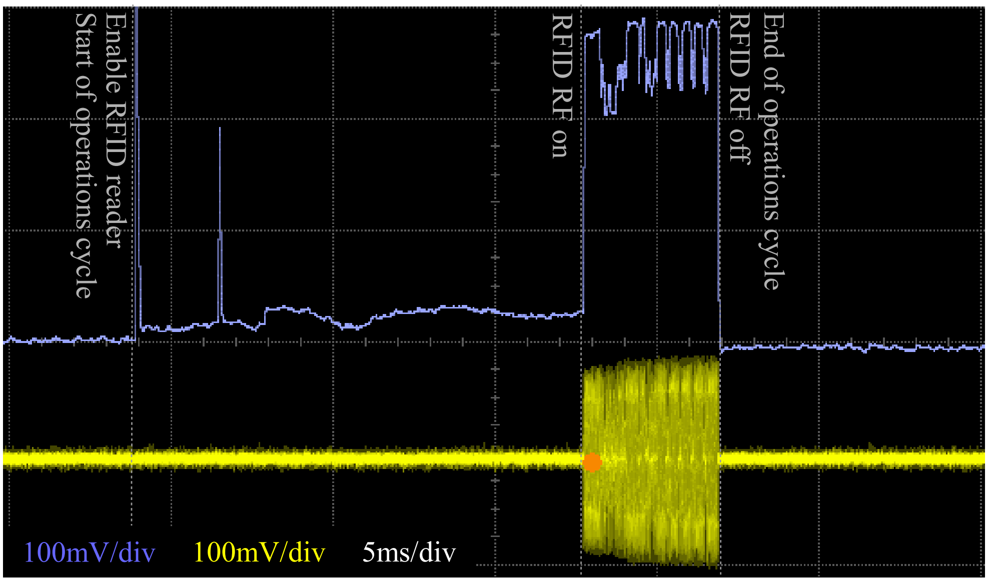

Figure 2.13: Power consumption (blue) of the UHF RFID reader IC during one operation cycle

The blue channel on the oscilloscope in Figure 2.13 shows the voltage measured on the 1.1 Ω shunt resistor. The yellow channel is the RF field radiated from the UHF RFID reader. This signal is measured with an antenna. The start of the operation cycle can be seen as a peak in the measured voltage (blue line). As can be seen, the enabled RF field has a high power consumption, which must be taken into account when choosing the buffer capacitor.

The reader needs approximately 23.5 mA during its 12.9 ms configuration phase. During its 6.4 μs transmission phase the peak current needed is 220 mA. Since the reader IC needs a minimum voltage of 4.1 V to function properly, a minimum supply voltage of 4.2 V is chosen for safety reasons, this results in a maximum voltage drop of 0.8 V. Using this informations the necessary capacity of the buffer capacitor C_3 can be calculated to:

$$C_3 = \frac{\Delta Q}{\Delta U} = \frac{23.5mA * 12.9ms + 220mA * 6.4ms}{0.8V} = 2139\mu F \qquad (2.3)$$

Chapter 3

System Implementation

3.1 Firmware Implementation on TPMS

The firmware on the TPMiS has two fundamental tasks. The first task is wireless communication with an UHF RFID tag which contains information about the tyre of a wheel. The second task is wireless communication with the central unit in the car which is handled via a special TPMS protocol.

The first task of development was to establish a communication between the TPMS and the UHF RFID reader. This is done by SPI and the other control functions described in Section 2.2. Once communication is established the next task is to configure and control the UHF RFID reader using the SPI.

The following sections show the detailed development of the TPMiS's firmware.

3.1.1 Test Hardware

An important aid to develop the firmware is the test hardware consisting of the TPMS development board and the UHF RFID reader demo board described in Section 1.4.3. The reader demo board has its own 8051 architecture micro controller which can control the reader IC. This is done by using the board's integrated communication interface. The final mayor component of the demo board is an analog UHF matching circuit with SMT antenna connector. This allows for any standard type of antenna to be connected to the demo board. The type of antenna used depends on the type of tag that needs to be accessed.

The board is powered by the development personal computer via the on-board USB connector. So no external power supply is needed. The 5 V needed by the RFID reader are directly supplied by the USB. The 3.3 V needed by the micro controller are supplied by the reader IC as described in Section 1.4.3.

Programming of the micro controller is handled by a JTAG (Joint Test Action Group) interface which is accessible via connectors located on the board.

The TPMS development board can be programmed directly via the USB interface on the board. As previously mentioned in Section 1.4.1 the TPMS IC contains an 8051 compatible

micro controller. This controller has the same instruction set as the micro controller on the UHF RFID reader demo board. The four GPIOs of the TPMS can be accessed via a connector interface on the board. The board also contains an UHF part that uses an SMT connector to connect any standard type of monopole and dipole antenna.
Debugging via the on-board programming interface is not possible due to the fact that the IOs are already used to communicate with the UHF RFID reader. Therefore an USB to UART converter is used to connect the development personal computer to the UART debug interface of the system. This allows the debugging of the micro controller's firmware via text output. The main advantage of using an UART interface for debugging purposes instead of using software debug break points is the much shorter time in which debug information can be obtained.

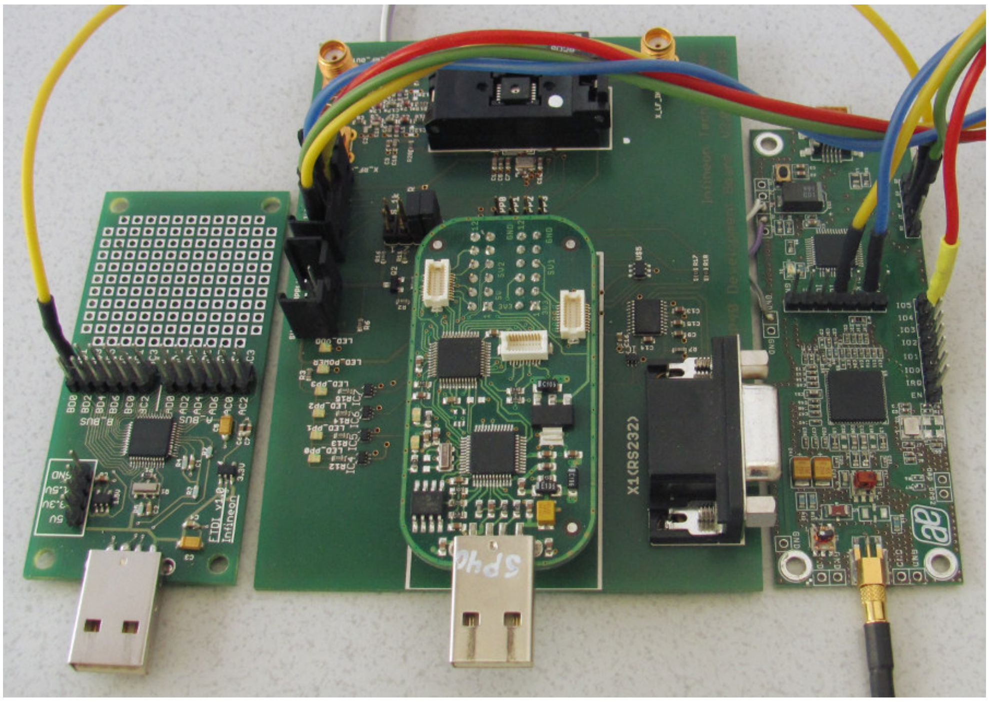

Figure 3.1: Test hardware setup

Figure 3.1 shows the complete hardware setup used during firmware development. The center board is the TPMS development board on which the control software runs. This board is connected to an Infineon generic micro controller program board called „UW-Link Board“ which is mounted on top of the TPMS development board, as can be seen in the figure. The TPMS IC itself is mounted on a black socket at the rear of the board. The board on the right hand side is the UHF RFID demo board which is described in Section 1.4.3. It is controlled via the cables connecting it to the TPMS development board. The board on the left hand side of the picture is the UART to USB converter used to send debug data directly to the personal computer.

This hardware setup was used to test the final software version before the hardware got combined on its own PCB (see Section 3.2). During the first stages of firmware development only the UHF RFID demo board was used. Once this part of software development was completed, the whole setup was used. The TPMS was used as the central micro controller, while the UHF RFID reader demo board's micro controller was used to simulate the inter-chip-logic. The UHF RFID reader was used to communicate with RDIF tags and the UART to USB converter board was used to communicate with the development personal computer. The detailes of the different test hardware setups are explained in the next sections.

3.1.2 Overview of the Firmware

As can be seen in Figure 3.2 the firmware is divided into several functional blocks. The two main firmware parts are the RFID and the TPMS part. The RFID parts responsibility is to obtain information about the wheels tyre. The TPMS part then transmits this data to the central unit in the car.

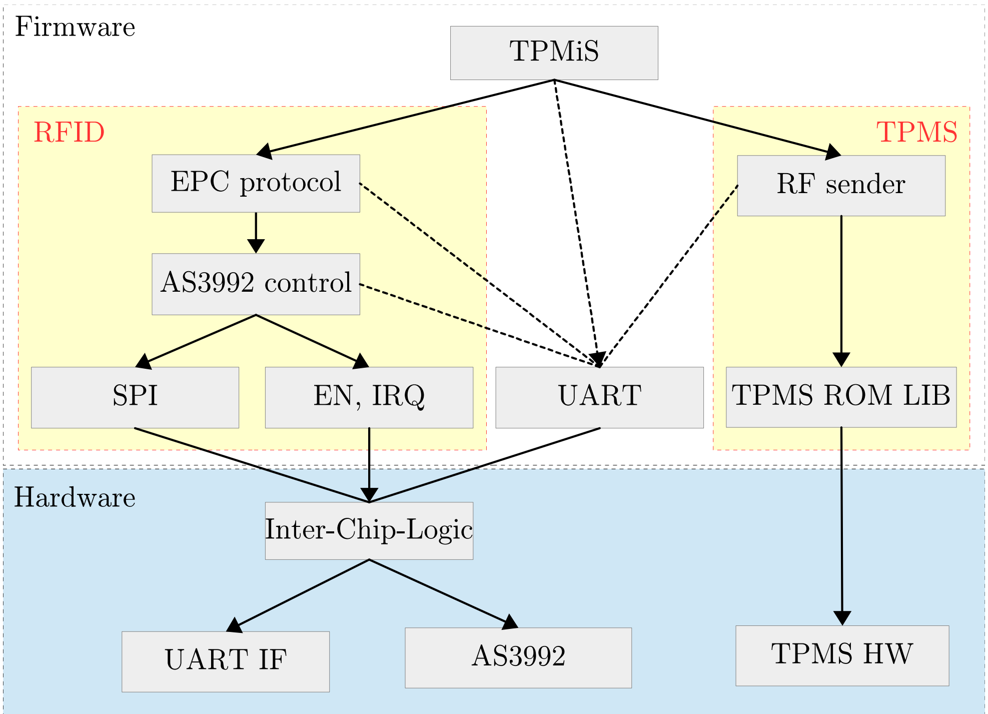

Figure 3.2: Overview of the firmware structure and the underlying hardware

The firmwares RFID part is split into three layers. The highest layer is the EPC protocol layer, which provides high level EPC compliant communication between the reader and the tag. A detailed description of the EPC protocol is available in Section 1.3 and the EPCglobal data sheet [EPC04]. The next layer is the „AS3992 control“ layer which configureres and controls the UHF RFID reader AS3992 IC. As previously mentioned in

Section 1.4.2, the reader can be controlled via SPI interface, interrupt request and chip enable. These interfaces form the lowest software layer in the RFID parf of the TPMiSs firmware and are directly linked to the inter-chip-logic hardware.
The TPMS part of the firmware is composed of two layers. The higher layer manages the protocol for the communication to the central unit in the car. Furthermore it is responsible for the compilation of the data to be sent. The underlying layer controls the hardware communication. This layer is hard coded in a ROM library on the TPMS micro controller. The last function block of the firmware is an UART interface which is used by both the RFID and the TPMS part to send debug messages to the development computer. The UART is also directly linked to the inter-chip-logic hardware.

3.1.3 TPMS to UHF RFID Reader Communication

The communication between the TPMS and the UHF RFID reader is divided into two parts which form the lowest layer of firmwares RFID part. The configuration and control of the reader is managed by the SPI interface. The other part is responsible for handling the chip enable and interrupt request signals. The implementation of both these parts is described in the next sections.

SPI interface

As previously mentioned in Section 1.4.2 the UHF RFID reader IC can be controlled via an eight bit parallel interface or an SPI interface. Due to the fact that the TPMS IC only has four available GPIOs the use of the SPI interface is necessary. Unfortunately the TPMS has no integrated hardware SPI module. Thus the SPI module has to be created in software.
The EPC Gen2 standard imposes certain timing constrains on UHF RFID communication which need to be adhered to. These limitations can easily be met when using the 8 bit parallel interface but are harder to achieve when using the SPI interface. The maximum achievable SPI communication speed is limited by timing constrains of the AS3992 reader IC. The relevant timing parameters are shown in Table 3.1.

Parameter	**Value**
Minimum clock high time	250 ns
Minimum clock low time	250 ns
Minimum data setup time	20 ns
Minimum data hold time	10 ns

Table 3.1: AS3992 timing parameters for SPI communication [Aus10]

Due to the fact that the SPI interface is so timing critical it already needed to be carefully considered during the system design phase, thus the implementation of this SPI interface is explained in Chapter 2 Section 2.2.2.

The resulting communication was measured with a digital oscilloscope. To show the results more clearly, the resulting graph has been edited using a graphics program and can be seen in Figure 3.3. The graph shows a complete transmit/receive sequence from the TPMS IC to the AS3992 reader. The operation shown in the sequence is a status register read. The first byte transmitted is the address of the status register on the reader IC while the second byte transmitted is the readers answer. The micro controller on the TPMS is the SPI master device and generates the clock and the data on MOSI. The data on MISO is prepared by the reader and is sent in sync with the clock signal. The rising edge of the CS „chip select“ terminates the sequence.

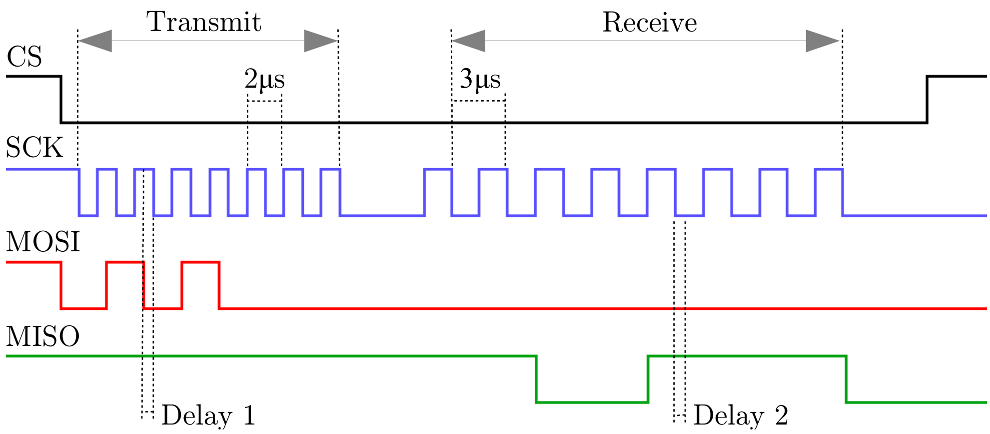

Figure 3.3: Software SPI communication

As already shown in Section 2.2.2 four instructions are needed to transmit one bit of data over the SPI. Since the system runs on an instruction cycle clock of 2 MHz this results in an SPI clock rate of 500 kHz during transmission. This results in clock high and low times of 1 μs which is more than the minimum required 250 ns defined in Table 3.1. The slave interface of the reader accepts the data on MOSI at the falling edge of the SPI clock.
According to the timing parameters of the AS3992 reader (see Table 3.1) the minimum data setup time (Delay 1 in Figure 3.3) is 20 ns and the minimum data hold time is 10 ns. To adhere to these limitation the data is set to MOSI one instruction cycle before the falling edge of the clock. The data is also held on MOSI for one instruction cycle after the falling edge of the clock. As shown in Section 2.2.2 one instruction cycle has a duration of 500 ns and is therefore long enough to adhere to the relevant limits.
Since the reception of one bit of data needs six instructions (see Section 2.2.2) the clock high and low times are 1.5 μs. This is more than the 250 ns required by the SPI interface of the reader IC. The data transmitted from the reader to the TPMS is set on MISO at the rising edge of the clock signal and will become valid on the TPMS at the falling edge of the clock. Since the TPMS needs one instruction cycle (Delay 2 in Figure 3.3) to store one received data bit and the data is available on the MISO pin for three instruction cycles, data can be safely transmitted from the reader to the TPMS.

In addition to the standard SPI transmit and receive functions other more specialized SPI functions are also required to react fast enough to the EPC protocol. These functions are a combination of the standard SPI transmit and receive functions. To save time these functions do not call the standard transmit and receive functions, but instead execute a copy of them. These functions are particularly advantageous to read and write registers on the reader which are more than one byte deep. This is due to the fact that they avoid the calling of sub functions in a loop which takes a relatively long time to execute. One example of these specialized functions is the so-called `read_check_write` function of which the program flow can be seen in Figure 3.4

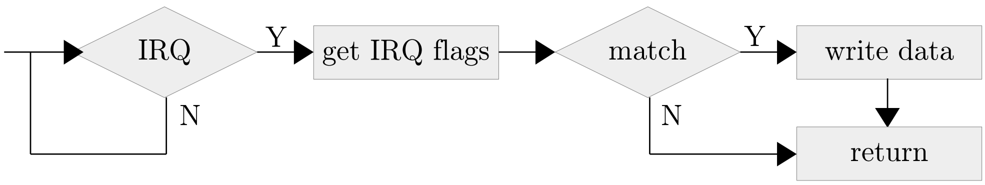

Figure 3.4: Program flow of the `read_check_write` function

Once this function is started, a program loop waits for an interrupt from the reader IC. This program loop has a time out to prevent a „deadlock“. If an interrupt occurs the function reads out the interrupt request status register on the reader via SPI. If the flags in this register match the function parameters, the function sends back a predefined answer or command. If the flags do not match the parameter, the function will return without performing any communication. This function is implemented for the most timing critical part of the firmware, where the reader has to answer to a pattern transmitted from an UHF RFID tag in a relatively short amount of time. More information about these timings can be obtained in the EPC Gen2 data sheet [EPC04].

Chip Enable

Even in its idle state the AS3992 UHF RFID reader IC has a high power consumption. In this idle state the reader needs a current of a few mA. If the IC is disabled via „chip enable“ (EN), the current drops to a few μA. Since the battery can not continuously deliver the current needed for the IC, the system needs to be able to disable the reader if it's not needed.

Due to the fact that the TPMS only offers four GPIOs for the communication with external hardware, it was already necessary to take the chip enable function into consideration during the design phase. It is therefore already explained in Section 2.2.4.

Interrupt Signal

Since the TPMSs four GPIOs also need to handle interrupt signals this had to be taken into consideration during the design phase. Interupt sinal handling is therefore already explained in detail in Section 2.2.4.

3.1.4 AS3992 UHF RFID Reader Control

Above the SPI communication layer sits the reader control layer which is responsible for the configuration and control of the AS3992 reader IC. This control layer is divided into three parts. The first part is responsible for accessing the control register on the reader IC. The second part is responsible for accessing the status registers of the reader. This part is also responsible for obtaining information about measurements performed by the reader IC regarding the RFID communication. The final part directly controls the reader IC via so-called direct commands. This commands can be used to perform tasks such as the transmission of a preconfigured EPC query pattern. All this communication between the TPMS micro controller and the AS3992 reader is handled by the SPI interface and the interrupt signal. The first byte sent from the SPI master is a command or configuration register address followed by one or more data bytes. To distinguish between a configuration or a command sequence the following addressing is used:

Bit	Bit Function	Address	Command
7	0 = Address, 1 = Command	**0**	**1**
6	1 = Read, 0 = Write	R/W	Not used
5	1 = Continuous mode, 0 = Single mode	C/S	Not used
4	Address bit	Adr4	Cmd4
3	Address bit	Adr3	Cmd3
2	Address bit	Adr2	Cmd2
1	Address bit	Adr1	Cmd1
0	Address bit	Adr0	Cmd0

Table 3.2: Address mode and command mode on SPI [Aus10]

The most significant bit (MSB) of the first byte sent via SPI defines whether the byte should be interpreted as an address to access a register or a command to perform a task. As previously mentioned, it is possible to read and write registers on the reader IC. The differentiation between a read or write access is handled by bit six of the first byte sent. Since registers are often more then one byte deep, a differentiation between single and continuous mode needs to be made, which is handled by bit five. In single mode only one byte of the register can be accessed, while in continuous mode several bytes can be accessed. Continuous mode communication ends with the rising edge of the SPI slave select signal which is the stop condition for this mode. In command mode bit five and six serve no function. The other 5 bits are used as address or command bits, depending on the mode used [Aus10].

Registers on AS3992 UHF RFID reader

There are three types of registers on the AS3992 reader IC, the control registers, First In First Out (FIFO) register and test registers. The control registers are further divided into configuration and status registers. The configuration register are used for the configuration itself, which is responsible for the behavior of the reader IC. The status registers provide information about the SPI communication between the TPMS and the reader IC, as well as the RFID communication between the reader and a tag. Data exchange is handled by a 24 byte deep FIFO transmit and receive register, which stores the RFID communication data. The FIFO register also contains an RX/TX length register to store the length of the communication data. The test registers are used for testing and measuring purposes only. Table 3.3 gives an overview of the registers of the AS3992.

<table>
<tr><th colspan="4">Registers on AS3992</th></tr>
<tr><td colspan="2">Control registers</td><td rowspan="2">FIFO registers</td><td rowspan="2">Test registers</td></tr>
<tr><td>Configuration registers</td><td>Status registers</td></tr>
</table>

Table 3.3: Overview of the registers on the AS3992 reader IC [Aus10]

For better handling the configuration registers are further divided into the „main control registers“ and the „protocol sub-setting registers“ [Aus10]. The two main control registers are responsible for chip status control and main protocol control. Chip status control includes functions such as power mode, global reader settings and transmitter and receiver module enable. Main protocol control covers functions such as protocol selection, RX decoding select and TX communication speed settings.

For a more detailed protocol configuration the protocol sub-setting registers can be used. The most important register of the protocol sub setting registers is responsible for the configuration of the EPC specific protocol settings. Section 2.3.1 and 2.3.2 already cover most of these protocol settings in detail.

Another important configuration setting for the TPMiS project is the transmission output power level adjustment. Since the maximum output power, as demanded by the project specifications is 5 dBm (see Section 1.1) the power level needs to be adjusted accordingly. Further settings included in the protocol sub setting register include among others the transmission speed for the communication between the reader and the tag, communication preamble length and reader voltage range.

The status registers provide status informations about the reader. The most important status register are the interrupt status register and the interrupt status mask register. The latter is responsible for enabling and disabling different types of interrupts. The AS3992 reader provides only one interrupt signal which only reacts to the enabled interrupt types of the reader. After detecting this interrupt signal, the external MCU has to access the interrupt status register to find out which interrupt was triggered. Accessing this status register also resets the interrupt signal.

The FIFO registers handle the communication data of the UHF RFID communication. Data stored in a 24 byte deep FIFO transmit and receive register. The length of the communication data is stored in special RX and TX length registers. The FIFO transmit and receive register can be configured to send or receive more than 24 bytes of data. If the register is configured in such a way an interrupt is sent as soon as the FIFO registers are nearly empty in transmit mode or nearly full in receive mode, so that a connected MCU can fill up or empty the registers. Unfortunately the software SPI interface implemented on the TPMS is too slow to react on these interrupts. Therefore the maximum transmittable data size for RFID communication is 24 bytes.
The test registers are used for measurements on internal function blocks. The most useful data in the TPMiS project taken from the test registers are the Received Signal Strength Indicator (RSSI) values of the two receive channels. These values are available after the reception of data from a tag and can be read out until a new transmission to a tag is started.

Figure 3.5: SPI access for reader configuration

Figure 3.5 shows a reader configuration sequence via SPI. The first byte transmitted contains the address of the target register and begins with a „0“ to denote address mode. The following bytes are data bytes which either are transmitted to the reader to change the configuration or in case of a register read, data bytes transmitted from the reader to the MCU. As previously mentioned in Table 3.2 this depends on bit six of the address byte (R/W). Bit five of the address byte (C/S) defines if more than one data byte is accessed. In this case the data transmission ends with the rising edge of the SPI slave select signal. The functions who are responsible for this communication are as follows:

```
void as3992_set_register(u8 address, u8* idata config_word,
    u8 config_word_length);
```

```
void as3992_get_register(u8 address, u8* idata config_word,
    u8 config_word_length);
```

All the other functions which read or write to the registers on the AS3992 are using these basic functions. The function `read_check_write` described in Figure 3.4 is an exception due to the fact that useing these two functions would be too slow for its task.

Direct Commands

The so-called direct commands do not directly interact with the registers on the reader IC. Instead they instrict the reader IC to perform certain tasks such as transmitting an

EPC query, resetting the FIFO or transmitting an EPC ACK. This is done using the configuration information and data stored in the registers. Just like the register access, theses commands are transmitted via SPI to the reader IC. The reader detects a direct command on the most significant bit which for direct commands is always „1“. The length of a command is always one byte. Table 3.4 shows the most important commands for the TPMiS project.

Hex cmd	**Command description**
8F	Reset FIFO
90	Transmission with CRC
98	Transmit an EPC query
99	Transmit an EPC query reply
9D	Transmit the EPC ACK

Table 3.4: Most important commands for the TPMiS project [Aus10]

The „reset FIFO“ command resets the FIFO pointers and clears all interrupt flags. This command is used for example before any new write process to the FIFO. The transmission commands are used to either transmit an EPC specific pattern or the data stored in the FIFO via the RFID channel. The „transmission with CRC“ command transmits the data stored in the FIFO and adds a 5 or 16 bit CRC at the end of the pattern. The length of the CRC can be configured via a configuration register [Aus10].
The other Transmit commands are custom-built for specific commands necessary for the EPC UHF RFID communication. More information about these commands can be obtained in Section 1.3 of the Introduction chapter and in the next section, which describes the overlying firmware layer [Aus10].

3.1.5 Control of the UHF RFID Communication (EPC)

The EPC layer handles the EPC Gen2 compliant communication between the UHF RFID reader and the tag. It is based in the underlying layer which directly controls the reader IC (Figure 3.2 on page 37). It uses the register access and command functions of the AS3992 control to configure the reader IC and prepare the data to be transmitted via RFID [Aus10].
The main task of this layer is to provide the EPC standard functions required to perform an inventory round which is used to access a tag in the RF field of the reader. More precisely, the inventory round is a process in which an interrogator (a reader) identifies a tag to subsequently access it [EPC04].
Before an inventory round begins, a so-called **Select** command is sent to select a particular tag population based on certain criteria. The tags can be selected based on the contents of their memory banks. If a tag's memory bank contains information which matches the information of the select command, the tag changes its inventory flags based on the

select commands parameters. For this comparison the select command contains a pointer denoting the starting position in the memory and a bit mask to compare it to [EPC04].
The **Query** command is the first command of the inventory round. The previously selected tags are now configured for the following RFID communication. This configuration contains the following essential information:

- Backscatter link frequency
- Modulation
- Preamble length
- Number of slots in the inventory round

The number of slots in the inventory round defines the degree of the collision avoidance during the inventory round.
The next command in the inventory round is the **Query-Reply** command which is part of the collision avoidance mechanism. The collision avoidance mechanism is explained in detail in Section 1.3.3. The only important information during this part of firmware implementation is the fact that the query-reply command needs to be sent until the tag replies. The tag replies by sending a randomly generated number. To acknowledge the reception of this reply, the same number must be sent back to it via the so-called **ACK** command. The tag replies to this ACK command by sending its identification data which consists of the Protocol Control (PC) and the EPC. The PC contains information about data sent while the EPC is the actual ID of the tag. Once the ID is received the inventory round is finished and the tag can be accessed [EPC04]. However, for the purposes of the TPMiS project the identification of the tag is already sufficient. Accessing of the memory of the tag will be implemented at a later stage.
The next couple of paragraphs show the implementation of these functions in the firmware.

```
u8 gen2_select(u8 target, u8 action, u8 mem_bank, u16 pointer,
               u8 mask_length, u8* mask, u8 truncate);
```

This first function is the select function which can be used to configure the tags within the range of the RF field. This function is not directly supported by the AS3992 reader IC and must be fully implemented in the MCUs software. The first step is to prepare the reader for the following transmission by sending the „transmission with CRC“ command. The next step is to tell the reader the exact length of the data which needs to be sent by writing the full byte size and the remaining broken bit size to the „TX length registers“ on the reader IC. After that, the data to be transmitted via RFID must be loaded into the transmission and receive FIFO registers. The transmission starts after the third byte is written to the FIFO. If less than three bytes have been written to the FIFO, the RFID transmission starts after the end of the FIFO data transfer.

```
void gen2_query(u8 dr, u8 m, u8 tr_ext, u8 sel, u8 session, u8 target,
                u8 q);
```

The query function is easier to implement, because it's natively supported by the reader IC. The configuration data passed on by the function to the reader must be arranged as required by the EPC standard before being sent to the FIFO registers. The transmission of the generated query pattern starts immediately after the data has been written to the FIFO registers.

```
void gen2_query_rep(void);
```

As previously mentioned the query reply command is part of the collision avoidance mechanism. After a query command has been sent via RFID the query reply command must be repeated by the TPMSs firmware until a tag answers or the maximum number of replies has been reached. Since the command is fully supported by the reader IC, the TPMSs firmware only has to send the „transmit EPC query reply" command without any further parameters.

```
u8 gen2_ack_fast(void);
```

If a tag receives the query reply pattern via RFID, it answers with a random number which must be sent back to the tag to acknowledge the correct reception of this random number. This is the task of the `gen2_ack_fast` function. This function is called directly after a query or query reply function to await a random tag number. Once such a number is received, the same number is immediately sent back to the tag and the function returns. This part is very time critical due to the use of the relatively slow software SPI communication between the MCU and the reader. To realize a fast reply to the random number (the acknowledge) an optimized assembler function called `read_check_write` is used. This function is explained in figure 3.4 on page 40.
After the tag received the acknowledge, the tag answers with its ID which then can be read form the FIFO registers. The first two bytes of this identification data are the protocol control bytes which contain among other information the length of the EPC ID. The MCU reads these first two bytes to determine the length of the EPC. Once the size has been determined, the tags EPC can be read from the FIFO registers.

3.1.6 TPMS RF communication

The tag ID collected by the RFID part must be sent from the TPMiS to a central unit in the car, which can do further processing of this data. The task of the TPMS part of the firmware is to prepare the data for sending, to configure the transmission hardware and to start the transmission procedure via a special TPMS protocol. The functions needed for the transmission procedure are implemented in hardware and can be easily accessed via a software ROM library located on the TPMS.
The first task for the software on the MCU is to prepare the data for transmission in accordance with the special structure of the TPMS transmission protocol (see Figure 3.6).

Sync 1	Sync 2	Data ...		CRC8	EOM	EOM

Figure 3.6: TPMS transmission protocol

The first two synchronisation bytes must match the preamble expected by the receiver side. The following bytes of the transmission are data bytes. The size of the data package must be defined in the hardware transmitter configuration settings. The next data byte is an eight bit CRC. The TPMS contains a hardware CRC module which can generate an eight bit CRC in three instruction cycles, so this task can also be handled by the hardware. The last two bytes of the message are End Of Message (EOM) bytes.
The configuration of the TPMS hardware transmission module is handled by setting several Special Function Registers (SFR). Table 3.5 shows the transmitter configuration settings used in the TPMiS project.

Configuration	**Value**
RF Carrier wave frequency	434 MHz
Modulation	FSK
Frequency deviation for FSK	75 kHz
Baudrate	9600 $Baud$
Encoding	Manchester
Transmission bit length	Send buffer size

Table 3.5: Configuration settings of the TPMS transmitter

After the configuration of the transmitter the TPMSs MCU is switched to sleep mode via a special function. This function also activates the low power transmission mode integrated in the TPMS, which does not need the MCU. The low power transmission is controlled by an independent state machine which has access to the upper 128 byte of the RAM. Due to this fact the transmission data must be stored starting at the 129^{th} byte of the RAM. The MCU remains in sleep mode after this low power transmission. After a preset wakeup interval the MCU returns to normal mode to perform the next cycle.

3.1.7 Overview of the implemented Communication Process

Finally, as conclusion of the firmware implementation of the wireless communication part of the TPMiS Figure 3.7 gives an overview of the entire communication flow between the RFID tag, the RFID reader, the TPMSs MCU and the TPMS RF transmitter.

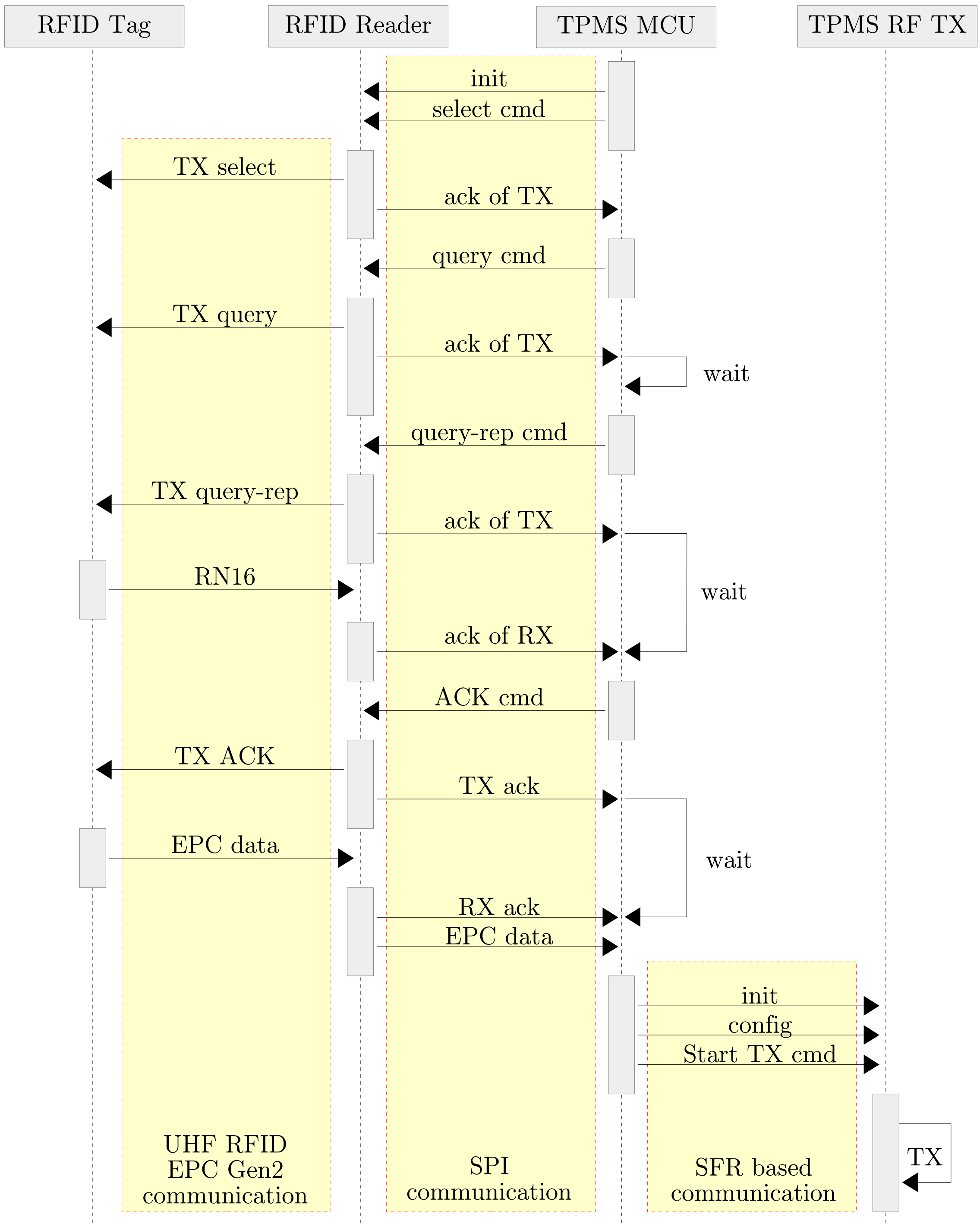

Figure 3.7: Sequence diagram of the whole TPMiS communication

The diagram shows an example in which the tag answers to the first query-reply command sent from the RFID reader. As can be seen the TPMSs micro controller unit manages the most of the communication flow. It has to configure and control all the other communication interfaces while preparing all the necessary data and adhering to all timing limitations.

3.1.8 Debug Interface

The debug interface is an important part for the firmware implementation. Although this section is explained at the end of the firmware implementation part, it was one of the first implementation steps. This made it possible to debug the firmware during most of the implementation. The first debug interface used was a software UART interface, which was identical to the integrated hardware UART interface.
The reason for which the UART interface is implemented in firmware is the complex structure of the inter-chip-logic, explained in section 2.2.5. As previously mentioned the SPI interface and the UART interface share the same four GPIO pins available on the TPMS IC. The SPI idle state for the MOSI and MISO signal is low, while the idle state of a standard UART RX and TX signal is high. To avoid this conflict between the SPI and the UART interface, the UART interfaces idle state must be inverted. So, in a second step the UART interface was changed to work with inverted signals. This is not supported on the hardware UART of the TPMS IC. The hardware inter-chip-logic inverts the UART signals again to there normal signal levels. Any external UART device can communicate with the TPMiS without any restrictions.
The software UART is written in assembler and is designed to work at different data rates. Since the UART standard works with an odd parity bit a parity generator has also been integrated into the software. Figure 3.8 shows a standard UART signal which must be approximated by the software. The upper signal is the transmission of one byte with the hexadecimal value `0x91`. The lower pattern shows the time at which the receiver should sample the TX signal.

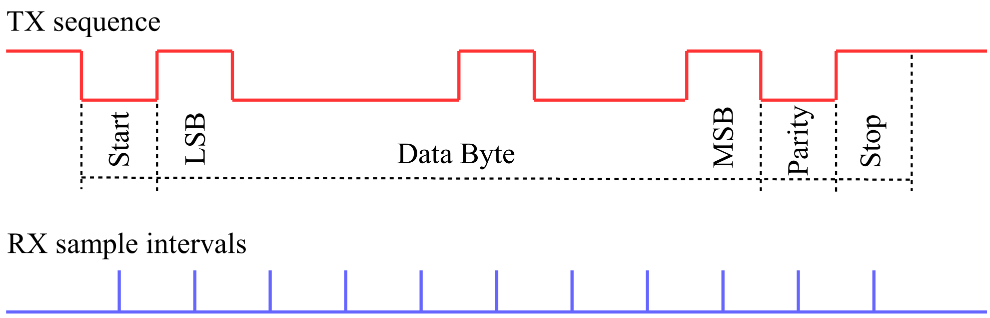

Figure 3.8: UART TX transmission and RX sample intervals

For ease of understanding the following explanations use the standard transmit and receive levels of the UART interface instead of the inverted versions actually implemented on the TPMiS.
To begins the transmission the assembler written UART transmit function clears the TX signal to send the start bit. The function must then wait for a specific amount of time, which depends on the configured transmission speed. To know how many instruction cycles the function needs to wait detailed knowledge of the instruction set and the instruction cycle length of every used instruction is needed. Fortunately most of the instructions used only need one instruction cycle. The MCU runs at an instruction cycle speed of 2 MHz (see Section 2.2.2).
The next step is to send the data bits via the TX signal. The data byte is send by beginning with the least significant bit (LSB). To achieve the necessary transmission bit length a wait function has to be used. To calculate the parity bit which needs to be sent after the data byte a counter counts all the high bits of the transmission. Finally the transmission stops by setting the TX signal to high which also returns it to its idle state.
The receive function waits for a falling edge on the RX signal and then starts the reception of the data. After this falling edge the receive function waits for half a bit length interval to sample the first received bit in the middle of the bit length. After that the RX signal is sampled with a one bit length interval (see Figure 3.8). The next eight received bits are data bits. They are followed by a parity bit which is checked immediately after its reception. Finally the stop bit is received to complete the reception and the function returns the received data. If the parity bit or the stop bit were not detected correctly, the function returns an error code.
As previously mentioned, the transmission speed can be configured via wait cycles. The number of these wait cycles has to be passed on to the send function as an argument in addition to the transmission data byte. The following equation shows the calculation of the number of wait cycles:

$$wait\_cycle\_count = \frac{instruction\_cycle\_speed}{2 * baudrate} - 10 \tag{3.1}$$

The maximum speed which can be reached with this software UART is 100 kBaud using a `wait_cycle_count` of zero and the minimum speed is approximately 3.9 kBaud using a `wait_cycle_count` of 247 which is the maximum number of wait cycles.

3.2 The Printed Circuit Board

This section and its subsections describe the hardware implementation of the TPMiS project. The system design chapter already explained the general functions which must be handled by the hardware. Hereby the hardware components are only functionally described. The following subsections describe the detailed implementation of this hardware. Similarly to the firmware implementation the hardware is also divided into a TPMS and an UHF RFID communication part. The communication between these two parts is handled by the inter-chip-logic, which is now implemented in hardware. Since the TMPS and the UHF RFID parts require different operating voltages the power management system is needed to supply both from the same battery. Since the TMPS and the UHF RFID parts work at different frequencies both need their own antenna matching network. Figure 3.9 gives another overview of the hardware components of the TPMiS project.

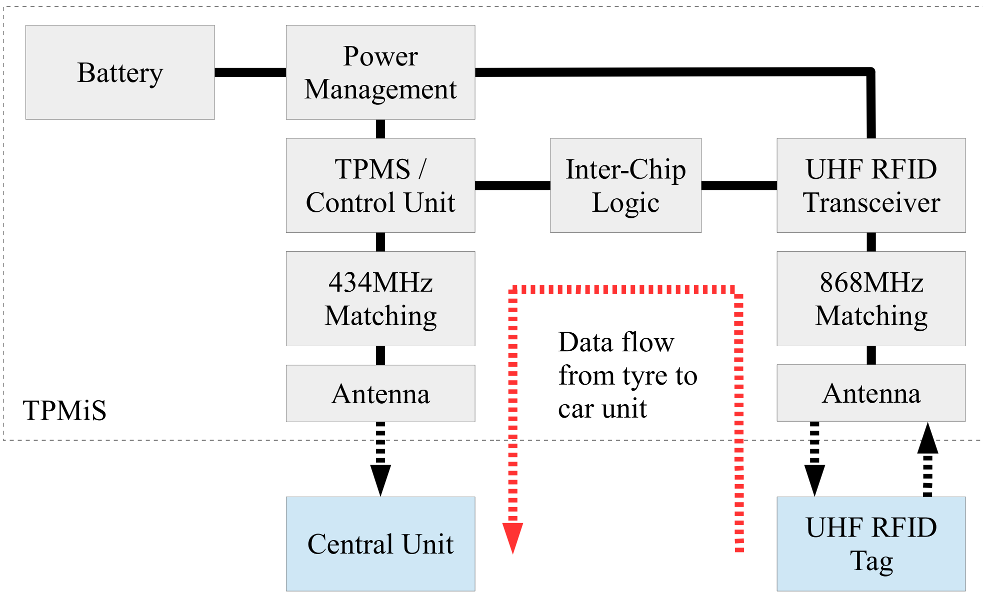

Figure 3.9: Overview of the hardware components of the TPMiS project

The TPMS part (on the left) and the RFID part (on the right) can be seen as two independent systems, whereby the TPMS part contains the micro controller which acts as the master control unit of this board. As previously mentioned the TPMSs MCU controls the RFID part via the inter-chip-logic.
The choice of the actual hardware depended on two main factors. Size was a big issue, since the system needed to be kept as compact as possible. On the other hand power consumption was also a big issue since not all of the hardware components can be shutdown to save energy.

The PCB was designed using the Eagle PCB layout editor by CadSoft. The library of this editor does not contain all of the hardware components required for the project, so some parts had to be added using the integrated library edit functions.
Figure 3.10 shows the Eagle layout of the final design of the PCB which contains the whole functionality described in the system design chapter. The upper half of the board contains the TPMS part while the lower half contains the RFID part.

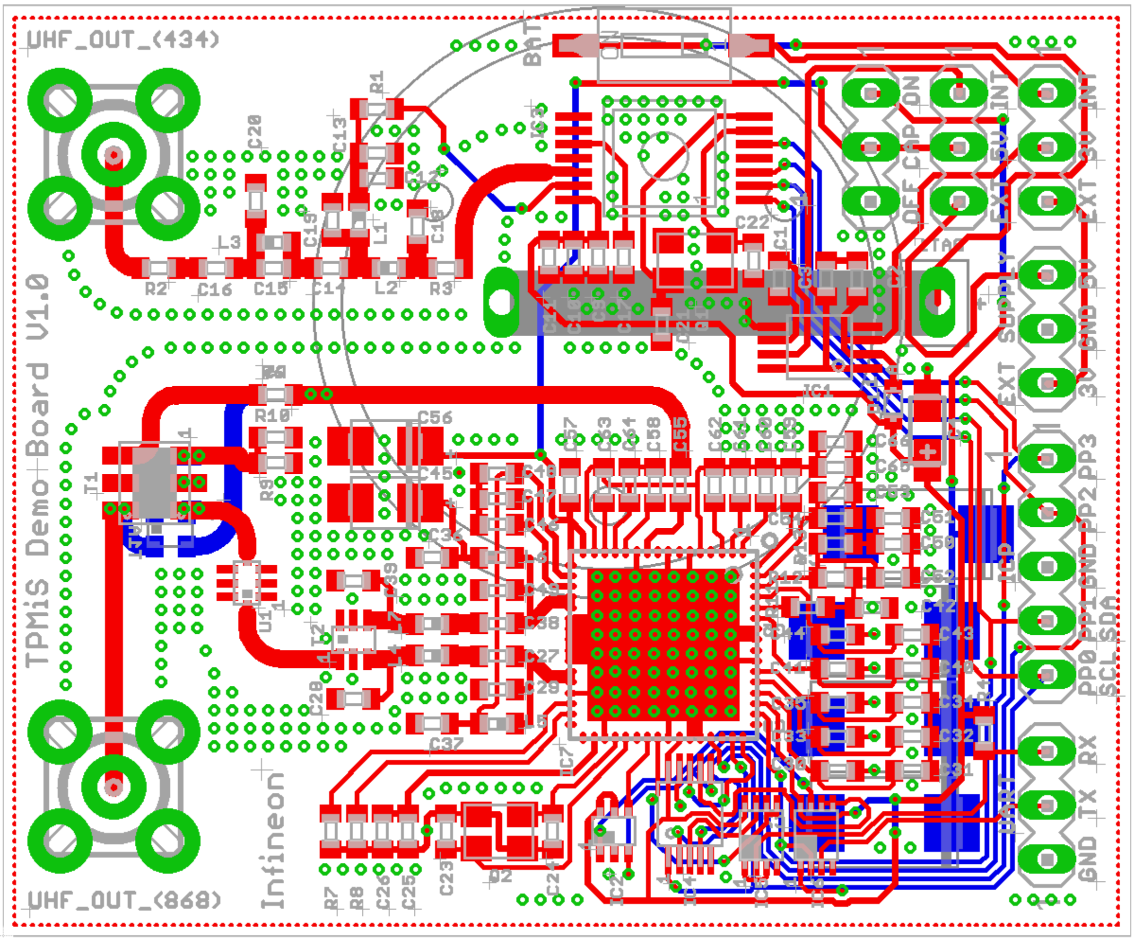

Figure 3.10: Final PCB design (upper side shown in red, bottom side shown in blue)

On the right hand side of the PCB connector pins and jumper pins are located. The connector pins are subdivided into power pins, GPIO pins and UART debug pins. The jumper pins in the upper right hand corner of the PCB are installed for debugging purpose. The large IC in the upper half of the PCB is the TPMS and the large IC in the lower half is the AS3992 UHF RFID reader. Both ICs have there own analog UHF matching network and antenna on the left hand side. The large components located on the bottom side of the PCB, are part of the power management which is described in the next section.

3.2.1 Power Management

As previously mentioned in Section 2.4 of the system design chapter the TPMiS works with two different voltage levels. The first level is the 3 V level which supplies the TPMS IC and its logical environment. The higher voltage level of 5 V supplies the UHF RFID reader. Figure 3.11 shows the implementation of the whole power management on the PCB.

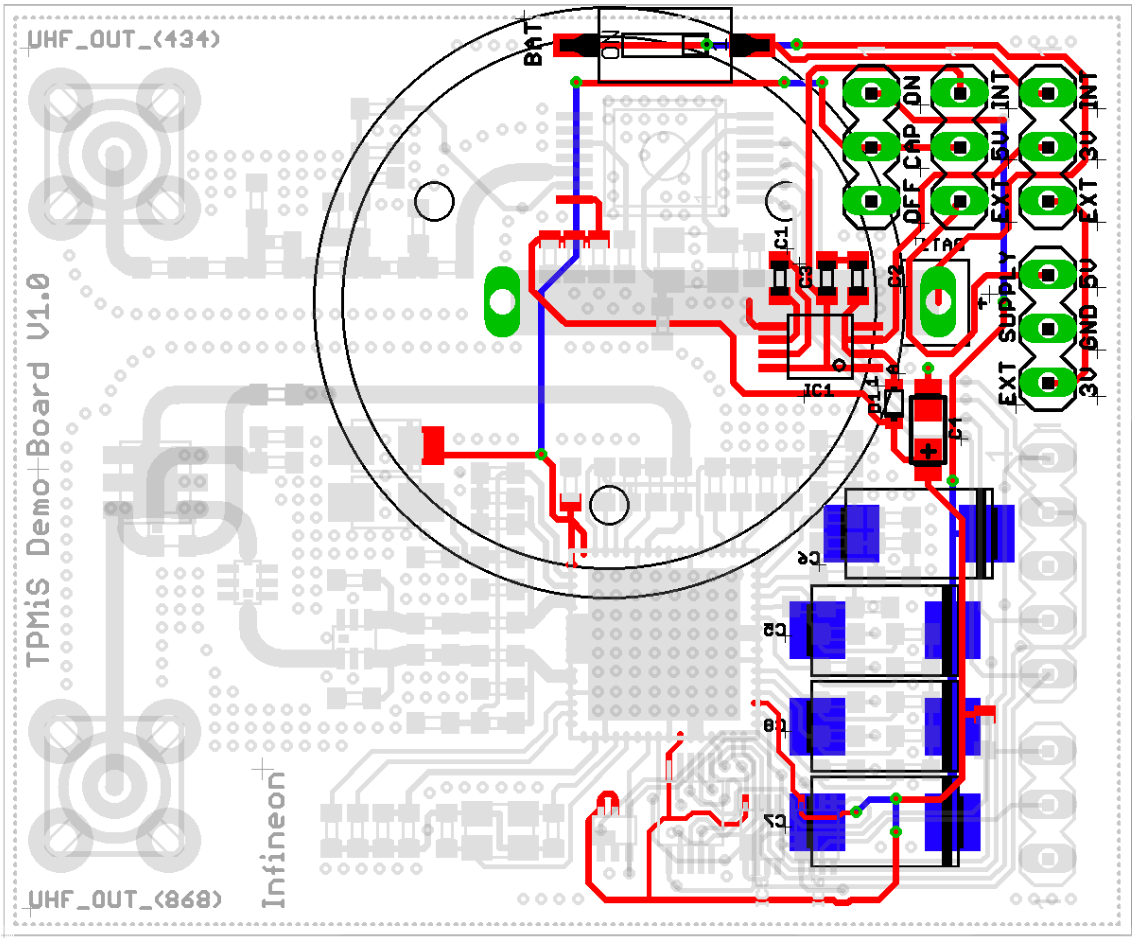

Figure 3.11: Power management

The largest part on the bottom side of the PCB is the battery. The chosen lithium button battery has a load-free voltage of 3 V. The TPMS and the logical components are directly powered by the battery. The UHF RFID reader requires a charge pump to supply it with 5 V. Since the maximum current required by the reader IC is more than the battery can deliver with an acceptable voltage drop, the four large capacitors on the bottom side of the PCB are used as buffer capacitors for the 5 V line.

The chosen charge pump is a „Maxim MAX1595“ which can deliver a maximum output current of 125 mA. The regulated output voltage is $5\ V \pm 3\%$. Its switching frequency is 1 MHz [Max11]. As already calculated in Equation 2.2 a 15.5 nF capacitor is required.

Since 15.5 nF capacitors are not commercially available a 15 nF capacitor is used.
As previously mentioned in Section 2.4.3 the battery should only be loaded with a maximum current of 50 mA. Since the UHF RFID reader needs a much higher current then this, a buffer capacitor needs to be used to supply the necessary current. The necessary capacity has been calculated in Equation 2.3 to a value of 2139 μF. Since such capacitors are not commercially available four 680μF capacitors are used.
The TPMS part on the PCB is directly supplied by the battery. To avoid a voltage drop on the 3 V supply line due tu the high power consumption of the reader on the 5 V supply line, the 3 V supply line has its own buffer capacitor (see Section 2.4.2). A 15 μF capacitor is used for this purpose. For debugging and development purposes an external power supply can be connected via connector pins located on the PCB. The jumper field in the right upper corner allows for the configuration of the usage of the external power supply. One jumper allows the configuration of the 3 V line which can either be supplied by an external power supply or by the internal battery. The 5 V line can be configured in a similar fashion, it can either be supplied by an external power supply or by using the charge pump. The jumper field also allows the deactivation of the buffer capacitors, to perform current measurement on the 5 V line during load.

3.2.2 Inter-Chip Communication and Debug Control Logic

Communication between the TPMS IC, the RFID reader IC, the UART debug interface and the program interface is handled via the inter-chip-logic. The function has already been described in the system design chapter and is shown in Figure 2.5. As can be seen, the inter-chip-logic requires a considerable amount of logic components.
All these different components need a lot of space on the PCB. Thus, it is desirable to reduce the number of components. To switch between the SPI and the UART interface the inter-chip-logic uses a multiplexer and demultiplexer which both can be switched using the slave select line. Furthermore there a so-called „delay flip flop“ (D-FF) is used for the chip enable logic. These components can not be replaced by any other component to save space on the PCB because their functionality is too complex. The logic AND, OR and inverter components that are also needed by the inter-chip-logic can however be replaced by NAND gates to reduce the component count on the PCB. The chosen IC packages two NAND gates each having two inputs into a small VSSOP8 package.
To replace the logic OR function three NAND gates are required. The following equation shows the logic replacement according to the DeMorgan's theorem:

$$A \vee B = \overline{\overline{A \vee B}} = \overline{\overline{A} \wedge \overline{B}} \tag{3.2}$$

Since one input of the OR of the inter-chip-logic is connected to one of the inverters of the UART interface, the OR and this inverter can be replaced by two NAND gates. The other inverter on the UART interface is replaced by an other NAND gate. The AND gate of the inter-chip-logic is replaced by a fourth NAND gate. The inverted output of the NAND gate needs to be compensated for by the software. Instead of placing three IC packages onto the PCB only two double NAND IC packages need to be placed on the PCB to perform all the necessary logic functions. The only other packages required by the inter-chip-logic are a small SOP23 package for the D-FF and a VSSOP10 package which holds the required multiplexer and demultiplexer.

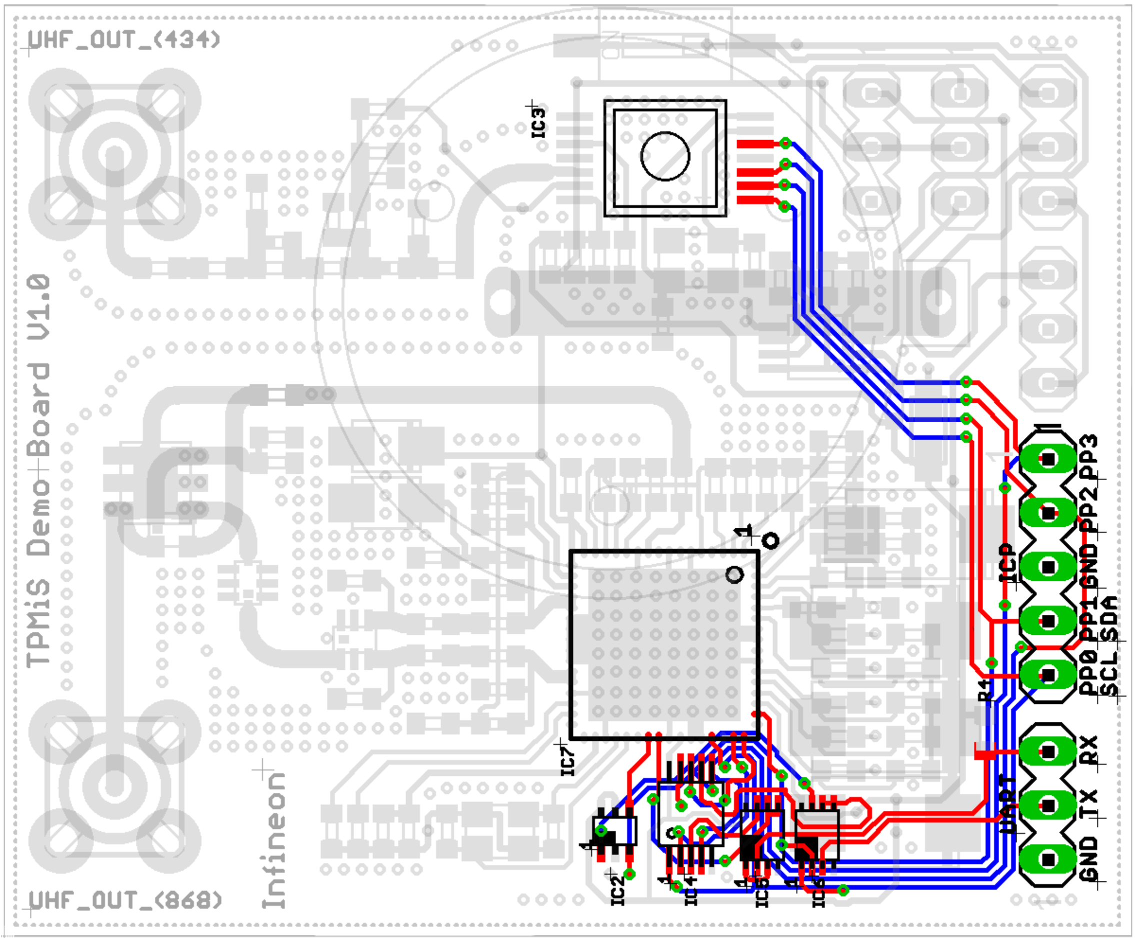

Figure 3.12: Inter-chip-logic

Figure 3.12 shows the whole inter-chip-logic part of the TPMiS PCB. The TPMS IC (IC3) is in the upper half of the PCB and the UHF RFID reader IC (IC7) in the lower half of the PCB. The inter-chip-logic components are located below the reader IC. The D-FF (IC2) is directly connected to the chip enable pin of the reader. IC4 contains the multiplexer and demultiplexer. IC5 and IC6 contain the four necessary NAND gates.
The upper interface port (ICP) on the right hand side is used for debugging purposes in the initial startup phase of the system and as a program flash interface for the TPMSs micro controller. The interface below the ICP is the UART interface which can be used by the TPMS micro controller to output debug messages to a personal computer.

3.2.3 Analog UHF Frontent

The TPMSs 434 MHz analog matching network as well as the UHF RFID readers 868 MHz analog matching network are copied directly from their respective development boards used during the firmware development phase. As can be seen in Figure 3.13 the upper part of the PCB contains the TPMSs matching network while the lower part of the PCB contains the UHF RFID readers matching network and receiver path.

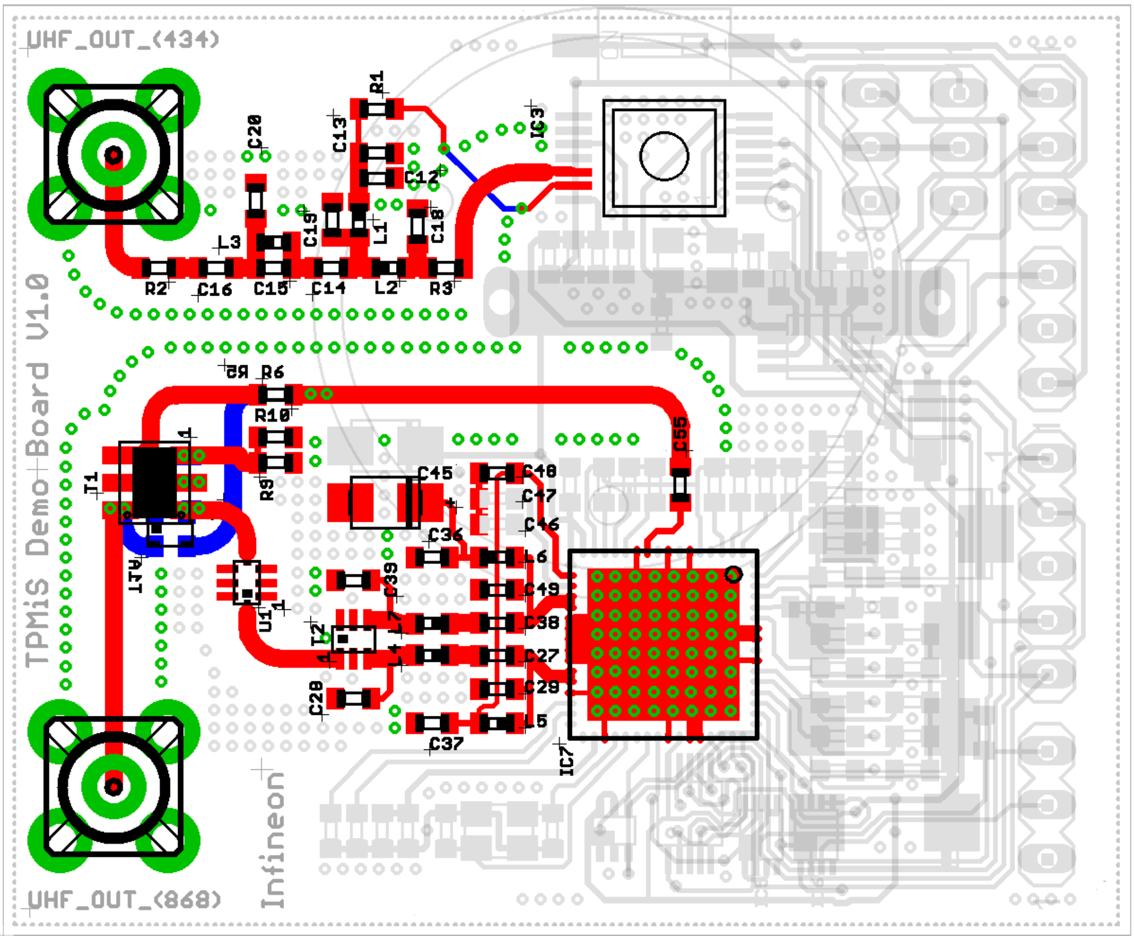

Figure 3.13: TPMS and RFID matching networks

To reach the maximum RF output power the TPMSs RF Power Amplifier (PA) needs to be operated in class E mode. It is therefore possible to reach an output power of 5 dBm on a maximum current of 7 mA. The analog network consists of two parts. The first part, which is connected directly to the power amplifier of the TPMS is the impedance matching part. It converts the PA output impedance to 50 Ω. The second part is a filter stage matched to 50 Ω to filter out the harmonics of the 434 MHz carrier wave.
The PA of the AS3992 UHF RFID reader outputs a differential RF signal. The connected analog network is divided into several parts. The first part, directly connected to the PA of the reader IC is the impedance matching network to convert the PA output impedance to 50 Ω. The following component T2 is a BALUN which converts a balanced signal

into an unbalanced signal. An unbalanced signal is a single signal which is measured against the ground level. This signal then passes a low pass filter (U1) to attenuate the harmonics of the 868 MHz carrier wave. The next component is a directional coupler (T1 or T1A), which connects the transmission and receive paths to the antenna. The directional coupler is capable of passing the transmitted carrier wave to the antenna and of passing the received wave to the receiver path. In simple terms, the coupler separates signals based on their propagation direction.
The PCB is designed to hold two different directional couplers. The reason for this was the unavailability of the coupler used on the AS3992 reader demo board. Therefore an alternative coupler can be soldered to the bottom side of the PCB.
The main paths connecting the RF network components are designed as 50 Ω „micro strip lines“. The PCB has four cooper layers with a thickness of 46 μm each and has a total thickness of 1.63 mm. The *FR4 DE 104* material between each pair of cooper layers has a thickness of 0.48 mm. For the lines to have a 50 Ω resistance their with must be 0.9 mm. For the micro strip lines to work properly the copper layer directly below these lines has to be grounded. As can be seen in Figure 3.13, the micro strip lines are accompanied by grounded vias to guarantee a fixed ground level with needs to surround the micro strip lines.

3.2.4 Flashing the Micro Controller on the PCB

Figure 3.14 shows the setup which is used to flash the firmware of the TPMSs micro controller on the TPMiS board. The TPMS has to be flashed via the I^2C interface. After a power on reset the TPMS waits for a short amount of time during which the programming procedure can be started [Inf13].

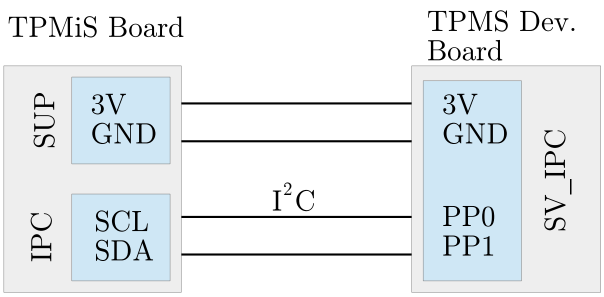

Figure 3.14: Setup to flash the MCU on the TPMS IC

For this procedure the TPMS development board has to be used. The figure shows how to connect the TPMS development board with the TPMiS board. The TPMiS board needs to be powered by the TPMS development board, so that the POR can be initiated by the TPMS development board. Therefore the power supply jumpers on the TPMiS board need to be set accordingly.

3.2.5 The completed TPMiS Demo Board

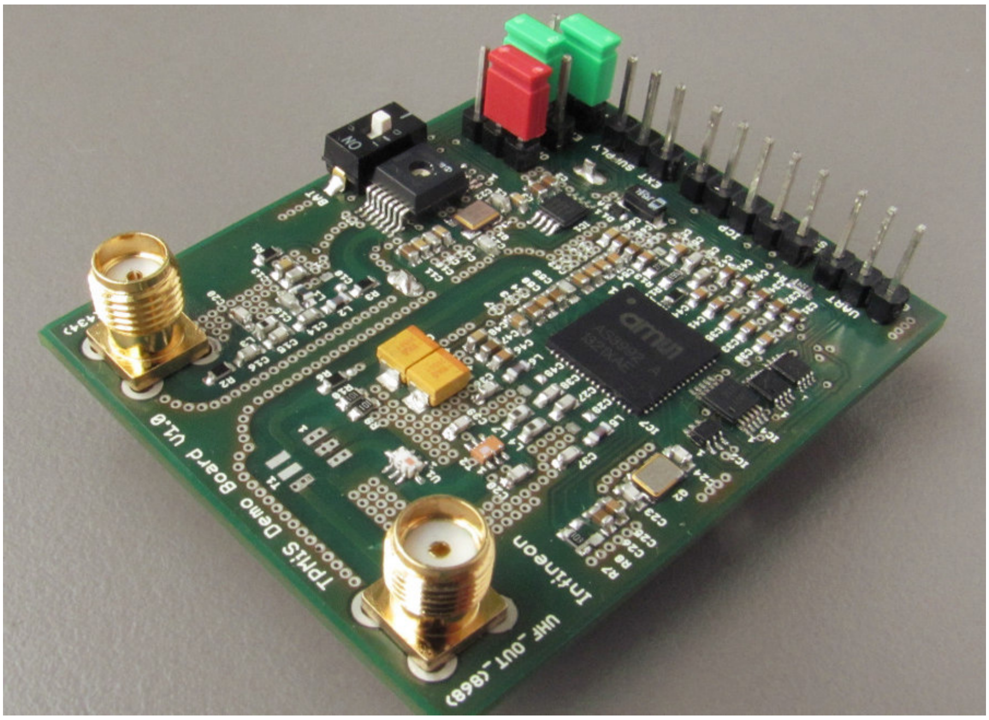

Figure 3.15: The top side of the completed TPMiS demo board

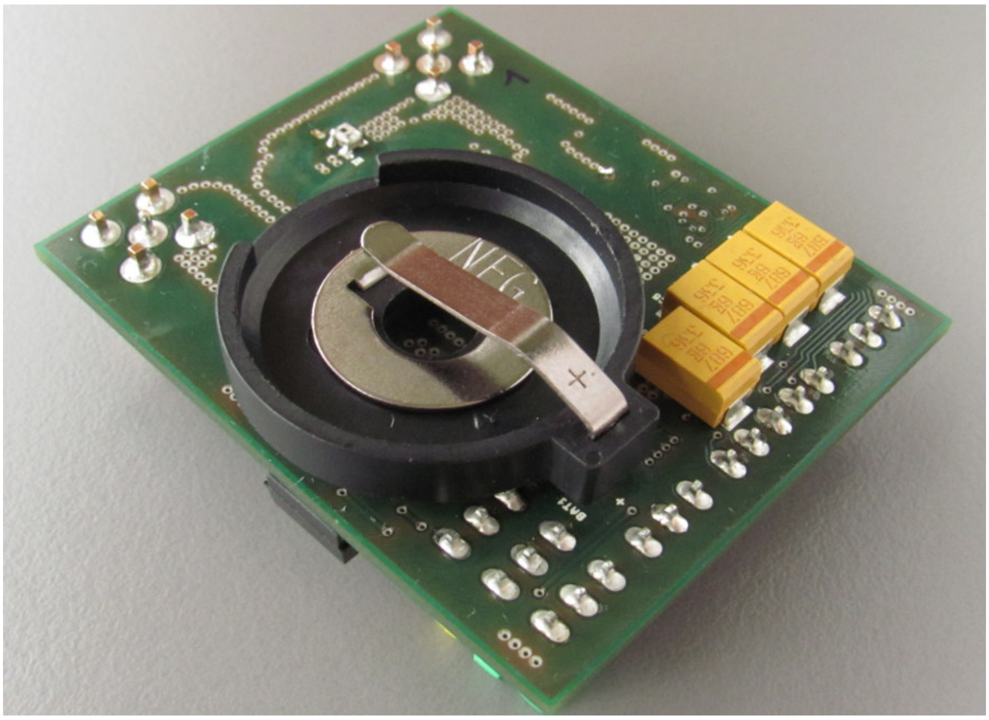

Figure 3.16: The bottom side of the completed TPMiS demo board

3.3 Antenna Design

Antennas can be designed in many different ways. One of the possibilities is the design via computer simulation. This approach requires detailed knowledge of the behavior of the antenna environment, especially in the near field of the antenna. Unfortunately the near field of the TPMiSs antennas contains a rim and a tyre which are not easy to simulate.
For this reason the antennas were designed empirically. The next sections describe the design approach for the TPMS antenna, the RFID tag antenna and the RFID reader antenna. Figure 3.17 gives an overview of the antenna setup.

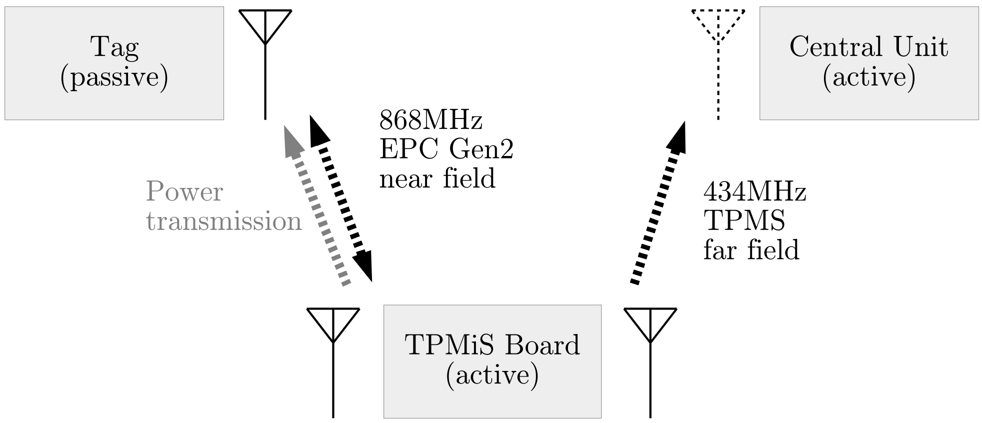

Figure 3.17: Overview of the required antenna settings

The first task of the TPMiS is to read out the tag. This tag is passive and must also be powered by the RF field of the RFID reader. The tag answers the reader by backscattering on the 868 MHz carrier wave. The second task is to transmit the obtained data to the central unit located somewhere in the car. The central unit and the TPMiS board are both battery powered (active).

3.3.1 TPMS Antenna

This antenna is used by the TPMiS to transmit the obtained data to the central unit located in the car. The demo boards RF part is designed to use Sub-Miniature-A (SMA) connectors to connect to an antenna with an impedance of 50 Ω at 434 MHz. This means that any standard type antennas with this properties can be used. The SMA connectors are also ideal to test different sets of antennas with a very little effort on the same demo board.
A disadvantage of this construction is the size of the antennas, resulting from the SMA adapter and the antennas themselves. To make the whole system smaller, a small loop antenna should be designed. This antenna should work in the far field and also have an input impedance of 50 Ω. For the empiric design of the antenna a network analyzer is used to measure the resonance behavior and the input impedance of the designed antenna.

Figure 3.18 shows the final version of the antenna with two red spacers to keep a fixed distance between the ground plane of the demo board and the antenna. This is important for the behavior of the antenna.

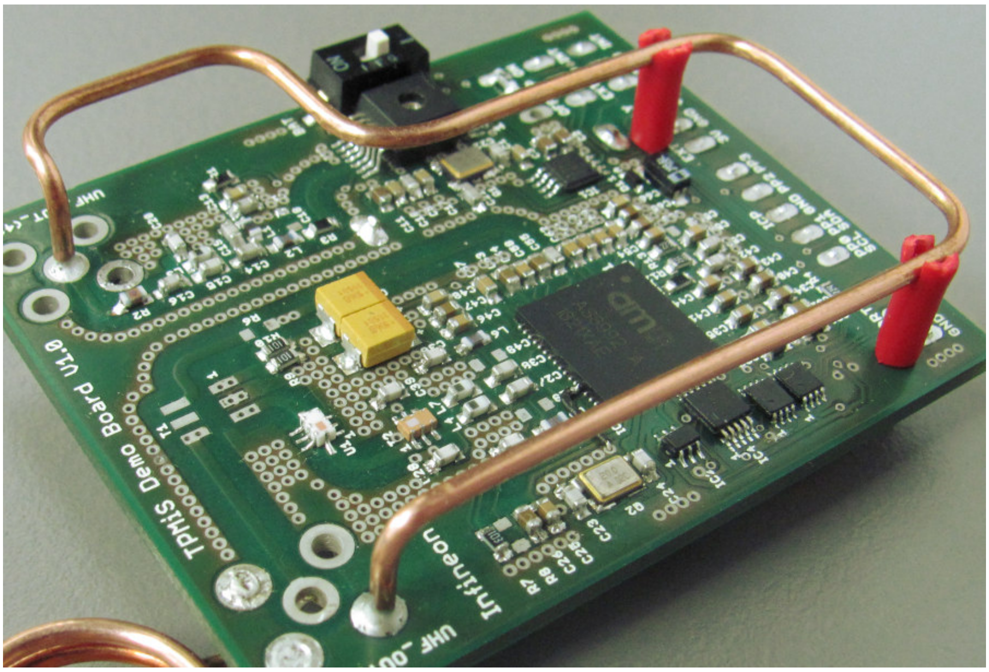

Figure 3.18: 434 MHz TPMS antenna

As mentioned above the board is designed to connect to antennas via SMA connectors. Now the challenge was to design an antenna which uses the already existing vias on the demo board. The upper SMA connector in Figure 3.18 is used for TPMS protocol communication while the lower SMA connector is used for UHF RFID communication.

There are different possibilities to design an antenna such as the one shown in Figure 3.18. The antenna can be designed using computer simulation but in his case it was easier to design it using trial and error. Various antennas with different length and shapes where created to be tested on the network analyzer. The first antennas to be tested only used the SMA connector pads of the 434 MHz part of the TPMiS. These antennas proofed to be mechanically unstable and their radiation characteristics were unsatisfactory.

Using an antenna that uses the TPMS antenna pads as well as the UHF RFID antenna pads proofed to be the better choice. This antenna proofed to be more mechanically stable as well as providing better radiation characteristics.

The best choice was an antenna which covers the whole surface area of the demo board, but since there is a switch on the top side of the demo board that needs to be accessible the antenna needed to be modified as shown in Figure 3.18. To avoid interferences with the antenna, the pin header connections for the different signal interfaces as well as the external power connectors and the jumper field had to be soldered at the bottom side of the demo board. Since this antenna was not mechanically stable enough it had to be supported using two spacers.

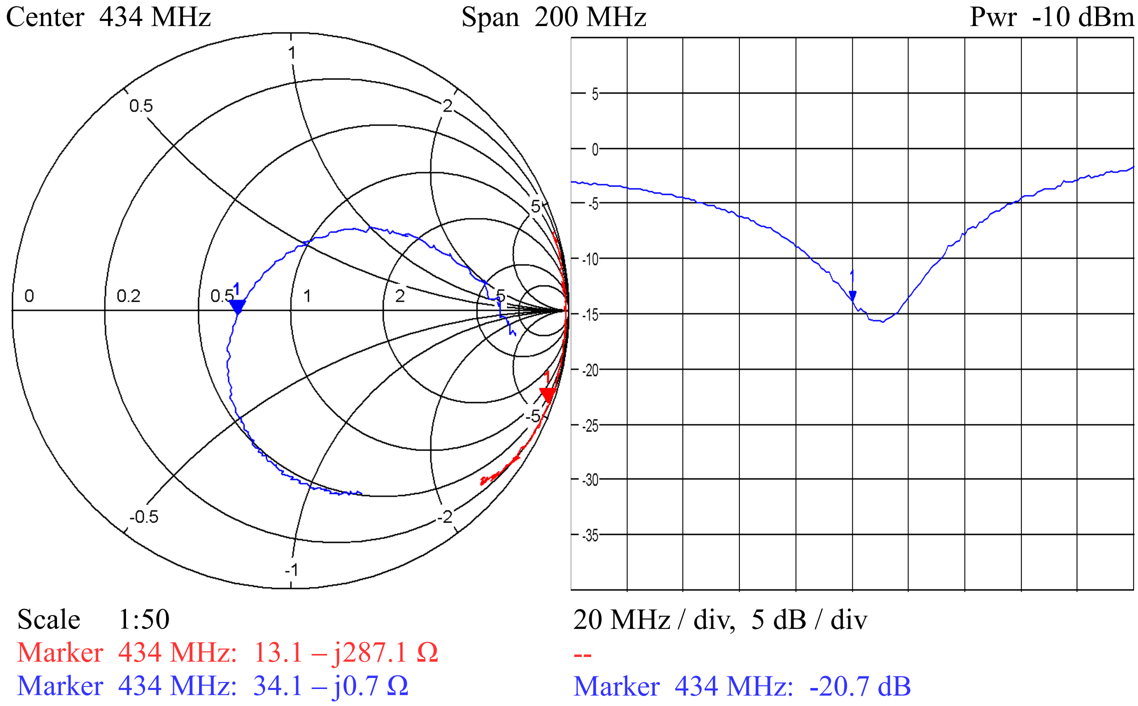

Figure 3.19: Antenna impedance without adjustment (red) and with adjustment (blue)

Figure 3.19 shows the network analyzer measurement results of the antenna shown in Figure 3.18. The red characteristic curve shows the antenna impedance without electrical adjustment. The impedance value of the antenna without impedance adjustment is far from the required $Z_{antenna} = 50\ \Omega$. To eliminate the imaginary part of the antenna impedance an inductance is required because the antenna itself is capacitive. The capacitive part of the impedance value is given from the red characteristic of the smith diagram: $X_C = 287.1\ \Omega$. The following equation can be used to calculate the needed inductor to:

$$L = \frac{X_c}{\omega} = \frac{287.1\Omega}{2\pi 434MHz} = 105.3nH \quad (3.3)$$

Since a 105.3 nH impedance is not available a 110 nH inductor has been used. The blue characteristic curve in Figure 3.19 shows the improvement after the impedance adjustment. The smith diagram shows the impedance of the adapted antenna, which is sufficiently close to the optimal 50 Ω for the antenna to work satisfactory. The logarithmic magnitude diagram shows the resonance frequency of the adapted antenna. This is also close enough to the required 434 MHz.

3.3.2 UHF RFID Tag Antenna

The first step of the antenna design for the 868 MHz UHF RFID part is the matching of the UHF RFID tag antenna. This antenna should work in the near field of the UHF RFID reader antenna inside of a wheels tyre.

This antenna is also designed empirically. According to the data sheet of the used Murata LXMS31ACNA-011 tag the impedance value of the tag itself is $Z_{tag} = 25 - j200\ \Omega$ [Mur09]. To design a matched antenna, the antenna impedance $Z_{antenna}$ should be as close as possible to the conjugated complex value of the tag impedance Z_{tag} [Sem08]:

$$Z_{antenna} = Re(Z_{tag}) - jIm(Z_{tag}) \tag{3.4}$$

As previously mentioned in Section 1.1 two possible applications for the TPMiS exist. For each one of these two applications different antenna settings are necessary. The first application is the TPMiS on rim scenario. Hereby the UHF RFID tag is on the tyre of the wheel while the TPMiS is located on the rim of the wheel. The RFID communication distance between reader and tag is much greater then in the TPMiS on tyre scenario. The tyre contains a metallic sheath which is also a challenge for antenna design.

Planar Inverted F-Shaped Antenna

One possible answer to these challenges is a Planar Inverted F-Shaped Antenna (PIFA). Figure 3.20 shows an example of such an antenna. Normally the metallic sheath inside of the tyre would strongly reduce the communication range. But this type of antenna differs from most other types of antenna in that it uses the metal structure to extend the communication range. Range measurement of this antenna can be found in Section 4.2.3 of Chapter 4. The antenna shown in Figure 3.20 is for experimental purposes only and not for use in a real tyre.

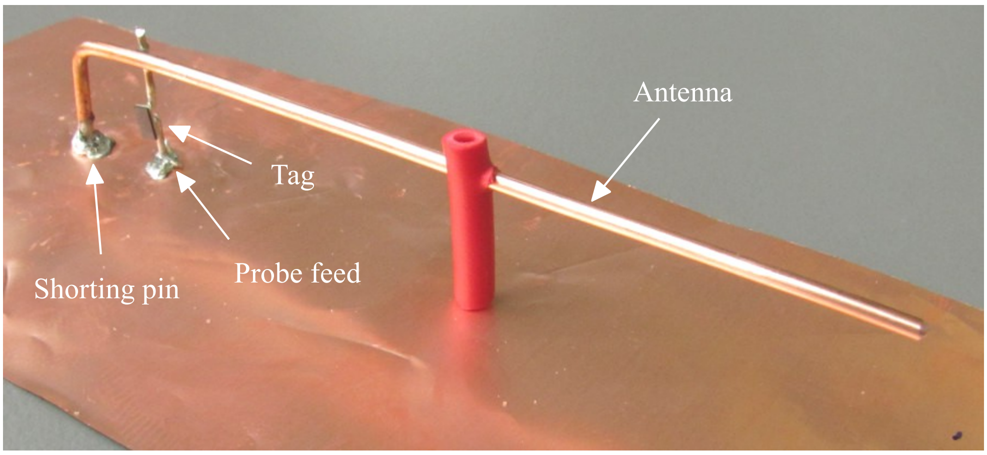

Figure 3.20: Experimental 868 MHz PIF antenna construction

The design of the antenna was very experimental. The distance between the probe feed and the shorting pin (see Figure 3.20) which connects the antenna to the ground plate was estimated. The distance between the antenna and the ground plate defines the bandwidth of the PIF antenna. Since the bandwidth has no significant impact on the experiments this distance was also estimated. The actual antenna was constructed long enough so that it could be tuned to the correct impedance by repeatedly shortening it. The antenna was repeatedly shortened while the impedance of the whole PIF antenna was measured using a network analyzer. Great care had to be taken because the impedance of the PIF antenna reacts extremely sensitive to changes of the length of the antenna. After several unsuccessful tries an acceptable antenna was created. The measured impedance values are shown in Figure 3.21.

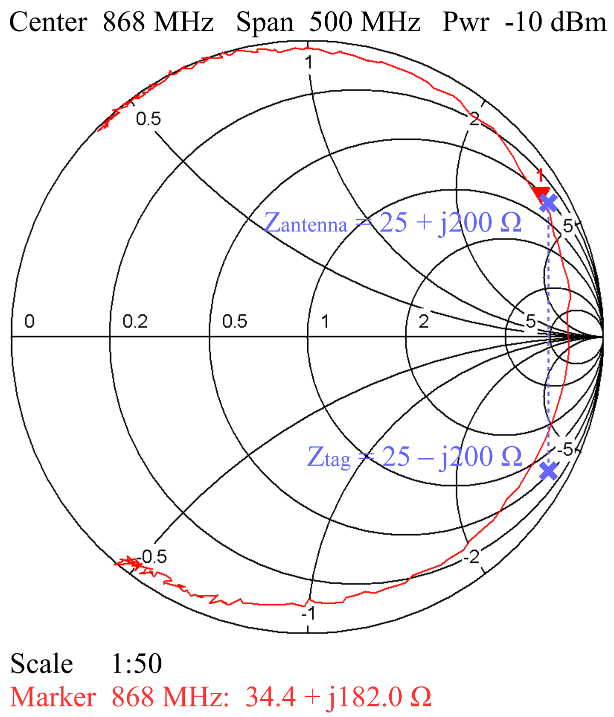

Figure 3.21: Impedance measuremen of
868 MHz PIF tag antenna

The Smith diagram shows the impedance of the antenna at 868 MHz (red marker). The measured frequency span is 868 MHz ± 250 MHz. The measured impedance is very close to the conjugated complex value of the tags impedance $Z_{antenna} = 25 + j200\ \Omega$ as calculated in Equation 3.4.

Loop Antenna

The TPMiS on tyre scenario is a more realistic prospect for the future. In this scenario both the module and the tag are located on the tyre of the wheel. The small distance between the UHF RFID reader and the tag reduces the energy consumption of the UHF RFID communication. Since loop antennas can only be used for short range UHF RFID transmission the tag and the reader must be positioned very close to each other. Ideally the readers antenna is positioned directly above the tags antenna. This scenario also suffers from the negative effects of the metallic sheath inside of the tyre on the UHF RFID communications range. To counter this effect antennas with magnetic coupling are used in this scenario. A detailed analasis of the communication range reduction is given in Section 4.2.2.

Figure 3.22: Loop antenna with tag

Figure 3.22 shows a basic loop antenna with attached tag. Since tag and antenna are directly mounted at the inside of the tyre and are also positioned very close to the UHF RFID reader interferences of the tyre and the reader have to be taken into account when designing the loop antenna. Since the computer simulation of all this influences is very complex an empirical approach to the antenna design has been chosen.
The UHF RFID tag requires an antenna with an impedance of $Z_{antenna} = 25 + j200\ \Omega$ at 868 MHz. The required inductance of the loop antenna can be calculated from $Z_{antenna}$ using the following equation:

$$L = \frac{X_L}{\omega} = \frac{200\Omega}{2\pi * 868MHz} = 36.7nH \tag{3.5}$$

The easiest way to create this inductance is the construction of an air cored coil. Since the coil is directly mounted at the inside of the tyre and is also magnetically and capacitively coupled with the RFID reader antenna (see Section 3.3.3) the impedance of the coil is hard to calculate. An approximation of the actual inductance of an air coiled inductor can be calculated using the following equation:

$$L = \frac{r^2 N^2}{9r + 10l} \tag{3.6}$$

The inductance L is given in μH, the radius r and the length of the coil l in inch and N represents the number of turns in the coil [Lea89].
For the UHF RFID antenna the number of turns is chosen as 1, while the coil length is chosen as 0.6 mm which is equal to the diameter of the copper wire used for the coil. Since Equation 3.6 can not easily be solved for the coils radius r an iterative process for solving this equation was used. Several values of r were tried until an acceptable solution was found using a coil radius r of 9 mm. Due to the small length of the coil this result is not very accurate and needs to be refined using a series of experiments.
Using the 9 mm radius which has been determined before as a baseline, several different antenna radii have been measured using a network analyzer until a sufficiently accurate impedance value had been found. To simulate the effect of the tyre on the tag antennas impedance, the test antennas were placed on a piece of tyre. At the same time the effects of the reader antenna on the tag antenna were simulated using a copper loop of the same radius as the test antenna positioned coaxially to it at a distance of 3 mm. An impedance value sufficently close to the needed $Z_{antenna}$ value of $25 + j200\ \Omega$ was achieved using a loop antenna radius of 7 mm. The impedance measurements for this antenna can be seen in Figure 3.23.

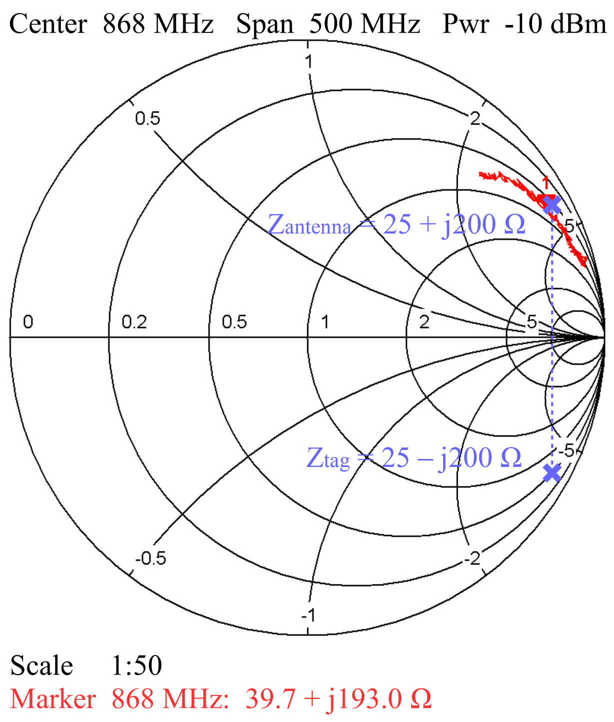

Figure 3.23: Impedance measurement of the tag loop antenna at 868 MHz

Further experiments using the 7 mm loop antenna showed that the antennas impedance is strongly dependent on the distance between the tag antenna and the RFID reader antenna. The antenna matching between the tag antenna and the reader antenna is only good in a small distance range. Fortunately this distance between the TPMiS and the tag is nearly constant in the TPMiS on tyre scenario, thus this does not pose a serious problem.

3.3.3 UHF RFID Reader Antenna

After the design of the UHF RFID tag antennas had been finalized 868 MHz reader antennas were designed for the different TPMiS scenarios. For the TPMiS on rim scenario a dipole antenna was chosen whereas for the TPMiS on tyre scenario a loop antenna was chosen.
Since the matching network of the UHF RFID reader on the TPMiS demo board is configured for a load of $Z_{antenna} = 50\ \Omega$ the antennas need to be designed so that they match the required load.

Dipole Antenna

For the TPMiS on rim scenario a 868 MHz $\lambda/2$ dipole antenna was chosen. The antenna consists of two identical poles of a total length of $\lambda/2$ and can be trimmed via the length of these poles. Figure 3.24 shows a dipole antenna.

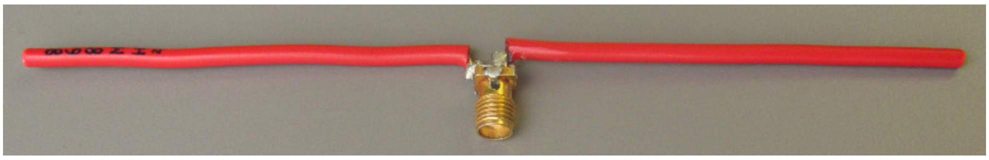

Figure 3.24: Dipole antenna for 868 MHz with SMA connector

Similarly to the other antenna types the computer simulation of the dipole antenna is very complex thus an empirical design approach has again been chosen. The theoretical length of the two identical poles is given by half of the wavelength of the communication frequency, which depends on the speed of light c and the frequency f of the signals carrier wave:

$$\lambda = \frac{c}{f} \tag{3.7}$$

The calculated value of λ is only true for infinitely thin pole wires. Thicker wire diameters reduce the resonance frequency. Items located close to the antenna also reduce the antennas resonance frequency mostly due to additional parasitic capacitances. The attenuation caused by the radiation of the electromagnetic wave further reduces the resonance frequency of the dipole antenna [Rol03].

Since all the effects just described reduce the antennas resonance frequency the actual antenna needs to be shorter than the calculated value of $\lambda/2$. So the first step was to construct an antenna with a length of $\lambda/2$. The impedance and the resonance frequency of the antenna was then measured using the network analyzer. The antenna was than shortened until a resonance frequency of 868 MHz was reached. The measurements of the resulting antenna can be seen in Figure 3.25.

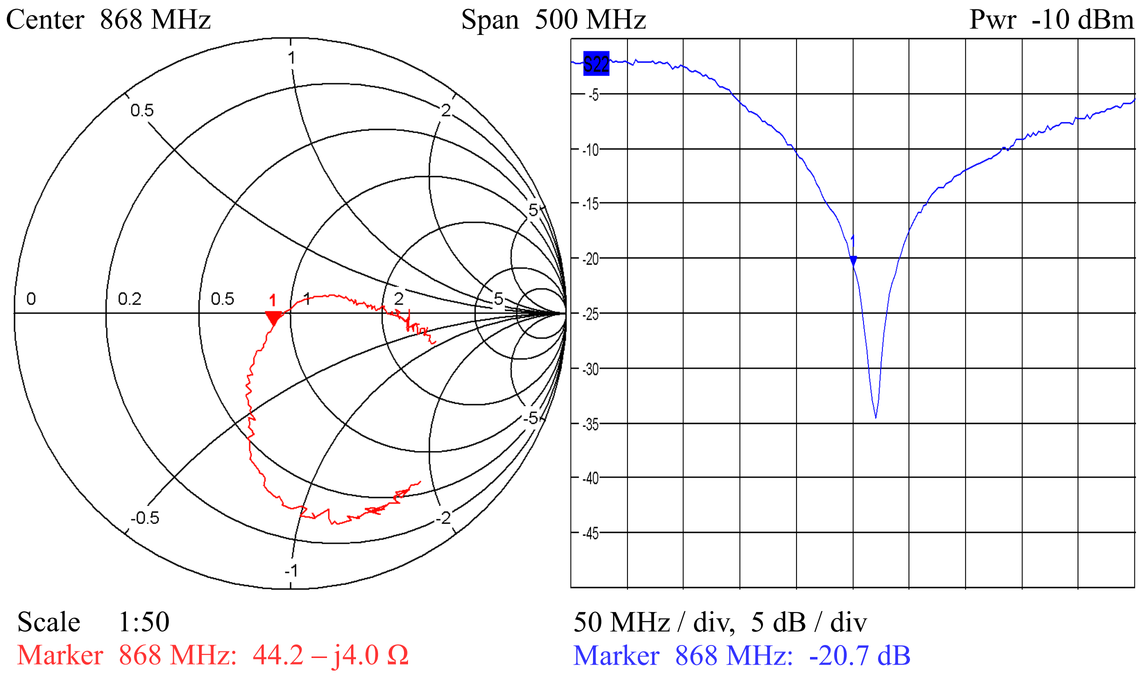

Figure 3.25: Impedance measurement of reader dipole antenna at 868 MHz

According to Equation 3.7 the theoretical length for a 868 MHz $\lambda/2$ dipole antenna is approximately 173 mm. The actual antenna length after trimming is 150 mm which is still unsuitably long for the TPMiS on rim scenario. It can be used to show the possibility of powering a tag and communicating with it over a relatively long distance while retaining a relatively low energy consumption. A detailed range analysis is given in Section 4.2.1. In this thesis the dipole antenna is as a reference point for the evaluation of other antenna types.

Loop Antenna Version 1

A loop type antenna was choosen for the TPMiS on tyre scenario. Since the distance between the reader and tag antenna is very small and the tag is fittet with a loop antenna this type of antenna is best suited for this scenario. Since the tags loop antenna has been designed for the tags requirements and is already fixed, the readers antenna needs to be matched to the tags antenna. To achieve a good magnetic coupling between the tags and the readers antenna while still keeping the antenna as compact as possible the tag antennas loop radius was also used for the reader antenna.

The tags loop antenna is designed to have impedance of approximately $Z_{antenna} = 25 + j200\ \Omega$. The exact value of the impedance of the antenna has been measured to be $39.7 + j193\ \Omega$. This value can also be used for the reader loop antenna, because both antennas have the same dimensions.

As previously mentioned, the matching network of the UHF RFID reader is designed for antennas with an impedance of $Z_{antenna} = 50\ \Omega$. To bring the antennas impedance to the required 50 Ω a capacitor is added in series to the readers antenna. Using the imaginary value X_L and the carrier wave frequency f its capacity can be calculated to:

$$C = \frac{1}{2\pi f X_L} = \frac{1}{2\pi * 868\text{MHz} * 193\Omega} = 0.95pF \tag{3.8}$$

Capacitors in this capacity range have very high tolerances and their exact capacitancies are influenced by outside parameters such as their solder pads. Since the impedance correction is very sensitive to changes in the capacity, several capacitors had to be tried out to until a 0.6 pF capacitor was found to provide the best antenna impedance.

Figure 3.26 shows the loop antenna mounted on its own small PCB. The PCB is also equipped with a Sub-Miniature-T (SMT) connector to connect the antenna to the TPMiS demo board. Between the loop antenna and the SMT connector the matching capacitor can be seen.

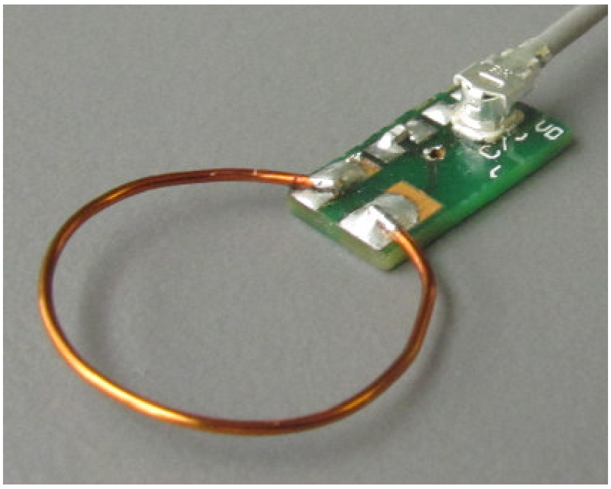

Figure 3.26: 868MHz loop antenna with matching capacitor

The size of this antenna is already acceptable for a TPMiS located on the tyre. The verification and evaluation chapter shows that it is already possible to use this antenna for communication with a tag which is positioned 3 mm to 5 mm from the reader antenna. The maximum possible radial displacement between the reader and tag antenna is also sufficient for UHF RFID communication and the powering of a tag. More information about the behavior of this antenna is available in Section 4.2.2.

Loop Antenna Version 2

The prior loop antenna version 1 can already be used in a TPMiS on tyre scenario. The only problem is that this antenna cannot be mounted directly onto the TPMiS demo board. The reason for this is that the grounded layer on the demo board significantly changes the antennas behavior.
For this reason a new antenna was designed which can be directly mounted onto the TPMiS demo board. At first closed loop antennas of various diameters were tried out. Due to the sensitivity of the closed loop antennas impedance to different matching capacitors it was impossible to sufficiently match these antennas to the UHF RFID reader.
Since mounting the necessary matching capacitors onto the PCB proved unviable the necessary matching capacitor needed to be integrated into the antenna. To achieve this two open loops stacked on top of each other with a small air gap between them acting as the necessary capacitor were used. The resonance frequency of this antenna can be trimmed using the size of this air gap.
The radius of this loop antenna is defined by the diameter of the tags loop antenna. Both need to be equal to reach a good magnetic coupling between the readers and tags antenna. Since each of the open loops is attached to only a single point on the PCB thicker copper wire had to be used to minimize the flexing of the antenna. The final design can be seen in Figure 3.27.

Figure 3.27: 868 MHz Loop antenna soldered onto PCB
with tag underneath

As with the other antennas an empiric design approach was used to design this antenna. The antenna needs to have a resonance frequency of 868 MHz and an antenna impedance of $Z_{antenna} = 50\ \Omega$. Since this antenna is designed for the TPMiS on tyre scenario all measurements were taken with the tag mounted onto a piece of tyre.

To trim the antenna to the desired resonance frequency only the air gap between the loops can be used. After several iterations an air gap of 0.6 mm between the two loops was found to provide adequate results. Under certain circumstances the resonance frequency is now exactly at 868 MHz. These circumstances are fulfilled if the UHF RFID tag is positioned at the inside of the rolling surface of a tyre and the tag and reader loop antenna have an axial distance of 3 *mm*. Measurement results for different axial distances can be seen in Figure 3.28.

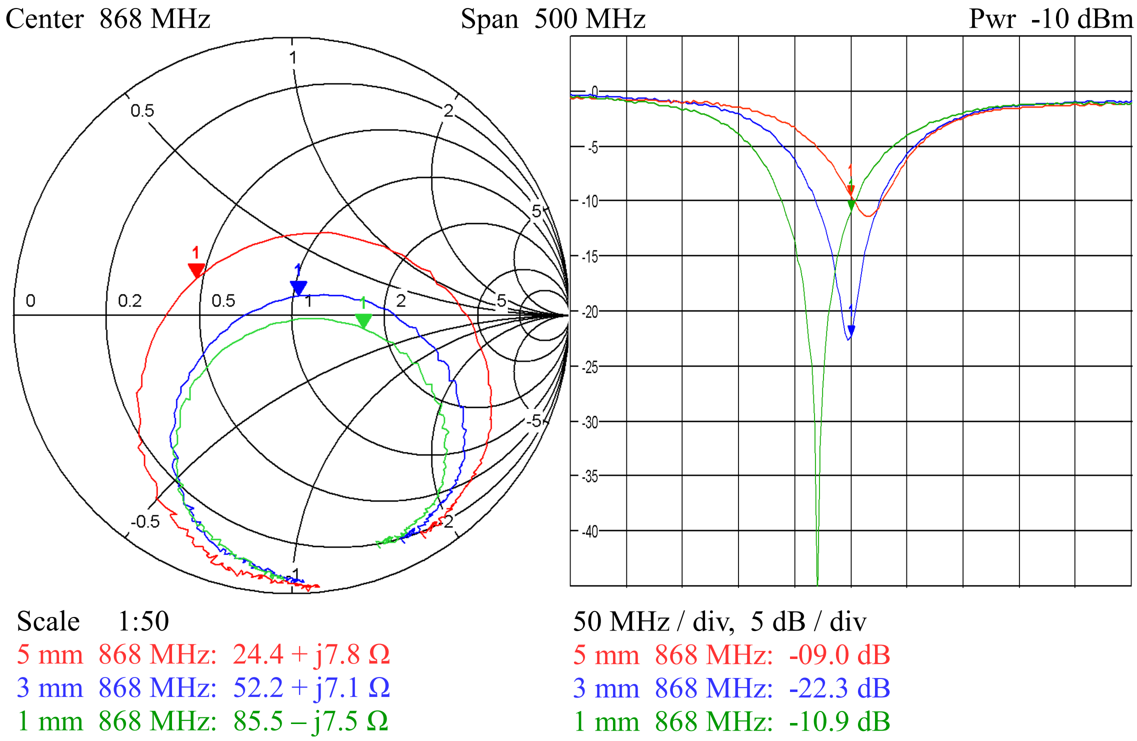

Figure 3.28: Impedance measurement of 868 MHz reader loop antenna

The measurement results in figure 3.28 are color coded. The different colors stands for a different axial distances between the readers and the tags loop antenna ranging from 1 mm to 5 mm. As can be seen the antenna behavior is strongly dependent on this axial distance. More information regarding the communication range can be found in Section 4.2.2.

Chapter 4

Verification and Evaluation

This chapter focuses on the verification of the principal functionality of the TPMiS demo board as well as the evaluation of the performance of the UHF RFID communication.
The principal task of this work was the verification and evaluation of the interaction between an UHF RFID reader and an UHF RFID tag during communication inside the wheel of a car. The most limiting factor was the maximum specified output power of 5 dBm which is also the maximum output power of the TPMS transmitter. As previously mentioned in the introduction chapter, the basic idea of this limitation is to allow for future direct communication between the TPMS IC and a RFID tag, without the need for an additional RFID reader IC.
The first part of this chapter focuses on the verification of the implemented hard- and software functionalities on the TPMiS demo board. The second part of this chapter deals with the evaluation of the possible ranges of the different antenna configurations.

4.1 System Verification

This section and its subsections describes the verification of the implemented hard- and software functionalities on the TPMiS demo board.
After the TPMiS prototype had been assembled several of the boards circuit components had to be tested for their functionalities. The first tested hardware components were the ones making up the inter-chip-logic which handles the communication between the TPMS IC and the UHF RFID reader IC as well as providing an UART debug interface which can be accessed via on board connector pins. The communication signals can be recorded using the on board ICP connection interface.
The second components to be tested are the ones making up the power management part of the TPMiS demo board. Special care had to be taken that the supply voltages stay within their acceptable ranges.

4.1.1 Inter-Chip Communication

The inter-chip-communication components are implemented as four logic ICs as shown in Section 3.2.2. Its functionality is described in detail in Section 2.2.5. A digital oscilloscope was used to verify that the inter-chip-communication works as intended via the ICP and UART connector pins. Figure 4.1 shows the inter chip communication activity during a complete RFID communication cycle.

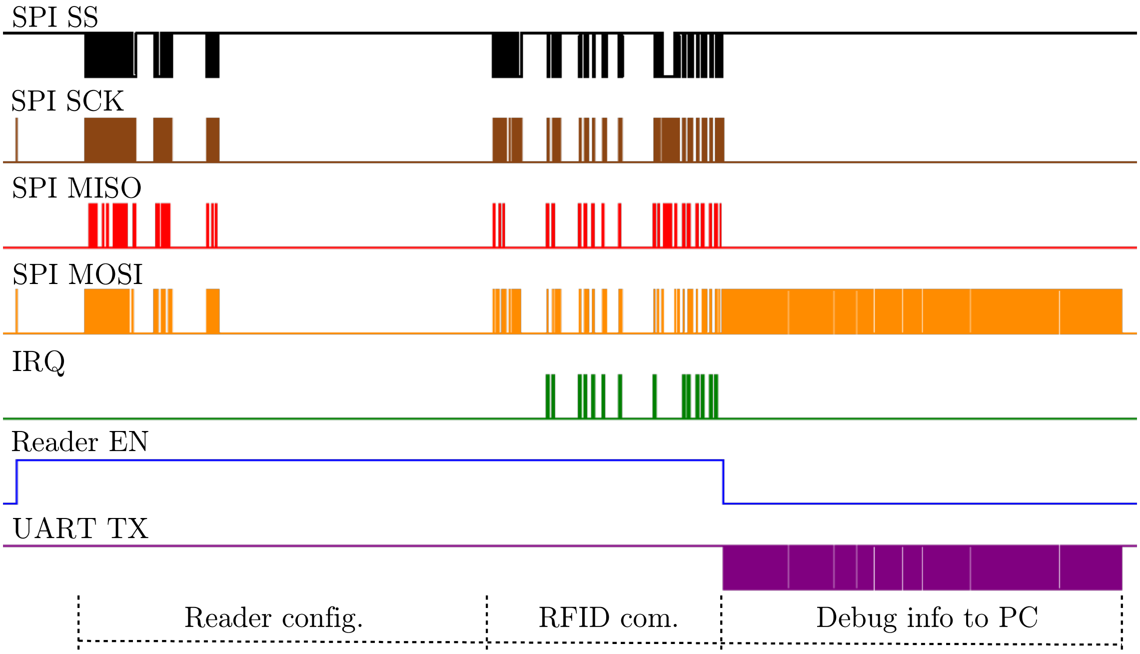

Figure 4.1: RFID communication cycle and UART TX debug signal

The communication between the TPMS IC and the UHF RFID reader IC is started by setting the chip enable of the reader to high. This is done using a special signal combination described in Section 2.2.4. After that the system waits until the reader has started correctly. Once the reader has started the RFID communication settings and reader operating modes are transmitted to the reader. The relatively long communication pause after configuration is required to set the frequency of the UHF carrier wave and to lock the phase-locked loop (PLL).
The following sequence handles the UHF RFID EPC Gen2 communication. The communication starts with a select command. The TPMS then waits until the first interrupt request (IRQ) occurs which denotes the end of this RFID command. The next command sent is the select command which configures all selected tags in range. After the next IRQ the reader begins with the transmission of the so-called „query reply“ patterns, to which the tag should answer. If a tag has answered, the so-called „ack“ command is sent to get the EPC data from the tag. After that the received tag data is sent via SPI to the TPMS micro controller. Figure 4.1 als shows the transmission of debug information via UART to a personal computer.

4.1.2 Power Management

This section verifies the implementation of the power management. The design of the power management is described in Section 2.4. The Implementation of this design is described in Section 3.2.1.
The power management needs to fulfill two main tasks. The fist task is to provide a 5 V power supply for the UHF RFID reader IC. The second task is to reduce the maximum load on the battery to prevent a high voltage drop on the 3 V line and to extend the batteries lifetime. The biggest negative impact on a batteries lifetime is the biggest voltage drop during operation. Figure 4.2 shows the voltage drop on the $5V$ and $3V$ supply line during the TPMiSs active time.

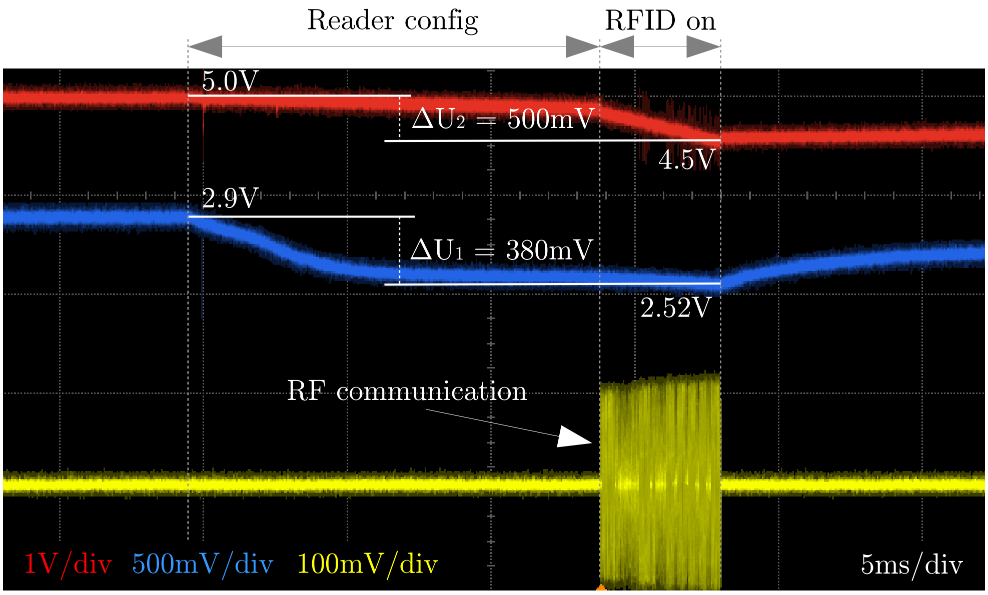

Figure 4.2: Voltage drop of the $5V$ (red) and $3V$ supply line (blue)

Since the TPMS needs a minimum voltage of 1.7 V to function properly, the maximum allowable voltage drop ΔU_{1Max} can be calculated to:

$$\Delta U_{1Max} = U_{Bat} - U_{TPMSMin} = U_{Bat} - 1.7V \tag{4.1}$$

In the example shown the load-free battery voltage U_{Bat} is $2.9V$. This results in a maximum allowable voltage drop of 1.2 V. The measured voltage drop ΔU_1 is only 380 mV, which means that the 3 V supply is stable enough.
The AS3992 reader IC needs a minimum supply voltage of 4.1 V. Therefore the maximum allowable voltage drop on the 5 V supply can be calculated to:

$$\Delta U_{2Max} = U_2 - U_{AS3992Min} = 5V - 4.1V = 0.9V \tag{4.2}$$

The voltage drop on the 5 V line measured in Figure 4.2 is only 500 mV, which means that the 5 V supply is also stable enough. As the measurements show the power management fulfills all the tasks required by the project.

4.2 Antenna Configuration Evaluation

The aim of the antenna design was to find a suitable antenna for each of the different usage scenarios. The TPMiS on rim scenario requires a relatively long communication range due to the fact that the TPMiS and the UHF RFID tag can be positioned relatively far apart. Since the reader also needs to be able to power the tag over this relatively long distance using an output power of only 5 dBm, this is the more complex of the two scenarios.
In the TPMiS on tyre scenario, both the TPMiS and the tag are located on the inside of the rolling surface of the tyre. This means that the communication distance between the reader and the tag is much smaller then in the TPMiS on rim scenario. This is an advantage regarding the required antenna output power and antenna size. The disadvantage is that the TPMiS module must be placed precisely on top of the tag which is fixed onto the inside of the tyre.

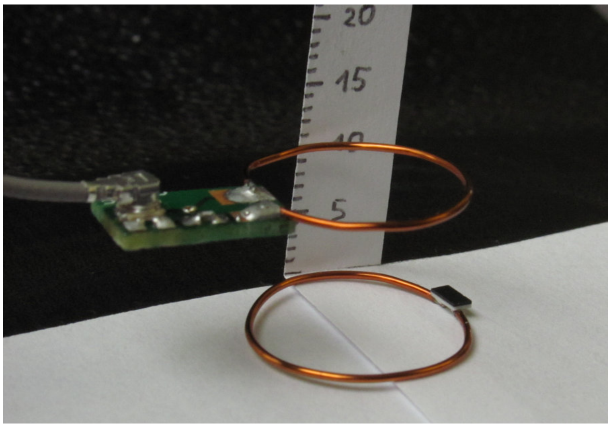

Figure 4.3: Range measurement with loop antennas

Figure 4.3 shows the range measurement setup between the reader loop antenna (above) and the tag loop antenna (below). The measurement is performed directly on the inside of a tyre which can be seen in the background.
The design of the different antenna types used in both scenarios described Section 3.3. The next section describes the range test conducted with the different antenna types. The possible communication range between the reader and the tag has been analyzed using different reader output power levels as well as different relative antenna positions. Another important aspect which has been analyzed in these experiments is the maximum range in which the RFID reader is able to sufficiently power the RFID tag.
The only antenna not analyzed in detail is the TPMS antenna. The TPMS antenna must have a certain range, but for this project it is not necessary to test its range behavior in dependency of the TPMS RF output power. The range at 5 dBm output power between the TPMiS and a test receiver is approximately 10 meters which is enough for the demo board. The RFID communication ranges are much more interesting for this project.

4.2.1 Dipole Antenna

First tested antenna is a 868 MHz $\lambda/2$ dipole antenna, which design steps are described in section 3.3.3. For this first test both the reader and the tag are fitted with a dipole antenna. The maximum achievable communication range of this antenna configuration is measured for different output powers. This is done using a tag mounted onto a piece of tyre as well as the same tag not mounted onto a piece of tyre. Figure 4.4 shows the results of this measurements.

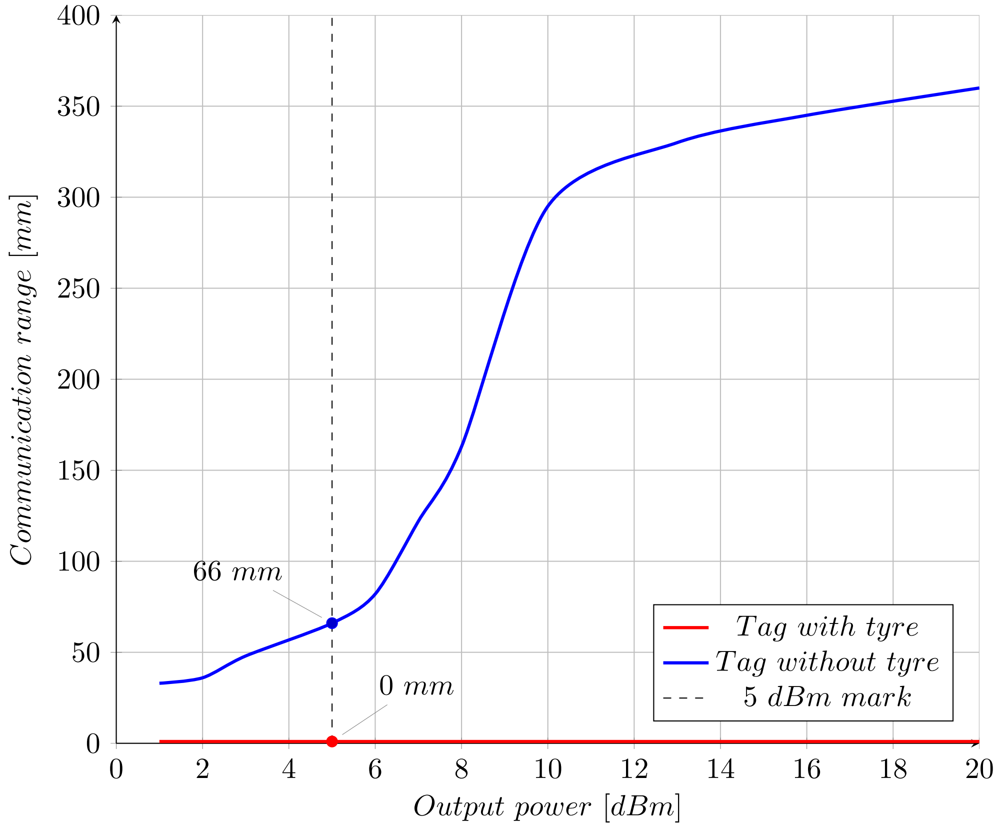

Figure 4.4: Communication range with dipole antennas

These measurement results indicate that dipole antennas are not well suited to work inside the tyre of a car. It was not possible to establish a connection between the reader and the tag even when using the maximum possible RF output power of the reader (red graph in Figure 4.4). The reason therefore is the metal structure inside of the tyre rubber, which causes a significant change in the resonance frequency of the antennas.
The blue graph in Figure 4.4 shows the measurement for the tag without the tyre. In the near field of the antenna the power to the tag is transmitted mostly via the magnetic field component of the RF wave. Since the magnetic coupling between dipole antennas in the near field is not very good, the graph starts with a small range and only a very slide

slope. Starting with the RF output power of 1 dBm the tag moves into the far field of the antenna. This can be observed by the much steeper slope in the graph. The beginning of the far field can be approximated with the following Equation 4.3.

$$r_{far} = \frac{\lambda}{2 * \pi} \tag{4.3}$$

Above an output power of 10 dBm significantly more output power is needed to achieve an increase in communication range. This manifests in the fattening of the curve.

4.2.2 Loop Antenna

Loop antennas for the reader and the tag are specifically designed for near field use (see Section 3.3.3 and Section 3.3.2). The loop antenna for the reader, (designed in section 3.3.3) and for the tag (designed in section 3.3.2) are constructed for the use in the near field. The magnetic coupling between the two loop antennas allows a maximum communication range of approximately 13 mm without the tyre. As can be seen in Figure 4.5 the presence of a piece of car tyre reduces the communication range to a maximum of approximately 9 mm.

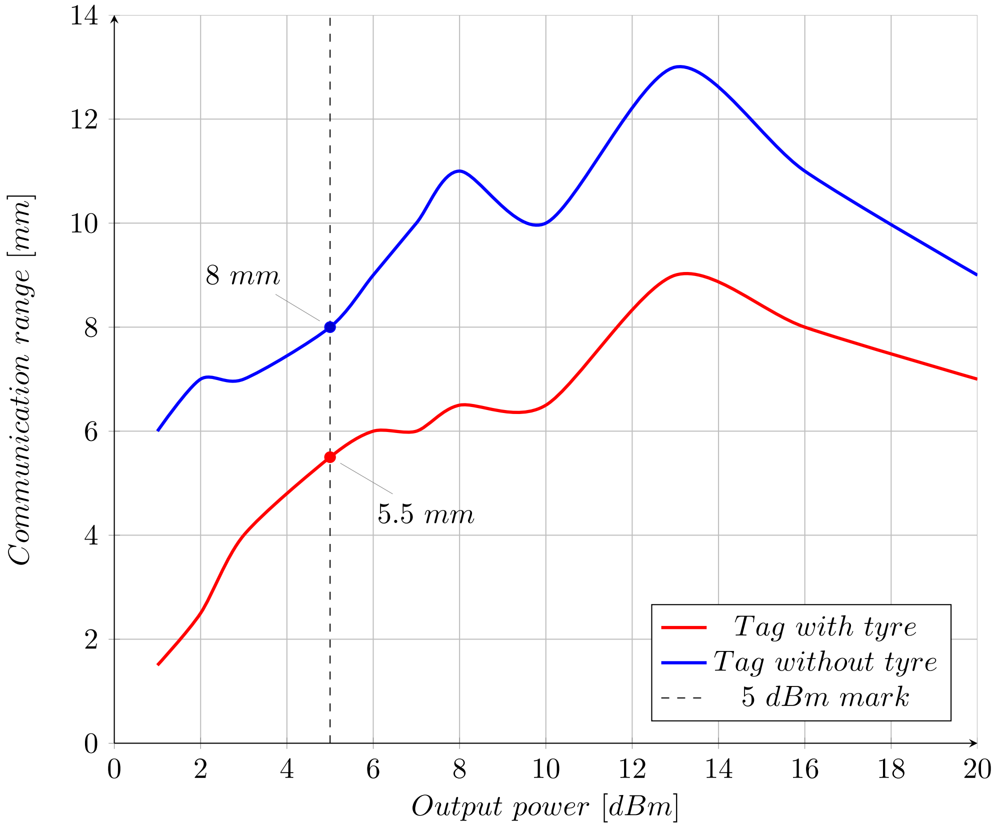

Figure 4.5: Communication range with loop antennas

The loop antenna is more efficient in the near field. The tag is almost exclusively powered via the magnetic coupling between the reader and the tag antenna. As can be seen in the chart, the communication range increases with the rinsing RF output power until it reaches a maximum at around 13 dBm. The only exception is a slide dip between 8 dBm and 11 dBm.
Above the maximum communication distance at 13 dBm, the range decreases with rising output power. This can be explained by the fact that the influence of the tags backscatter signal on the RF field is too weak to be detected by the receiver part of the reader. This is caused by the increasing distance between the readers and tags antenna, which makes it harder to detect the tags backscatter signal. It is also caused by the higher output power of the readers RF field, which makes it easier to power the tag but makes it harder for the tag to influence the field.
If the TPMiS and the tag are both located at the inside of the rolling surface of the tyre, a communication range of 5.5 mm at 5 dBm is acceptable. The advantage of this setup is the small size of the antennas. They both have a diameter of only 14 mm as already shown in Section 3.23 of the design chapter.
The disadvantage of these small loop antennas is the need for relatively precise antenna placement. Since the RFID tag is supposed to be integrated into the tyres construction and the TPMiS is later mounted on top of it, a displacement between the two loop antennas is unavoidable. The following table shows the maximum possible planar displacements for different output power levels and loop distances.

	Loop distance 3 mm	**Loop distance 1 mm**
RF output power level	**Max. planar displ.**	**Max. planar displ.**
[dBm]	[mm]	[mm]
2	1	1
3	3	5
5	5	5.5

Table 4.1: Maximum possible planar displaced

At an axial distance of 3 mm between the two loop antennas, the maximum allowable planar displacement is 5 mm for an RF output power of 5 dBm. Therefore the TPMiS module has to be placed precisely over the underlying tag in the tyre. At this point the question is if the module can be positioned with a maximum displacement of 5 mm or less in a commercial production process.

4.2.3 PIF Antenna

The last tested antenna configuration is the planar inverted F type (PIF) antenna. In the TPMiS on rim scenario the TPMiS module and the RFID tag are located inside the tyre of a car. They are therefore surrounded by the metal structures of the tyre as well as the rim of the car. Since a PIF type antenna is more efficient in the far field and is designed to work on metal surfaces it is an ideal candidate for this type of scenario. As can be seen in Figure 4.6 relatively long communication ranges can be achieved using this type of antenna.

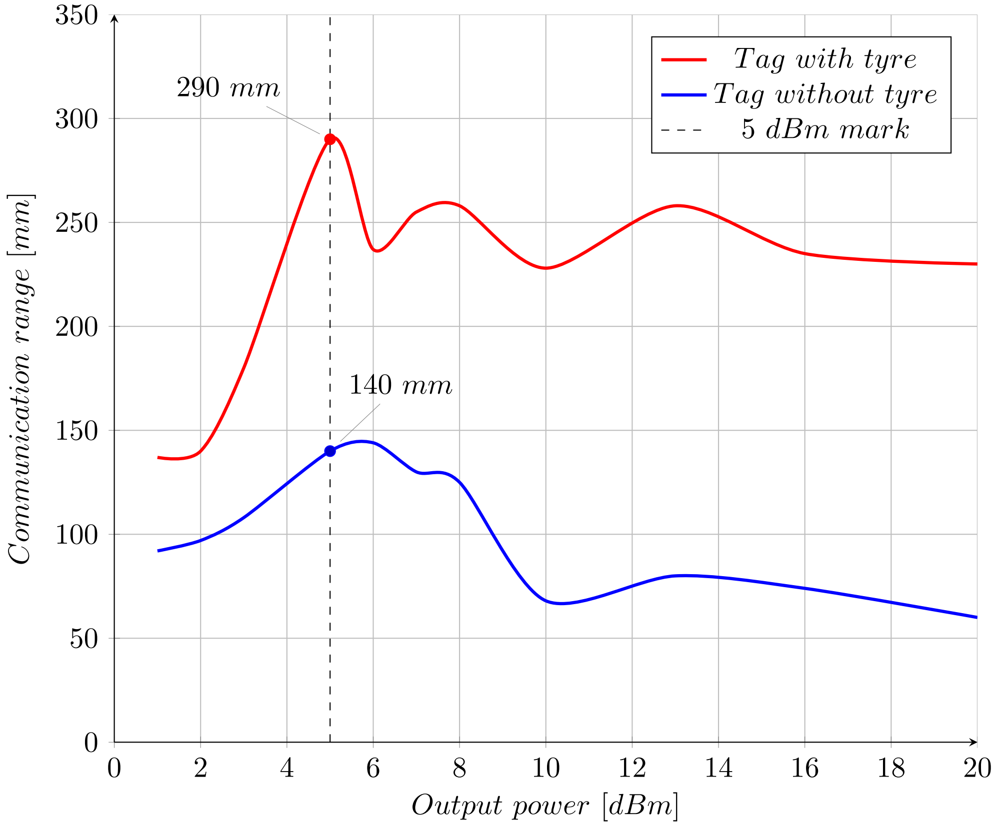

Figure 4.6: Communication range with PIF antenna

Of particular note is the fact that the PIF antenna is the only antenna type which is more efficient when placed on a large metallic surface such as the rim or the metal structure inside the tyre.

As can be seen, the antenna is not very efficient in the near field. Above an output power of 5 dBm the achievable communication range decreases with increasing RF output power. This can be explained by the fact that the higher output power makes it harder for the tag to influence the RF signal to backscatter.

Chapter 5

Conclusion and Outlook

The aim of this project was the design and implementation of an extension to an already existing Tyre Pressure Monitoring System (TPMS) followed by its verification and evaluation. An 868 MHz UHF RFID system should be added to the TPMS to form a Tyre Pressure Monitoring and Identification System (TPMiS). The overall system should be able to read out the tags Electronic Product Code (EPC) from tags located at the inside of a tyre of the wheel of a car. This EPC should then be sent to a central unit located at the inside of the car for further processing.
Two different operating scenarios for the TPMiS needed to be examined. The TPMiS on rim scenario where the TPMiS module is located on the rim of the wheel whereas the UHF RFID tag is located on the inside of the rolling surface of the tyre. This scenario imposes some requirements on the positioning of the tyre on the wheel of a car. The maximum communication ranges for this scenario, taken from the Verification and Evaluation chapter, determine a positioning guideline for the tyre on the rim. This positioning demands makes the replacement of tyres in an automobile workshop more complex and thus more expensive.
The TPMiS on tyre scenario is simpler. A TPMiS module holder is placed on the inside of the rolling surface of a tyre, directly on top of a tag which is embedded into the tyre. As described in the Verification and Evaluation Chapter, the main disadvantage of this application is the need for precise placement of the TPMiS module holder on top of the tags antenna. This working step is only necessary once after the production of a tyre. If the tyre of a car wheel is changed, the only additional steps to take are to remove the TPMiS from the old tyre and to fit it into the module holder of the new tyre.

The results achieved fulfill all the requirements set, but are still far from ideal. Two ideas to expand upon the existing project are given in the next sections.

5.1 TPMiS without separate RFID reader

The idea is to use the RF transmission channel of the TPMS which is normally used to send data to the central unit in the car, to power a tag and transmit information to it. This idea is also the most probable continuation of the TPMiS project. It was the reason for the RFID RF field power target of a maximum of 5 dBm used in this thesis, since this is also the maximum RF output power of the TPMS IC. The 868 MHz UHF RFID band was used for this project because any problems with interference of the rim or the tyre at this frequency are less pronounced at the 434 MHz used by the TPMS. This project would also require the evaluation of the viability of using 434 MHz RFID tags for identification purposes.

5.2 Central Unit detects RFID Backscatter Signal

Another idea is to port the reader functionality of the TPMiS to the central unit in the car. The TPMS transmission channel should power the tag and transmit data to it. However, the backscatter signal of the tag is not received by the TPMS, but rather by the central unit in the car. The question arises whether the central unit is able to receive the backscatter signal of a tag positioned a few meters away.

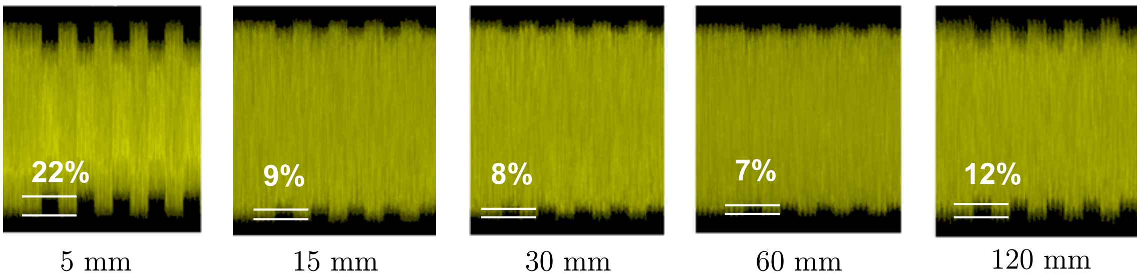

Figure 5.1: Backscatter signal of a tag at different distances

Figure 5.1 shows the backscatter signal of a tag measured with an oscilloscope at different distances from the tag. To obtain these measurements, the tag is positioned close to the TPMiS so that the tag can have a significant influence on the readers RF field. As can be seen in the figure, the backscatter signal is still visible on a distance of 120 *mm* using a reader output power of 5 *dBm*. The question is, if this backscatter can be detected from the central unit inside the car without comparison to the readers RF field, which is the common way to reach the necessary receiving sensitivity.

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