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# Wireless Sensor Network Systems in Harsh Environments and Antenna Measurement Techniques

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### **Abstract**

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Wireless sensor network (WSN) has become a hot topic lately. By using WSN things that previously were difficult or impossible to measure has now become available. One of the main reasons using WSN for monitoring is to save money by cost optimization and/or increase safety by letting the user knowing the physical status of the monitored structure. This thesis considers four main topics, empirical testing of WSN in harsh environments, antenna designs, antenna measurements and radio environment emulation.

The WSN has been tested in train environment for monitoring of ball bearings and inside jet engines to monitor strain of blades and temperatures. In total, two investigations have been performed aboard the train wagon and one in the jet engine. The trials have been successful and provide knowledge of the difficulties with practical WSN applications. The key issues for WSN are robust communication, energy management (including scavenging) and physical robustness.

For the applications of WSN in harsh environments antennas has to be designed. In the thesis, two antennas has been designed, one for train environment and one for the receiver in the jet engine. In the train environment, a more isotropic radiation pattern is preferable; hence a small dual layered patch antenna is designed. The antenna is at the limit of being electrically small; hence slightly lower radiation efficiency is measured. For the WSN in the jet engine, a directive patch array is designed on an ultra-thin and flexible substrate. The thin substrate of the antenna causes rather lower radiation efficiency. But the antenna fulfils the requirements of being conformal and directive.

In reverberation chambers are used to measure antennas, but there are difficulties to provide a realistic radio environment, for example outdoor or on-body. In this thesis, a large reverberation chamber is designed and verified. It enables measurement between 400 MHz and 3 GHz. Also, a sample selection method is designed to provide a post processing possibilities to emulate the radio environment inside the chamber. The method is to select samples from a data set that corresponds to a desired probability density function. The method presented in this thesis is extremely fast but the implementation of the method is left for future research.

**Keywords:** Wireless Sensor Network, Antenna, Jet engine, Train, Reverberation chamber, WISENET, Wisejet

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*To Sophia*



# List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I     **Mathias Grudén**, Malkolm Hinnemo, Dragos Dancila, Filip Zherdev, Nils Edvinsson, Kjell Brunberg, Lennart Andersson, Roger Byström, Anders Rydberg, "Field Operational Testing for Safety Improvement of Freight Trains using Wireless Monitoring by Sensor Network" IET Wireless Sensor Systems, December 2013.
- II    **Mathias Grudén**, Alexander Westman, Janis Platbardis, Paul Hallbjörner, Anders Rydberg, "Reliability Experiments for Wireless Sensor Networks in Train Environment", European Wireless Technology Conference, 2009, EuWIT 2009, Page(s):37-40, Rome.
- III   **Malkolm Hinnemo**, **Mathias Grudén** and Anders Rydberg, "Design of a miniaturized patch antenna for easy deployment on metal surfaces", Microwave and Optical Technology Letters, Vol.: 55, Issue: 4, Page(s): 723-727, 2013.
- IV    **Mathias Grudén**, Magnus Jobs, Anders Rydberg, "Empirical Tests of Wireless Sensor Network in Jet Engine Including Characterization of Radio Wave Propagation and Fading", Submitted to Antennas and Wireless Propagation Letters, IEEE.
- V     **Mathias Grudén**, Magnus Jobs and Anders Rydberg, "Design and Evaluation of a Conformal Patch Antenna Array for use with Wireless Sensor Network inside Jet Engines", Antennas and Propagation (EuCAP), Proceedings of the 7th European Conference on, Gothenburg, 2013.

- VI **Mathias Grudén**, Paul Hallbjörner and Anders Rydberg, "Large Ad Hoc Shielded Room with Removable Mode Stirrer for Mobile Phone Antenna Tests", Transactions on Electromagnetic Compatibility, IEEE, Vol.: 55, Issue: 1, Page(s): 21-27, 2013.
- VII Juan D. Sánchez-Heredia, **Mathias Grudén**, Juan-F. Valenzuela-Valdés, David A. Sánchez-Hernández. "Sample-Selection Method for Arbitrary Fading Emulation Using Mode-Stirred Chambers", Antennas and Wireless Propagation Letters, IEEE, Vol.: 9, Page(s): 409-412, 2010.
- VIII Marín-Soler, Adoración, **Mathias Grudén**, Juan D. Sánchez-Heredia, Paul Hallbjörner, Juan F. Valenzuela-Valdés, David A. Sánchez-Hernández and Anders Rydberg, "Sample Selection Algorithms for Enhanced MIMO Antenna Measurements Using Mode-Stirred Reverberation Chambers", Antennas and Propagation, IEEE Transactions on, Vol.: 60, Issue: 8, Page(s):3892-3900, 2012.

## Comments on the author's contribution to the papers

- I. Planning the tests, supervising thesis workers, evaluating the results and writing the manuscript.
- II. Planning the tests, performing measurements with WSN aboard the wagon and wave propagation, analysing the results and writing the manuscript.
- III. Planning the work in cooperation with Malkolm Hinnemo and supervising the work.
- IV. The planning of wave propagation measurements and final tests, performing the measurements and writing the manuscript were in cooperation with the second author, Magnus Jobs. Analysis the wave propagation was performed by me.
- V. Design and simulations of the antenna, analysis and writing the manuscript was performed by me. Measuring the antenna was in cooperation with the co-author, Magnus Jobs.
- VI. The design of chamber and stirrer, planning and performing the measurements and major part of writing the manuscript.

- VII. Performed simulations of genetic algorithm and partially writing the manuscript.
- VIII. Development of the single step method in cooperation with the co-author Paul Hallbjörner, performing simulations, analysis of results on my own and partially writing the manuscript.

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## Related Papers

The following papers by the author is not included in the thesis due to they are covered by other papers, or out of scope of the thesis.

- IX Martin Berglund, **Mathias Grudén**, Greger Thornell and Anders Persson, "Evaluation of a Microplasma Source Based on a Stripline Split-Ring Resonator", *Plasma Sources Science and Technology*, vol. 22, No. 5, 2013.
- X Anders Rydberg, **Mathias Grudén** and Magnus Jobs, "Wave Propagation in Jet Engine Turbines", *Antenna EMB*, Stockholm 2012.
- XI Magnus Jobs, **Mathias Grudén**, Paul Hallbjörner, Anders Rydberg, "Antenna Diversity With Opportunistic Combining for ASK Systems With Single Channel Receivers". Presented at *Conference on Antennas and Propagation (EuCAP)* 2010, Barcelona.
- XII **Mathias Grudén**, Magnus Jobs and Anders Rydberg, "Diversity Techniques for Robustness and Power Awareness in Wireless Sensor Systems for Railroad Transport Applications", Book chapter published in the book "*Wireless sensor networks*", ISBN 978-953-307-297-5, December 2010.
- XIII Magnus Jobs, **Mathias Grudén**, Anders Rydberg, Sanel Zenkic, Edvard Svenman, Melker Härefors, Olof Hannius, Are Björneklett, Peter Nilsson, Jakob Viketoft, "Wireless Sensor Networks for Aircraft Engines", Presented at *Smart Systems Integration* in Dresden, March 2011.
- XIV **Mathias Grudén**, Magnus Jobs and Anders Rydberg, "Measurements and Simulations of Wave Propagation for Wireless Sensor Networks in Jet Engine Turbines", *Antennas and Wireless Propagation Letters, IEEE*, Vol. 10, 2011, Page(s): 1139-1142.
- XV Anders Rydberg, **Mathias Grudén**, Magnus Jobs, Wireless Sensors Networks in Electromagnetically and Physically Hostile Environments, *Smart Systems Integration*, Amsterdam 2013.

- XVI Anders Rydberg, **Mathias Grudén**, Magnus Jobs, Dragos Dan-cila and Robin Augustine, "Research on Wireless Sensors Networks for Electromagnetically and Physically Hostile Environments", Swedish Microwave Days, GigaHertz, 2014, Göteborg.
- XVII **Mathias Grudén**, Magnus Jobs and Anders Rydberg, "Investigation of Antenna Performance with Various Coatings Appearing in Railroad Environment", Swedish Microwave Days, GigaHertz, 2014, Göteborg.
- XVIII Juan D. Sánchez-Heredia, Miguel A. García-Fernández, **Mathias Grudén**, Paul Hallbjörner, Anders Rydberg, David A. Sánchez-Hernández, "Arbitrary fading emulation using mode-stirred reverberation chambers with stochastic sample handling", Antennas and Propagation (EuCAP), Proceedings of the 5th European Conference on, Page(s): 152-154, 2011.
- XIX Paul Hallbjörner, **Mathias Grudén** and Magnus Jobs "Broadband Space-Time Measurements in Reverberation Chamber Including Comparison With Real Environment", Antennas and Wireless Propagation Letters, IEEE, Vol.: 8, Page(s): 1111-1114, 2009.
- XX Magnus Karlsson, Owais Owais, Joakim Östh, Adriana Serban, Shaofang Gong, Magnus Jobs and **Mathias Grudén**, "Dipole antenna with integrated balun for ultra-wideband radio 6-9 GHz", Microwave and Optical Technology Letters, Vol.: 53, Issue: 1, Page(s): 180-184, 2011.
- XXI Owais Owais, Magnus Karlsson, Shaofang Gong, Zhinong Ying, **Mathias Grudén** and Magnus Jobs, "Wideband planar antenna with modified ground plane" Microwave and Optical Technology Letters, Vol.: 52, Issue: 11, Page(s): 2581-2585, 2010.
- XXII Malkolm Hinnemo, Filip Zherdev, Thomas Edling, Nils Edvinsson, **Mathias Grudén**, Kjell Brunberg, Erik Jansson, Ulf Hellström, Lennart Andersson and Anders Rydberg, "Continuous Monitoring of Train Wagons Using Wireless Sensor Network and Battery Assisted RFID Tags", Gigahertz 2012 Conference, Stockholm, Sweden, 2012.

- XXIII Johannes Hjerdt, **Mathias Grudén** and Anders Rydberg, Titti Ekegren and Jonas Bergqvist, "Near field terahertz imaging for biological tissue measurements", Gigahertz Conference 2010, Lund Sweden, 2010.
- XXIV Magnus Jobs, **Mathias Grudén** and Anders Rydberg, "Performance Evaluation of Conformal Dual Patch Antenna in Indoor Environment", Antennas and Propagation (EuCAP), Proceedings of the 7th European Conference on, Gothenburg, 2013.
- XXV Magnus Jobs, **Mathias Grudén** and Anders Rydberg, "Wireless body area networks (WBANs) and efficient energy conservative designs", Conference GigaHertz 2010, Lund, Sweden, 2010.
- XXVI Magnus Jobs, **Mathias Grudén**, Anders Rydberg, Sanel Zenkic, Edvard Svenman, Melker Härefors, Olof Hannius, Are Björneklett, Peter Nilsson and Jakob Viketoft, "Wireless sensor networks for aircraft engines", Smart Systems Integration Conference, Dresden, Germany, 2011.
- XXVII Jouni Rantakokko, Joakim Rydell, Peter Strömbäck, Peter Händel, Jonas Callmer, David Törnqvist, Fredrik Gustafsson, Magnus Jobs and **Mathias Grudén**, "Accurate and reliable soldier and first responder indoor positioning: multisensor systems and cooperative localization", Wireless Communication, IEEE, 2011.

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# Abbreviations

PDF	Probability Density Function
WSN	Wireless Sensor Network
LoS	Line of Sight
NLoS	Non-Line of Sight
LNA	Low Noise Amplifier
BER	Bit Error Rate
GPS	Global Positioning System
IR	Infra-Red
GA	Genetic Algorithm
RC	Reverberation Chamber
ASK	Amplitude Shift Keying
QAM	Quadrature Amplitude Modulation
FFT	Fast Fourier Transform
ISM	Industrial, Science, Medical
CW	Continuous Wave
RFID	Radio Frequency Identification
LQI	Link Quality Indicator
RSSI	Received Signal Strength Indicator
CPU	Central Processing Unit
IC	Integrated Circuit
NFFP	Nationella Flygforskningsprogrammet
EM	Electromagnetic
SMA	Sub Miniature version A
AUT	Antenna Under Test
TRP	Total Radiated Power
TIS	Total Isotropic Sensitivity
EMC	Electromagnetic Compatibility
LUF	Lowest Usable Frequency
RMS	Root-Mean-Square
VNA	Vector Network Analyser
DC	Direct Current



# 1. Introduction

As the development of electronic is progressing, the fabrication of smaller and more powerful devices is possible. This has enabled many new products such as laptop computers and smart phones. Previously, one of the most common ways to connect devices was via infrastructure. A good example is the cell phones that connect via the base station to other cell phones. The mobile devices also increase in its complexity, which means they can handle amounts of data and various types of peripheral units. When one starts to talk about interconnectivity of devices, one of the most interesting markets today is watches to be used while exercising. As peripheral units to your watch, it is now possible to connect a foot pod to measure running pace or heart rate monitor to monitor your heart beats [1]. The watch can even be equipped with a Global Position System (GPS) receiver. After the exercise, you can upload the measured information from your device to any social media network and share it with your friends all over the world. Then we may ask the question, why do we want to know so much information about ourselves during the exercise? Mainly, there are two purposes; see your health status meanwhile you're exercising and keep track of the improvements after the exercise.

This is a good example of the new possibilities using a sensor network - one or several sensors that measures various parameters, then transmitting the information to a device that stores the information and present it to an end user. Most of these devices are also without wires; therefore, the networks can be called wireless sensor networks (WSN). Another type of area where the WSN is useful is to optimize the energy management in homes [2] [3], [4]. By using WSN, the heating and light can be controlled and optimized both in respect of the outdoor temperature and where people are located in the building. Also, the WSN can be used to detect fires, burglars and gas leaks. Using a wireless system, not only newly build buildings can be equipped with the sensors, but also older buildings where the wiring is more difficult [5].

When changing from one technology into a new technology, old problems are solved, but new problems are introduced. When taking away cables, two things become more difficult than before. The first problem arises is how to provide power to the node, and the second is how to communicate with other sensor nodes or with the gateway. Since the life time of batteries is limited there is a need of replacing batteries or charge them. This is where the en-

ergy scavenging comes into the picture. A solution is needed where the nodes can extract energy from its environment. Regarding the antennas, the behaviour of them differs depending on which environment the antenna is positioned in. The antenna will behave differently if it is placed in an environment with any conducting material nearby or if it is placed in an environment with conducting materials. Seen from this point, it is important to design antennas with as little influence from the environment as possible. Also, how to test the antennas in a proper way before the deployment is of interest. To test an antenna and be sure that it is working in the final deployment saves a lot of money.

## 1.1 Wireless Sensor Networks

In this thesis two examples of WSN applications are presented along with their publications. The first example is when a WSN is mounted aboard a train wagon to increase safety and reduce maintenance cost by measuring the status of the ball bearings. The second project is to replace a wired telemetry system used to monitor jet engines during development. In this project, the aim is to reduce the time of mounting the system from several months to only a few weeks. These two applications show how beneficial WSN are when used in the right conditions.

Deployment of WSN can be an easy task when having static structures and a lot of energy to power the nodes, for instance in an office building or similar. However, most situations are not as friendly as an indoor deployment with nearly infinite amount of energy.

One of the two main topics in this thesis is how to build WSN in difficult environments. As one of the main ideas of using WSN is to measure parameters that earlier were impossible or difficult to measure. It can be in situations where moving parts making it impossible to use wires, the wires become too expensive or when an object that is already built needs to be monitored. Since no wires need to be installed, either no major modification to the structure that is going to be measured is needed. This results in that mounting a WSN-system can greatly reduce the cost compared to a wired system.

### 1.1.1 WSN aboard Trains

The usage of the capacity of the railroads is almost at its top limits at the moment, which implies that there are almost no room for errors. This makes the railroad rather sensitive to delays of any kinds and both the operators and railroad authorities' want to minimize the risk of introducing delays in the system. If an error occurs aboard a train, it is usually causing extended de-

lays, not only to the specific train where the error occurs, but also to all other trains running in the area. Delays can in worst case sustain the rest of the day.

One of the most common faults occurring aboard trains is overheated ball bearings. Therefore it is of interest to monitor them and predict when the ball bearings need maintenance. In the Swedish railroad today, there are about 120 stationary detectors that are monitoring the ball bearings. The stationary detectors measure the infrared (IR) radiation from the axles of the train. But since the detectors are mounted too sparse, the measurements are performed too seldom to be able to predict maintenance. The measurements are not related to any certain wagon, but to a specific axle in a train set that is passing a detector and it does only alarm when an overheating occurs. Hence, trending the status of a certain ball bearing is not possible. This is a perfect example where the WSN can solve the problem. In this thesis, two investigations have been performed to gain knowledge regarding how to apply the WSN aboard a train wagon. Small electronic devices, sensor nodes, are mounted near the ball bearings to enable temperature measurements. The sensor nodes then transmit the information to a gateway placed aboard the wagon. The gateway collects the information from all sensor nodes aboard the wagon and then transmits it to the end user. When the end user, the wagon owner, receives the status of the wagon they can use it to schedule maintenance, hence reduce the risk of an overheated ball bearing cause an emergent stop or derailling.

The uniqueness of this project is to perform practical tests with a WSN to monitor each ball bearing and report the status to an end user. Previously, most applications have been focused on having the WSN on wayside, and not aboard the wagons. One paper is found that is dealing with real-time monitoring of defect bearings [6]. However, the test in the paper was performed in laboratory environment and not on a moving wagon. Another paper, [7], presents a very similar application to what is presented in this thesis - a sensor node that is alarming when the bearing temperature is increased. But [7] cannot be used for maintenance scheduling since it is only alarming when the bearing temperature has risen.

The Swedish Traffic Administration (Trafikverket) has regulations that all new high speed trains must have continuous monitoring of some important properties, such as ball bearings. This regulation does not solve any problems that can occur in already existing passenger trains, or aboard freight trains. Since high speed trains are electrified, there is almost (from a WSN perspective) infinite amount of energy. This makes it easy to use large and power consuming computers with large computational capacity. But for older personal wagons or freight wagons, it is not feasible to redesign the wagon just for this purpose. This is why it is easier in these situations to apply a smaller WSN node that has its own power supply and communication. No power cables needs to be drawn and no communication wires needs to be

attached aboard the wagon. In contrast to the stationary detectors, the WSN nodes are related to a specific wagon and can also be related to a specific ball bearing. This enables the possibility of monitoring the ball bearings over a time period; hence the possibility of predicting failures is also enabled.

### 1.1.2 WSN in Jet Engines

In this project, a WSN has been placed inside the jet engine and wirelessly transmit information to a receiver placed outside the engine. This application of WSN is used to replace a wired telemetry system. The wired telemetry system is used to evaluate the engine during research and development and measures strain of blades and temperatures inside the engine. The difficulties with the wired system are that it is extremely time-consuming to install in the engine and the engine has to be modified to enable data acquisition. In able to acquire data from the rotating blade of the fan in a jet engine, the nose cone placed to cover the centre axis of the engine has to be replaced with a slip ring. This implies that the engine is not exactly the same engine as without this system, the air flow in the air intake is slightly changed.

The sensor nodes are placed on the first rotor disc inside the jet engine. Two types of sensor nodes are used. One type of node measures strain of blades and the other measures temperatures inside the engine. The nodes transmit the information from the sensors to a gateway positioned outside the engine. The rotation of the fan disc and the obstruction of stators between sensor node and receiver will affect the radio performance. When using a WSN for measure strain of blades and temperatures inside the engine, the old wired telemetry system used by engine manufacturers can be abandoned. Since no wires has to be drawn (except from node to antenna and sensors), the WSN is much cheaper and faster to mount. The time of mounting is reduced from several months to only a few weeks.

This type of application of a WSN has, in the literature, never been presented before. Only simulations and measurements of wave propagation in jet engines have been performed in [8].

To be able to develop a WSN to be used inside an engine, both the radio wave propagation has to be characterized as well as new antennas have to be built. Also, few environments are as harsh as inside a jet engine with both high temperatures and high wind speeds. The air temperature constrain where the nodes can be placed. In this case, they are placed in the coldest part, which is the fan. The transmitting antennas are to be placed on the fan blades and the receiving on the inside of the outer casing. In order to successfully build a system that works in this environment, the antennas must be both extremely thin, and conformal to be shaped on curved surfaces. Also, the characteristics of the wave propagation must be known.

## 1.2 Reverberation Chambers

Many situations do not allow the engineer to test a designed antenna in the real situation before the final test. In the worst case, the antenna will not work at all in the final deployment. To handle this, the antenna needs to be tested in as similar situation as the final deployment environment as possible. One of the most versatile tools for testing antennas nowadays is to use Reverberation Chambers (RC). With the RC, it is possible to measure for instance radiation efficiency and diversity gain in a fast and cheap way. Two drawbacks using RC to measure antennas are the difficulties of measure low frequencies and to mimic the real environment in a controlled and repeatable way.

A reverberation chamber is designed as a shielded box/room with one or several rotating paddles to stir the energy. Since the paddle is rotating, the physical geometry is changed inside the chamber, thus also changing the electromagnetic boundary conditions. When an antenna inside the chamber is transmitting a signal, under the assumption that the stirrer is stationary, the reflections of the radiating electromagnetic waves inside the chamber will cause a fading, but stationary environment. As the paddles start to move, the geometry changes, thus the radio waves are reflected differently than before. This means that the paddle is changing how the travelling waves are reflected inside the chamber. This leads to that a chamber with a paddle has an environment with homogeneous power distribution and a fading signal amplitude as the paddle turns. Large RCs have been built and used before, but the novelty with this part is to build a simple measurement setup with a mobile mode stirrer. The chamber built in this thesis is a normal EMC room, which is going to be used also for other experiments, thus, the equipment mounted inside the chamber has to be removable and mobile. Another main issue to this problem is how to build the chamber in such a way that the mode stirrer could be easily removed meanwhile the chamber is not going to be used as an antenna measurement facility.

The second sub project was on how to perform emulations of real environment inside the chamber. Normally, the chamber has an environment that does not correspond well with normal (outdoor or indoor) radio environment. The environment inside the chamber is isotropic and with a homogeneous power distribution. In real world environments, this is a rare environment. To mimic real world environment, attenuators and body phantoms are placed inside the chamber. The phantoms are filled with a lossy material that is mimicking, for instance ab head or a hand, and are attenuating the signals from a certain direction. This is well researched topic, among many papers, [9] - [12] presents various techniques to manipulate the  $K$ -factor to mimic certain environments. The common solution for the papers is that they use physical absorbers that are placed in the chamber. What has been introduced in the papers presented in this thesis is the use of post processing to emulate

radio environments. This has been performed by designing algorithms for selecting samples that fit to a desired probability density function (PDF). In the papers presented in this thesis, three algorithms have been used to select a subset of data with a certain PDF. These algorithms are a genetic algorithm (GA) [13.], a linear algorithm and a hybrid of these two. Since my main contribution in the area of sample selection is the development of the linear method, the thesis will only present the linear method.

With these algorithms, it is possible to measure an antenna in a small reverberation chamber and post process the result to see how the antenna behaves in a certain environment. The emulated scenario can for instance be urban scenario or on body.

## 1.3 Thesis Outline

This thesis contains a rather wide range of areas and is outlined as follows:

**Chapter 2** presents wave propagation mechanism are presented and defined. Also, useful parameters for antennas are presented. These theories are later used to explain the features in both the case of the reverberation chamber and when designing antennas.

**Chapter 3** introduces some general aspects when designing WSN such as energy management, communication and sensors.

In **Chapter 4** the two investigations performed when applying WSN aboard train wagons is presented.

**Chapter 5** presents the application and difficulties of having WSN in jet engines.

In **Chapter 6** the antennas that were used in both the investigations aboard trains and in jet engines is designed and verified.

**Chapter 7** consists of designing and verification of a large RC as well as the single step sample selection algorithm.

**Chapter 8** contains the summary of the papers presented in this thesis.

## 2. Radio Wave Propagation and Antennas

The topic of radio wave propagation and antennas is an extremely wide and advanced topic. The wave propagation is important to understand when designing the WSNs in chapter 4 and 5 and when designing the RC and the sample selection algorithms in chapter 7. Also, some useful definitions of antenna parameters are presented.

### 2.1 Radio Wave Propagation

#### 2.1.1 Single Path Propagation

One of the simplest models when dealing with wave propagation is the case when there is only one single path that the radio wave can propagate. At a distance  $d$ , away from the transmitter, it is fairly simple to calculate the received signal power. To represent the received signal power we can introduce a narrow-band low-pass signal,

$$S_n = a_n + jb_n \quad (2.1)$$

where  $a_n$  and  $b_n$  are the in-phase and quadrature components (I and Q) respectively. The signal  $S_n$  is a complex valued signal, therefore, the amplitude of the signal is

$$A_n = \sqrt{a_n^2 + b_n^2} \quad (2.2)$$

Since the signal described in eq. (2.1) is a complex valued signal, it can also be described in the Euler notation as,

$$S_n = A_n e^{j\theta_n}, \quad (2.3)$$

where  $A_n$  is the amplitude and  $\theta_n$  is the phase of the signal. This can also be visualized as a vector with size (the amplitude) and direction (phase) in a complex plane as seen in Figure 2.1.

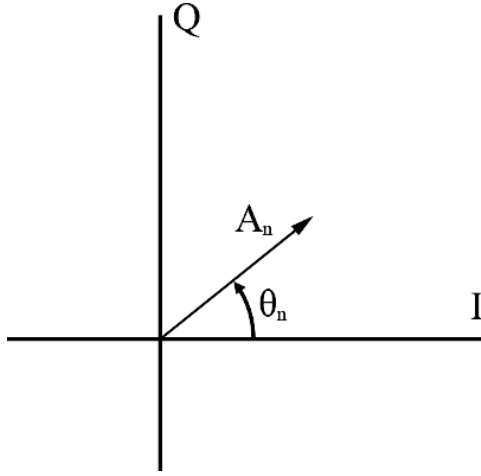


Figure 2.1. The notation of a vector in the IQ-plane.

As the waves propagate further away from the transmitting antenna, they will also be attenuated, both by the fact that the energy is spread out on a larger surface area and by attenuation in atmosphere (if not transmitted in vacuum). This attenuation has been derived many times and is also known as the Friis transmission equation [14],

$$P_r = P_t G_r G_t \left( \frac{\lambda}{4\pi d} \right)^2, \quad (2.4)$$

where  $P_t$  is the transmitted power,  $P_r$  is the received power,  $G_r$  and  $G_t$  are the antenna gain for the receiver and transmitter,  $\lambda$  is the wavelength in vacuum and  $d$  is the distance between the transmitter and receiver. The Friis transmission equation in this form does not take impedance mismatch between radio and antenna into account. This equation is useful in the most cases where the radio waves propagate through an environment with no or few obstacles. When many and large objects (in relation to the wavelength) reflect the signals, the equation becomes rather inaccurate, which is described in section 2.2.

### 2.1.2 Multi Path Propagation and PDFs

Unfortunately, the environment is almost never as simple as described in section 2.1.1. The single path propagation model is more or less only valid in the extreme case when there are nothing close to, or in between, the transmitter and receiver. A real world will cause a multipath behaviour of the signal. An example of this is seen in figure 2.2 where a direct signal is between

the transmitter and the receiver, and a reflected signal is reflected on an obstacle nearby. Since the two rays of radio waves can be described as sinusoid signals with a phase, corresponding to the travelled distance, these are summed at the point of reception. The phase and amplitude behaviour is seen in equation (2.3). When there are several rays between the transmitter and receiver, they will cause interference at the receiver. This can also be described as the sum of the signals as,

$$S_M = S_1 + S_2 + \dots + S_i = \sum_i S_n \quad (2.5)$$

where  $S_n$  corresponds to each separate component, and  $S_M$  is the sum of all components.

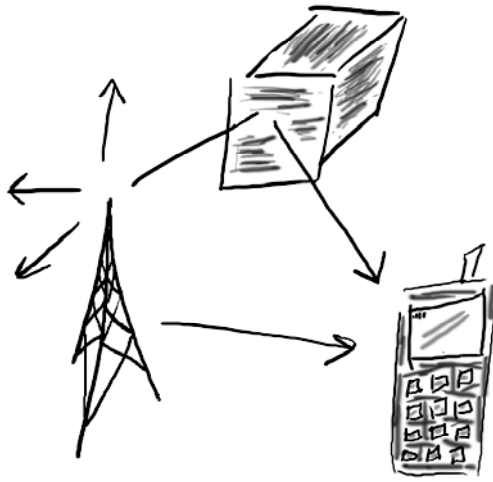


Figure 2.2. A sketch of a more realistic situation with reflected waves.

As an example, when having three components, each of them with independent phases and amplitudes, the sum of the three vectors is the received component can be visualized as in figure 2.3 and described by eq. (2.5).

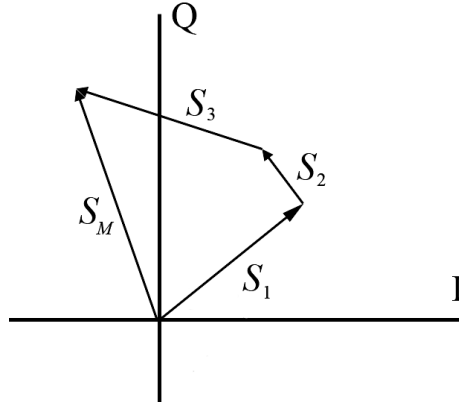


Figure 2.3. The sum of the vectors in the IQ-plane.

As the paths from transmitter to receiver are not exactly known, the received signal strength is highly dependent on the geometry of the environment. With only one obstacle and two rays, this task can be possible to perform. But with several obstacles and several rays this easily becomes a complex task. To achieve a deterministic signal, the physical environment and all its electromagnetic properties must be perfectly known and described, which in reality is cumbersome to perform. Additional reflections increase the difficulties of describing the signal in a deterministic way. Since this procedure is not realistic to perform; the received signal is described as a random variable with a certain probability density function (PDF). From the PDF, the estimated average signal amplitude can be seen as well as the variation of the amplitude.

One of the most common PDFs to describe the amplitudes of a multipath signal is the Rician PDF, which is described as [15]

$$p_{rician}(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} e^{-k} I_0\left(\frac{r\sqrt{2k}}{\sigma}\right), \quad (2.6)$$

where  $k$  is a shape parameter of the PDF,  $r$  is the amplitude of the signal. The variable  $k$  varies from 0 to  $\infty$ . When  $k = 0$ , the PDF becomes into a Rayleigh distribution. The Rayleigh distributed PDF appears in environments with rich multipath behavior where all incident radio waves have amplitudes of same order. The variable  $k$  is a good variable to show how severe the fading is. The Rician  $k$ -factor is defined as [16]

$$k = \frac{a^2}{2\sigma^2}, \quad (2.7)$$

where  $a$  is the average of all complex samples in the data set, and  $2\sigma^2$  is the variance of the data set. The data set can be visualized by both scalar and complex amplitudes. When  $k = 0$ , the sampled amplitudes in an IQ-plot the samples are around the origin of the complex plane. This is the worst case for radio transmissions since the amplitudes are highly varying.

When a dominant signal appears, the average of the data set is shifted off centre. This means that the variable  $a$ , is no longer zero. In theory, the  $k$ -factor varies from 0 to  $\infty$ , but in reality, it is unusual with a  $k$ -factor of more than 30-40 [17]. Extreme values of the  $K$ -factor are about 180 [18]. These values correspond to an environment with strong LOS component and small variation of the signal.

## 2.2 Antenna Parameters

### 2.2.1 Matching

Assuming a non-matched network of components, such as low noise amplifiers (LNAs), amplifiers, power dividers, antennas etc., power loss will be introduced in the interconnections between the components. To avoid the power loss, the loads impedance shall be the complex conjugate of the generators impedance. This is also formulated by as [19],

$$Z_g = Z_L^* . \quad (2.8)$$

Generally, there are two ways of having the antenna matched to the radio receiver with passive devices. The first one is to simply build the antenna with the correct impedance from the beginning. The second way is to use a matching network. Basically, there are two types of matching networks. One is to use discrete components, such as inductors, capacitors and dielectric lumps of materials. The second way to match by using open or shorted sections of transmission lines, so called stubs.

A good impedance matching between transmission line (or radio) and antenna is crucial when designing an antenna. A standard radio system, which is also used in this thesis, usually has a characteristic impedance of  $50 \Omega$ . This is the most common impedance in most wireless applications. However, for ordinary single components, it is rare that they have an impedance of exactly  $50 \Omega$ , instead, it is often not exactly a real number either.

A matching network affects the overall performance of the system. By using a more complex network, the bandwidth can be improved on the expense of higher losses for the system. The antennas in this thesis are matched to  $50 \Omega$  without any matching stubs or network.

### 2.2.2 Radiation efficiency

Another of the most important parameters for an antenna is the radiation efficiency. This is a relative indicator of how much of the inserted energy that is transferred from the antenna into the air. With low radiation efficiency, the losses in the so called link budget will increase, implying more difficulties of communicating. The radiation efficiency  $\eta$  is simply defined as

$$\eta = \frac{P_{out}}{P_{in}}, \quad (2.9)$$

where  $P_{in}$  and  $P_{out}$  are the input power and output power respectively.

### 2.2.3 Radiation Patterns

The radiation pattern an antenna shows in which direction the antenna is radiating. When measuring radiation pattern, it is possible to measure full sphere around the antenna, but this is extremely time consuming if not using the right equipment. The standardized procedure of measure an antenna is described in [20]. In the IEEE standardization document, it is stated that the radiation patterns should be measured in great-circle cuts or in applicable, cases so called principal-plane cuts. This implies that two measurements are performed in perpendicular planes. One of the measured planes should include the major lobe of the antenna.

The measurements can also be presented in two forms, by showing either the relative or absolute gain. An absolute measurement will show how much gain, in absolute terms that the antenna has in a certain direction. The relative gain implies that the measurements are scaled by the highest value in the measurement sequence. This results in that it is only possible to see the direction that the antenna is radiating towards, and not how much. It will be possible to determine the beam width and angle between two directive maximums, but no information on gain in a certain direction is available.

The gain can also be used as a directional filter. The signal can gain amplitudes from a certain direction and suppress from another. This is especially used in Paper V where an antenna is designed for the WSN in jet engines.

Also, as the size (compared to the wave length) shrinks, the directivity reduces and the radiation of the antenna becomes more isotropic. The opposite also occurs, when the antenna can be made larger, the possibilities of controlling the directivity during the design phase increases. This issue mentioned above becomes more visible during the design when having both size restrictions and a desired directivity of the antenna.

## 3. Design Aspects of Wireless Sensor Networks

This chapter describes considerations about the building blocks that have to be designed for a WSN. Even though the topics presented in this chapter may look separate, a design decision in one area will affect the possible decisions in the other areas.

### 3.1 Network Topology

For WSN, various configurations of how to transmit the information are available. Many engineers aim to have an adaptive network where the nodes communicate with the neighbours and establish a network depending on which other nodes that are nearby, so called Ad hoc networking [21]. The drawbacks are that the rearrangement of communication links cost energy and there is usually no obvious route to the end user. This means that the energy is often wasted trying to transmit the data to the user.

In the WSN presented in this thesis, the network topology is decided to be of star configuration. This means that all sensor nodes are connected only to the gateway and no communication between the nodes is established. This simplifies a lot and since the communication is going directly to the end point (the gateway/receiver). This is also the most energy efficient for our situation.

### 3.2 Energy Management

One of the major drawbacks using wireless communication is the fact that it is wireless. To be able to have a device that is fully wireless and mobile, it has to have a battery or other energy sources to provide energy. If only an energy harvester is used without storage, the power has to be consumed immediately as it is scavenged. To provide higher level of usability, energy storage i.e. battery, have to be used. This enables momentarily higher power consumption than what the scavenging device can provide. The WSN node can also be used when the scavenging is not scavenging any energy [22].

When looking at how the different devices are working, it is seen that each device has its own level of usage. For instance, a cell phone is not used in the same way as a laptop. The cell phone is usually consuming most its energy in shorter time periods, e.g. when calling. In between the calls, the power consumption is low. To optimize the power consumption for a device, firstly, what the device is going to measure has to be known. If it is a continuous process, for instance a vibration, that is going to be measured, the WSN must consume more energy than if it is only have to measure slower or stationary processes, for instance temperatures. This is due that the micro-controller must be more active and sample more often and longer time periods to be able to measure the vibrations than the temperatures.

Also, depending on the process, the sampling of the sensors, which are mounted e.g. in order to detect a damage in a structure, must be performed within certain time periods. If looking for instance after an error that can occur, it must be clear how fast the error will develop from a detectable and small error, to a major failure of the complete system. If the error develops extremely fast, also the measured parameter has to be measured more often. The answer to this question depends both on how often a problem occurs and its consequences.

Since the radio is using much of the energy in a WSN node, the transmission and reception must be kept at a minimum. In many cases, it can be preferable to measure a process and analyse the data locally and then transmit the results instead of transmit the complete measurement sequence for post processing in another node. Electronic devices can intermittently be hibernating to save energy, this is also known as duty cycling [23]. However, that not all processes can be duty cycled. For instance, control and automation processes have to be monitored more or less continuously. The control and automation process is clearly the most energy consuming and most difficult to measure with wireless sensors.

How to measure, what to measure and when to transmit are important to answer in the papers about the WSN aboard trains, Paper I and II, and in Paper IV, where the WSN in jet engine is tested. Even though the sensor nodes in both scenarios are measuring the temperatures, the requirements of how often the process should be measured are different. The temperature shifts are much faster in the jet engine than aboard the train, which increases the requirements of how often the temperatures must be measured in the jet engine. Beside temperatures in the jet engine, strain of blades is also measured. Apart from less hibernation, this means that the sampling must be much faster for the strain measurements than the temperatures.

### 3.3 Energy Scavenging

To have a sustainable node, the node must have both energy storage and some sort of scavenging. The storage is to power the node when the scavenging is not providing energy, and the later part is to extend the life time of the battery and to reduce the maintenance. Firstly, to fit an energy source to an application it is crucial to analyse the environment to see which energy type that is most useful to use for environmental energy harvesting. It is possible to group all types of energy sources into a few different types, such as:

- Mechanical (Kinetic and Potential)
- Nuclear
- Chemical
- Thermal
- Electric
- Magnetic
- Electromagnetic

Transfer between these energy types is possible, but not all of them are suitable for WSN and transfer between the energy types introduces loss of energy. Another issue to deal with is the amount of energy that can be scavenged in each environment. First, an analysis about the available energy in a certain environment has to be performed, in other words, which types of energy can be scavenged, and how much energy can be provided from the environment? When answering these questions, also the maximum size of the device has to be included. This is due to the fact that the energy must be seen as energy density ( $\text{W}/\text{cm}^3$ ). Indirectly, the maximum power scavenged will be as a function of the maximum size of the scavenging device. Typical energy densities for standard applications are from about  $4 \mu\text{W}/\text{cm}^3$  to nearly  $1 \text{ mW}/\text{cm}^3$  [24]. A larger device can usually scavenge more energy than a smaller one. But for WSN nodes, the electronic is in general only a few square centimetres, therefore a smaller scavenging device is preferable. A typical WSN node consumes 50-150 mW, thus if the electronic is duty cycled it can be possible to have a device that very seldom need attention from the user.

#### 3.3.1 Energy Scavenging Devices

The current situation with energy scavenging devices is that there are several different types of scavenging devices on the market [25]. The most common devices are solar cell (well known), piezo electric, thermoelectric and electromagnetic induction via vibrations. In this section, no data from trials are presented but only the general functionality and the pros and cons of the devices.

In Paper I, the three first scavenging devices, solar cell, piezo electric and thermoelectric, are evaluated. The solar cell, probably do not need any detailed explanation. It provides power when it is exposed to sunlight. However, the efficiency of the device is reduced if it is covered by dirt or other coatings.

The piezo electric is a wafer which is providing energy when it is bent. The characteristic of the piezo crystals is that it produces high voltages when it is deformed. On the other hand, it is not producing high power since the output current from the piezo electric device is low. The device used in the investigation also had a resonance frequency. This limits the usage since it can be difficult to tune the device to the vibrations of the environment.

The thermoelectric device is a peltier-device which produces power when there is a temperature gradient between the two surfaces of the device. In relation to the power used by the system, this device delivers rather high output power. However, a large temperature difference is also needed. This is not available for all environments which make this device difficult to use.

Beside the devices mentioned above, there is also a common type of device that is using a magnet vibrating in a coil or wind energy. However, these devices were not tested in the investigations aboard the trains, but the magnet vibrating near a coil is probably the type of device that is most suitable for powering nodes in a vibrating environment. But as the piezo electric devices, this type of device also need tuning to provide the optimum amount of power. Both the vibrating magnet in a coil and wind energy produces high power in the right environment, but the devices itself are usually both significantly larger and heavier than the WSN nodes.

### 3.4 Communication

When a radio is transmitting the information, the radio has some internal hardware properties as well as software protocols to follow. In this thesis, the protocols are neglected. Secondly, the antenna is connected to the radio and has its both complex and interesting properties. This is seen in both the projects about WSN aboard trains and inside jet engines. Thirdly, what will be seen later in chapter 5, about the WSN in jet engine project, is that the temperature affects how well the radio on the nodes performs.

The modulation plays an important role in having a robust communication link. When having a fading channel, normal amplitude-based modulation schemes are vulnerable. This is due to the fact that the environment affects the amplitudes of the signals travelling through the air, hence the received amplitudes and phase will be distorted. Normal types of amplitude modulation schemes are amplitude shift keying (ASK) and quadrature amplitude modulation (QAM). For a fading channel, a preferred modulation scheme is frequency or phase modulation [26].

When designing the radio link for a WSN, it is crucial to know how much communication there will be and if the communication should be uni- or bidirectional. Energy wise, one has to keep in mind that listening for transmissions cost about equally as transmitting data. For low power nodes, it is preferable if the nodes transmit as seldom as possible and if the communication is unidirectional.

### 3.5 Sensors

A WSN would not be useful if there were no sensors in the network. The sensors work as the interface from the surrounding world to the electronics. Depending of what is of interest to measure, the most common sensors are accelerometers, thermometers, buttons, magnetometers, etc. For an energy efficient WSN, the sensors are needed, but is also consuming power, which is shortening the life time of the network. Since the WSNs presented in this thesis is using thermistors for measuring temperature and strain gauges to measure strain in blades it is interesting to compare these two.

The thermometers usually consumes small amount of energy since the microprocessor only need to sample once, and the accelerometers/strain gauges do need faster sampling to be able to read the data. The thermistors are temperature dependent resistors, which mean that the current or voltage is proportional to the temperature. This also only needs one sample to provide the result.

The accelerometers provide an output voltage depending on which acceleration it is subject to. With the accelerometers, the voltage needs to be sampled several times and with a sampling frequency in proportion to the measured frequency content; hence this is more energy consuming sensor than the thermistor. Also, the data must be treated locally, with e.g. fast Fourier transform (FFT) and analysed or transmitted to another node where the data can be analysed more thoroughly. The first will consume more energy for calculations, but less for transmitting and vice versa.

Since not all communication links can transmit high data rates, many types of measurements are not possible to perform. To be able to decide what kind of sensors that is possible to use, one have to study especially the sampling rate of the microcontroller and the data rates of communication links.



## 4. Wireless Sensor Networks aboard Trains

To reduce the risk of overheated ball bearings aboard trains, two different WSN have been investigated. The first investigation was performed during 2008, and the second in 2011. In both investigations the measured variable was the temperature of the ball bearings. Since the temperatures are only increasing in the very late stages of the degradation process of a ball bearing, this is a rather weak method of predicting failures. A more promising alternative is to measure vibrations, but to be able to determine a faulty ball bearing by vibrations, the characteristics of the faulty ball bearings must be known. Each model of ball bearing has its vibration spectrum which must be known by the sensor node. So, in this case, this is too difficult task to embrace. But since most of the focus is in the projects is to have a proof of concept of a WSN, the temperatures is an adequate method.

This project has been performed within WISENET (Uppsala Vinn Excellence Center for Wireless Sensor Networks), which is a 10 year, interdisciplinary, excellence centre at Uppsala University including both academia and industrial partners. The collaboration on WSN aboard trains is carried out, mainly, with the partners Swedish Traffic Administration (Trafikverket), UPWIS AB and Uppsala University. In the early stages of the project, another company were also involved, TNT Elektronik AB, nowadays named SensiNet AB.

### 4.2 The First Investigation

During the autumn of 2008, the first test with wireless sensor network onboard train was performed. This investigation is presented in Paper II. In total, three wireless sensors were mounted on the ball bearings and one were measuring the air temperature. In this trial, the WSN was manufactured and delivered by SensiNet AB and the Swedish Traffic Administration Supported had a wagon available for the test bed, seen in figure 4.1

The temperatures were transmitted from the sensors onboard the train to a gateway inside the wagon, using the free industry, science and medical band (ISM-band) at 434 MHz. The temperatures were then transmitted via a 3G-datalink to a database. In figure 4.2 (a)-(d), the positions of the nodes in the first trial are seen.



Figure 4.1. The measurement wagon is passing Uppsala during the first trial.

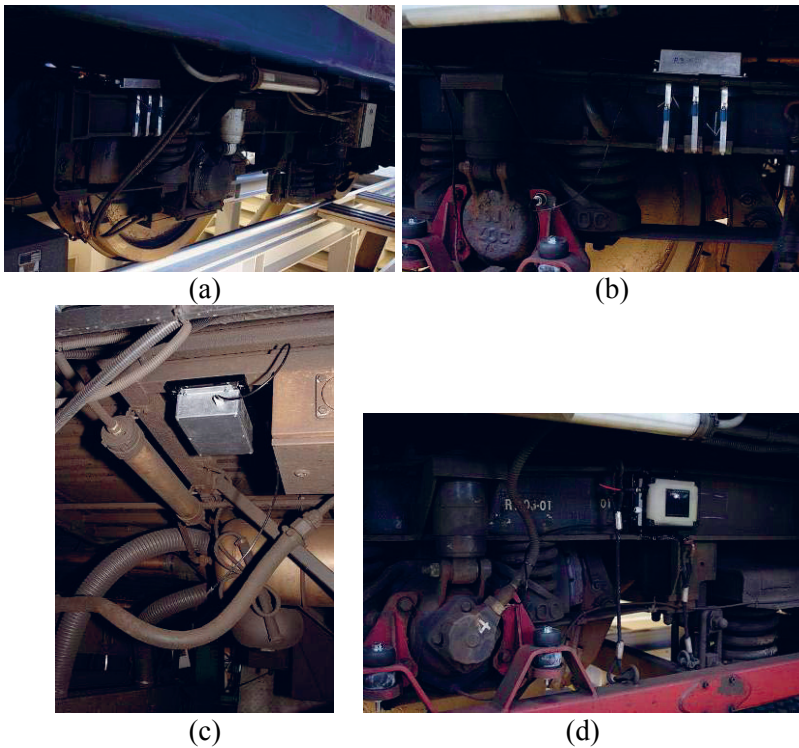


Figure 4.2. All four sensors used in the first trial. All sensors, except, (c) is measuring the bearing temperature, sensor (c) measures the air temperature as reference.

Before the WSN was applied aboard the wagon, the radio wave environment was characterized at 434 MHz to ensure successful communication in this

investigation, and 2.45 GHz for future investigations. As signal source for the measurements, a signal generator was used in continuous wave (CW) mode. The signal generator was connected to a dipole antenna which was mounted aboard a wagon, as seen in figure 4.3. On the receiver side an identical dipole antenna was used with a spectrum analyser set in “zero span”-mode with a computer as storage device. In the wave propagations measurements presented [27], it is seen that propagation at 434 MHz has less initial losses at a reference distance. But surprisingly, the 2.45 GHz have less loss over the distance. This is most probably due to the size of the metal parts which act as directors and wave guides for 2.45 GHz. The severity of fading was about the same for both frequencies.

As mentioned, the temperature was measured in this investigation. In figure 4.3, both the air temperature and measured ball bearing temperature is seen.

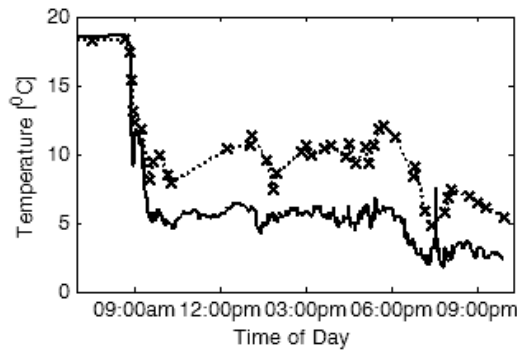


Figure 4.3. An example of the measurements from the first investigation. The dotted line is the ball bearing temperature, and the solid line is the air temperature.

## 4.2 The Second Investigation

The second investigation was performed during the fall of 2011. In Paper I the second trial is presented in detail. In this paper, also, an investigation on the power scavenging devices is presented. This trial had, in comparison of the first investigation, slightly different setup. Instead of using a 3G modem to unload the data from the train, which is not optimum in respect of energy consumption, a RFID-link is used. The network nodes in the second investigation are a modular system with a central processing unit (CPU) as the mother board. To this CPU, it is possible to add peripheral unit, such as, energy management, 2.45 GHz radio and RFID emulating chip. The 2.45 GHz radio communicated with the IEEE 802.15.4 protocol [28], and the RFID communicated with the readers on according to the GS1 standard for RFID readers on 860-960 MHz [29]. In this investigation, two different node setups were used. There is one setup for the sensor nodes and one for the

gateway. The similarities and differences in the setup of the nodes and gateway are seen in Table 4.1.

Table 4.1. The setup of each type of node.

Device	2.45 GHz Radio	RFID emulator	Energy Management	External Temperature Sensor
Gateway	X	X	X	
Sensor Node	X		X	X

The way of unloading the information to the end user is novel in this second investigation. This is performed by reading a battery assisted passive (BAP) RFID-tag where the reader is not only reading the ID of the tag, but also the memory of the tag. This memory is from the RFID-readers point of view, not visible, and is only appearing as data on read out. From the nodes point of view, the RFID behaves as a memory. The CPU writes information to the memory, which is later read by the RFID-emulator and converted to an RFID response. Why RFID is chosen as the interface to the end user is due to the Swedish Traffic Administration is currently building a system of RFID readers to monitor where wagons are located. This will help the industry to know more exactly where the freight is and when it will arrive. Hence, this system will work as a piggy back on this RFID system.

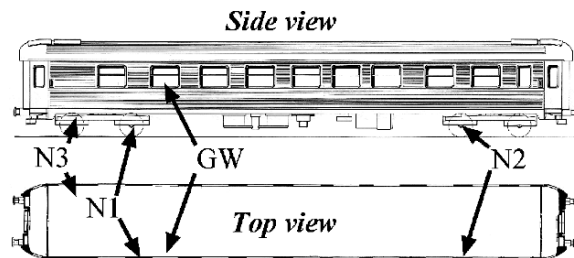


Figure 4.4. The positions of the nodes (N1, N2, N3) and gateway (GW) aboard the wagon.

In total, three nodes were used along with one gate way. The positions of these are seen in figure 4.4, and the way of mounting the nodes is seen in figure 4.5. During the trial, also the RSSI (Received Signal Strength Indicator) and LQI (Link Quality Indicator) values were recorded for each transmission. The RSSI provides the received power for each transmission, and the LQI provides information on how well the shape of the received packaged corresponds to an ideal transmission. For the radio used in this trial, a higher LQI value than 170 indicates less than 10 % package loss, and vice versa. The LQI for node 1 and 3, and the RSSI for node 1 is seen in figure 4.6.

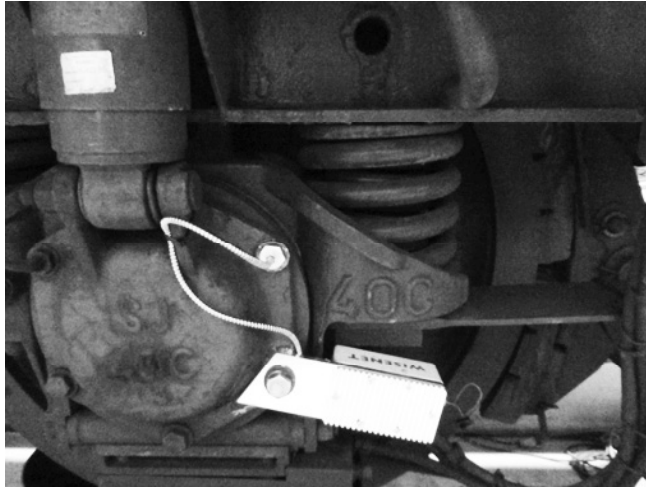
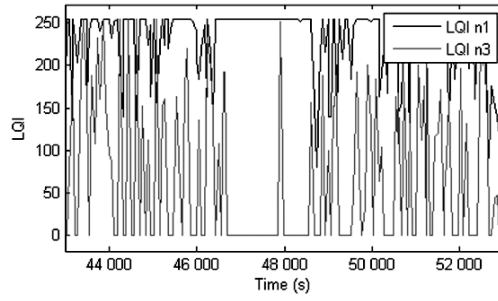


Figure 4.5. The position of one of the nodes aboard the wagon in the second investigation.

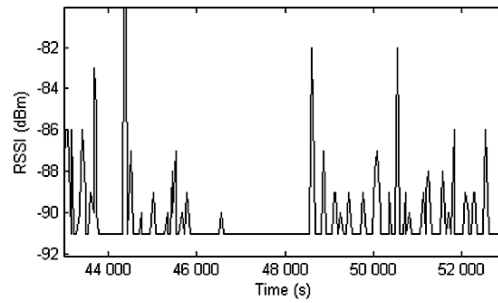
The measured temperature is seen in figure 4.7. The figure presents the same time period as in figure 4.6. In the figure, it is interesting to see that the temperature rises when the train is moving. The temperature of the ball bearing is about 5 °C higher than the temperature measured on the circuit board. For this wagon, this heating is normal, but since the wagon is well maintained, a larger heating is expected for other wagons.

In this investigation, three different power scavenging devices were evaluated in lab environment before the application aboard the train. These devices are seen in figure 4.8 and were solar cell, piezo electric to scavenge from vibrations and thermoelectric.

The test shows that the solar cell scavenges most energy of the tested devices, but since it is an optic device it is not suitable for the dirty environment aboard a train wagon. The thermoelectric harvester is the least suitable since it only will provide energy when there is a temperature gradient between the two surfaces. This is usually only occurs when the ball bearing is degrading. The best option to use in respect of suitability aboard a train wagon and output power is the piezoelectric vibration harvester. In optimum it can provide up to 2.32 mW, which is enough for a device that is duty cycled.



(a)



(b)

Figure 4.6. Subplot (a) shows the LQI of node 1 and 3 and (b) shows the RSSI for node 1 during the same time period.

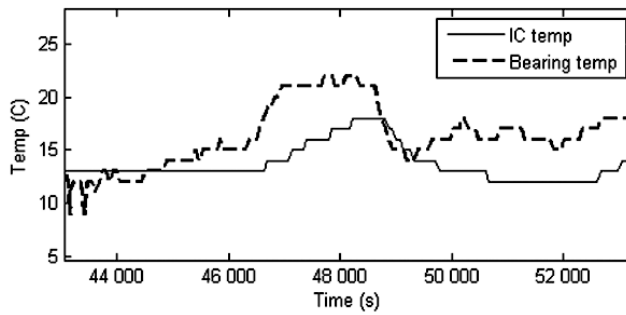


Figure 4.7. The measured temperatures at the same time period as figure 3.6. "IC temp" is the temperature at the CPU, and "Bearing temp" is the temperature of the ball bearing.

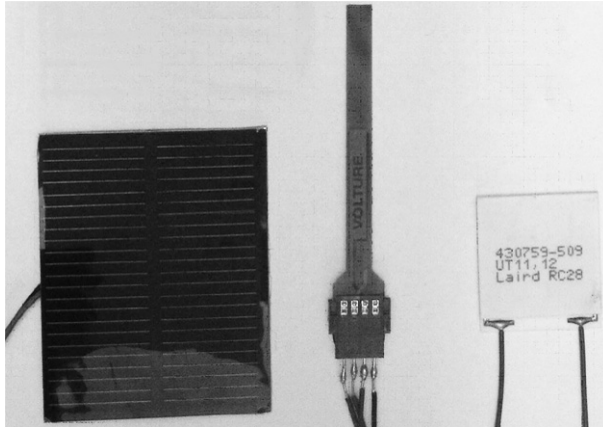


Figure 4.8. The energy scavenging devices used in the investigation. From left to right, solar cell, piezo electric wafer and thermoelectric device is seen.

### 4.3 Discussion and Conclusions

The application of WSN aboard train introduces several difficult problems to solve. Firstly, what is measured is one of the key parameters to decide. In this situation it is possible to measure vibrations, acoustics and temperature. Since the investigations mainly aimed to have proof of concept having WSN aboard trains, the two first options, vibrations and acoustics, are too cumbersome to implement. To be able to verify if a ball bearing is damaged, it is easier in this case to implement temperature measurements.

In the two implementations, there are two different ways of transporting information from the train to the end user. In the first trial, this was performed by transmitting the information via a 3G- modem and a computer, and in the second trial this was performed by using a RFID link. Since the energy aboard a normal freight wagon is limited, the 3G link is not as suitable as the RFID.

Most of the freight wagons are not electrified, this means that the energy resources aboard a freight wagon is extremely limited. In the second investigation, three scavenging devices were tested, solar cell, piezo electric and thermo electric. None of them are perfect for this situation. The solar cell will be dirty and its efficiency will degrade. The piezo electric device is providing enough power, but is both rather fragile and provides low output currents. And the thermoelectric device provides enough power, but since the thermoelectric device is only working when there is a temperature gradient between the surfaces, the device will only work when the ball bearing already is overheated. The difficulties are to find an energy harvesting technology that is mature and meet the requirements of being of the same size the nodes.

The general conclusion of the investigations performed aboard train wagon is that the WSN works well; the information is transmitted to the end user. But also, the environment sets limitations on both the communication and the scavenged energy.

## 5. Wireless Sensor Networks in Jet Engines

The WSN is a good tool to both increase safety and reduce the cost of a system. In this project, the main task is to perform a test with a WSN inside a jet engine to see the possibilities of replacing a wired telemetry system. Since the safety in the aircraft engine industry is already of high standard, it is not possible to have increased safety as an argument. In this case, the reduced amount of time mounting the WSN relative to the wired telemetry system is the key issue. With the wired system, the time to mount it was several months, up to half a year. Most of that time was consumed due to gluing wires inside the engine. With the WSN, the only a few parts needed to be glued such as the antennas and sensor nodes. This implies that the time of mounting the system is reduced to only a few weeks. The engine used in the live test was an RM12 engine, seen in figure 5.1, which is normally used in JAS 39 Gripen.

Since the temperatures inside most parts of the jet engine are too high for the electronics to survive, the WSN is mounted in the fan, which is the first stage of the engine. This section is most favourable in respect of both radio communication and temperatures. This is the place where the short distances enables radio communication and the temperatures are kept below 150-200 °C. A figure of a half scale jet engine fan is seen in figure 5.2. This is the part that is of interest to study both regarding WSN and wave propagation.

This project was performed in collaboration with GKN Aerospace Engine Systems AB and AAC Microtec AB and was funded by NFFP (Nationella Flygforskningsprogrammet).

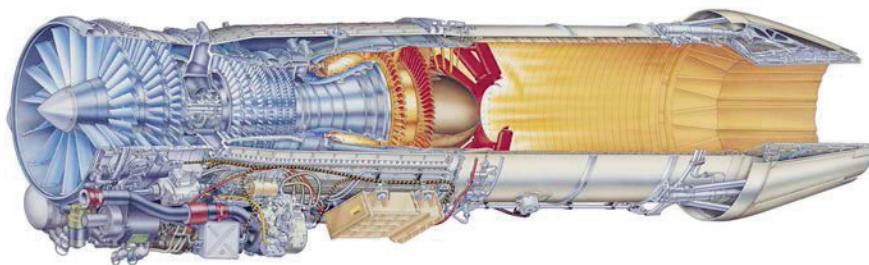


Figure 5.1. A drawing of the RM12 engine used in the final test. The fan, where the WSN is placed, is the part nearest the air intake to the left. (Courtesy of GKN Aerospace Engine Systems AB)

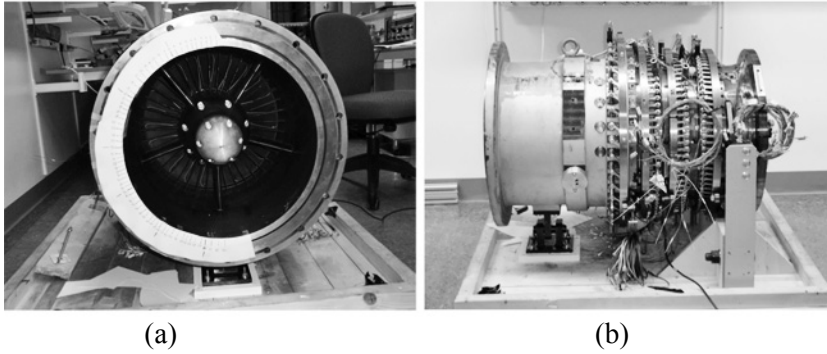


Figure 5.2. The half scale engine used for wave propagation measurements. Figure (a) is the engine seen from the front and (b) is from the side.

## 5.1 System Design

As we want to measure two different processes, one slow (for temperatures) and one fast (strain measurements), the system contains two different types of sensor nodes, and also one receiver for each type of sensor. The difference between the two nodes is the sampling frequency. The slower node can measure the temperature and the faster node can sample up to 40 kHz, which implies that it can measure signals (the strain gauges) up to 20 kHz without aliasing.

The sensor nodes were mounted on a metallic washer which is mounted to the rotor disc. The rotor disc is holding the fan blades into position. Since the metallic washer with its sensor nodes are placed on the fan disc, the disc with the washer must be balanced. An unbalanced disc will break the engine into parts. The transmitting antennas were mounted on the fan blades, and were connected to the nodes with a thin coaxial cable. The task of balancing the disc with its fan blades was performed by the technicians at GKN Aerospace Engine Systems AB.

The receivers were placed outside the engine in a sound and vibration shielded box. Without doing so, there was a major risk that the sound and vibrations from the engine could damage the electronics. From this box, cables were drawn to the receiving antennas, which were placed as close to the engine as possible. Two antennas were used, one primary and one secondary. The primary antenna was positioned at the edge of the air intake. This was a standard patch antenna with ultrathin and flexible substrate, Roger ULTRALAM 3850. The secondary antenna is made of the same substrate but is a patch array antenna. The design of this antenna is seen in Paper V and is also presented in chapter 6. The antennas used in the final tests are seen in figure 5.3. The left antenna in the figure is also used as the transmitting antenna inside the engine.

Both sensor nodes used the same radio circuit, NRF2401. To optimize the energy consumption, the two nodes used different settings of the radio. The slow nodes transmitted the information more seldom than the fast one. This, in accordance with what is mentioned about saving energy in chapter 3.

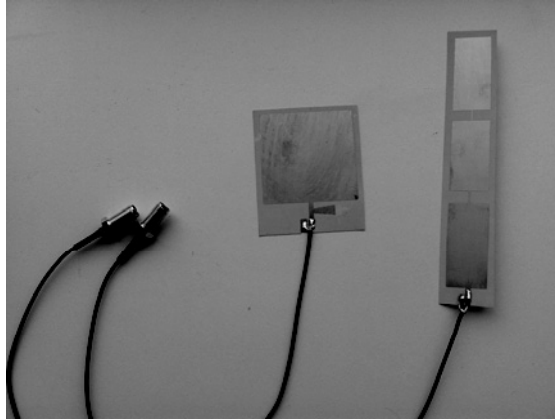


Figure 5.3. The two types of antennas used in the final test. The left is positioned inside the engine, and the right one is mounted a bit further away from the engine.

## 5.2 External Effects on the Electronics

Before the final test was performed, some of the sub systems were tested to ensure they will survive the harsh environment inside the engine. The circuits were spin tested to ensure that all components stay in place. The batteries were tested to see that they will be able to provide enough energy as the temperature increases and the radio circuits were tested to see how they were affected by the heat.

The radio circuitry was seen to be sensitive to the temperatures reached inside the engine. Above about 160 °C, the radio stopped transmitting data. This is probably due to change in frequency of the crystal oscillator in the radio that controls the microcontroller. When the resonance frequency of the crystal shifts too much, the microcontroller is not able to sustain its functionality.

When monitoring the voltage of the batteries, it is seen that the voltage drops as they rotate with the jet engine. Since the sensor nodes are transmitting all the time, this voltage drop cannot be an effect of the transmission but possibly due to the centrifugal force. This affects the internal pressure and thereby the voltage characteristics of the batteries.

### 5.3 Wave Propagation in Jet Engines

To ensure that it is possible to communicate from a sensor node inside the jet engine to an external receiver, a survey is needed to study the possibilities. This task has been performed in several steps. First by simulate a model of the engine in a full wave EM-simulator. Secondly by measure wave propagation in a half scale model and thirdly, verify the simulations and measurements performed in the first and second stages by measure in a real RM12 engine. The model used in the simulations corresponds well with the half scale engine, but these look geometrically a bit different than the RM12 engine. Since the half scale engine is approximately half the size of the RM12, the measurement frequency must be scaled as well. However, both the half scale engine and RM12 engine provide about the same severe fading.

The wave propagation is published in total in two papers. In this thesis, Paper IV describes the measurements in the half scale engine and the final test. Previously, the simulations of wave propagation and measurements in half scale engine were presented in both [30] and [31.]. One of the key results from these publications is the time between two consecutive fading dips when the engine is running. The time is expected to be about 130  $\mu\text{s}$ , and the time for one data package is about 128  $\mu\text{s}$ .

### 5.4 Final Tests

The final tests with the WSN in the jet engine were performed in February 2013. Due to unknown technical mishap, the fast nodes were not transmitting the data correctly. On the other hand, both the slow nodes were transmitting the temperature data from inside the engine. The only problem seen was that the receiver sometimes received packages from both nodes simultaneously. This caused some data losses since the receiver could only interpret one package at a time. It could easily be solved by having one receiver per node.

A temperature curve of the trial is seen in figure 5.4. Interesting to know is that the start engine rotated the engine twice before the engine was ignited. In figure 5.4, these two positions are seen at about 6 kSamples and 13 kSamples. Since the engine is running on air taken from the outside of the test facility, and the temperature that day in February was well below 0 degrees, the temperature is decreasing until the engine is started for a short time period at about 18 kSamples. Also, the total amount of lost packages were about 2.8 %

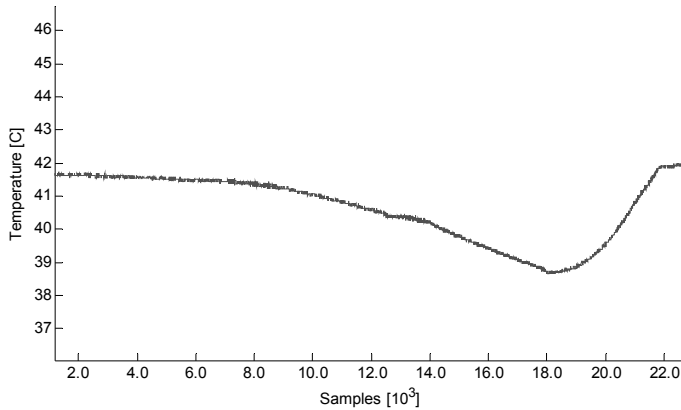


Figure 5.4. The measured temperature inside the engine.

## 5.6 Discussions and Conclusions

During the investigations of using WSN in jet engines, it is shown that one of the most difficult issues to deal with is the energy constraint. Since the nodes must transmit the information about every second or faster, there must be a way to have the nodes in sleep mode from the point of mounting them into the engine, to the engine test. In this specific test, the battery cables were soldered a few hours before the test. Then the transmitters did not transmit any information until they had an external triggering signal.

When communicating inside a jet engine, the distance is not a problem since the communication range is only about 1 m. In the jet engine, the fading is causing more problems than the distance does. In my licentiate thesis [30], the fading is characterized to see if it is possible to have a WSN inside the engine. Since the time between two fading dips are slightly longer than a transmitted data package, the conclusion was that in theory, it is possible to have a working WSN inside the engine. This was also confirmed in the full scale tests with a real engine.



## 6. Antenna Designs

In the projects presented in this thesis, two antenna designs have been developed. The common topic for both the antennas presented is that they have to work properly in a highly metallic environment. This chapter presents the challenges and some solutions when building antennas for an electromagnetic harsh environment.

### 6.1 The Train Wagon Antenna

For the second investigation aboard train an antenna was designed to enable the communication on 2.45 GHz ISM-band. Despite there are much space aboard the train the physical size of the antenna is one of the constraints. During the antenna design, it is aimed to be small, cheap but still have high radiation efficiency in the train environment. This implies that the aim is to have as little influence of the surrounding as possible.

The antenna is a two-layer patch antenna with the feeding strip in between the layers. The feeding between the feeding strip and the patch is a capacitive coupling. The bottom layer is made of 1.524 mm thick FR-4 substrate, and the top layer is made of Rogers RO3003, with relative permittivity,  $\epsilon_r$ , of 3. This layer is used to increase the radiation efficiency. The microstrip line from the patch is extended to simplify the soldering of the SMA-connector. The manufactured antenna is seen in figure 6.1.

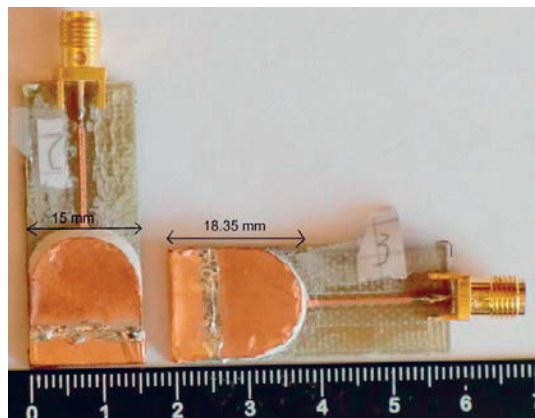


Figure 6.1. A photo of the manufactured antennas.

After the design and manufacturing, the antenna is characterized in both the anechoic and reverberation chambers. Also the  $S_{11}$  parameter is measured. The  $S_{11}$  is -12 dB at -12 dB, and the bandwidth is adequate within the band intended to be used.

The radiation efficiencies are measured at three frequencies corresponding to the lowest, middle and highest frequencies of the ISM-band, 2.40, 2.44 and 2.48 GHz. The measured radiation efficiency is -2.75, -0.79 and -2.82 dB respectively for these bands. The conclusion is that the antenna is a rather good radiator in this environment. Also, the size of the antenna is small, 18.35 x 15 x 3 mm. This implies that the longest side of the antenna is only 14.9 % of the wavelength, which means that the antenna is at the border of being an electrically small antenna. The small size makes the antenna having high  $Q$ -value which makes it difficult of having an antenna with high radiation efficiency.

## 6.2 Antenna in Jet Engine

In the jet engine, there were special requirements on the antenna to be designed. The receiving antenna had to be placed just outside the air intake of the jet engine during the test. This sets a number of requirements, beside the radiating properties of the antenna, it must not, for example, affect the properties of the engine itself. This set limitations on the thickness of the antenna substrate. Since the antenna must be flat and mounted on the inside of the external casing of the engine, the type of antenna must be a patch antenna. Unfortunately, a standard patch antenna usually has its major antenna lobe perpendicular to the ground plane of the antenna [14]. This will cause problems since the antenna must point inwards, to the engine. Therefore, an array of patches is designed. Since the antenna must be both flexible to follow the curved outer casing of the engine and thin to not affect the air flow, the substrate ULTRALAM 3850 from Rogers Corp is chosen which has a thickness of 0.1 mm and a relative permittivity,  $\epsilon_r$ , of 2.9.

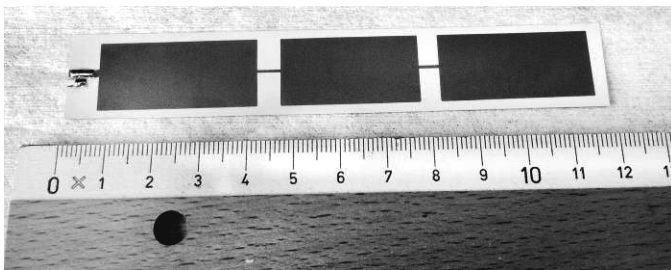


Figure 6.2. A photo of the manufactured antenna with the feeding point to the left.

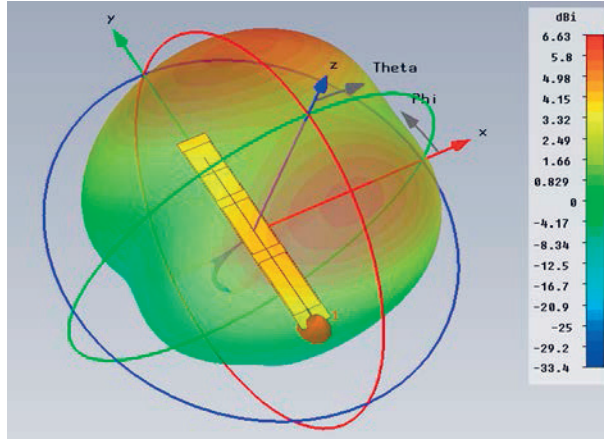


Figure 6.3. The simulated antenna with its radiation pattern.

The final design is presented in Paper V consists of a patch antenna array, see figure 6.2. The array changes the radiation pattern from a pattern that has its major lobe perpendicular to the ground plane, into a pattern that is pointing forward into the fan of the engine. In section 2.2.3, the directivity is mentioned as a tool to increase the communication distance and suppress unwanted signals from other directions.

The antenna is first simulated in CST Microwave Studio as seen in figure 6.3, after which the manufactured antenna is measured in both anechoic and reverberation chambers to verify its properties see figure 6.4.

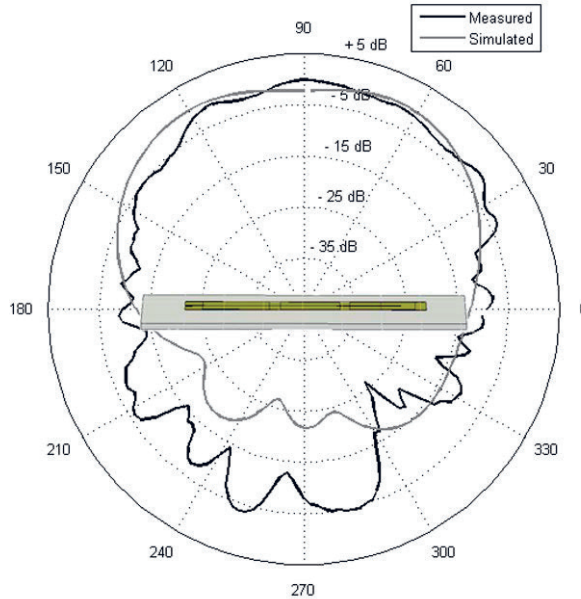


Figure 6.4. Simulated and measured radiation pattern.

The measured and simulated data agree well, but the drawback is the high losses in the substrate. The overall radiation efficiency of the antenna is -13 dB and is mostly due to the ultra-thin substrate. Since the thickness is only 0.1 mm, the E-fields between the microstrip lines and ground plane will be extremely strong. But since the distance between the transmitter and receiver is short, about 1-1.5 m, the path loss between transmitter and receiver is rather low. This reduces the risk that the antenna causes the system to fail.

## 7. Reverberation Chamber

The electromagnetic reverberation chamber (RC) has during the history been used for measuring various electromagnetic parameters. Firstly the RC was used to measure EMC in electronic. In 1976 the reverberation chamber was introduced to measure antenna properties [31]. However, it was not until the 1990's the telecom industry started to use the RC as a facility to test the antenna performance. Since then, it is a very useful tool to measure various parameters of antennas, such as Total Radiated Power (TRP) [32], diversity gain [33], total isotropic sensitivity (TIS) [34] and especially radiation efficiency. The benefit of using the RC is that the measurements are, compared to other measurement methods such as full sphere measurements in an anechoic chamber, extremely fast, cheap and simple.

The idea with the RC is to feed an antenna inside a metallic cavity with a continuous signal. The signal is then propagating inside the chamber and be reflected on the walls. As the several reflected signals reaches the antenna under test (AUT) they are incident from all angles at the same time. This provides a radio environment with a homogeneous power distribution and received signal amplitude that is Rayleigh distributed. However, this environment does not correspond to a realistic environment where antennas usually are deployed. That is why it is of interest to either perform measurements with antennas close to phantoms or with real persons in the chamber. Both these topics are presented in this thesis - emulation of specific radio environments and how to build chambers that are large enough to contain persons inside.

### 7.1 Chamber Limitations

An RC has limitations concerning operation frequencies and what can be measured. Since the RC is an over-moded EMC chamber it has a basic limitation in how low in frequency the chamber can measure. When determining the lowest possible frequency that can be used, it is needed to both take into account for the physical dimension of the chamber along with eventual attenuating materials inside the chamber and what material the wall of the RC is made of. In [35], the lowest usable chamber frequency (LUF) is expressed as the number of resonances below a certain frequency, where the number of resonances at a frequency  $f$  is described by

$$N(f) = \frac{8\pi}{3} V \left( \frac{f}{c} \right)^3, \quad (7.1)$$

where  $V$  is the volume of the chamber,  $f$  is the frequency used and  $c$  is the speed of light in vacuum. It is also stated in [36] that the number of simultaneous modes,  $N$ , must be greater than about 60 to achieve electrical field uniformity. This is also related to the number of wavelengths in the chamber at the lowest frequency. To be working properly, a chamber needs to be approximately  $5\lambda$  or more in one side.

The chamber also has a highest usable frequency that is determined in similar way as for the LUF by taking into account by both the size of the chamber and the material used inside the chamber. Simply, if there is less loss in the chamber, the higher frequency can be used. When the frequency increases, the size of the chamber relative to the wavelengths also increases. This implies that the distance between two walls (in wavelengths) increases. If the signal is transmitted from one side of the chamber to the other side, a signal with higher frequency will more attenuated than one with lower frequency. Also, the conductivity of the chamber walls will affect how much of the signal that is reflected back into the chamber. Since the fading environment inside the chamber is dependent on having as many reflected waves as possible to provide an isotropic and homogeneous environment, a signal with high frequency will be too much attenuated if the size of the chamber is too large and if the conductivity of the walls are too low.

## 7.2 Mode Stirring

The accuracy of the measurements performed in the chamber is proportional to the number of independent modes,  $N_{ind}$  that are propagating in the chamber. Assume that an antenna is excited by a continuous wave (CW) in a chamber. Since everything is stationary inside the chamber, the fields will after a short time period (nano seconds) become stable in respect of power distribution. Nothing is changed inside the chamber; hence, the received power will be varied but stationary at all positions inside the volume. The number of independent modes is a function of the size of the chamber. To increase the accuracy of measurement a larger number of independent samples is needed. When measuring an antenna in the chamber, a time varying field is desired. To vary the fields inside the chamber, one or several mode stirring techniques can be used, such as mechanical [37], platform [38] polarization [39] and frequency stirring [40]. These stirring techniques will cause a time varying signal, which increases  $N_{ind}$  and indirectly the accuracy,  $\varepsilon$ , of measurement according to

$$\varepsilon = \frac{1}{\sqrt{N_{ind}}} . \quad (7.2)$$

When performing measurements, the measurement accuracy is determined by the number of independent samples. Where the theoretical  $N_{ind}$  is calculated by [41]

$$N_{ind} = \frac{QV_s}{V} , \quad (7.3)$$

where,  $Q$  is the  $Q$ -factor,  $V_s$  is the minimal volume the stirrer is enclosed by when rotated and  $V$  is the total volume of the chamber. This equation answers the second question regarding how large the stirrer inside the chamber must be to provide enough stirring. The  $V_s$  is also indicating that accuracy is lost when the mode stirrer is symmetric. In principle, if the stirrer is symmetric, let's say with  $180^\circ$  symmetry, the environment has exactly the same geometry every half turn of the stirrer. To increase the stirred volume, thus increased measurement accuracy, multiple or larger stirrers can be used.

## 7.3 Probability Distributions

To describe the CW signal, two parameters are used i.e. amplitude and phase. For simplicity it is assumed that the phase is a random and uniformly distributed parameter. The amplitude on the other hand is the interesting parameter. In the paper [42], the statistical model for a mode stirred chamber is presented. The paper also presents three different motivations to why the statistical model inside a RC is behaving as a Rayleigh distributed model.

### 7.3.1 Absorbers in the Chamber

As mentioned in Section 2.1, the amplitude is Rayleigh distributed when all incidental waves are at about equal amplitude. In the reverberation chamber, this occurs when there is no attenuating material placed inside the chamber. If attenuating material is placed inside the chamber two effects will be seen. Firstly, the waves from that certain direction, in relation to the receiver, will be attenuated. Secondly, the  $Q$ -value of the chamber will decrease. The first effect will cause a more dominant behaviour from the rest of the waves. Hence, the received amplitude will be Rician distributed. Utilizing this, it is possible to change the amount of reflected waves to mimic a certain environment. If the antenna, for instance, is a cell phone antenna, it will not perform in the same manner inside the chamber as it will when it is in use in the final application environment. If an antenna is only measured under the con-

ditions of Rayleigh distributed amplitudes, surprises can be revealed when the antenna is later in use - it might not even work at all. Many techniques have been developed to meet this requirement of a more realistic environment - to introduce a Rician distributed field. The most common techniques are to mimic a real situation by for instance use a phantom head and a hand that is holding the cell phone. One publication that describes this method is [43]. In the papers VII and VIII, the method of sample selection is introduced to improve the emulation of different scenarios. This method can emulate various scenarios without using attenuating materials to change the interior of the chamber.

## 7.4 Applications

As seen in the introduction of this chapter, the reverberation chamber is a very useful tool for a wide range of tests. Since the reverberation chamber is used in two projects within this thesis, they are presented separately below.

### 7.4.1 Large Reverberation Chamber for on body Measurements

As stated before, the lower cut-off frequency of the reverberation chamber is inversely proportional to the size of the chamber. This means that if a lower frequency is to be measured, a large chamber is needed. As one side need to be approximately  $5\lambda$  or more in a side, most reverberation chambers that are currently available on the market cannot be used to measure as low frequencies as is desired for many applications. Therefore it is extremely useful to use a large EMC shielded room, and design the interior in such way that it can be used as an RC. A large EMC room also provides a possibility to measure other scenarios than only a single antenna, such as on body antennas mounted on a real human being. In paper VI a chamber is designed to be used both empty and with several persons inside. The novelty of the chamber is its size along with the unique way of build the stirrer with metal mesh instead of solid surfaces. The measurements show that the chamber is fully functional between 400 MHz and 3 GHz. The paper shows that the design of an RC can be rather simple and be designed in already existing EMC-rooms.

#### 7.4.1.1 Design Considerations

Since the EMC room is usually not used only for antenna measurements, several aspects have to be taken into consideration. Firstly, how can the electric fields can be stirred in a proper way? Since the mode stirrers should be of an electromagnetic reflective material, a solid metal is desired. In a smaller reverberation chamber, the stirrers can be made out of stiff and massive metal without being too heavy and difficult to construct. A question related to this is how large the stirrer has to be to fully stir the fields so the environ-

ment becomes homogeneous and isotropic? Here, practical problems are also introduced. The room must be available for other measurements as well. Therefore the design of the stirrers in our case must be light weight and mobile.

The  $Q$ -factor is closely related to the root-mean-square (RMS) of delay spread. A large  $Q$ -factor implies that the cavity has low losses and that the propagating EM waves inside the cavity are less influenced by attenuation over time. Thus, the number of reflected waves increases as the  $Q$ -factor increases. From [44], the  $Q$ -factor can be used to determine the RMS decay time as,

$$\tau = \frac{Q}{2\pi f}. \quad (7.4)$$

By knowing the decay time,  $\tau$ , it is rather simple to use this value to understand how many times the propagating waves are reflected inside the chamber. This mean distance is simply calculated by multiplying,  $\tau$ , with the speed of light,  $c = 2.99 \cdot 10^8$  m/s, and then dividing the distance with the cross dimension of the room. In this case, a higher value indicates that the waves are reflected many times, which is providing an evenly distributed field inside the cavity. Loading the chamber with attenuating material, the  $Q$ -value will decrease.

When designing the stirrer, there are a few things to consider. According to the equation of number of independent samples (7.3), which is indirectly determining the accuracy of the measurements performed in the chamber, a large stirrer volume is preferable. In this case, it was determined to build one large stirrer instead of several smaller. Since the floor area of the chamber is 4x8 m, a stirrer with a diameter of 2 m is mounted about 3.5 m away from the short side wall. A sketch of the chamber is seen in figure 7.1. Since as many independent modes as possible are generated, the reflectors are designed and mounted in such a way that there is no rotational symmetry. Also, it was decided to evaluate the possibilities to use metal mesh instead of solid metal. What is important to investigate in this case is how fine pitched mesh is needed to ensure that it will behave as a normal metal sheet. Several researchers see e.g. [45] [46] has investigated the shielding effectiveness of the metal mesh.

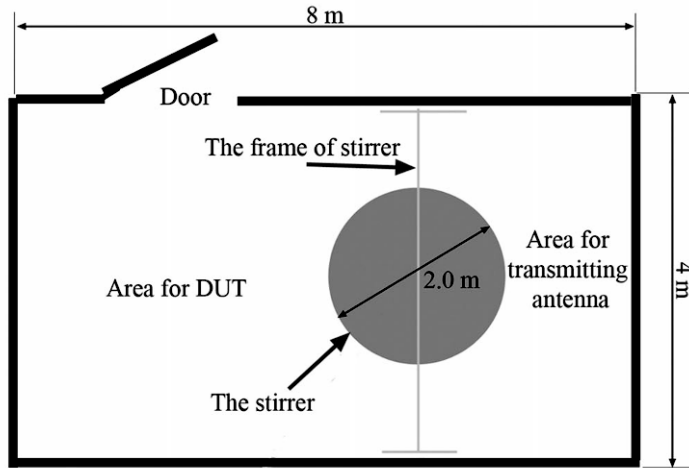


Figure 7.1. The layout of the chamber with the device, or antenna, under test to the left and the transmitting antenna to the right.

To verify the complete range of operation for the metal mesh, measurements between about 200 and 3000 MHz had to be performed by having two wave guide ends face-to-face and with the metal mesh under test placed between. With this setup it is a rather simple operation to measure shielding and transmission using a Vector Network Analyzer (VNA). In Table 7.1, the result of this measurement is presented. As  $S_{11}$  shows, it is about zero decibels for all mesh pitches measured. It was noticed during the measurements that the mesh is electromagnetic "transparent" in only a few very narrow-band frequencies. But since none of the resonances are located at frequencies that are commonly used in wireless applications, it will not degrade the performance of the chamber. Aluminium bars are used to stabilize the mesh which is mounted on a metal rod. The metal rod is at its top position mounted to a DC-motor seen in figure 7.2.

Table 7.1. S-parameter measurement with metal sheet and different types of metal meshes.

	Metal sheet	Mesh pitch		
		5 mm	10 mm	20 mm
$S_{11}$	0 dB	~0 dB	~0 dB	~0 dB
$S_{21}$	-40 dB	-20 dB	-20 dB	-10 dB

Since the environment inside the chamber should be as isotropic as possible, as small unstirred energy as possible is wanted. In other words, this means that as small direct coupling as possible between the transmitting and receiving antenna is wanted. By placing the transmitting antenna and the antenna under test (AUT) on separate sides of the stirrer, the direct coupling between them is reduced. This also reduces the LoS (Line of Sight) component and

the number of NLoS (Non-Line of Sight) components is increased. By doing so, the environment becomes more isotropic; hence, measurement accuracy is increased. This setup is seen in figure 7.3.

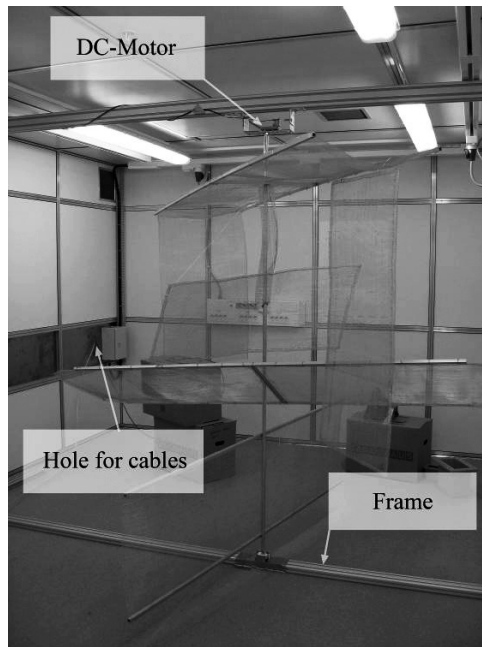


Figure 7.2. The figure show where the DC-motor is mounted on the frame, and where the cables are put through the wall.



Figure 7.3. The final setup of the reverberation chamber. The transmitting antenna is at the left, pointing away from the stirrer which is placed in the middle. The receiving antenna is placed on the box to the right.

The RC is verified by measuring radiation efficiency of antennas and compare the values with other measurements performed in another chamber. Also, antenna correlation coefficient are measured on diversity antennas and compared to its simulated results.

### 7.4.2 Emulation of Scenarios

Since it is difficult to control the environment with the phantoms and attenuators, a faster and more reliable technique is desired. In this section, a novel post processing technique to emulate a desired propagation environment is described. This technique is selecting specific samples to fit certain, predetermined, PDF. However, the PDF does not reveal all parameters of a wireless system. It is only an amplitude distribution, and does not provide any information on delay spread or angle of arrival.

By placing attenuators or phantoms in the chamber, the antennas can be measured in a more realistic environment than in an empty chamber. However, when measuring antennas in smaller chamber head or body phantoms is possible to use. If the antenna is supposed to be placed in a different environment, for instance urban or vehicular environment such scenario cannot easily be handled in the chamber. For these cases we have investigated the sample selection method which simulates/emulates the environment.

The idea behind the sample selection is seen in figure 7.4; a subset of data that corresponds to a certain environment is selected from a larger set of data. This process simply explained, selecting samples from a set of data, with a certain probability density function (PDF), and then chooses those samples that together matching a specific, and desired PDF, also known as target distribution. In Paper VII a genetic algorithm (GA) [13] is tested to sample select a set of data. The GA is an iterative process which is similar to a population growth. Each sample has its own sets of properties, i.e. amplitude. A set of data is called a generation, and each generation fit the final distribution differently. This fitting is compared with a goodness of fit value. For each generation the individual samples are altered which provides another goodness of fit value. This process lasts until a predetermined goodness of fit value is reached. The drawback the GA is that it will find a minimal goodness of fit, but it cannot be seen if it is local or global minimum. Along with the amplitude distribution it is of interest to also study the RMS delay spread, angle of arrival etc. The interpretation of the results and the implementation of other propagation parameters have been left to further studies.

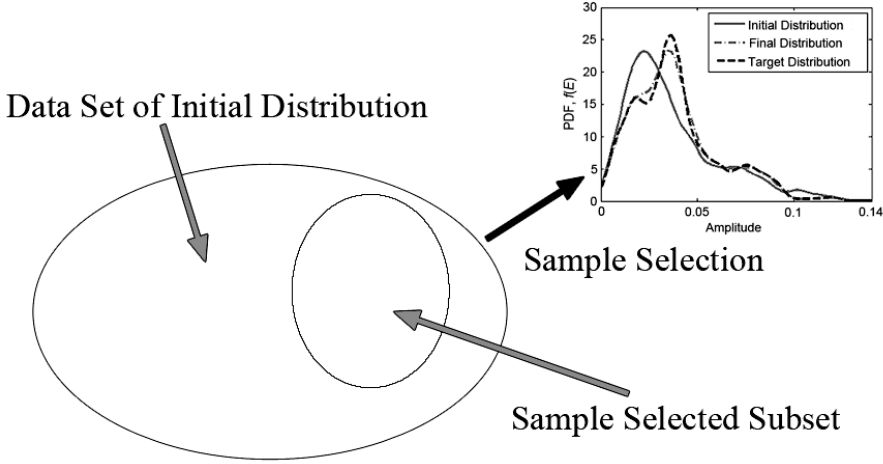


Figure 7.4. The idea with sample selecting a set of data to achieve a final sub set, with the correct distribution.

The main contribution in this thesis regarding sample selection is the development of the non-iterative sample selection method. This is a mathematical, probability based method of selecting samples from a set of data. Since this method is only briefly explained in Paper VIII, a more rigorous approach is presented here.

Since the amplitudes in an RC is Rayleigh distributed, it is of interest to study what will happen when the initial distribution is an Rayleigh distribution, and when the target distribution is Rice distributed. Firstly, the Rayleigh distribution is defined as [47]

$$f_{Rayleigh}(|S_{21}|) = \frac{|S_{21}|}{s^2} \exp\left(-\frac{|S_{21}|^2}{2s^2}\right), \quad (7.5)$$

where,  $S_{21}$  is the scattering parameter and the  $2s^2$  is the mean power of the signal. This is the distribution that describes how the amplitudes statistically behave when there is no dominant signal in an environment. This distribution is what is going to be sample selected into a second distribution that is Rice distributed. If a signal is Rice distributed, it means that there is a dominant LoS component. The Rician distribution is defined as [47],

$$f_{Rayleigh}(|S_{21}|) = \frac{|S_{21}|}{s^2} \exp\left(-\frac{|S_{21}|^2 + a^2}{2s^2}\right) I_0\left(\frac{|S_{21}|a}{s^2}\right). \quad (7.6)$$

This Rician distribution is also, as mentioned in chapter 2, characterized by the  $k$ -factor, which is the ratio between the direct and scattered powers, also is mathematically be described as a function of  $S$ -parameters as,

$$K = \frac{a^2}{2s^2} = \frac{|\langle S_{21} \rangle|^2}{\langle |S_{21} - \langle S_{21} \rangle|^2 \rangle}. \quad (7.7)$$

The single step algorithm has a rather simple approach. Let's assume that the initial distribution is unknown,  $f_{initial}(S_{21})$ . The dataset is consisting of  $n$  number of  $S_{21}$ -samples, and from this dataset a so far, an initially unknown number of samples is chosen so we achieve the final PDF,  $f_{final}(S_{21})$ . By doing so, we can formulate and define the weighting function  $D(S_{21})$  as,

$$f_{initial}(S_{21}) \cdot D_1(S_{21}) = f_{target}(S_{21}). \quad (7.8)$$

Since the relation between  $f_{initial}$  and  $f_{final}$  is known in the equation above, it is simple to find the weighting function  $D$  as

$$D_1(S_{21}) = \frac{f_{target}(S_{21})}{f_{initial}(S_{21})}. \quad (7.9)$$

The variable  $D_1$  describes the probability of  $S_{21}^i$  to be chosen from the initial distribution into the final dataset. But since  $f_{initial}$ , can be zero or close to zero,  $D_1$  can be given an extremely high probability (more than 1) that  $S_{21}^i$  is going to be saved into the subset. Here, the solution is to restrict the weighting function,  $D_1$ . This restriction is performed by formulating the new weighting function  $D$ , as,

$$D(S_{21}) = \frac{D_1(S_{21})}{\max(D_1(S_{21}))}. \quad (7.10)$$

This leads to the possibility of deciding whether or not, if the sample  $S_{21}^i$  is to be saved to the final subset of data, or discarded. Simply, the sample  $S_{21}^i$  is saved if

$$D(S_{21}^i) > U(0,1) \quad (7.11)$$

is true, otherwise discarded. The notation  $U(0,1)$  is defining a random variable between 0 and 1 with a uniform distribution.

Above, the approach is based on using theoretical distributions as in (7.5) and (7.6). Using MATLAB, it is easy to generalize the sample selection into a generalized method that works well with distributions that are measured data.

In Paper VIII, a comparison between the three methods, GA, linear and hybrid is performed. The computational time is compared as a function of the accuracy the resulting PDF. The accuracy means that the area between the final distribution and desired distribution is measured. In the comparison, it is seen that the three methods has slightly different properties. The GA can find extremely good accuracy, but the method is time consuming. The linear method has slightly lower accuracy, but is extremely fast, and the hybrid method uses the linear method to find a coarse, intermediate, distribution that the GA can continue work with. This makes the sample selection both fast and accurate for lower and medium accuracy. The drawback is when a high accuracy distribution is desired. At this point, the linear method is discarding too many samples, leaving not enough samples for the GA to handle, thus the GA need extremely long time period to handle the remaining samples.

## 7.5 Discussion and Conclusions

### 7.5.1 The Reverberation Chamber

The performance of the RC at Uppsala University is presented in this chapter and in Paper VIII. The chamber has its lowest frequency at about 400 MHz and its frequency highest at about 3 GHz. However, in our case, the lowest frequency measured is mostly set by the fact that the antenna performance degrades below this frequency. So, having an antenna with a wider bandwidth it is possible to measure slightly below this frequency.

The chamber is fully operational with a person inside it. This means that the measurements performed in the chamber can meet the requirements of testing equipment in as real environment as possible. It is easy to deploy an antenna on a human body, let the human stay inside the chamber and measure the radiation efficiency of the antenna. With a test facility of this kind, it is possible to measure the antenna without any phantoms that introduce uncertainties, such as; will the antenna behave in the same way on the phantom as on the body?

As mentioned in the sections above, the mesh is behaving mostly as a solid metal sheet. It is only in a few narrowband frequency sections where it is more transparent. Also, one have to notice that as the frequencies increases, the pitch of the mesh, wave length wise, becomes larger and will finally be more or less transparent and loose its shielding properties. Using metal mesh, the stirrer can be made cheaper and lighter weight than before.

### 7.5.2 The Sample Selection

The sample selection is a new and novel technique to provide a controlled test environment inside reverberation chamber. The papers VII and VIII, presents three new methods of selecting samples from a data set. The three different methods are genetic algorithm, a linear method and a combination of these two. The first steps towards a fully functional test method are to develop a method that with high accuracy can provide a resulting PDF. This has successfully been performed in the papers presented and described in this thesis.

It is seen that the sample selection method is a fast and user friendly method to provide the desired environment. It can provide a sample selected data set within a reasonable time frame. Several other issues are still to be solved such as how to treat the delay spread and angle of arrival and practical implementation with the chamber.

## 8. Summary of Papers

### 8.1 Paper I: *Field Operational Testing for Safety Improvement of Freight Trains using Wireless Monitoring by Sensor Network*

**Mathias Grudén**, Malkolm Hinnemo, Dragos Dancila, Filip Zherdev, Nils Edvinsson, Kjell Brunberg, Lennart Andersson, Roger Byström, Anders Rydberg

The paper describes the second investigation performed with wireless sensor network aboard trains. The investigation was performed during the fall of 2011 and aimed to investigate the aspects of applying WSN aboard trains, radio wave propagation and energy scavenging. In this investigation, the sensor nodes were communicating with the gateway at 2.45 GHz ISM-band. The gateway has a RFID emulating chip to communicate to an external reader that is unloading the information. The RFID is communicating at 868 MHz. Since the energy is a problem to overcome, in this paper, also energy scavenging devices are evaluated. Solar cells, piezo electric and thermo electric devices are tested.

During the investigation, it is seen that the radio environment is highly unpredictable. This makes it difficult to have a robust radio communication in this environment. Also, it is seen in the investigation that only one of the energy scavenging devices are suitable for the train environment. The efficiency of the solar cell degrades with layers of dirt or snow on the surface. This means that it must be cleaned manually, which is not a sustainable solution. The thermoelectric device is working when there is a temperature difference between its two sides. The drawback with this is that there is only a temperature difference when the ball bearing starts to degrade. The only suitable device is the vibration harvester. It provides enough energy and is a device that needs no maintenance or special solution. During the lab tests, the vibration harvester provided 2.32 mW.

## 8.2 Paper II: *Reliability Experiments for Wireless Sensor Networks in Train Environment*

**Mathias Grudén**, Alexander Westman, Janis Platbardis, Paul Hallbjörner, Anders Rydberg

This paper describes the first investigation with WSN aboard trains. It was performed during the fall of 2008 and is aiming for a proof of concept having WSN aboard trains and to determine the wave propagation characteristics in train environment for 434 MHz. The path loss exponent is determined to be between 2.27 and 3.67 depending on the positions in the train environment. The investigation lasted for about five weeks. During this period, on average 92 % of the data packages were successfully transmitted between the sensor nodes mounted near the wheels and the gateway inside the train wagon. The sensor information was transmitted to an online database with a 3G modem. However, the solution with a 3G modem aboard the wagon is not a viable solution in long term.

## 8.3 Paper III: *Deployment of a Miniaturized Patch Antenna for Easy Deployment on Metal surface*

Malkolm Hinnemo, **Mathias Grudén** and Anders Rydberg,

The antenna designed and manufactured in this paper is the 2.45 GHz antenna used in Paper I. The antenna designed is a dual-layer patch antenna designed to be placed in a train environment. This also assumes a large ground plane in order to reduce the size of the antenna.

The antenna is designed to be used with the IEEE 802.15.4 standard at the 2.45 GHz ISM band. This puts some extra demands on the bandwidth. As mentioned, the antenna is designed as a two-layer design. The lower layer is a FR-4 substrate with standard thickness of 1.524 mm. This makes the production cheaper and enables integration with standard printed circuit boards. The upper substrate is a Rogers RO3003 with a lower relative permittivity than FR-4, this to increase the radiation properties of the complete antenna.

The resonance frequency covers the 2.45 GHz ISM-band and within this frequency band, the antenna has a radiation efficiency of between -0.79 dB and -2.82 dB.

## 8.4 Paper IV: *Empirical Tests of Wireless Sensor Network in Jet Engine Including Characterization of Radio Wave Propagation and Fading*

**Mathias Grudén**, Magnus Jobs, Anders Rydberg

This paper is a part of the WiseJet project and aims to describe the radio environment inside a jet engine as well as the empirical tests performed with the WSN inside the jet engine. Simulations using the full wave EM-simulator, CST Microwave studio is performed using rudimentary jet engine model after which measurements are performed on a half scale model of the jet engine. The average path loss is calculated and the characteristic of the fading is extracted. Since the simulated model cannot have any moving parts, one of the difficulties in this paper is to acquire simulated data to correspond to a time domain measurements with moving parts. This is solved by acquire data along a circle inside the engine. Each lap of the circle where the data is acquired from corresponds to one revolution of the engine.

The measurements are performed with the turbine rotating at two different speeds, 30 and 60 rpm. It is seen in the time domain measurements that the fading is twice as fast for 60 rpm in relation to 30 rpm. This leads to the conclusion that it is possible to measure at these rotation speeds and scale the fading to full speed of the engine, which is about 10 000 rpm. When doing this scaling, it is possible to investigate the shortest time between two consecutive fading dips. In the measurements, the shortest time is between 126 and 295  $\mu$ s. Also, the fading in the simulations agree with the measured in the half scale engine and the  $k$ -factor varies from about 1 to 15. The effects of using circular polarized antennas are also investigated, but no improvement regarding the fading is found.

The final tests were performed with the WSN inside the jet engine. The conclusions are that the WSN survived the environment and the total loss of data is in the range of 2.8-10.5%.

## 8.6 Paper V: *Design and Evaluation of a Conformal Patch Antenna Array for use with Wireless Sensor Network inside Jet Engines*

**Mathias Grudén**, Magnus Jobs and Anders Rydberg

The paper describes the design, manufacturing and verification of the receiver antenna used in the project with WSN in jet engines. The system transmits the information from the inside of the jet engine to the receiver outside the air intake. To ensure a robust communication with the external

receiver a good antenna had to be designed. Since the antenna is positioned in an environment with extremely high velocity of the airflow, the antenna must be designed with an extremely low profile. In this situation, a patch antenna array is designed on an ultra-thin substrate, Rogers ULTRALAM 3850.

In the paper, the antenna is designed and simulated as well as manufactured and verified. The measured radiation efficiency agrees well with the simulated. However, the radiation efficiency is low, -13dB. This is mostly due to the thickness of the substrate. Since the substrate is only 0.1 mm, the E-fields inside the substrate are extremely large, hence high losses. The simulated and measured radiation patterns agree well.

A feature with this substrate is the flexibility of the substrate. Since it is very flexible, the antenna can be attached onto surfaces with small curve radius.

## 8.7 Paper VI: *Large Ad Hoc Shielded Room with Removable Mode Stirrer for Mobile Phone Antenna Tests*

**Mathias Grudén**, Paul Hallbjörner and Anders Rydberg

In this paper, a large reverberation (RC) is designed and verified. The RC can be used to measure antenna performance (radiation efficiency etc.) and various parameters for MIMO systems. The lowest usable frequency of the chamber is related to the size of the chamber. This means, a larger chamber can measure at lower frequencies. The larger chamber gives also the possibility of measure antennas on real persons.

Since the RC in this case is a shared room, the interior must be mobile. With this specification, a mode stirrer is designed to be light weight and mobile. In most other chambers, the stirrers are made of solid metal, in this chamber a metal mesh is used as the reflective surfaces. In the paper, the shielding properties of the metal mesh are tested.

The verification of a chamber is performed by measure the received signal in the time domain and the frequency response of the chamber. The combination of these shows how well the chamber performs. Also, measurements are performed with an empty chamber and with one person and or two persons inside the chamber. The measurements show that the chamber is fully working between 400 MHz and 4 GHz.

## 8.8 Paper VII: *Sample-Selection Method for Arbitrary Fading Emulation Using Mode-Stirred Chambers*

Juan D. Sánchez-Heredia, **Mathias Grudén**, Juan-F. Valenzuela-Valdés, David A. Sánchez-Hernández

This paper is the first paper which is describing the theory behind sample selection. In this paper, the sample selection is based on using genetic algorithms (GA).

The radio environment inside a fully working RC chamber is isotropic and the amplitude distribution of the signal can be described by a Rayleigh shaped PDF. The drawback with this measurement method is that real environments usually not have these properties. The amplitude distribution in most other environments can be described by a Rician PDF. This PDF exists when there is a strong incidental component in relation to the other waves. This type of environment can be emulated inside the RC by using absorbing materials, hence, reducing the incident waves from a certain direction.

In this paper, an antenna is measured inside an unmodified RC. From the acquired data set, a subset of samples is selected. This subset has a PDF corresponding to a Rician environment with a stronger line of sight component in relation to the incident waves. The target distributions are both ideal PDFs and measured distributions. Also, two of the distributions have different mean powers than the initial distributions. In the paper, it is seen that these two distributions cause some problem for the method. A larger number of samples are discarded in these cases.

The paper shows the possibilities by using the GA to select samples from a data set wherein the resulting PDF have any desired shape as long as the mean power of the subset is not affected.

## 8.9 Paper VIII: *Sample Selection Algorithms for Enhanced MIMO Antenna Measurements using Mode-Stirred Reverberation Chambers*

Adoracion Marín-Soler, **Mathias Grudén**, Juan D. Sánchez-Heredia, Paul Hallbjörner, Juan F. Valenzuela-Valdés, David A. Sánchez-Hernández and Anders Rydberg

This paper is along with Paper VIII presents the sample selection algorithms. In this paper the linear method is defined along with the hybrid method. These two methods are compared with the GA, presented in Paper VIII.

In this paper, the aim is to demonstrate the possibilities of the sample selection techniques which is used to emulate an arbitrary PDF based on

measured data from an RC. Three methods are tested genetic algorithm (GA), linear and a hybrid of these two. The methods have been validated for MIMO antenna parameters such as the MIMO capacity. It is seen in the paper that the three methods have different computational times and accuracies. The accuracy is adequate for the most cases and there is also a trade of between the accuracy and computational time. The best method described in this paper is the hybrid method. It utilizes the speed of the linear method and the accuracy of the GA.

## 9. Summary in Swedish

Denna avhandling behandlar trådlösa sensornätverk, antenner till dessa och teknik för emulering av radiomiljö i reverberationskammaren. Trådlösa sensornätverk har på senare tid kommit att revolutionera möjligheterna att kunna mäta förlopp som har varit svåra eller omöjliga att mäta. I denna avhandling används trådlösa sensornätverk för att övervaka tåg för att möjliggöra proaktivt underhåll på godsvagnar samt för att realtidsövervaka jetmotorer. Den parametern som har övervakats på tåg är hjullagertemperaturer. I det senaste testet ombord på tåg har temperaturerna överförts trådlöst från sensornoder monterade i närheten av hjullagerkåpan på boggin till en central enhet ombord på tågvaggen. Denna centrala enhet kommunicerar lokalt med hjulnoderna på det fria ISM-bandet på 2.45 GHz och externt, för att överföra data till Trafikverket, med RFID på 868 MHz. Denna centrala enhet är aktiv, men RFID-läsaren som är placerad bredvid järnvägen ser enheten som en passiv RFID-tag. För att få systemet att fungera som tänkt behöver man bland annat lösa frågor kring vågutbredning, dvs. vilken karaktär fädningen har samt vågutbredningsförluster. Under de tester som genomförts har det visat sig att radiokommunikationen och energitillgången varit de stora svårigheterna att hantera.

Den andra applikationen där trådlösa sensornätverk används i denna avhandling är för att realtidsövervaka jetmotorer. I detta scenario används sensornätverket för att ersätta ett trådbundet telemetrisystem. Det trådbundna telemetrisystemet som används idag av flygmotorindustrin tar i vissa fall upp till ett halvår att montera i en motor som ska testas. Mycket av den tiden som krävs för monteringen går åt till att limma trådar i motorn. Detta motiverar användandet av trådlös teknik för att överföra informationen från motors inre till en yttre mottagare. Denna miljö är ännu mer fysiskt och elektromagnetiskt besvärlig än tåget för trådlösa sensorer. I detta projekt har trådlösa sensorer placerats på första rotordisken i en RM12-motor, som annars används i JAS 39 Gripen. Detta medför att sensornoderna och sensorerna monteras på de roterande delarna, vilket sätter extremt höga krav på funktionalitet och hållfasthet. Även i detta projekt krävs studier av radiovågutbredning, men i detta fall inuti motorn. På grund av de många roterande delarna visar mätningar att miljön är extremt snabbt fädande. I de snabbaste fädningsfallen är det endast ca 130  $\mu$ s mellan två fädningsminima. När de praktiska testerna genomfördes resulterade detta i ca 2 % paketförluster.

Till dessa två applikationer har även antenner utvecklats för att tåla varje specifik miljö. I fallet för tåget ligger fokus på att få en antenn som fungerar över längre avstånd (10-30 m). För sensorerna i jetmotorn har en antenn utvecklats som är böjbara. Detta är viktigt då mottagarantenn monteras på insidan av jetmotorns krökta ytterhölje och måste ligga plant mot ytan för att inte störa luftströmmar. För tågmiljön krävs det att antennen är liten, robust samt mer rundstrålande för att nå den centrala enheten oavsett var den är placerad.

För att kunna mäta egenskaper hos antenner har även en stor reverberationskammare designats. Denna reverberationskammare har utvecklats i syfte att kunna mäta antenner med personer i kammaren, samt på låga frekvenser. Storleken är viktig då den nedre gränsfrekvensen är omvänt proportionell mot storleken av kammaren, dvs. vid låga frekvenser behövs en stor kammare. Vad som är unikt för denna kammare är att istället för att bygga omrörare av solida metallplåtar är dessa bygga av metallnät. Detta är i syfte för att kunna göra omröraren både lätt och flyttbar. Kammaren har full funktion mellan 400 MHz och 3 GHz, och klarar samtidigt av att ha flera personer i kammaren utan att signifikant tappa noggrannheten i mätningarna.

För att kunna emulera olika radiomiljöer i reverberationskammare har en teknik utvecklats för att välja ut vissa uppmätta sampel från en större datamängd, så kallad sample selection. Syftet med metoden är att återskapa hur en antenn fungerar i önskad miljö utan att använda dämpande material i kammaren. Reverberationskammaren ger under ideala förhållanden en Rayleigh-fördelad fädning när det gäller amplituden. Med sample selection-tekniken kan man från en Rayleigh-fördelad datamängd välja ut vilka mät-punkter som tillsammans bildar en godtycklig och fördefinierad sannolik-hetsfunktion (Probability density function, PDF). I detta fall har Rice-modeller används som målfördelning tillsammans med fördelningar som är uppmätta med antenner placerade på människor i en stor reverberations-kammare. Den linjära algoritmen som presenteras i avhandlingen är en snabb och enkel metod för att välja ut en mängd data från en ursprunglig data-mängd.

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