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Design of an Antenna for a Wireless Sensor Network for Trains

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Abstract

Design of an Antenna for a Wireless Sensor Network for Trains

Malkolm Hinnemo

An antenna for a wireless sensor network for trains is designed and built. The network will monitor temperature and vibrations of the wheel bearings on the train wagons. Doing this will allow for an earlier detection of damaged wheels, which will ease planning of maintenance and reduce wear on the rails considerably. The requirement of the system is that it is to be installed without any cables attached to the sensor nodes. This calls for wireless communication, and that for that antennas are needed.
A train is a difficult environment to transmit electromagnetic (EM) waves in. It is full of metal and EM-waves cannot pass through a conducting material. Having much metal in its vicinity also affects the function of the antenna. This needs to be taken into consideration when making the design.
The constructed antenna is a small dual-layer patch antenna. Dual layer means that it is constructed out of two sheets known as substrates of isolating material with different characteristics. The lower one of these substrates is made in such a way that integration with a circuit board is possible. Such integration would reduce the production cost considerably. The antenna is designed for direct placement on a conducting surface. This surface could be part of the train. It uses the surrounding metal as a ground plane in order to reduce its size. The result is a small patch antenna with good radiation qualities in metallic surroundings. The longest side is 18.35 mm, equaling 14.9 % of the wavelength that the antenna is designed for.

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Sammanfattning

En antenn tänkt att användas i ett trådlöst sensornätverk för tåg är designad och byggd. Nätverket ska övervaka temperatur och vibrationer på tvagnarnas hjulaxlar. Genom att göra det så möjliggörs tidigare upptäckt av skadade hjul, något som underlättar planeringen av underhåll och kommer att minska slitaget på rälsen. Systemet måste installeras på tågen utan några externa kablar. Detta kräver trådlös kommunikation, och för det så krävs antenner.

Ett tåg är en besvärlig miljö för trådlös kommunikation. Det är fullt med metall och de elektromagnetiska vågor som är informationsbärare kan inte passera ett elektriskt ledande material. Om det finns mycket metall nära en antenn så påverkar det även antennens funktion, så även det måste tas hänsyn till i designprocessen.

Den färdiga antennen är en liten dubbellagrig antenn. Att den är dubbellagrig innebär att den är skapad av två isolerande skivor, så kallade substrat, med olika elektriska egenskaper. Det undre lagret är gjort på ett sådant sätt att det lätt ska gå att integrera med ett kretskort. Om det görs så kan produktionskostnaderna kapas. Antennen är gjord för att placeras direkt ovanpå ett ledande plan. Den kan då använda detta plan, som skulle kunna vara en yta på tåget, som jordplan och därmed kan antennens storlek minskas. Resultatet är en liten antenn med goda strålningsegenskaper i metallisk omgivning. Den lngsta sidan på antennen är 18.35 mm vilket motsvarar 14.9% av våglängden vid den frekvens som antennen är tänkt för.

Index Terms—Patch antennas, Metallic environment, Antenna measurements, Wireless Sensor Networks

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Introduction

1.1 Project description

The goal of this project is to design, build and test an antenna for the 2.45 GHz ISM-band. This antenna is to be a part of a temperature sensor network placed on trains. The network will monitor temperature and in a later stage vibrations of the wheel bearings on the train wagons. This is done in order to detect faulty and broken wheels. The goal is to enable better planning of wagon maintenance by detecting which wheel will break before it actually does. Today detection is only possible after the wheel gets so badly damaged that it starts to cut into the rails. When this happens the wheel will damage the rail along the whole way from the point it starts to cut until it gets repaired or replaced. Being able to replace the wheels before this happens would thus reduce the need for rail maintenance. Research on the radio environment of trains has been performed previously [1]. One sensor node is placed on each wheel bearing of each car, and a gateway is placed on the side of the car where an RFID antenna will send the information to the stationary readers that the Swedish railway authority Trafikverket has mounted along the rails of Sweden. The antennas will also be sending the information between the nodes and in this way sending the information from wagon to wagon. This is called multi hopping. The information will thus be transported forward towards the locomotive that is equipped with GSM-R, a version of the GSM network specially designed for railways.

The short term goal for the project i.e. - the goal that is to be reached at the end of thesis project - is to get a functioning prototype system with direct communication between the sensor nodes and the gateway. This is as far as antennas concern equal to a system that includes multi hopping as this is a problem concerning signal treatment, which is out of range for this thesis.

The antenna is desired to be small. It should work in metallic surroundings, a condition that puts tough requirements on the antenna design. When currents are flowing on the surface of the antenna there will be a coupling between the antenna and the metal in its surroundings. This will affect the performance of the antenna. It has to be designed in such a fashion that it will work at the desired frequencies in a position very close to a metal wall. The design also has to make sure that the energy is actually radiated and not dissipated into the train.

The antenna has been designed by simulating its radiation characteristics and by comparing these to experimental results. It has been constructed by milling out the shapes from copper covered substrates and by then gluing these together.

My part of the project also includes assembling the enclosure for the gateway and assisting in the assembling of the nodes. This includes deciding what box is to be used and securing them so that they will be able to withstand vibrations.

1.2 Background

There are today a very large variety of antenna models. There has been an explosion of new models due to the introduction of simulation software.

Many antennas made today are designed to work in empty space. This is the simplest environment, where only the antenna needs to be taken into consideration. Those antennas will not work for this application, since the antenna is mounted on a large piece of metal and has an electric circuit close to it. Both of these factors will affect the performance of the antenna. There are antennas designed for hostile environments. Some are designed to have a large bandwidth in order to make them work even after detuning [2]. Detuning is the unwanted change in operating frequency that takes place due to the surroundings of the antenna. Others are made in such a way that they will be very robust to changes in their surroundings and can work in difficult environments. The goal of those designs is to keep the fields within the structure of the antenna and in that way minimize the sensitivity of the antenna to its surroundings [3]. There is however no general solution to this problem and there are no antennas available to buy that will work well in any hostile environment. This means that for each application one needs to find the solution that works the best in that particular environment.

2. Theory

2.1 Maxwell´s equations

Maxwell´s equations are the four basic equations that determine all electromagnetic interaction [5].

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

These equations describe how electric and magnetic fields are intertwined, and they show how charges and currents are linked with the fields. An electric current will create an electric and a magnetic field. This field will induce a current on all conducting surfaces in the vicinity of the antenna. The current has thus been transferred from one conductor to the other through a non-conducting medium or even vacuum [6].

2.2 Antennas

Antennas are devices especially designed for transmitting and receiving radio waves. The word antenna comes from the resemblance between early devices and the antennas of bugs. Electromagnetic waves are formed by accelerating electric charges. The acceleration can be due to bending of the medium where the charges are traveling or by discontinuity in the medium be it a change of medium or a termination. If there is an oscillating current the charges in it are accelerating and so there will be radiation [5]. This means that almost anything can act as an antenna albeit often a poor one. All alternating current will lead to radiation and even direct current in a bent conductor will radiate. What defines an antenna is that the radiation is the goal, instead of an unwanted side effect.

Antennas are designed for an alternating, and in most cases sinusoidal, current. This current creates waves that are led through a transmission line to the antenna where they are radiated into space. What happens is that the electromagnetic waves that reach the antenna will not stop when the conductor ends but the waves will continue [5].

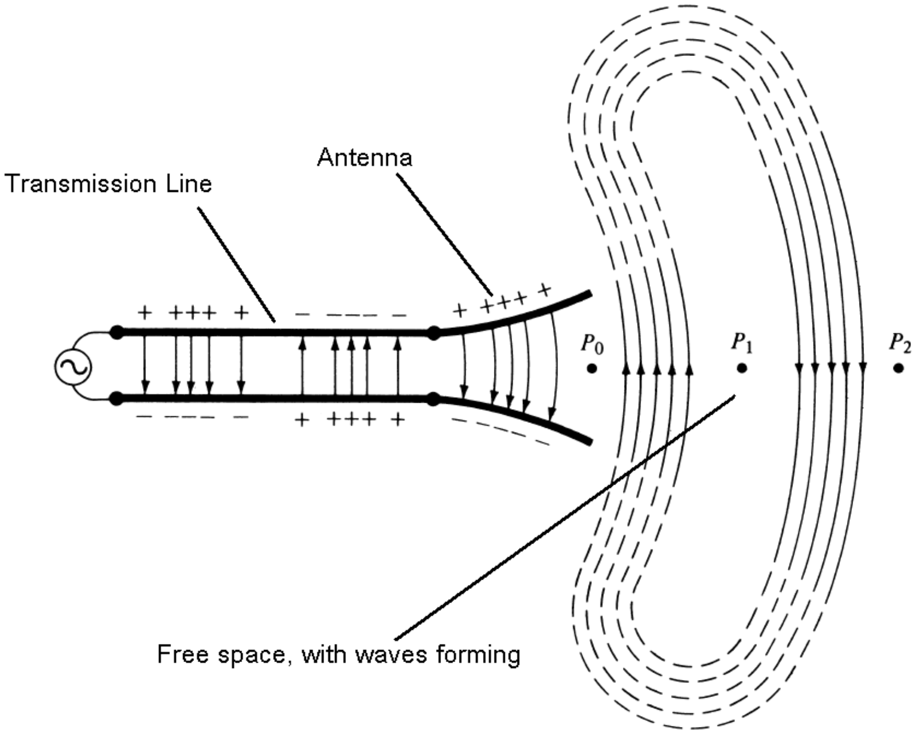


Fig 1: Illustration of waves leaving antenna

The reason that not all conductors radiate perfectly is that there are losses, for example resistivity, and for conducting devices that are not meant to radiate these losses are usually much greater than the radiation (which is itself considered a loss in those cases).

2.3 Patch Antennas

Patch or microstrip antennas are one kind of antennas. A patch antenna design is presented in this report which means that a more detailed explanation of their function is in order. The classic patch antenna consists of a ground plane and a thin layer of conducting material that are separated from each other by a dielectric sheet called substrate. Current is led to the thin layer or patch and will induce an electric field between the patch and ground. This field will directly beneath the patch be straightly directed from the patch to ground or the other way around depending on the phase of the current. But at the edges it will be more spread out since there is more room. This effect is called fringing and it is this that makes patch antennas work.

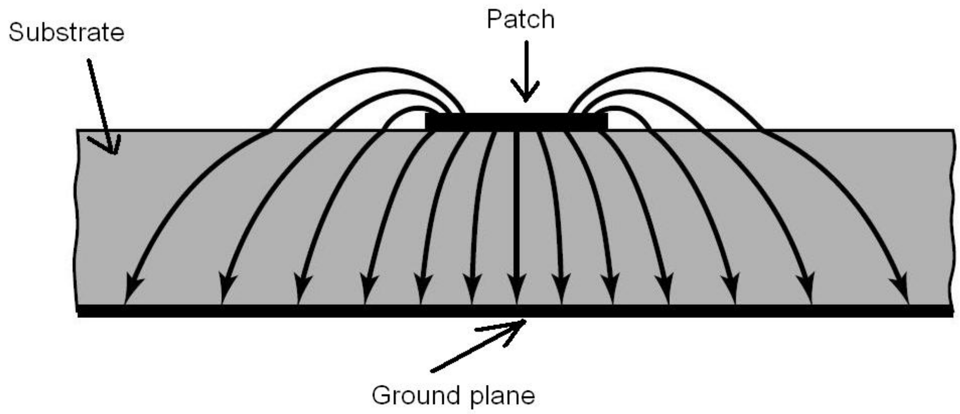


Fig 2: Patch antenna with fields

To describe this a basic half wavelength rectangular patch antenna, which is shown in Fig 2, will be used as an example. Half wavelength means that at resonance frequency the wavelength will be about double the length of the antenna and the current will thus form half a wave. In this kind of antenna the electric potential will reach its maximum values at the edges but with a sign change. This is the situation shown in Fig 2. What happens is that near the patch the electric field will be directed towards positive y on both sides of the patch. That means that they will have the same phase and for the radiation normal to the patch surface the fields will add up [6]. This is the direction of the strongest radiation. For waves traveling in the y direction the interference will be negative since there is one half wavelengths distance between the two edges where most of the radiation originates meaning that a wave that has traveled from one side to the other will experience a sign change and the interference will therefore be negative. Theoretically no radiation should be possible to detect in the positive or negative y directions [5].

At the edge of a conductor the current needs to be zero. This is because current is transportation of charge and if the conductor ends the charges need to stop. For an antenna with open ends such as the patch antenna described above this means that the longest standing wave will be twice the size of the antenna. If there is a way for the current to continue to flow, it can instead reach its maximum value at the end. This can be accomplished by short- circuiting the conductor or by placing a load at the edge. By doing this the current pattern can be a quarter of a wavelength and so this is an efficient way to reduce the size of the antenna [7].

2.4 Reflections and Matching

An important loss factor is the *Return Loss*. It is a loss than comes from standing waves in the transmission line. The transmission line and antenna can be represented by an equivalent Thevenin circuit as shown in Fig 3 [5].

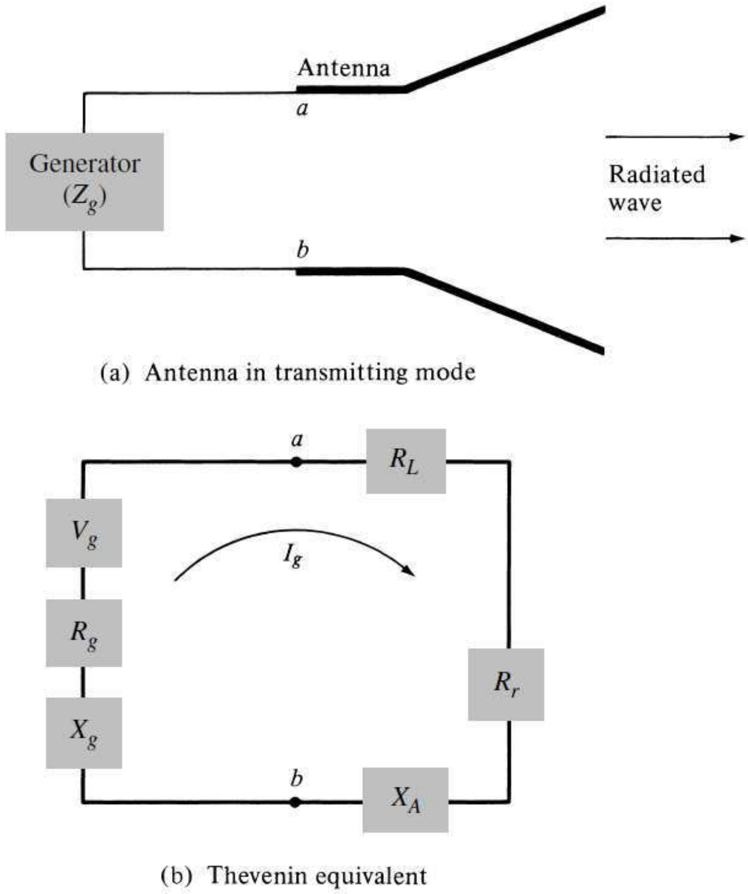


Fig 3: Thevenenin equivalent circuit

The antenna is here represented by a load with specific impedance Z. The impedance is the ratio of voltage V to current I, which for a load means that for a given current that passes through the load the electric potential drops by Z*I. This energy is lost to the circuit and is radiated and dissipated as heat. Every wave has a characteristic impedance and if this is not the same as the one of the load part of the wave it will be reflected so that the requirement of impedance of the load will be met [8]. This reflected part will, together with the incident current, form a standing wave in the transmission line and is lost to the antenna.

To avoid this loss one of the main goals of antenna design is to match the impedance of the antenna to that of the transmission line. In an antenna this is mostly done by changing the geometry. A long thin line will give a higher inductance, while a slot tends to build up electric charge on each side and thus increases capacitance. The standard impedance for transmission lines is 50 Ω real. In this project matching means matching to this impedance.

2.5 Polarization

The electrical field has at any given point in time and space a direction. How these directions vary is called polarization [4]. When the wave reaches a conducting material it will induce a current on it in the direction of its polarization. If the conducting material is part of an antenna this current will be recorded, but only to the extent that the current can propagate in that particular direction. This is the receiver´s polarization and if there is a polarization mismatch between the incoming wave and the receiver less or no energy will be received. For this reason polarization is very important to bear in mind when considering radiation characteristics. The electromagnetic waves that propagate large distances in space are all transverse electromagnetic waves. There are a few main types of polarization:

- Linear
- Circular
- Elliptic
- Unpolarized

Linear polarization is the kind that will be of interest in this article. It means that the direction of the electric field will be along one axis at all times. This axis does not have to be one of the principal axes in the coordinate system, it just means that the field will point in direction or in the direct opposite direction. This definition is valid for one wave, another wave close to it might be linearly polarized in another direction.

Circular polarization is a special case of elliptic polarization. In this kind of polarization the direction of the electric field rotates around the axis of propagation. This is desirable in applications when it is difficult to know the polarization of the transmitter/receiver that one wants to communicate with.

Unpolarized radiation is when the polarization of different photons is uncorrelated. To an observer this will seem like the polarization of each photon is random. An example of unpolarized radiation is sunlight.

2.6 Friis Transmission Equation

The Friis Transmission Equation is one of the most commonly used equations when testing antennas. It gives the power received as a function of the power transmitted, the geometry, and various loss factors.

$$\boxed{\frac{P_r}{P_t} = e_{cdt} e_{cdr} (1 - |\Gamma_t|^2)(1 - |\Gamma_r|^2) \left(\frac{\lambda}{4\pi R}\right)^2 D_t(\theta_t, \phi_t) D_r(\theta_r, \phi_r) |\hat{\boldsymbol{\rho}}_t \cdot \hat{\boldsymbol{\rho}}_r|^2} \qquad (2.1)$$

The subscripts t and r refer to transmitter and receiver respectively. The e-terms are radiation efficiency, the gamma terms are the reflection losses, D is directivity, and the term to the utmost right is polarization losses. $(\lambda/4\pi R)^2$ is called the free space loss factor, which shows the losses that appear due to the waves spreading in a spherical way. This is, as the name hints, only valid for free space. Radiation efficiency takes into account the combined effect of conduction and dielectric losses. These are lumped together since it is most often very hard to separate them. Radiation efficiency is defined as the ratio of the power radiated to the power that reaches the antenna. Directivity is a measure of how much power is transmitted in a particular direction. The free space loss factor assumes isotropic radiation, which is never the case in reality. The directivity adjusts for this. It is defined as 4*pi*U/P_{rad}. Where U is the radiation intensity in the direction of interest and P_{rad} is the total radiated power. What this does is that it gives a coefficient of how much the intensity in the given direction varies compared to the average value. Sometimes the parameter gain is mentioned. Gain is the radiation efficiency multiplied by the directivity. Total gain is the total efficiency multiplied by the directivity.

2.7 Power levels

Power levels are often mentioned in this thesis. The most commonly used term is dBm, which may require some explanation. It measures the power level in comparison to 1 mW on a decibel scale. 0 dBm thus equals 1 mW, while -10 dBm equals 0.1 mW.

3. Antenna Design Procedure

3.1 Early simulations

The first step in designing the antenna was to find a basic idea of how the antenna should work. There are many different ways to make a radiating structure and the first step in the design process is to determine which structure would suit this application best. This was done by reading articles about other antennas and when a promising design was found, simulating that design and looking at what kind of behavior it showed. Simulations were done in CST Microwave studio. For the initial tests all boundaries were modeled as open boundaries, which mean that the behavior in free space was be simulated. The simulations were done in the time domain. In these early simulations the goal is to get a quick look at how the design works, and so the accuracy is not very important. The mesh settings are therefore kept at the default settings which are 10 lines per wavelength in the regions of interest and a lower limit of 5 lines per wavelength. For the same reason the ports used are discrete ports. The frequency spectrum is large, since many of the designs presented in the articles do not work as expected when simulated. By simulating over a very large range of frequencies it is possible to analyze how the antenna might work but not in the area specified by the article in which it was mentioned. The aspects that were given most importance in this early stage were bandwidth, size, directions in which the radiation was the strongest and, the most important aspect for this application, how it reacted when large metal objects were nearby.

3.2 The first model

The model that was found to have the best characteristics was a kind of dual layer patch antenna [9]. This antenna had a large enough bandwidth even though patch antennas usually are narrow banded. The largest radiation was in the normal direction of the patch which in this test also meant that it was in the normal direction of the train. This is the only direction where there is no receiver so that energy is wasted. There was however sufficient radiation along the sides of the train for the design to be interesting. What really made this design stand out was the fact that it was not very sensitive to metal being placed behind its ground plane. This is because the near fields do not reach outside of the region defined by the ground plane. For this reason it was concluded that the antenna used in this project should be one that has its own ground plane. As described in section 2.3 patch antennas all have a ground plane. There are however many other kinds of antennas that do not have one. An example would be wire antennas, where the simplest ones are just a straight conducting wire. They are also more sensitive to their surroundings. The size was however not very appealing. This structure was 6x6 cm or about 0.5x0.5 wavelengths. This size leaves much room for optimization.

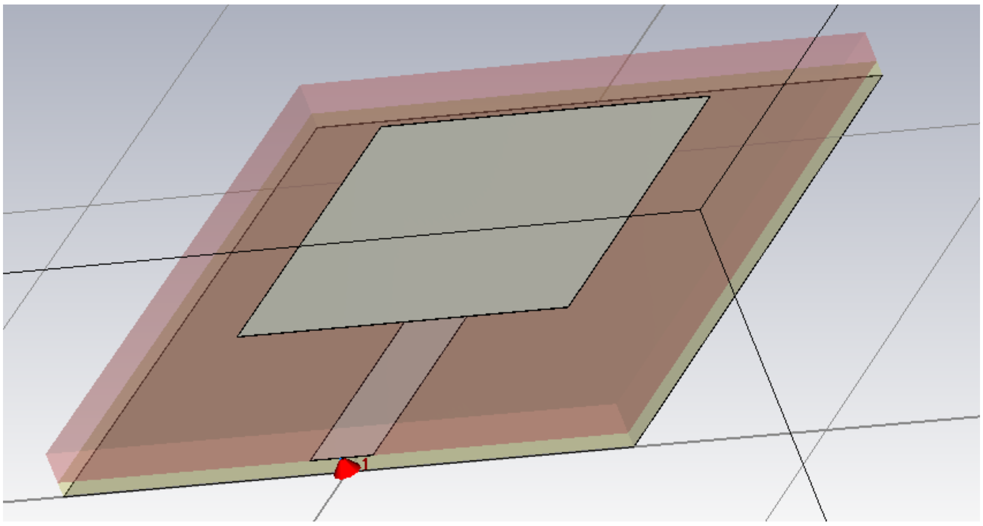


Fig 4: Antenna as described in the article [9]

In order to decrease the size different approaches were tried. One was to introduce slots in the patch. This did reduce the size but not by very much. The next idea that turned out to be very fruitful was to short circuit the patch to ground at the end opposite to the feeding point. An article that discussed this tactic was found and it suggested that 3-5 metal pins could be used [7]. This reduced the size considerably.

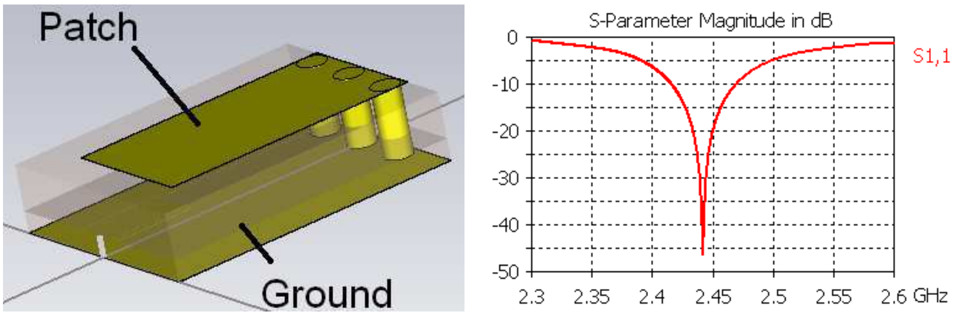


Fig 5: First shortened version

This would however not have been practical to make, so short circuiting with a patch was tried instead and results were similar.

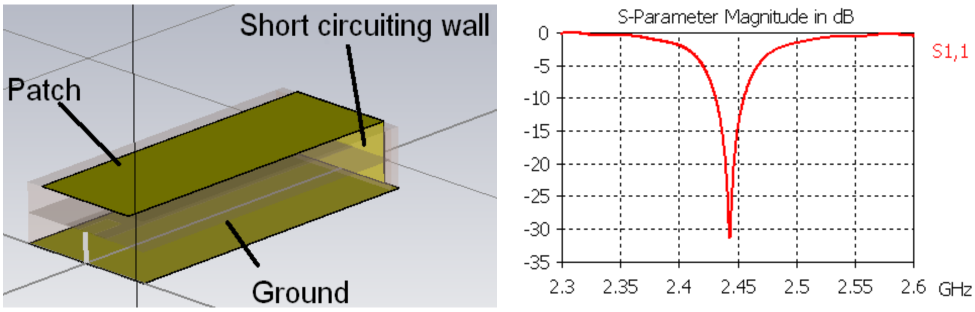


Fig 6: Antenna with shortened wall

With one end short circuited the behavior of the antenna changed drastically. First of all the current changed in the way that it was intended to do, and changed from having an half wavelength resonance to having a quarter of a wavelength resonance. Secondly and much more unexpected the direction of radiation changed. It became more isotropic but with two directions of stronger radiation, one normal to the shortening patch and one away from the feeding point. This radiation pattern is perfect for the application on the train where there will be antennas in many directions. Fig 7 shows the system setup on one wagon. In the final system the intention is that each node is to be connected to both gateways on the wagon where it is placed and to the gateways on the neighboring wagons. This requires that each node antenna radiates to the left, right, and inwards where the directions are the ones of the picture.

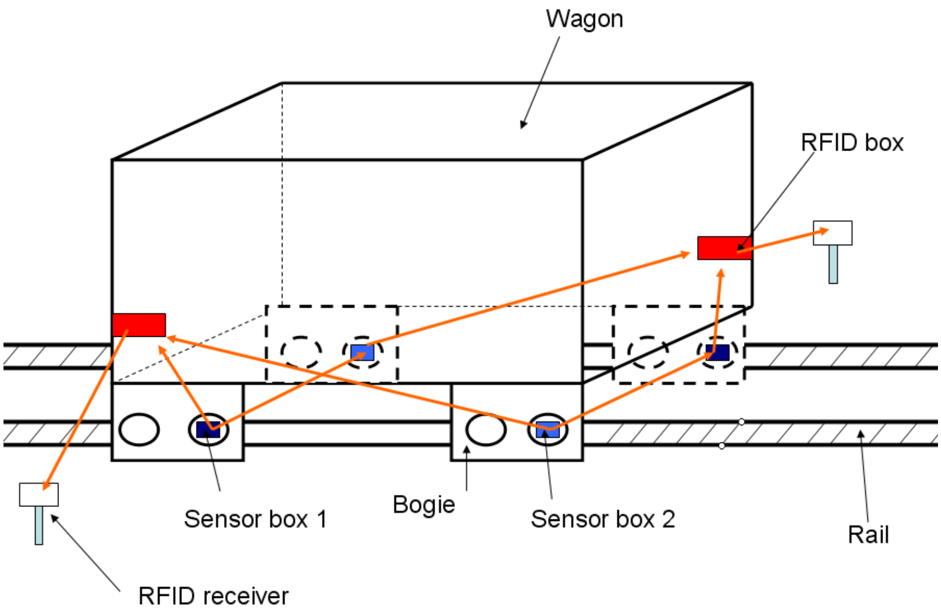


Fig 7: System setup on one wagon. Sensor nodes(blue) gather data and sends it to the gateways(red). The processed data is sent to the supervisor through RFID

The materials that was used for the substrate modeling was taken directly from the article on which the first model was based. The material choice for the upper substrate turned out to be a very costly one as no substrates with that electric permittivity are made as thick as 3 mm. In order to avoid having to order a custom made substrate, a search of the office was made and a new material was found. This was a Rogers 3003 substrate with thickness 1.524 mm. This material is a low loss dielectric with electric permittivity 3. This was higher than the 2.2 that was used in the simulations but it was the lowest that could be found. New simulations were conducted to see how this material would work. It was clear that radiation efficiency and bandwidth both suffered from this change. The radiation efficiency sank by about 1 dB or 21%. The bandwidth decreased dramatically but it was still large enough to meet what was thought to be the requirements and so this was considered acceptable.

The goal this far had been to make an antenna that would be as efficient as possible. This forced a turning point in the design process. Either these results were considered to be too bad and a new design would be drafted, or new goals for the project had to be made. The latter option was decided upon. The new goal of the design was to make the antenna small that is to make the antenna about the same size as one module of the printed circuit boards made by UPWIS. If this could be achieved the lower layer could be integrated on the chip, which would reduce production costs and facilitate use of the system. These benefits would be large enough to compensate for the antenna not being 100% efficient. With the efficiency demand loosened the antenna could be made substantially smaller.

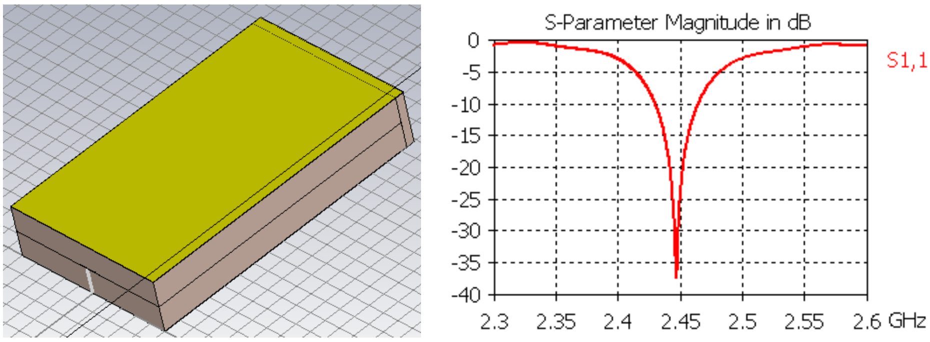
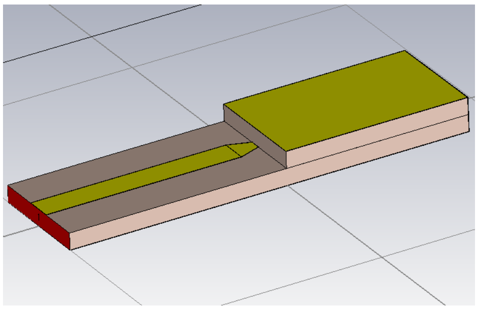


Fig 8: Antenna with top layer of Rogers 3003. This is the model for the first prototype.

3.3 *Prototype Building*

The method used for making the antennas was milling. The mill used is a Solectro LPKF ProtoMat C60. The dielectric materials i.e. FR-4 and Rogers 3003 are made as substrates with either one or two sides covered with a thin copper film. The copper is then milled into the shapes desired. For this project substrates with both sides covered, or double sided substrates, were used. For the FR-4 this was necessary in order to use the bottom side as ground and to mill out the transmission line and feed on the top side. For Rogers 3003 it would have been better with a single sided substrate but the one that was available was double sided. The unwanted copper on the bottom side thus had to be milled away. The mill is controlled by a computer and the program LPKF Boardmaster 4.0. To get the data on what to mill from CST Microwave Studio a CAM(Computer Aided Manufacturing) program called Circuit Cam 4.0 was used. It allows for an accurate 2D control of the mill. Fig ??? shows a screenshot of the program. The third dimension which is height is not varied that much and is controlled manually at the machine.

A first prototype was made modeled on the design shown in Fig 8 and it was realized that connection to a coaxial cable was a problem. As connector a rigid coaxial cable that had been cut in one end was used. The problem was that currents were induced on the cable and this led to a lowering of the resonance frequency. In order to solve this problem the lower substrate was made longer and on this extra part was a microstrip conductor.



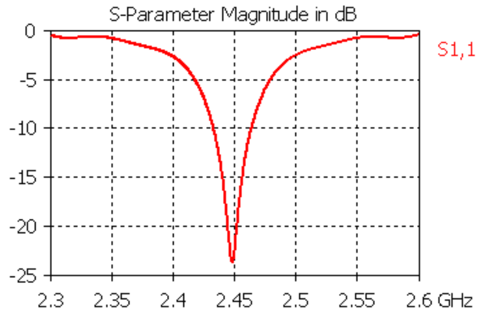
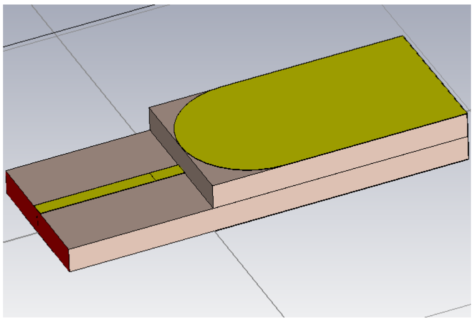


Fig 9: The first version with a microstrip extension

This conductor is basically an extension of the microstrip feed. This extension was made 20 mm long as this was considered at least long enough to not affect the antenna. In the simulations it was found that the narrower this conductor strip was the more efficient radiator the antenna became. The width of this conductor strip was thus set to 0.5 mm. A second prototype was made and it now worked as planned. It was tested in two ways. The first test was to see how large reflection losses would be. They turned out to be very similar to the simulated reflection losses. And these were already approved. The second test was to measure the radiation efficiency in a reverberation chamber [10]. The radiation efficiency was around -1.3 dB which equals about 74% of the energy that goes in to the antenna is radiated. The rest is lost as heat.

Due to a misunderstanding the antenna had been designed for a frequency range (bandwidth) corresponding to only half the IEEE 802.15.4 band that the communication was to use. This was a problem since, as mentioned earlier, the patch antenna is inherently narrowbanded, and this antenna was even more so. This could only be solved by going back to simulations to try to find a new design that would have a larger bandwidth. A patch antenna is a resonator. It only works around the frequency in which the current will form a standing wave. This is the reason for it being narrowbanded. The further away you get from the resonance frequency the less clear the standing wave pattern will be and the less efficient the antenna will be. This means that to increase the bandwidth one needs to increase the range of wavelengths that will resonate. One way to do this is to create different paths for the current. This can be done discretely i.e. creating two different paths will create two resonance frequencies and if they are close to each other there can be one band of usable frequencies. This was attempted but it could not be done on the present design. The way it was tested was to introduce asymmetrical elements in the design and thus create two paths that would be slightly offset. This did not work as the two paths were placed close to each other and were thus correlated. This could be avoided by moving them further apart but that would break the size limitations. Another way is to introduce a spectrum of paths. This is best done by having circular shapes on the antenna. A number of configurations were tested and the one that was chosen was to add a semicircle on the feeding side. The current is traveling from the feed entrance to the shortening patch, which means that the goal of the different paths for the current to take is to make the distance from the feed to the shorted end to be different lengths. With a semicircle at the feeding side the current can travel along the circular edge, go straight forward, or something in between these two options.



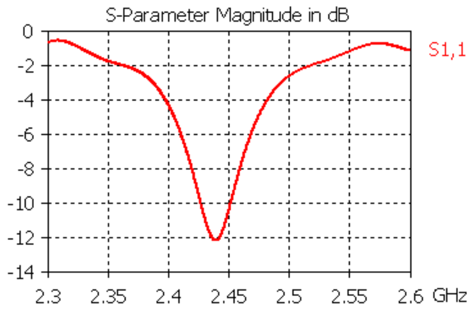
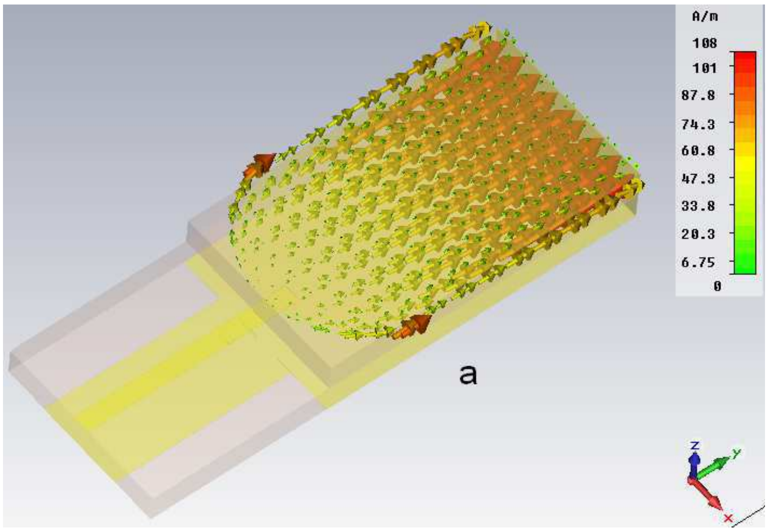


Fig 10: Antenna with semicircle



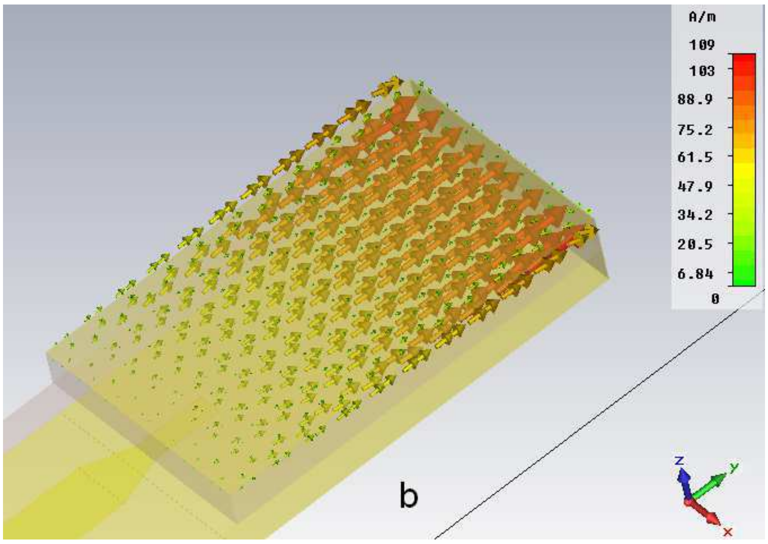
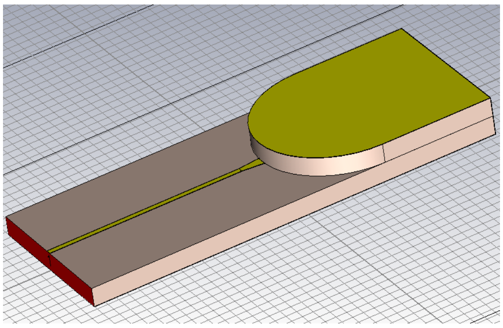


Fig 11: Current distribution on antenna, a) with semicircle, b) without semicircle

This approach did increase the bandwidth dramatically. It was soon found that the wider the antenna was the more the bandwidth could be expanded. Since each module of the PCB is 15 mm wide it was decided that the antenna should be 15 mm wide. This is as wide as possible without giving up the goal of being able to integrate the antenna with the circuitry. Since the current flow was changed with the new shape it was once again attempted to insert slots to affect the performance, but the radiation was affected in a negative way. The resulting antenna was 17.75 long from the bottom of the semicircle to the shortening patch. It was 15 mm wide and each layer was 1.5 mm thick.



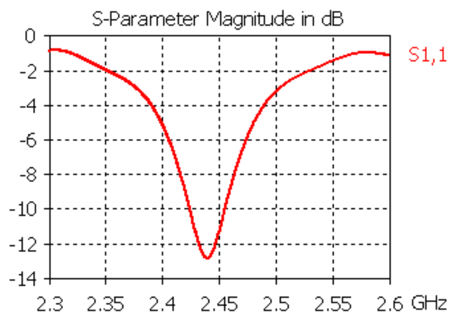


Fig 12: Final simulated antenna

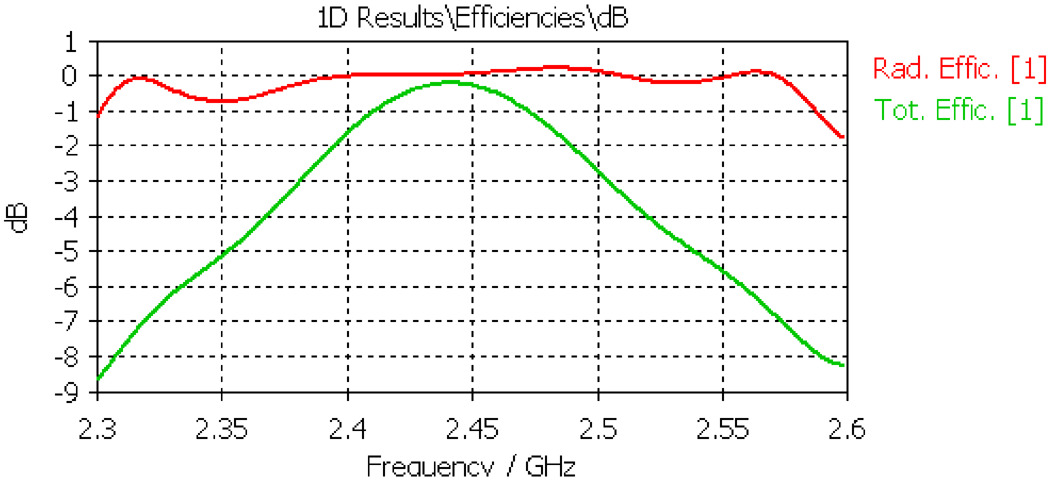


Fig 13: Radiation and total efficiency of final simulated antenna

A prototype was made and it was working as expected but at a higher frequency than it showed in the simulations. A couple of prototypes were made before the right length of the antenna and thus the resonance wavelength could be found since the required accuracy was of the order of the error in the contour routing made by the mill. The final length was 18.35 mm and the feeding strip was 8 mm long and 1 mm wide.

4. Measurements

5 types of measurements have been performed on the antenna.

4.1 The return loss

4.2 Total and radiated efficiency

4.3 Radiation pattern

4.4 Application test 1: Open environment

4.5 Application test 2. Train

4.1 *The return loss*

The first test was to measure how much energy is reflected back into the cable that connects to the antenna. This is called the S_{11}-parameter. In order to do this test an Agilent E8364B PNA series network analyzer was used. It was calibrated using a Rosenberger kit to make sure that only the wave reflected at the antenna was measured. The antenna was connected, a signal was sent to it and the network analyzer recorded how much of the effect was reflected back into the cable as a function of frequency. This is one of the largest loss factors in wireless transmission, which means that if the results of this test were too bad the antenna would not work. It is also a quick and easy test and so it is always done as a first test. One should always bear in mind though that even if the return loss is kept at a minimum there are other loss factors and they might be very large. A resistor would for example show an excellent pattern in this test but it would be utterly useless as an antenna. This test gives an opportunity to see more characteristics of the antenna as well. It shows the return loss as a function of frequency, which shows over which frequencies the antenna could possibly work. It is quite common to find that the S_{11}-parameter is good over a large spectrum but not for the spectrum that it was intended for. This problem is usually caused by either making the antenna slightly larger or smaller than it should or not taking proper notice of its surroundings. A third problem that can be identified during this test is ground currents. Ground currents are caused by the reflections in the antenna and at the connection point. The way to detect them is to move one hand along the wire and look for disturbances in the pattern. If currents are flowing on the ground conductor of the coaxial cable part of the current will transfer into the hand and so the reflection coefficient measured in the network analyzer will change depending on where the hand is. If all currents are on the inner conductor the outer conductor will work as shielding and so there will be no dependence on conductors outside the cable.

Several prototypes have been made during this project and they have all been tested for their S_{11}-parameter. The results of these tests are presented in section 3.

4.2 Total and radiated efficiency

The efficiency of the antenna was measured in a reverberation chamber [10]. It is a chamber made entirely of conducting material, in this case steel. Inside this chamber there are two reference antennas that are considered to be ideal in the frequency spectrum that the chamber supports. There are also two mechanical stirrers. The idea is that you have one antenna transmitting a signal that is reflected on all the surfaces. The two stirrers are rotating at different speeds making the environment different at all times. If another antenna measures its received signal and a time average is taken a measure of the radiated power in all angles is achieved. This is first done between the two reference antennas. Since both antennas are considered ideal the losses are only the losses in air and the losses to materials placed in the chamber. If there are losses caused by leakage they will also appear here. Then the antenna under test is used as transmitter. The losses during the reference test are the same which means that all additional losses occur in the tested device. The total efficiency of the antenna is the difference between these two measurements. For this test to work the environment inside the chamber has to be identical during the two tests. This means that both the transmitting antennas need to be inside the chamber and at the same place at all times.

The results were analyzed using Matlab. The network analyzer also records the S_{11}-parameter meaning that these losses can be subtracted and what is left is called the radiation efficiency. The final antenna was tested for 3 different frequencies: 2.40, 2.44, 2.48 GHz. The results are presented in Table I.

TABLE I. TOTAL AND RADIATION EFFICIENCY

	2.40GHz	*2.44GHz*	*2.48GHz*
Radiation efficiency (dB)	-2.75	-0.79	-2.82
Total efficiency (dB)	-3.59	-1.52	-3.30

At 2.44 GHz the total efficiency was -1.52 dB which is the equivalent of 71%. This is a good result, but the 2.40 and 2.48 GHz results were not as satisfactory. At the end frequencies the efficiency was about 44%. The antenna radiates but it could have done much better. This is a result of the goal of the project. Radiation efficiency was not first priority, robustness and size were. The system was still working though and more tests were in order.

4.3 *Radiation Pattern*

This is a test to see in which directions the antenna radiates, or rather in which directions is the radiation stronger and in which is it weaker. It is performed in an anechoic chamber, which is a room where the walls are specially made to absorb electromagnetic radiation. The result is that the measurements made in such a chamber are as close to free space results as possible. This is desirable since it means that we have minimized the interference of objects other than those we use in the experiment and it also means that the results will be directly comparable to theory. In this case we want to measure the angular dependence of the radiation. It is then very important not to get radiation that is reflected of the walls since that is radiated in another angle. That is why the experiments were done in an anechoic chamber.

The tests were made with a fixed receiver and a rotating transmitter seen in Fig 12.

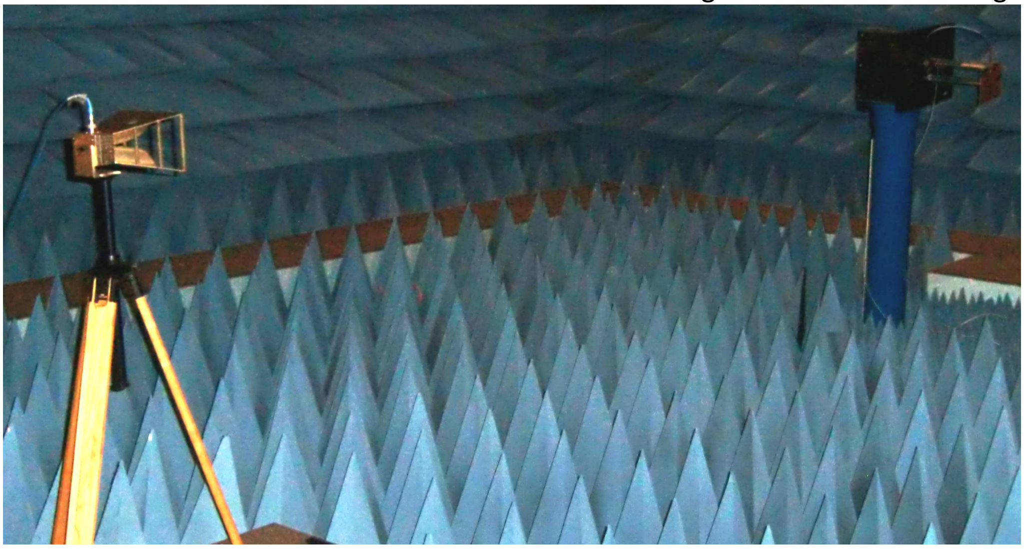


Fig 12: Measuring setup with both transmitter(right) and receiver(left)

The receiver was a Vivaldi horn antenna seen in Fig 13. It has a very high efficiency over a large frequency interval and is linearly polarized. It can be turned 90° in order to measure different polarizations. This was done during the test to get a better understanding of the radiated fields.

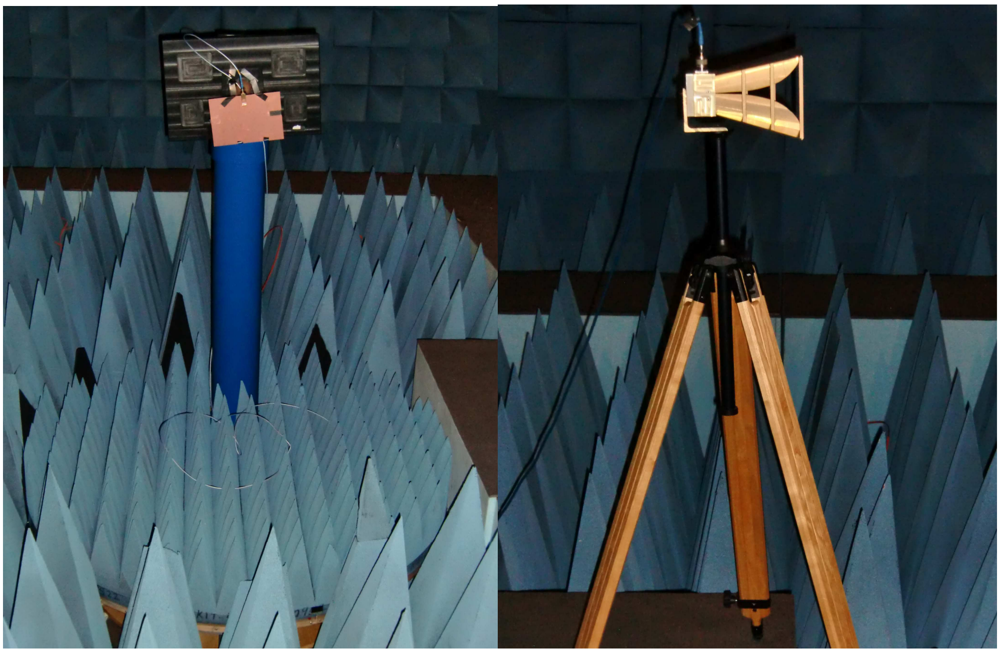


Fig 13: Transmitting (left) and receiving (right) antennas

The transmitter was the antenna under test. By rotating the antenna the room was rotated in the coordinate system fixed to the antenna. The angular radiation was thus measured for the same physical path for every angle. The same measurement could have been done by moving the receiver but that would have taken a much larger room. The antenna was rotated by a robot where the motor was placed on the floor and a tower of dielectric materials (mostly plastics) was used to lift up the test device and to carry out the rotation.

It would have been too extensive to measure the radiated fields for all angles so it was measured for three angles of rotation shown in Fig 14.

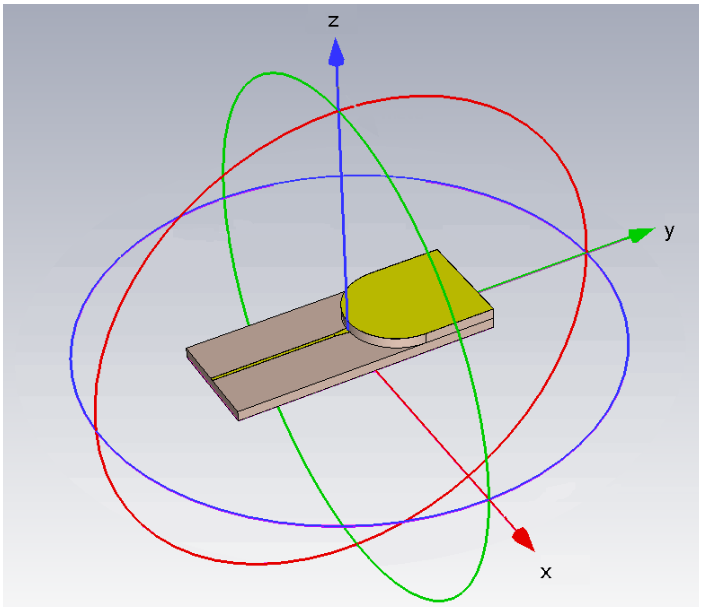
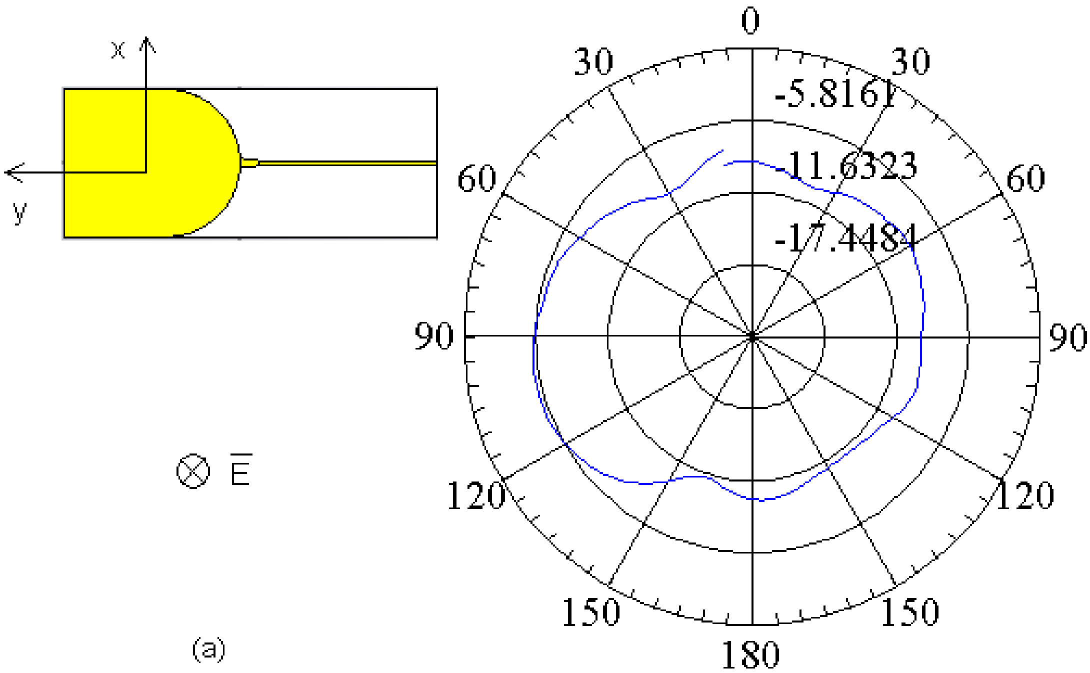
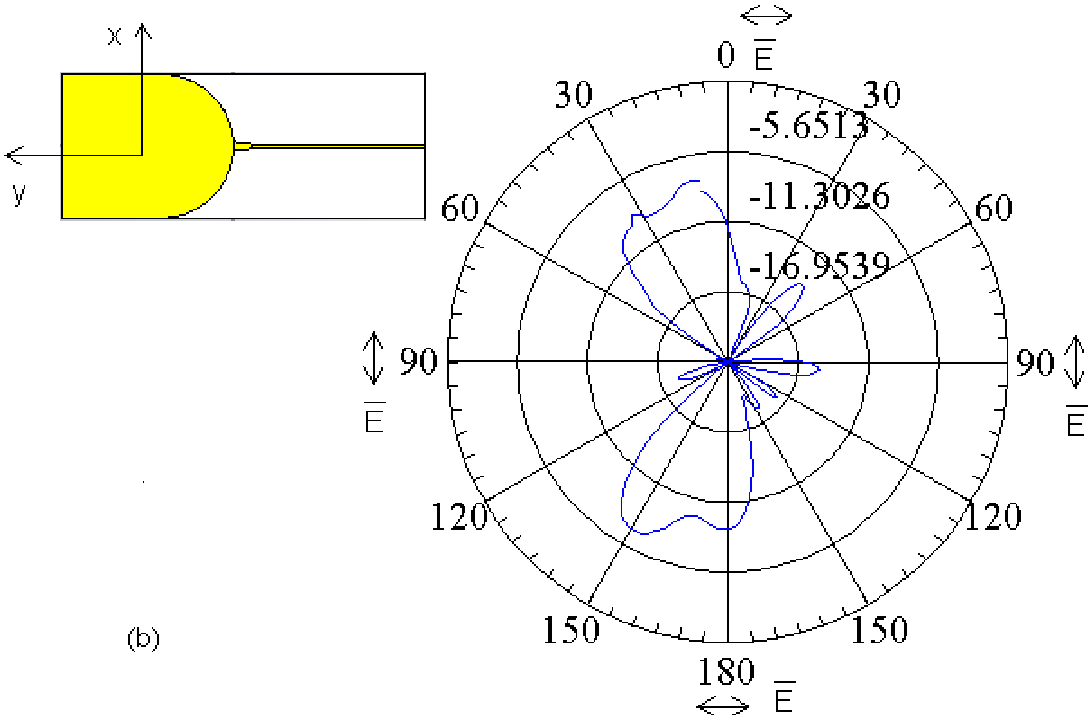


Fig 14: Axes of rotation

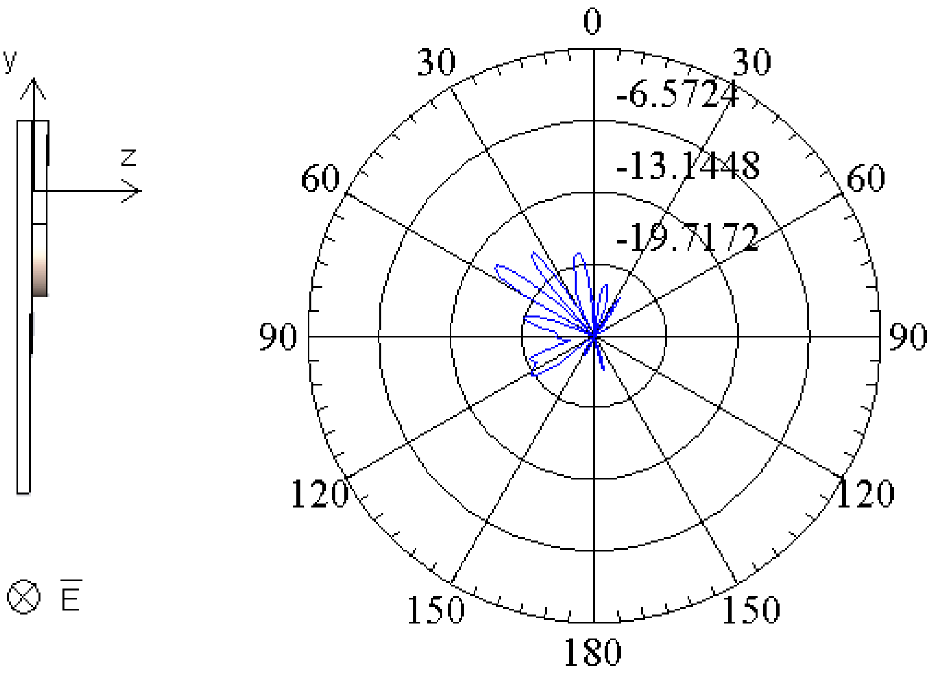
The fields that are emitted are linearly polarized and so measurements were performed for two orthogonal directions of polarization. Measurements were done with an interval of 2°. To do a test of efficiency at the same time as testing the pattern and thereby finding the gain would have required two ideal antennas which were not available. The levels of radiation were for this reason only measured relative each other and the strongest fields measured were set as reference. Results can be seen in Fig 15a-f.



(a)


x
y
0
30
30
60
60
90
90
120
120
150
150
180
-5.6513
-11.3026
-16.9539
E

(b)


y
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E
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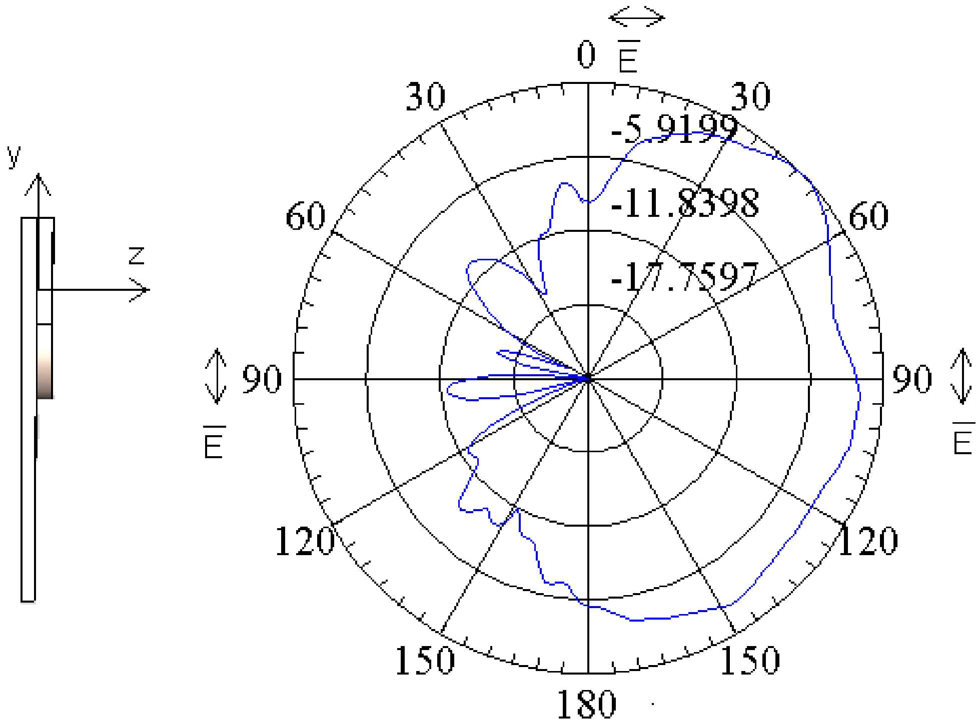
-6.5724
-13.1448
-19.7172

(c)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-11.8398
-17.7597
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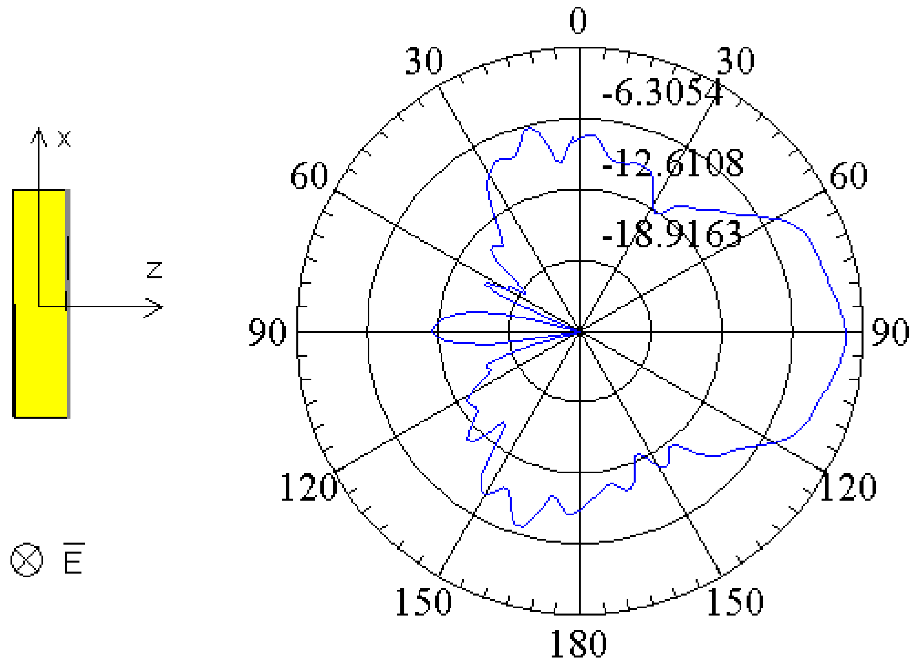
E

(d)


x
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(e)

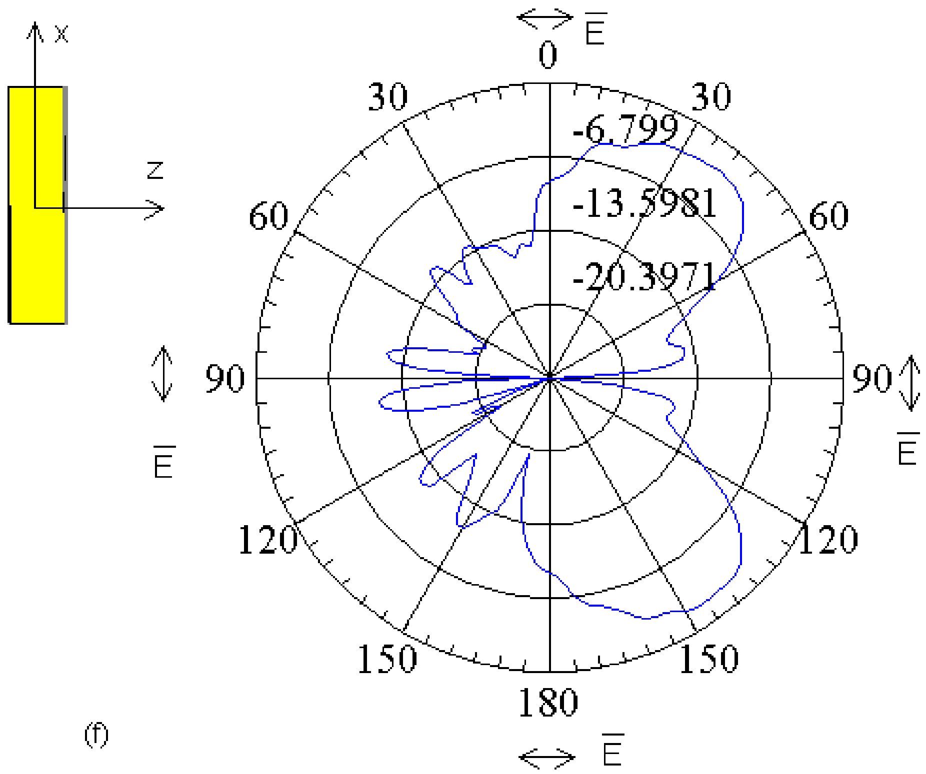
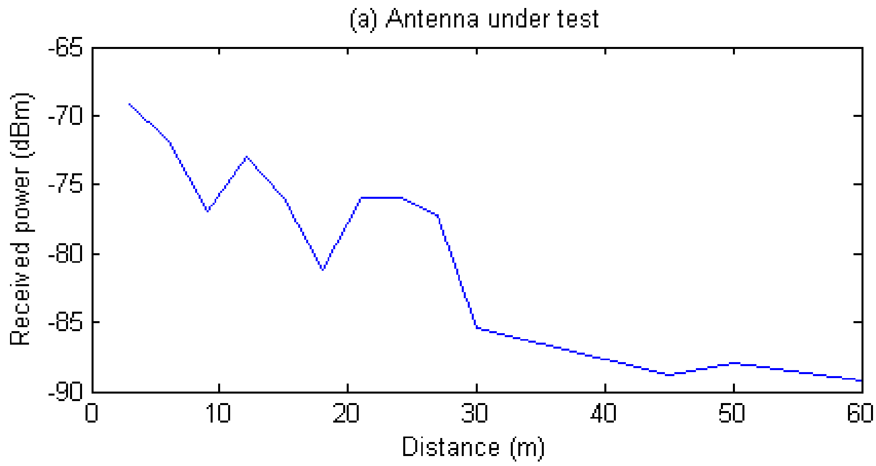


Fig 15: Radiation pattern normalized with respect to the largest measured field strength. a) Rotation around z-axis, polarization along z-axis, b) Rotation around z-axis, polarization in xy-plane, c) Rotation around x-axis, polarization along x-axis, b) Rotation around x-axis, polarization in yz-plane, a) Rotation around y-axis, polarization along y-axis, b) Rotation around y-axis, polarization in xz-plane

The strongest level of radiation is found in Fig 15d. That is waves traveling in the positive z-direction polarized in the y-direction. A patch antenna is usually directed normal to the patch surface [5], which is the z-direction. It was not a very good result for this project however as the original design plan was to have that side away from the train and thus not use the radiation in that direction. One of the reasons for choosing this design was that the simulations showed it radiated mostly in the directions of positive and negative y. The polarization in the y-direction corresponds well to the current forming a path in this direction from the feed to the shortened edge. It can also be seen that in all directions the polarization in the x-direction is very weak. The radiation is also strong in the y-directions with a z-polarization. This is most likely due to currents in the shortening patch and is the originally desired radiation. It is still accountable but the radiated field is only 27% as strong as the one in the main direction.

4.4 Application test 1: Open Environment

The fourth test was to use the antenna with the circuitry that is used in the project. The aim was to see how it would perform in normal surroundings and to compare it to the commercially available antennas that had been used to test the circuit before the beginning of this thesis. The environment chosen for the test was a long and wide corridor. It was chosen because it was the largest open space that was still close to an electrical plug, and to record the data a computer was needed. The receiver was a JC-W-001-SMASM monopole antenna. The experiment was repeated with two different antennas transmitting, first with the project antenna and then with another JC-W-001-SMASM monopole to get a reference. In both the experiments the transmitter was placed on top of an aluminum plate that simulated the train. For the project antenna this was a requirement since the design was based on this, and for the monopole this was an improvement because the theory of monopoles is based on an infinite conductor plane at its base. The radio used was an Atmel AT86RF231-ZF that transmitted at -18 dBm or 16 µW. It could receive currents as weak as and even slightly lower than -91 dBm. That is currents of the order 0.1-1 pW. Fig 16 shows the results for both the antenna designed in this project and for the monopole.



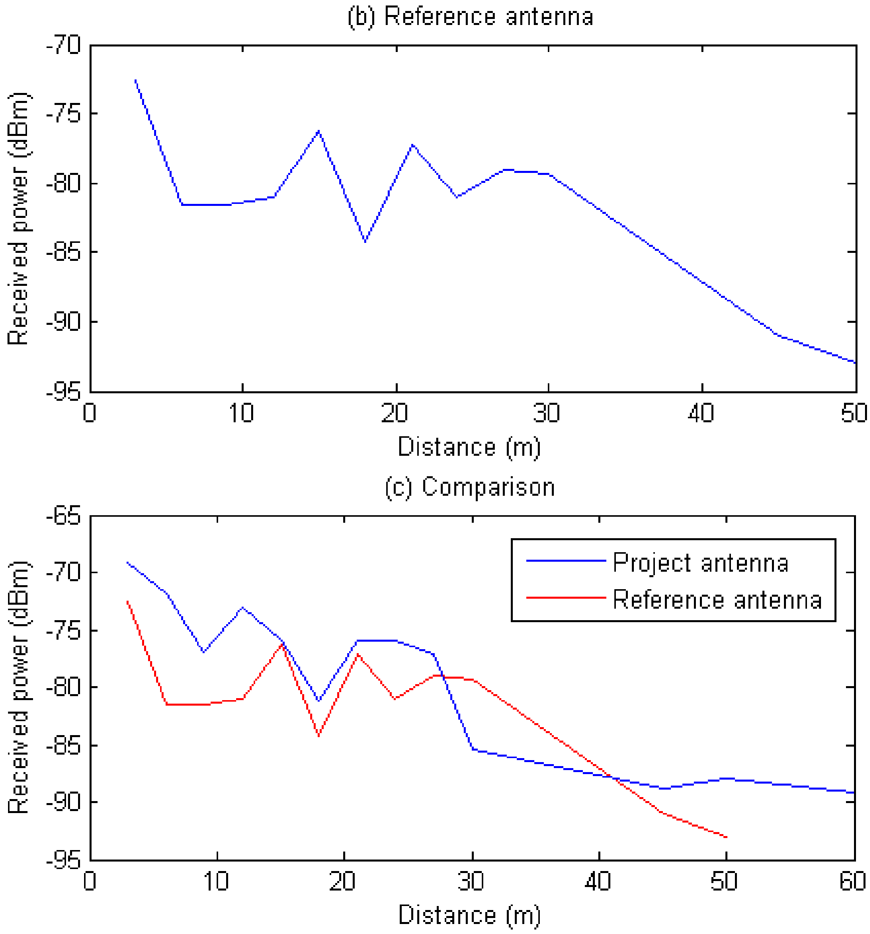


Fig 16: Received power a) from the project antenna, b) from the reference antenna, c) a comparison between the two antennas

The fields measured should show attenuation proportional to $1/r^2$, which means that if the distance is doubled the measured effect should go down by 6 dBm. The results indicate just that but with large variations. These variations come from an effect known as fading. It is the result of the test not being made in open space but in an environment with obstacles that interfere. A low received signal could be due to some obstacle blocking part of the radiated waves. If the transmitter is slightly moved the same obstacle might instead reflect the waves in such a way that the received effect is higher than expected.

The two antennas are comparable but the antenna designed in this thesis shows slightly higher values and also works on a longer distance.

A train wagon is usually much shorter than 60 m. This indicates that each node will be able to not only transfer its data to the nearest gateway but also to at least two others and several nodes. The transfer of information along one side of the train should work perfectly fine. There is a more problematic communication link left however i.e. the one that goes from one side to the other.

4.5 Application test 2. Train

This second application test was done around an actual train wagon. The wagon was in this case a freight wagon that belongs to "Trafikverket".

Fig 17: The wagon which the tests were performed on.

The wagon had a rather high ground clearance, about as high as some lower freight wagons have. The ground clearance is of interest since we want to transmit from one side of the wagon to the other and the shortest path is under the wagon. For passenger cars this path is almost nonexistent since the ground clearance is kept at a minimum, but for freight wagons there can be large open spaces between the wheels. No signal can be sent through metal so the more space the better it is. Since most freight wagons have similar or more open space than the wagon used in the test, what works in this test should work on most other wagons. The test was performed outside the service hall of “Trafikverket”, with the wagon standing on normal rail and to the sides there were groups of trees about 5 m away.

The equipment used was two antennas made in this project and each one was connected to a version 1 circuit. One of the circuits was programmed to transmit and the other one to receive. The receiver was connected to a computer that recorded the data. The setup was similar to the setup in test 4.4 but with the difference that only the antennas designed in the project were used. The antennas were placed against different surfaces of the train close to where an installation of the system prototype was planned. The test consists of 2 parts: one to test how transmission between node and gateway would work and one to see how transmission from side to side would function. In both parts the receiver was kept at the front right wheel and the transmitter was moved.

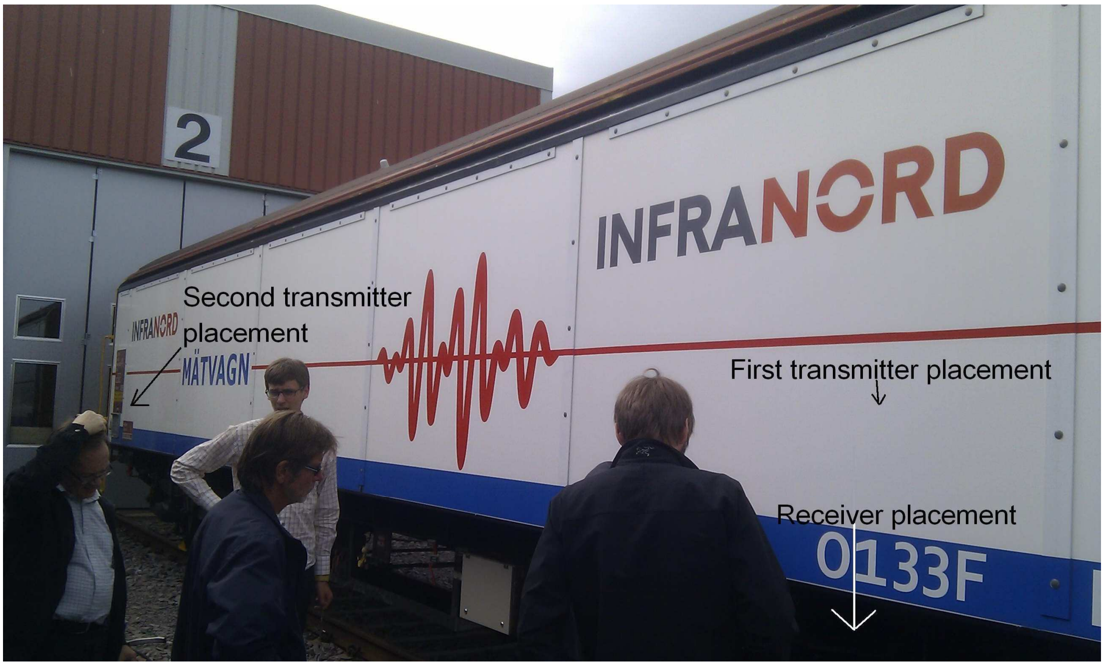


Fig 18: The wagon where measurements were made

The transmitter was first moved to the planned location of the gateway. For the location directly above the wheel, marked as “First transmitter placement” in Fig 16, the signal received was of the order of -77 dBm, and for the location above the other wheel but still on the same side, marked as “Second transmitter placement” in Fig 16, signal strength of about -84 dBm was measured. The cut-off was somewhere between -91 and -94, which meant that these values left a margin for unexpected disturbances. It also implied that transmission to gateway boxes on other cars should be possible. This was not tested though since only one car was present at the test site. These results were in line with test 4.4.

For the second part the transmitter was moved to the front left wheel i.e. the wheel directly opposite to the position of the receiver. Several locations around the wheel and the wheel bearings were tested and for the best ones a signal of about -88 dBm was recorded. For the bad locations no signal was received at all. In the locations that were deemed reasonable for a node installation the signal strength was around -91 dBm but several messages were lost. This is a setup that does manage to transmit the signal but it was very unstable. One should keep in mind that the system does not need to transmit the state of each wheel constantly. It is enough if this information reaches the gateway once per day or perhaps even once per week. If the link is not perfect the system can be set to try more often so that some signals should reach the other side. This does use more energy and so it is something that should be avoided if possible. The transmitter was also moved to the side of the wagon at a gateway position and to the wheel diagonally opposite to the receiver but in both cases no signal was received. This means that in order for each gateway to have information about each node, the nodes need to relay information. This is known as multi-hopping and is planned for the project in the future but is not implemented at this stage. In the first prototype the gateway will therefore only be able to transmit information through RFID about the nodes at the same side as itself. The radio of each node will however receive the signals from the other nodes and so it will be possible to see if the information could be sent reliable using a relay function in the future.

5. Mechanical Construction

The project also includes assembling the prototype system. It was of utmost importance that no parts could fall of and destroy something else. The casing used had to secure that even if some parts break they still stay inside the box. It was decided that four nodes and two gateways would be built. It was my task to be in charge of the gateway assembling and to also assist in the assembling of the nodes. It was decided that a plastic box was to be bought as casing. Plastics were chosen since any conducting material would work as a Faraday cage and shut down all communication. The boxes had to be water and dustproof since the train is a dirty environment and the electronics are sensitive.

5.1 Gateways

The gateway needed to include one RFID antenna, one 2.45 GHz antenna, one solar cell, one battery, and one circuit. Before buying a box a plan for how to assembly the parts needed to be made. The antennas and the solar cell all needed to be on the top, while it did not matter where the battery and circuit was placed. The antennas both radiate strongly in the direction away from the train and placing anything on top of them would greatly reduce their use. They are however less sensitive to objects to the side of them as long as they are not between them and the transmitters or receivers that they are communicating with. For the RFID the direction where communication will take place is a cone with the central direction straight away from the train. For the 2.45 GHz antenna it is downward and diagonally downward to the nodes. The solar panel needed to be somewhere where it could be reached by sunlight. The box would need to allow this to happen either by having a clear lid or by having a hole to let the solar panel be a part of the lid.

The 2.45 GHz antenna was designed for placement on a conducting surface but in this construction where everything is inside a plastic box it is not possible to use the train as that surface and a special surface needed to be built for the prototype. It was decided that this surface would best be built using copper plated FR-4 substrates. The reason was simply that there was an abundance of these substrates in the department and they could be made from leftovers from other projects. It was tested how large this ground plane had to be by placing the antenna on a large copper surface and placing a large heat sink close to it. It was found that 1 cm on each side and 2 cm in front of the shortening patch should be left. That gives a minimum surface size of 6x4.5 cm.

The design was to place the RFID-antenna on the side of the gateway that would be placed upwards on the train, the solar panel below on the left side, and the 2.45 GHz on the lower right side. The 2.45 GHz antenna is placed on the right because the prototype will be tested on one wagon and the gateway is placed on the left side of each wagon. That means that this placement will give line of sight. The RFID antenna measures 161x60 mm and the solar panel 55x70 mm. The smallest box found that would still meet these demands of surface was Multicomp G218, with inner dimensions 196x103x45 mm. It did not have a clear lid so a modification needed to be made. It was decided that the lid of the box would be replaced with one milled out from an acrylic plastic sheet. This could not be done at the university and so we had to order the job from a workshop called ESSDE Teknik. The new lid would be of the same dimensions as the original one and have the same profile on the inner side so that it would be possible to use the same seal as was originally intended. The changes made was apart from the material change that the lid would now have to be thicker and that for simplicity the lid would now be flat instead of having some low walls and thus leaving some space inside the box as the original did. There was plenty of space in the z-direction so this was not a problem. This solution would result in a loss of effect from the solar cell due to absorption in the lid. A 4 mm layer of acrylic plastic would result in a loss of less than 5% [11]. A 8 mm thick sheet should then result in a loss of less than 10%, which is acceptable.

The box is much larger than the total size of the components. To fill up space and secure the components from shaking to pieces a mould was made of Styrofoam. The pieces were assembled into this mould and the lid was screwed with a rubber seal in between the lid and the box. The gateway box was now ready to be mounted on the train.

5.2 Nodes

The node had to be much smaller than the gateway, while it at the same time had to be much more complex. Its design was made up of layers as shown in Fig 19.

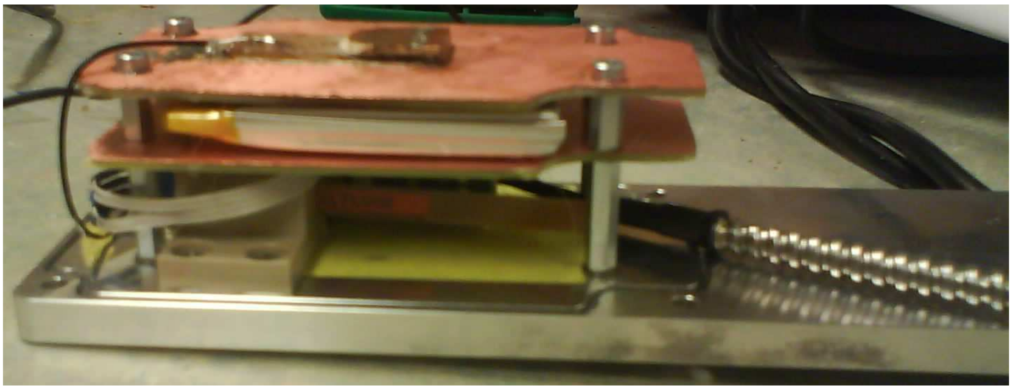


Fig 19: Prototype without outer casing. On the bottom “floor” a vibration driven power generator can be seen and the integrated circuit is found behind it. On the middle “floor” the battery is placed. On the top “floor” the antenna is glued to the ground which also serves as the supporting plane.

Between each layer there would be a board holding the construction together. The board used for the bottom layer had to be electrically conducting on one side since it is used as ground for the 2.45 GHz antenna. For this reason and for simplicity it was decided that all the boards would be milled out from FR-4 substrates. As with the ground planes in the Gateway the material came from leftovers. The task to mill these boards fell on me since I knew how to use the mill.

6. Measurements onboard train

The measurements onboard the train were performed with 2 nodes and one gateway. Three nodes were mounted on the train but one of them ceased to function before the wagon left the service hall. The nodes were mounted as shown in Fig 20, where node number 2 was the malfunctioning one.

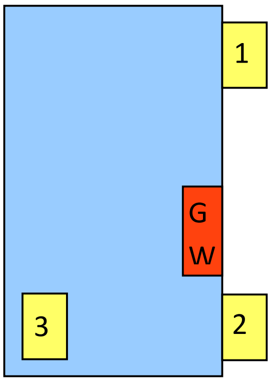
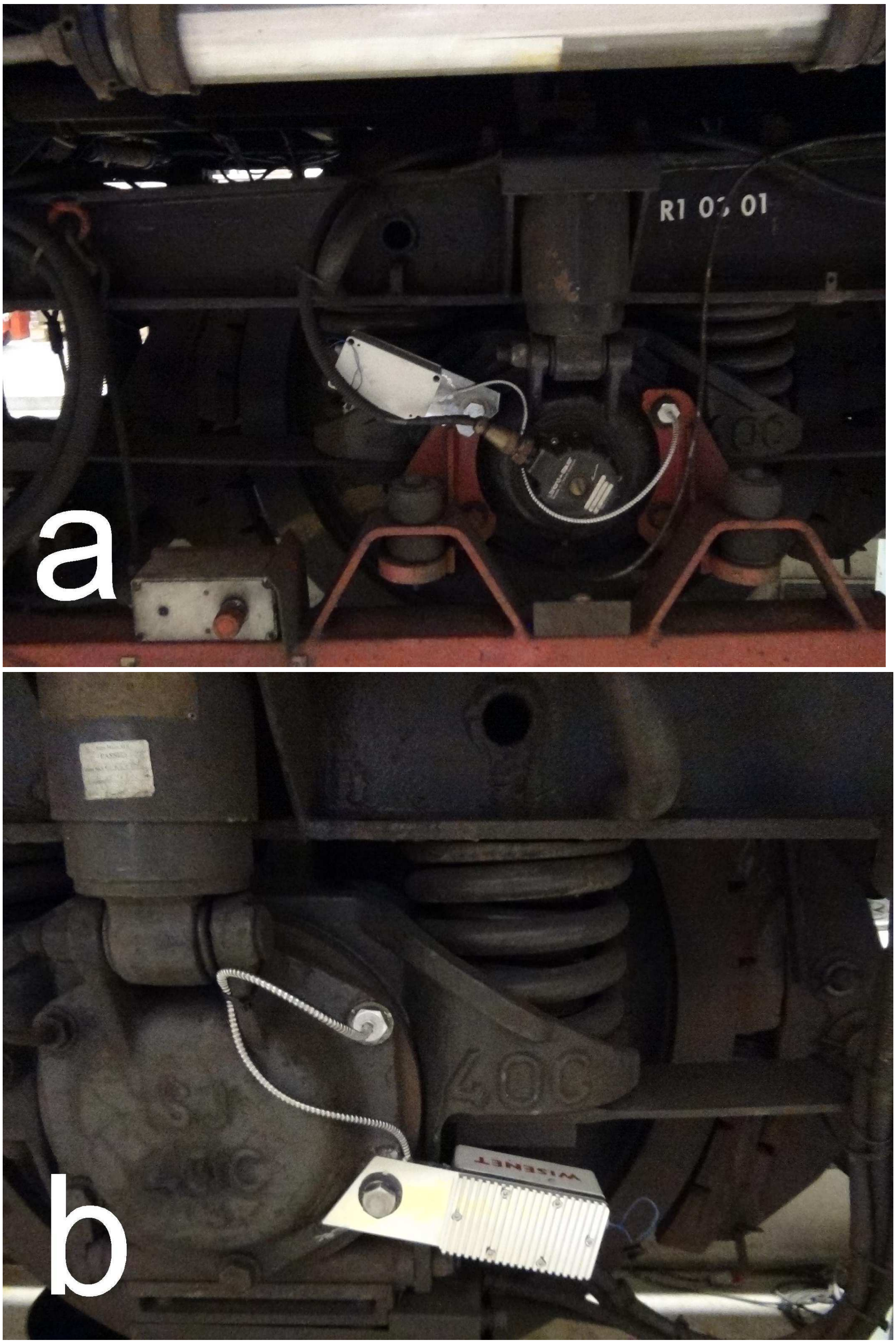


Fig 20: Test setup. Nodes are marked with numbers. Gateway is marked with GW

The nodes were measuring the temperature in the bearings and transmitting the data to the gateway. Fig 21a-c shows the nodes on the train.

Node 3 was mounted on the other side of the wagon than the gateway, and the tests described in section 4.5 had shown that transmission through the train was going to be difficult. It was clear that if the node was mounted on the wheel bearing like the other ones no radio communication would have been possible. It was instead mounted on top of a beam slightly above the wheel. There was some space between the main body of the car and this beam on both sides leaving a narrow canal open where the waves could propagate. For stability reasons the node could only be mounted in such a way that the direction of the short circuiting patch of the antenna was in the forward direction of the train. This meant that it was the side of the antenna that faced towards the gateway and as can be seen in section 4.3 the power transmitted to sides are around 3 dB lower than that transmitted in the forward direction and around 8 dB lower than that transmitted upwards. A significant improvement of the data link could thus be achieved by simply turning the node.


a
b

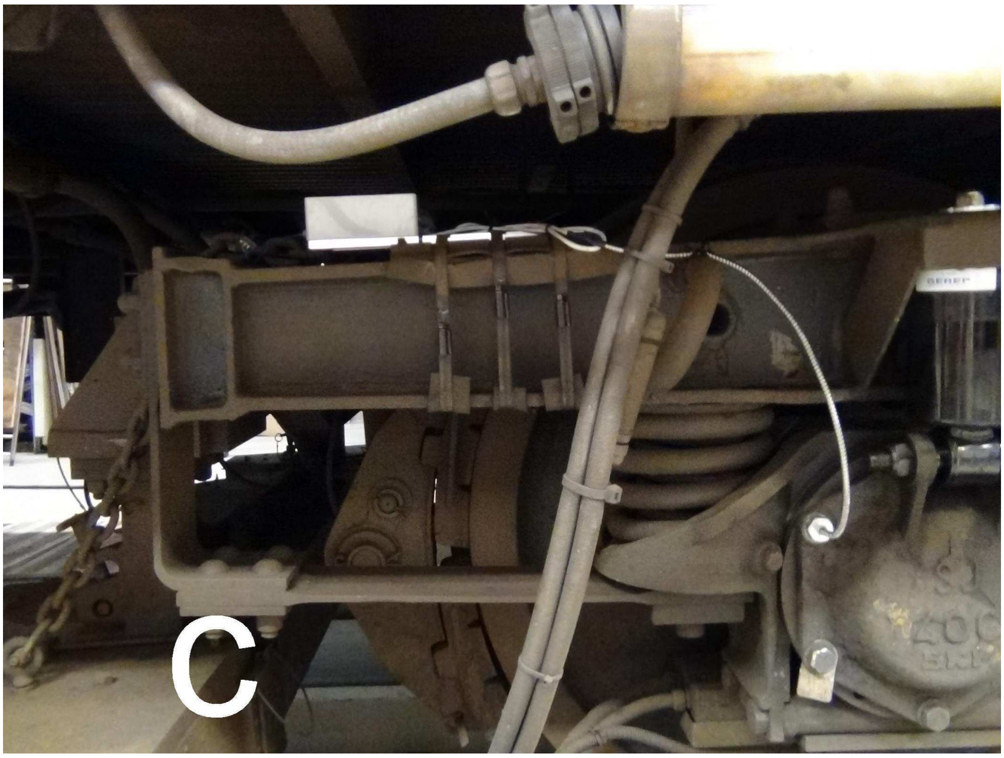


Fig 21: Pictures of the sensor nodes mounted on the train. A) node 1, b) node 2, c) node 3

The gateway could not be mounted safely on the outside of the train and it was thus place on the inside of a window where it could not hurt anyone if it would fall. This lowered the power received by around 4-5 dB. An RFID reader was then used to read the information stored in the gateway and log it on a laptop connected to it by cable. The setup is shown in Fig 22.

Fig 22: Gateway to computer setup

The data was measured during a trip from Borlänge to Uppsala which took slightly more than 2 hours. During this trip many different types of landscapes were passed and the received signal varied accordingly. Two parameters showing the signal quality were measured. One was the power of the received signal in dBm and the other was Link Quality Indication (LQI). LQI is a number between 0 and 255 showing the quality of the transmission. 255 means that transmission quality is as good as it gets and 0 means that it is not working at all. It is given by the receiver and it is a function of power and signal to noise ratio of the received signal. A LQI over 170 means that less than 10% of the transmitted data is lost and can be seen as good. The received power is only measured if it is stronger than -91 dBm, otherwise -91 dBm is shown as the strength.

The received signal power and LQI is shown in fig 23. The received signal from node 1 varied strongly in effect. It was however stronger than what was necessary most of the time. The LQI is on the maximum level for the larger part of the test. There are two occasions where communication is lost, they can be seen as the two points where LQI reaches zero for both nodes, but one of them is the result of the computer losing power and the other one is most likely caused by the computer as well since it affects both nodes simultaneously. This leaves two periods where link quality dropped below 170, but a few minutes with bad communication is acceptable. This works since the goal is to detect faulty wheels and the wheels do not break in an instant. It is interesting to know the status of the wheels once every day, not more. This means that the communication does not need to work every second as long as the data this is taken into consideration when programming the schedule for data transmission.

The signal received from node 3 is never larger than -91 dBm. Transmission works but it is not stable. LQI was for the larger part of the test below 170 and so this is not good enough. Turning the node 90° would however raise the signal strength remarkably.

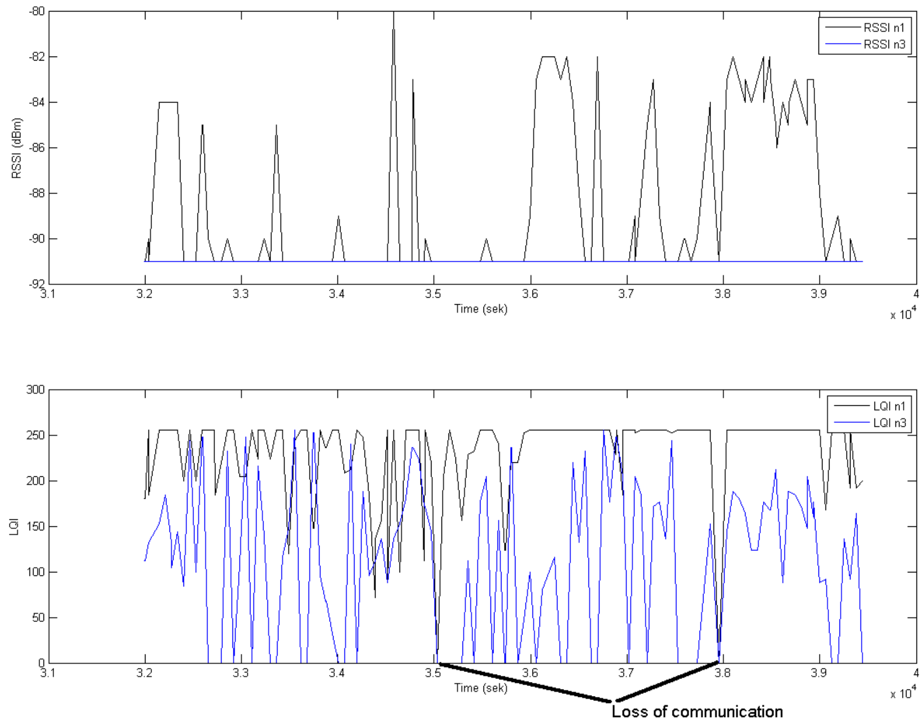


Fig 23 : Received signal power (upper graph) and LQI (lower graph as a function of time. The time is the time in seconds counted from 0:00 that day.

7. Discussion and Conclusions

7.1 The antenna

The goal of the project was to make an efficient, small, and robust antenna that would be possible to produce at low cost. The antenna is efficient enough for the system to work, but a higher efficiency would increase the robustness of the transmission from side to side on the train. One should keep in mind that very few of the losses that occur when transmitting under the train are due to the antenna. Most of the losses come from the hostile environment. This means that the best way to improve the quality of the transmission is to cut those losses. This can be done with a relay or with diversity and most importantly the placement of the nodes needs to be considered. A relay has the draw back that it would be yet another box that needs to be designed and installed. It would raise cost and is for now not even discussed. Diversity is to use more than one antenna to enhance the received signal. Two antennas with orthogonal polarization could for example be used in order to read more of the reflected waves. Diversity is probably the most effective way to improve the transmission quality and so it should be the first thing to do in the continuation of this project. Then there is the placement of the nodes. The first tests were made with the antennas close to the wheels since that is where the temperature and vibration measurements will be made. These measurements did not give a very good result and so when the system was mounted on the train the node on the far side of the wagon as seen from the gateway, that is node 3, was placed on top of the supporting beam. This together with the increased transmitting effect made it possible to communicate directly from node to gateway. For radio there is however an even better placement and that is on the back of this beam as is shown in Fig 24.

Fig 24: Suggested placement of nodes

There is a gap there on all train cars to allow for turning and the empty space is what is needed to improve transmission quality.

If an improvement of the antenna should be undertaken there are a few ways in which this could be done. Relaxing the size requirement on the antenna will open up new possibilities. Making the antenna wider would increase bandwidth and thus increasing the efficiency at the edges of the band. Another way to use the possibility of increasing the size is to have a larger ground plane compared to the patch. This would decrease the dependency on the surface that the antenna is placed upon. This would be good as it would make it easier to adapt the antenna to new applications, but as long as the antenna is placed directly on top of a conducting surface this is not really a problem an so this might not be the most important improvement. If the size requirement still stands it might be a good idea to see if it would be possible to flip the antenna 90° and then put the feed on the side. A wider antenna would give a larger difference in path length for the current and increase the bandwidth. Only a few simple simulations have been made on this idea and it might be worth looking into.

7.2 The System

The system can now measure temperature and send it directly to the gateway. What is needed in the near future is to measure vibrations and analyze them. As was written in part 7.1 the radio would work better if placed on the end of the bogie. Placing the entire node there would also have the advantage of it being less vulnerable to the vibrations in the wheel since it is placed on top of the damping. For the same reason it is impossible to do measurements of the vibrations at that position but just like the nodes place on the train now are using a bolt to measure the temperature and using cable to send the data to the node, a bolt solution could be used for measurements of vibrations. It is possible to make a bolt with both vibration and temperature sensing if the sensors are placed on the bottom of the screw thread. Most of the forces that are applied to a bolt are applied at the edge of the material where it is inserted and if the sensors were placed further in they would not affect the durability of the bolt much [12].

Another improvement that should be made to the system is multi-hopping. It is desirable that the two gateways on each wagon can communicate with each other and there is no direct radio link. The way to solve this is to use the nodes as relays.

More improvements need to be made but they are outside the radio field and are thus not related to this report.

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