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Measurement and Analysis of Radio Wave Coverage in Industrial Environments

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Preface

This work was conducted as an activity in the research project “Reliable Wireless Machine-to-Machine (M2M) Communications in Electromagnetic Disturbed Industrial Environments” at the Center for Radio Measurement Technology, University of Gävle (HiG) together with the Swedish Defence Research Agency (FOI). Project collaboration partners were Green Cargo, STORA Enso Kvarnsveden, SSAB Tunnplåt, Agilent Technologies Sweden, Åkerströms i Björbo and Syntronic.

The measurement campaign described herein was carried out in close cooperation with the staff at STORA Enso Kvarnsveden, SSAB Tunnplåt and LKAB to whom I am very grateful. Furthermore, the access to state of the art measurement instruments from Agilent Technologies was invaluable.

The support and cheering from my supervisor professor Peter Stenumgaard is much appreciated. I also direct special thanks to my colleagues from HiG in the project Dr. José Chiló and Tekn.Lic. Javier Ferrer Coll.

Abstract

Several studies have characterized the path loss properties in industrial environments. However most of them have focused on one frequency, and some two or maximum three frequencies, usually cellular telephone frequencies or the unlicensed ISM bands that are commonly used in various industries. Few, if any, have characterized a larger part of the useable frequency range.
This thesis is taking that challenge and investigates the path loss characteristics over a large frequency range, 300 MHz – 3 GHz, in industrial environments.

First a measurement system suitable for the harsh environments found in industries is designed and verified. The measurement system is designed as two asynchronous stand-alone units that can be positioned at an arbitrary position to measure the path loss characteristics in any environment without interfering with the normal activities at the location.

After that a measurement campaign involving three different types of environments is carried out. The environment types are: first, one highly absorbing – a paper warehouse at a paper mill; second, one highly reflective – a furnace building filled with metal objects and constructions and third, a mine tunnel – located 1 km below the surface of earth which is neither highly reflective nor absorbing but exhibits somewhat wave-guide like characteristics.

The environments are shown to have very different behavior when it comes to propagation characteristics. Observations in the first environment reveal an environment that almost cancels out certain frequency bands and only line-of-sight communication is possible, hence no improvement will be achieved if installing systems that take multipath propagation into account, like MIMO.
In the second environment reflections are legion; there are so many reflecting surfaces at different angles so any polarization of the signal is almost completely eliminated. Large fading variations were observed.
The third environment is the underground mine where signals propagate inside the tunnels like in waveguides. It is shown that there are regions in the spectrum where the path loss dips and that these dips at least partly can be modeled with a simple two-beam propagation model normally used for outdoor propagation over infinite fields.

The overall conclusion is that industrial environments are more heterogeneous regarding propagation characteristics than commonly assumed when selecting communication solutions. And that the only way to really know if a radio system will work at a certain location is to measure and characterize the environment.

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1 Introduction

1.1 Background

Modern industries of today have developed a dependency of reliable radio communication; quite often with high data transfer rates. The information transferred ranges from simple alarm circuits to advanced real time production control data and streaming video to monitor the processes.
Internal material-in-process as well as finished products needs transport for relocation between process steps or to finished-products warehouses awaiting pick-up for delivery. These transports, especially heavy goods such as steel or paper rolls weighing tens of tons, may be conducted by Autonomous Guided Vehicles (AGV). These AGV's may in clean industries be guided by optics while in heavy base industries like mines, steel works etc. the optics will soon be clogged with dust and malfunction, hence radio control is the more viable solution.

Furthermore communication between staff on the floor and in control rooms is done over radio. Over the last decade we have also seen virtually an explosion in the use of Radio Frequency Identification (RFID) tags attached to all kinds of products and on top of it all wireless sensors, alone or in networks, to report the status of various machines and tools involved in the processes.
In the spectra of industrial locations we also find mine and railway tunnels which pose rather divergent propagation environments from the indoor halls indicated above.

1.2 Problem Lead-In

The research project "Reliable Wireless Machine-to-Machine (M2M) Communications in Electromagnetic Disturbed Industrial Environments" at the Center for Radio Measurement Technology at University of Gävle (HiG), focuses on reliable wireless machine-to-machine communications in industries.

Paper warehouses in paper production plants have shown to be challenging environments for radio wave coverage. Radio technology is necessary to use to transfer logistics data to and from the forklift trucks expediting the delivery orders from the warehouse.

Experience shows that no satisfactory solution with necessary radio coverage over a whole warehouse hall has yet been found. The common solution is to conduct the data transfer over 2.4 GHz WLAN links. This is done with some little success; however the cost is a multitude of access-points, many more than would be reasonable to expect in this limited space. At the same time cordless DECT telephones works perfectly well in the same environment while cellular telephones show difficulties on GSM 900 and WCDMA (i.e. the 3G system) but not on GSM 1800. These observations together indicate a strong frequency dependence of the radio channel in the warehouse.

Plausible reasons for the above mentioned problems are essentially the signal attenuation caused by the material properties of the stored paper products and possibly reflections caused by the geometry of the paper rolls and the warehouse hall dimensions.

Many studies have been conducted on indoor radio channel characteristics [1-20]. Excellent surveys on indoor propagation can be found in [1-3] where [1] is focused on radio communication in factories and the special issues therein; [2] deals with indoor propagation in general and sub-divides the indoor environment in different categories where “Factory buildings with heavy machinery” is one and “Underground” is another; [3] talks about propagation parameters in the indoor channel and does at the same give an excellent library of references on the subject.

However, only few of the studies have been focusing on factory halls and other production settings [1-2, 4-7, 18-20]. The Indoors studies found have focused on cellular telephone frequencies (around 900 MHz) and the 2.4 GHz ISM-band (Industrial, Scientific and Medical) including WLAN, Bluetooth, Zig-Bee etc, and some frequencies not used for industrial communications in Sweden. The number of frequencies studied range from one single to three different frequencies with the emphasis on single frequency measurements. None of them have had the approach to study the full radio frequency range including the TETRA (Terrestrial Trunked Radio) band (starting at 380 MHz) via ISM-bands from 430 to 2500 MHz.

Since the multi-path variance cannot be eliminated it is essential to know the environment to be able to adapt receivers and transmitters to work as efficiently as possible in the given channel, or even change the operating frequency band. In order to alleviate this current lack of measurement data, a thorough investigation of the radio channel path loss versus frequency for this challenging environment is necessary. In this thesis a measurement system is designed, dedicated to the characterization of the unique indoor radio propagation channel that the industrial environments constitute.

1.3 Scope

In order to make a more systematic investigation of the radio wave coverage in a paper warehouse as well as other possible industrial environments, a measurement system will be developed. With this system the radio wave coverage, in terms of path loss versus frequency could be measured for a large frequency region; 300 MHz – 3 GHz. With such a measurement system, a thorough investigation of the frequency dependence of the radio wave coverage can be executed. An investigation of the frequency dependence of the radio propagation will be done so that optimal frequency region can be determined for a certain industrial environment.

The thesis involves:

- Development of measurement methodology and design of a measurement system for radio wave coverage in the frequency region 300 MHz – 3 GHz. The measurement system must be able to perform in an industrial environment with continuous operation, without interfering with the production processes.
- Verification measurements in laboratory environment shall be done to verify the function of the measurement system.
- Applied measurements in real industrial environments will show the usefulness of the measurement system.
- The thesis shall include a complete description of the measurement system developed as well as the measurement results from the verification of the system properties.
- The thesis should present measurements of radio wave coverage in the frequency region 300 MHz – 3 GHz in a paper warehouse and in other selected industrial environments.

2 Introduction to Radio Propagation

Radio propagation affects all radio systems in many ways. First, the received signal power must be high enough for the receiver to be able to detect the message, typically above the background noise floor, but at the same time not too strong since co-channel interference may then occur in another receiver. The received power level will not only have a dependency of the distance between transmitter (Tx) and receiver (Rx) but also of the fading in the channel, i.e. slow variations of power depending of wave length and more or less obstructive objects in the signal path.
Second, the quality of the signal must be such that the receiver can interpret the message. For digitally modulated signals this involves error correction methods such as channel encoding and decoding.
Finally, the quality of the signal will rather depend of rapid variations from scattering and multipath delay spread. However, here we will keep focus on the first effect, the signal level variations due to radio channel propagation losses and fading.

2.1 Propagation Mechanisms

The radio waves propagating in normal indoor environments are basically subject to three fundamental mechanisms namely reflections, diffractions and scattering [9, 21].
Reflection occurs when an electromagnetic wave hits an object with much larger dimensions than its wavelength and bounces, i.e. reflects from the surface of the object.
Diffraction is caused by objects in the line-of-sight, obstructing in the waves. If the object has sharp edges and is not large enough to shadow the signal completely the radio waves are bent around the corners of the obstructing object and the corner can be seen as a secondary transmitter.
When the propagating wave strikes a rough surface where the dimensions of the irregularities are of the wavelength size or smaller, the effect is known as scattering. First free space path loss, FSPL, is derived and then various path loss models will be discussed.

2.1.1 Propagation in Free Space

When trying to make an estimate of the possibility for a radio system to function it is common practice to set up a link budget. Due to the problems of making accurate estimates of all parameters involved in the processing of the signal from transmitter to receiver simplified models are frequently used. The following equation is known as Friis' Free Space Formula:

$$P_R = \frac{P_T G_T G_R \lambda^2}{L_T L_R (4\pi d)^2} \tag{1}$$

where:

P_R = Received power	P_T = Transmitted power
G_R = Receiver antenna gain	G_T = Transmitter antenna gain
L_R = Receiver losses	L_T = Transmitter losses
λ = Signal wavelength	d = Distance between transmitter and receiver antennas

If separating the parameters related to the radio system equation 1 can be rearranged to:

$$\frac{P_R L_R L_T}{P_T G_R G_T} = \frac{\lambda^2}{(4\pi d)^2} \tag{2}$$

The expression on the right side is representing the transfer function of the radio channel or one over the path loss. The path loss is proportional to the distance squared between transmitter and receiver, d, and inversely proportional to the wavelength, λ, squared. In decibels the free space path loss can be written as follows [21].

$$L_{PFS} = 10\log\left(\frac{4\pi d}{\lambda}\right)^2 \tag{3}$$

2.1.2 Log-distance Path Loss Model

Free space is a condition rarely met in a radio channel. In a realistic channel the signal will be band limited and suffer from large and small scale fading. Even if the situation is line-of -sight (LOS) there will be reflections from large objects such as buildings and nature formations like hills. The very same objects may also cause shadowing giving us a non-line-of-sight (NLOS) situation. When roaming around with the receiver this will cause slow variations in the path loss around a local mean. Smaller objects, foliage, and edges will cause the signal to diffract or scatter and hence cause rapid variations in the received signal strength. A path loss model taking this into account is the Log-distance Path Loss Model shown in equation 4 where the loss is calculated over a distance d [1-3].

$$L_P(d) = L_P(d_0) + 10\eta log(d/d_0) \tag{4}$$

The variable d_0 represents a close-in reference distance and η is the path loss exponent representing how fast the path loss increases with distance. For free space calculations the variable η equals 2. The reference distance d_0 must be long enough to assure that the measurements are made in the far-field, i.e. the separation of the antennas is greater than the Fraunhofer distance. According to [21] the Fraunhofer or far-field distance, d_f., may be calculated according to equation 5.

$$d_f = \frac{2D^2}{\lambda} \tag{5}$$

D is the largest physical linear dimension of the antenna. To assure that the antenna is in the far-field region

$$d_f \gg \lambda \tag{6}$$

and

$$d_f \gg D \tag{7}$$

must be fulfilled.
When measuring path loss, not only at one frequency, but extending to a desired frequency range the equation changes to

$$L_P(d,f) = L_P(d_0,f) + 10\eta log\{(d,f)/(d_0,f)\}. \tag{8}$$

2.1.3 Using the Log-distance Path Loss Model in Practice

Two measurements have to be executed to be able to calculate the path loss according to equation 8. First, a reference measurement is taken at a distance d_0 = 3m, and then, a measurement is taken at the chosen distance. The reference distance is chosen to 3 meters to avoid severe near-field problems during the measurements according to equation 5. The expression in equation 8 is implemented as

$$L_P(d,f) = L_{PFS}(d_0,f) + 10\eta log\left\{\frac{P_{R_d}(f)}{P_{R_{d_0}}(f)}\right\}. \tag{9}$$

When both measurements are made with the same equipment at the same time, all parameters according to equation 1, such as the output power level, transmitter and receiver antenna gain, and cable losses will cancel in the calculations. Left will be $10\eta\log(d,f)/(d_0,f)$ and L_{PFS} which is calculated from the free space formula given in equation 3, meaning that the resulting path loss figures are only depending on the environment. Hence the need for calibration is avoided. For this reason the environment must be constant between measurements and the transmitter location has to be stationary.

2.2 Indoor Radio Propagation

The indoor radio propagation is influenced by the same fading mechanisms as outdoor propagation. However, the local conditions have a stronger impact due to the limited volume. Indoor radio channels differ from the common outdoor radio channels in several parameters, where smaller geometries and greater variance of the environment are two major factors.

As with the outdoor channel the signal level will drop with distance. The building layout, materials in boundaries like walls, floors and ceilings etc. as well as materials in furniture and other effects will all affect the fading characteristics. Also antenna positions of the access points and the mobile units will give impact on the amount of losses. Here we must distinguish not only between line-of-sight (LOS) and non-line-of-sight (NLOS) behavior but also obstructed line-of-sight (OLOS) depending on the floor layout [1-3, 9]. OLOS appears when the direct signal is obstructed by objects small enough to not cause real shadowing and hence not giving NLOS. The main signal is often propagating via e.g. knife-edge diffraction.

Several reports means that the indoor path loss can be modeled by using the Log-normal Shadowing Path Loss Model shown in equation 10 where the loss is calculated over a distance d [4, 9-10, 12]. The variable X_σ represents a zero mean, random Gaussian variable (with the standard deviation, σ) that reflects the variation in average power, i.e. the fading.

$$L_P(d,f) = L_P(d_0,f) + 10\eta log\{d(f)/d_0(f)\} + X_\sigma \qquad (10)$$

For free space calculations the variable η equals 2. Inside factory buildings η can vary between 1.6 and 1.8 for LOS situations in hallways and tunnels and similar while for NLOS it spans 4-6. With OLOS in factory buildings values for η between 2 and 3 have been obtained [1-3, 5, 9]; values as low as 1.1 has been reported in [6].

2.2.1 Alternative Models for Indoor Path Loss Calculations

When discussing industrial facilities like factory halls we can identify four parameters that may cause signal degradation:

- Strong reflections from large metal constructions and various kinds of machinery and conveyors.
- Strong absorptions due to large absorbents in warehouse storages
- Temporal variations of the channel from moving objects like industrial robots, forklifts, conveyed products et cetera; this could of course also be caused by the mobility of the users.
- Size. Factory halls are by tradition physically large causing large delay spread in the received signals.

Since the indoor environments are heterogeneous and in many cases complicated to describe a commonly accepted path loss model has not yet been presented. In [3] four different path loss models for indoor propagation are described. These four models all have in common that they assume single or few storey buildings. If considering multi-storey buildings more complex methods are required [10].

2.2.1.1 <u>The One-slope Model</u>

The One-slope model is the same log-distance path loss model described in section 2.1.2 above, following equation 4 where the path loss is proportional to an exponential law of the distance. The exponent, η, varies with the specific environment.

2.2.1.2 The Multi-slope Model

This model is based on the one-slope model but the exponent, η, varies with the distance. In an example in [3] η varies from 2 for a distance between 1 and 10 m, over 3 (10 – 20 m), 6 (20 – 40 m) to 12 (distances over 30 m). It can be observed that as the number of obstacles increases between transmitter and receiver the exponent increases substantially.

2.2.1.3 The Individual Attenuations Model

Here an initial path loss according to equation 3 is calculated before individual attenuation factors (AF) for the various structures between the transmitter and receiver antennas. E.g. a "double plaster board wall" could be associated with an AF of 3.8 dB per wall the signal has to pass through, and an example states that concrete walls and floors give AF in the range 8.5 – 10 dB. However, the AF values are frequency dependent and will vary with the material constitution in every given case.

2.2.1.4 The dB per Unit of Distance Model

In this model a certain dB per unit of distance between the Tx and Rx is given to calculate the path loss. The model has been combined with the One-slope model with good results [3] while others successfully have used varying attenuation per meter for different distance quite similar to the Multi-slope model.

3 Spectrum Analysis – Receiver constraint

Radio transmission, even for measurement purposes, is strictly regulated by laws as well as national and international regulations. Broadband measurements like the ones proposed in this thesis are also covered by these regulations. Hence it is a fundamental requirement to have permission from the appropriate regulatory board. The receiver noise floor, signal-to-noise ratio (SNR) and receiver bandwidth will all be parts of the background information to determine the required transmitter power when applying for the transmission permission.

3.1 Noise Floor in a Receiver

The parameter that sets the quality limits for a radio system, apart from transmitted power and path loss, is the noise floor in the receiver. Since every radio system has a specified minimum SNR and is designed to work with a certain receiver bandwidth it is a simple task to find the receiver threshold. This is maybe the most important parameter making a radio frequency measurement system function properly.

3.1.1 Background Noise Density

The first step is to calculate the background noise density, N_0.

$$N_0 = kT \tag{11}$$

T represents the absolute temperature measured in Kelvin while k is the Boltzmann constant, $1.38065 \cdot 10^{-23}$ J/K. A commonly used value of ambient temperature is T = 290 K (i.e. +17 °C). This results in a background noise density of $3.8 \cdot 10^{-21}$ W/Hz which may be represented as -174 dBm/Hz.

3.1.2 Receiver Noise Level

Then we use equation 11 to compute the receiver noise level with the knowledge of the specified channel bandwidth.

$$N = N_0 B = kTB \tag{12a}$$

Here B is the bandwidth in Hz. To make calculations simpler this may be rewritten in logarithmic format as:

$$N = N_0 + B = k + T + B \tag{12b}$$

Now we make the bandwidth logarithmic by $10 \cdot \log B$, e.g. 10 kHz becomes 40 dBHz and the receiver noise floor becomes N = -174 dBm/Hz + 40 dBHz = -134 dBm.

3.2 Signal-to-Noise Ratio (SNR)

The signal-to-noise ratio tells how much stronger the received signal must be compared to the noise floor in order for the receiver being able to use the received signal. In a power measurement system this instead relates to the measurement uncertainty. The noise will be added to the received signal. If the received signal level is too close to the noise floor the noise power will give a substantial contribution to measurement errors. As a rule-of-thumb a separation of 10 dB between the signal and noise RMS levels causes a measurement uncertainty less than ±0.5 dB [22].

3.3 Receiver Sensitivity

To get the receiver sensitivity (also known as the receiver threshold) only two more parameters are needed namely the *SNR* and the receiver noise figure. The receiver noise figure is a measure of how much noise the receiver front-end adds to the received signal. For this the following equation is used:

$$P_R = N_0 + B + SNR + NF \tag{13}$$

where all numbers are in dB. The receiver sensitivity is a measure of how low signal levels the receiver can detect with satisfactory quality. Lower signal levels will be more or less distorted by noise and may hence not be useful to the end user.

In the case of the spectrum analyzer receiver the specified noise floor given in dBm/Hz has to be found. By adding the logarithm of the chosen resolution bandwidth, in dBHz, the receiver noise floor lest the *SNR* is found. This means that to the spectrum analyzer noise floor the logarithmic resolution bandwidth and the required *SNR* has to be added to achieve the receiver threshold for the intended measurements.

3.4 Measurement Time in a Sweeping Receiver

3.4.1 Analog Resolution Band Width

All band limited devices require a finite time for charging and discharging. The rise time, t_r, of a band pass filter depends of the bandwidth according to

$$t_r = \frac{k}{B} \tag{14}$$

where k typically varies between 2 and 3 for near-Gaussian filters as the resolution band pass filter in the spectrum analyzer [23].

The time a certain input signal frequency will remain in the pass band is defined as the total sweep time, t_s, related to the proportion the resolution bandwidth, *RBW*, constitutes of the total span, *S*.

$$Time\ in\ Pass\ Band = \frac{t_s \cdot RBW}{S} \quad (15)$$

As a boundary condition the time in the pass band must at least correspond to the rise time of the filter. When that condition is fulfilled, equations 14 and 15 may be set equal and result in

$$t_s = \frac{k \cdot S}{(RBW)^2} \quad (16)$$

As can be seen the sweep time in a superheterodyne analyzer is governed inversely by the RBW squared. If not obeying the minimum t_r versus t_s the result will be a too low amplitude representation since the filter is not allowed to reach its final level and a frequency error, seemingly a slight shift to higher frequencies.

3.4.2 Digital Resolution Band Width

In modern spectrum analyzers the digitizer has been moved closer to the front end giving more possibilities with digital signal processing. A Digital RBW filter will have impact on the sweep time compared to analog RBW filters. Implemented in a traditional sweeping analyzer the typical speed gain makes a digital RBW around 2 – 4 times faster than the corresponding analog filter.
Turning to mathematical filters, i.e. FFT based filters; the effect on the sweep time is even higher since the signal is analyzed in frequency blocks [23]. This opens up for substantially faster measurements if using a signal analyzer.

4 Path Loss Measuring Methods

In most of the papers found where real propagation loss measurements have been conducted the measurements were narrow band [4-6, 11, 14 and 18]; all having in common the use of a separate transmitter and receiver where the receiver is manually tuned to the transmitter frequency. These set-ups had a high degree of freedom in locating the transmitter and the receiver.

In [16] a system with separate transmitter and narrow band receiver was set up using discrete component blocks; all synthesizer blocks were frequency locked with coaxial cables to a Rubidium reference oscillator to also be able to accurately determine the received signal phase characteristics. In [12] a vector network analyzer (VNA) was used to generate the stimuli and to measure the channel response. A similar approach was made in [15] using the tracking generator of a spectrum analyzer as transmitter and the spectrum analyzer as the receiver. These methods were giving less freedom in the sense that the cable losses could reduce the available signal to noise ratio and also since the sensitive coaxial measurement cables had to be rolled out over the floor.

4.1 Synchronous Measurements

With ‘synchronous measurements’ is understood measurements where the receiver tuning is somehow synchronized with the transmitter frequency while making synchronized sweeps over the desired frequency range, thus measuring exactly the same frequency as is generated from the transmitter at every moment.

4.1.1 Network Analyzer

A network analyzer is an instrument which traditionally has a built-in transmitter, also known as Source, and three different receivers that simultaneously measure forward power, reflected power and transferred power. The basic version, see Figure 1, offers two test ports. However, versions with various numbers of ports, e.g. 4, 8 or 16, do exist.

As the signal generator sweep is controlled by the local oscillator (LO) frequency the receivers are tuned to the very same frequency. At every measuring point the forward power (R) is measured simultaneously with the transmitted power (B) and the processing unit can compute the transmission loss as the ratio between the reference and transmitted power levels.

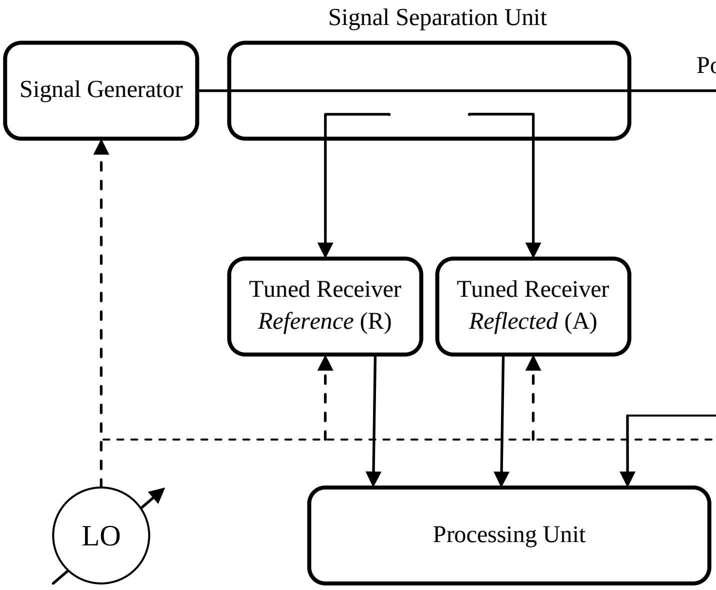


Figure 1. Simplified block diagram of a 2-port Vector Network Analyzer

From Figure 2 can be seen that the network analyzer solution requires coaxial cables reaching the full distance to be measured, plus a couple of extra meters to protect the sensitive coaxial cables from stretching or bending more than allowed in specifications.

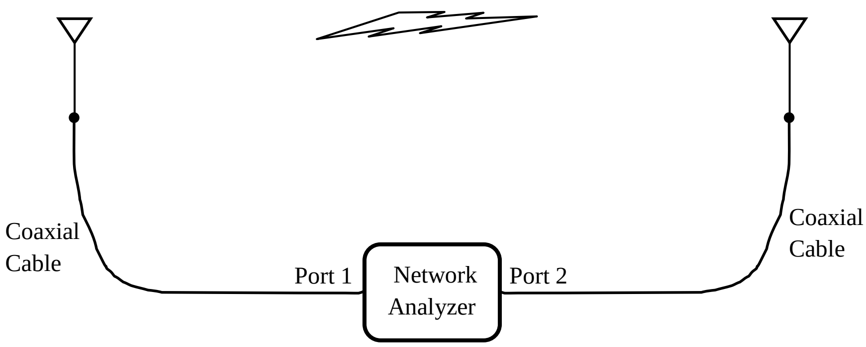


Figure 2. Test set-up for synchronous measurements using a network analyzer.

A spectrum analyzer equipped with a tracking generator is used in the same way as a network analyzer with a sweeping signal generator output which is synchronized with the spectrum analyzer sweep. Although, internally there is only one receiver measuring the transmitted signal, corresponding to the B receiver in the network analyzer, see Figure 1. The receivers for reference and reflected signals do not exist here.

4.1.2 Synchronized Systems

A few different implementations of wire synchronized systems can be identified:

- Coaxial
- Pair cables
- Optical fiber cable

The principle is the same for all of them. The Ramp Generator generates a voltage ramp which is transmitted to the receiver through the chosen medium as shown in Figure 3. In the optical fiber case a conversion from voltage into light has to be done on the transmitter side and vice versa on the receiver side.

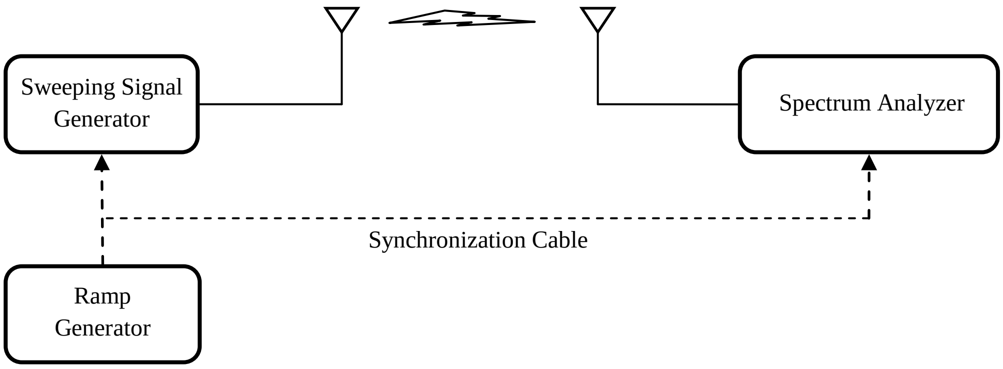


Figure 3. Simplified block diagram of a Wire synchronized system with voltage ramp controlling the sweep.

This voltage ramp is controlling the sweep between the selected start and stop frequencies in both signal generator and spectrum analyzer. This requires that the instruments have analog sweep control inputs.

Another way to accomplish the same effect is to have the sweep control signal generated locally at both transmitter and receiver side. The ramp generator is then substituted by a synchronization pulse generator. A synchronization (start) pulse is sent to trig the sweep in both instruments simultaneously. A prerequisite is that both instruments must have the option to start the sweep by a trigger signal.

4.1.3 Radio Synchronized System

Radio synchronized systems and the wire synchronized systems are very much alike, with the major difference that the synchronization pulse is transferred over a radio interface to set off the sweep instead of using a wire.

Optical links can be considered as a special case of radio synchronized systems. However, they will only work under line-of-sight conditions and will suffer from the sometimes dusty air found in some industries, which might deteriorate their function.

4.2 Asynchronous Measurements

Instead of making efforts to synchronize the signal source and the receiver it is possible to use a signal generator and a spectrum analyzer set to measure with Max-Hold. Both are covering the same frequency range but sweeping without correlation between the two instruments. The measurement set-up is according to Figure 4. After a certain minimum time the signal generator and the spectrum analyzer will have covered the same frequency at the same time at least once, meaning that a frequency sweep has been accomplished without synchronization between the two instruments.

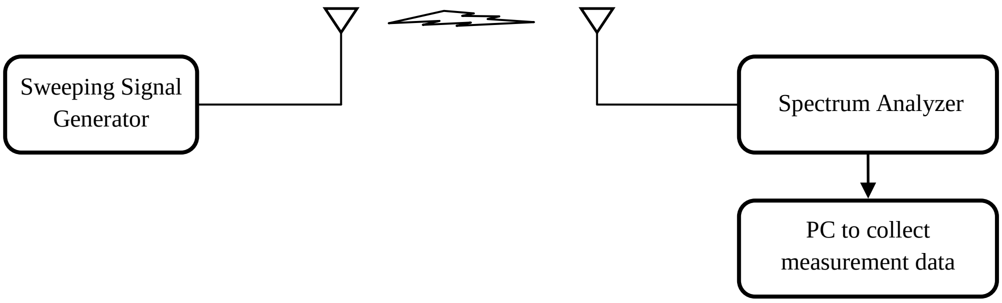


Figure 4. Block diagram of an asynchronous measurement system.

The advantage with the asynchronous measurement method is that there is no need for having cables rolled out over the floor. The generator and analyzer sites are completely stand-alone. The asynchronous measurements can be performed in two ways; either with the generator sweeping slower than the analyzer, or with the analyzer sweeping slower than the generator. The test set-up, however, remains the same. Since with this approach the instruments are uncorrelated the test-time is substantially longer than with a synchronized measurement.

4.2.1 Slow Sweeping Signal Generator

In this method the signal generator performs one or a few slow frequency sweeps while the spectrum analyzer makes many fast sweeps to register the received power levels over the complete frequency range. The factor limiting test-time is the Resolution Bandwidth (RBW) filter settling time in the spectrum analyzer.

4.2.2 Slow Sweeping Spectrum Analyzer

In this method the signal generator makes many fast frequency sweeps while the spectrum analyzer performs one or a few slow sweeps to register the received power levels over the complete frequency range. Here the limiting factor is the frequency settling time in the signal generator when performing a frequency step.

This method is likely to interfere less with the active radio systems in the surroundings than would be the case with the slowly sweeping generator which will dwell longer time at each frequency.

5 Choice of Method

5.1 Comparing the Methods

To select which method to proceed with, a number of parameters must be addressed, e.g. robustness against the harsh environment, flexibility, possibility to position transmitter and receiver at desired spots, calibration etc.

a. The network analyzer solution requires long coaxial cables for measurements to meet the long distance, up to several tens of meters. This causes higher attenuation which limits the dynamic range. Having long cables rolled out over production floors implies safety issues and is generally not allowed. Furthermore the sheathing of the expensive coaxial cables is usually sensitive to oils and other chemicals that may appear on a factory floor and there is also the risk that the cables may be damaged by production vehicles. However it is an excellent solution in small dimension environments.

b. The synchronized solutions all have in common that there is no need for measurement cables running over the factory floors, which eliminates the high attenuation – low dynamic range problem. Still the wired methods suffer from the same problem with rolled out cables, but now in the form of synchronization cables, although less expensive, they imply safety hazards for personnel and may be damaged by the rough environment.
The wireless solution, synchronized via radio or optical link, must be precluded. The radio synchronized solution is excluded since a synchronization signal over a radio frequency could interfere with the measurements. Furthermore false triggering might be caused by electromagnetic interference, EMI, from the environment. The optical link requires line-of-sight between transmitter and receiver which cannot always be guaranteed and may in some environments be distorted by vapor, smoke or other fumes.

c. The asynchronous methods overcomes all above mentioned issues, i.e. no need for long signal or synchronization cables rolled out and no over-the-air synchronization that might be disturbed. The transmitter and receiver work completely stand-alone. On the other hand the measurements tend to be quite time consuming.

In common for all methods was that they required free space propagation to measure P_R at distance d_0 when using the Log-distance Path Loss Mode according to section 2.1.3. Two measurements have to be executed to be able to calculate the path loss according to equation 4. First, the reference measurement is taken at a d_0 = 3m, and then, a measurement is taken at the chosen distance.
None of the methods require calibration since when using the Log-distance model, the power measurement at the actual distance, is compared to the power at the reference distance. By doing this all parameters that are equal in both measurements, e.g. antenna gain, coaxial cable losses, instrument

deficiencies etc. will cancel. However, it is essential that all parameters are kept constant meaning that everything from the output power to the transmitter and receiver antennas with associated cables has to be the same for all measurements.

5.2 The Expected Environment

From the very beginning this work was initiated by a strong interest from a paper industry to have their communication problems in a paper warehouse scientifically analyzed. Hence the first approach was that the expected environments would be lossy due to absorbent materials. As the project idea settled the number of possible environments increased rapidly. Thus a selection had to be done resulting in the choice of two further environments; a furnace building where the tree bark refuse was burnt to generate energy for the paper process, and a mine tunnel that functioned as a transportation passageway for remote controlled mine trains loaded with iron ore. This expansion of the scope resulted in three quite different environments with extreme variation in radio channel characteristics. Industrial environments have in common that in the halls there may be a continuous movement of e.g. industrial robots, fork-lifts, trains, conveyors with material in production and/or the personnel. This imposed some limits on the possibility of selecting measurement method which is discussed below. In general the locations were very harsh and could be contaminated with dust, oils and other chemicals.

5.2.1 An absorbing environment

Since there have been communication problems in the paper warehouse there was an assumption from the paper mill representative and their communications supplier that the environment would be highly absorbing, at least for certain communication frequency bands. The warehouse constituted a comparatively clean environment where the temperature varied with outdoors temperature, i.e. cold in winter and warm in summer.

5.2.2 A reflecting environment

The bark furnace was located in a building covered with corrugated steel sheets and metal grid floor plates. Internally in the building there was the furnace itself and all supporting installations like feeders, heat pipes etc. All together a multitude of reflecting surfaces meaning that this environment could be expected to be highly reflecting. This was a quite clean location but very warm due to the burning process, with a risk of smoke or dust and humidity.

5.2.3 A mine tunnel

Some reports of radio coverage measurements in mine drifts and other tunnels have been published, e.g. [18, 19]. However, since the examined mines were coal mines, the tunnel walls were all filled with carbon. Measurements in mine tunnels where the walls are of granite have not been found. The behavior was assumed to be as that of concrete lined road tunnels and hallways since the concrete aggregate generally consists of gravel and sand from granite. This would include reflections from ceiling, floor and walls depending of the polarization of the antenna. If the tunnels would be long, no back-wall reflections would enter through the antenna back lobes. Here the temperature is stable around the year at around +15 °C. The biggest problem would be dust from the iron ore which due to its conductivity could affect the antenna performance.

5.3 Concerns regarding the implementation

The planned measurements spanned over many frequency bands that are allocated for specific purposes like mobile telephony, airport control etc. which means that permission was required from the Swedish Post and Telecom Authority, (Post- och telestyrelsen, PTS), see Appendix A. Objectives that must be considered were:

- The environments were either absorbing or reflective and enclosed with corrugated metal walls which indicate there will be little interference seen outside the halls. Deep in a mine negligible power would be expected to leak in or out.
- Which output power level would be allowed by PTS and would that be enough for the measurements? In [4] and [6] the used power level was P_T=25 dBm.
- Which signal-to-noise ratio, SNR, would be required? To keep the measurement uncertainty below ±0.5 dB a minimum SNR of 10 dB would be required according to [22].
- One environment was expected to be highly absorbing – would it cancel the signal?
- Due to possible high attenuation from the environment it might be required to use the built-in pre-amplifier in the receiver and thus improve the receiver sensitivity. However high level interfering signals from the normal environment (e.g. GSM and DECT phones) might overdrive the amplifier, saturating the receiver and hence distort the measurements.
- An obvious problem due to the inherent nature of industrial environments is that there will always be interfering signals present that are not possible to control or switch of, e.g. GSM, 3G, DECT, W-LAN, Bluetooth and other systems operating in the ISM band. In the preparatory work before the measurements are conducted these sources had to be identified to make post-processing processing possible, usually in the form of excluding the identified problem frequencies.

5.4 Implementation

With the comparison of methods and the considerations above in mind the choice of measurement system fell on an asynchronous system with slow sweeping signal generator.
The measurement set-up consists of a signal generator, a spectrum analyzer, and a pair of directive antennas, as shown in Figure 5. Photos of the final system are shown in Figure 6. The signal generator transmitts a sinusoidal continuous wave, CW, stepping the output frequency in 1 MHz steps from 300 MHz to 3000 MHz, see Table 1.

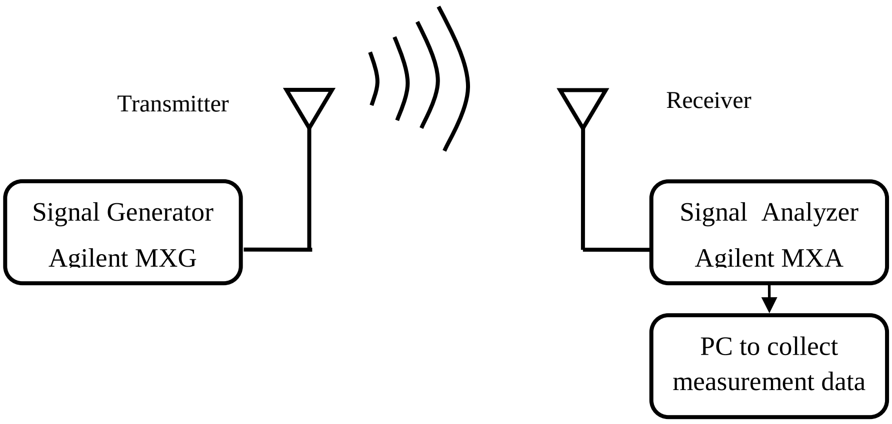


Figure 5. Block diagram over the chosen measurement system.

The steppings of the signal generator and the signal analyzer sweep are not synchronised. The signal analyzer sweeps fast enough to make at least two passes over the current output frequency from the signal generator. The analyzer is set in average detection mode, meaning that the signal for each frequency is represented by the average of the total number of samples in the corresponding bin. To be able to plot the complete spectrum without gaps, Max Hold is used.

Table 1. Instrument settings for the proposed measurement system

Spectrum Analyzer		Signal Generator	
Start frequency	300 MHz	Start frequency	300 MHz
Stop frequency	3 GHz	Stop frequency	3 GHz
No. of points	2701	Frequency sweep	Linear
RBW	300 kHz	Step Size	1 MHz
Sweep Time	~46 ms	Dwell time	100 ms/step
Sweep Mode	Max Hold	High Output Power	Installed
Detector Type	Average		
Pre-amplifier	Active		

During the frequency sweep the signal generator is stepped in 1 MHz steps, dwelling 100 ms per step while the spectrum analyzer spends approximately 46 ms per sweep. The spectrum analyzer is set to use a 300 kHz resolution bandwidth filter (RBW) to be on one hand narrower than the step size while on the other hand not too narrow to affect the sweep time negatively. The output power of the signal generator has to be set according to the permission from the authorities. The reference level of the spectrum analyzer must be adapted to the transmitter power level used and the SNR achieved from a test measurement at the highest frequency range at the farthest intended distance.

Figure 6. The measurement set-up in its final version. The receiver and receiver antennas to the left and transmitter with transmitter antenna to the right.

Depending on antenna bandwidth the measurements may have to be executed in several bands and in the end be stitched together to a single propagation loss vs. frequency plot.

Due to the harsh industrial environment, this unorthodox solution is chosen over the more traditional network analyzer or synchronous detection solutions, which are synchronised by means of fibre optic or coaxial cables or radio links. Having cables rolled out on a factory floor is often not allowed for safety reasons, and is not desirable because environmental parameters such as heat, chemicals, and transportation vehicles may permanently damage them. Since radio performance is the parameter being evaluated, a synchronisation signal over a radio frequency would interfere with the measurements.

5.5 Improving the System

Multipath effects on the measurement results can be averaged out by mounting the receiver antenna on a beam attached to a tripod which then may be rotated to make measurements along the circumference of a circle with the radius r, see Figure 7. In this way a number of samples are made at positions symmetrically distributed around the desired measurement position producing a local mean value. This is a time-consuming procedure since the measurements have to be repeated several times, often as much as eight times or more.

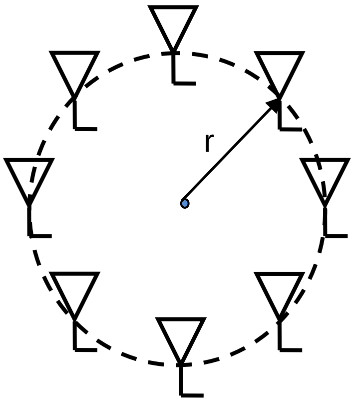


Figure 7. Positioning the receiver antenna along a circle can give statistical improvement.

Diversity could help solving the problem. A simple compromise is to use two-antenna diversity where the signals, from two receiver antennas separated by minimum a quarter of a wavelength to make them uncorrelated, are added and fed into the receiver [1]. Hence a form of local mean value is achieved, see Figure 8.

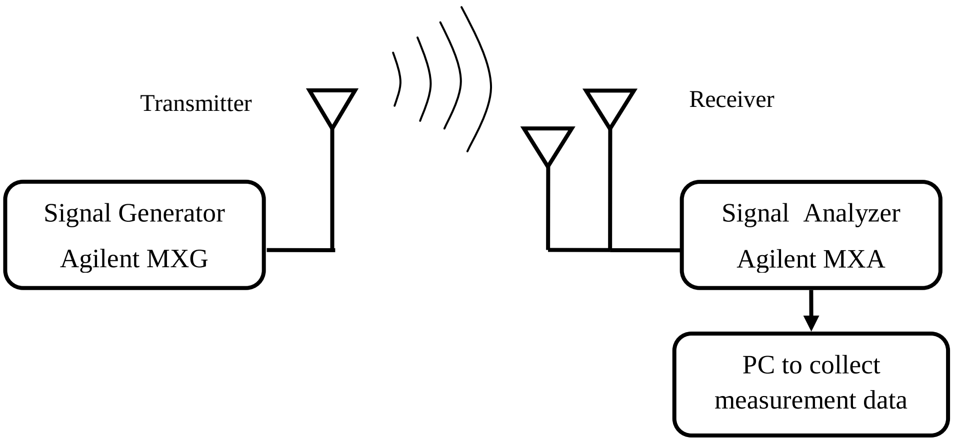


Figure 8. An improved measurement setup with two receiving antennas to reduce fading effects.

Staub and Zürcher [7] suggest bilateral averaging by alternately moving the receiver and transmitter, referring to Honcharenkos work [24]. Bilateral averaging means interchanging the position of the transmitter and receiver to transmit in both directions at each Tx-Rx antenna positioning. In the proposed environments of this work this could be supposed to have little impact on the results in the high reflective and the high absorbing situations. However, it might affect the results in some tunnel measurements since a tunnel may be seen as a kind of large waveguide that opens up and/or bends.

6 Test and Verification

The selected method was tested in a corridor on floor 5 in building 99 at University of Gävle, cf. Figure 6. The test environment was a corridor approximately 40 m long, constructed by plasterboard walls with some doors on the sides. The floor and ceiling was made of concrete with a plastic carpet on the floor and an inner ceiling of sound reduction baffles hung in metal truss work.
The approximate dimensions were: width 2.3 m, height 3.6 m to the concrete ceiling and 2.8 m to the inner ceiling.

Due to a fatal mistake in the instrument settings discovered at a late stage the verification measurements had to be repeated. As the original system with an MXG signal generator equipped with a ‘high power’ output option and an MXG signal analyzer equipped with a built-in pre-amplifier were no longer available, these measurements had to be conducted with an Agilent Technologies CXA signal analyzer and MXG signal generator both lacking the aforementioned options. This led to that the dynamic range of the system decreased by more than 30 dB at frequencies above 2 GHz, which can be seen in the plots in the following paragraph.

6.1 Benchmarking with a VNA

The verification measurement results are shown in Figure 9. The top line shows measurements made by the proposed system while the bottom line shows reference measurements made with a vector network analyzer. It can be observed that the measurements in the top line exhibited less strong amplitude variations than the bottom line measurements. This was expected, since the proposed method was based on the use of the averaging per bin and ‘Max hold’ functions of the spectrum analyzer. The results were supposed to have smaller variations than those of the VNA which cannot perform ‘Max hold’ measurements.

As expected, when studying the left column (the original 1 antenna system), the amplitude variations over frequency could be observed being stronger for the VNA. However, the core of the VNA trace was identical to that of the proposed system from 300 MHz up to 2 GHz.
In the range above 2 GHz the proposed system showed a flat line due to the aforementioned dynamic range problem while the VNA reference measurement displayed frequency variations. As no reasons exist to expect the behavior to differ at frequencies above 2 GHz the conclusion was that the proposed system worked as intended.

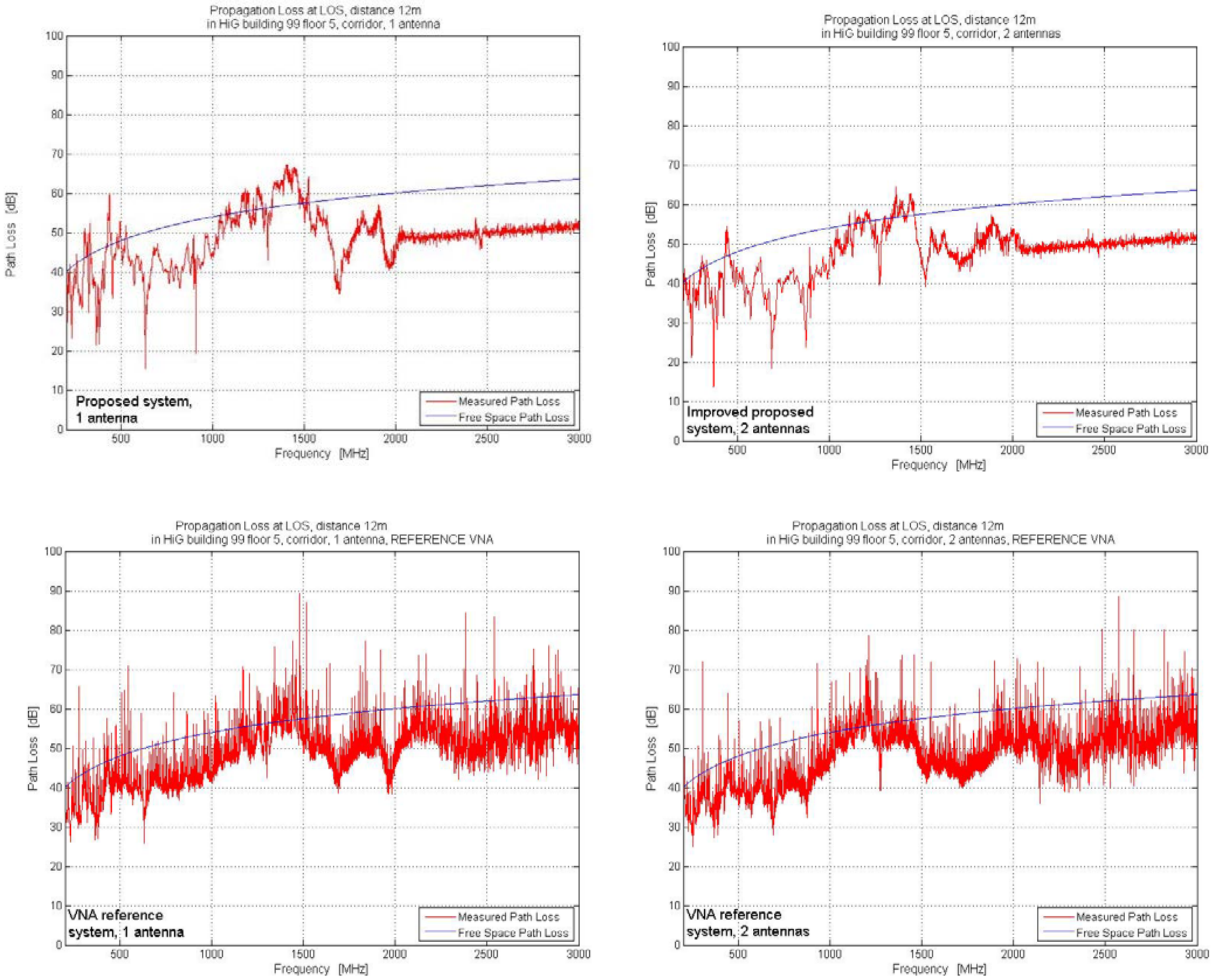


Figure 9. Measurements results from 12 m LoS verification measurements. The upper line of subplots shows measurements with the proposed system while the lower line shows the corresponding measurement with a VNA. The left column shows the original system and the right column the improved system with two receiver antennas.

6.2 Checking the improved system

Since multipath fading dips appears and the results have a spatial dependency the systems was altered by introducing a second antenna, where the two antennas were positioned more than a quarter wavelength apart. The left column in Figure 9 shows the measurements performed with the original measurement system design with one antenna at the receiver side while the results from the two-receiver antenna approach can be seen in the right column. It can be observed in the right side diagrams that the amplitude variations seen in the left side diagrams have been reduced. Fading dips (e.g. between 0.5 and 1 GHz, and between 1.5 and 2 GHz) were reduced and strong signal super-positions (like the peaks just below 0.5 and 1.5 GHz) were reduced, a result which was expected from the discussion in chapter 5.5. It can be concluded that the proposed improvements worked as intended.

7 Investigation of Frequency Dependence of Path Loss in Industrial Environments

The measurement method was applied to the three selected industrial environments and here the results are presented and analyzed. The three sites were quite dissimilar which was also reflected in the results. Permission was been acquired from PTS to transmit in the desired frequency band, see Appendix A.

7.1 Brief description of the sites

7.1.1 Site A – Absorbing Environment

Site A was the aforementioned paper warehouse at Stora Enso paper mill in Kvarnsveden, Borlänge, Sweden. The measurement location was a 85 by 150 meters hall in a building with an average internal height of approximately 8 meters and tarmac coated floors. Paper rolls were stored standing along long aisles, often several rolls stacked on top of each other. The diameter of each paper roll varied between 1.25 and 1.70 m and the height between 1 and 3 m. In one end of the hall the loading dock was located. Figure 10 shows a photograph of the paper rolls (finished products) along an aisle where the measurements were conducted.
For the geometry and dimensions of the rolls, and since the paper itself is a dielectric or isolating material, it was expected that diffraction, scattering and reflections would expressed at extremely low levels [25].
The paper type produced was impregnated with kaolin clay to achieve certain qualities. This gave special dielectric parameters to the paper rolls probably causing highly absorbing characteristics, at least for some frequencies.

Figure 10. Interior view of the paper warehouse at Stora Enso paper mill [26].

7.1.2 Site B – Highly Reflective Environment

Highly reflective environments may cause severe distortion in wireless communications due to multipath propagation of the signals. Multipath distortion, also known as inter-symbol interference (ISI) is a form of RF interference that appear when a radio signal has more than one path between the receiver and the transmitter. This occurs in environments with metallic or other RF-reflective surfaces. The measurements presented here were performed at Stora Enso paper mill in Kvarnsveden, Borlänge, Sweden, in the bark furnace building called Panna 8, see Figure 11. The building was 30 m high, and divided into nine floors constructed from metal grid floor plates. The internal construction consisted of metallic walls and pipes, and had a high density of machinery (as well as other metal objects) [27].

Figure 11. Interior view of the bark furnace (Panna 8) at Stora Enso paper mill [26].

7.1.3 Site C – Mine Tunnel Environment

The third site was a mine tunnel environment in the LKAB Kiirunavaara iron mine located near central Kiruna, Sweden. The measurements were conducted at Level 1045, 1045 meters under the top of the mountain. [28].

Mines offer a special environment with certain characteristics for radio wave propagation. In modern underground mines wireless communication has become a necessity for real-time operation of remote trains, and monitoring of mining equipment. Furthermore radio communication systems have been deployed for inter-personal communications, alert systems for manned areas such as service areas, restaurants and locker rooms for underground personnel etc. However, wireless systems could face problems when trying to get a good reception along the tunnel infrastructure for example due to clogging of the distributed slotted-line antennas.

The intention with the conducted measurements was to see if frequency bands exist that are more suitable than others, or bands that definitely should be avoided due to the propagation properties of the mine tunnels.

The measurements were carried out in two tunnels of different dimensions, at the underground level 1045 meters from the top of the mountain, as shown in Figure 12. The first tunnel which was quite narrow contained a siding track used for filling the mining trains with iron ore. The second, wider tunnel to which the first tunnel joined to was the main track for several sidings, heading to an area where the ore was collected for transportation to the surface.

Figure 12. The measurement locations, a wide (left) and narrow tunnel (right) at an underground level of 1045 meters in Kiirunavaara iron mine [26].

7.2 Measurement results

7.2.1 Results from Site A

Measurements of propagation loss were conducted in the range 300 MHz to 3 GHz. The measurements were done with a signal generator sweeping slowly across the band and a spectrum analyzer making fast sweeps uncorrelated to the signal generator sweep in peak detector mode according to the specifications in chapter 5.4 [26].

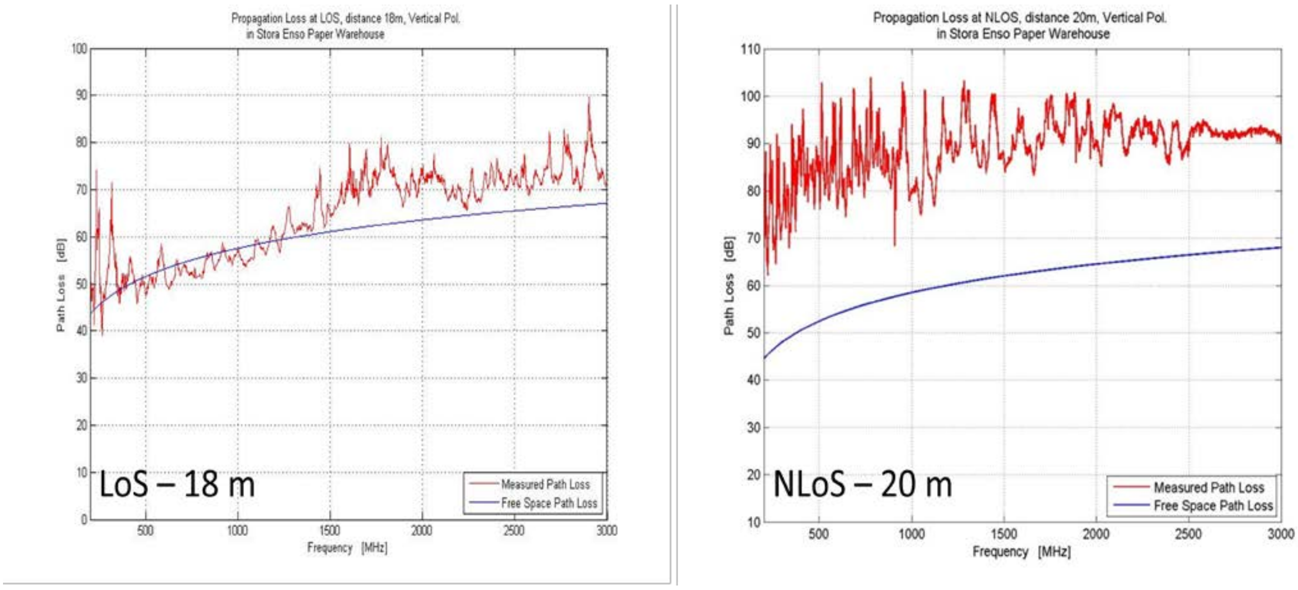


Figure 13. Propagation Loss in the paper warehouse, LOS (left) and NLOS (right).

In Figure 13results are presented from measurements with 18 – 20 m distance at line-of-sight and non line-of-sight respectively. When performing non-line-of-sight measurements the receiving antenna was placed behind a wall of paper rolls stacked on top of each other. Along the aisles, for frequencies below 1.5 GHz the propagation behaved like one would expect in free space or in an anechoic chamber. The attenuation increased by the square of the increase in distance. Above 1.5 GHz the signal was attenuated 5 – 10 dB more than FSPL. No multipath effects could be detected which makes MIMO (Multiple Input Multiple Output) systems that rely on multipath propagation practically without improving effect since only a single path existed.

When measuring non-line-of-sight the attenuation increased radically. Measurements were made with vertically or horizontally polarized antennas, v-v or h-h to see if there was any difference between the polarization modes. Quite strong polarization effects could be noted compared to other halls with large volume. The difference between vertically and horizontally polarized propagation was found to be in the range of 20 dB and sometimes more, see Figure 14, where the horizontally polarized signal was more attenuated.

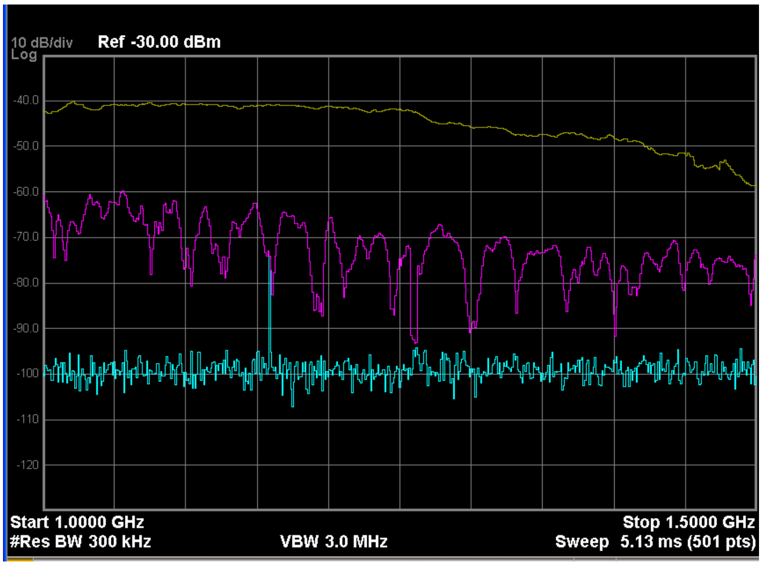


Figure 14. Vertically polarized vs. horizontally polarized antenna measurements. The top trace shows a recorded power measurement with vertically polarized antenna and the center trace with horizontally polarized antenna. The lower trace is the live measurement.

Figure 15 shows the difference in attenuation (in dB) between LOS and NLOS vs. frequency in the frequency range of 300 MHz–3 GHz. This comparison showed a frequency dependent attenuation due to absorption properties of paper. The high attenuation at 2450 MHz frequency band, a band that is used in this hall, may cause communication problems. Here the existence of non-reflective and very high absorption industrial environments has been shown, where wireless communication is impossible at certain frequencies. From Figure 15 the conclusion could be made that large improvements in communication performance can be achieved by a proper choice of communication frequencies.

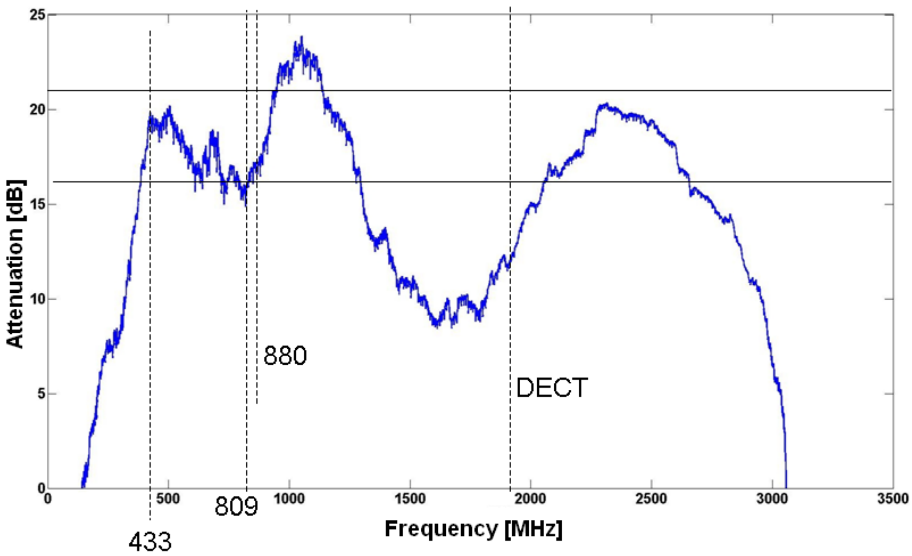


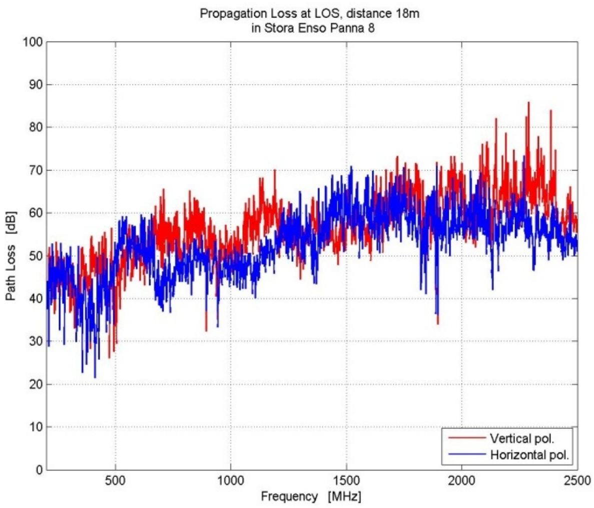
Figure 15. Difference in attenuation when comparing LOS and NLOS due to the presence of paper rolls [25].

7.2.2 Results from Site B

Measurements of propagation loss have been conducted in the range 300 MHz to 2.5 GHz. The stop frequency 2.5 GHz was used because of limitations in the antenna system used. The measurements were done with a signal generator sweeping slowly across the band and a spectrum analyzer making fast sweeps uncorrelated to the signal generator sweep in peak detector mode according to the specifications in chapter 5.4 [26].

Measurements were made with vertically or horizontally polarized antennas, v-v or h-h to see if there was any difference between the polarization modes. When performing non-line-of-sight measurements the receiving antenna was placed behind a large metal construction or around the corner of an intersecting corridor.

From the large variations in attenuation between adjacent frequencies in Figure 16 it can be clearly seen that this compact reflecting environment tended to give really large fading variations due to the presumably higher number of multipath components which were added together in different phase and gave strong variation effects.



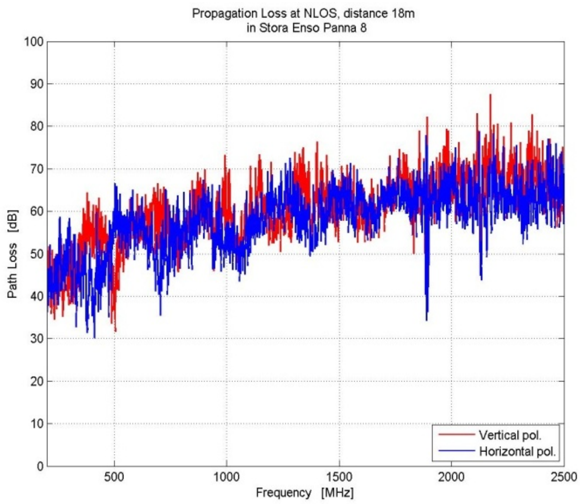


Figure 16. Propagation Loss in the bark furnace, Panna 8, LOS (left) and NLOS (right) [26].

The high amount of reflections made the radio propagation quite special, since the reflecting surfaces were of various angles and texture; polarization was more or less eliminated. It was noticed when changing antenna polarization that it was often the case that a vertical transmission was better received with a horizontal antenna or vice versa instead of the expected optimum v-v or h-h.
The reflected signals arrived from all angles meaning that the difference between line-of-sight (LOS) and non-line-of-sight (NLOS) could be disregarded from a propagation loss point of view.

7.2.3 Results from Site C

In this case the measurement setup was improved by adding space diversity at the receiver by combining two received signals, cf. Figure 8. Figure 17 and Figure 18 show examples of measurement results for different cases, LoS and NLoS at different distances. In these plots the path loss (dB) vs. frequency is shown.
As can be seen in Figure 17 for straight tunnels, i.e. LoS conditions, the narrow tunnel followed slightly below FSPL almost perfectly while the wider main tunnel revealed some clear attenuation dips at a frequency band just above 1 GHz and one above 2 GHz. In Figure 18 the narrow tunnel was studied in NLoS conditions when the signal had to pass along a sharp bend. Here the dips, where the attenuation was lower, became more pronounced with increasing distance between transmitter and receiver.

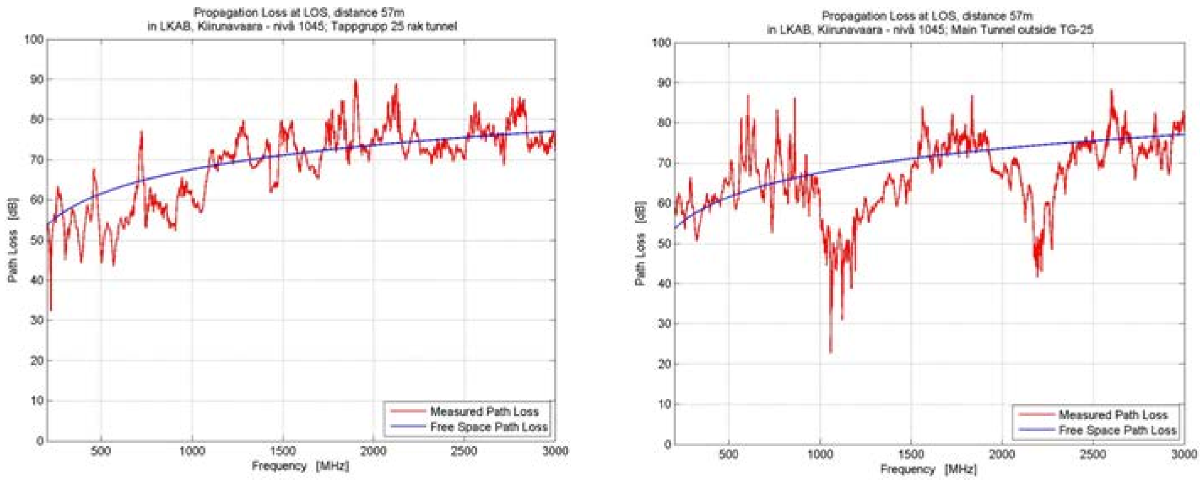


Figure 17. Narrow tunnel (left) and wide tunnel (right), LoS case and 57 m distance [26].

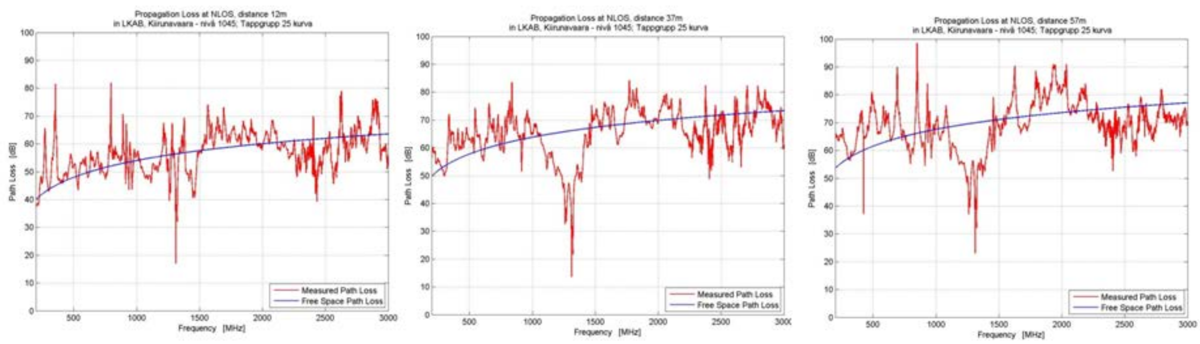


Figure 18. NLoS at narrow tunnel for three distances 12 m (left), 37 m (center) and 57 m (right) [26].

The frequency location of the dips was analyzed by a simple two-beam propagation model. For values of antenna distances, *d*, not beyond line of sight, a simple two-beam model could be used to model the wave propagation between disturbance source and radio receiver, see Figure 19 [29].

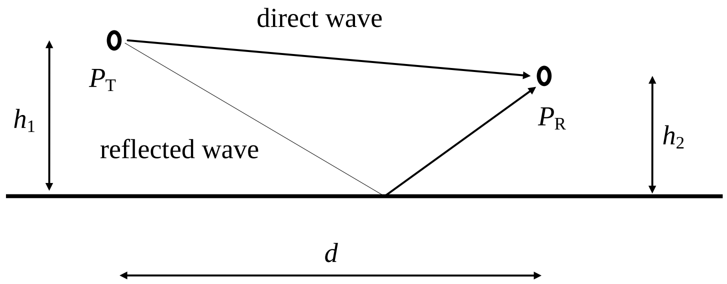


Figure 19. Geometry for a two-beam plane earth model of the wave propagation [29].

It has been shown that the received power P_R in the receiving antenna in Figure 19 can be calculated as [30]:

$$P_R \approx \frac{P_T A_R}{\pi d^2} \left[\sin\left(\frac{2\pi h_1 h_2}{\lambda d} \right) \right]^2 \tag{17}$$

where A_R is the effective cross section of the receiving antenna and P_T is the transmitted power. The transmitter and receiver antenna heights are depicted by h_1 and h_2 respectively. From (17), the received power P_R will be theoretically zero for

$$h_1 h_2 = (2n+1)\lambda d \tag{18}$$

where n=0, 1, 2, 3……

Even though (17) was designed for outdoor propagation over an infinite ground-plane, the two-ray propagation model still could help explaining the measured dips in propagation loss in the mine tunnels. The propagation loss deviations in frequency could be explained as an effect of this two-ray propagation model by using (18). These results show that large performance improvements would be achieved by selecting a suitable frequency and location of the access points in the wireless communication. For this, ray-trace simulation tools can be used to predict the channel characteristics [29], but to perform measurements is the unique way to optimize the performance of the wireless system in a particular environment.

8 Analysis and Future Work

Few (if any) studies have this far been conducted of the frequency dependence of the indoor radio channel path loss in industrial environments.
For this purpose a dedicated measurement system has been developed for measuring the frequency dependence of path loss in industrial environments. Due to the harsh industrial environments an asynchronous method was preferred over other more conventional solutions. The freedom of cables on the floor was one of the main reasons. The log-normal path loss assumption made it possible to use any set of antennas since the frequency dependence of the antennas as well as cables and instruments were cancelled out.

8.1 Conclusions

The method was proven functional but slower than synchronized measurement systems. The system has been verified in indoor measurements at University of Gävle and found to be working satisfactory. An improvement has been introduced; using two-antenna diversity minimized the fading variations in the results. Still relatively large variations originating from the fading nature in the environments discussed could be seen in the results.

Thorough frequency analysis has been conducted in advance at each measurement site to not interfere with critical systems. Special Permissions for Radio Transmission for experimental purposes has been acquired from the Swedish Post and Telecom Authority (Post- och telestyrelsen, PTS).

Three disparate but still characteristic industrial environments have been subject to this investigation, one highly absorbing, one highly reflective and one mine tunnel environment.
The first environment was a finished-product warehouse hall for paper. The rolls were huge, ~1.5 m in diameter and 1– 3 m high. It has been shown that there is a strong frequency dependency in the propagation loss between the paper rolls. This frequency dependency was probably related to the content of kaolin clay in the paper. The strong absorption of the radio signal at some frequencies made only line-of-sight communication possible, i.e. systems like MIMO taking multipath propagation into account were basically working as single input – single output (SISO) systems since they did not have multiple signal paths available.
The second environment was inside a bark furnace building that was 30 m high and divided into nine floors by metal grid floor plates. The walls were of corrugated steel sheets. The interior was composed by pipes, motors, conveyors, burners and other metallic objects. This manifested itself in an

environment where the fading variations were extremely large and the polarization of antennas was more or less eliminated.

The third environment was a mine. Measurements were made 1045 m below the mountain top in two tunnels, one narrow side-track for retrieving iron ore and one wide main track where several side-tracks join together. The path loss exponent presented lower values than the theoretical free-space loss. Moreover, sharp dips were observed in different frequency ranges. Thus, the operating frequency of wireless systems could have a large impact in the performance in complex environments such as tunnels. Consequently it could be recommended to be careful when choosing the frequency and access point locations before deploying a new wireless infrastructure in a tunnel environment. The 2-ray model could explain some attenuation dips. For this, ray-trace simulation tools could be used to predict the channel characteristics, however to really know a particular environment measurements are the unique way to optimize the performance of the wireless system.

As a general conclusion it can be stated that industrial environments are far from being a homogenous group of highly reflective environments implying that installations of commercial-of-the-shelf equipment (COTS), e.g. WLAN and Bluetooth, in industrial environments should not be done without a previous assessment of the electromagnetic properties of the environment.

8.2 Future Work

The common way in single frequency measurements is to acquire a large number of samples and calculate the mean and the spatial variation of the fading. For a large frequency span as discussed here it will be more complex but not impossible, it just takes more time.

An extensive measurement campaign would be required to reveal/define the statistical parameters in the path loss model(s) for the different sites.

The dependence of antenna locations as discussed in chapter 5.5 is a topic worth investigating.

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Appendix A

Permission for Radio Transmission for Experimental Purposes from the Swedish Post and Telecom Authority, PTS.

PTS

Tillstånd
att använda radiosändare

Sida 1(1)

Enheten för landmobil radio
Handläggare,telefon
Tomas Jelder, 08-678 5742

Diarienummer
10-2534

Utskriftsdatum
2010-05-07
Tillståndshavare
HÖGSKOLAN I GÄVLE
CENTRUM FÖR RF MÄTTEKNIK
801 76 GÄVLE

Er referens
PER ÄNGSKOG

Tillståndsnummer	Tillståndets giltighetstid (fr.o.m. - t.o.m.)	Tillståndshavarens Organisations-/Personnummer
566180	**2010-05-07 -- 2010-12-31**	**202100-2890**

Post- och telestyrelsen beslutar om tilldelning av radiofrekvenser, villkor och tillståndstid enligt 3 kap. 6, 9, 11 och 12 §§ lagen (2003:389) om elektronisk kommunikation (LEK).

Om tillstånd med samma tillståndsnummer utfärdats tidigare, upphör det äldre tillståndet att gälla. I övrigt gäller vad som följer av LEK och Post- och telestyrelsens föreskrifter.

Tillståndsvillkor
Tillståndet gäller för mätning av radiovågutbredning i industrilokaler.

Tillståndet gäller för fyra mättillfällen inomhus per år med max tio mätserier per mättillfälle.

Villkor vid olika mätmetoder enligt ansökan:

1. Utbredningdämpning
Följande frekvensområde får användas: 20 MHz - 3 GHz.
Sveptid: 30 s per band.
Sändningstid: Max 2 minuter per mätserie.
Max uteffekt: -30 dBm.

2. Flervägsutbredning
Följande frekvensområde får användas: 183-683 MHz, 1640-2140 MHz, 2200-2700 MHz och 4838-5338 MHz.
Max sveptid per frekvens: 0,5 ms.
Max uteffekt: 15 dBm.

Tomas Jelder

Kommunikationsmyndigheten PTS – Post- och telestyrelsen

Postadress:
Box 5398
SE-102 49 STOCKHOLM

Besöksadress:
Valhallavägen 117
www.pts.se

Telefon: 08-678 55 00
Telefax: 08-678 55 05
pts@pts.se

PTS

Tillstånd
att använda radiosändare

Sida 1(1)

Enheten för landmobil radio
Handläggare,telefon
Tomas Jelder, 08-678 5742

Diarienummer
10-9363

Utskriftsdatum
2010-12-17
Tillståndshavare
HÖGSKOLAN I GÄVLE
CENTRUM FÖR RF MÄTTEKNIK
801 76 GÄVLE

Er referens
PER ÄNGSKOG

Tillståndsnummer	Tillståndets giltighetstid (fr.o.m. - t.o.m.)	Tillståndshavarens Organisations-/Personnummer
568739	**2010-12-31 – 2011-06-30**	**202100-2890**

Post- och telestyrelsen beslutar om tilldelning av radiofrekvenser, villkor och tillståndstid enligt 3 kap. 6, 9, 11, 12 och 12a §§ lagen (2003:389) om elektronisk kommunikation (LEK).

Om tillstånd med samma tillståndsnummer utfärdats tidigare, upphör det äldre tillståndet att gälla. I övrigt gäller vad som följer av LEK och Post- och telestyrelsens föreskrifter.

Tillståndsvillkor
Tillståndet gäller för mätning av radiovågsutbredning i industrilokaler och gruva på följande platser:
-Stora Enso Kvarnsvedens pappersbruk, Borlänge.
-SSAB Tunnplåt AB, Borlänge.
-LKAB, Kiruna. Enbart mätning under jord.

Tillståndet gäller för fyra mättillfällen per år med max tio mätserier per mättillfälle.

Villkor vid olika mätmetoder enligt ansökan:

1. Utbredningdämpning
Följande frekvensområde får användas: 20 MHz - 3 GHz.
Sveptid: Max 50 s per band.
Sändningstid: Max 5 minuter per mätserie.
Max uteffekt: 0 dBm. Lägsta möjliga uteffekt ska tillämpas.

2. Flervägsutbredning
Följande frekvensområde får användas: 183-683 MHz, 1640-2140 MHz, 2200-2700 MHz och 4838-5338 MHz.
Max sveptid per frekvens: 0,5 ms.
Max uteffekt: 15 dBm.

Tomas Jelder

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