WIDEBAND RADIO CHANNEL MEASUREMENT IN A MINE

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ABSTRACT: The aim of this paper is to present propagation characterization based on wideband radio channel measurements made in a mine at center frequency of 1 GHz. The main attention is focused to path loss and delay profile analysis. The path loss has been found to be 40 dB/dec in a straigth cave and 80 dB/dec in curved cave. Delay spread was less than 0.5 µs. Radio channel in mine proved to be non-reciprocal.

INTRODUCTION

The results presented in this paper are based on radio channel measurements made in the Outokumpu Mining Oy Pyhäsalmi mine in Finland. The products of the mine are zinc, copper and sulfide. The radio channel measurement system is based on a spread spectrum measurement signal. The receiver (RX) utilises a sliding correlation technique. In the field measurements, the radio wave propagation characterization was determined inside a mine. Main parameters were propagation loss and number of propagation paths and delay spreads in different tunnel structures.

Doppler domain studies were not carried out in this research.

INTRODUCTION OF THE MEASUREMENT SYSTEM

The radio channel measurement system was installed in two vehicles. The antennas used were rooftop ¼ λ–NMT-900[i] antennas. The transmitted power at the antenna was 5 W (≘37 dBm).

The measurements were made on the center frequency of 1 GHz. The measurement signal was a BPSK-modulated maximum length code with code length of 127. The chip rate was fixed to 15 MHz that yields 30 MHz signal main lobe bandwidth. The time scaling factor of sliding correlation receiver was 1000. These parameters limit the maximum detectable delay to 8.5 µs and the Doppler shift to 59 Hz. The delay of 8.5 µs corresponds the path length difference of 2.55 km. The delay resolution of the measurement system was 83 ns (≘25 m) [1]. System parameters are presented in table 1.

Table 1. System parameters.

Carrier frequency [MHz]	1000
Transmitted power [W]	5
Spreading code	m-sequence
Code length	127
Chip rate [MHz]	15
Time scaling factor	1000
Bandwidth [MHz]	30
Delay resolution [ns]	83
Minimum delay [ns]	83
Minimum delay [m]	25
Maximum delay [us]	8,5
Maximum delay [km]	2,55

The principle and performance of the system is described in [1].

The measurement was controlled by a laptop PC that contained also a hard disk to where the radio channel estimate samples of the correlator output (impulse response estimates) were saved. At the frond-end of the receiver were also the automatic gain control (AGC) attenuator to keep the input signal level constant before the A/D conversion. The corresponding AGC values were saved with the samples of correlator output. The AGC value were changed (if necessary) every 8 impulse responses.

Before the analyzing procedure the saved sample values had to be converted to different format and the AGC values had to be separated from the impulse response estimate samples.

The radio channel can be assumed to be static due to immobile vehicles during the measurements.

RADIO CHANNEL MEASUREMENTS

The radio channel was measured in different tunnel structures. The basic idea was that the RX vehicle was parked near the electricity network and 220 V_{AC} was

[i] NMT=Nordic Mobile Telephone

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used to feed the receiver. The transmitter (TX) was movable and the system power was applied by battery.

During storage of the impulse response estimates the vehicles were stationary. The TX vehicle was driven through the tunnels and the measurements were repeated several times. For better statistical behaviour the TX was moved a few meters 4-5 times for each measurement locations under the delay resolution (25 m). The method of measurements can be seen in Figure 1.

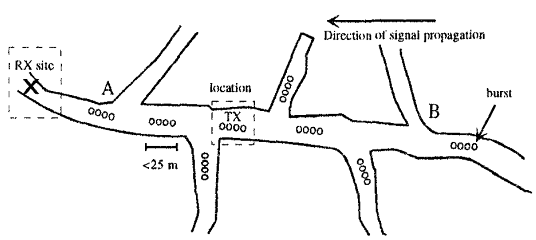

Figure 1. The measurement method in the cave.

The dots in Figure 1 present the measured bursts during the radio channel measurements in one RX site (X in the Figure 1). During the measurement day seven different RX sites were measured. The levels were 210 m, 270 m and 400 m below the earth surface.

During the measurements, different tunnel structures were studied. Tunnels were straight, curved, there were junctions, tunnels were parallel etc. All places where the recordings were made, were marked on a map for the post-processing procedure. At the analysis phase the distance between RX and TX were calculated from the maps. Path lengths were limited below 250 m.

The TX vehicle was driven through the tunnels until the signal level reached a level where the signal did not differ from noise at the receiver.

STORED DATA

The radio channel measurement was made by storing a burst of 1024 consecutive radio channel impulse responses. Each burst is marked using ring in Figure 1. During the measurement day, 158 bursts were saved. High humidity of the mine gave trouble to the measurement system occasionally. 133 of 158 recorded bursts were usable for the final analysis.

In the analysis phase, 51 bursts had to be rejected due to inadequate received power level. The final number of usable bursts was 82 which is 62 % of all saved bursts. That gives 83968 usable measured impulse responses for the final analysis.

ANALYSED PARAMETERS

At the Telecommunication Laboratory an analysis software, HANA1, for the whole analysis procedure has been developed [2]. The application has been built on Matlab™ and it works both in interactive and in automatic modes.

From the measured data some channel characterization parameters were calculated for each burst. Those parameters were

- Total received power [dBm], P_r
- Power level difference between two strongest paths [dB], P_l
- Number of propagation paths, N_{path}
- Total delay spread [μs], L_{tot}
- Probability of path occupancy, P_{PO}

Because of the stationarity of the environment during the measurements the Doppler domain parameters were not analysed.

PARAMETER DESCRIPTION

In the analysis procedure, 5 consecutive samples of the impulse responses were combined to one sample that corresponds the delay resolution of the measurement system (83 ns). Combined samples are called a *bin*. The power of each bin is the same as the total power of the five samples belonging to the corresponding bin. Power calculation is carried out by applying trapezoidal rule to squared voltage samples [3]. Using binned data the maximum values of resolvable propagation paths can be found by dividing the length of one impulse response by delay resolution (8.46 μs/ 83 ns ≈ 101.9). The last bin that does not include five samples can be rejected.

Delay power spectrum: Delay power spectrum was calculated as an average over the burst using squared voltage sample values of impulse responses. Sampled estimate of impulse response can be presented by

$$h(t) = \sum_{k=1}^{508} a_k \delta(t - \tau_k) \,,^{\text{ii}} \qquad (1)$$

where a_k is the amplitude of sample k, τ_k is the delay of sample k and δ is Dirac's delta function. Delay is the excess delay compared to the shortest path. The power of binned impulse responses was calculated over all bins.

The total power of one burst can be calculated using equation

[ii] 508=4 (samples/ chip)*127 (code length in chips)

$$P_r(t) = \sum_{j=1}^{101} \left(\frac{1}{1024} \sum_{i=1}^{1024} b_{ij} \right) \delta(t - \tau_j) \qquad (2)$$

where i is the index of the different impulse responses, j is the index of different delay bins in one impulse response and b_{ij} is the power value of a bin in delay j in impulse response i.

Delay power spectrum presents the distribution of the received power into different delays. The area of the average delay spread spectrum is relative to the total power received in the corresponding burst.

The bin power value is not an absolute power but a relative power compared to the strongest bin power in an impulse response.

Delay spread, L_{tot}: Delay spread was defined to be the difference between the rising edge of the first bin and the tailing edge of the last resolvable bin in the delay power spectrum.

Number of propagation paths; N_{path} : Delay spread spectrum was also used to determine the number of propagation paths. The cutting level (noise floor) of the delay spread spectrum was chosen to be 25 dB below the strongest path. If the bin power was above the noise floor it was interpreted as a resolvable propagation path.

P_l: The difference between the relative power of two strongest paths was determined using the delay power spectrum (see Figure 2).

Probability of path occupancy, P_{PO}: Also the probability of path occupancy was calculated from the delay power spectra of every burst. P_{PO} determines the percentage of how many times signal power is above the noise floor in different delays in a burst. P_{PO} is independent of signal power of the bin.

These parameters will be become familiar with Figure 2. The delay between y-axis and the first bin presents the propagation delay with is not of interest in this study.

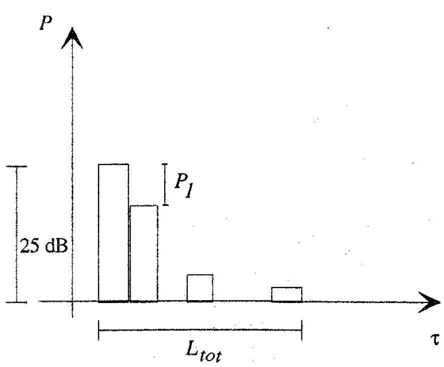

Figure 2. Parameter description.

RESULTS

First the propagation loss is studied. Power level is calculated for every single burst and the path length is measured using the map data. In Figure 3, linear regression lines are presented. Curve fitting is done for data that has been measured in the line-of-sight (LOS) or obstructed LOS (OLOS) paths. In one measured locations all 4-5 measured bursts within the delay resolution were averaged (see Figure 1) to one power sample (Figure 3).

In RX site 210A (Figure 3), the cave was straight and few junctions were between the RX location and the maximum distance point of TX. Path length is about 240 m.

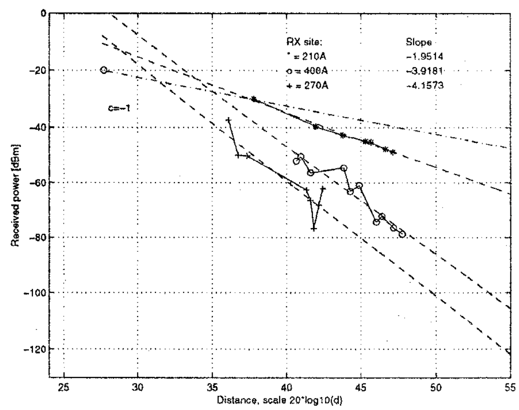

Figure 3. Received power in a function of distance.

The RX site 400A lies in a junction were two almost straight caves open. 100 m from the RX location the cave began to curve at an angle of 13°. Signal can be detected as far as 250 m.

In the RX site 270A, the cave made a curve 70 m away from the RX at an angle of 30°. There were two junctions in the signal path. The signal can be detected only to a 150 m distance.

The received power estimate is approximated with a linear regression line

$$P_r = c\ 20\log(d) + A \text{ dB} \qquad (3)$$

where P_r is the received power, d is distance, A is system loss and c is constant.

When the constant c is −1, the path loss follows a free space law (20 dB/dec or 12 dB/oct). As can be seen in Figure 3, the lowest path loss was found in the straight cave, as was assumed. The constant c equals to −2, which respects the signal attenuation of 40 dB/dec (≙24 dB/oct). In other situations the attenuation was about 80 dB/dec (≙ 48 dB/oct). Free space line is also presented as a reference line.

The regression lines predict that the attenuation is less than in free space in very short distances (d<70 m). A wave guide propagation can explain the phenomenon. However the measurements were too limited to solve the exact reason for that.

We assume that if there were measuring points closer than 70 m a knee point can be found in the regression lines. For distances shorter than the knee point, the $|c|$ would be smaller than after the knee point.

The measurements proved that radio signal attenuates more if the crossing cave junctions were opened in the same direction as the signal propagates (junction B in Figure 1). This particular part of the cave was measured on both sides of the junction. The attenuation was 6 dB higher if the cave was opened in the direction of the signal propagation than in the opposite direction (junction A in Figure 1). The measurements indicate that radio channel in the mine environment is not resiprocal.

The observed variation of the power level in the curved caves can be explained with unresolvable multipath propagation (Δd<25 m). There were more near scattering points in the curved cave than in the straight cave.

In Figure 4, an example of measured delay power spectrum can be seen. It can also be seen that the reflections with long delays were attenuated more than 25 dB compared to the strongest path. Resolvable propagation paths can be seen as column bars with width of 83 ns.

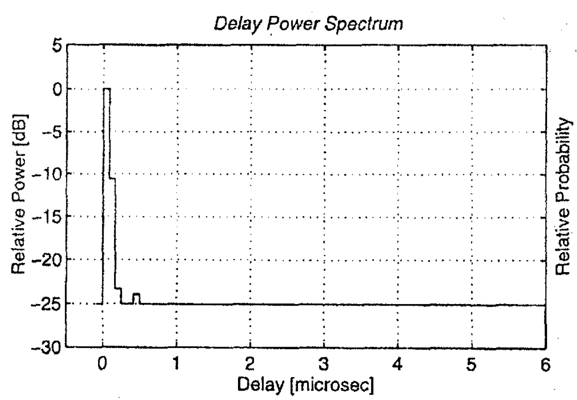

Figure 4. Measured delay spread spectrum.

The number of propagation paths on the average was 2 or 3.

In Figure 5, the distribution of the number of propagation paths over the all stored data can be seen.

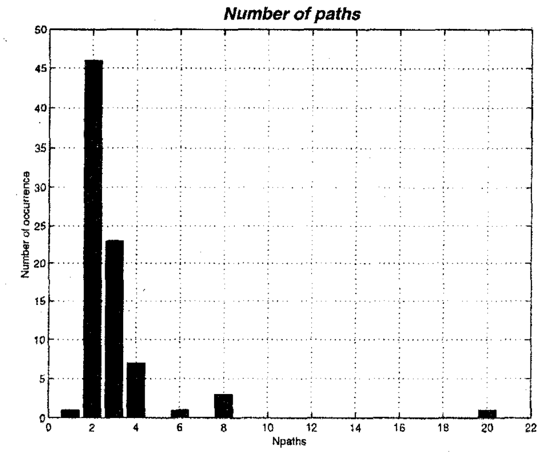

Figure 5. Number of propagation paths.

Typically P_{PO} for the paths 1-3 was 1. This indicates that for these delays the power always exceeded the noise floor. Typically, the distribution P_{PO} was less than 0.2 for paths whose delay was greater than 0.3 μs. Figure 6 shows the estimated P_{PO} for the delay spread spectrum shown in Figure 4.

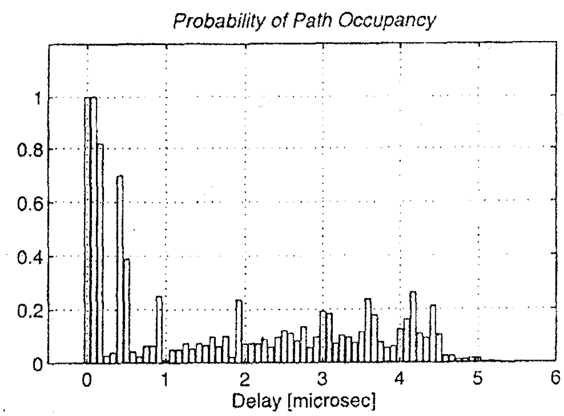

Figure 6. Probability of path occupancy for the delay spread spectrum shown in Figure 4.

It can be seen in Figure 7 that the average delay spread was 0.17 μs. Delay spread has been calculated using delay resolution (bin) grid. The results were calculated over the all measured data.

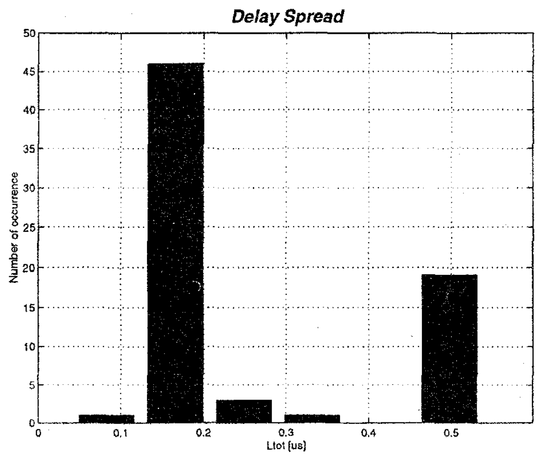

Figure 7. Total delay spread.

The power difference between the two strongest propagation paths, P_1, is presented in Figure 8. It can be seen that P_1<10 dB in 20 % of cases and <5 dB in only 5 % of the cases. In half of the cases the power lever difference between the two strongest paths was < 16 dB. In all cases the shortest path was stronger than other paths.

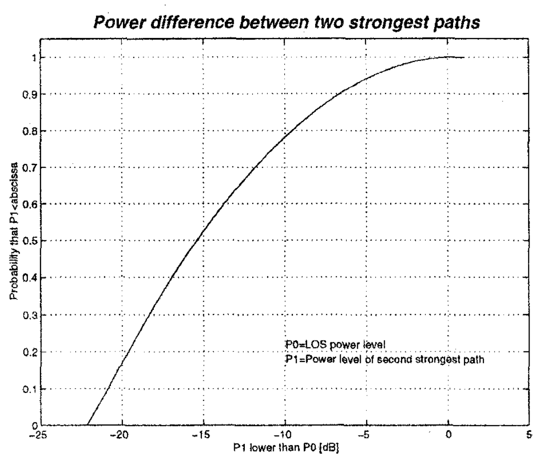

Figure 8. Cumulative distribution function of power difference between two strongest paths.

CONCLUSION

The results of the wideband radio channel measurement in the mine show that the radio signal attenuates 40 dB/dec in a straight cave and 80 dB/dec in a curved cave. The radio channel is not resiprocal if the tunnel contains crossing caves. The attenuation depends on the opening direction of the crossing caves, and the difference can be as much as 6 dB.

Most of the time 2 or 3 propagation paths can be found. If the chip rate of the measurement system had been higher more propagation paths would have been resolved due the improved delay resolution.

Total delay spread was typically less than 0.5 μs and the power difference between the two strongest path was <10 dB only in 13% of cases. The shortest path was always the strongest path.

ACKNOWLEDGEMENT

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