Wideband Propagation Characteristics at 312 MHz in Eastern Norway and Impact on Waveform Requirements

Vivianne Jodalen, Jeffrey Pugh, Phil Vigneron

Abstract—**A wideband Pseudo-Noise channel sounder built by CRC in Canada has been used to measure the wideband channel characteristics in three different types of terrain in Eastern Norway. The channel characteristics at 312 MHz are described in terms of path loss, RMS delay spread and maximum delay interval. The multipath delays were found to be quite long containing considerable power, particularly in the mountain valley. The long delays require extensive equalization of a single carrier wideband waveform, and for a typical high data rate 5 MHz waveform at UHF, the required equalizer depth was found to be more than 100 symbol periods.**

Index Terms — **channel measurements, channel equalization, multipath propagation, radio propagation, UHF, VHF, wideband characterization, wideband waveform**

I. Introduction

Wideband radios providing 1 Mbit/s or more are needed and will be procured by the Norwegian land forces in the near future. Traditional Combat Net Radios providing voice and data services up to a few kbit/s are no longer satisfying all communication needs when new sensors are introduced in the field, producing for instance video.

Military specified wideband tactical radio operating in the lower UHF band 225-400 MHz is probably the strongest candidate to satisfy the new requirements. There is no ratified NATO standard on wideband communications yet, but there are a few international programs that aim to develop multinational standards for wideband military communications.

A number of proprietary wideband waveforms residing on different military hardware platforms have been developed by different vendors, and some of them have been tested in Norwegian terrain.

In order to satisfy the increasing demand for higher data rates, all layers of the waveform protocol stack must be optimized. This applies in particular to the physical layer that needs to trade robustness against bit errors for high data rates and low delays. Good knowledge of the wideband properties of the radio channel is required to design an efficient physical layer. This paper addresses the wideband properties of radio channels measured in terrain where Norwegian land forces are typically operating.

Narrowband measurements and the development of path loss models for various frequency bands have taken place over many decades. Many wideband measurements characterizing the channel in terms of multipath delay spread and fading characteristics have also been published for the mobile telephony frequencies 900 and 1700 MHz, for instance [1]. However, there is not much published data for the military VHF (30-88 MHz) and lower UHF (225-400 MHz) bands [2], [3].

The Communication Research Centre (CRC) in Ottawa has developed a wideband sounder that operates on six frequencies in the VHF and lower UHF band. Measurements have earlier been conducted in Ottawa and Halifax and the data used as input in the standardization of a narrowband waveform (NBWF) in NATO. In January 2014 the sounder was moved to Norway to conduct new measurements in other types of terrain and to collect important channel information for the Norwegian Defence.

The data collected and analyzed in this study can give guidelines for the design of the physical layer in wideband waveforms and for the requirements to multipath performance that need to be set in future radio procurements by the Norwegian Defence.

II. Measurement system and data analysis

A. The channel sounder

The multiband channel sounder developed by CRC consists of a transmitter (Tx) installed in a trailer and a receiver (Rx) which resides in a van. During the measurements the trailer is positioned statically at an appropriate Tx site, and the mobile van receives and processes the channel probes as it drives around in the surroundings. Ordinarily, propagation measurement data is recorded in six VHF frequency bands in a quasi-simultaneous manner. However, for the current study the system was operated at fixed radio frequency of 312.0 MHz.

A pseudo-noise (PN) probing sequence of length 511 bits is transmitted and at the receiver sampled and cross-correlated with a replica of itself in order to produce a complex channel

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impulse response (CIR). The chip rate of the PN sequence is 5 Mb/s with a corresponding signal bandwidth of 10 MHz null-to-null. The resulting time resolution of the measured CIR is approximately 0.3 µs, and the maximum resolvable multipath delay is 102.2 µs. Channel snapshots were collected by the Rx at a rate of 100 per second, which corresponds to about 6 CIRs per wavelength of travel at typical land vehicle speeds. Each snapshot is the coherent average of 4 consecutive sequences in order to increase the receiver sensitivity.

In nearly all of the measurement scenarios to be reported, both the Tx and Rx antennas were situated at low heights (< 2 m above ground) common of tactical mobile communications. The only exception was the Bødalen region where the Tx antenna was masted at a height of 8 m. Military dipole antennas with omnidirectional radiation patterns were used in all scenarios. A transmit power of 41 dBm yielded good coverage of the surveyed environments for Tx-Rx ranges of up to 10 km typically.

The location of the Rx van was monitored and recorded once per second with a GPS unit. Later, the GPS data was used in conjunction with terrain elevation maps of the environments to check for line-of-sight (LoS) conditions between the Tx and Rx terminals. Small scale position information was obtained through the use of a high resolution rotary encoder attached to the vehicle wheel.

B. Data processing and analysis

To be able to accurately estimate average received power (or path loss) on mobile radio channels, spatial averaging can be applied over short segments of the channel impulse response series over which the channel can be assumed to be stationary. The channel snapshots to be averaged should be uncorrelated, implying some distance between them, but at the same time there should be as many as possible within the stationary segment to increase statistical confidence. For example, a distance of 4-10 wavelengths has been reported for RMS averaging of fast fading [4]. We have selected 10λ for the averaging interval in our analysis and we use every recorded snapshot within this distance (note 10λ = 9.6 m at 312 MHz). More specifically, the number of consecutive CIRs used to estimate the channel's average power delay profile (APDP) is typically 40-100 depending on the driving speed of the vehicle.

After applying a threshold of -20 dB relative to the peak of the APDP to identify valid multipath echoes, each APDP is subsequently translated into one observation of path loss or delay spread in the larger analysis. The average received power is calculated by summing all profile samples above the noise threshold, and the number thus contains the power contributions from all scattered and reflected signal components. In addition, we also examine the received power from the direct Tx-Rx path only (as is considered by most signal strength prediction algorithms), and this is estimated by summing only the earliest four profile samples.

Several metrics are defined in the literature for the characterization of time dispersive multipath channels. Probably the most popular is the RMS delay spread, which is the power weighted standard deviation of excess delay. We calculate RMS delay spreads using the APDP rather than the individual CIRs, which leads to a somewhat optimistic portrayal of the channel conditions faced by real radios. A second metric is the "delay interval", defined as the time interval between the first and last profile sample above the threshold. Additionally, we consider a metric referred to as "delay window" that is based on the signal to co-channel interference requirements for a specific communication waveform. If this requirement is for instance 10 dB, a delay window is defined based on the APDP as the time interval containing 10 times as much power as the power of the profile left outside the window. This metric is an approximation to the "sliding delay window" defined in [1].

III. Measurement paths

The measurements reported here were conducted on three different paths in south eastern Norway. The following table shows some characteristics of the topography where the measurements took place. The data is calculated within a circular area of radius 20 km from the transmitter sites and with a digital map resolution of 10 m.

TABLE I
Topographical data for the three measurement sites

	Rena	Gausdal	Bødalen
Max elevation (m)	956	1242	1360
Ave elevation (m)	478	669	781
Min elevation (m)	194	122	160
Std dev elevation (m)	175	235	218
Ave slope (deg)	5,23	8,74	8,53
Std dev slope (deg)	5,00	7,95	7,93
Tx antenna elev (m)	273	432	393

The Rena area is characterized by soft rolling hills, heavy forest basically consisting of pine trees that can be as high as 20 meters, and a rural/remote environment. There is a village called Rena consisting of one story high buildings. The transmitter was located at a parking lot with close-by pine trees in the direction of the receiver. The trees were snow covered during the measurements. The mobile Rx van drove away from the Tx, first experiencing non-LoS conditions for the first kilometer, then LoS conditions while driving through the Rena town center at around 2 km. After the town center the Tx-Rx distance decreased to 1.2 km before increasing steadily while driving through varying density of forest until the signal was lost at 12 km. LoS conditions were dominating only interrupted by marginal non-LoS conditions. A picture of the forest experienced on most of the path can be seen in Fig. 1.

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Fig 1. Typical vegetation in the direction from the Rx to the Tx on the Rena path

At 60-70 km west of Rena is Gausdal, which is classified as a lower mountain valley. The relative difference between hill tops and valley bottoms is larger than at Rena. The forest is not as heavy, and the trees are lower. There is some agriculture in the area and spread housing. In this rural/remote area the transmitter was placed relatively high up on a hill side with a very clear LoS view to the mid-part of the measurement series. The receiver drove down the hill from the Tx while experiencing non-LoS, then entering the area with clear LoS which also had a shorter distance to the Tx, and then finally drove away from the Tx in non-LoS conditions until measurements were stopped at a distance of 7 km.

The Tx site of the third path in Bødalen is only about 7 km (air distance) away from the Gausdal Tx site. Bødalen is a side valley to Gausdal and it is classified as a higher mountain valley. The topographical characteristic is much the same as for Gausdal, as seen in Table I. The difference to the Gausdal measurement was that the transmitter was here located at the bottom of the valley and the Tx antenna mounted on a 8 m mast. The valley was relatively narrow with some curvature, therefore LoS conditions were quickly lost. The Rx van drove away from the Tx approximately at the same elevation as the Tx and out to a range of about 10.5 km. The topography imposed non-LoS conditions for the whole path except for the start of the measurement.

IV. RESULTS

To illustrate the range of propagation conditions encountered in the measurements, first consider the average power delay profiles (APDPs) shown in Fig. 2. In Fig. 2a there was a clear LoS between Tx and Rx that dominates the channel impulse response. In contrast, for the Fig. 2b measurement, the direct path was heavily obstructed by a hill near the Tx and delayed multipath of considerable strength was received from a large elevation located a few km from the Rx. A third example is shown in Fig. 2c where multipaths nearly as strong as the first signal were received at a delay of ~50 µs. The RMS delay spreads for the three scenarios were 0.24 µs, 4.56 µs and 23.6 µs, respectively.

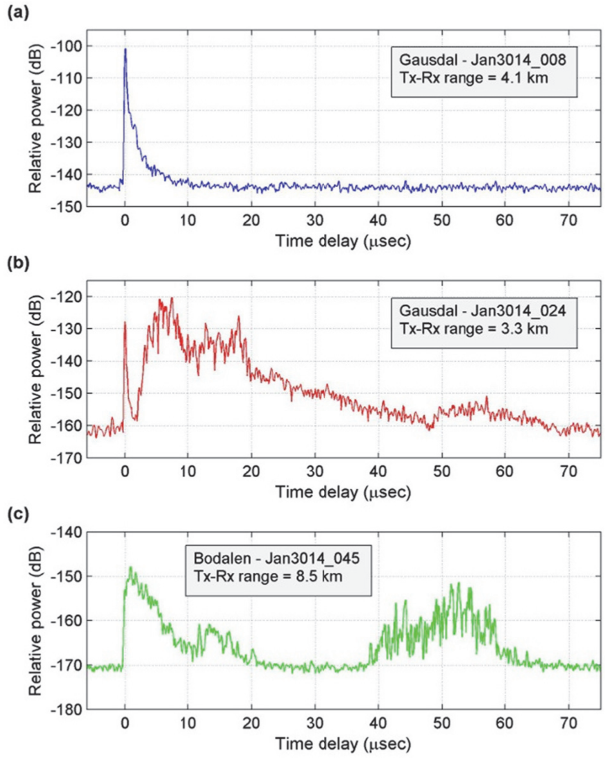

Fig 2. Examples of power density profiles measured

A. *Path loss*

The measurements allowed us to calculate both the average total path loss of all received multipath components, and of the signal arriving over the direct path from transmitter to receiver. The path loss will be larger for the direct path, since the power received via reflected paths will be considered lost in this calculation.

The average total path loss for the Rena measurements is displayed in Fig. 3. Red data points correspond to non-LoS conditions and blue to LoS conditions. The x-axis shows indicies that represent the distance travelled from the start of the measurements. The direct distance between the Tx and Rx in km is indicated above the x-axis.

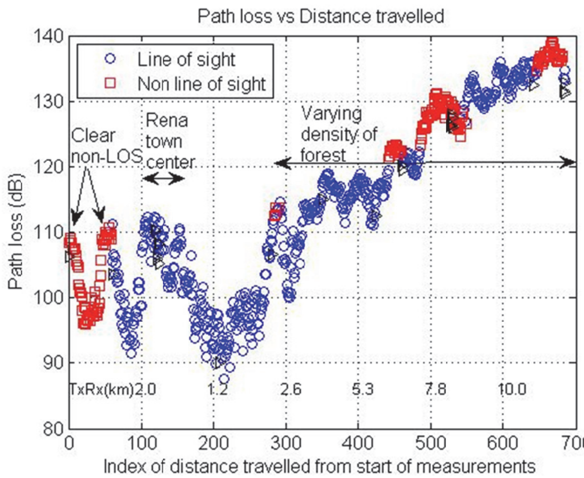

Fig 3. Averaged total path loss as the receiver is driving away from the transmitter. Rena data.

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The 10 dB difference in path loss at the start of the measurements during the non-LoS conditions can be explained by very marginal non-LoS in the middle of this section. Very marginal non-LoS exist also for the later non-LoS sections. The Rena village center imposes increased path loss of 20 dB even though the paths are topographically LoS. As the receiver drives away from the transmitter from 2-12 km the path loss increases steadily with a variation around the mean of 5-8 dB. Using Google Earth to inspect the vegetation, the variation of path loss seems to be well correlated with the density of the forest.

In Fig. 4 the same blue and red curve as in Fig. 3 are displayed, but we have added the calculated path loss for the direct path (black points). It can be seen that if a radio waveform is able to utilize the power received by reflected and delayed signal paths, 10 dB or more received power can be gained in certain positions. The gain is largest at the longer distances where the direct path is most attenuated.

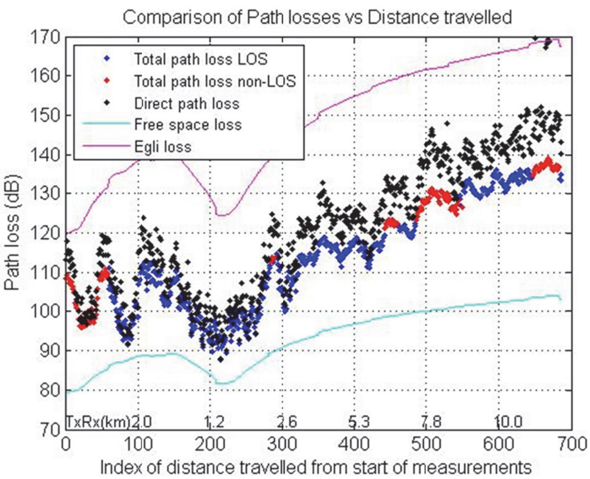

Fig 4. Averaged total path loss compared with direct path loss, theoretical free space loss and Egli predicted loss. Rena data.

Also in Fig. 4 we have calculated the theoretical free space loss and the loss predicted by the empirical Egli formula [5]. The Egli formula obeys a d^4 power law (40 dB loss/decade of distance) while the free space loss obeys d^2. The statistical mean Egli formula overestimates the path loss for this path.

Linear regression analysis of the data gave us a path loss of 34 dB per decade of distance, as seen in Fig. 5.

For the measured path in Gausdal, the propagation was of a different nature. The same plot as in Fig. 4 for these measurements is given in Fig. 6. During the clear non-LoS part at the start of the measurement series, there is about 25 dB to be gained if the power in the reflections can be utilized by a receiver. The Egli prediction of path loss is performing well for a receiver only being able to utilize the direct path. In the LoS section of the data, the measured path loss is close to the theoretical free space loss, and almost all power is contained in the direct path. The LoS condition on this path was not obstructed by forest, as opposed to the Rena path.

We did not have a sufficient amount of data on this path to give a useful number for the power loss per decade of distance.

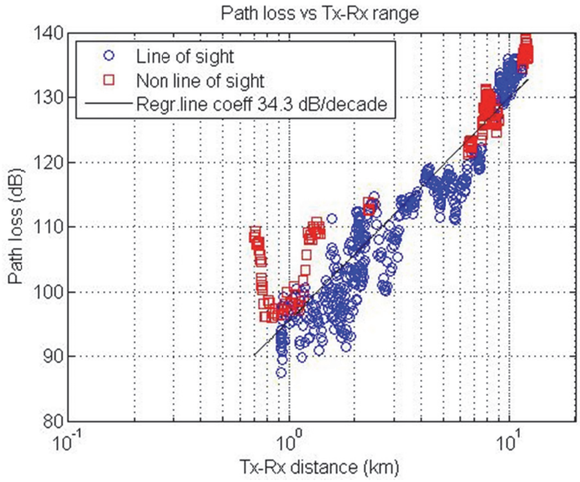

Fig 5. Averaged total path loss displayed on a semi- logarithmic scale. Rena data

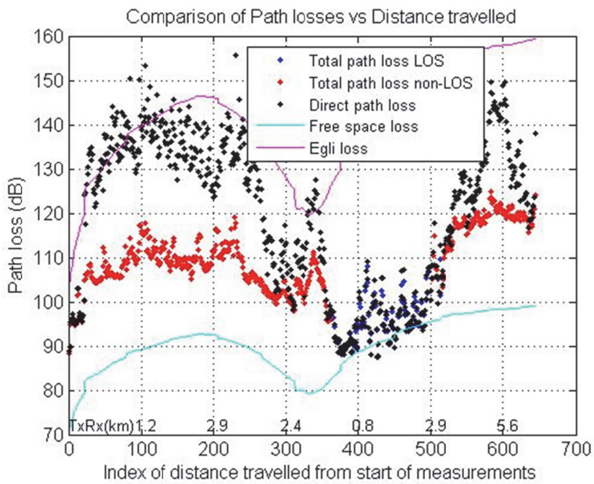

Fig 6. Averaged total path loss compared with direct path loss, theoretical free space loss and Egli predicted loss. Gausdal data

For the path in Bødalen that experienced non-LoS conditions on almost the entire path, the results also showed much power in the reflected paths. The path loss versus distance was here 37 dB per decade of distance.

B. Multipath

Shown in Fig. 7 is a scatter plot of RMS delay spreads vs Tx-Rx distance for the measurements divided by region. While average RMS delay spread does exhibit a noticeable increase with respect to transmission range, it is clear from the data that the distinctness and functional nature of the trend changes significantly between the three propagation environments. For example, the Gausdal data shows RMS delay spreads evenly distributed in the 0-9 µs range with no particular dependence on Tx-Rx distance. The Rena measurements indicate a relatively linear increase in RMS delay spread of about 0.6 µs per km. Contrast these to the more extreme results of up to 24 µs from Bødalen which would be better modeled by a power law or exponential function.

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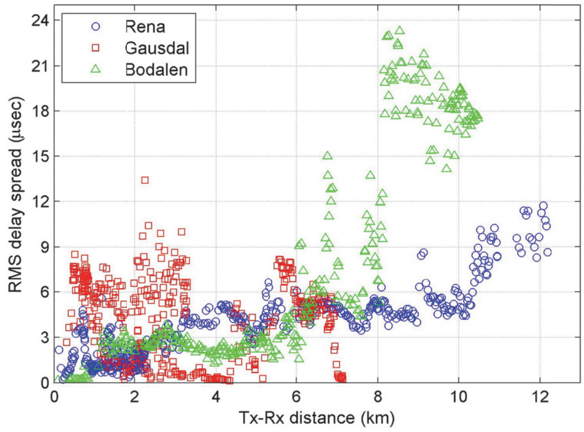

Fig 7. RMS delay spread of averaged power delay profiles vs distance between Tx and Rx

We have calculated the complementary cumulative distribution functions (CCDF) for our selected metrics. An example is shown in Fig. 8 for the measured delay interval in Gausdal. The CCDF based on a -10 dB threshold relative to the peak of the impulse response is also applied in order to characterize the data in another dimension.

The 90 percentile and 50 percentile (median) values of all three measured paths are given in the following tables for the RMS delay spread and the delay interval respectively.

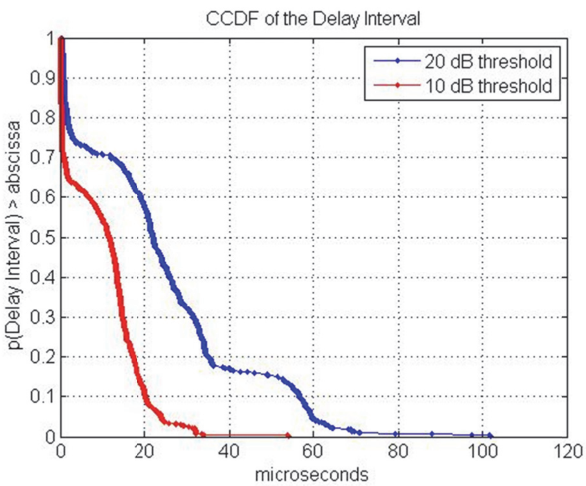

Fig 8. Complementary cumulative density function of the delay interval. Gausdal

TABLE II

Summary of distributions of the RMS delay spread

RMS delay spread	50 percentile (µs)	90 percentile (µs)
Rena	3	5,5
Gausdal	4,5	7
Bødalen	3	18,5

TABLE III

Summary of distributions of the delay interval

Delay interval	Threshold rel peak (dB)	50 percentile (µs)	90 percentile (µs)
Rena	-10	2	13
	-20	12	37
Gausdal	-10	12	20
	-20	22	57
Bødalen	-10	3	47
	-20	14	56

V. Discussion and analysis

A limited amount of measurements have been collected on three different paths, each in a different type of terrain. The different types of terrain are very representative of most of the remote/rural areas in eastern Norway. The data has given us some insight into what multipath conditions can be expected at 312 MHz in these areas. It is interesting to use this channel information in forming guidelines for radio waveform requirements.

Long delays of multipaths translate into intersymbol interference/frequency selective fading of the received signal if the symbol period is short relative to the delays. For a high data rate waveform and single carrier modulation it is impossible to meet the requirement of T_s >> maximum multipath delay, and equalization of the channel is necessary. For instance, for the 5 MHz frequency assignments given to wideband communications within the 225-400 MHz band, the T_s of a single carrier modulation would be in the order of 0.2 µs. Equalization enables the exploitation of independently fading paths to increase the received signal-to-noise ratio.

Multicarrier waveforms such as OFDM achieve high data rates by using many orthogonal carriers within the bandwidth, each modulated with a symbol rate fulfilling to some extent the requirement of T_s >> maximum multipath delay.

A technique similar to that used in [1] to evaluate the performance of a single carrier waveform on multipath channels has been used here to indicate the number of symbols over which an equalizer ideally should operate (equalizer depth), given the measured channel conditions and a qualified assumption of a typical wideband waveform. In [1] a sliding window of minimum length, containing a certain percentage of the total power, is placed on top of the power delay profile. The percentage of the power within the window is given by the required signal-to-co-channel interference ratio (S/I) for a specific waveform. The length of the window determines the number of symbols that ideally should be equalized. The technique was found to give a good description of the GSM performance on measured multipath channels in [1].

For a typical UHF wideband waveform giving 8-10 Mb/s at the physical layer, the required S/I can be up to 20 dB. For a more robust, lower data rate waveform, this number could typically be 10 dB. We did not use a sliding window, but rather anchored the window at the first sample of the power delay profile above the threshold, and determined the length of the window from the 20 dB and 10 dB S/I requirement. Since the maximum power was almost always at the start of the

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profile (the PDP example shown in Fig. 1b was rare), the error made by not applying a sliding window was small. For the Gausdal data a CCDF of the length of the delay window is shown in Fig. 9. In this example 90% of the measurements will be covered by a delay window of 32 µs for the high data rate waveform (20 dB S/I). We have further calculated the number of symbols the delay window comprises for a symbol rate of 0.2 µs, and the results are shown in Table IV for all three paths. The number of symbols over which an equalizer should be able to operate is very high. For comparison, the equalizer of the GSM standard is designed to equalize 4 symbols [1].

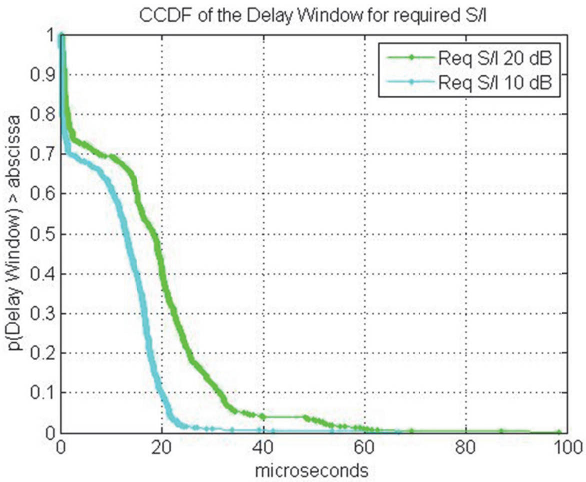

Figure 9. Complementary cumulative density function of the delay window. Gausdal data

TABLE IV

Summary of distributions and implication on equalizer design

Required equalizer depth	S/I (dB)	90 percentile (µs)	Number of symbol periods
Rena	10	13	65
	20	23	115
Gausdal	10	20	100
	20	32	160
Bødalen	10	47	235
	20	53	265

The two paths in the mountain valley, Gausdal and Bødalen, had a similar maximum delay interval (90 percentile) for the 20 dB threshold as shown in Table III. The (90 percentile) delay windows for the two paths are meanwhile quite different in Table IV, with the need for a larger equalizer depth at the Bødalen path. This shows that the maximum delay interval is not necessarily a good measure for the required equalization depth. The Bødalen data was all non-LoS with much power present in the reflected paths whereas the Gausdal data was a mixture of two different propagation regimes; clear LoS without vegetation and non-LoS. The conclusion is that extensive equalization making use of the power in delayed echoes is needed for single carrier modulation in these mountain valleys, otherwise strongly degraded performance is the result.

VI. Conclusion

Channel parameters of interest to waveform designers have been extracted from measurements in Norway taken in environments and at frequencies that are typical for tactical mobile radios. We have not attempted to present complete propagation models based on the measurements.

The measured delay spreads at 312 MHz were large compared to earlier reported measurements (in Canada). The spreads were largest for the two mountain valley measurements showing reflections from distant hills. The snow-covered forest in the flatter area at Rena nevertheless caused significant spreading of the signal arrivals even though the path was topographically LoS. The spread was correlated with the density of the forest between the Tx and Rx. For a single-carrier, high data rate modulation scheme, extensive equalization over more than 100 symbol periods is needed to give acceptable waveform performance. For multicarrier modulation schemes long guard intervals of tens of microseconds are needed.

The total path loss was well correlated with the delay spread of the channel, and for the LoS path at Rena it varied with 5-8 dB as the receiver drove through varying forest. The path loss versus distance was estimated to be 34-37 dB per decade for both the flat forested region and for the mountain valley.

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