Eigen-analysis of UWB channel on the basis of information theoretic criteria

Abdellah Chehri
LRCS Laboratory
Val-d’Or, Qc, Canada
zehri@gel.ulaval.ca

Paul Fortier
ECE Department
Laval University, Qc, Canada
fortier@gel.ulaval.ca

Pierre-Martin Tardif
ECE Department
Laval University, Qc, Canada
tardif@gel.ulaval.ca

Abstract — Underground mine galleries can be considered as complex transmission lines where multipath, attenuation, reflection, diffraction and scattering effects are dominants. However, some companies have started to deploy modern wireless system networks in mine galleries with the objective of increasing safety and productivity. In the last decade, ultra-wideband (UWB) technology has gained much interest for its application to wireless communications. This paper reports on experimental results of UWB channel propagation in an underground mine. Eigen-decomposition and subspace-based statistical signal processing on the autocorrelation matrix of the channel impulse response are used. We apply information theoretic criteria to estimate the number of significant eigenvalues. This result is then used to calculate the RMS delay spread of the channel.

Keywords— UWB, propagation, underground mines, delay spread, information theoretic criteria.

I. INTRODUCTION

The necessity for wireless communications in underground mines is well understood. However, underground mine galleries are known to be harsh environments for any wireless technology since diffraction, multipath, scattering and fading phenomena are frequent. This makes it very difficult to provide reliable and robust wireless communication that can be used for monitoring, surveillance, voice, localization and automation [1].

Ultra wideband radios have relative bandwidths larger than 20% or absolute bandwidths of more than 500 MHz. UWB is a wireless technology that can operate at very low-power density to communicate at high data rates over short distances [2]. UWB is emerging as a particularly appealing transmission technique for applications requiring either high bit rates over short ranges or low bit rates over medium to long ranges. The high-bit-rate/short-range includes wireless personal-area networks (WPANs) for multimedia traffic, the low-bit-rate/medium-to-long-range case applies to long-range sensor networks such as indoor-outdoor distributed surveillance systems, non real-time data applications, and in general all data transfers compatible with a transmission rate on the order of 1 Mbit/second over several tens of meters. A recent release of the IEEE 802.15.4 standard for low-rate WPANs (IEEE 802.15.4 - 2003) has increased attention for the low-bit-rate case [3].

In a mine gallery there is a requirement for many types of communications. Among these, voice communications between mine workers are very critical. Video surveillance through infrequent snapshots in mine galleries is another application of interest and is used for data analysis. In addition to applications for improved public safety through the use of vehicular radar systems for collision avoidance, remote control applications are also of interest to the mine operators so that machinery can operate in extreme conditions. Wireless sensor monitoring is another application that is very crucial for the safety of mine workers. Since UWB has excellent spatial resolution it can be advantageously applied in the field of localization and navigation [5]. There are a number of applications that would benefit from precise indoor positioning and navigation such as automatic storage and tracking of various targets [4]. All these types of communications can use UWB technology.

In this paper we give an analysis of the UWB channel in underground mines based on measured radio sounding data. We use an eigen-analysis of the channel covariance matrix and apply information theoretic criteria to estimate the number of significant eigenvalues. This result is then used to calculate the RMS delay spread of the UWB channel in underground mines.

The remainder of the paper is organized as follows. In the next section we give details about the environment, the measurement campaign and the methodology used for data acquisition. Section III deals with eigen-analysis of the channel covariance matrix. We give in section IV the results of our measurements and some analysis. Section V is the conclusion.

II. MEASUREMENT SETUP, ENVIRONMENT AND METHODOLOGY

Accurate channel models are extremely important for the design of communications systems. Knowledge of the features of the channel provides communications system designers with the ability to predict the performance of the
system for specific modulation, channel coding, and signal processing.

A number of propagation studies for ultra wideband channels have been done which take into account temporal properties of a channel or characterize a spatio-temporal channel response. A good overview of the work done to characterize UWB channels is given in [6].

Our measurement campaign was carried out in a real underground mine. This former gold mine is located approximately 530 kilometres northwest of Montreal and is now managed by MMSL-CANMET (Mining and Mineral Sciences Laboratories – Canadian Center for Minerals and Energy Technology). In this mine, in-situ tests and trials can be performed in a realistic experimental environment.

As can be seen in Fig. 1, the gallery walls have a significant roughness. The gallery constitutes a channel with multiple paths. Many obstacles are present (electric wires, ventilation systems, cables and pipes located near the ceiling) and they act as more or less reflective surfaces for the waves. The floor of the gallery is rather undulating and one can see water puddles of different sizes.

Channel measurements were performed using an HP 8753 ES vector network analyzer (VNA). The VNA measures both amplitude and phase, so that if the time domain response is desired, the inverse Fourier transform can be calculated for

\[ H(w) \], yielding \( h(t) \), the channel impulse response (CIR).

Both transmitter and receiver were equipped with an Electro-Metrics EM-6116 antenna. At the transmitter side, we mounted the antenna on a positioning table 1 m above the floor. The receiving antenna was also fixed at the same height. The Tx/Rx distance was fixed at 9 m (typical distance for short communication systems and short-range peer-to-peer systems). Because the mine topology is often irregular and composed of interconnected corridors, both line-of-sight (LOS) and non-LOS (NLOS) scenarios were considered.

During the measurements, the VNA was set to transmit 1601 continuous wave tones uniformly distributed over the 2-5 GHz frequency range (3 GHz of frequency span), which resulted in a frequency step of 1.874 MHz. This frequency resolution gave a maximum excess delay of about 533.33 ns and a maximum distance range of approximately 160 m. The sounding signal was transmitted at a power level of 25 dBm to overcome the cable loss between the receive antenna and the VNA. The VNA measured the S-parameter, \( S_{21} \), of the UWB channel, which essentially corresponds to the CIR. In order to get a reliable channel models, the sweeping time should not exceed the channel coherence time.

The impulse response measurements were made at 40 locations, arranged in an 8×5 rectangular grid with 7 cm spacing\(^1\). This grid is in fact a wooden box with 40 holes in which it is possible to put a support for a Tx antenna. For both LOS and NLOS cases, we took three measurement points, separated by 10 cm at the receiver locations (Fig. 2).

\[ h(t, \tau, d) = \sum_{i=1}^{L} a_i(t, d) \exp(j \theta_i(t, d)) \delta(t - \tau_i) + w(t) \] (1)

\(^1\) This grid spacing is slightly smaller than half the wavelength at the lowest measured frequency (2 GHz), to obtain approximately independent samples.
Where $d$ denotes transmitter-receiver separation, $L$ is the number of multipath components, $a_i$ represents the amplitude of the $i^{th}$ multipath component, $\theta_i$ is the phase associated with the $i^{th}$ path, $\tau_i$ is the time delay of the $i^{th}$ path in the channel with respect to the first arriving multipath, and $\delta$ is the Dirac delta function. The noise vector $w(t)$ is an ergodic Gaussian process independent of the signal. The use of eigen-analysis for modeling in the case of wideband radio channel measurements has been previously reported in [8]. A similar analysis is adopted for the indoor UWB channel [9], [10].

Now let $h = [h(1), h(2), \ldots, h(N)]$ be the instantaneous sampled complex impulse response of the channel process, which is assumed to be Gaussian\(^2\). We assume that the measurements are made under the conditions of stationarity and slow fading. If it is assumed that the signal component of (1) is independent of the noise component, the covariance matrix of the measured channel samples, $h$, is written as [11]:

$$ R = E[hh^H] = E[gg^H] + W $$

(2)

where $H$ means complex conjugates transpose, $g$ is a vector of samples of the noise-free channel process, and $W$ is the covariance matrix of $w_n$. For our analysis $W$ is assumed to be equal to $\sigma_w^2 I$ and $I$ is the identity matrix. In the simplest case, the matrix $R$ is diagonal (this is the case of a wide-sense stationary uncorrelated scattering, WSSUS, channel).

### B. Eigen-decomposition

The covariance matrix $R$ is Hermitian and positive definite. For this reason, a unitary matrix $V$ exists and $R$ can be decomposed into an eigenstructure (using Karhunen-Loève decomposition) of the form [8]:

$$ R = V \Lambda V^H + \sigma_w^2 I = \sum_{i=1}^N \lambda_i \psi_i \psi_i^H $$

(3)

It can be shown that $R$ has $k$ eigenvalues $\{\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_k\}$ that are greater than $\sigma_w^2$ and they are commonly referred to as principal eigenvalues and $k$ represents the degrees of freedom of the channel [9], and the corresponding eigenvectors are called principal eigenvectors (PEs). The rest of the eigenvalues of $R$ are due to receiver noise and are identically equal to the noise power $\sigma_w^2$ in the ideal case, i.e. $\{\lambda_{k+1} = \lambda_{k+2} = \ldots = \lambda_N = \sigma_w^2\}$.

A fundamental propriety of the eigenvectors of $R$ is that they are mutually orthonormal. In geometrical terms the eigenvectors $\{\lambda \geq \lambda \geq \ldots \lambda\}$ span a subspace $\Gamma$, that is the orthogonal complement of the space $\Gamma_n$, spanned by the eigenvectors $\{\lambda_{k+1} = \lambda_{k+2} = \ldots = \lambda_N\}$. $\Gamma_n$ is usually referred to as the signal plus noise space and $\Gamma$ as the noise space.

### C. Information theoretic criteria

The number of significant eigenvalues, $k$, can be determined by noting the multiplicity of the smallest eigenvalues of $R$. In practice, this is difficult because the true covariance matrix is not available. When the estimation is based on a finite sample size, the resulting eigenvalues are all different with probability one, thereby making it difficult to determine the multipath components merely by “observing” the eigenvalues. Fortunately, we can exploit information theoretic criteria to solve the problem.

Information theoretic criteria for model order selection address the following problem: given a set of $N$ observations of $h = [h(1), h(2), \ldots, h(N)]$ and a parameterized family of probability densities $f(h | \theta)$ (a family of models), select one model that best fits the set of observations. An approach proposed by Wax and Kailath [11] which avoids the setting of a subjective threshold is based on the use of information theoretic criteria introduced by Akaike [12], Schwartz and Rissanen [13] and Hannan [14].

The statistical performance of the AIC and the MDL criteria in terms of their probability of error have been studied by Wang, Kavel and Hung [15], [16].

The first criterion, AIC, has the form

$$ AIC(k) = -2L(\hat{\theta}) + 2k(2p - k) $$

(4)

The second criterion is referred to as the MDL criterion and is given by:

$$ MDL(k) = -2L(\hat{\theta}) + \frac{1}{2} k(2p - k) \log(N) $$

(5)

The last criterion is referred to as the HQ criterion:

$$ HQ(k) = -2L(\hat{\theta}) + \frac{1}{2} k(2p - k) \log(\log(N)) $$

(6)

In (4), (5) and (6), $L(\hat{\theta})$ is the log-likelihood function for the parameter vector $\hat{\theta}$ of the model, which is given by [11]:

$$ L(\hat{\theta}) = \log \left( \prod_{i=k+1}^p \frac{1}{\lambda_i^{1/(p-k)}} \right)^{N/(p-k)} $$

(7)

The number of significant eigenvalues is the value of $k \in \{0, 1, \ldots, p-1\}$ for which the AIC, MDL or HQ criterion is minimized.

### IV. RESULTS AND ANALYSIS

The results presented in this section were based on the data collected in our measurement campaign. The number of significant eigenvalues was first estimated. Applying the AIC, MDL and HQ criteria to the data sets, the results are

\(^2\) This is justified by the Central Limit Theorem: if each tap is made up of a large number of contributions from different scatterers, the resulting tap distribution can be modeled as complex Gaussian.
shown in Fig. 3 (LOS) and Fig. 4 (NLOS). The values of $k$ minimizing the criteria for the LOS and NLOS cases are given in Table I.

![Graph showing criteria vs. index k (LOS)](image)

**Fig. 3: All criteria vs. index $k$ (LOS).**

![Graph showing criteria vs. index k (NLOS)](image)

**Fig. 4: All criteria vs. index $k$ (NLOS).**

**Tab. I: The values of $k$ minimizing the criteria for the LOS and NLOS cases.**

<table>
<thead>
<tr>
<th></th>
<th>LOS</th>
<th>NLOS</th>
</tr>
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<tbody>
<tr>
<td>AIC</td>
<td>43</td>
<td>86</td>
</tr>
<tr>
<td>MDL</td>
<td>42</td>
<td>84</td>
</tr>
<tr>
<td>HQ</td>
<td>47</td>
<td>91</td>
</tr>
</tbody>
</table>

A. Captured energy

It has been shown that the number of significant eigenvalues increase linearly with the bandwidth of the signal. However it can be noticed that starting from a certain bandwidth the number of significant eigenvalues increases slowly [10]. To give an idea, we computed the eigenvalues $\lambda_i$ directly from the sampled CIR obtained from the measurement campaign and using (3). An example of an eigenvalue distribution is shown in Fig. 5. The captured energy for $k$ considered eigenvalues out of all $N$ eigenvalues is defined by the following relation:

$$E_k = \frac{\sum_{i=1}^{k} \lambda_i}{\sum_{i=1}^{N} \lambda_i}$$  \hspace{1cm} (8)

In Fig. 6 we plot for the LOS and NLOS cases the percentage of captured energy for different number of significant eigenvalues, $k$, using (8) with $N$ the total number of eigenvalues. We remark that for 95% of energy we need approximately 45 eigenvalues for the LOS case. This value increases to 85 for the NLOS case.

![Graph showing captured energy for a certain number of significant eigenvalues](image)

**Fig. 6: Captured energy for a certain number of significant eigenvalues.**
B. Delay spread

The classical approach used for the characterization of the selectivity of multipath fading channels is based on the root mean square (RMS) delay spread, $T_d$ [6]. This parameter, or equivalently the coherence bandwidth, $B_c$, is defined as:

$$B_c = \frac{\beta}{T_d}$$  \hspace{1cm} (9)

where $0 < \beta < 1$, a constant, is widely used as a measure of channel frequency selectivity. This approach is generally correct when the signal bandwidth corresponds to a small portion of the coherence bandwidth. But in UWB channels, the coherence bandwidth can only be seen as a local measure and does not give an accurate description of channel selectivity. It has been shown in [9] that the relationship between the number of significant eigenvalues and the RMS delay spread is given by the following equation:

$$T_d = \frac{k}{W}$$  \hspace{1cm} (10)

where $W$ is the frequency band. To evaluate the RMS delay spread for our measurements we use (10) and by taking $k = 43$ and $86$, we find $T_d = 14.33$ ns and $28.67$ ns for LOS and NLOS, respectively.

V. CONCLUSION

In this paper we presented an eigen-analysis of the UWB channel in underground mines. The measurements were made in an experimental mine (CANMET). We have employed information theoretic criteria to detect the significant eigenvalues (called also the degrees of freedom of the channel). The results show that the values vary form 43 to 86 significant eigenvalues for the LOS and NLOS cases. We have also used these results to estimate the RMS delay spread of the channel. The results give $T_d = 14.33$ ns for LOS and $T_d = 28.67$ ns for NLOS.

REFERENCES


