

An Investigation of UWB-Based Wireless Networks in Industrial Automation

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Summary

Ultra-wideband (UWB) communication has been the subject of extensive research due to its unique capabilities and potential applications. Some see UWB as an enabling technology for new wireless applications that span from high-data-rate transmission of raw multimedia video to new location-aware, low-data-rate, and low-power communication of sensor and actuator data. Underground mines, which are characterized by their tough working conditions and hazardous environments, require fool-proof mine-wide communication systems for smooth functioning of mine workings and ensuring better safety. During the last years, a number of Canadian mining companies have started to deploy modern communications systems in order to automate processes, reduce operational costs and with the objective of increasing safety and productivity. However, many important aspects of UWB communication systems have not yet been thoroughly investigated in this kind of environments. In this paper we give an overview on UWB communication. Also we investigate via measurements and simulations the applications and design challenges for UWB communication and ranging in underground mines.

Key words: UWB, Time Hopping, Rake receiver, IEEE 802.15.4a, IEEE 802.15.3a, Underground mines, UWB Ranging.

1. Introduction

Mining industry is one of the most difficult industries, concerning production and technological processes. The surroundings in which we are providing these works in mines is influenced by factors like the possibility of gas explosion, harmful atmosphere, high temperature, humidity, dust, noise, vibration, etc. The harsh physical environment and distinct topology that make mining dangerous act as a hindrance or constraint to the very techniques and technologies that could improve safety and productivity.

Up until the late 1980's, instant, reliable radio communication was almost non-existent in underground mines. The difficulty and high cost and lack of reliable technologies being widely available made communications underground difficult. With industry demanding better communications underground as a major part of dramatic safety and productivity improvements in underground mining. In the interests of mine safety and productivity, it is vital that operators are continuously aware of underground conditions and risk profiles. They must be able to locate and communicate with mine workers at all times - particularly in the event of fires, roof falls or other life-threatening situations.

Some companies start to develop new technology that would provide robust wireless notification and coordination under normal operations and during disasters.

The world of ultra-wideband has changed dramatically in very recent history. In the past two decades, UWB was used for radar, sensing, military communications and many other applications. A substantial change occurred in February 2002, when the FCC issued a ruling that UWB could be used for data communications as well as for radar and safety applications [1].

Considering the importance of this technology, future deployment of UWB wireless networks in underground mine will be an interesting application. UWB systems have potentially low complexity and low cost, have a very good time domain resolution, which facilitates location and tracking applications, extremely simple design (and thus cost) of radio, large processing gain in the presence of interference, extremely low power spectral density for covert operations. UWB can provide an excellent combination of high performance and low complexity for wireless communication and networking.

This paper deals with the potential applications and the challenges of using UWB based-wireless networks as future solution for automation in underground mines.

2. Application of UWB Wireless Communication in underground mines

Traditionally, various hard wired and wireless mine communication systems are available on the market. These systems differ in the use of their physical communication infrastructure as well as in the communication protocols used. Data communication is performed using e.g. phone lines, mobile radio systems, leaky feeder cables and fiber optic backbones together with wireless communication basing on mine radio and mobile phone system technology. Different philosophies exist regarding the use of analog or digital communication and big differences are visible in the available bandwidth.

In mining, infrastructure cost is essential. Thus, a communication system should be integrated as a multi purpose system capable of transferring all types of information as data, voice and video on an identical infrastructure.

An obvious advantage of wireless transmission is a significant reduction and simplification in wiring and harness. It has been estimated that typical wiring cost in industrial installations is US \$ 130 - 650 per meter and adopting wireless technology would eliminate 20 - 80 % of this cost [2]. Another advantage of wireless terminal is their mobility (these terminals can be placed in transporting vehicles, rotating equipment,...). In fact, the motivation for using wireless communication in industrial mining automation is generally twofold: economy and safety.

Wireless communication technologies in mining will have a significant impact on mine operations in the coming decades, giving mine managers and staff much greater understanding and control over mining processes in under to monitor and optimize mining operations. Increases in wireless communication capabilities also are establishing the technology base necessary to support remote and autonomous mining operations.

In a mine gallery there is a requirement for many types of communications. Among them voice communication among mine workers is very critical. Video surveillance through infrequent snapshots in mine gallery is another application of interest and is used for data analyses. On top of 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 [3]. In the proposed applications for IEEE 802.15.4, several companies mention sensor networks, which stand to derive huge benefits from the low power and location aware properties of UWB. Since UWB has excellent spatial

resolution it can be advantageously applied in the field of localization and tracking [4]. There are a number of applications that would take advantage from precise positioning and navigation such as automatic storage and tracking of various targets [5]. All these types of communications can use UWB technology. An example for a modern underground UWB communication system integrating both communication and automation demands are given in Fig. 1.

An example of simplified diagram representing global UWB wireless communication in underground mines is shown in Figure 2. Three major components are shown: an application layer system, an integration layer and a communication layer. The application layer includes, for example, the graphical user interface that is displayed on the end user's computer. The display will provide an overall picture of the current risk profile of the mine and show a specific sensor data for security monitoring, agents (drift, vehicle, mines) location and process data (production management, working place...) when requested. All the data displayed can use UWB-communication (PHY layer).

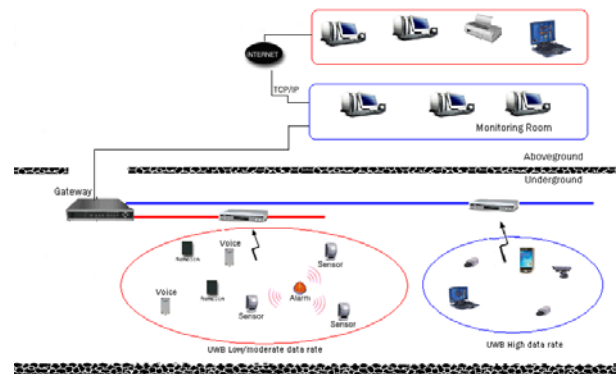


Fig. 1: Integrated underground communication system.

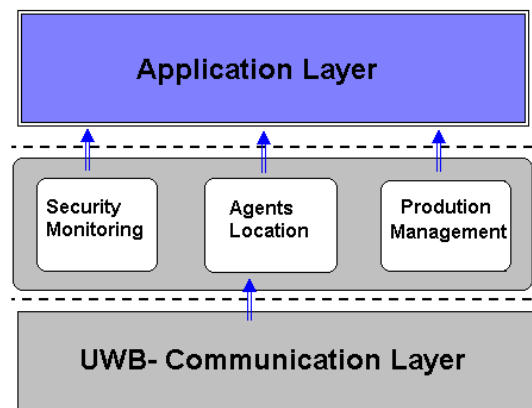


Fig. 2: Simplified diagram of the monitoring application for mining industry.

3. UWB Communication

Advantage of UWB

Compared to narrowband systems, UWB has several advantages. Because of the combination of wide bandwidth and low power, UWB signals have a low probability of detection and intercept. Additionally, the wide bandwidth gives UWB excellent immunity to interference from narrowband systems and from multipath effects. Another significant advantage of UWB is its high data rate. Also, the carrierless nature of UWB gives it potential for simple circuit implementation without intermediate oscillators and mixers. UWB devices may have a nearly all digital implementation in CMOS without minimal analog RF electronic [1]. This simple architecture can translate to low power dissipation and low cost, which opens a variety of possible mobile applications. In general, UWB technology has many benefits due to its Ultra-wideband nature, which include the following:

- Coexistence with current narrowband and wideband radio services,
- Large channel capacity: it can support real-time high-definition video streaming,
- Ability to work with low SNR: offers high performance in noisy environments.
- High performance in multipath channels: delivers higher signal strengths in adverse conditions.
- Simple transceiver architecture: which can enables ultra-low power, smaller form factor, and better mean time between failures, all at a reduced cost.

Challenges

UWB technology for wireless networks is not all about advantages. In fact, there are many challenges involved in using nanosecond-duration pulses for communications. Some of the main difficulties of UWB communications are summarized in following Table [1].

Challenge	Problem
Pulse-shape distortion	Low performance using classical matched filter receivers.
Channel estimation	Difficulty predicting the template signals.
High-frequency synchronization	Very fast ADCs required.
Low transmission power	Information can travel only short distances.

Table 1: Some challenges and problems associated with UWB systems.

4. TH-IR-UWB Communication

A time hopping modulation format employing impulse signal technology has several features which may make it attractive for multiple-access communications. A typical hopping format with pulse-position data modulation (PPM) is given by:

$$s_{tx}^{(i)}(t) = \sum_{m=0} \sqrt{E_x} w(t - mT_f - c_m^{(i)}T_c - \delta b_{\lfloor m/N_s \rfloor}^{(i)}) \quad (1)$$

where $s_{tx}^{(i)}(t)$ is random process describing the transmitted signal. $w(t)$ is the basic pulse monocycle that nominally begins at time zero on the transmitter's clock, and the quantities with superscript (k) indicate transmitter-dependent quantities.

Hence the signal emitted by the k^{th} transmitter consists of a large number of monocycle waveforms shifted to different times, the m^{th} monocycle nominally beginning at time $t - mT_f - c_m^{(i)}T_c - \delta b_m^{(i)}$. The frame time T_f is typically hundred times the pulses duration T_p . The value $\beta = T_f / T_p$ called spreading ratio. A pseudo-random time hopping code $(c_m^{(i)})$, $0 \leq c_m^{(i)} \leq N_h$; provides an additional shift in order to avoid catastrophic collision in multiple-access. The sequence $(b_m^{(i)})$ is the binary steam generated by the m th source and δ is the additional time shift utilized by binary pulse position modulation. If $N_s > 1$ a repetition code is introduced.

Multiple Access Interference

When N_u transmitters are active in UWB networks, the received signal can model as:

$$r(t) = r_u(t) + r_{mui}(t) + n(t) \quad (2)$$

Where $r_u(t)$ and $r_{mui}(t)$ are the useful signal and MUI contributions at the receiver input. With

$$r_u(t) = \sum_{m=0}^{N_s-1} \sqrt{E_{rx}^{(1)}} w(t - mT_f - c_m^{(1)}T_c - \delta b_m^{(1)}) \quad (3)$$

and

$$r_{MUI}(t) = \sum_{n=2}^{N_u} \sum_{m=0}^{N_s-1} \sqrt{E_{rx}^{(n)}} w(t - mT_f - c_m^{(n)}T_c - \delta b_m^{(n)} - \tau^{(n)})$$

The average symbol error rate coincides with the average bit error rate $P(e)$ since modulation is binary and corresponds to the probability of misdirecting a reference bit transmitted by the useful transmitter.

In the case of PPM orthogonal case and under the hypothesis for perfect power control, bit error probability (P_e) is given by [6]:

$$P_e = \frac{1}{2} Q(\sqrt{1/2A}) \tag{4}$$

$$A = \left((N_0)/(E_b^{(1)}) + (2R_b^2(N_u - 1) \int_{-T_p}^{T_p} R_0(\tau) d\tau) / N_s T_f \right)$$

Where: $R_0(t)$ is the autocorrelation function of pulse $w(t)$.

- R_b is the bit rate.

- $Q(x)$ is complementary error function.

The asymptotic theoretical (P_e) is represented for high multi-user interference (Fig. 3) and low multi-user interference (Fig. 4) for different bit rate.

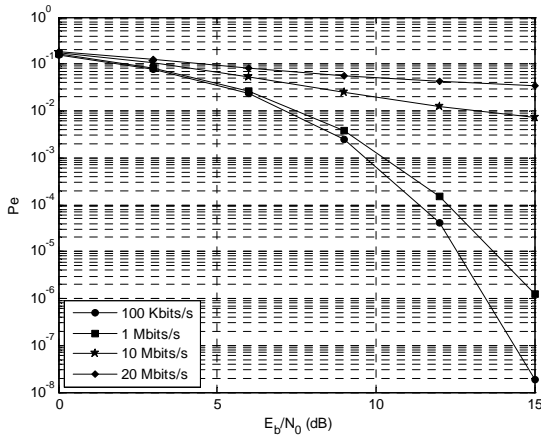


Fig. 3: PEB for high multi-user interferences (Nu=30).

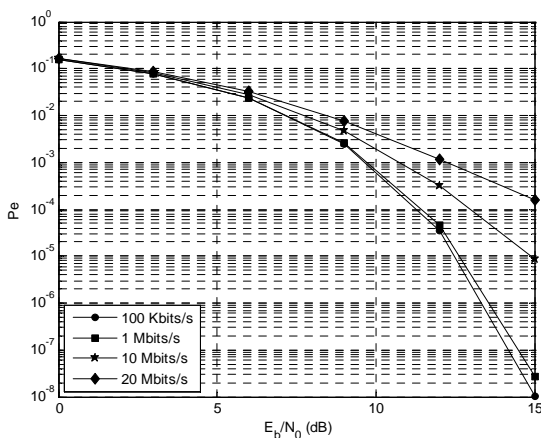


Fig. 4: PEB for low multi-user interferences (Nu=5).

Capacity of Multi-user UWB

With more than one user active in the networks, multiple-access interference (MAI) is a factor limiting performance and capacity, especially for a large number of users. The capacity of a UWB multiple access system that is dependent on a specific pulse shape is computed by Zhao and Haimovich in [7] and summarized in [8].

According to [7], the single user capacity C_{M-PPM} (measured in bit by symbol) as a function of the channel symbol SNR, is given by:

$$C_{M-PPM}(SNR) = \log_2 M - E_{v_1} \log_2 \sum_{m=1}^M \exp(\sqrt{SNR}(v_m - v_1)) \tag{5}$$

where v_m are random variables with $1 \leq m \leq M$, and they have the following distribution conditional on the transmitted signal x_1 :

$$v_1 : N(\sqrt{SNR}, 1)$$

$$v_m : N(0, 1), \quad m \neq 1$$

For multi-user capacity, each user contributes a fraction of the traffic in the channel. The aggregate capacity in the channel can be assumed as the sum of all singer user capacity.

Fig. 5 presents the aggregate multi-user capacity in bits per PPM symbol of UWB as a function of the numbers of users for various numbers of modulation levels M , and for fixed $\beta = T_f / T_p = 150$.

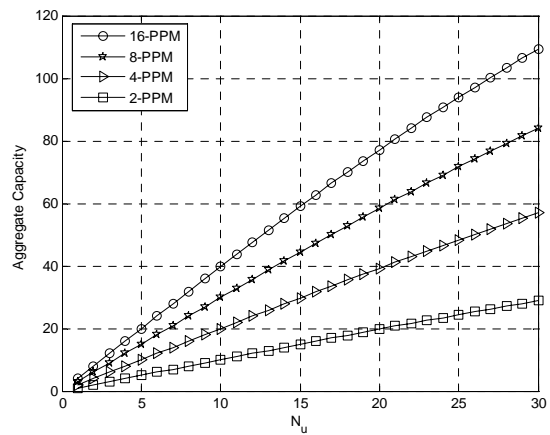


Fig. 5: Number of Users vs. Aggregate Capacity (bits/symbol) $\beta=150$.

5. UWB Channel Measurement

Propagation modeling is vital for the design and development of wireless communications systems. Channel characterization refers to extracting the channel parameters from measured data. The extracted parameters are used to quantify the effect of the channel on communication UWB systems using this channel as signal transmission medium e.g., in deriving optimal reception methods, estimating the system performance, performing design tradeoffs, etc.

Wireless channel quality causes fundamental limitations on the performance of wireless networks in underground mines. The propagation in underground channel is complicated due to scattering and rough surfaces diffraction. The quality of a channel is a complex combination of effects due to path loss, multipath fading.

Measurement procedure and locations

The measurements are carried out in an real underground mine gallery i.e., in a former gold mine now operated by the Canadian Center for Minerals and Energy Technology (CANMET) as a mine-technology laboratory in 530km northern of Montreal, Qc, Canada.

To our knowledge, our previous UWB channel measurements and modeling in the mining environment were the first work in these kinds of environments [9]. The measurements were performed at spatially distributed locations throughout the test area by fixing the transmitter in central location and moving the receiver. These measurements are adopted for wireless access point scenarios, short range peer-to-peer systems, and other applications with mobile terminals should take the variability of the channel over space into account.



Fig. 6: Example of underground mine gallery (LRCS).

Large scale parameters

The average path loss is, in general, expressed as a distance-power law function. Path loss for every measurement position is obtained by averaging all power profiles. The empirical model of power attenuation is given by the formula:

$$PL(dB) = Pl_o + 10n \log_{10}(d/d_0) + S_\sigma \tag{6}$$

where d is the distance in meters between the transmitter and receiver, and S_σ is the shadow fading. The path loss exponent n obtained from performing a least-square fit is 1.47 and 2.45 for environment LOS and NLOS respectively (Fig. 7).

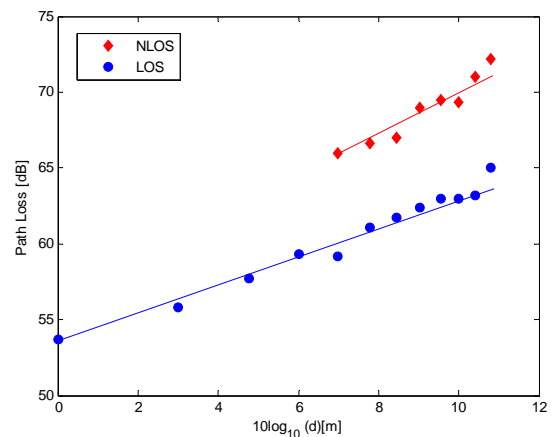


Fig. 7: Scatter plot of path loss vs. Tx/Rx separation.

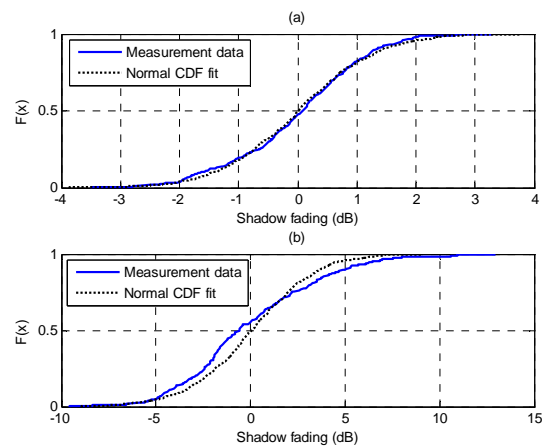


Fig. 8: CDF of shadow fading fit to Normal distribution- (a) LOS, (b) NLOS.

The shadow fading is considered to have a zero-mean Gaussian distribution with standard deviation σ_s . The

statistical analysis of S gives $\sigma_S = 1.1$ dB for LOS and $\sigma_S = 2.94$ dB for NLOS respectively (see Table. 2).

Scenario	n	Pl_0	d_0	σ_S
LOS	1.47	53.7	1	1.1
NLOS	2.45	66.4	5	2.94

Table 2: Large scale channel's parameters.

Analysis of RMS Delay Spread

The RMS delay spread is a good measure of multipath spread, it is defined:

$$\tau_{rms} = \left(\int_0^{\infty} (\tau - \bar{\tau})^2 p(\tau) d\tau \right) / \left(\int_0^{\infty} p(\tau) d\tau \right) \quad (7)$$

where $p(\tau)$ is the power delay profile and $\bar{\tau}$ is the mean excess delay defined as:

$$\bar{\tau}_m = \left(\int_0^{\infty} \tau p(\tau) d\tau \right) / \left(\int_0^{\infty} p(\tau) d\tau \right) \quad (8)$$

The maximum variations in the RMS delay spread for LOS environment were about 11.8 ns for 15 dB and 23.6 ns, for 20 dB¹. For NLOS environment, they were about 29.07 ns (15 dB) and 44.38 ns (20 dB). This indicates that NLOS channels are subject to high spatial variations of the RMS delay spread. This could be attributed to the presence of more scatterers, and hence more paths in NLOS environments than in LOS environments. The variation of the mean excess delay also indicates a similar pattern. The variations of RMS and mean excess were summarized in Tab. 3.

	τ_{rms}		τ_m	
	$\mu_{\tau_{rms}}$	$\sigma_{\tau_{rms}}$	μ_{τ_m}	σ_{τ_m}
LOS (-15dB)	11.8	4.4	22.61	3.4
LOS (-20dB)	23.6	5.14	33.76	5.72
NLOS (-15dB)	29.07	8.8	49.42	12.04
NLOS (-20dB)	44.38	10.6	58.30	8.46

Table 3: Average values of RMS and mean excess delay in underground mines (in nsec).

Small Scale Analysis

¹ The arrival time of the first path can be found by applying a threshold to the peak of the received signal. For our study, we used two different thresholds (e.g., 15 dB and 20 dB).

In order to evaluate the small-scale amplitude fading statistics, the relative amplitudes over small-scale areas were calculated. Empirical data from bins at specific excess delays were matched to some typical theoretical distributions for amplitude fading statistics such as log-normal [10], Rice [11], Rayleigh [12], Nakagami [13], and Weibull [14]. From our measurement campaigns we have found that the Nakagami distribution can be a good fit for small-scale amplitude fading statistics in underground mines. The advantage of Nakagami distribution is that, for special cases such as $m=1$ and for very large values of m , it can be generalized to become the Rayleigh and log-normal distributions, respectively.

6. TH-IR-UWB Demodulation/Detection

Coherent Rake Receiver

As the channel exhibits frequency-selective fading due to the extremely wideband nature of the transmitted signal, the received signal is inherent with path diversity [6].

A RAKE receiver can be used to exploit the diversity by constructively combining the separable monocycles from distinguishable propagation paths for improving transmission performance. Consider a RAKE receiver with L fingers to collect received signal energy from the L strongest paths. This can be characterized as a type of time diversity. The combination of different signal components will increase the SNR, which will improve link performance.

In theory, the receiver structure consists of a correlator filter that is matched to the transmitted waveform that represents one symbol, and a tapped delay line that matches the channel impulse response. It is also possible to implement this structure as a number of correlators that are sampled at the delays related to specific number of multipath components; each of those correlators can be called "RAKE finger."

In UWB systems, frequency dependency is taking into consideration [15], the receiver uses several RAKE fingers for each multipath component (MPC) spaced at the Nyquist sampling distance in order to collect the energy in the MPC. The number of rake fingers in this case becomes very large [16]. Due to this problem of energy capture, several simplified RAKE structures have been proposed. Selective Rake (Srake) and Partial rake (Prake). The Srake receiver collect energy from L strongest MPCs while the Prake collects energy from the L first MPCs. The Srake structure has been adopted in this section. Srake outperforms Prake because Srake collects more channel energy than the Prake [6].

The BER simulation results obtained using simulated UWB underground mines channel data is shown in fig. 9.

Regardless of LOS or NLOS, the BER performance of the SRAKE receivers improves with the escalating number of fingers, since increasing the number of fingers enlarges the amount of energy captured by the receiver. In fact, the performances of Prb of Fig 9 depend on the particular realization of each channel impulse response. Hence, to derive the average performance of the Selective RAKE, on should average Prb values over several realization of the channel.

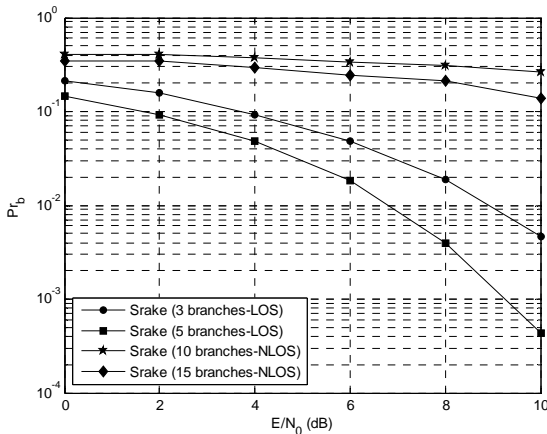


Fig. 9: Performance of Selective RAKE receiver under LOS and NLOS (underground mines environment)

Non Coherent receiver

The coherent receiver structures such as RAKE receivers provide good BER performance at the expense of high computational and hardware complexity [17]. For optimal coherent reception, several parameters need to be estimated including multipath delays, channel coefficients for each delayed multipath components.

In UWB systems, the number of multipath components is very large, while the power in each of the multipath components is very low [16]. Therefore, the estimation of delays and coefficients of the received multipath components is not a trivial task. Non coherent receivers do not require channel estimation or received pulse estimation, and exploit the rich multipath channel characteristics of the UWB channel.

Among the non-coherent UWB detectors, we consider three types which are interesting because of their performance, their robustness to channel fading, and their relative simplicity. The first one is called transmitted reference (TR). TR scheme is not a new technique but had been proposed for spread spectrum communication [18]. It has regained popularity with UWB communication systems after Hoorcar and Tomlinson [19] proposed a UWB TR system with a simple receiver structure which captures all of the energy available in a UWB multipath channel for demodulation at the receiver. TR is a

correlation receiver system; thus a TR system does not require channel estimation and has weak dependence on distortion. The second one is the Differential Transmitted Reference. DTR based on the concept of autocorrelation demodulation and differential encoding [20]. A DTR system is obtained by a simple modification to the TR system in which a reference is not transmitted separately but instead the pulse previously sent is used as a reference pulse. The third receiver is called MDTR. Chao and R. Scholtz [21] recommended a receiver configuration which generates a reference by combining *M* consecutively generated symbol waveforms in a DTR receiver.

An overview of performance of non-coherent, IR-UWB receivers specifically focussed transmitted reference schemes is given in [17], [21], [22], [23].

The performance (BER) of different receiver structures, versus bit energy per noise power ratio (E_b/N_0) is presented in figure 10.

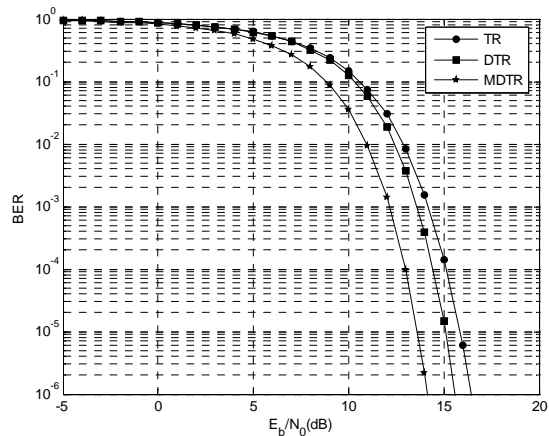


Fig. 10: Closed form curves of BEP of the three receiver structures in dense multipath environment.

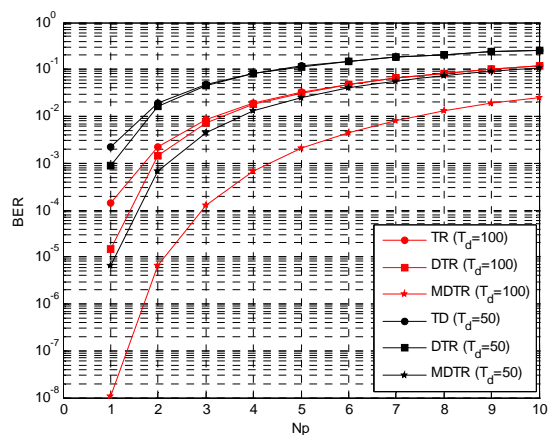


Fig. 11: Simulated bit error rates as a function of number of pulses for different non-coherent receivers in AWGN channel Bs Np and for different T_d ($E_b/N_0 = 15\text{dB}$).

In figure 11, BER performance is presented versus number of pulse and for different a multipath channel with multipath delay spread time T_d .

7. UWB Ranging in underground mines

Wireless UWB positioning techniques can provide ideal solution for locate a miner and equipment in real-time. Some potential uses include locator UWB-beacons for emergency services, traffic management, miners and asset tracking in order to increased safety and security in underground mines. The characteristics of UWB signals provide the potential of highly accurate position and location estimation. The main issue of positioning is how to achieve good estimation ranging accuracy. UWB radio seems to be a prone solution for achieving such high accuracy.

Statistical characterization of the UWB ranging

In UWB time-based range estimation, the distance calculation is corrupted by error sources such as measurement error, time synchronization, inaccuracies in the processing algorithms and the transmitter/receiver structure, multipath fading.

All of these types of errors can degrade the positioning accuracy. However, the major sources of error in time-based localization are measurement noise and NLOS propagation error. Measurement noise is usually modeled as a zero-mean Gaussian random variable, while NLOS error usually has an unknown distribution. Recently it has been shown that the NLOS error in TOA measurements can be modeled by the combination of zero mean Gaussian and Exponential distribution [24].

In order to modeling the distance measurement error in underground mines, we differentiate the small errors caused by multipath from the large errors produced by the occurrence of UDP (undetected direct path) conditions. First, assuming the actual distance between the Tx and the Rx is d ; the estimated distance (\tilde{d}) in a TOA positioning system evaluated using two step energy detectors. This estimator is used to increase the performances of the estimator. First step is a coarse search; the goal is interesting to detect the block where there is a large presence of the cluster. While the second step (fine search) is used detect the first path with more accuracy (Fig 12).

In fact, the idea of two-step ToA estimation method can be traced back to [25]. However, the authors employ

jointly energy detection and match filtering for ToA estimation. Here, both detectors use energy detection; hence, coarse and fine search could be executed in the same bank of integrators.

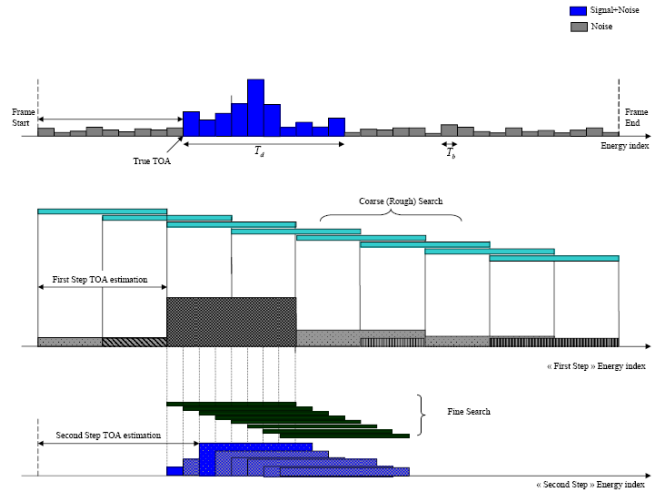


Fig. 12: Illustration of two steps ToA estimation.

In our simulation, we consider the normalized ranging error estimated using the proposed algorithm and ignore the other types of error (i.e., synchronization, thermal noise, receiver sensitivity...). Without considering these errors, the normalized ranging error between the transmitter and receiver can modeled as:

$$\tilde{d} = d + d * \psi(d) \tag{9}$$

Fig. 13 shows the Pdf of the normalized ranging error. It can be observed that Normal distribution fits well the simulated data in LOS case. However, the Weibull distribution fits well with the simulated data in NLOS case. The general formula for the Weibull distribution is given by:

$$f(x) = \frac{\gamma}{\alpha} \left(\frac{x - \mu}{\alpha} \right)^{(\gamma-1)} \exp \left\{ - \left(\frac{x - \mu}{\alpha} \right)^\gamma \right\} \tag{10}$$

where $\alpha, \gamma, \mu \in R$, $\alpha, \gamma > 0$ and $x \geq \mu$, α is scale parameter, γ is the shape parameter, and μ is the location parameter (or zero shift). The values of both distributions parameters for LOS (i.e., Normal) and NLOS (i.e., Weibull) cases were presented in Fig. 13.

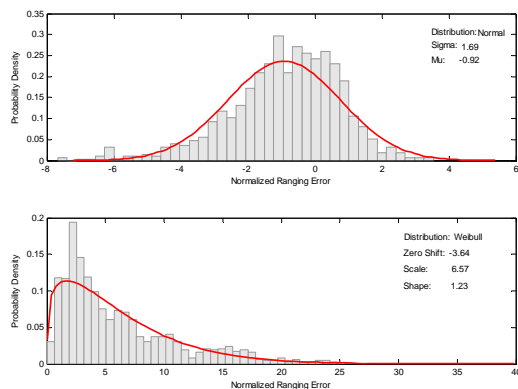


Fig. 13: Pdf characteristic of the normalized ranging error (simulated over 1000 UWB underground mines channel realizations) for both LOS (a) and NLOS (b) environments, ($E_b/N_0=10\text{dB}$).

8. Conclusion

Ultra-wideband technology is revolutionizing the wireless industry by opening doors for new applications as well as complementing existing wireless systems. With UWB's distinctive properties due to its ability to simultaneously provide both communications and positioning, make it particularly attractive for industrial mining applications.

In the next few years, UWB will become a viable, competitive wireless technology for transmitting information rates with high rate data over short distances and low. In Fact, UWB-wireless communication can potentially improve process operations, product quality, and productivity, boost the safety of mining and improve rescue operations during disasters. However, UWB wirelesses for underground mining automation have unfortunately been poorly investigated.

This paper we explored the fundamentals of UWB technology with particular emphasis on impulse radio (IR) techniques. The goal is to provide an investigation of using UWB technology in industrial mining applications for communication and ranging (localization). More generally, the analysis discussed in this paper can be considered to provide an opening for future computer and communications research in UWB communication in underground mining environments.

The results presented herein (with other works) are currently exploited in the design of wireless local area networks communication and for localization applications in underground mining environments.

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