Research Article

Low-Power and Reliable Communications for UWB-Based Wireless Monitoring Sensor Networks in Underground Mine Tunnels

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This paper investigates the bit-error-rate (BER) and maximum allowable data throughput (MADTh) performance of a novel low-power mismatched Rake receiver structure for ultra wideband (UWB) wireless monitoring sensor networks in underground mine tunnels. This receive node structure provides a promising solution for low-power and reliable communications in underground mine tunnels with more than 90% reduction in power consumption. The BER and MADTh of the proposed receive nodes are investigated via Monte-Carlo simulations in UWB line-of-sight (LOS) and non-line-of-sight (NLOS) underground mine tunnels. The proposed mismatched receive nodes achieve a MADTh and BER performance approaching the corresponding optimal nodes with ≈1 dB and 1.5 dB BER performance degradation in LOS and NLOS scenarios, respectively. The mismatched PRake (M-PRake) receiver model with \( L_p = 5 \) represents the best choice for low-power and reliable communications in sensor networks in underground mine tunnels with BER performance degradation of 1 dB and 3 dB in LOS and NLOS scenarios, respectively, as compared to the optimum detector. This minimal degradation in performance is traded for more than 90% reduction in power consumption.

1. Introduction

Underground mines are characterized by their hazardous and complex nature. In particular, they are characterized by being flammable environments, and thus they require reliable networking and communication systems for safe operation. Due to this tough nature, transmission power and power consumption are two main limitations for communications in such environments [1, 2]. Typically, wireless sensor monitoring networks are crucial in underground mine channels, and they are mostly used for emergency response in critical cases. Thus, low-power communication techniques that provide reliable transmission are essential for safe and productive working conditions in underground mines [3–5].

Ultra wideband (UWB) technology has been proposed in the literature as one of the efficient data transmission techniques in underground mines. In particular, it has been proposed for communications in critical cases, such as worker safety, remote control, and wireless monitoring networks [5–9]. Typically, UWB technology provides high data-rate, low-power, and robust communications in dense multipath environments. These advantages make it an attractive candidate for the application in underground mines [10–12].

The design of a power efficient UWB receiver that provides robust performance is a challenging task, as reduced power consumption is generally traded for bit-error-rate (BER) performance degradation. Ideal all-Rake (ARake)
coherent receiver is the optimal detector in multipath environments, which typically captures the energy in all multipath components. However, the robust BER performance is traded for high complexity and high power consumption of this receiver structure. Other low-complexity Rake receiver alternatives have been proposed in the literature for UWB communications, such as partial-Rake (PRake) and selective-Rake receivers. However, the analog-to-digital converter (ADC) power consumption and template generation remain as the bottleneck of the power-consumption reduction [13, 14].

On the other hand, noncoherent receivers, such as transmitted reference (TR) and energy detection (ED) receivers, do not require the generation of template pulses; thus they are less complex as compared to Rake receivers. But, again low-power consumption is traded for BER performance degradation. The receiver structures studied in the literature for UWB communications in underground mine channels included TR and ARake receivers, but both receivers have limitations for operation in underground mine channels. ARake receivers require high power consumption, and TR receivers do not provide sufficiently reliable communications required in such hazardous environments [15, 16].

Intuitively, coherent detectors seem more promising for operation in underground mines, but they require efficient power-consumption reduction techniques. In this paper we propose and investigate the performance of low-power UWB-based Rake receiver structures that provide low-power consumption with minimal BER performance degradation as compared to the optimal detectors in underground mine channels and compare them to the optimal Rake and suboptimal noncoherent detectors in underground mine tunnels. The proposed receiver structure is based on analog wavelet template-based correlators, which consume less power as compared to the commonly used Gaussian template-based detectors. Yet, they provide an approaching performance to the optimal detectors.

In [17], we provided theoretical analysis of BER and data-throughput of green-radio receiver model for in-mine communications. In this paper, we provide a comprehensive study and comparison of the models proposed in the literature, namely, optimum rake receivers and low-power transmitted receiver model, in addition to novel Rake receivers based on low-power analog correlation with suboptimal templates and finding the optimum solution for both reliable communications and low-power consumption in wireless monitoring sensor networks in underground mine tunnels in line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. More specifically, low-power wavelet template-based Rake receiver models, namely, partial rake (P-RAKE) and selective-rake (S-RAKE) receiver models, are considered. We assume binary equally probable pulse position modulation (EC-PPM) scheme. The performance of these models is studied and compared to the optimal highly complex A-Rake and corresponding PRake and SRake receivers models with Gaussian templates. We further compare the performance to the suboptimal TR receiver, which was proposed in the literature for communications in underground mines. The rest of the paper is organized as follows. Section 2 introduces the system model and proposed receiver structure. Section 3 describes the UWB-based mine channel model for LOS and NLOS scenarios. Section 4 introduces the BER and MADTh performances of the receivers under investigation. Section 5 provides numerical results, and Section 6 gives the paper conclusions.

2. System Model

This Section describes the system model. Typically, the most commonly used pulse in UWB systems is the Gaussian pulse. The zeroth order Gaussian pulse is defined as [18]:

\[ \omega_0(t) = \exp\left(-2\pi \left(\frac{t^2}{T_p^2}\right)\right), \]

where \( T_p \) is the pulse-width and \( r_p = 0.5 * T_p \). The corresponding \( n \)th order Gaussian pulse is given by [7]:

\[ \omega_n(t) = \frac{d^n}{dt^n}\left(\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{t^2}{2\sigma^2}}\right), \]

where \( \sigma^2 = T_p^2/2\pi \). Generally, the selected pulse parameters must comply with the Federal Communication Commission (FCC) mask. In our system, we select the eighth order Gaussian pulse. The selection of the eighth order Gaussian pulse is to comply with FCC regulations and to maximize the normalized cross-correlation coefficient \( \beta_{\text{eq}} \) of the selected pulse and the wavelet template. Assuming equally-probable pulse-position modulation (EC-PPM) scheme, the typical modulated signal is defined by [19]:

\[ s(t) = \sum_{j} \omega(t - jT_j - a^j \tau_{\text{min}}), \]

where each \( s(t) \) represents the \( i \)th signal in an ensemble of \( M \) signals. Each signal is completely identified by a sequence of time shifts \( a^j \tau_{\text{min}} \in \{0, \tau_{\text{min}}\} \), where \( a^j \) takes 0 and 1 values representing the \( i \)th cyclic shift of \( m \)-sequence of length \( N_j \). The frame period is \( T_j \), and \( j \) is the number of transmit pulses. The selection of the time shifts allows for the choice of \( M \)-ary equally-correlated PPM signals [19].

Underground mine tunnels are complex environments, which are rich in multipath components. The optimum detector in complex multipath channels is the optimum ARake receiver, where it captures the energy present in all multipath components. However, for UWB communications, the channels become highly frequency selective, and the number of resolvable paths is huge. Thus, such a receiver structure requires a very large number of Rake fingers. Alternate low-complexity Rake structures have been proposed in the literature, such as PRake and SRake receivers. Ultimately, these receivers save power and complexity as compared to ARake receiver [20]. However, low-complexity is traded for performance degradation [21]. Noncoherent receiver alternatives, such as TR and ED receivers, save power, but at the expense of highly degraded performance.

Communications in underground mine channels on the other hand require not only low-power consumption, but also...
a reliable performance. More specifically, the implementation technique of the receiver will have a great impact on the power consumption.

The main implementation categories proposed in the literature for UWB receivers are all-digital, analog, and partially-analog implementation techniques [22, 23]. The most power demanding approach is the all-digital implementation approach, where the complexity is directly affected by the high sampling frequency of UWB signals, which is typically on the order of tens of Gigahertz. This in turn will put high restrictions on the ADC power consumption and will consequently present a major challenge for UWB system power consumption. Typically, for UWB systems the analog approaches are more convenient due to the ultra wide bandwidth, which reduces the minimum required sampling rate and consequently the power consumption [23, 24]. An ADC used in the all-digital implementation approach with a figure of merit of approximately 4e11 requires a power consumption of≈160mW for 4-bit and 4 GSample/sec sampling rate [24]. Typically, for low-power approaches, a simple template is preferred in correlator receivers [13, 14].

Considering the analog implementation approach of correlator receivers, the analog Gaussian pulses are generally hard to generate in the analog domain and require high power consumption. For instance, the power consumption reported in the literature for the fifth order Gaussian pulse in the analog domain is 95 mW [25]. On the other hand, wavelet UWB pulses can easily be generated in the analog domain and consume much less power as compared to Gaussian pulses, on the order of 1µW, which leads to more than 90% power saving [26, 27]. In addition, with the careful selection of the pulse parameters, they can ultimately resemble the Gaussian monocycles. Analog wavelets are typically implemented using a single scale of the continuous-wavelet transform by constructing a linear system of the impulse response which matches a time reversed and shifted Gaussian wavelet function [26, 27].

The impulse-response of the linear filter is given by [27]:

$$h_w(t) = \frac{1}{\sqrt{\sigma_p}} \psi \left( \frac{-t}{\sigma} \right),$$  (4)

where $\sigma_w$ is a fixed scale and $\psi(t)$ is the wavelet function.

There have been multiple pulses proposed in the literature for the analog implementation of wavelet pulses, such as Morlet, Mexican Hat, Gaussian, and Daubechies wavelets [27, 28].

In this paper, we investigate a mismatched Rake (MRake) receiver structure for reliable communications in underground mine tunnels, line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. The MRake receiver basically employs the low-power wavelet pulse $\psi(t)$ as the correlation template. With a careful selection of the template pulse parameters, the performance degradation is minimal as compared to the optimal Rake receiver. Figure 1 shows the schematic diagram of the MRake receiver. In this receiver, the correlation is performed in the analog domain [29], and thus the ADC requirements are greatly relaxed. The wavelet template pulse parameters should be selected in such a way to maximize the normalized cross-correlation coefficient with the transmitted pulse. Without loss of generality, we assume the Gaussian wavelet pulse. Figure 2(a) shows a comparison

![Figure 1: Block diagram of the mismatched Rake-based receive node.](image-url)
between the eighth order Gaussian pulse and Gaussian wavelet with adjusted parameters to resemble the transmitted Gaussian pulse. The corresponding cross-correlation of the two pulses is compared to the autocorrelation of the eighth order Gaussian pulse in Figure 2(b). As can be seen, the wavelet pulse properly resembles the eighth order Gaussian pulse, and this is obvious from the cross-correlation of both pulses, which is very close to the autocorrelation of the eighth order Gaussian pulse. The obtained normalized cross-correlation coefficient for the selected pulses is 0.9989.

The normalized autocorrelation function \( \beta_\omega(\tau) \) of the transmitted Gaussian monocycle \( \omega(t) \) is calculated as

\[
\beta_\omega(\tau) = \frac{1}{E_\omega} \int_{-T/2}^{T/2} \omega(t) \omega(t - \tau) dt, \tag{5}
\]

where \( E_\omega \) is the pulse energy. The normalized cross-correlation of the transmitted pulse \( \omega(t) \) and mismatched receiver template \( \psi(t) \) function is calculated as

\[
\beta_{\omega\psi}(\tau) = \frac{1}{\sqrt{E_\omega \sqrt{E_\psi}}} \int_{-T/2}^{T/2} \omega(t) \psi(t - \tau) dt, \tag{6}
\]

where \( T \) is the window-length and \( E_\psi \) is the wavelet template pulse energy.

### 3. Channel Model

Recently, many measurement campaigns have been conducted in order to characterize the UWB mine tunnel channel. Most of these measurement campaigns were conducted in the Canadian Centre for Minerals and Energy Technology (CANMET), which represents a physical environment for unground mine channels. In these measurement campaigns, both fading statistics and propagation loss were modeled. According to [3, 4, 30] the path-loss model was found to be normally distributed on the decibel (dB) scale; that is, the large-scale fading has a lognormal distribution. The path-loss is modeled as follows [4, 31, 32]:

\[
PL(d) = PL_0(d_0) + 10n \log\left( \frac{d}{d_0} \right) + X_\sigma, \tag{7}
\]

where \( PL(d) \) is the path-loss in decibel measured at distance \( d \), \( PL_0(d_0) \) is the mean path-loss, also in decibel, at reference distance \( d_0 \), \( n \) is the path-loss exponent, and \( X_\sigma \) represents the shadowing effect and is modeled as a Gaussian random variable in decibel with zero mean [4, 31, 32].

For LOS scenario, the mean path-loss at reference distance \( d_0 \) is \( PL_0 = 48.97 \) dB, and the path-loss exponent \( n = 1.8 \). Whereas for NLOS scenario, the mean path-loss at reference distance \( d_0 \) is \( PL_0 = 86.90 \) dB, and the path-loss exponent \( n = 4.01 \) [3, 32].

On the other hand, for small-scale fading characterization, UWB mine tunnels are dense multipath channels, in which many obstacles are present that cause the signal to be reflected. Mine UWB channels follow the IEEE 802.15.3a channel model with special parameters. According to the IEEE 802.15.3a channel model, it is characterized by being based on the cluster approach proposed by Saleh and Valenzuela (S-V) model. The S-V model is based on the fact that multipath contributions generated by the same pulse arrive at the receiver grouped into clusters. The time of arrival of cluster is modeled as a Poisson arrival process with rate \( \Lambda \), and it is given by [15, 33]:

\[
P\left( \frac{T_n}{T_{n-1}} \right) = \Lambda e^{-\Lambda(T_n-T_{n-1})}, \tag{8}
\]
where \( T_n \) and \( T_{n-1} \) are the time of arrival of the \( n \)th and \((n-1)\)th cluster, respectively. Within each cluster, subsequent multipath components also arrive according to a Poisson process with rate \( \lambda \), which is given by [15, 33]:

\[
p \left( \frac{T_{nk}}{T_{(n-1)k}} \right) = \lambda e^{-\lambda(T_{nk}-T_{(n-1)k})}, \tag{9}\]

The IEEE 802.15.3a channel impulse response is given by [15, 33]:

\[
h(t) = X \sum_{n=1}^{N} \sum_{l=1}^{L(n)} \alpha_{nk} \delta(t - T_n - \tau_{nk}), \tag{10}\]

where \( X \) is a random variable that represents the magnitude of channel gain, \( N \) is the observed number of clusters, \( L(n) \) is the received number of multipath in the \( n \)th cluster, and \( \alpha_{nk} \) are coefficients of the \( l \)th path in the \( n \)th cluster. \( T_n \) is the arrival time of the \( n \)th cluster and \( \tau_{nk} \) is the \( l \)th path delay in the \( n \)th cluster [15, 33].

The distribution of arrival times is the modified Poisson distribution, and \( \theta_n \) are assumed to be, a priori, statistically independent uniformly distributed random variables \([0, 2\pi)\) [4, 34]. Most of the measurements conducted in the literature for UWB underground mine channels reported that the best fit for amplitude distribution is Ricean for LOS scenario and Rayleigh for NLOS scenario [4, 30, 34]. According to [35], the average Ricean \( K \)-factor is 17.60 dB for LOS scenario.

4. BER Performance and Maximum Allowable Data Throughput

In this section, we investigate the performance of ARake receiver structure. For optimum correlator, the probability of bit error of EC-PPM in additive-white-Gaussian-noise (AWGN) channel is given as

\[
P_b = Q \left( \sqrt{\frac{E_1 + E_2 - 2\beta_{w_{min}} \sqrt{E_1 E_2}}{2N_0}} \right), \tag{11}\]

where \( E_1 \) and \( E_2 \) are the bit energies of the bits 1 and 0, respectively. For equal energy signals, \( E_1 = E_2 = E_b \). Consider

\[
P_b = Q \left( \sqrt{\frac{E_b}{2N_0}} \left(1 - \beta_{w_{min}}\right) \right), \tag{12}\]

where \( E_b \) is the bit energy and \( N_0 \) is the two-sided Gaussian noise power-spectral density (PSD). \( \beta_{w_{min}} = \beta_w(\mu_{opt}) \) and \( \delta_{opt min} \) are given by

\[
\mu_{opt} = \arg \left\{ \min_{\mu} \beta_{w}(\mu) \right\}. \tag{13}\]

The BER performance of mismatched correlator receiver assuming binary EC-PPM (EC-BPPM) scheme is given by

\[
P_b(E) = Q \left( \sqrt{\frac{E_b}{2N_0}} \left( \beta_{w_{max}} - \beta_{w_{min}} \right) \right), \tag{14}\]

where \( \beta_{w_{max}} = \beta_{w}(\delta_{opt max}) \), \( \beta_{w_{min}} = \beta_{w}(\delta_{opt min}) \), and \( \delta_{opt max} \) and \( \delta_{opt min} \) are given by (15) and (16), respectively:

\[
\delta_{opt max} = \arg \left\{ \max_{\delta} \beta_{w}(\delta) \right\}, \tag{15}\]

\[
\delta_{opt min} = \arg \left\{ \min_{\delta} \beta_{w}(\delta) \right\}. \tag{16}\]

Figure 3 shows a comparison of the BER performance of optimal and mismatched template correlation receivers.

In dense multipath channels, the BER is hard to evaluate. Usually, it is estimated via averaging the BER performance obtained via Monte-Carlo simulations over \( N_{ch} \) realizations of the channel under investigation:

\[
P_{min}(z) = \frac{1}{N_{ch}} \sum_{k=1}^{N_{ch}} Q \left( \frac{\text{SNR} \cdot \sigma_{k,i}^2(z)}{2} \right). \tag{19}\]
Figure 4: BER performance of O-ARake and M-ARake receive nodes in LOS underground mine tunnels for EC-BPPM modulation scheme.

Figure 5: BER performance comparison of O-ARake and M-ARake receive nodes in NLOS underground mine tunnels for EC-BPPM modulation scheme.

Figure 6: BER performance of O-SRake and M-SRake receive nodes in LOS underground mine tunnels for EC-BPPM modulation scheme.

\[
N_{ch} \text{ is the number of channel realizations, SNR is the signal-to-noise-ratio, } d_{\text{min}}(z) = \min_k d_{kj}(z) \text{ is the minimum normalized distance, } k^* = \arg\min_i d_{k,i}^2(z), \text{ and } k \text{ is the argument of the minimization [36, 37].}
\]

Maximum throughput is the maximum achievable data-rate for specific modulation technique, transmit power, and target BER [38, 39]. The maximum allowable data throughput (MADth) for a specific modulation scheme as given in [38] is

\[
R_{b, \max} = \frac{1}{E_b} P_t \left( \frac{\lambda_c}{4\pi d} \right)^n, \tag{20}
\]

where \( P_t \) is the maximum allowable transmit power = \( P_{sd} \times \) B.W., \( P_{sd} \) is the maximum allowable power spectral density = –41 dBm/MHz, B.W. is the bandwidth, \( d \) is the range in meter, and \( \lambda_c \) is the carrier wavelength. For the maximum allowable UWB B.W. of 7500 MHz, the corresponding central frequency is \( f_c = 6.85 \) GHz, and \( \lambda_c = 3 \times 10^3/f_c \).

5. Numerical Results

This section provides numerical results based on the analysis introduced in Section 4 as well as Monte-Carlo simulations of the system under investigation in UWB-based underground mine tunnels for LOS and NLOS scenarios. First, we compare the BER performance of ARake receivers assuming optimal template (O-ARake) and mismatched wavelet template (M-ARake) in LOS scenario as shown in Figure 4. As can be seen, the O-ARake receiver outperforms the corresponding M-ARake with \( \approx 0.5 \) dB for a target BER = \( 10^{-2} \). Figure 5 shows a similar BER performance between O-ARake and O-MRake receivers in NLOS scenario. As can be seen, the difference is \( \approx 1.5 \) dB for the same target BER.

Then, we consider the low-complexity receiver alternative SRake receiver, which combines the instantaneously strongest \( L_s \) multipath components, and thus it is less complex as compared to the ARake model [40]. We compare the BER performance of the proposed low-power receiver structure assuming SRake receiver (M-SRake) to the corresponding optimal receiver structure (O-SRake). Figure 6 compares the BER performance of the optimal SRake (O-SRake) and mismatched SRake (M-SRake) structures in LOS channel model for number of fingers \( L_s = 2 \) and 5. The figure shows that the difference in performance between the O-SRake and M-SRake is \( \approx 1 \) dB for \( L_s = 2 \) and 5. Similarly,
Figure 7: BER performance comparison of O-SRake and M-SRake with \( L_s = 2 \) and 5 fingers receive nodes in NLOS underground mine tunnels for EC-BPPM modulation scheme.

Figure 8: BER performance of O-PRake and M-PRake with \( L_p = 2 \) and 5 fingers receive nodes in LOS underground mine tunnels for EC-BPPM modulation scheme.

Figure 9: BER performance comparison of optimal and M-PRake assuming \( L_p = 2 \) and 5 fingers receive nodes in NLOS underground mine tunnels for EC-BPPM modulation scheme.

Figure 7 compares the BER performance of the same receivers in NLOS channel model. Also, the difference in performance between the O-SRake and M-SRake is \( \approx 0.9 \) dB.

Also, we investigate the BER performance of the low-complexity alternative PRake receiver model, which captures the first arriving \( L_p \) multipath components [40]. So, it is less complex than both the ARake and SRake models. Figures 8 and 9 show a BER performance comparison between the optimal PRake (O-PRake) receiver and the PRake receiver using the mismatched wavelet template (M-PRake) in LOS and NLOS scenarios, respectively. As can be noticed from figures, O-PRake outperforms the corresponding M-PRake by \( \approx 1 \) dB and 1.5 dB in LOS and NLOS scenarios, respectively.

Then, we compare the BER performance of all the aforementioned receiver models to the noncoherent TR receiver, which was investigated in the literature for operation in underground mine tunnels. The TR receiver model, shown in Figure 10, transmits the reference signal along with the information data instead of locally generating it at the receiver [15]. Figure 11 shows a BER performance comparison of all optimal template-based receivers and TR receiver in LOS channel model. As can be seen Rake receivers outperform the TR receiver. Also, O-SRake and O-PRake with 5 fingers give an approaching performance to the O-ARake model. Figure 12 shows a BER performance comparison of the same receiver models in NLOS scenario. Also, Rake receiver models outperform the TR receiver. O-PRake and O-PRake give approaching performance to O-ARake with performance degradation of \( \approx 0.5 \) dB and 1.5 dB, respectively. Whereas, the performance degradation caused by the TR model is \( \approx 9 \) dB as compared to the O-ARake model. Similarly, Figures 13 and 14 compare the BER performance of all mismatched Rake receiver models to the TR model in LOS and NLOS channel, respectively. Also, all mismatched Rake models outperform the TR receiver in both scenarios, and M-SRake and M-PRake with 5 fingers achieve an approaching performance to the M-ARake model. The performance degradation of the M-SRake as compared to M-ARake receiver is \( \approx 0.5 \) dB and 0.1 in LOS and NLOS scenarios, respectively. The corresponding degradation in performance caused by M-PRake receiver with \( L_p = 5 \) as compared to M-ARake receiver is \( \approx 0.5 \) and 1.5 dB in LOS and NLOS scenarios, respectively.

Finally, we compare the MADTh of all receiver models under investigation for the same target BER = \( 1 \times 10^{-2} \).
Figures 10 and 11 compare the BER performance of O-SRake and O-PRake with 2 and 5 fingers, O-ARake, and TR receive nodes in LOS underground mine tunnels for EC-BPPM modulation scheme.

Figures 12 and 13 compare the BER performance of M-SRake and M-PRake with 2 and 5 fingers, M-ARake, and TR receive nodes in NLOS underground mine tunnels for EC-BPPM modulation scheme.

Figures 15 and 16 compare the MADTh of all optimum receiver structures in LOS and NLOS channels, respectively. As can be seen, at a distance of 1 m, the MADTh in LOS scenario is in the order of Gigabits/second; whereas in the NLOS scenario, this value reduces to few tens of kilobits/second. This is due to the fact the underground mines are generally complex environments, and in NLOS they tend to become more complex, and thus this highly affects the attainable
MADTh. In LOS scenario, O-ARake, O-Srake with \( L_s = 5 \), and O-PRake with \( L_p = 5 \) fingers achieve approaching MADTh \( \approx 38.5 \text{ Gbps} \). Whereas, O-SRake with \( L_s = 2 \) and O-PRake with \( L_p = 2 \) achieve MADTh \( \approx 15 \text{ Gbps} \), and TR receiver achieves 4 Gbps MADTh. In NLOS scenario, O-ARake achieves 50 Gbps, and O-Srake with \( L_s = 5 \) achieves a slightly lower MADTh = 46 kbps, and O-PRake with \( L_p = 5 \) achieves MADTh = 36 kbps. TR receiver achieves \( \approx 6 \text{ kbps} \).

Considering the proposed mismatched receiver architectures, Figures 17 and 18 compare the MADTh of the all mismatched Rake models and TR receiver. As can be seen from figures, all mismatched Rake models achieve an approaching MADTh to the optimal Rake models in both LOS and NLOS scenarios with an average degradation of 5 Gbps in LOS scenario and 10 kbps in NLOS scenario.

Based on the results obtained from both the BER and MADTh performances, the M-PRake receiver model with
\(L_p = 5\) is the best choice for low-power and reliable communications in underground mine tunnels. The BER performance degradation is 1 dB in LOS scenario and 3 dB in NLOS scenario as compared to the O-ARake receiver. Also, the difference in MADTh is \(\approx 7\) Gbps in LOS scenario and 25 kbps in NLOS scenario as compared to O-ARake receiver. This minimal degradation in performance is traded for more than 90% reduction in power consumption.

6. Conclusions

This paper investigated the BER and MADTh performance of a low-power mismatched Rake UWB-based receive nodes for reliable communications in wireless sensor monitoring networking in underground mine tunnels. The proposed structure was investigated for ideal, partial, and selective Rake receivers and was shown to achieve an approaching performance to the corresponding optimal receiver structures with minimal performance degradation. It was also compared to the TR receive nodes proposed in the literature for communications in underground mines. Generally, the mismatched Rake receiver structure was shown to achieve an approaching performance to the optimal Rake and outperform the TR receiver structure. Based on the trade-off between performance on power consumption, the M-PRake structure with \(L_p = 5\) fingers was shown to represent the best choice for reliable and low-power communications in underground mine tunnels.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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