Transmission Performance Investigation of IR-UWB Signals over Existing optical fiber Transmission link

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ABSTRACT
Recently there is increasing interest in using optical fiber links to distribute impulse radio-ultrawideband (IR-UWB) signals in order to increase the coverage area. This paper investigates the transmission performance of these signals over existing fiber links and addresses the possibility of increasing the coverage area beyond 30 km. The transmission link consists of a single-mode fiber, dispersion compensating fiber (DCF) and, optical amplifiers. Simulation results are presented using Optisystem (version 13.0) software package for both Gaussian monocycle and 5th-order derivative Gaussian systems, each operating with ON-OFF keying (OOK) and biphase modulation (BPM) formats. The results reveal that extending the coverage area for 625 Mb/s UWB signal toward 100 km is possible for the UWB signals and modulation formats adopted in this study.

Indexing terms/Keywords
IR-UWB -over- fiber; radio-over-fiber.

Academic Discipline And Sub-Disciplines
Optical Communications

SUBJECT CLASSIFICATION
UWB-over-Fiber

TYPE (METHOD/APPROACH)
Analysis and simulation
1- INTRODUCTION

Ultra wide band (UWB) communication is an emerging technology that uses very low energy levels for transmitting data over a wide portion of the radio spectrum [1,2]. This technology has attracted increasing interest in recent years for short range high speed wireless communication over high bandwidth within unlicensed spectrum (3.1-10.6 GHz) as specified by the Federal Communicating Commission (FCC) [3,4]. The UWB-based communication is characterized by low interference to existing wireless systems due to its very low signal-to-noise ratio (SNR) operation and extremely low radiation power spectral density (PSD) (below -41.3 dBm/MHz) [3,5]. Modern UWB communication systems may be realized in the impulse form leading to the concept of impulse radio (IR) UWB transmission. Here, information is carried in a set of narrow pulses of electromagnetic energy where the bandwidth is approximately proportional to the pulse width [4,6]. Different applications based on IR-UWB communication have been emerged such as wireless body sensor networks [5], interchip data transmission [7], high resolution ranging system [8,9], wireless sensor network synchronization [10], and in-building network applications [1]. These applications are driven by the progress reported in the design of IR-UWB transmitters capable of shaping the power spectrum of the UWB signal to mitigate mutual interference [11,12] and receivers with narrow band interference mitigation capabilities [13,14].

However, one fundamental limitation of IR-UWB technology is the extremely low power density which restricts the coverage distance to a few or tens of meters. One solution to extend the transmission distance is to take advantages of optical fiber, such as low loss, large bandwidth and immunity to electromagnetic interference [4,15]. This leads to new communication technology called UWB-over-fiber (UWBoF) which attracts increasing interest in recent years [16,17]. This new technology can be considered as interdisciplinary field combining the best of the optical and wireless words and makes use of the concepts behind optical fiber-based access technologies such as fiber-to-the-home and fiber-to-the-building [3]. Impulse radio UWBoF communication exhibits additional features such as [3,18]

(i) No RF carrier modulation is required at the transmitter side, the signal is transmitted through the fiber in UWB native format.

(ii) No RF up-conversion is required at the receiver side. The UWB signals can simply photodetected, filtered and radiated to establish a wireless communication.

The transmission performance of IR-UWB signals over fiber link has been investigated both theoretically and experimentally in the literature. The main point under investigation was to photonically generate IR-UWB signals and address its transmission characteristics on single-mode fiber (SMF) or multi-mode fiber. For example, Pan and Yao [19] presented a comprehensive study on the implementation of multiple modulation schemes in an UWBoF system based on a polarization modulation and an electrical reconfigurable field combining the best of the optical and wireless words and makes use of the concepts behind optical fiber-based access technologies such as fiber-to-the-home and fiber-to-the-building [3]. Impulse radio UWBoF communication exhibits additional features such as [3,18]

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\[
g_i(t) = \sum_{n=0}^{N} g(t - kT_0) \tag{1a}
\]

where \(T_0\) is the repetition period and \(g(t)\) is a single Gaussian pulse.
In eqn. 1b, $\tau$ represents the full-width of the Gaussian pulse corresponding to $e^{-1}$ point. The full-width at half-maximum (FWHM) 

$$(\Delta t)_{\text{FWHM}} = \sqrt{\ln 2} \tau = 0.833\tau$$

\[ g(t) = e^{\frac{-2t^2}{\tau^2}} \]  

\[ (1b) \]

**Fig. 1:** Block diagram of the optical IR-UWB transmitter.

The output of the AWG, corresponding to train of $n^{th}$ order derivative Gaussian pulses, is given by

\[ g_{nz}(t) = \sum_{n=-\infty}^{\infty} g_n(t) \]  

where

\[ g_n(t) = \frac{d^n}{dt^n} g(t) \]  

\[ (2a) \]

\[ (2b) \]

The output of the electronic switch can be expressed

\[ e_o(t) = d(t) g_{nz}(t) \]  

where $d(t)$ represents the binary data as follow

\[ d(t) = \begin{cases} 1 & \text{OOK} \\ 0 & \text{} \end{cases} \]
The bipolar switch used to generate the BPM signaling can be implemented using two unipolar switches as shown in Fig. 2.

The RF signal $e_0(t)$ is used to modulate the intensity of a continuous wave (CW) semiconductor laser using external modulator. The power of the modulated optical carrier at the modulator output can be written as

$$p(t) = P_0[1 + m e_0(t)]$$

where $P_0$ is the CW laser power and $m$ is the modulation index.

The optical IR-UWB receiver is essentially an energy detector and can be modeled by a photodiode followed by an electrical signal processing unit as shown in Fig. 3.

![Fig. 2: Simplified block diagram of the bipolar switch. The binary data $\overline{d(t)}$ is obtained from $d(t)$ through logical NOT operation.](image-url)
Fig. 3: Block diagram of the IR-UWB receiver.

The radiated RF signal will be detected by the corresponding IR-UWB receiving antenna. The resultant RF signal is then down converted to the baseband using RF mixing with local oscillator (LO). The LO is assumed to be fully synchronized with one of the harmonics of the Gaussian pulses using phase-locked loop technique. The mixer output is filtered using a low pass filter having a cutoff frequency equals to (0.75×bit rate) to reject unwanted frequencies. The filtered signal is then DC-blocked to remove the DC component before applying to a baseband digital (binary) receiver. This device compares the sample value of the bit under observation with a threshold level to decide the logic of the detected bit (i.e., logic 1 or logic 0).

The Gaussian train of pulses described by eqn. 1a can be expanded using Fourier series

$$g_s(t) = \frac{1}{T_0} \sum_{k=1}^{\infty} a_k \cos(k \omega_s t + \phi_k)$$

where $\omega_s = 2\pi f_0 = 2\pi / T_0$ is the fundamental radian frequency and

$$a_k = \frac{2}{T_0} \int_0^{T_0} g(t) \cos(k \omega_s t) \, dt$$

the $n^{th}$-order derivative pulse series (eqn. 2a) can be expanded as

$$g_{ns}(t) = \sum_{k=1}^{\infty} A_k \cos(k \omega_s t + \phi_k)$$

where $A_k$ is the amplitude of the $k^{th}$-harmonic of $g_{ns}(t)$ and

$$A_k = (k \omega_s)^n a_k$$

$$\phi_k = \omega_s k T_0 + n \pi / 2$$

Note that both $g_s(t)$ and $g_{ns}(t)$ waveforms have the same repetition period $T_0$ and they are periodic functions of time. However, $g_{ns}(t)$ has no DC component since it is generated from $g_s(t)$ after applying differentiation process. Note further, $g(t)$ according to eqn. 1b is a real even function of time. Therefore, $\phi_k$ and $\phi_k = 0$ for all values of $k$ ($k \geq 1$).

The Fourier series coefficients $a_k$ are proportional to the amplitudes of the samples obtained by sampling the Fourier transform of $g(t)$ at $kT_0$ instances. The Fourier transform of the $g(t)$ is given by
\[ G(\omega) = \sqrt{\frac{\pi}{2}} \tau \exp\left(\frac{-\omega^2 \tau^2}{8}\right) \]

(9)

Note that \( G(0) = \sqrt{\frac{\pi}{2}} \tau \) and the e\(^{-1}\) bandwidth is given by \( \Delta \omega = \frac{2}{\tau} \). The FWHM bandwidth is related to \( \Delta \omega \) by

\[ (\Delta \omega)_{FWHM} = \sqrt{\ln 2} \Delta \omega = 0.833 \Delta \omega. \]

Therefore

\[ (\Delta \omega)_{FWHM} = \frac{2 \ln 2}{\Delta \omega}. \]  

(10)

It is clear from eqn. 9 that \( a_k \) is proportional to \( \exp\left(\frac{-\tau \omega^2}{8}\right) \) and hence it is positive and a decreasing function of \( k \). According to eqn. 8

\[ A_k \propto (k \omega_0)^k \exp\left(\frac{-\tau \omega^2}{8}\right) \]  

(11)

where the symbol \( \alpha \) denotes proportionality.

Note that \( A_k \) is the product of two terms, one is an increasing function of \( k \) while the other is a decreasing function of \( k \). Therefore, there is a certain value of \( k \) which maximizes \( A_k \). This can be obtained by considering \( k \) as a continuous variable and setting \( dA_k / dk \) to zero

\[ \frac{(k \omega_0)^k}{4} \cdot \exp\left(\frac{-\tau \omega^2}{8}\right) - \left[ \exp\left(\frac{-\tau \omega^2}{8}\right) \cdot (n \omega_0^2 h - 1) \right] = 0 \]

This leads to

\[ \frac{(k \omega_0)^2}{4} = n \]

Therefore

\[ k = \frac{\sqrt{4n \omega_0^2}}{\sqrt{T}} \]

(12)

Equation 12 reveals that the order of the highest-level harmonics increases with \( \sqrt{n} \). For monocycle and \( n^{th} \)-order derivative Gaussian pulses, the values of \( k \) corresponding to the highest-level harmonics are related by \( k_5 / k_1 = \sqrt{5} \).

The analysis can be carried further to describe the generated photocurrent. For seek of simplicity, the effect of fiber (losses, dispersion and nonlinear fiber optics) and system noise (amplifier spontaneous emission noise and receiver thermal noise) are neglected. Under this optimistic situation, the photocurrent is given by

\[ i_{ph}(t) = R \dot{p}(t) \]

(13a)

where \( R \) is the photodiode responsitivity. Using eqns. 3a and 4 into eqn. 13a leads to

\[ i_{ph}(t) = R \dot{P}_o \left[ 1 + m d(t) g_h(t) \right] \]

(13b)

After blocking the DC component

\[ i_p(t) = R m d(t) \sum_{k=1}^{\infty} A_k \cos(k \omega_0 t + \phi_k) \]  

(14)

Equation 14 characterizes that the photocurrent is a series of double-side band suppressed carrier (DSB/SC) signals generated by modulating the harmonics of the \( n^{th} \)-order derivative Gaussian pulse train by the data \( d(t) \). The data can be recovered from any DSB signal using a coherent (synchronous) demodulation based on mixing the received signal with LO which is synchronized with one of the harmonics. To increase SNR at the demodulation output, synchronization should be done with one of the highest-level harmonics.

3- IMPULSE RADIO ULTRA WIDE BAND (IR-UWB) OVER FIBER

Recently there is increasing interest in transmitting IR-UWB signals over long distances of existing SMF transmission links. Unfortunately, the performance of such transmission, designed to operate at 1550 nm wavelength, is degraded mainly by the fiber group-velocity dispersion (GVD) due to the wide spectrum of the transmitted signals. To solve this problem, it is assumed here that DCF is used at the end of the SMF section to compensate its dispersion as shown in Fig. 4. Two optical amplifiers of gains \( G_1 \) and \( G_2 \) can be inserted after the SMF and DCF, respectively, to compensate the losses. The length of the DCF can be a part of the transmission link length or just inserted as a loop at the dropping node. This leaves the SMF length determining the transmission link length.

Let the SMF (DCF) is characterized by \( L_{SMF} (L_{DCF}) \) length, \( D_{SMF} (D_{DCF}) \) group-velocity dispersion, and \( \alpha_{SMF} (\alpha_{DCF}) \) loss measured in dB/km. Therefore the gains of the two amplifiers (measured in dB) are given by \( G_1 = \alpha_{SMF} L_{SMF} \) and \( G_2 = \alpha_{DCF} L_{DCF} \). Further, to achieve full dispersion compensation
The required length of the DCF is
\[ L_{DCF} = \frac{-D_{SMF}}{D_{DCF}} L_{SMF} \]

The DCF is designed to have negative GVD at 1550 nm to compensate the positive dispersion of the SMF at this wavelength. The length of the transmission link \( L_T = L_{SMF} + L_{DCF} = (1 - \frac{D_{SMF}}{D_{DCF}}) L_{SMF} \) when DCF is used as a part of the transmission link; otherwise \( L_T = L_{SMF} \).

Two modifications can be introduced to the system configuration shown in Fig. 1

(i) The two optical amplifiers can be replaced by a single amplifier, inserted at the end of the DCF, having gain of \( G_T = G_1 + G_2 \) in (decibels).

(ii) An optical bandpass filter can be inserted at the receiver input to suppress partially the amplified spontaneous emission (ASE) generated by the optical amplifiers, that incident on the photodiode. This leads to an increase in the receiver performance.

Fig. 4: Block diagram of IR-UWB over fiber system.

The parameters values of the SMF and DCF used in the simulation are listed in Table 1 for 1550 nm operation. Unless otherwise stated, the data rate is 625 Mb/s and the waveform generator produces \( n^{th} \)-order derivative Gaussian pulses at 625 MHz repetition rate. The FWHM of the basic Gaussian pulses is set to 85 ps. The laser diode emits 0 dBm power under CW operation at 1550 nm. According to Table 1, \( D_{SMF} = 17 \) ps/(ns.nm) and \( D_{DCF} = -85 \) ps/(ns.nm) at 1550 nm. Therefore, \( L_T = 1.2 L_{SMF} \) when the DCF is considered as a part of the transmission link.

Table 1: Parameter values for a standard-single mode fiber (SMF) and dispersion compensating fiber (DCF) at \( \lambda = 1550 \) nm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation, ( \alpha )</td>
<td>0.2 dB/km</td>
</tr>
<tr>
<td>Group velocity dispersion, ( D )</td>
<td>17 ps/(ns.nm)</td>
</tr>
<tr>
<td>Dispersion slope</td>
<td>0.075 ps/nm2/km</td>
</tr>
<tr>
<td>Differential group delay</td>
<td>0.2 ps/km</td>
</tr>
<tr>
<td>Effective area, ( A_{eff} )</td>
<td>80 ( \mu )m²</td>
</tr>
<tr>
<td>Nonlinear refractive index, ( n_2 )</td>
<td>( 26 \times 10^{-7} ) m²/W</td>
</tr>
</tbody>
</table>
3-1 Gaussian Monocycle Pulses

This subsection illustrates the transmission performance of the IR-UWB signals over SMF supported by DCF for perfect GVD compensation. The receiver uses RF mixing with 3.75 GHz local oscillator for down conversion. Further, a bandpass filter (2.5-10.6 GHz) is used in the simulation and inserted before the transmitter antenna to fix the spectrum of the transmitted IR-UWB signals within FCC mask. Figure 5 shows the variation of BER with transmission length for OOK and BPM formats. The transmission length is represented by two ways in this figure, one corresponds to the SMF length and the other to the total length \( L_T = L_{\text{SMF}} + L_{\text{DCF}} \). To achieve a BER of \( 10^{-9} \), the SMF length should be less than 77.5 km and 107.25 km for OOK and BPM, respectively. These values correspond to total fiber lengths of 93 km and 128.7 km, respectively.

![Fig. 5: BER as a function of fiber length for monocycle OOK and BPM modulation formats.](image)

Figures 6a and b show the received eye diagrams after 77.5 km transmission over a SMF operating without and with DCF, respectively. This SMF length corresponds to a received BER of \( 10^{-9} \) when DCF is employed. It is clear that the presence of DCF will improve the eye opening and hence improve the BER characteristics. The corresponding power spectrum of the transmitted RF signal is shown in Fig. 6c which contains both discrete and continuous spectra.

The simulations are repeated for BPM and the results are depicted in Fig. 7 using 107.25 km of SMF. This corresponds to a BER = \( 10^{-9} \) when DCF is inserted. Note that the eye diagram is completely closed in the absence of DCF leading to a BER = 1. Note further, that the spectrum of the RF signal lies within the required FCC mask. The improvement gained by using BPM over OOK is expected since the continuous part of its spectrum contains high-level frequency contents. Recall that the average optical power \( P_{av} \) is equal to half the CW laser power \( P_{cw} \) in OOK system. In contrast, \( P_{av} = P_{cw} \) in BPM system.
Fig. 6: Characteristics of the received signal after transmission over 77.5 km SMF fiber for 625 Mb/s OOK monocycle system. (a) Eye diagram when DCF is not used. (b) Eye diagram when DCF is used. (c) Power spectrum density of the transmitted RF signal when DCF is used.
Fig. 7: Characteristics of the received signal after transmission over 107.25 km SMF fiber for 625 Mb/s BPM monocycle system. (a) Eye diagram when DCF is not used. (b) Eye diagram when DCF is used. (c) Power spectrum density of the transmitted RF signal when DCF is used.

The effect of using optical filter in front of the receiver is also investigated and the results are depicted in Fig. 8. In this figure, the variation of BER with filter bandwidth is shown for OOK and BPM formats. In each case, the SMF length is chosen to give BER=10^{-9} in the presence of DCF, i.e., L_{SMF} = 77.5 km and 107.25 km for OOK and BPM, respectively. Not that using a 16 GHz bandwidth will improve the BER from 10^{-9} to 6.4\times10^{-12} in the case of OOK signaling. These values are to be compared with 10^{-9} to 5.1\times10^{-12} in the case of BPM signaling.
3-2 Fifth-Order Derivative Gaussian Pulses

This subsection addresses the transmission performance of IR-UWB signals over optical fiber link using 5th-order derivative Gaussian pulses. The simulations carried out in the previous section are repeated here for 625 Mb/s data rate using 8.125 GHz local mixing frequency and the results are reported in Figs. 9-12. The main conclusions drawn from these figures can be compared with the results related to monocycle-based system as listed in Table 2. This table shows the maximum allowable transmission distance for BERs equal to $10^{-7}$ and $10^{-9}$. 

Fig. 8: BER as a function of optical filter bandwidth for (a) Monocycle OOK (b) Monocycle BPM.
Table 2: Transmission distances at two given BERs for monocycle and 5th-order derivative IR-UWB operating with OOK and BPM modulation formats.

<table>
<thead>
<tr>
<th>BER</th>
<th>Pulse type</th>
<th>Modulation formats</th>
<th>SMF length (km)</th>
<th>Total link length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monocycle</td>
<td>OOK</td>
<td>85</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BPM</td>
<td>115</td>
<td>138</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>5th-order Derivative Gaussian</td>
<td>OOK</td>
<td>65</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BPM</td>
<td>97</td>
<td>116.5</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>Monocycle</td>
<td>OOK</td>
<td>77.5</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BPM</td>
<td>107.25</td>
<td>128.7</td>
</tr>
<tr>
<td></td>
<td>5th-order Derivative Gaussian</td>
<td>OOK</td>
<td>57</td>
<td>68.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BPM</td>
<td>90</td>
<td>108</td>
</tr>
</tbody>
</table>

Fig. 9: BER as a function of fiber length for 5th-order derivative Gaussian OOK and BPM modulation formats.
Fig. 10: BER as a function of optical filter bandwidth for (a) 5th-order derivative Gaussian OOK (b) 5th-order derivative Gaussian BPM.

$L_T = 68.5$ km
Fig. 11: Characteristics of the received signal after transmission over 55 km SMF fiber for 625 Mb/s 5th-order derivative Gaussian OOK system. (a) Eye diagram when DCF is not used. (b) Eye diagram when DCF is used. (c) Power spectrum density of the transmitted RF signal when DCF is used.
Fig. 12: Characteristics of the received signal after transmission over 90 km SMF fiber for 625 Mb/s 5th-order derivative Gaussian BPM system. (a) Eye diagram when DCF is not used. (b) Eye diagram when DCF is used. (c) Power spectrum density of the transmitted RF signal when DCF is used.
Investigating the results in Table 2 and Figs 9-12 reveals the following findings:

(i) The PSD of the transmitted RF signal associated with 5th-order derivative Gaussian system lies perfectly within FCC mask and characterized by high attenuated low frequency contents.

(ii) For a given received BER, monocycle system yields longer transmission link as compared with 5th-order derivative Gaussian system. At BER = 10^{-9}, the maximum allowable transmission length is reduced by 57/77.5 = 0.74 and 90/107.25 = 0.84 for OOK and BPM, respectively, when 5th-order Gaussian system are used to replace the monocycle system.

(iii) A slightly wider optical bandpass filter can be used to enhance the performance of the 5th-order Gaussian system as compared with monocycle system. Using 24 GHz bandwidth filter in the 5th-order derivative Gaussian system will enhance the BER from 10^{-9} to 9.7\times10^{-11} and from 10^{-9} to 7.1\times10^{-11} in OOK and BPM formats, respectively.

4- CONCLUSIONS
Transmission performance of 625 Mb/s IR-UWB signals over optical fiber link incorporating SMF, DCF, and optical amplifiers has been investigated. The simulation results reveal that longer transmission distance can be achieved by using monocycle BPM. To achieve a received BER less than 10^{-9}, the maximum transmission distance is 93 km and 128 km for monocycle system operating with OOK and BPM modulation formats, respectively. These values are to be compared with 68 and 108 km for 5th-order derivative Gaussian system operating with OOK and BPM modulation formats, respectively.

5- REFERENCES


Author Biography

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