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Abstract:} Radio-over-fiber (RoF) systems have been widely investigated due to such advantages of optical fiber as low loss, large bandwidth, and transparent characteristics for radio signal transmission. By utilizing RoF systems, various radio frequency (RF) signals including cellular services and wireless local area network (WLAN) signals can be efficiently distributed to densely populated areas or outdoor ranges. This paper investigates RoF-transport systems that have the potential to offer large transmission capacity, significant mobility and flexibility, as well as economic advantage due to its broad bandwidth and low attenuation characteristics. The high performance of RoF communication systems are investigated against traditional optical communication systems using different coding formats over wide range of the affecting operating parameters. Moreover we have analyzed the transmission bit rates and products per channel based standard single mode fiber made of both silica-doped and plastic materials with using modified Shannon technique in addition to use different coding format such as non-return-to-zero (NRZ) code for ultra long haul transmission applications. We have taken into account the bit error rate (BER) for RoF systems with comparing it with traditional optical fiber communication systems as a proof for improvement of signal to noise ratio.

Keywords: Radio-over-fiber systems, BER, NRZ coding, Signal-to-noise ratio, and Classical transmission bit rates.

1. Introduction

The next generation of access networks is rushing the needs for the convergence of wired and wireless services to offer end users greater choice, convenience, and variety in an efficient way [1]. This scenario will require the simultaneous delivery of voice, data, and video services with mobility feature to serve the fixed and mobile users in a unified networking platform. In other words, new telecom systems require high transmission bandwidths and long haul with reliable mobility. The radio-over-fiber (RoF) technology represents a key solution for satisfying these requirements, since it jointly takes advantage of the huge bandwidth offered by optical communications systems [2] with the mobility and flexibility provided by wireless systems. RoF systems consist of heterogeneous networks formed by wireless and optical links. Unlike traditional optical communications networks, in which a baseband signal is transmitted into the optical fibers; in RoF systems, one or multiple analogous carriers are transported into the fibers. In this way, the radio frequency wireless carrier signal is transmitted over an optical fiber link. The transmission is performed by directly or externally modulating lasers by the analogous radio frequency signal. On the receiver side [3, 4], the transmitted signal is recovered by using a photodiode.

Compared with traditional optical systems, RoF technology provides the advantage of eliminating optical electronic and electronic optical converters. This simplifies the system complexity and reduces the operational costs and the expenses with site acquisition and rental. The maintenance is also lessened since the antenna remote unit is a lot simplified. Furthermore, RoF technology enables centralization of network management, processing, and radio functions. It supports current and next generation wireless network deployment and management strategies. RoF systems can provide specialized coverage of wireless services by using an extended optical backbone. These systems are suitable for variety applications, such as in building coverage, outdoor cellular systems, and broadband fixed and mobile wireless access. They are entirely transparent to the system frequency, protocol, and bit rate. This characteristic makes them extremely interesting for the convergence of optical and mobile systems [5].

ROF systems have been widely investigated due to such advantages of optical fiber as low loss, large bandwidth, and transparent characteristics for radio signal transmission. By utilizing RoF systems, various radio-frequency signals including cellular services and/or wireless local area network (WLAN) signals can be efficiently distributed to densely populated areas or outdoor ranges [6-8].

In the present study, we have deeply analyzed ed the Radio over fiber communication systems compared to a traditional fiber optical communication system at long distances and high data rates using non return to zero (NRZ) coding formats over wide range of the affecting parameters. The system can be limited either by the losses (attenuation-limited transmission) or, assuming that the link is not limited by the source or detector speed, by the (dispersion-limited transmission) and we have treated it using modified Shannon technique.

2. Modeling Description and Analysis

Considering a direct intensity modulation at the laser diode, the instantaneous optical power output P(t) from the laser in response to input electrical signal s(t), neglecting laser nonlinearity, is generally given by [9]:

\[
P(t) = [1 + m s(t)] P_0 \quad , \quad (1)
\]

Here, \(P_0\) is the mean optical power, and \(m\) is the optical modulation index. The received optical signal at the receiver illuminates the photo detector, which produces a detected current \(I_D(t)\) =\(\rho P(t)\) where \(\rho\) is the detector responsivity. Total detected current \(I_D(t)\) is the sum of the mean current \(I_0\)
(t) and the ac component $i_a(t)$. The losses in the laser modulator, fiber and optical receiver need to be added. The loss in the direct modulated laser transmitter comes from the modulation gain of the laser $G_m$ in mW (optical power)/mA (injected current), which depends on the external and internal gains of the laser. With a resistive matching network that will provide maximum power transfer, the optical output power from the laser in dBm is [10]:

$$P_{opt,Laser} = P_{RF,Laser}/2 + 10\log(G_m\sqrt{1000/Z_{in}}), \quad (2)$$

Where $Z_{in}$ is the input impedance of the laser transmitter (50 Ω). The RF output power from the detector in dBm, again considering impedance mismatch is given by [10]:

$$P_{RF} = 10\log(p + Z_{opt,Laser}), \quad (3)$$

The factor 2 reflects the square law detection and $Z_{opt}$ is the output RF impedance of the O/E converter (50 Ω). By Substituting from Eq. (2) into Eq. (3), the total loss due to the RoF link with resistive matching at the O/E and E/O converters can be shown as the following equation [11]:

$$L_{opt} = 20\log(G_m R^2/0.001) + 10\log(Z_{out}/Z_{in}) + 2OL, \quad (4)$$

Where OL is the optical losses including fiber attenuation and connector losses. The second term is zero when the input to the laser and the output of the optical receiver are matched to the same RF impedance ($Z_{out} = Z_{in} = 50$ Ω). In a point-to-point fiber link, OL = $2L_c + \alpha L_p$ where $L_c$ is the fiber link length, $L_p$ is the connector loss and $\alpha$ is the fiber attenuation in dB/km. Typical values for the prototype used are, $G_m = 0.12$ mW/mA and $p = 0.75$ mA/mW. This gives a 39 dB loss due to E/O and O/E conversion which should be added to OL to get $L_{opt}$. For $\langle i_1^2 \rangle = 2qP_0B = 2q (I_0 (t))$; B is the shot noise variance after the ideal band pass filter (BPF). $\langle i_1^2 \rangle = 4 \frac{K_BT_xB}{R_x}$ is the thermal noise variance where, $K_B$ is the Boltzmann’s constant, F is the amplifier noise factor and $T_x$ is the absolute temperature and $R_x$ is the load resistance. In Radio-ove-fiber links, the resistance of the photodiode as well as that of the preamplifier add to thermal noise. The noise power due to the relative intensity noise (RIN) is given as $\langle i_2^2 \rangle = (RIN) I_0^2$. Shot, RIN and thermal noises terms are involved in the optical signal to noise-ratio (OSNR). Thermal noise has constant variance and white spectrum. The variance of the shot noise is linearly proportional to mean optical power in the fiber and has a Poisson distribution. Although the instantaneous optical power in the fiber fluctuates due to RF intensity modulation, if $E[s(t)] = 0$, the mean optical power does not change unless the DC bias current is changed. If the thermal noise at the receiver optical amplifier is made negligible with an improved design, when the RIN value is specified for a given laser diode in dB/Hz, Typically for value of -155 dB/Hz, the linear scale RIN (A^2/Hz) is obtained by the following expression:

$$RIN (A^2/Hz) = 10^{10^{10}}, \quad (5)$$

In the shot noise limited case, the optical signal-to-noise ratio of RoF link can be expressed as [11]:

$$OSNR = \frac{m^2 I_{dB} E_{dB}}{2 q B} 10^\alpha_{dB} / 10, \quad (6)$$

That is the OSNR increases with mean detected current $I_0$ linearly and with $m$ in second order. Mean detected current is proportional to mean optical power $P_0$. However, note that typically larger $P_0$ means lower $m$ again due to nonlinear effects. Nevertheless, the OSNR eventually would increase with $m$. In the RIN limited case, Eq. (6) can be deduced as in Ref. [12]. That is the OSNR is independent of mean optical power and increases with RF power. However, when the RF power is too large the OSNR would saturate due to large RIN as observed by [12]. The signal-to-noise ratio (SNR) can be expressed as a function of OSNR as follows [11, 12]:

$$SNR = OSNR \left[ \frac{1 + \frac{\alpha_{dB}}{G_{opt}}}{10} \right], \quad (7)$$

Let us consider a general fiber link area in which the maximum power loss is specified as $\alpha$ in dB. $\alpha$ depends on the fiber link area and radio environment. At the maximum power loss in the fiber link, $\alpha_{dB} = 10^{\alpha/10}$. Hence, the worst case SNR is given as in Ref. [12], and then the required optical receiver amplifier gain for different values of the maximum loss $\alpha$ in the fiber link area given the value for OSNR and worst case SNR at the portable and then the maximum loss, $\alpha$ and minimum required OSNR are also given in Ref. [12].

2.1. Optical link attenuation analysis

Based on the models of Ref. [13], the silica-doped spectral losses are cast as:

$$\alpha = \alpha_I + \alpha_S + \alpha_{UV} + \alpha_{IR}, \quad dB/km \quad (8)$$

where: $\alpha_I$ = the intrinsic loss $= 0.03$, dB/km, and $\alpha_S$ = Rayleigh scattering $= 0.75 + 66A (T^3/10)$, dB/km (10)

where $T$ is ambient temperature, and $T_0$ is a room temperature (300 K), $\Lambda$ and $\lambda$ are the relative refractive index difference and optical wavelength, respectively. The absorption losses $\alpha_{UV}$ and $\alpha_{IR}$ are given as [13]:

$$\alpha_{UV} = 1.1 \times 10^{-4} \omega_{Ge} \lambda^{2.9}, \quad dB/km \quad (11)$$

where $\omega_{Ge}$ % is the weight percentage of Ge, the correlated $\omega_{Ge}$ % and the mole fraction $x$ under the form:

$$\omega_{Ge} = \frac{213.27x - 594x^2 + 2400x^3 - 4695x^4}{\lambda^4} \quad (13)$$

Plastics, as all organic materials, absorb light in the ultraviolet spectrum region. The absorption depends on the electronic transitions between energy levels in molecular bonds of the material. Generally the electronic transition absorption peaks appear at wavelengths in the ultraviolet region [14]. According to urbach’s rule, the attenuation coefficient $\alpha_{e}$ due to electronic transitions in plastic optical fiber. In addition, there is another type of intrinsic loss, caused by fluctuations in the density, orientation, and composition of the material, which is known as Rayleigh scattering. This phenomenon gives rise to scattering coefficient $\alpha_{e}$ that is inversely proportional to the fourth power of the wavelength, i.e., the shorter is $\lambda$ the higher the losses are. For a plastic fiber, it is shown that $\alpha_{e}$ is given [15], then the total losses of plastic material is given by:

$$\alpha = 1.10 \times 10^{-5} \exp \left( \frac{8}{\lambda} \right) + 13 \left( \frac{0.633}{\lambda} \right)^4, \quad dB/km \quad (14)$$
2. Optical link dispersion analysis

The standard single mode fiber cable is made of the silica-doped material which the investigation of the spectral variations of the waveguide refractive-index, $n$ require empirical equation under the form [16]:

$$n^2 = 1 + \frac{A_1}{\Delta^2} + \frac{A_2}{\Delta^4} + \frac{A_3}{\Delta^6}$$  \hspace{1cm} (15)

The empirical equation coefficients as a function of temperature and Germania mole fraction, $x$ as:

- $A_{1S} = 0.691663 + 0.1107001x$, $A_{2S} = (0.0684043 + 0.000568306x)(T/T_0)^2$, $A_{3S} = 0.4079426 + 0.3102158x$,
- $A_{1S} = (0.1162414 + 0.0377246x)(T/T_0)^2$, $A_{2S} = 0.8974794 - 0.043311091x$, $A_{3S} = (9.896161+1.94577x)^2$. Where $T$ is ambient temperature in K, and $T_0$ is the room temperature and is considered as 300 K. Then the second differentiation of pervious empirical equation w. r. t operating wavelength $\lambda$ as in Ref. [17]. For the plastic fiber material, the coefficients of the Sellmeier equation and refractive-index variation with ambient temperature are given as: $A_{1P} = 0.4963$, $A_{2P} = 0.6965$ ($T/T_0$), $A_{3P} = 0.3223$, $A_{4P} = 0.718$ ($T/T_0$), $A_{5P} = 0.1174$, and $A_{6P} = 9.237$.

2. Transmission capacity analysis

The rise time of an optical fiber communication system $\Delta \tau_{\text{system}}$ is given by [18]:

$$\Delta \tau_{\text{system}} = \sqrt{\frac{\Delta \tau_{\text{source}}^2 - \Delta \tau_{\text{receiver}}^2 + \Delta \tau_{\text{mat}}^2}{2}}$$  \hspace{1cm} (16)

where $\Delta \tau_i$ is the rise time of each component in the system. The three components of the system that can contribute to the system rise time are as the following:

i) The rise time of the transmitting source $\Delta \tau_{\text{source}}$ (typically equal to value of 16 ps).

ii) The rise time of the receiver $\Delta \tau_{\text{receiver}}$ (typically equal to value of 25 ps).

iii) The material dispersion time of the fiber $\Delta \tau_{\text{mat}}$ which is given by the following equation:

$$\Delta \tau_{\text{mat}} = \left(\frac{L \cdot \Delta \lambda}{c} \right) \left(\frac{d^2 n}{d \lambda^2}\right)$$  \hspace{1cm} (17)

Then the total dispersion of the optical communication system can be expressed as:

$$\Delta \tau_{\text{system}} = \Delta \tau_{\text{source}} + \Delta \tau_{\text{receiver}} + \Delta \tau_{\text{mat}}$$  \hspace{1cm} (18)

The bandwidth for standard single mode fibers for both materials based optical link length $L_0$ is given by:

$$BW_{\text{Sig}} = \frac{0.44}{\Delta \tau_{\text{system}} \cdot L_0}$$  \hspace{1cm} (19)

The transmission data rate that the system can support NRZ coding as the following [19]-[21]:

$$Br(\text{NRZ}) = \frac{0.7}{\Delta \tau_{\text{system}}}$$  \hspace{1cm} (20)

The bit error rate (BER) essentially specifies the average probability of incorrect bit identification. In general, the higher the received SNR, the lower the BER probability will be. For most photo detectors as receivers, the noise is generally thermally limited, which is independent of signal current. The bit error rate (BER) is related to the signal to noise ratio (SNR) as follows [22]:

$$BER = 0.5 \left[ 1 - \text{erf} \left( \frac{0.3535(\text{SNR})^{1/2}}{2} \right) \right]$$  \hspace{1cm} (21)

3. Simulation Results and Performance Analysis

We have investigated the high performance of RoF communication systems for ultra high transmission capacity within NRZ coding formats under the set of the wide range of the operating parameters as listed in Table 1:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value and unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>Ambient temperature</td>
<td>300 K ≤ T ≤ 340 K</td>
</tr>
<tr>
<td>$L_e$</td>
<td>Fiber link length</td>
<td>40 km ≤ L_e ≤ 320 km</td>
</tr>
<tr>
<td>$\Delta \tau_{\text{source}}$</td>
<td>Rise time of the transmitter</td>
<td>16 psec</td>
</tr>
<tr>
<td>$\Delta \tau_{\text{receiver}}$</td>
<td>Rise time of the receiver</td>
<td>25 psec</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>Reference temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>RF signal operating wavelength</td>
<td>1 mm ≤ \lambda ≤ 1.5 mm</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>Mole fraction of germanium</td>
<td>0.0 ≤ x ≤ 0.3</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Spectral line width of the optical source</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>$\Delta \lambda$</td>
<td>Signal to noise ratio</td>
<td>5 dB ≤ Optical loss ≤ 65 dB</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Detector responsivity</td>
<td>0.75 mA/mW</td>
</tr>
<tr>
<td>$G_m$</td>
<td>Modulation gain of the laser</td>
<td>0.12 mA/mW</td>
</tr>
<tr>
<td>$OSNR$</td>
<td>Optical signal to noise ratio</td>
<td>5 ≤ OSNR ≤ 25</td>
</tr>
<tr>
<td>$\Delta F$</td>
<td>Amplifier figure noise</td>
<td>5 dB</td>
</tr>
</tbody>
</table>

Based on the basic model equations analysis, assumed set of the operating parameters as listed above, and based on the series of the Figs. 1 to 14, the following facts are assured:

i) As shown in Figs. 1 through 4 have assured that as optical modulation index increases; this leads to decrease in BER at constant of both optical signal-to-noise ratio and optical amplifier gain. Moreover, as both optical signal-to-noise ratio and optical amplifier gain increases, this results in decreasing BER at constant optical modulation index. Silica-doped material based optical link has presented lower BER than plastic material based optical link.

ii) Figure 5 has proved that ambient temperature increases, bit rates for both silica-doped at different level of doping of germanium and plastic materials decrease within NRZ coding format.

iii) Figures 6 through 9 have assured that as ambient temperature increases, signal bandwidth decreases for both silica-doped at different level of doping of...
germanium and plastic materials at constant fiber link length. Also as fiber link length increases, signal bandwidth decreases at constant ambient temperature.

iv) Figure 10 has demonstrated that as fiber link length increases, this results in increasing of optical loss for both silica-doped and plastic materials-based optical link. As well as plastic material presents higher optical loss than silica-doped material. Also as germanium percentage amount increases this result in increasing optical loss.
Fig. 5. Variations of transmission bit rate against ambient temperature at the assumed set of parameters.

Fig. 6. Variations of transmission bit rate against ambient temperature at the assumed set of parameters.

Fig. 7. Variations of transmission bit rate against ambient temperature at the assumed set of parameters.
Fig. 8. Variations of transmission bit rate against ambient temperature at the assumed set of parameters.

Fig. 9. Variations of transmission bit rate against ambient temperature at the assumed set of parameters.

Fig. 10. Variations of the optical loss against fiber link length at the assumed set of parameters.
Fig. 11. Variations of signal to noise ratio against optical modulation index at the assumed set of parameters.

Fig. 12. Variations of signal to noise ratio against optical modulation index at the assumed set of parameters.

Fig. 13. Variations of signal to noise ratio against optical modulation index at the assumed set of parameters.
v) As shown in Figs. 11 through 14 have assured that as optical modulation index increases, this leads to increase in required signal-to-noise ratio at constant of both optical signal-to-noise ratio and optical amplifier gain. As well as both optical signal to noise ratio and optical amplifier gain increases, this results in increasing required signal to noise ratio at constant optical modulation index. Silica-doped material-based optical link has presented higher SNR than plastic material-based optical link.

4. Conclusions
In summary, Radio over-Fiber communication technology represents a key solution for satisfying the requirements of: high transmitted signal bandwidth, high transmission bit rates, high signal to noise ratio, and lower bit error rates; since it jointly takes advantage of the huge bandwidth offered by optical communications systems. This paper has demonstrated that the above-mentioned requirements are satisfied for Radio-over-fiber communication systems compared to traditional optical fiber communication systems for long haul transmission applications. It is theoretically found that the silica-doped material with different doping of germanium level-based optical link presents higher transmission bit rates and transmitted signal bandwidth than plastic material-based optical link. Also, it is indicated that RoF communication systems present high efficiency compared to traditional optical fiber communication systems. We have recommended for future study, the trends for wireless radio over fiber communication systems.

References


