Investigations on Electronic Equalization for Step-Index Polymer Optical Fiber Systems

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Electronic equalization can allow for significant mitigation of impairments induced by modal dispersion in the step-index Polymer Optical Fiber. In this work we show the performance of digital T-spaced equalizer technologies like Feed Forward Equalization (FFE) and Maximum Likelihood Sequence Estimation (MLSE) with data rates from 100 Mbit/s to 500 Mbit/s. The simulations are based on a channel model, which combines all three major fiber effects of modal attenuation, modal dispersion and mode coupling.

1. Introduction

The standard 1 mm PMMA Polymer Optical Fiber (SI-POF) is a highly attractive candidate for wired communication links in application scenarios such as industrial automation, automotive and in-building networking. Its unique advantage is the easiness of handling, allowing large alignment and dimensional tolerances for components and connectors together with the possibility of field installation by non-professionals. Probably the most critical disadvantage of the 1 mm SI-POF is the limitation of its bandwidth-length product to approximately 35 MHz×100 m mainly due to modal dispersion. In this paper, we present first investigations on electronic equalization to overcome this limitation. Simulations are carried out with a new simulation model [1] which includes the three major fiber effects in Polymer Optical Fibers: the mode-dependant attenuation, the modal dispersion and the mode coupling process.

2. System Simulation Model

Figure 1 shows the system simulation model. In the Bit Source, a pseudorandom bit sequence is generated. A Light Emitted Diode (LED) is used as the transmitter (TX), which is modeled as a simple low pass filter with bandwidth $B_{TX}$.

As launch condition into the fiber, uniform mode distribution (UMD) is assumed, which approximates an LED quite well. The POF channel $h(t)$ corresponds to a new simulation model [1], which is presented in the next chapter in details. At the receiver (RX), the optical signal power is converted to an electrical current by means of a simple
multiplication with the responsitivity $S$. After that, thermal noise resulting from the PIN-diode and the amplifier is added as additive white Gaussian noise (AWGN) to the system. The distorted signal is then passed through a low pass filter with bandwidth $B_{RX}$ to reduce the impact of noise. Finally, this signal is fed into the equalizer or directly into the decision device.

3. Simulation model for the impulse response

Here the principle of the simulation model is shown, for more details see [1]. The starting point is the time-dependent power flow equation (1) depicted by Gloge [2]:

$$\frac{\partial P}{\partial z} = -\alpha(\theta)P - \tau(\theta) \frac{\partial P}{\partial t} + \frac{D}{\theta} \frac{\partial}{\partial \theta} \left( \frac{\partial P}{\partial \theta} \right)$$  \hspace{1cm} (1)

where $P = P(\theta, z, t)$ is the power distribution in angle $\theta$ with respect to the fiber axis, in $z$ along the fiber and the time $t$. $\alpha(\theta)$ is the mode-dependent attenuation [3-5], given in Eq. 2. $\tau(\theta)$ is the delay (modal dispersion) for modes excited at angle $\theta$ (Eq. 3). $D$ is the diffusion constant for mode coupling, which is modeled as a diffusion process.

$$\alpha(\theta) = \frac{\alpha_{core}}{\cos(\theta)} + \frac{\tan(\theta)}{2a} \ln(1-T) + \frac{\alpha_{clad}}{\cos(\theta) 2\pi \sqrt{n_{core}^2 \cos^2(\theta) - n_{clad}^2}} \frac{\lambda}{\theta} \hspace{1cm} (2)$$

$$\tau(\theta) = \frac{n_{core}}{c_0} \left( \frac{1}{\cos(\theta)} - 1 \right) \hspace{1cm} (3)$$

$\alpha_{core}, \alpha_{clad}$ and $n_{core}, n_{clad}$ are respectively the attenuation coefficients and the refractive indices of the core and the cladding. $a$ is the core radius and $T$ is the transmission factor of the core-cladding interface. $\lambda$ is the mean wavelength and $c_0$ is the speed of light in vacuum. So equation (1) relates all three major fiber effects: the mode-dependent attenuation, the modal dispersion and the mode coupling.

To solve equation (1), it is transformed into the frequency domain, resulting in

$$\frac{\partial p}{\partial z} = -\left(\frac{(\alpha(\theta) + j \omega \tau(\theta))p}{L_p} + \frac{D}{\theta} \frac{\partial}{\partial \theta} \left( \frac{\partial p}{\partial \theta} \right) \right).$$  \hspace{1cm} (4)

The solution of equation (4) is approximated by solving the two part $\tilde{L}$ and $\tilde{N}$ separately. So the solution of this equation for a small fiber step size $\Delta z$ is

$$p(\theta, z + \Delta z, \omega) = \exp \left\{ \frac{\Delta z}{2} \tilde{L} \right\} \exp \left\{ \Delta z \tilde{N} \right\} \exp \left\{ \frac{\Delta z}{2} \tilde{L} \right\} p(\theta, z, \omega).$$  \hspace{1cm} (5)

At the end of the fiber, the impulse response is calculated by integrating the power distribution in the time-domain over the angle $\theta$:

$$h(t) \bigg|_{z=z_0} = \int P(\theta, z_0, t) \, d\theta$$  \hspace{1cm} (6)
4. Equalizer schemes
In this work, we consider two types of equalizers: a Feed Forward Equalizer (FFE) and a full-state Maximum Likelihood Sequence Estimation (MLSE). The filter coefficients of the FFE are calculated by solving the Wiener-Hopf-Equation [6]. For all data rates a 15 T-spaced FFE is applied. As reference, the MLSE implemented in MATLAB® is used.

5. Simulation results

Impulse Response
In Figure 2, the simulated impulse responses for different lengths of standard 1mm Step-Index Polymer Optical Fiber (SI-POF) are shown. The resulting fiber parameters including bandwidth and overall attenuation are given in Table 1.

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>BW_{3dB} (MHz)</th>
<th>Att (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>200</td>
<td>2.1</td>
</tr>
<tr>
<td>30</td>
<td>89.9</td>
<td>5.1</td>
</tr>
<tr>
<td>50</td>
<td>65.7</td>
<td>8.1</td>
</tr>
<tr>
<td>100</td>
<td>43.1</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Table 1: Fiber Parameters

So the impulse response used in the simulations has a bandwidth-length product of 43 MHz×100 m and an overall attenuation of 15.5 dB at a fiber length of 100 m.

System Simulations
For evaluating the performance of the different equalizers, we did Monte-Carlo simulations for bitrates \( R \) of 100 MBit/s, 250 MBit/s and 500 MBit/s. The launch power is 0 dBm and the transmitter bandwidth \( B_{TX} = R \) is equal to the bitrate. The receiver has a responsivity of \( S = 0.4 \) A/W and a bandwidth of \( B_{RX} = R/0.707 \). Only thermal noise is added as white gaussian noise with a noise figure of \( F_N = 4 \). The number of transmitted bits is \( 4 \times 10^6 \).

In Figures 3a,b and d, the BER values versus fiber length are shown for the three different data rates. The equalization gain given in reached fiber length is measured at a BER of \( 10^{-5} \). The results are shown in Figure 3c.
6. Conclusions
The simulation results show the performance bounds of electronic equalization techniques for SI-POF. The MLSE shows the best achievable performance, at the cost of highest complexity. The FFE is a relatively simple equalizer with low complexity, but achieves less performance. Nevertheless, it can be seen from the results that even the relatively simple linear FFE can obtain good performance gains in a SI-POF system.

7. References