Design of Optical Access Systems using Computer Modeling

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Abstract— **We present numerical techniques that allow efficient modeling of the transport of broadband services over fiber-optic links in access networks using various technologies. Application examples of Hybrid Fiber Coax (HFC), Radio-over-Fiber (RoF) systems and 10-Gb/s Ethernet transport over multimode fiber are provided to demonstrate the value of simulation during the R&D and deployment phases of product introduction.**

Index Terms— **Hybrid Fiber Coax (HFC), Radio over Fiber (RoF), 10-Gb/s Ethernet, broadband access, Self Phase Modulation (SPM), Rayleigh backscattering (RBS), Stimulated Brillouin Scattering (SBS).**

I. INTRODUCTION

Modern access networks need to transport different types of traffic that impose conflicting performance requirements on the optical transport layer. The requirement for large carrier to noise ratio (CNR), but low distortion from composite second order (CSO) and composite triple beat (CTB) to transport analog services enforces high launch powers with little margin for degradations over the link. The transport of services using digital modulation formats, such as Quadrature Amplitude Modulation (QAM), is more robust when transmitted stand-alone. However, even more stringent distortion limitations may arise when these services are merged with analog services. Careful computer modeling can help to predict and optimize the network layout, channel plan and equipment specifications.

For instance, the optical launch power needs to be increased to overcome performance limitations due to low CNR when increasing the optical path length. Stimulated Brillouin Scattering (SBS) in fiber, however, increases the RF noise floor and 2nd order intermodulation products due to Self-Phase Modulation (SPM) in high-power scenarios. This forces designers to increase the laser linewidth and chirp or use an external modulator to mitigate these impairments. Further on, Rayleigh backscattering (RBS) can drastically limit the reach of bi-directional transmission systems.

Three systems based on the HFC, RoF and 10-Gb/s Ethernet technologies are investigated here to illustrate the value of numerical modeling for the design and optimization of access systems. Limitations due to SBS, RBS, inter-modal dispersion and nonlinear distortions are investigated using *VPItransmissionMaker* from VPIsystems [1]

II. HFC AND FTTX NETWORKS

While the emphasis in optical transport is generally in the purely digital domain, there remains a large portion of video and broadband services that is delivered over analog channels. This includes legacy analog video as well as digital video and data over QAM carriers.

The distortion and CNR requirements, while relaxed from 100% analog video, are still stringent. Many factors including imperfect modulation and fiber impairments need to be included in the complete analysis of access networks.

A. Effects of Self Phase Modulation

In HFC applications where fiber is built out deep into the network, the reliance on optical transport to deliver services in a cost effective manner leads to relatively long distance transmission systems. It is not unusual to have links ranging from 100 to 300 km. There are numerous problems to overcome in these applications, such as transmitter performance, EDFA noise contributions, chromatic dispersion, SBS and SPM. While all of these contribute to the degradation of performance and need to be considered, there is a significant contribution to second order distortion due to an interesting interplay between SPM, SBS and transmitter performance, namely chirp [2], [3]. In order to explore this interaction, we consider a simple 65 km link with one launch EDFA as shown in Figure 1.

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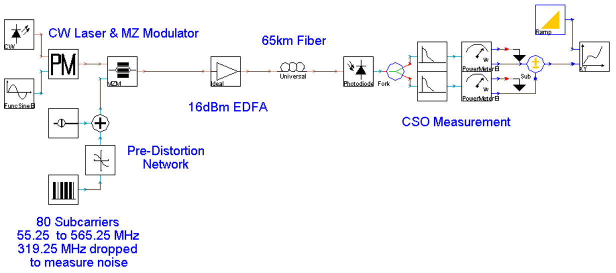

Figure 1. Simulation Setup for modeling a 65km HFC link with 80 channels, SBS suppression and a linearized MZ with chirp.

In this design there is an externally modulated transmitter used to spread the spectrum to mitigate SBS due to the high launch powers. The transmitter is built up of a continuous wave laser source, a linearized Mach-Zehnder (MZ) modulator, a 16 dBm EDFA and a phase modulator. It is important to note that some of the highest performing transmitters employ dual cascaded MZ modulator arrangements for linearization and have an intrinsic alpha of -1.3 for the positive slope bias [4]. The described transmitter setup is used here to transport 80 analog carriers over 65 km. CSO will be monitored using a measurement system based on electrical filters and power meters.

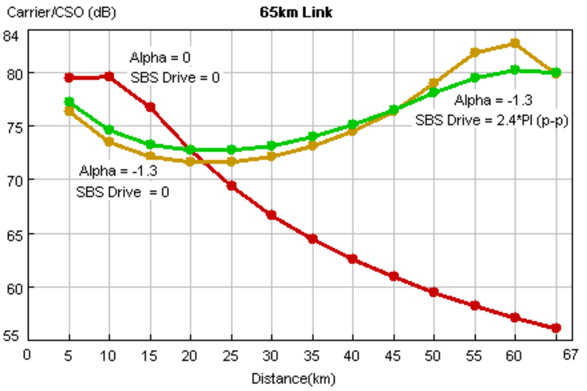

Figure 2. Carrier/CSO [dB] vs. distance for a 65 km link.

One method suggested to limit the rise of CSO terms along the fiber is to prechirp (alpha of the modulator) the signal in the transmitter such that the CSO due to the transmitter chirp cancels the one that is caused by the SPM induced chirp [2], [3]. It is important to note that this kind of investigation cannot be performed in isolation from the SBS suppression technique because the spreading of the optical spectrum in this fashion is known to induce its own CSO contribution. Figure 2 shows the result of the CSO performance of this link with and without prechirp and phase modulation for SBS suppression. The model shows that this approach is feasible, but the complete picture of all three effects coupled with dispersion and launch power must be taken into consideration when designing HFC transmission systems even for this relatively moderate link length.

When the distances are increased and additional EDFAs are required the problems compound. Not only is there one region, at the beginning of the fiber, where the SPM impact is largest, there will be additional regions after each EDFA providing a boost to the SPM induced chirp. Results for a 100 km link consisting of two spans of 50 km and two EDFAs with output powers of 14 dBm each are shown in Figure 3.

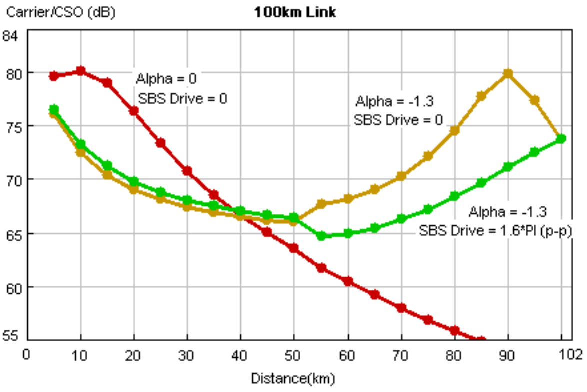

Figure 3. Carrier/CSO [dB] vs. distance for a 100 km link comprised of two 50 km spans each with a 14 dBm EDFA.

This system requires SBS suppression phase modulation that can also be used to create the necessary CSO to cancel the CSO due to the two high power launch sections. Figure 4 shows CSO versus distance for two different phase modulation depths. Again, the results of modeling show that there is a value of SBS suppression phase modulation depth that is optimum for CSO at 100 km. The design of more complex and longer length links can also be considered using straight forward modeling techniques. Link lengths larger than 300 km have been demonstrated [3]. Requirements for acceptable CSO performance simultaneously at intermediate distances and the end point to accommodate drops at various points along the path require even more aggressive approaches involving dispersion compensation. Accurate modeling taking into account transmitter performance as well as all of the fiber impairments is imperative for successful system design.

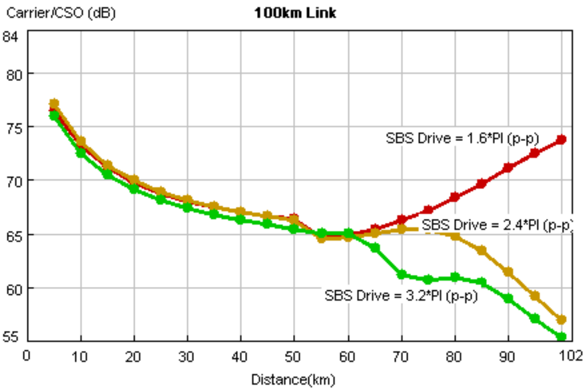

Figure 4. Carrier/CSO [dB] vs. distance for 14 dBm launch for each of 2 spans and SBS drive = 1.6π, 2.4π and 3.2π

III. RADIO-OVER-FIBER SYSTEMS

Wireless communication networks are based on a combination of different technologies (WiFi, WiMax, UMTS, GSM, Bluetooth, etc.). This evolution implies more complexity at the base stations, and thus, higher costs for the network. A significant part of the cost and complexity can be removed by deploying RoF systems where a single central station is connected via fiber-optical links to the individual base stations (acting as passive antennas). Another advantage of RoF systems is the possible seamless integration of different wireless technologies with analog video and broadband Internet (e.g. Ethernet) services.

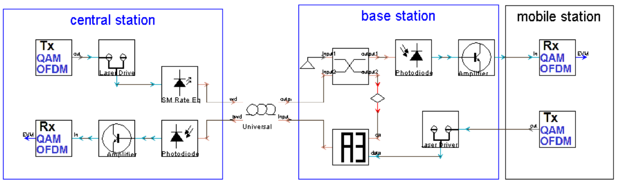

Figure 5. RoF simulation setup (*VPItransmissionMaker*).

In what follows, we propose a feasibility study for a Radio over Fiber system intended to transmit WiFi ([5]) channels over several km's of optical fiber for remote antenna feeding application (see Figure 5). Each channel is carrying data at a signal rate of 36 or 54 Mb/s. The channels are placed 20 MHz apart from each other between 2.5 and 2.6 GHz.

A. *Multi-mode fiber*

First, a low-cost solution using multi-mode fiber (MMF) is considered. A DFB Laser is used at the central station that emits light at 1300 nm with -150 dB RIN and 20 MHz linewidth. It is directly modulated by 3 WiFi channels that are electrically multiplexed.

The modulation depth, m, is kept under 30% to ensure linear modulation and an average output power of 2 mW. The spurious free dynamic range is larger than 100 dB*Hz$^{2/3}$. The optical signal (ideal Gaussian beam with 5 mm spot-size) is coupled into a 62.5 mm MMF. At the base station, the optical signal is detected by a PIN photodiode that feeds a passive antenna. The electrical signal is down-converted to the base-band and processed by an OFDM-QAM receiver module performing equalization and EVM (error vector magnitude or relative constellation error) measurement.

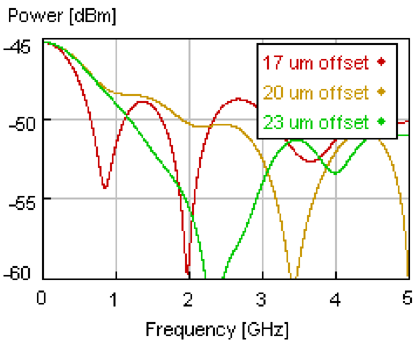

Figure 6. Transfer functions of a typical MMF (1 km) for different launch conditions

Signal propagation in MMF is governed by differential-mode dispersion (DMD) that depends on the length and refractive index profile of the fiber and on the launch conditions (offset) [6]. Radio signals using multi-level modulation formats are less sensitive to dispersion than their base-band counterparts due to their narrow spectrum. However, DMD generates destructive interferences at certain frequencies and leads to lower SNR for the channels located in these “dips” (see Figure 6).

B. *Single-mode fiber*

Modal dispersion can be avoided by using single-mode fibers (SMF). This solution allows the transmission of radio signals over several tens of kilometers [7], but on the expense of more cost-intensive coupling techniques.

A possible low-cost solution for the uplink (from base to central station) takes the form of a bi-directional transmission using single light source. At the base-station, a fraction of the incoming light is modulated by the radio signal that is to be transmitted to the central station and coupled again into the fiber. This solution necessitates a photodiode and optical modulator or even a single reflective SOA [8] at the base station. In such bi-directional transmissions, where up- and downlink signals use the same wavelength, RBS can be a major impairment for the backward-propagating (uplink) signal [9].

A DFB laser that emits light at 1550 nm with a α-factor of 3 is used in the investigated SMF system. The laser is directly modulated with a modulation index of m < 40% by 3 WiFi channels operating at 54 Mb/s. At the base station (see Figure 5), 30% of the incoming optical power is re-modulated with an EAM (m > 90%; α-factor = 1) and coupled into the fiber. The residual 70% are detected by a photodiode and transmitted (via an ideal antenna) to the users. This arrangement ensures identical performance for the down- and uplink signal for 5 km fiber.

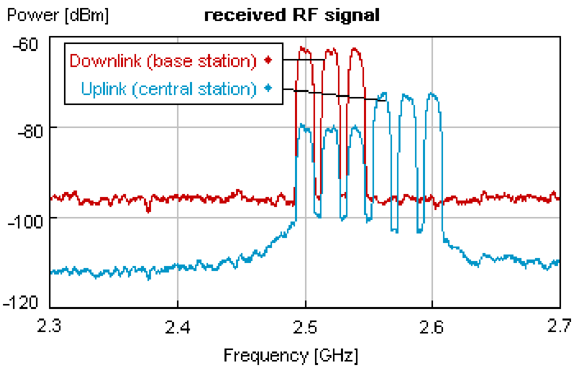

Figure 7. Spectra of the received RF signals at the base and central stations for 5 km single-mode fiber.

The RF spectra of the uplink and downlink signals (after transmission and detection) are displayed in Figure 7. The EVM of the uplink and downlink signals are displayed in Figure 8 versus the fiber length. The results show that Rayleigh backscattering is the major impairment for the uplink signal. In this configuration, the maximum fiber length is 15 km, what should be satisfactory for most remote antenna feeding applications.

Note that in the present analysis, only the main component (corresponding to the optical carrier) of the Rayleigh backscattered signal has been taken into account. This simplification is motivated by the fact that most of the power is carried by the central optical frequency.

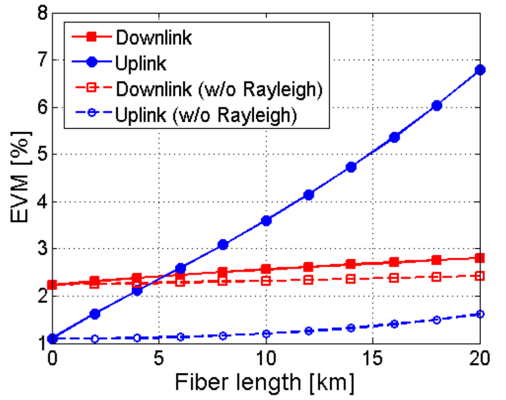

Figure 8. EVM vs. fiber length (averaged over 3 uplink and 3 downlink 54 Mb/s channels).

C. System nonlinearities

Not only electrical noise (photodiode, electrical amplifiers) and optical noise (laser's RIN & linewidth, ASE, Rayleigh etc.) limit the performance of RoF systems. As for HFC and FTTx networks the interplay between laser chirp and fiber chromatic dispersion generates second order distortions that can lead to significant signal degradations. Similarly, laser clipping (over-modulation), and more generally, the nonlinear modulation characteristic of the laser (or of the external modulator) leads to inter-modulation distortions that can fall into the signal bandwidth.

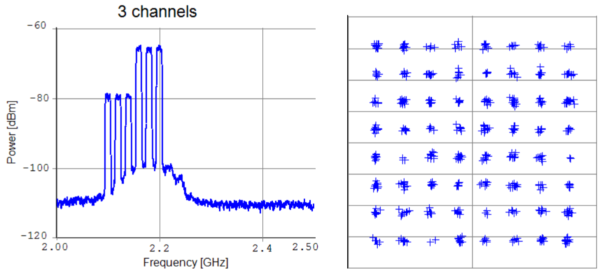

Figure 9. a. Constellation diagrams and RF spectra of the uplink signal for 3 channels

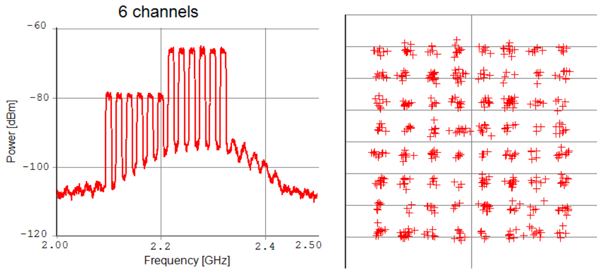

Figure 9. b. Constellation diagrams and RF spectra of the uplink signal for 6 channels

As an example, increasing the number of transmitted channels while maintaining the SNR necessitates a larger modulation index leading to an increase of CSO and CTB distortions. Figure 9 shows the RF spectrum of the uplink signal and the constellation diagram of one of the uplink channels for the case that 3 and 6 channels are transmitted. More CTB terms are generated in the later configuration leading to visible signal degradation.

IV 10-GB/S ETHERNET OVER MULTIMODE FIBERS

Ethernet-based solutions are good candidates to meet the need for rapid deployment of low-cost and high-capacity local and wide area networks. Standards for long (10GBase-LR/ER) and short (10GBase-SR) 10-Gigabit Ethernet fiber-based applications have already been proposed (IEEE 802.3ae). Additionally, the 802.3aq task force is working on the *10GBase-LRM* standard supporting up to 300 meters for 10-Gigabit Ethernet over legacy MMF.

A. Physical Limitations

The transmission distance of a 10-Gb/s signal over MMF is limited by differential-mode dispersion (DMD). For conventional 62.5 and 50 µm fibers, the overfilled launch bandwidth (or maximal bandwidth-distance product) is around 500 MHz-km, corresponding roughly to a maximum transmission distance of 50 meters for a signal modulated at a rate of 10 GHz. Fortunately, the transmission distance can be increased by almost one magnitude with the help of decision feedback equalizers (DFE) [10]. However, this statement is difficult to verify since the signal propagation (and ultimately the bit-error rate) is governed by the launch condition, which may vary from connector to connector, and by the fiber refractive index, which differs from fiber to fiber (defects) and is modified by external stress and bending [6]. Ingham, Penty and White have developed a model in order to address this problem: They determined a set of 108 MMF refractive index profiles intended to be statistical representatives of legacy MMF links [11]. We implemented this model in *VPItransmissionMaker* to assess the performance of DFE for the mitigation of DMD-induced impairments in 10-Gb/s Ethernet systems.

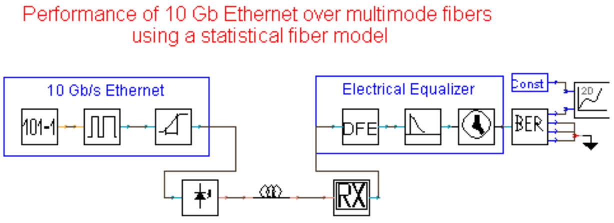

Figure 10. 10-Gb/s Ethernet over MMF simulation setup (*VPItransmissionMaker*).

B. Mitigation of DMD-induced impairments

The setup of the investigated system is displayed in Figure 10. A DFB laser (1300 nm, α-factor = 1) is directly modulated by a 10-Gb/s NRZ signal and driven such that large relaxation oscillations are avoided (bias >

threshold = driving current). The optical signal is then coupled into a 65-µm MMF fiber with an offset of 23 µm. The fiber length can be varied between 0 and 400m. The electrical output waveform is obtained for all 108 fibers of the model and the BER is evaluated using the Gaussian approximation.

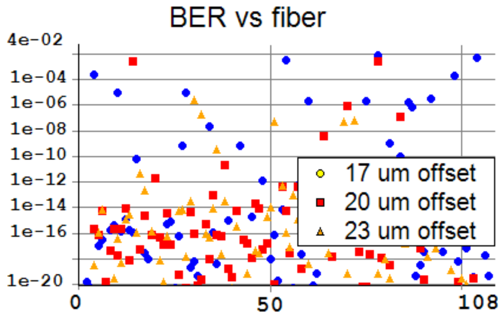

Figure 11: Performance of 10-Gb/s Ethernet for 150 m of different MMFs (statistical study using the [9]).

A 7-taps (5 forward, 2 backward, bit-spaced) DFE filter is placed before the BER module in order to mitigate the impact of DMD. The filter coefficients are optimized with the least mean square algorithm. Digital filters (like DFE) may not be as effective as Viterbi equalization but are much simpler to implement and present a good cost-performance trade-off, which is of importance in cost-sensitive broadband access systems. The simulation results shown in Figure 11 demonstrate that the transmission of 10 Gb/s Ethernet over 150m MMFs is not possible for some fiber configurations under certain launch conditions without equalization. On the contrary, transmission lengths of up to 300 m are possible (target BER of 10^{-6}) with the proposed DFE structure whatever the fiber and launching conditions are. The eye-diagram obtained with one of the worst configurations is displayed before and after equalization in Figure 12.

CONCLUSIONS

The impact of differential mode dispersion (DMD) in transmission of 10Gb/s Ethernet over multimode fibers (MMF) has been characterized using a statistical model. It has been shown that decision feedback equalizers can help to mitigate the DMD-induced impairments and allow transmission lengths of up to 300m over legacy MMFs.

Two concepts for fiber-based analog (video) and digital radio (WiFi) distribution systems have been presented and investigated with the help of numerical simulation. It has been shown that besides nonlinear distortions, noise, inter-modal and chromatic dispersion, stimulated Brillouin scattering and Rayleigh backscattering can have a significant impact on the system performance. The interplay between the various effects can be predicted and optimized using careful computer modeling, which enables to fulfill stringent equipment specifications and aggressive service distribution plans.

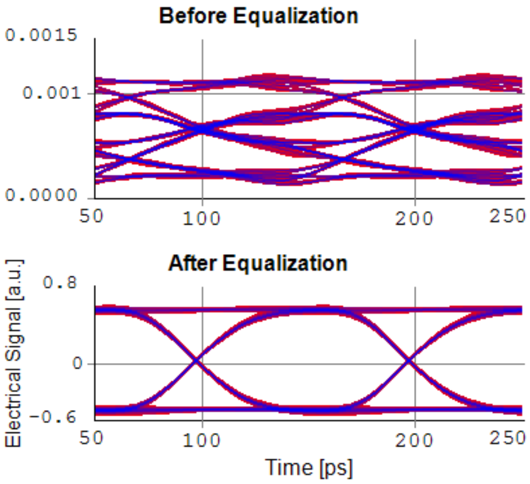

Figure 12: Received signal for a 300 m MMF link (fiber n°61) before and after equalization.

ACKNOWLEDGMENT

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Since Dr. Richter joined the VPIphotonics team in 1997, he contributed to the development of various modeling tools for optical components, subsystems and systems. He invoked an industry training and consulting program in Photonic Design Automation (PDA) that has served more than 850 engineers worldwide. Dr. Richter authored or co-authored more then 25 publications and has given several invited presentations on different topics of optical component, subsystems and WDM systems design.

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