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Fiber over Wireless Chromatic Dispersion Compensation for a Better Quality of Service

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"Anywhere" and, in particular, "anyhow": these are the two best words that can describe an ad hoc wireless network that is due to the increasing demand for connectivity in such an information society. Ad hoc wireless networks can be described as dynamic *multihop wireless networks* with *mobile* nodes. However, the mobility condition can be relaxed, and we can consider an ad hoc wireless network as a reconfigurable network where all the nodes are connected to the local environment through wireless links, and where there is not a central or dominant node—as opposed to, for example, the case of cellular wireless networks where a base station is located in each cell. When ad hoc networks are backboned by fibers, distortion of the optical link presents one of the major issues. In this paper, we will be addressing one of the fundamental problems, namely, chromatic dispersion in the fiber optic prior reaching the access points. This will ensure an adequate quality of service (QoS).

1. INTRODUCTION

The underlying technology is less and less satisfying the need and desire of the present communications users who are incessantly demanding more flexibility (mobility, QoS, any portable unit, etc.) as well as more capacity (bandwidth). Indeed, on the one hand, these consumers are asking for more and more cost-effective communication systems that can support anytime and anywhere any media they want. On the other hand, the users of wireless communications are demanding more capacity and therefore higher frequencies. Unfortunately, these two trends (flexibility and capacity) cannot be simultaneously fulfilled in the scope of wireless communications because of the limits of the radio spectrum.

A clever solution consists in combining the two complementary technologies, namely, wireless and fiber. The resulting system (Figure 1), commonly referred to as a hybrid fiber-wireless system, offers a high QoS in addition to mobility and immunity to electromagnetic interference without largely occupying additional radio spectrum. While wireless systems offer flexibility including mobility, optical fiber communications provide, in a cost-effective way, the massive bandwidth that fuelled the huge demand on Internet traffic, video on demand, and so forth.

In particular, ad hoc networks offer total mobility. Two main categories of ad hoc networks are distinguished. The first category consists in ad hoc networks that can function as standalone networks meeting direct communication requirements of their users. In addition to existing ad-hoc infrastructure, the second category will be used to extend and enhance the coverage of the first. The second category, which presents a valuable solution to incomplete networks, can be connected via a radio access point to an optical link leading to high-speed fiber-based ad hoc wireless access systems. In this situation, the connection to the fiber and possibly to Internet requires a fixed access point (Figure 1). The optimization of the rapidity of such a system will be a subject of future work where hardware as well as networking issues are of consideration.

The wireless-optic combination is however not without its difficulties. One of the major difficulties is chromatic dispersion that is a serious source of intersymbol interference (ISI). In fact, since higher bit rates require smaller pulse width, sources of wave distortion, such as chromatic dispersion and nonlinear effects, become not negligible. In this paper, we focus on one of the most important limitations of high bit rate transmission, namely, chromatic dispersion of order 2. Higher orders will be subject to future work. Our solution for dispersioncompensation is based on a well-known

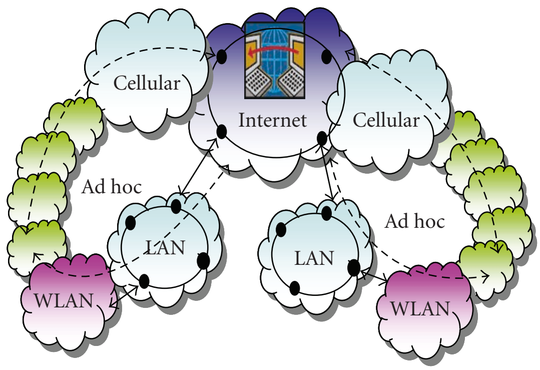

Figure 1: A possible wireless infrastructure topology.

phenomenon in physical optics, namely, the self-imaging effect, also commonly called the Talbot effect.

The remainder of this paper is organized as follows. Section 2 enumerates some advantages for high-speed fiber-based wireless systems in a separate subsection. Then, some of the issues with fiber backboned ad hoc wireless networks are outlined. Section 3 briefly discusses fiber impairments that may result in a significant reduction of the QoS of the ad hoc network. Section 4 presents Talbot-based compensation method where our solution lies. Section 5 addresses the mathematical background of limitation considered in this paper, namely, chromatic dispersion. After briefly covering the temporal Talbot effect, for illustration, simulation results are given in Section 6. Finally, Section 7 presents some discussions of the results.

2. HIGH-SPEED FIBER-BASED WIRELESS NETWORKS

2.1. Advantages of high-speed fiber-based wireless systems

As stated above, while the wireless part (subsystem) of the hybrid system offers mobility, the main contribution of the optical fiber communication subsystem is to transmit the maximum number of bits per second over the maximum possible distance with the fewest errors. Optical fiber is still the best medium for long-haul and very-high-bit-rate transmissions. It is considered as a low-cost solution to respond to the exponential needs of bandwidth to carry huge data required for exponential demand of bandwidth for the Internet and related technologies.

Besides, the fiber can be combined to wireless to offer many advantages such as huge capacity (bandwidth) that enables multiplexing several radio frequency (RF) channels. As a consequence, each RF channel may belong to a different system such as ad hoc wireless and cellular systems. The transmission of RF signals over the fiber allows for transparent operation because the RF to optical modulation is typically independent of the base band to RF modulation. Third, in continuity with the last point, hybrid wireless-fiber systems allow for easy integration and upgrades since the electrical-to-optical conversion is independent of baseband-to-RF modulation format. Fourth, the introduction of the optical link offers immunity to electromagnetic interference. Fifth, no additional infrastructure effort is required to provide high-speed fiber-based wireless networks since the already installed fibers running in our neighborhood in most major cities can be used for this purpose.

2.2. Issues with fiber backboned ad hoc wireless networks

In hybrid wireless-optical systems, chromatic dispersion is particularly a major issue. Indeed, transmitting traditional double sideband (DSB) signals is problematic due to chromatic dispersion. This frequency-dependent fiber dispersion produces a deleterious time delay between the two transmitted sidebands, causing serious RF power fading that is a function of subcarrier frequency, fiber distance, and accumulated dispersion. Indeed, if the RF signal (with optical carrier) is transmitted over fiber, chromatic dispersion causes each optical sideband to experience a different phase shift, which varies with fiber length, radio frequency, and fiber dispersion parameter [1, 2]. Thus, using the conventional DSB modulation scheme, the RF power detected at the base station suffers from a periodic degradation due to the fiber chromatic dispersion. As the RF frequency or fiber-link distance increases, this effect is even more severe and limits the system performance [3, 4].

In particular, the use of ad hoc wireless networks, used as an extension to an existing infrastructure, may amplify the difficulty of chromatic dispersion. Indeed, total mobility is one of the most common reasons to apply ad hoc topologies. Each node in a wireless ad hoc network has a wireless access interface and is free to enter or leave the network at any time. Thus, it is desirable not to modify each mobile node because of the constraints of wireless-fiber link including limitations due to high-speed transmission. Each node should not be aware of the existence of this link leading to a transparent seamless information flow between the fiber and the portable units.

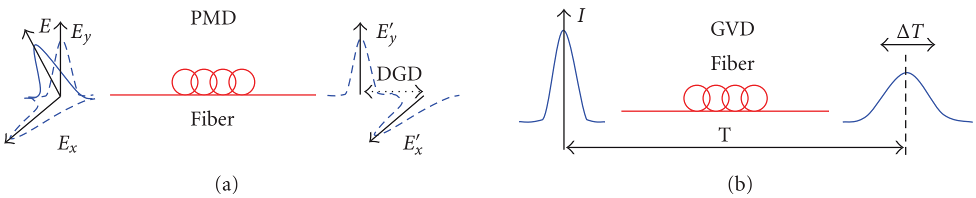

FIGURE 2: (a) PMD: polarisation mode dispersion, DGD: differential group delay, E: input field, E': output field, E_x: x-component of the field, (b) GVD: group velocity dispersion.

3. FIBER IMPAIRMENTS

Nonidealities of optical fiber place restrictions on the distance that can be tolerated without introducing signal regenerators, in-line optical amplifiers. These nonidealities can be broadly classified into attenuation which causes a loss in the signal power, distortion which causes pulse broadening, and thus ISI, and fiber nonlinearity which causes self phase modulation, cross phase modulation, and four wave mixing in WDM.

3.1. Attenuation

Attenuation in fiber occurs due to absorption, scattering, and radiative losses of the optical energy. Absorption losses are caused by atomic defects in the glass composition, intrinsic absorption by atomic resonance of fiber material, and extrinsic absorption by the atomic resonance of external particles (like OH ion) in the fiber. Scattering losses in fiber arise from microscopic variations in the material density and from structural inhomogeneities. There are four kinds of scattering losses in optical fibers, namely, Rayleigh, Mie, Brillouin, and Raman scattering. Radiative losses occur in an optical fiber at bends and curves because of evanescent modes generated [5–8].

3.2. Signal distortion

Optical fiber, by its very nature, is a dispersive media. As an optical signal travels through the glass, it becomes more and more distorted over longer distances for a variety of reasons. The primary contributors to signal distortion are polarization-mode dispersion, chromatic dispersion, and fiber nonlinearities. A brief description of these three phenomena shows how each affects the signal within the optical fiber.

(i) *Polarization-mode dispersion.* Polarization-mode dispersion (Figure 2) is another phase-related distortion. As light is polarized in the optical fiber, the two polarizations travel at different speeds within the glass. The resulting phase distortion between the two polarizations is known as polarization-mode dispersion.

(ii) *Chromatic dispersion.* Chromatic dispersion is a variation in the velocity of light (group velocity) according to wavelength. This variation in velocity, which will be mathematically developed in the next section, causes the pulses of a modulated laser source to broaden when traveling through the fiber, up to a point where pulses overlap and bit error rate increases. As this increase in bit error rate interferes with both the quality and speed of the signal, chromatic dispersion (CD) is a major limiting factor in high-speed transmission. Therefore, to ensure adequate quality of service (QoS), it is extremely important that carriers compensate for this type of signal distortion. The widespread use of DWDM systems covering the C and L bands (1530 nm to 1625 nm) will certainly create a need for accurate wideband CD compensators.

4. TALBOT-BASED COMPENSATION

4.1. Self-imaging

Light propagation is a spatial phenomenon and therefore it associates three dimensions x, y (transversal), and z (propagation) in a physical harmony, maintained by the principle of energy conservation in any longitudinal position z in free space. Because periodicity presents a spatial link in the transversal plane (x, y), it allows the association mentioned above to be the source of interesting optical effects observed at particular distances z [5, 9]. Depending on the nature (spatial or temporal) of the periodic structures, we distinguish two phenomena: spatial Talbot effect and temporal Talbot effect. For the purpose of dispersion compensation, we will focus on the temporal Talbot effect.

The temporal Talbot effect occurs when a periodic sequence of pulses, produced by a laser for example, propagates in a dispersive medium. We remind the reader that a dispersive medium is a medium in which the various harmonics, composing the pulse, propagate with different speeds, therefore causing a stretching of the pulse during propagation.

When a periodic pulse train, with period T, progressively propagates in a dispersive medium, it undergoes a temporal widening in its both wings. At a certain distance of propagation, each pulse overlaps with its two neighboring pulses. Thus, information transported by the periodic signal is affected. For further transmission distances, the widened pulses continue stretching so that each one may overlap with several pulses in both sides. We then observe several areas along the axis of propagation where either constructive or destructive superimposition occurs. As will be explained later in the analysis section, for particular distance z, the areas of constructive or destructive superimposition may be distributed so that the initial periodic train is integrally re-observed. This phenomenon of self-imaging is referred to as the temporal Talbot effect.

The overlapping of the widened pulses may be constructive in some areas and destructive in other areas so that new pulses, having the same shape of the initial pulses, are formed. Thus, the period train contains additional pulses and consequently the frequency of the pulses is doubled, tripled, and in general replicated N times. It deals in this case with the temporal fractional Talbot effect [5, 9].

5. PROPOSED METHOD BASED ON TALBOT EFFECT

Pulse propagation through optical fiber is widely described in several literatures. In its easiest formulation when the pulse width is larger than five picoseconds under the assumption of slowly varying envelop approximation (SVAE), the variation of the complex envelop $u(t)$ is governed by the nonlinear Schrödinger equation (NLSE)

$$i\frac{\partial u}{\partial z} + \frac{i}{2}\alpha u - \frac{1}{2}\beta_2\frac{\partial^2 u}{\partial T^2} - \frac{i}{6}\beta_3\frac{\partial^3 u}{\partial T^3} + \gamma|u|^2 u = 0, \quad (1)$$

where α is the attenuation coefficient, $T = t - \beta_1 z$ is the related time frame, γ is the nonlinear parameter known as self-phase modulation (SPM), and β_2 and β_3 are, respectively, the second- and third-order dispersion parameters referred to as the group velocity dispersion (GVD) and third-order dispersion (TOD). While dispersion is responsible for a temporal broadening of the signal, SPM effect is observed in the spectral domain through a spectral enlargement. With the aim of quantifying the effect of those phenomena along a transmission length, it is practical to introduce some characteristic variables; $L_D = T_0^2/|\beta_2|$, $L'_D = T_0^3/|\beta_3|$, and $L_N = 1/\gamma P_0$ are, respectively, the second- and third-order dispersion lengths, and the nonlinear lengths. In what follows, we consider a lossless medium ($\alpha = 0$).

Generally, the GVD effect is more important than TOD ($L'_D \gg L_D$) and the latter is usually neglected except in the ultrashort pulses (> 100 Gbit/s) and in the zero-dispersion conditions. When $L_D \cong L_N$, both GVD and SPM effects have a comparable contribution. In this case, Soliton-like pulse is the ideal signal shape for very long distances. This pulse is the analytical solution of the NLSE using inverse scattering method [6]. It results from the interplay between GVD and SPM effects. When $L_N \gg z$, the most contribution of physical phenomenon arises from the chromatic dispersion. So (1) can be easily solved in Fourier domain:

$$U(w,z) = U(w,0)\exp\{i2\pi D(w)z\}, \quad (2)$$

where $D(w) = ((\beta_2/2)w^2 + (\beta_3/6)w^3)$.

Both nonlinearity and dispersion effects are undesirable in optical fiber transmission. They distort the propagated signal resulting in intersymbol interference.

Let us turn back to the Schrödinger equation (1), neglect nonlinearity ($\gamma = 0$) and fiber loss, and normalize the complex amplitude and the time scale:

$$i\frac{\partial u}{\partial z} = \frac{1}{2}\beta_2\frac{\partial^2 u}{\partial T^2}, \quad (3)$$

where $u(z,\tau)$ is the normalized amplitude (P_0: the peak power of the incident pulse):

$$g(z,\tau) = \sqrt{P_0}\exp\left(-\frac{\alpha z}{2}\right)u(z,\tau) \quad (4)$$

and $\tau = T/T_0$ is the normalized time (T_0: pulse width).

The Fourier transform of the solution of the differential equation (5) is given by

$$U(z,\omega) = U(0,\omega)\exp\left(\frac{i}{2}\beta_2 z\omega^2\right), \quad (5)$$

where $U(0,\omega)$ is the Fourier transform of the optical signal $u(0,\tau)$ that was injected into the fiber and $U(z,\omega)$ is the Fourier transform of the signal exiting this dispersive medium.

Equation (6) points out that the Fourier transforms of the input and output signals are identical except for a phase term. They may be exactly identical if this term is neutralized, $\exp(i(\beta_2/2)\omega^2 z)$ = constant.

Unfortunately, this term is a continuous function in ω and is not constant. However for discrete values of ω, this function may take a constant value.

Then, $\exp(i[(\beta_2/2)\omega^2]z)$ is equal to 1 if only the angular frequencies ω, satisfying the following relations, are active:

$$\frac{\beta_2}{2}\omega^2 z = 2k\pi, \quad (6)$$

where k is an integer.

In particular, a periodic signal $u(0,\tau)$ may satisfy this condition. Indeed, its Fourier transform is sampled with the sampling interval $1/T$ where T is the period of the signal. Thus, only the angular frequencies $\omega = 2\pi n f = 2\pi n/T$ are active (n is an integer). Let us see whether there is a particular distance z for which relation (6) is fulfilled. We can easily prove that all periodic distances of the form $z = mZ_T$ where $Z_T = T^2/\pi\beta_2$ satisfy this relation. As mentioned above, the distance Z_T is referred to as the Talbot distance (see next section). We intend to use this phenomenon to perform post-compensation of chromatic dispersion (CD). Before tackling our technique, let us briefly address the phenomenon of temporal Talbot effect.

6. SIMULATION RESULTS

We provided a simulation of light propagation through a dispersive medium in form of an applet that is publicly assessable through an Internet browser [10]. In addition, we simulated periodized signal at the receiver side and the retransmitted the signal through another dispersive medium as illustrated in Figure 3. Indeed, Figures 4 and 5 show the obtained simulated results using the optical post-compensation

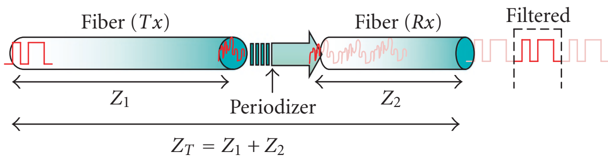

FIGURE 3: Schematic model of the post-compensation model.

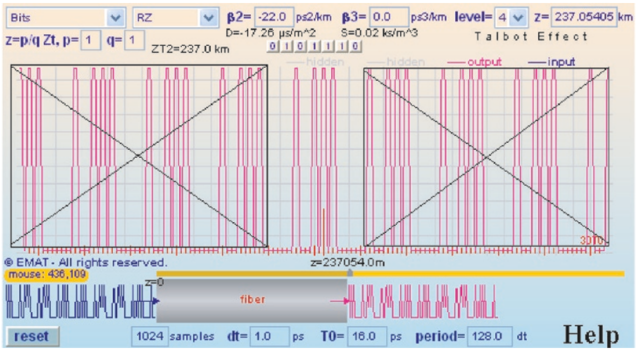

FIGURE 4: Received signal after transmission along the fiber (Tx) and periodization and propagation through the fiber (Rx); the unwanted signal could be filtered as shown above.

technique based on the temporal Talbot effect in an optical transmission link. Figure 4 shows that after 237 km, we obtained exactly the same transmitted signal ($\beta_2 = -22.00$, this parameter can be modified in the applet). The signal is represented by 1024 samples. The sampling interval is $dt = 1.0$ ps and the pulse width is $T_0 = 16$ ps. We choose the input bit sequence 0101110. The user of the applet can choose any other sequence. This sequence is coded according to the RZ code. Four encoding formats are available: RZ, NRZ, Duobinary RZ, Duobinary NRZ. The applet allow to display the input and output signal as well as the spectrum of the input signal, which is identical to that of the output signal in terms of intensity profile. Figure 5 shows the effect of chromatic dispersion on the same signal with the same parameters as in Figure 4. Also one can notice that the received signal is drastically deformed and it would be almost impossible to restore the signal without the post-compensation technique.

7. DISCUSSION AND CONCLUSION

The proposed method is an optical post-compensation technique based on the temporal Talbot effect as seen in Figure 2. After propagation through the dispersive medium with a length Z_1, the received signal is unfortunately affected by fiber impairments, mainly CD, as shown in Figure 2. Indeed, it may be significantly corrupted and totally deformed so that its reconstruction becomes very difficult not to say impossible. Our alternative consists of introducing a periodizer and propagating the periodized signal through another standard fiber with length Z_2 in such a way that $Z_1 + Z_2 = nZ_T$, where n is a positive integer. The propagated signal along the distance Z_2 is an exact replica of the originally transmitted signal.

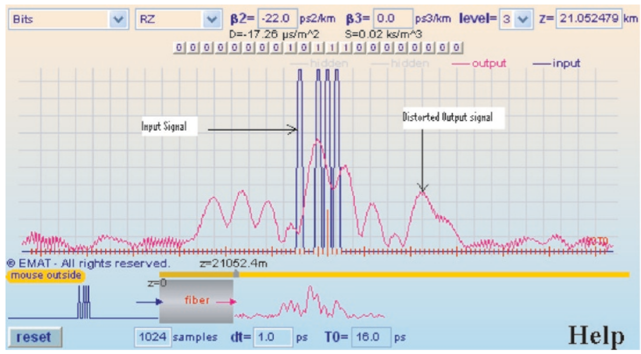

FIGURE 5: Received signal without the Talbot-effect-based post-compensation.

Then a truncation process is performed at the very end to restore the wanted signal.

This method has many advantages; to name a few,

(1) signal received may be totally altered;
(2) it offers total degree of freedom in choosing the period, the high-order Talbot distances;
(3) no need to increase the number of repeaters, which leads to the decrease in the cost;
(4) it is independent from the bit rate sent originally, meaning that it can handle bit rates in excess of 40 Gbit/s;
(5) no special fiber is required. Standard single mode fibers can be used.

All the above-mentioned advantages lead to a better QoS in an ad hoc network where dynamic reconfiguration of a wireless network without the need of a centralized control is possible. This network is crucial for communications between hosts without any existing infrastructure. So, for some applications, an ad hoc network needs to be linked to a wired network to have access to Internet or/and other related services via wireless local area networks. In a wireless access point, the big challenge is to allow transporting heterogeneous services with transparency. Radio over fiber solution is proposed. It takes advantage of the optical fiber capacity to carry RF signals. This is performed by directly modulating the RF signal by means of an electro-optic modulator. In a heterogeneous wireless network, the base station should be able to provide different services for different distant hosts. Even though the bit rate in an ad hoc network is not very constraining for a standard wired network, transporting other services simultaneously can increase the transmission bit rate rapidly. Then the chromatic dispersion problems appear in the fiber link depending on modulation format of the transmitted radio signal where the quality of transmission is being improved by using chromatic dispersion compensation stages over the fiber link. For a best chromatic dispersion compensation network configuration, a preequalization is suggested in the downlink and a postequalization in the uplink leading to simple BS architecture. In this paper, a new technique is proposed to compensate the chromatic dispersion optically by applying Talbot effect. Results obtained are inline with what's proposed. This method is easy to implement and versatile since any type of fiber can be used. Moreover, our technique has the strength to revive a totally deformed signal regardless of the bits transmitted.

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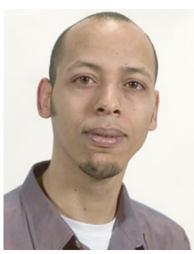

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