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Equalization Advantages of OFFH-CDMA over WDM in EDFAs

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ABSTRACT

The gain of an EDFA (erbium doped fiber amplifier) is in general wavelength-dependent, leading to different amplification levels among WDM (wavelength division multiplexing) channels. The use of Optical FFH-CDMA (fast frequency hopped code division multiple access) offers a natural diversity of wavelength, and therefore gain, thus eliminating the requirement of an equalization stage to achieve flat gain on all channels. Computer simulations are developed to analyze and compare equalization performance of these two transmission approaches (CDM and WDM) in EDFAs, especially in situations where the EDFA operating point is subject to change (i.e., variable input traffic). We find that Optical FFH-CDMA presents several advantages including dynamic gain equalization.

Keywords: EDFA, WDM, FFH-CDMA, Equalization, and Self-similar traffic.

1. INTRODUCTION

Communication in the optical medium has been made more economically attractive due to erbium-doped fiber amplifier (EDFA) technology. By virtue of their ability to compensate for fiber attenuation and splitting losses, EDFAs have become a key component in the fiber optic link.

The gain of an EDFA is in general wavelength-dependent, leading to different amplification levels among WDM (wavelength division multiplexing) channels. Signals traversing a cascade of several amplifiers will experience a steadily worsening gain tilt among channels [1]. EDFA equalization is applied to overcome this effect [4]. Such methods are based on analysis of a fixed EDFA operating point, *i.e.*, a gain *vs.* wavelength relationship that is static and does not vary with time. However, operating points change when amplifiers are faced with non-periodic input power changes due to: a) channel add/drop, b) network reconfiguration, c) fiber cuts, or d) packetized traffic such as Internet data. Such situations lead to dynamic changes in the EDFA gain *vs.* wavelength profile, thus forming new conditions where the inherently static EDFA equalizers and pre-emphasis are no longer able to maintain equal gain at all wavelengths.

We propose to avoid WDM's single wavelength dependence by using an optical spread spectrum technique, such as optical Fast Frequency-Hop CDMA (OFFH-CDMA) [3], thus improving amplifier gain dynamics. Our simulations demonstrate clear advantages in the use of CDMA for equalization.

2. SIMULATION MODEL

Optical FFH-CDMA has been proposed as an alternative all-fiber access network technology [3]. An OFFH-CDMA encoder uses a series of Bragg gratings in a single fiber to convert uniform broadband data pulses to CDMA hopping frequencies. Reversing the order of the Bragg gratings at the decoder removes the translation between the frequency components and realigns them to reconstitute the original data pulse.

We suppose that data arrives in packets, whose duration falls within the time response of an EDFA. EDFA gain is insensitive to chip or bit level power fluctuations [1]. The encoding operation is modeled as an equal partition of source power over the CDMA wavelengths included in the code. Likewise, decoding is modeled as the summing of the output power in these wavelengths (Fig. 1). We assume orthogonal codes.

We apply a numerical model that solves a single transcendental differential equation for the total number of excited ions in the EDFA [2]. The latter consists of a 35-m Erbium fiber with 70 mW of pump power at 980 nm. For both WDM and Optical FFH-CDMA, 30 communication channels are carried by 30 wavelengths centered on 1550 nm and having a uniform spacing of 0.4 nm. Each Optical FFH-CDMA channel uses 12 wavelengths determined by its unique code. Code generation is based on the Extended Hyperbolic Congruential (EHC) frequency hop code algorithm [6].

After the preliminary steady-state and channel drop simulations, Internet-type traffic, characterized by a network utilization factor r determined as described in [1], is fed to the EDFA. Each channel is modeled as an independent ON/OFF burst-mode packet switching traffic source, with ON and OFF times having a heavy-tailed Pareto distribution [1], [5]. The bit rate per channel is 1.25 Gb/s. Besides, each equalizer is modeled as a fixed band-pass filter with an attenuation characteristic that inverts a certain gain profile, and having a tolerance of 0.01 dB [4].

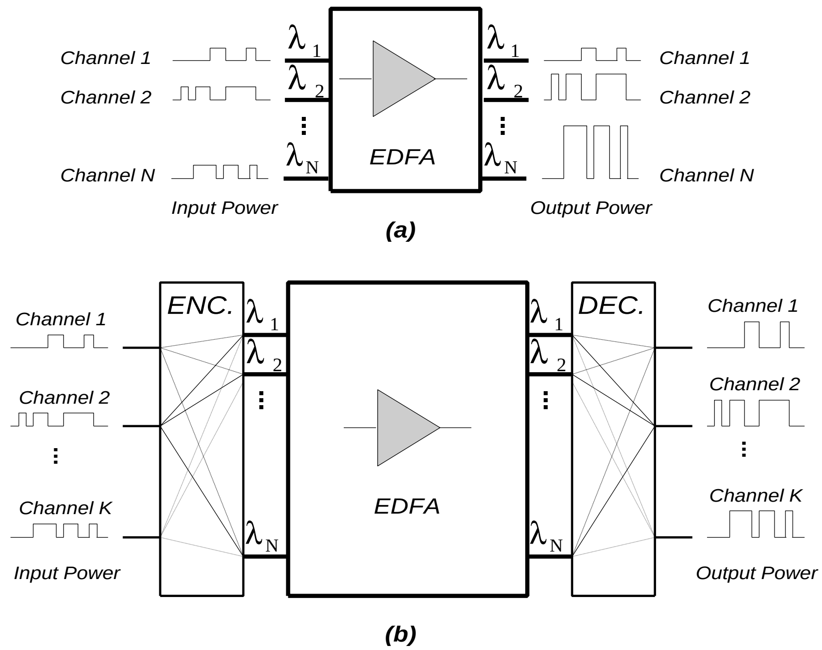
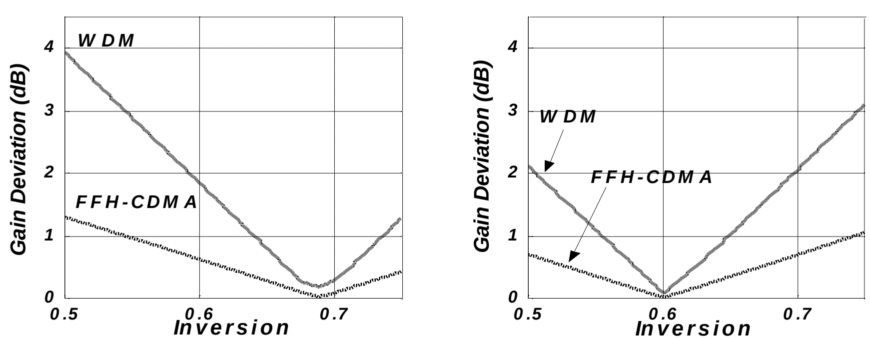


Figure 1. Power distribution model: (a) Each WDM channel is carried by a single wavelength, whereas (b) Optical FFH-CDMA channels distribute over CDMA code-assigned wavelengths.

3. SIMULATION RESULTS

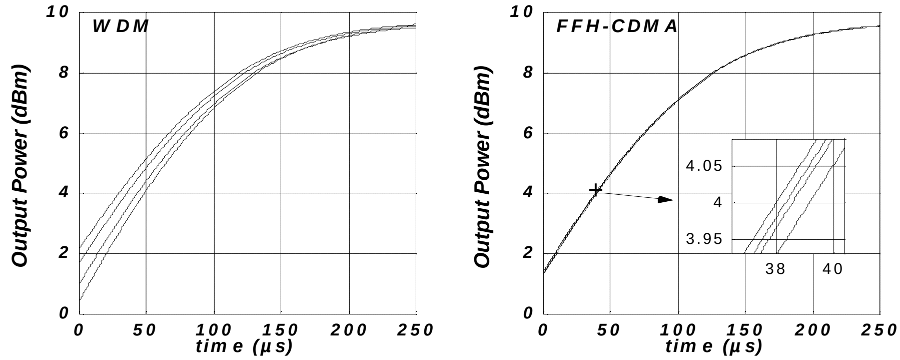
EDFA inversion, *i.e.*, the mean fraction of excited ions, has been identified as the major EDFA state variable for it uniquely determines the gain profile [2]. Fig. 2(a) depicts the maximum gain deviations among continuous wave (CW) channels in WDM and CDMA. The range of possible inversion levels is inferred from the dynamic study in [1]. It is clear that as the EDFA moves away from its natural optimal inversion level of 0.69, where deviations are minimal, larger disparities among channel gains appear in WDM, reaching 4 dB at low inversions. In CDMA, however, deviations among gain on various channels grow more slowly and remain distinctly inferior at all inversions, never exceeding 1.4 dB. We add an equalizer optimized for an inversion level of 0.6 at the output of the EDFA (Fig. 2(b)). Although the equalizer efficiently shifts the optimal operating point, for which it removes gain disparities, WDM equalization fails when the operating point changes. Deviations of 3dB in WDM and 1 dB in CDMA are seen in our simulations. In a dynamic scenario where all inversion levels can occur, CDMA (Fig. 2(a)) is superior to WDM with an equalizer (Fig. 2(b)). Note that the inherent power penalty (equalizer attenuation) is another disadvantage of the WDM/equalizer in the presence of dynamic operating conditions.



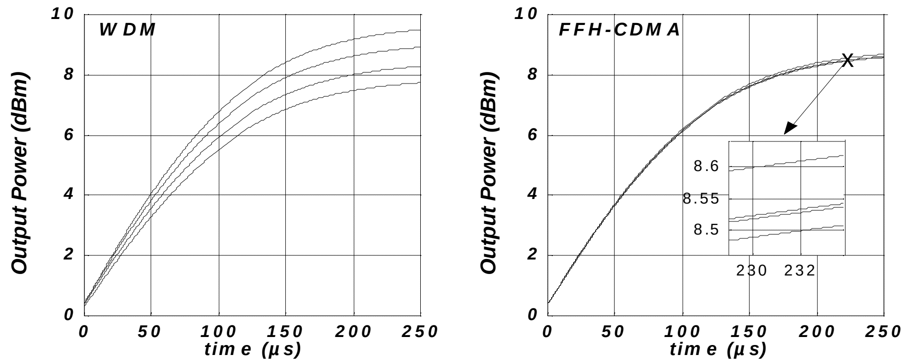
(a) (b)

Figure 2. Maximum channel gain deviations in steady-state (a) without or (b) with an equalizer.

Operating point shifts are likely in burst-mode networks because inversion depends on input power [2]. Using the EDFA parameters given above with -18 dBm of input power per channel yields a steady-state inversion level of 0.6. Fig. 3(a) depicts the 4 survivor power transients after a 26 channel-drop in WDM (left) and CDMA (right).



(a)



(b)

Figure 3. Surviving channel output powers for WDM (left) and CDMA (right) (a) without or (b) with an equalizer.

The drop operation corresponds to shifting the EDFA operating point to an inversion level of 0.687, which explains the narrowing of the WDM output power range in the new steady-state. CDMA channel deviation is remarkably less sensitive to the EDFA input power configuration. Fig. 3(b) shows the impact of adding the EDFA equalizer described previously in the same drop scenario. As expected, the deviations among WDM channels in the initial steady-state (t=0), coinciding with the equalized EDFA operating point, are removed. However, large disparities appear in the final state where the equalizer loses its effect. Whether it is with or without an equalizer, CDMA insures notable power equity among channels at both operating points, hence its dynamic advantage.

In our packetized traffic simulations, the aim is to construct histogram estimates of the probability density functions (PDF) of EDFA inversion as well as output power for each of the 30 channels. That is accomplished by calculating inversion and power transients over a period of 340 ms, then arranging them in a histogram of 10000 bins uniformely tiled from 1 to 8 dBm for output power, and from 0.60 to 0.70 for inversion.

Fig. 4 shows the inversion PDFs for 3 different network utilization factors in WDM. The PDFs were also computed in CDMA and were found to be identical. That is due to the fact that, in the current signal frequency band, inversion dynamics respond to the total EDFA input power more than to individual channel fluctuation [2]. The total input power is indeed similar in WDM and CDMA since the power per channel and data sequences are identical. We identify two important PDF parameters: the central, or most-probable, value, and the PDF span at the probability level of 10^{-5}. The results for the PDFs of fig. 4 are listed in Table 1.

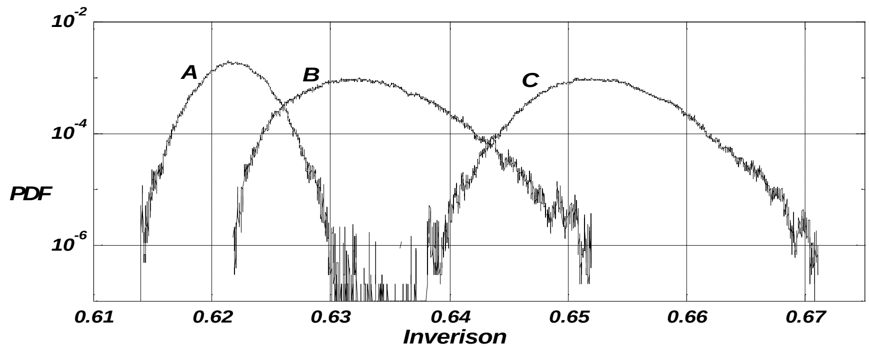


Figure 4. Inversion PDFs for network utilization factors (A) r = 0.7, (B) r = 0.5, and (C) r = 0.3

Network Utilization (r)	0.7 *(Curve A)*	0.5 *(Curve B)*	0.3 *(Curve C)*
PDF Center	0.621	0.632	0.651
PDF Span	0.0141	0.0254	0.0264

Table 1. Inversion Statistics

As network utilization decreases, less power is input into the EDFA. The average number of excited ions will therefore increase, hence the clear shift to the right of inversion PDFs. With higher average inversion levels, channel fluctuations will draw more power from the EDFA, which may account for the wider inversion spreads at higher values of r. It should be noted that inversion levels are not affected by equalization, since the latter operates only on EDFA output powers. However, equalization will have a significant impact on inversions in a cascade of EDFAs, as an equalizer filter at a certain level in the cascade affects the input powers of the following EDFAs.

In order to examine power equalization properties, we propose to compare the PDF centers and spans for four monitoring channels. Whereas the four CDMA channels cover the discrete signal spectrum, the four WDM channels have been selected such that they evenly represent it. In Figs. 5 and 6, the labels A, B, C, and D thus designate the WDM channels centered on wavelengths 1544.2, 1547.8, 1551.8, and 1555.8 nm, respectively.

Fig. 5 depicts the superposed PDFs of the four monitoring channels when r = 0.5. The plots represent WDM channels without or with equalization (top and middle plots respectively), as well as CDMA channels with no equalization (bottom plot). The equalizer is designed to operate at the gain profile corresponding to the most probable inversion level at r = 0.5, *i.e.* 0.632 (see Table 1). Maximum deviations among the power PDF centers and spans are listed in Table 2 as indicators of the equalization properties in the three cases of Fig. 5.

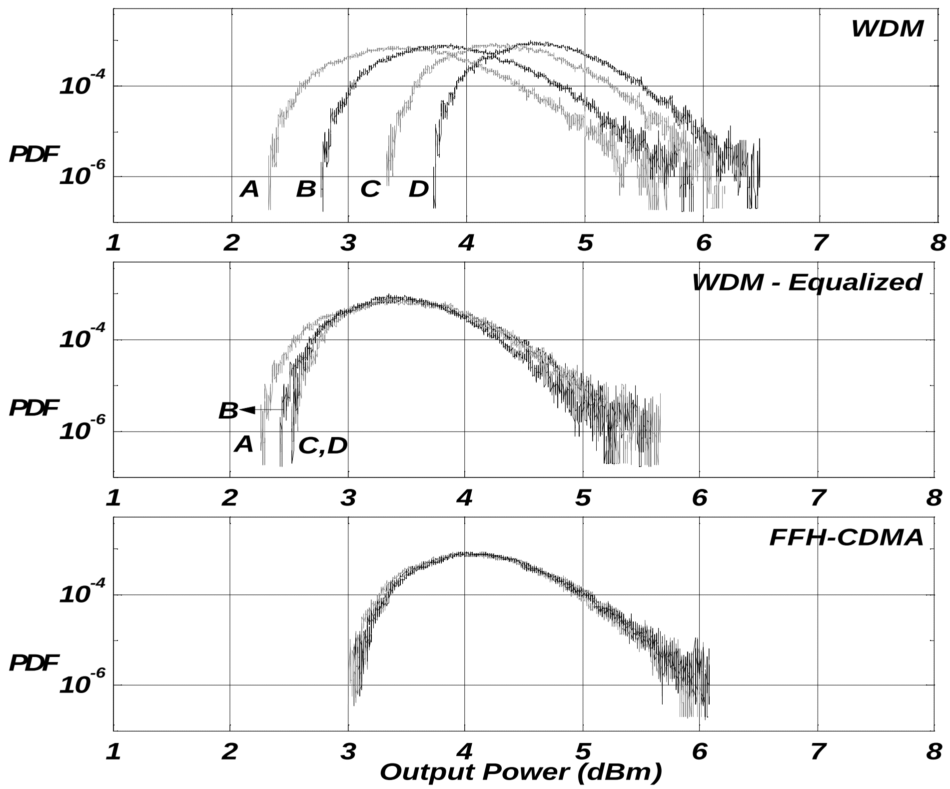


Figure 5. Output power PDFs in WDM (top), WDM with an equalizer (middle), and CDMA without any equalizer (bottom), with r = 0.5

Maximum Deviation (dB)	In PDF Centers	In PDF Spans
WDM	1.12	0.46
Equalized WDM	0.15	0.45
FFH-CDMA	0.16	0.06

Table 2. Output Power Statistics with r = 0.5

From Fig. 5, it is clear that the shift among PDF centers exceeds 1 dB, and may imply output power deviations of 3.5 dB among WDM channels. This shift falls to 0.15 dB when placing the equalizer at the output of the EDFA. The deviation in PDF spans, however, remains in the order of 0.5 dB, implying that the power fluctuation range is channel dependent in WDM. FFH-CDMA channels exhibit perfectly superposed power PDFs at the output of the EDFA, where both PDF shift and span deviations are removed, without resorting to equalization.

As optical communications migrate towards access environments and packet-over-WDM technologies, network design is required to accommodate various traffic types and densities. Such variation implies conditions where network utilization may change. In Fig. 6, we plot the output power PDFs for r = 0.7 and r = 0.3, in the equalized WDM (top plot) or non-equalized CDMA (bottom plot) cases. The increase of power PDF centers and spans accompanying the decrease of network utilization can be expected from the characteristics of the inversion PDFs shown in Fig. 4, since EDFA output power is directly related to inversion through gain [2].

The maximum center and span deviations in the PDFs of Fig. 6 are listed in Table 3. The central power level variations and PDF span disparities indicate that equalization is no longer effective when network utilization changes. This also can be anticipated from the results in Fig. 4, since the modifications in inversion induced by changes in r imply variations in the gain profile, thus requiring different equalizer properties. Fig. 6 and Table 3 clearly demonstrate the superiority of FFH-CDMA equalization, with perfectly superposed power PDFs and central power deviations below 0.09 dB for the new network utilization factors.

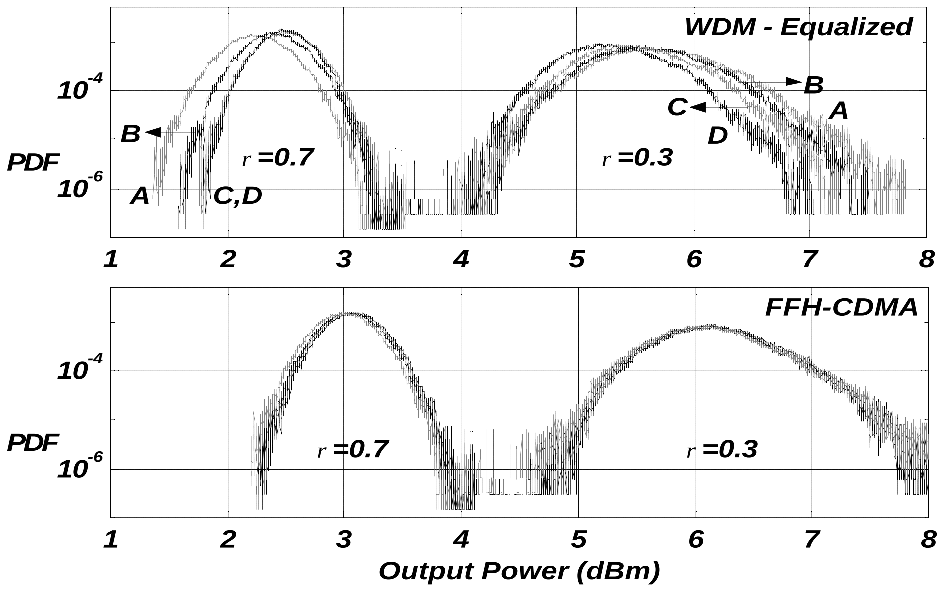


Figure 6. Output power PDFs in Equalized WDM (top) and CDMA without any equalizer (bottom), for r = 0.7 and r = 0.3

	r = 0.7		r = 0.3	
Maximum deviation (dB)	**Centers**	**Spans**	**Centers**	**Spans**
Equalized WDM	0.27	0.30	0.32	0.51
FFH-CDMA	0.09	0.06	0.09	0.15

Table 3. Output Power Statistics for r = 0.7 and r = 0.3

4. CONCLUSION

Wavelength diversity characterizing Optical FFH-CDMA has been shown to eliminate the need for static equalizers or dynamic EDFA monitoring systems by providing natural dynamic equalization. Improving CDMA wavelength diversity should enhance its equalization properties. That can be achieved by increasing the code length, i.e., the number of wavelengths used by each FFH-CDMA channel, or by selecting code families where the frequencies of each channel are evenly spread over the spectrum.

Inexact equalization is compounded by passing through several EDFAs, so that signals exiting a cascade of EDFAs experience much greater divergence in gain among WDM channels [1]. Therefore, the sensitivity of static equalization methods for WDM will be even more evident in these systems. Since CDMA equalization is due to wavelength diversity, and therefore responds to changing EDFA operating points, cascades of EDFAs should show less sensitivity for CDMA-encoded channels.

Optical CDMA technologies are also expected to reveal similar channel equity advantages with other wavelength-dependent imparities such as Raman scattering.

5. REFERENCES

[1] L.Tancevski, A. Bononi, and L. A. Rusch. "Output Power and SNR Swings in Cascades of EDFAs for Circuit- and Packet-Switched Optical Networks." *IEEE Journal of Lightwave Technology*, vol. 17, no. 5, pp. 733-742, May 1999.

[2] A. Bononi and L. A. Rusch. "Doped-Fiber Amplifier Dynamics: A System Perspective." *IEEE Journal of Lightwave Technology*, vol. 16, no. 5, pp. 945-956, May 1998.

[3] H. Fathallah, L. A. Rusch, and S. LaRochelle. "Passive Optical Fast Frequency-Hop CDMA Communications System." *IEEE Journal of Lightwave Technology*, vol. 17, no. 3, pp. 397-405, March 1999.

[4] M. Rochette, M. Guy, S. LaRochelle, J. Lauzon, and F. Trépanier. "Gain equalization of EDFA's with Bragg Grating." *IEEE Photon. Techn. Lett.*, vol. 11, no. 5, May 1999.

[5] W. E. Leland, M. S. Taqqu, W. Willinger, and D. V. Wilson. "On the Self-Similar Nature of Ethernet Traffic." *IEEE/ACM Transactions on Networking*, vol. 2, no. 1, February 1994.

[6] L. D. Wronski, R. Hossain, and A. Albicki. "Extended Hyperbolic Congruential Frequency Hop Code: Generation and Bounds for Cross- and Auto-Ambiguity Function." *IEEE Trans. Commun.*, vol. 44, no. 3, March 1996.