J.Thi-Qar Sci. No. (2) Vol.1 Aug./2008

ISSN 1991- 8690 **الترقيم الدولي ٨٦٩٠ - ١٩٩١**

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Modified Unequally Spaced Channels Wavelength Division Multiplexing System

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Abstract

The channels contributed in creating new pulse during the four-wave mixing (FWM) process are a subject of two features: the first is the fact that all channels are not working with probability 100%**, but with** p **probability. Second, the bits transmitted are not all "1". Therefore, the equation of power generated using these features should be corrected. On the other hand, the use of equally spaced channels wavelength division-multiplexing (ESC WDM) system cause an increase in the number of new components generated that interfere with the active channels and increase the bit error rate. In order to reduce these interferences, we have provided an unequally spaced channels wavelength division-multiplexing (USC WDM) system composed of several sets. Each set consists of only four channels, which locations have been selected to cause no interferences between them. Neighboring sets are separated by a frequency spacing which should be large enough to reduce the interferences between the sets, and small enough to increase the total number of channels of the system.**

1. Introduction

In wavelength division multiplexing (WDM) systems, four wave mixing (FWM) is the most influential effect. When FWM occurs, three input signals generate a fourth signal, called FWM signal, which may affect the input signal operating at the same wavelength. Obviously, the performance of multi- WDM system may be seriously affected by FWM crosstalk due to the interaction of various combinations of the active signal wavelengths [1,2].

Equally spaced channels (ESC) WDM system greatly increase the total bandwidth of each optical fiber using a number of closely spaced channels at wavelengths within the typical 1540 nm to 1560 nm to take advantage of the "low loss" transmission window in optical fibers and to enable the use of erbium doped fiber amplifiers EDFA's [2,3]. Any interaction between these channels will lead to degradation of the bit error rate (BER) of the system for two reasons. Firstly, the pump channels will experience signal depletion as optical power is transferred to a different wavelengths. Secondly, if the frequency of a FWM product coincides with one of the allocated system channels, then this channel will suffer from noise. This is a particular problem for channels that are equally spaced in frequency [4-6]. It should be noted that each optical channel is completely independent of the other optical channels. It may run at its own rate (speed) and use its own encodings and protocols without any dependence with each others [5]. Channels speed for wide area network (WAN) applications are typically 2.4 Gb/s in current operational WDM systems [6].

One way of minimizing the impact of FWM is to place WDM channels such that the generated signals do not fall within other WDM channels, i.e unequally spaced channels (USC). Thus they don't interfere with other channels too much. This does help but it can not overcome the problem of noise generated in the source WDM channels by power being transferred out of them [1,7].

Crosstalk can be defined as a small proportion of the optical power that should have ended up in a particular channel actually ends up in an adjacent (or another) channel [1,2]. Crosstalk is critically important in WDM systems, when signals from one channel arrive in another they become noise in the other channel. This can have serious effects on the signal to noise ratio (SNR) and hence on the bit error rate (BER) of the system [3,6].

In this paper, a novel method for the accurate determination of FWM components in USC WDM system over nonzero dispersion fibers was proposed, which focuses on the correction of FWM power equation and to present a new arrangement that decreases the degradation as much as possible.

2. Theoretical Aspects

2.1: Basic Formalism

This formalism subsection is intended to provide an overview of the FWM equation that is important for understanding the modification discussed in latter sections. Essentially, FWM originates from the phenomenon that the polarization, induced in the electric dipoles of a medium by an electric field, E, is nonlinear in E. The third-order parametric process results in the lowest order nonlinear effects in optical fibers. Among them, FWM is the most influential factor for optical network design. In multi-channel system, a signal channel suffers from FWM, which generates various combinations of different frequencies and causes crosstalk degradation. The FWM is a third order nonlinear effect in which three optical waves at frequencies f_i , f_j, and f_k mix to originate a new wave at frequency $f_m = f_i + f_j - f_k$.

Considering that the input continuous waves are not depleted by the generation of mixing products, and that the states of polarization of these waves are coincided and not changing along the propagation, the optical power P_{FWM} of the new generated wave is given by [8]

$$P_{FWM}(f_m) = \psi\, d^2 \eta_{ijk} \qquad \textbf{(1)}$$

where

$$\psi = \left(\frac{2\pi\, n_2}{A_{eff}\lambda}\right)^2 P_i P_j P_k e^{-\alpha L}\, \frac{(1-e^{-\alpha L})^2}{\alpha^2} \qquad \textbf{(2)}$$

P_i , P_j , and P_k represent the input power at the frequencies f_i , f_j, and f_k, respectively ; λ is the wavelength; A_{eff} is the effective mode area of the fiber; α is the fiber loss coefficient; L is fiber length; d is the degeneracy factor, which takes value 3 and 6 for degenerate and non-degenerate terms, respectively; and n_2 is the nonlinear index coefficient. For L much longer than $1/\alpha$, the expression of mixing efficiency η_{ijk} takes the form given by [6]

$$\eta_{ijk} \approx \frac{\alpha^2}{\alpha^2 + \Delta\beta_{ijk}^2} \qquad \textbf{(3)}$$

where $\Delta\beta_{ijk}$ represents the phase mismatch. The phase matching factor $\Delta\beta_{ijk}$ at far off zero dispersion wavelength may be expressed in terms of signal frequency differences [4]

$$\Delta\beta_{ijk} = \frac{2\pi\lambda^2}{c} \,|\, f_i - f_k \,||\, f_j - f_k \,|\, D = |\, i-k \,||\, j-k \,|\, \Delta f^2 \,\frac{2\pi\lambda^2}{c}\mathbf{D} \qquad \textbf{(4)}$$

where D is the fiber chromatic dispersion. Note that, even zero dispersion wavelength is not constant along the fiber, Eqs.(1) to (4) accurately predict FWM power. Inserting Eq.(4) into (3) yields

$$\eta_{ijk} \approx \frac{1}{1 + n^2 \xi^2 \Delta f^4} \qquad \textbf{(5)}$$

where $n = |\, i-k \,||\, j-k \,|$ and $\xi = 2\pi\lambda^2 D / c\, \alpha$. If we substitute Eq.(5) into (1), yields

$$P_{FWM}(f_m)=\psi\, d^2\,\frac{1}{1+n^2\xi^2\Delta f^4} \qquad \textbf{(6)}$$

Eq.(6) combines two cases; the first is the DFWM process where $d=3$, $n=|i-k|^2$, and the second is the NFWM where $d=6$, $n=|i-k||j-k|$. Therefore, the last equation may be written in the following form

$$P_{FWM}(f_m)=\psi\,\left\{\sum_k\sum_i\frac{9}{1+|i-k|^4\,\xi^2\Delta f^4}+\sum_k\sum_{j(i\neq j)}\sum_i\frac{36}{1+|i-k|^2|j-k|^2\,\xi^2\Delta f^4}\right\} \qquad (7)$$

When only the noise caused by FWM is considered, the SNR of the reconstructed signal at f_m can be expressed as [7]

$$SNR(f_m)=2\sqrt{\frac{P_{in}e^{-\alpha L}}{P_{FWM}(f_m)}} \qquad \textbf{(8)}$$

If the Gaussian approximation is used to describe the noise caused by FWM interference, BER for an intensity-modulated ON-OFF keying signal is written as [9]

$$BER(f_m)=\sqrt{\frac{2}{\pi}}\int_{SNR(f_m)}^{\infty}e^{-t^2}\,dt \qquad \textbf{(9)}$$

2.2: FWM Components Number

Every active channel will interfered with a large number of the new components generated due to FWM process. This interference will effects badly the quality of the reconstructed signal. We have analyzed the behavior of many ESC WDM systems that have different number of channels (even). As a result, we find that the number of new components generated, which fall at each active channel, can be divided into two parts one of its due to degenerate FWM and the other due to non-degenerate FWM as follows

$$M_1(f_m)=0.5N-1 \quad , \quad \mathbf{M}_2(f_m)=0.125(3N^2-10N+8)-\sum_{s=0}^{0.5N-m}s \qquad \textbf{(10)}$$

where $m=1,2,....,N/2$, and $M_j(f_m)=M_j(f_{N-m-1})$, $j=1,2$.

A cursory inspection of Eq.(10) reveals that the number of FWM components can be found if N and m are known. For example, for $N=10$ ESC WDM system, the number of generated components at $ch5$ is 30, where $M_1=4,\ M_2=26$. For $N=50$ WDM system, the number of generated components at $ch25$ is 900, where $M_{1,}=24,\ M_2=876$. Clearly, the difference M_2-M_1 increases rapidly if N increased.

2.3: Correction of FWM power

Neither all channels fully operate, i.e. at ON state, the whole time nor the sending bits are “1” only. In turn, the FWM power becomes a random variable depending on the operating time of each channel and the specification of the sending bits either “1” or “0”. Assuming that, the operating probability (ON state) of each active channel is p, then the operating probability of two and three active channels are p^2 and p^3, respectively. On the other side, degenerate FWM takes place due to operating two channels, each channel may be “1” or “0” bit. Such that, the operating probability must be multiplied by $(1/2)^2$. Thereafter, the non-degenerate FWM is created due to interacting of three channels. So, the probability p^3 must be multiplied by $(1/2)^3$. By inserting the above arrangement into Eq.(7), the corrected total FWM power at f_m was obtained as follows

$$P_{FWM}^{cor}(f_m) = \psi \left\{ 2.25 p^2 \sum_k \sum_i \frac{1}{1+|i-k|^4 \xi^2 \Delta f^4} + 4.5 p^3 \sum_k \sum_{j(j\neq i)} \sum_i \frac{1}{1+|i-k|^2 |j-k|^2 \xi^2 \Delta f^4} \right\} \tag{11}$$

Remember that, the first term represents M_1 combinations of i,k (DFWM), while the second term represents M_2 combinations of i, j, k (NFWM). As it was evident two features to correct the FWM power are inserted.

2.4: Unequally Spaced Channels

Using a WDM in four channels only at the locations 1,2,5,10 that will cancel any FWM components. This cancellation is exact for WDM system, which can remove all interference from WDM system. It is impossible to get a system that consists of N channels without interference. In order to achieve an efficient suppression, we are adopted a new N channels model based on neighborhood sets . The present arrangement attempts to minimize the FWM effects as much as possible. The channels of system is divided into many sets, each one contains only four channels, where their frequency spacing are Δf, $3\Delta f$, and $5\Delta f$. This consideration to ensure that no interference occur in each set, and to reduce the number and power of FWM components that may be degrade the active channels. The neighborhood sets are spaced with frequency spacing $11\Delta f$ to prevent the influence of mutual interference. Note that, the combinations M_1 and M_2 in Eq.(10) does not represent the actual number of FWM components in the case of USC WDM system . Fig.(1) illustrates the present model.

For ESC WDM system with N channels, the frequency spacing is $\Delta f_1 = B/(N-1)$, where B is total bandwidth. For present work, it is straightforward to show that the frequency spacing is $\Delta f_2 = B/(5N-11)$. Typically, if a system contains $N = 100$ and $B = 2000\ GHz$, then $\Delta f_1 \approx 20.2\ GHz$, $\Delta f_2 \approx 4.08\ GHz$, and the frequency spacing between the proposed two neighborhood sets is about $44.9\ GHz$. By comparing $\Delta f_1, \Delta f_2$, and the sets spacing, the difference between the FWM components of two systems can be etracted since the efficiency is function of frequency. In other words, ESC WDM system is the larger for interaction and degradation. However, making $\Delta f_1 = \Delta f_2$ in ESC WDM system will raise the number of active channels to $5N$, but this multiplication will effect badly the quality of the reconstructed signals, where clear degradation happens at each channel (especially the median).

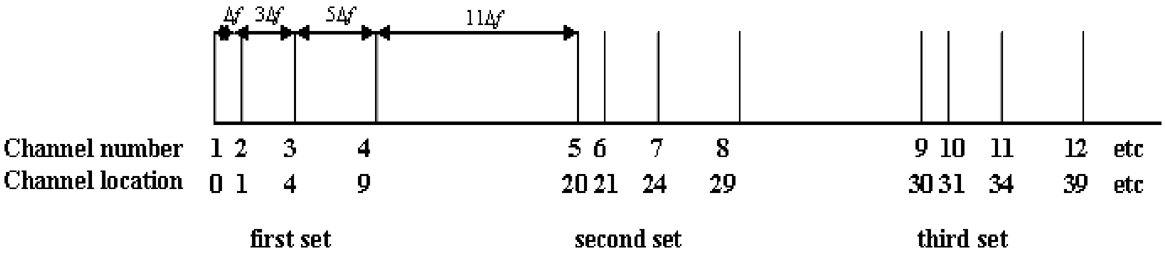

Fig.(1): The present USC WDM model arrangement.

3. Simulation Results

The parameters used in the simulation are as follows: $L = 80\,km$, $\lambda = 1.55\,\mu m$, $D = 0.3\,ps/nm\,km$, $A_{eff} = 5\times10^{-11} m^2$, $\alpha = 0.2\,dB/km$, $n_2 = 3.2\times10^{-20} m^2/W$, the power of each channel $P_{in} = P_i = P_j = P_k = 10\,mW$, Δf for ESC is $B/(N-1)$, and Δf for USC is $B/(5N-1)$, where $B = 2000\,GHz$. The results will be displayed on the figures using three lines: continuous, discrete, and dotted which refer to USC, corrected ESC, and conventional ESC systems, respectively.

Fig.(2) represents the power generated at each channel for different values of N and assuming that $p = 0.7$. It is evident that the curves of ESC WDM system are symmetric while the present USC WDM is asymmetric. This behavior may be attributed to the channels distribution nature over frequency range. However, the power generated is minimum for the present system.

Fig.(3) presents the relation of the power generated at each channel with $N = 20$ for different values of the operating probability p. The conventional ESC system does not depend on p, but the other two systems depend strongly on p. Also, Fig.(3) illustrates the lower power generated for the present model as compared to the corrected ESC system.

Fig.(4) represents the BER at each channel for different values of N and assuming that $p = 0.7$. It shows that the FWM power of both ESC systems is more than that for USC system developed in this paper. Clearly, increasing the number of channels will increase the crosstalk for all systems but the USC system is the best.

4. Conclusions

In conclusion, a novel technique was proposed for wavelength division multiplexing. It was confirmed that the actual power generated at a specified active channel does not represent the sum of all combinations of the channels i, j, k. Numerical results have demonstrated that the effect of actual FWM crosstalk is significant when system is heavily loaded, i.e. higher p. The present technique should also, in theory, be applicable to any number of channels. There was also presented a comparison with other known ESC systems, which shows that the higher precision of the present method.

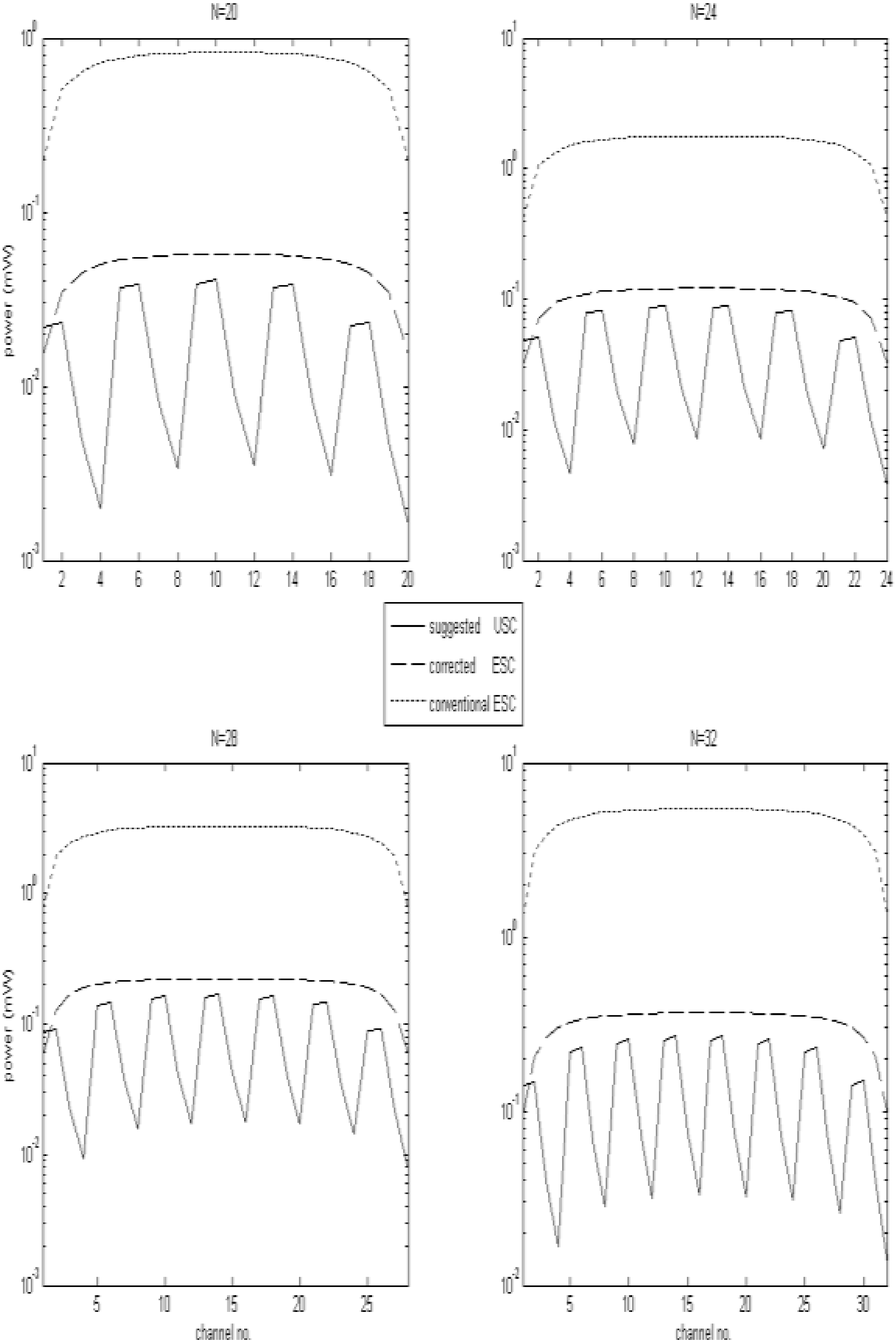

Fig.(2): FWM power at each channel with different values of N and assuming $p = 0.7$

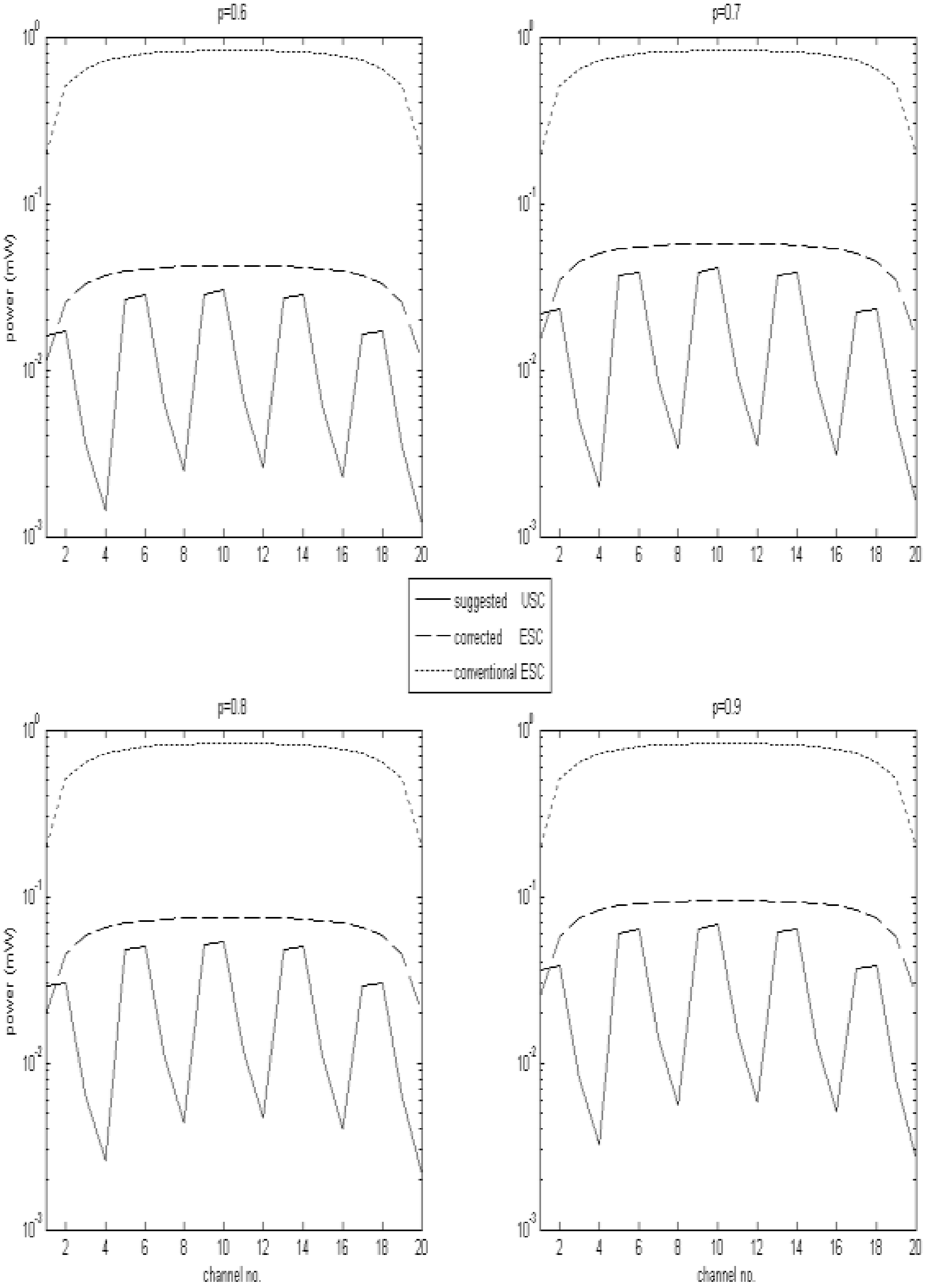

Fig.(3): FWM power at each channel with different values of p and $N = 20$

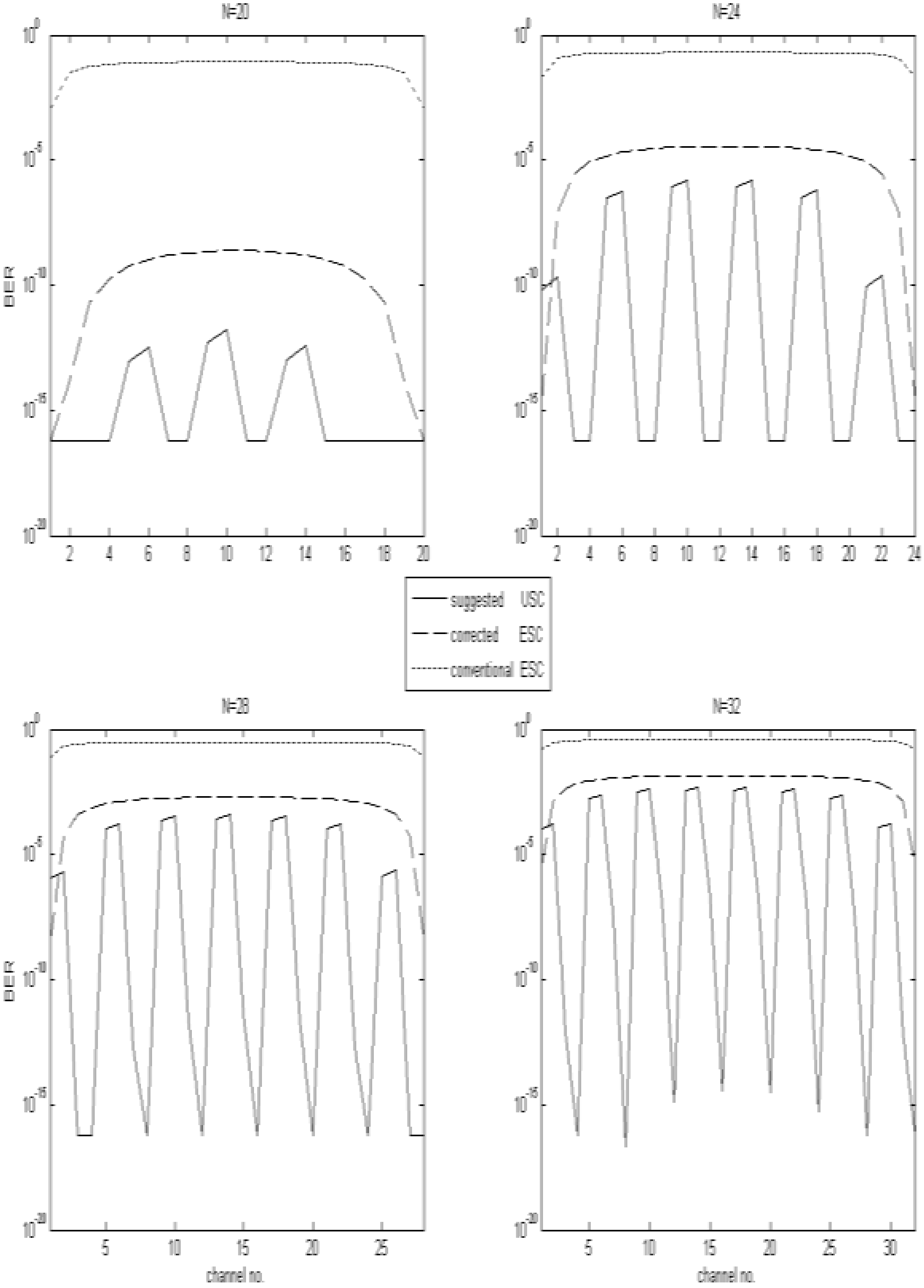

Fig.(4): BER power at each channel with different values of N and assuming $p = 0.7$

References

[1] Agrawal G.P, 2007 "Nonlinear Fiber Optics", Academic Press,.

[2] Lowe E., 1998. "Current European WDM Employment Trends", IEEE Comm. Magazine, .32, .(2) .

[3] R. Tkach, 1995 "Four Photon Mixing and Higher Speed WDM systems", J. of Lightwave Tech.,.13, (8).

[4] M. Maeda and R. Laming, 1990 "The Effect of FWM in Fibers on WDM Systems", J. of Lightwave Tech..8, (9).

[5] L. Zhang, and J. Tang, 2000 "The Effect of IP Traffic on WDM Based Networks", IEEE Comm. Letters,.4,(9).

[6] I. Neokosmidis, T. Kamalakis, and T. Sphicopoulas, 2005 " Accurate Estimation of The Impact of IP Traffic Burstiness on The Performance of WDM Networks", Optics Express, 13, (24) .

[7] B. Hwang, and O. Tonguz, 1998 "A generalized Suboptimum Unequally spaced Channels Allocation Technique-Part I: In IM/DD WDM systems", IEEE Trans. On Comm., 46,(8) .

[8] A. Bogoni, L. Poti, and A. Bononi, 2003 "Accurate Measurement of In-Band FWM Power in DWDM systems Over Nonzero Dispersion Fibers", IEEE Phot. Tech. Let., 15, (2).

[9] G.P Agrawal, 2001 "Applications of Nonlinear Fiber Optics", Academic Press,.

نظام مطور لمزج- قسمة الطول الموجي بقنوات غير متساوية الفاصلة

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الخلاصة

أن القنوات المساهمة في خلق نبضة جديدة خلال ظاهرة مزج الموجات الأربع تخضع لخاصيتين: الأولى، هي كون جميع القنوات لا تعمل بالاحتمال 100% بل بالاحتمال p . الثانية، ان البتات المرسلة ليست جميعها "1". وعليه فقد أدخلنا هاتين الخاصيتين لتصحيح معادلة القدرة للنبضة المتولدة. من جانب أخر، ان استخدام نظام مزج-قسمة الأطوال الموجية المتساوي الفاصلة يسبب زيادة في عدد المركبات الجديدة المتولدة والتي تتداخل مع القنوات العاملة وتسبب زيادة نسبة الخطأ. وبهدف تقليل هذه التداخلات فقد قدمنا نظام مزج- قسمة الأطوال الموجية غير متساوي الفاصلة مؤلف من عدة مجموعات كل مجموعة بأربعة قنوات فقط تم اختيار مواقعها بحيث لا تسبب أي تداخلات فيما بينها. المجموعات المتجاورة تم فصلها بفاصلة ترددية تكون كبيرة كفاية لتقليل التداخلات بين المجموعات وتكون صغيرة كفاية لزيادة عدد قنوات النظام الكلية.