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ANALYSIS OF SIGNAL-TO-CROSSTALK RATIO VARIATIONS DUE TO FOUR-WAVE MIXING IN DENSE WAVELENGTH DIVISION MULTIPLEXING SYSTEMS IMPLEMENTED WITH STANDARD SINGLE-MODE FIBERS

Sait Eser KARLIK *

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Abstract: In this paper, variation of the signal-to-crosstalk ratio (SXR) due to effects of four-wave mixing (FWM) has been analyzed on center channels of 5-, 7-, 9-channel dense wavelength division multiplexing (DWDM) systems implemented with G.652 standard single-mode fibers (SSMFs) for 12.5 GHz, 25 GHz, 50 GHz and 100 GHz equal channel spacing values. Center channels on such systems are the most severely impacted channels by FWM. Therefore, results obtained are the worst-case values for the DWDM system performance and important for system design. Simulations have been performed for systems using three different commercially available SMFs having different design parameter values for chromatic dispersion, dispersion slope, nonlinearity coefficient and attenuation coefficient which are all in the scope of the G.652 Recommendation of Telecommunication Standardization Sector of International Telecommunication Union (ITU-T) for SSMFs. In those simulations, under the impact of FWM, variation of SXR with variations in input powers, channel spacings and link lengths have been observed. Simulation results display the combined effect of the optical fiber and system design parameters on FWM performance of DWDM systems and give important clues for not only long-haul but also access network implementations of DWDM systems.

Keywords: Four Wave Mixing, Dense Wavelength Division Multiplexing System, Optical Fiber, Signal-to-Crosstalk Ratio

Standart Tek-Modlu Fiberler İle Kurulmuş Yoğun Dalgaboyu Bölmeli Çoğullama Sistemlerinde Dört Dalga Karışımından Kaynaklanan İşaret Çapraz Karışım Oranı Değişimlerinin Analizi

Öz: Bu makalede, G.652 standart tek-modlu optik fiber (SSMF) kullanan, 12.5 GHz, 25 GHz, 50 GHz ve 100 GHz eşit kanallar arası boşluk değerlerine sahip, 5, 7 ve 9 kanallı yoğun dalgaboyu bölmeli çoğullama sistemlerinin (DWDM) merkez kanallarında, dört dalga karışımı (FWM) etkisinden kaynaklanan işaret çapraz karışım oranlarının (SXR) değişimi incelenmiştir. Belirtilen tipteki sistemlerde, merkez kanallar, tüm kanallar arasında FWM olayından en ağır şekilde etkilenen kanallardır. Bu nedenle, incelemeden elde edilen sonuçlar DWDM sistem performansı için en kötü hal değerleri olup sistem tasarımı açısından önemlidir. Benzetimler, SSMF fiberler için Uluslararası Haberleşme Birliği Haberleşme Standardizasyon Birimi'nin (ITU-T) G.652 Tavsiyesi'nde belirtilen değerler aralığında bulunan farklı değerlerdeki kromatik dispersiyon, dispersiyon eğimi, doğrusalsızlık katsayısı ve zayıflama katsayısı tasarım parametrelerine sahip üç farklı SSMF ticari ürününü kullanan sistemler için gerçekleştirilmiştir. Benzetimlerde, FWM etkisi altında, kanal giriş güçlerindeki, kanallar arası boşluk değerlerindeki ve fiber uzunluklarındaki değişimler ile SXR'ın nasıl değiştiği gözlemlenmiştir. Sonuçlar, optik fiber ve sistem tasarım parametrelerinin DWDM sistemlerin FWM performansı üzerindeki birleşik

* Uludağ University, Faculty of Engineering, Department of Electrical and Electronics Engineering, 16059, Görükle, Bursa, Turkey

Correspondence Author: Sait Eser Karlık (ekarlik@uludag.edu.tr)

etkisini göstermekte olup DWDM sistemlerin hem uzak mesafe hem de erişim ağı uygulamaları için önemli ipuçları vermektedir.

Anahtar Kelimeler: Dört Dalga Karışımı, Yoğun Dalgaboyu Bölmeli Çoğullama Sistemi, Optik Fiber, İşaret Çapraz Karışım Oranı

1. INTRODUCTION

Currently, the most widely-used method in long-haul and access telecommunication networks to transmit optical signals is the wavelength division multiplexing (WDM). Significant advantages of WDM usage can be listed as enhancement in the transmission capacity, high data rates and flexible network design. The term 'dense wavelength division multiplexing (DWDM)' has been defined by Telecommunication Standardization Sector of International Telecommunication Union (ITU-T) for WDM devices having channel spacings less than or equal to 1000 GHz (ITU-T Recommendation G.671, 2002). In ITU-T Recommendation G.694.1 (2012), nominal central frequencies that support applications of DWDM for 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacing values have been determined. Among all nonlinear optical phenomena resulting from increases in input powers, data rates and channel numbers and the decrease in channel spacing values, four-wave mixing (FWM) has major impacts on performance limitations in DWDM systems. FWM generates new optical frequencies called FWM products, which can interfere with DWDM channel frequencies and cause severe channel crosstalks (Schneider, 2004; Agrawal, 2005). Thus, analysis of FWM impact and its suppressing methods in DWDM systems is an important topic covering various papers (Bogoni et. al., 2004; Wehmann et. al., 2005; Kaur and Singh, 2009; Singh et. al., 2009; Kaler and Kaler, 2012; Noshad and Rostami, 2012; Hiçdurmaz et. al., 2013; Rostami et. al., 2013; Abd et. al., 2014; Bi et. al., 2014; Handa et. al., 2014; Karlık, 2016). In this paper, using the signal-to-crosstalk ratio (SXR) parameter, the FWM effect on center channels of 5-, 7-, 9-channel DWDM systems implemented with three different commercially available standard single-mode fibers (SSMFs) whose design parameters are all in the scope of ITU-T Recommendation G.652 (2009) has been analyzed for channel spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz. In Section 2, theoretical background required for FWM analysis is given. Simulation models and SSMF characteristics are described in Section 3. Presentation and interpretation of simulation results can be found in Section 4.

2. THEORETICAL BACKGROUND

Three optical waves with frequencies f_i, f_j and f_k propagating in the optical fiber interact via the third order material susceptibility and generate a new wave with frequency f_{ijk}, which can be computed with

$$f_{ijk} = f_i + f_j - f_k \tag{1}$$

where k ≠ i, j. This phenomenon is called FWM. In (1), i, j and k denote three channels of a WDM system. The impact of the FWM on a WDM system occurs as new optical signals generated by triple combinations of optical signals that propagate in WDM channels and effects of that new signals on transmission performance of the system. In WDM systems whose channels are equally spaced, a significant number of FWM products, i.e. optical signals generated, may propagate with the same frequencies of original channels and thus FWM crosstalk occurs. FWM crosstalk degrades the signal-to-noise ratio (SNR) of the system. (Tkach et. al., 1995).

The power of FWM signal, whose frequency is f_{ijk}, can be described as

$$P_{FWM}(f_{ijk}) = \left(\frac{d_{ijk}\gamma L_{eff}}{3}\right)^2 P_i P_j P_k e^{-\alpha L}\eta_{ijk} \tag{2}$$

In (2), d_{ijk} denotes the degeneracy factor, where $d_{ijk} = 3$ for $i = j \neq k$ and $d_{ijk} = 6$ for $i \neq j \neq k$; γ denotes the nonlinearity coefficient; L_{eff} is the effective fiber length; P_i, P_j and P_k are the input powers for channels i, j and k, respectively; α denotes fiber attenuation coefficient and η_{ijk} is FWM efficiency (Schneider, 2004).

L_{eff} and η_{ijk} can be computed with

$$L_{eff} = \left(\frac{1 - e^{-\alpha L}}{\alpha}\right) \tag{3}$$

and

$$\eta_{ijk} = \frac{\alpha^2}{\alpha^2 + \Delta B_{ijk}^2}\left[1 + \frac{4e^{-\alpha L}}{(1 - e^{-\alpha L})^2}\sin^2\left(\frac{\Delta B_{ijk} L}{2}\right)\right] \tag{4}$$

respectively. ΔB_{ijk} in (4) is the phase mismatching factor (Schneider, 2004)

$$\Delta B_{ijk} = \frac{2\pi\lambda_k^2}{c}\left(|f_i - f_k||f_j - f_k|\right)\left[D_c + \frac{\lambda_k^2}{2c}\frac{dD_c}{d\lambda}\left(|f_i - f_k| + |f_j - f_k|\right)\right] \tag{5}$$

where λ_k is the wavelength of channel k; D_c is the chromatic dispersion; $dD_c/d\lambda$ denotes the chromatic dispersion slope and c is the speed of light in vacuum.

In a WDM system having equally-spaced channels, total FWM crosstalk in a channel with a frequency f_c can be given as (Maeda et. al., 1990)

$$P_{FWM}(f_c) = \sum_{f_k = f_i + f_j - f_c}\sum_{f_j}\sum_{f_i} P_{FWM}(f_i + f_j - f_k) \tag{6}$$

To interpret total FWM crosstalk impact in a channel accurately, a parameter called signal-to-crosstalk ratio (SXR) can be defined as

$$SXR = 10log_{10}\left(\frac{P_{out}}{P_{FWM}}\right) \tag{7}$$

where P_{out} is the channel output power that can be given as $P_{out} = P_c.e^{-\alpha L}$ for the input power P_c.

3. SIMULATION MODELS AND FIBER PARAMETERS

In this research, we focus on the impact of FWM on 5-, 7- and 9-channel DWDM systems implemented with SSMFs that have equally-spaced channels with spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz. In such systems, it is very important to determine the most heavily affected channel and the FWM products falling into that channel since results obtained for that channel will be the worst-case values and therefore they will be vital for a reliable system design. In systems using SSMFs, center channels are the most severely impacted channels (Harboe et. al., 2008). Therefore, our simulations have been performed for the center channels of 5-, 7- and 9-channel systems, i.e. the 3rd, 4th and 5th channels, respectively. In

Table 1-3, channel triple combinations that form FWM products in center channels of 5-, 7- and 9-channel DWDM systems are shown, respectively.

Table 1. Channel triple combinations that form FWM products in the center channel of a 5-channel DWDM system

i/j	1	2	3	4	5
1				k=2	k=3
2		k=1		k=3	k=4
3					
4				k=5	
5					

Table 2. Channel triple combinations that form FWM products in the center channel of a 7-channel DWDM system

i/j	1	2	3	4	5	6	7
1					k=2	k=3	k=4
2			k=1		k=3	k=4	k=5
3			k=2		k=4	k=5	k=6
4							
5					k=6	k=7	
6							
7							

Table 3. Channel triple combinations that form FWM products in the center channel of a 9-channel DWDM system

i/j	1	2	3	4	5	6	7	8	9
1						k=2	k=3	k=4	k=5
2				k=1		k=3	k=4	k=5	k=6
3			k=1	k=2		k=4	k=5	k=6	k=7
4				k=3		k=5	k=6	k=7	k=8
5									
6						k=7	k=8	k=9	
7							k=9		
8									
9									

In Tables 1-3, i, j and k show channel numbers that form a FWM product in the center channel, e.g. signals of channel 2 (i=2), channel 4 (j=4) and channel 3 (k=3) generate a FWM product in the center channel, i.e. the 3rd channel, of the 5-channel DWDM system in Table 1. As mentioned in Section 2, $k \neq i, j$ and since i and j are interchangeable, only half-spaces in Tables 1-3 are considered.

In simulation models, systems that use a single-span SSMF are considered. The block diagram of such a system is given in Figure 1.

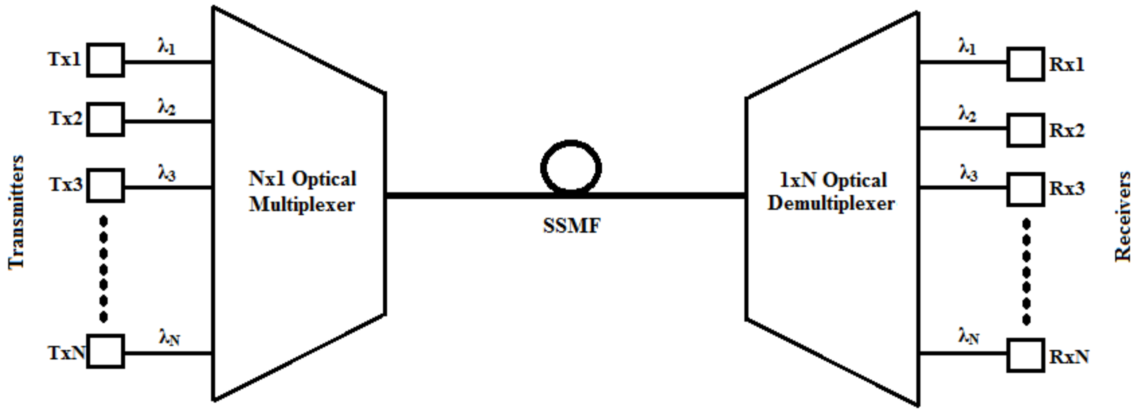

Figure 1:
N-channel DWDM system block diagram

Table 4. SSMF parameters

Fiber	D_{C0} (ps/nm.km)	S (ps/nm^2.km)	γ (1/W.km)	α (dB/km)
SSMF1	17.00	0.085	1.300	0.21
SSMF2	16.50	0.058n	1.200	0.20
SSMF3	16.00	0.086	1.315	0.20

MATLAB R2011b has been used for simulations and three different commercially available SSMFs whose design parameters are all in the scope of ITU-T Recommendation G.652 (2009) have been considered. Related parameters of those fibers used in simulations are shown in Table 4, where D_{c0} denotes chromatic dispersion at 1550 nm wavelength; S is the slope of chromatic dispersion; γ is the nonlinearity coefficient at 1550 nm wavelength and α is the attenuation coefficient at 1550 nm wavelength.

4. SIMULATIONS

In this section, results of simulations analyzing variations of SXR with variations in input powers, channel spacings and fiber link lengths under the impact of FWM in 5-, 7- and 9-channel DWDM systems are reported and interpreted.

4.1. Variation of SXR with variations in input powers

To understand the effect of input powers on FWM crosstalk, simulations have been done at center channels of 5-, 7- and 9-channel DWDM systems having equal channel spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz, all channel input powers have been considered as equal and varied in the range of 1–40 mW. The operating wavelength of the center channel has been fixed to 1550 nm in all systems and a 100 km fiber link has been taken into account for all SSMFs of Table 4. Simulation results showing SXR variation with variations in channel input powers for 5-channel DWDM systems using three different SSMFs and having channel spacing values in 12.5-100 GHz range are given in Figs. 2-4 and comparative results for 5-, 7- and 9-channel systems using three different SSMFs and having channel spacing values of 12.5 GHz and 100 GHz are shown in Figs. 5-10.

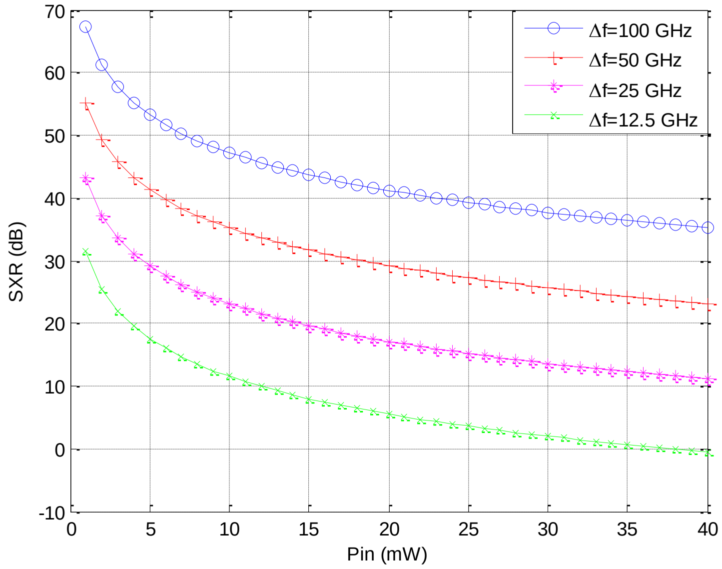

Figure 2:
Variation of SXR with variations in input powers for center channel of 5-channel DWDM systems implemented with 100 km SSMF1

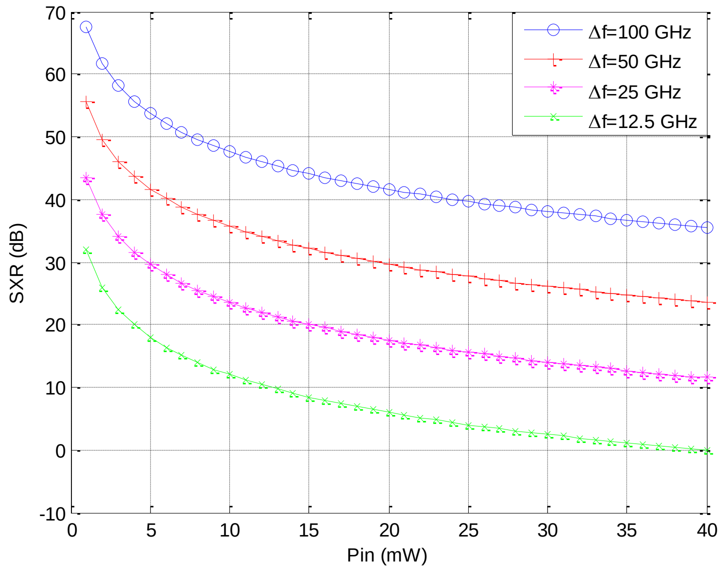

Figure 3:
Variation of SXR with variations in input powers for center channel of 5-channel DWDM systems implemented with 100 km SSMF2

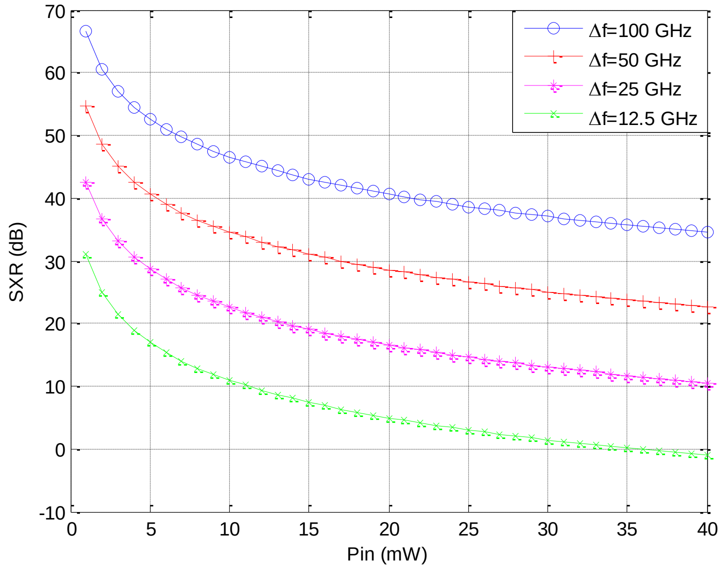

Figure 4:
Variation of SXR with variations in input powers for center channel of 5-channel DWDM systems implemented with 100 km SSMF3

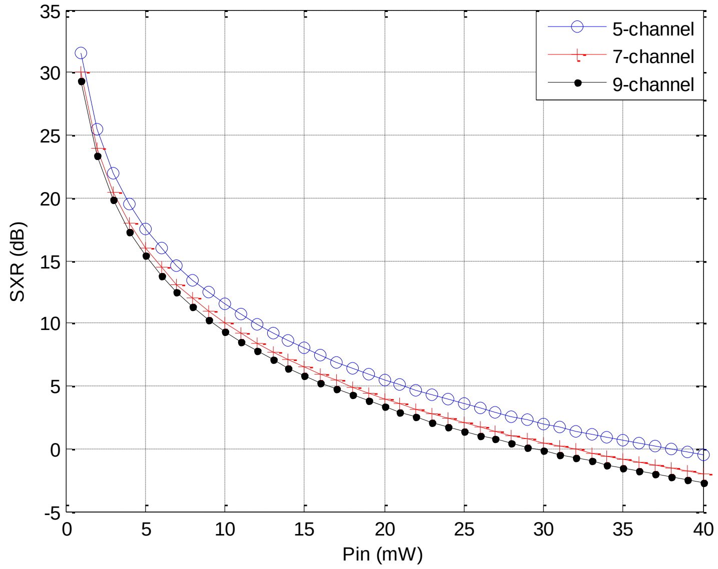

Figure 5:
Variation of SXR with variations in input powers for center channels of 5-, 7- and 9-channel DWDM systems implemented with 100 km SSMF1 and 12.5 GHz channel spacing

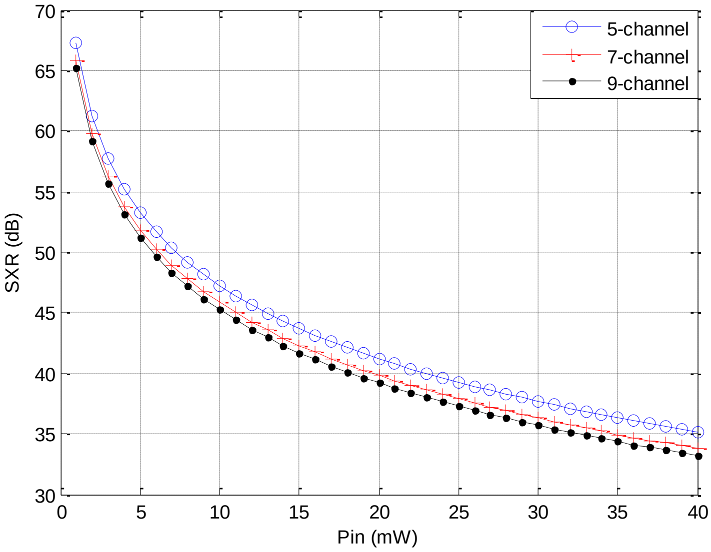

Figure 6:
Variation of SXR with variations in input powers for center channels of 5-, 7- and 9-channel DWDM systems implemented with 100 km SSMF1 and 100 GHz channel spacing

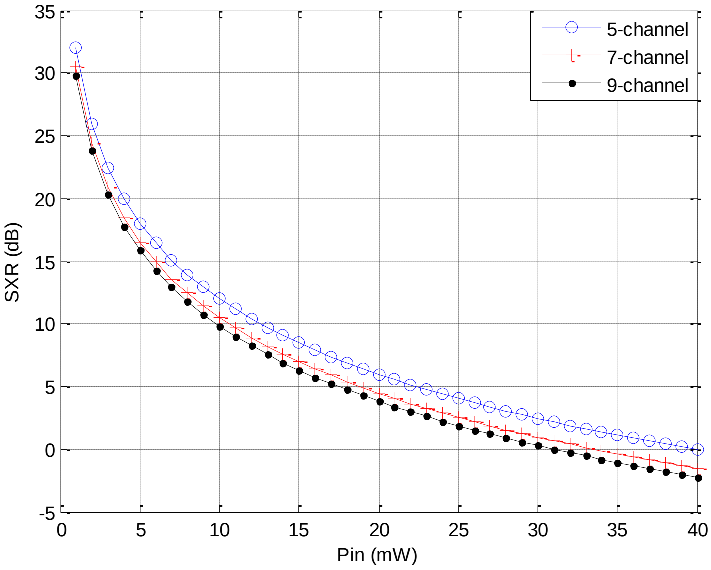

Figure 7:
Variation of SXR with variations in input powers for center channels of 5-, 7- and 9-channel DWDM systems implemented with 100 km SSMF2 and 12.5 GHz channel spacing

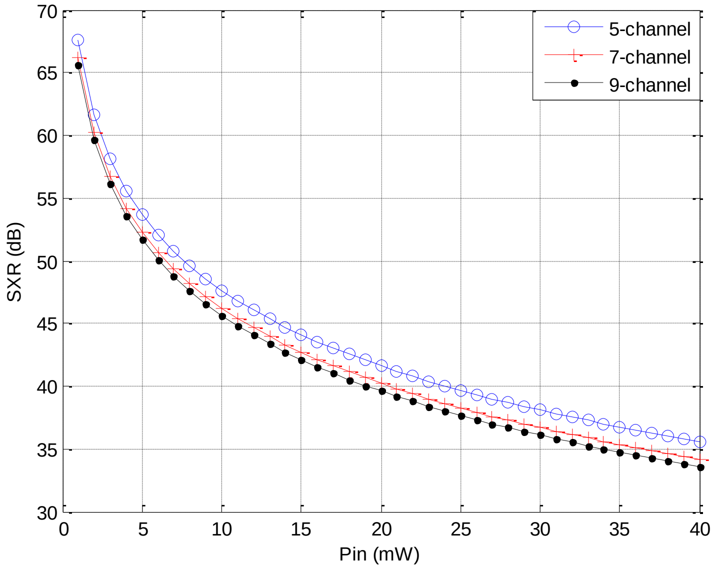

Figure 8:
Variation of SXR with variations in input powers for center channels of 5-, 7- and 9-channel DWDM systems implemented with 100 km SSMF2 and 100 GHz channel spacing

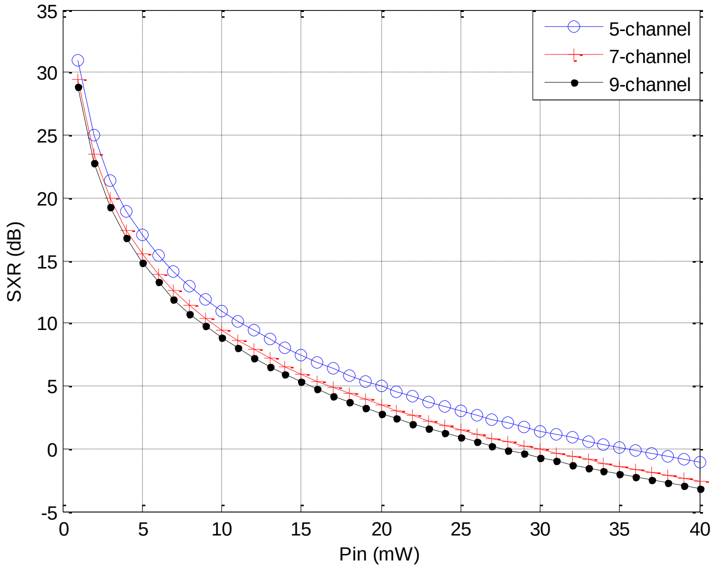

Figure 9:
Variation of SXR with variations in input powers for center channels of 5-, 7- and 9-channel DWDM systems implemented with 100 km SSMF3 and 12.5 GHz channel spacing

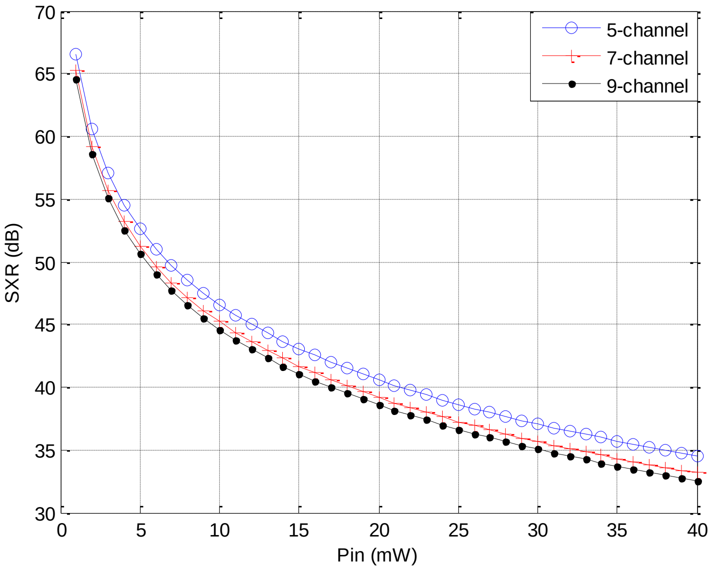

Figure 10:
Variation of SXR with variations in input powers for center channels of 5-, 7- and 9-channel DWDM systems implemented with 100 km SSMF3 and 100 GHz channel spacing

In Figs. 2-10, it is clear that SXR values decrease with increasing channel input powers, decreasing values of channel spacings and increasing channel numbers. This is due to the increase in FWM crosstalk since it is obvious in (2), (4) and (5) that

- the FWM signal power generated in the channel is directly proportional to channel input powers.
- narrowing the channel spacing causes a degradation in the phase mismatching factor ΔB_{ijk} which increases the FWM efficiency η_{ijk} and so the power of FWM signal generated in the channel increases with the increase in η_{ijk}.
- increasing channel numbers raises the number of FWM products generated in center channels which increases the FWM crosstalk.

Table 5. Comparative results for maximum channel input powers satisfying 23 dB SXR condition at center channels of 5-, 7-, 9-channel DWDM systems using 100 km SSMFs

Fiber Type	DWDM Systems	Δf (GHz)	12.5	25	50	100
SSMF1	5-channel	Maximum input powers (mW) satisfying 23 dB SXR condition at center channels	2.71	10.14	40.81	162.68
	7-channel		2.28	8.65	34.65	138.57
	9-channel		2.09	8.05	32.31	129.30
SSMF2	5-channel		2.84	10.68	42.99	170.31
	7-channel		2.41	9.06	36.49	144.93
	9-channel		2.23	8.47	34.01	135.31
SSMF3	5-channel		2.55	9.58	38.02	151.37
	7-channel		2.12	8.13	32.27	128.93
	9-channel		1.96	7.59	30.08	120.30

It is important to choose a convenient SXR level for FWM crosstalk analysis on DWDM systems. In the literature, a minimum 20 dB, 23 dB or 25 dB SXR values have been considered in various papers (Nakajima et. al.,1997; Bogoni and Poti, 2004; Harboe et. al., 2008). In this research a 23 dB minimum SXR value has been selected. From simulations analyzing variations of SXR with variations in input powers under the impact of FWM in 5-, 7- and 9-channel DWDM systems, comparative results obtained for maximum channel input powers satisfying 23 dB SXR condition at center channels are shown in Table 5.

Analyzing the simulation results for SSMF1, SSMF2 and SSMF3, one can conclude that SSMF2 has the best SXR performance among all while SSMF1 takes the second place and SSMF3 has the third in ranking. This is due to the combined effect of the fiber parameters given in Table 4 on the FWM signal power generated and subsequently on SXR. For SSMF2, having the lowest nonlinearity coefficient γ among all fiber types is the dominant factor on having the best SXR performance. The better performance of SSMF1 with respect to SSMF3 occurs because of its higher chromatic dispersion D_{c0} and lower nonlinearity coefficient γ.

4.2. Variation of SXR with variations in channel spacing values

To understand effects of channel spacing values on FWM and SXR thoroughly, simulations have been performed on systems having 100 km single-span fiber links and equal channel input powers of 1 mW. Simulation results are shown in Figs. 11-13. Comparative SXR values obtained from simulation results displayed in Figs. 11-13 for 5-, 7- and 9-channel DWDM systems having 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacing values are given in Table 6.

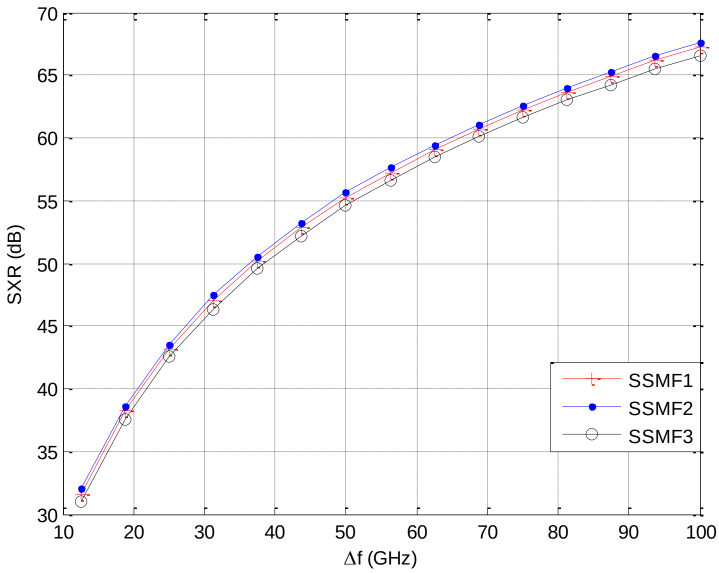

Figure 11:
Variation of SXR with variations in channel spacing values for center channels of 5-channel DWDM systems implemented with 100 km fiber links of SSMF1, SSMF2 and SSMF3 and 1 mW input powers

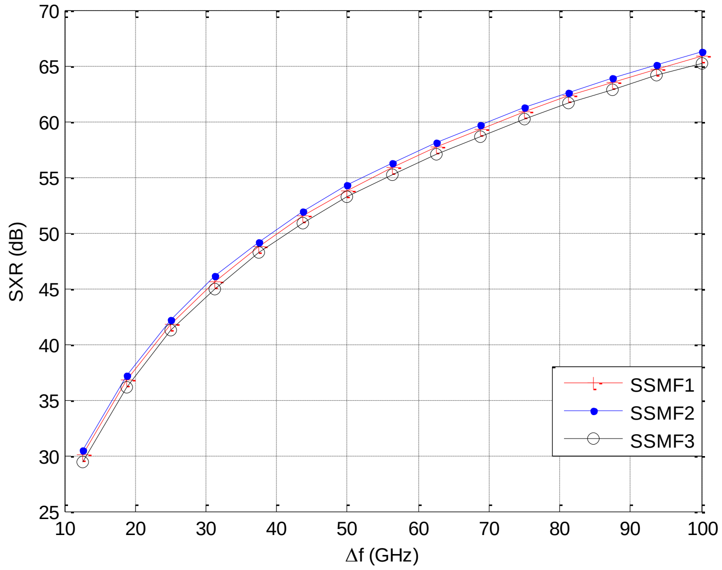

Figure 12:
Variation of SXR with variations in channel spacing values for center channels of 7-channel DWDM systems implemented with 100 km fiber links of SSMF1, SSMF2 and SSMF3 and 1 mW input powers

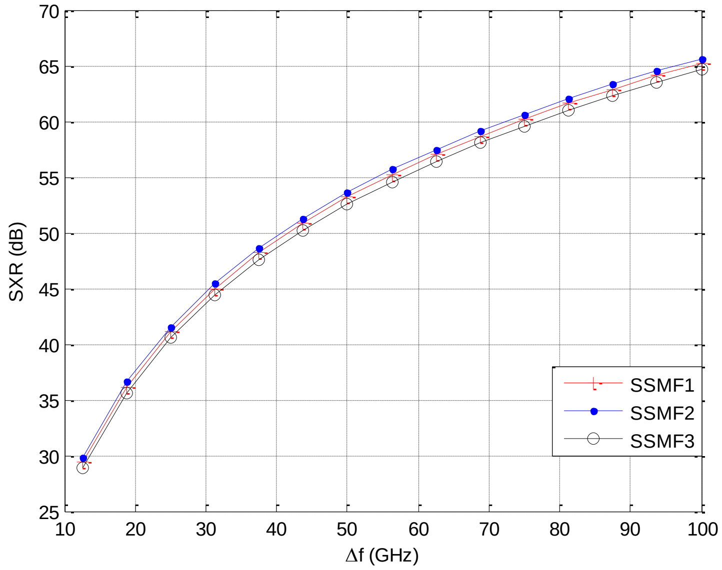

Figure 13:
Variation of SXR with variations in channel spacing values for center channels of 9-channel DWDM systems implemented with 100 km fiber links of SSMF1, SSMF2 and SSMF3 and 1 mW input powers

Table 6. Comparative SXR values at center channels of 5-, 7-, 9-channel DWDM systems implemented with 100 km SSMFs and 1 mW input powers

Fiber Type	DWDM Systems	Δf (GHz)	12.5	25	50	100
SSMF1	5-channel	SXR value (dB) at the center channel	31.53	43.12	55.22	67.23
	7-channel		30.02	41.73	53.79	65.83
	9-channel		29.37	41.12	53.19	65.23
SSMF2	5-channel		31.99	43.56	55.67	67.63
	7-channel		30.49	42.14	54.24	66.22
	9-channel		29.84	41.54	53.63	65.63
SSMF3	5-channel		30.97	42.62	54.60	66.60
	7-channel		29.47	41.20	53.18	65.21
	9-channel		28.83	40.59	52.57	64.61

Since channel input powers have been chosen as 1 mW, all SXR values in Figs. 11-13 and Table 6 are greater than 23 dB. Results show that channel spacing value has a significant effect on SXR values, e. g. SXR values at 100 GHz are more than twice the values at 12.5 GHz, while the increase in channel numbers at a specific spacing value has a slight effect on SXR, i.e. the difference between SXR values of 5- and 9-channel systems for all fiber types and channel spacing values is approximately 2 dB. This is an important result for DWDM system implementations. One must consider that narrowing the channel spacing values for a more efficient use of the fiber bandwidth may result in a dramatic degradation in SXR and the minimum SXR level for a reliable data transmission may not be provided under the impact of FWM unless appropriate input powers are chosen.

4.3. Variation of SXR with variations in fiber link lengths

The fiber link length has been fixed to 100 km in all previous sections. In this section, the effect of fiber link length variations on SXR is taken into account. For 5-, 7- and 9-channel DWDM systems implemented with 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacing values and 1 mW channel input powers, simulations have been done in 1-200 km fiber link length range. Simulation results of 5-channel systems are shown in Figs. 14-17. It is obvious in Figs.14-17 that SXR shows an increasing oscillatory variation with the increase in channel spacing values, in particular over 12.5 GHz and up to approximately 60 km link lengths. Generally, that oscillatory variation fades away in 60-100 km range and takes a stationary value after 100 km. This oscillation occurs because of the phase mismatch becoming stronger with increasing channel spacings. The degradation in η_{ijk} with increasing fiber lengths and channel spacings causes the fading of the SXR oscillation and taking a stationary value after 100 km. This is also another important result for DWDM implementations. Since fiber link lengths in long-haul DWDM networks generally exceeds 100 km, SXR oscillations due to fiber link lengths at higher channel spacing values can be neglected. However, it must be taken into account in implementations of access networks, e.g. dense wavelength division multiplexing-passive optical networks (DWDM-PONs), since those networks reach to distances below 30 km.

Simulation results obtained for 7- and 9-channel systems are similar to results of 5-channel systems shown in Figs. 14-17, of course with less SXR ranges. Therefore considering the page limitations of the journal and to prevent repetition, results of those simulations are not given in this paper. However, it should be mentioned that the fading distance of SXR oscillation exceeds 100 km and reaches to 120 km as the channel numbers are increased from 5 to 9.

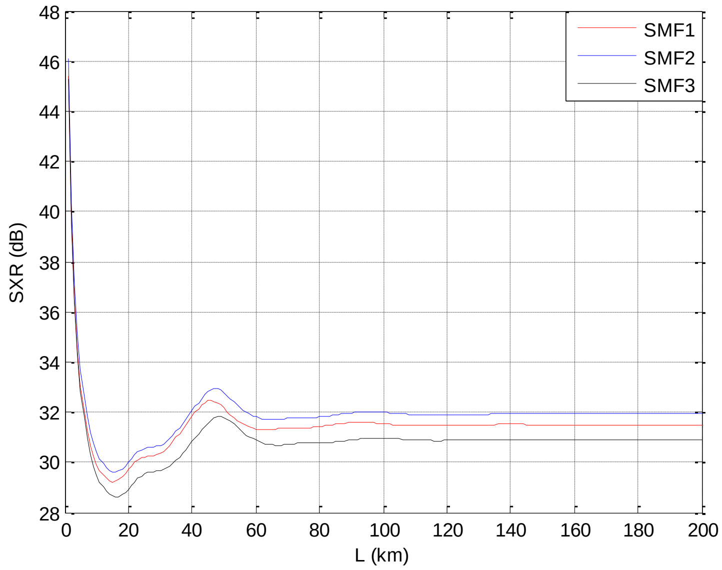

Figure 14:
Variation of SXR with variations in fiber link lengths for center channels of 5-channel DWDM systems implemented with 1 mW channel input powers and 12.5 GHz channel spacing values

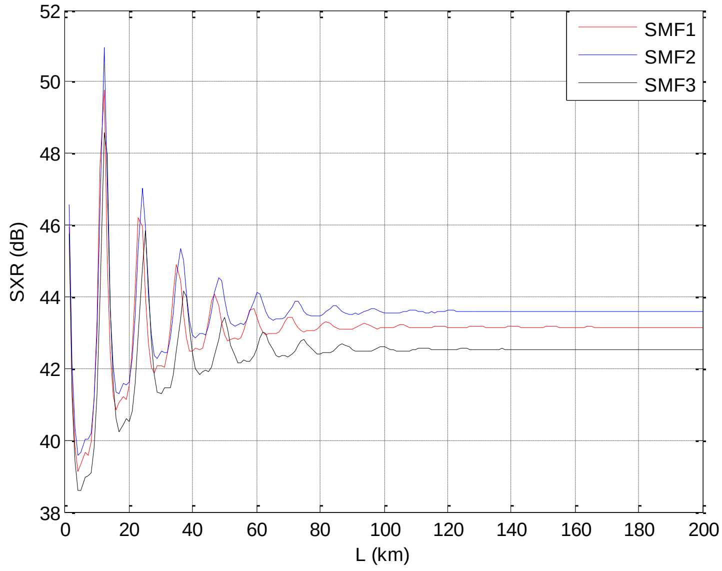

Figure 15:
Variation of SXR with variations in fiber link lengths for center channels of 5-channel DWDM systems implemented with 1 mW channel input powers and 25 GHz channel spacing values

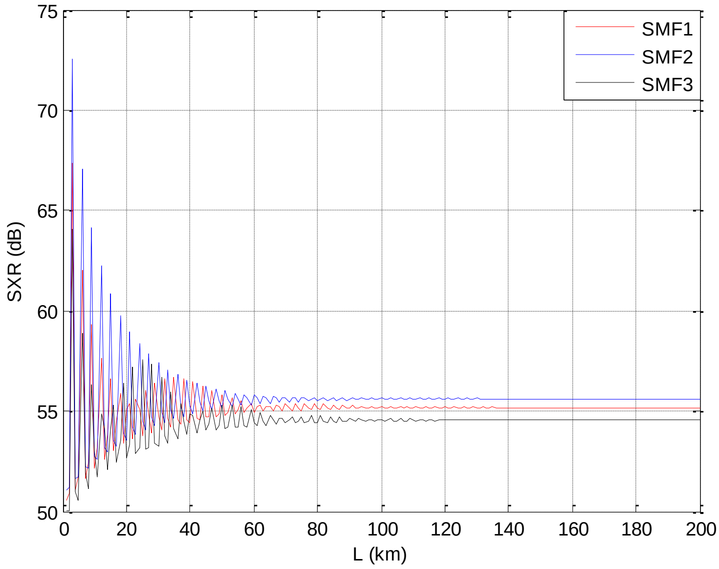

Figure 16:
Variation of SXR with variations in fiber link lengths for center channels of 5-channel DWDM systems implemented with 1 mW channel input powers and 50 GHz channel spacing values

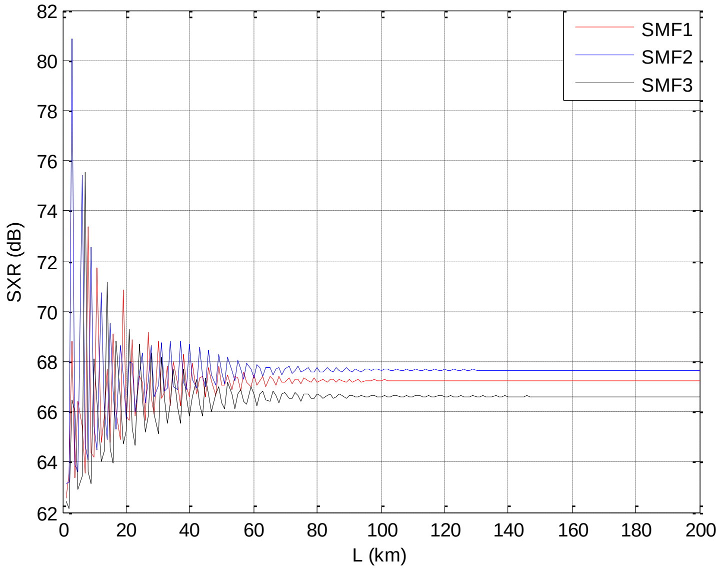

Figure 17:
Variation of SXR with variations in fiber link lengths for center channels of 5-channel DWDM systems implemented with 1 mW channel input powers and 100 GHz channel spacing values

5. CONCLUSION

In this paper, SXR variation of 5-, 7- and 9-channel DWDM systems implemented with three commercially available SSMFs have been analyzed under the impact of FWM focusing on the most severely impacted channels. Simulations have been done to observe variations of SXR with variations in channel input powers, channel spacing values and fiber link lengths.

Simulation results for SXR variations with variations in channel input powers exhibit that to satisfy a minimum 23 dB SXR condition, maximum channel input powers that can be used in 5-, 7- and 9-channel DWDM systems that have 12.5 GHz channel spacing are in the range of 1.96-2.84 mW while they are in ranges of 7.59-10.68 mW, 30.08-42.99 mW and 120.30-170.31 mW for systems having channel spacings of 25 GHz, 50 GHz and 100 GHz, respectively. Those results emphasize the reason of choosing higher channel spacing values in DWDM system implementations. Simulation results obtained for three different commercially available SSMFs also show the combined effect of the fiber parameters, i.e. chromatic dispersion value, dispersion slope, nonlinearity coefficient and attenuation coefficient, on FWM and subsequently on SXR.

Simulation results for SXR variations with variations in channel spacing values give important clues for DWDM system implementations such as narrowing the channel spacing values for a more efficient use of the fiber bandwidth may result in a dramatic degradation in SXR, e.g. for 100 GHz channel spacing values, SXR at center channels of 5-, 7- and 9-channel systems varies in the range of 64.61-67.63 dB while it varies in 28.83-31.99 dB range for 12.5 GHz channel spacing values, and the minimum SXR level for a reliable data transmission may not be provided unless appropriate input powers are chosen.

Simulation results for SXR variations with variations in fiber link lengths display the strong oscillatory behaviour of the SXR variation for link lengths shorter than 60 km and channel spacing values higher than 12.5 GHz. This is an important point in particular for DWDM-PON system implementations where fiber link ranges are below 30 km.

It can be concluded that results of this research show the combined effect of the optical fiber and system design parameters on FWM performance of DWDM systems and give important clues for not only long-haul but also access network implementations of DWDM systems.

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