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EFFECT OF MULTIPLEXER/DEMULTIPLEXER BANDWIDTH ON UPGRADING CURRENT 10G TO 40G OPTICAL COMMUNICATION SYSTEMS

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ABSTRACT

Many current 10G optical systems need to be upgraded to higher data rates (for example 40G, 100G, etc…), in order to satisfy the increased demand for higher bandwidth. However, many system providers in the third world countries have limited budgets and could not just replace all equipment to upgrade their systems. Thus, it is important to investigate what equipment could still be used in the upgraded system. In other words; which equipment could be used for both 10G and higher data rate transmitters? The bandwidth of the passive modules is a crucial specification that enables optical communication systems. Therefore, the effect of multiplexer (MUX) and demultiplexer (DEMUX) bandwidth on the performance of hybrid 10G/40G optical communication systems is investigated in this work. Hybrid optical systems enable adding new channels with higher data rate on current 10G common equipment. Numerical simulations are conducted on eight consecutive dense wavelength division multiplexing (DWDM) channels selected on 100-GHz ITU-grid each carrying data rate of 10 Gbps or 40 Gbps. Different loading configurations of wavelengths with data rates are considered in this work. In addition, different MUX/DEMUX bandwidths of 40, 50, 60 and 70 GHz are used to investigate the performance of each selected hybrid system configuration. It is found that the optimal MUX/DEMUX bandwidth for all investigated hybrid configurations is 60 GHz. The hybrid system performance is evaluated for both return-to-zero (RZ) and non-return-to-zero (NRZ) pulse format. The maximum reach of a selected hybrid configuration is also numerically investigated using circulating loop configuration for both RZ and NRZ pulse formats.

KEYWORDS

Effect of MUX/DEMUX bandwidth on signal transmission, Hybrid optical fiber communication, Upgrading 10G to 40G systems, Dispersion and non-linearity interaction in optical fibers.

1. INTRODUCTION

The demand for new services which are bandwidth hungry is increasing all over the world. These services include education on demand, interactive video gaming, IP-TV, voice over IP, high definition TV, video on demand, video conferencing, video surveillance etc... Optical fiber cables offer huge bandwidths which can be exploited to support such services. Commercial optical fiber communication systems are implemented in long haul, metropolitan and access area networks to support the required bandwidths [1]-[3]. The bandwidth of an optical communication system is typically increased by either deploying new systems with higher data rates or upgrading current systems. The later technique can be achieved by increasing the number of wavelengths used on an existing wavelength plan with each wavelength having the same data rates or by using different data rate for the different wavelengths. Using different data rates in a system at different wavelengths is known as a hybrid communication system, which is also known a heterogeneous system [4]-[7]. Commercial DWDM systems are deployed initially with channels carrying lower data rate (10G), then upgraded using wavelengths carrying 40G data rate. Different methods have been proposed in the literature to enable hybrid communication systems: flexible reconfigurable optical add/drop multiplexer (ROADM) bandwidths [8], coherent modulation schemes for 40G and 100G rates [9] and group delay management technique [10]. Already published techniques did not investigate the optimal bandwidth of MUX and DEMUX that could be

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used to enable hybrid communication systems.

Typically, ON/OFF keying modulation scheme is used for 10G optical communication systems, which also use non return-to-zero (NRZ) pulse format. However, advanced modulation schemes are used for 40G and 100G systems such as differential phase-shift keying (DPSK) and dual-polarization quadrature phase shift keying (DP-QPSK) [11]-[12]. DP-QPSK systems can be implemented employing duobinary or return-to-zero (RZ) pulse formats with different pulse width to bit periods [13]-[14].

Signals carrying different data rates in a hybrid optical communication system travel through the same optical fiber and use the same passive and active optical modules. Usually, lower data rate signals are deployed at earlier stages in any commercial system. Then, higher data rate signals are added to the system. The added signals have different modulation bandwidths and require different passives' bandwidths. In addition, the interaction of dispersion and non-linearity for each signal will be different depending on its location on the ITU-grid, optical fiber dispersion slope and fiber zero-dispersion wavelength. Thus, each signal will have different performance which must be taken into account in designing and operating newly upgraded systems. The interaction of dispersion and non-linearity in optical fiber is investigated for optical communication systems with independent 10G or 40G modulated signals and for a single MUX/DEMUX bandwidth [15]-[18]. The interaction for hybrid communication system is not published -to the best of our knowledge- and cannot be foreseen. Therefore, numerical simulations are conducted to study hybrid system performance due to fiber dispersion and non-linearity interaction.

In this work, the effect of MUX/DEMUX bandwidth on the performance of 10G/40G data rate hybrid optical communication system is investigated using Optisys software from Optiwave, Inc. Although very high data rate systems (100G, 200G) exist commercially in the market [19]-[20], there is still a great need for such investigation, especially for system providers who have limited budgets available to upgrade their current 10G systems into higher data rate systems. The upgrade could be implemented by carrying higher data rate signals (40G) on wavelengths distributed over the same common equipment used for the 10G system.

MUX/DEMUX bandwidths of 40, 50, 60 and 70 GHz are used in the investigation. Commercial 10G MUX/DEMUX passband bandwidth differs from vendor to vendor and from technology to technology. An example of an arrayed waveguide MUX 3-dB passband bandwidth parameter is 50 GHz (0.4 nm). Numerical simulations are conducted at different MUX/DEMUX bandwidths to evaluate the system performance for different hybrid configurations listed in Table 1. Return-to-zero (RZ) and non return-to-zero (NRZ) pulse formats are used in this investigation. The system performance of different hybrid configurations is compared with standard standalone 10G and 40G communication systems. A circulating loop configuration is also used in the simulation to investigate the maximum propagating distance of signals for a selected hybrid communication system using RZ and NRZ pulse formats.

2. HYBRID SYSTEM CONFIGURATION

Figure 1 shows the block diagram of the hybrid optical communication system used in the numerical simulations. Eight neighboring DWDM channels on a 100-GHz ITU-grid are selected around 1550.12nm with a linewidth of 10 MHz. Each channel carries either 10 Gbps or 40 Gbps data rate, depending on the selected hybrid configuration as listed in Table 1. The laser center wavelength is assumed stable and no drifting is considered in this work. A dispersion compensating fiber (DCF) piece with a dispersion of -85 ps/(km.nm) at 1550 with a dispersion slope of -0.3 ps/(km.nm^2) is used in the simulation. The used DCF piece offsets the dispersion accumulated by the single mode fiber (SMF) piece which has a dispersion of 17 ps/(km.nm) at 1550 nm with a dispersion slope of 0.075 ps/(km.nm^2). Two erbium-doped fiber amplifiers (EDFA) are used to compensate the attenuation in the fiber link due to SMF and DCF pieces which have attenuation of 0.2 dB/km and 0.5 dB/km, respectively. The EDFA noise figure (NF) is set to 6 dB. The EDFA NF parameter affects the overall system performance at the receiver, which is defined by optical signal-to-noise ratio (OSNR). The laser continuous wave (CW) power launched into the modulator is set to 4 dBm. The MUX and DEMUX modules are assumed lossless with Bessel filer shape of second order. Adjacent channels crosstalk of the MUX/DEMUX is assumed 30 dB. The bandwidth of the MUX/DEMUX pair is varied (40, 50, 60 and 70 GHz) to investigate its effect on the performance of each channel in hybrid optical communication systems. A Mach-Zehnder external modulator is used to modulate ON/OFF keying (OOK) pseudo-random bit sequence using NRZ and RZ pulse formats. The chirp of the modulator is set to zero and the sequence length is 11 bits. The power level of the eight channels at the output of the modulator for H 10 - 40 hybrid configuration is shown in Figure 2. The variation in power level for the different channels is due to wavelength-dependent modulator transfer function. At the receiver end, an optical attenuator is used to control the received power level launched into the bit error-rate (BER) tester in order to create waterfall BER curves. A pin detector with low-pass filter is used as a receiver.

Table 1. Different 10G/40G hybrid and standalone configurations.

Configurations	**Names**
10-10-10-10-10-10-10-10	R 10
40-40-40-40-40-40-40-40	R 40
10-40-10-40-10-40-10-40	H 10 - 40
10-10-40-40-10-10-40-40	H 2 10 - 2 40
40-40-10-10-40-40-10-10	H 2 40 - 2 10
10-10-10-10-40-40-40-40	H 4 10 - 4 40
40-40-40-40-10-10-10-10	H 4 40 - 4 10

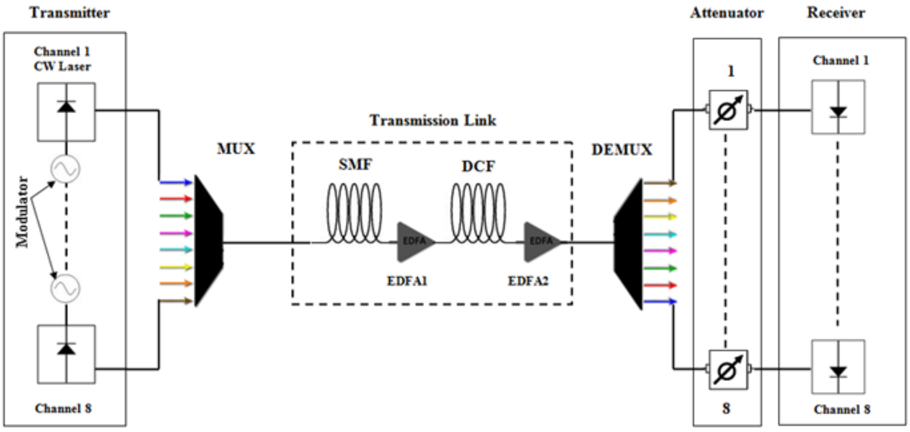


Figure 1. Optical communication system used in the simulations. EDFA: erbium-doped fiber amplifier; SMF: single mode fiber; DCF: dispersion compensated fiber; CW: continuous wave; MUX: multiplexer; DEMUX: demultiplexer.

3. MUX/DEMUX BANDWIDTH EFFECT

The bandwidth of propagated optical signals in the fiber depends on their data rate and the pulse format used. The optical bandwidth equals the signal data rate for NRZ pulse format. However, the bandwidth of an optical signal that uses RZ pulse format depends on pulse duty cycle; 50% of the duty cycle RZ pulses occupy twice the bandwidth of NRZ pulses for the same data rate. Thus, an optical modulated signal at 10Gbps using NRZ pulses occupies 10GHz bandwidth. When the MUX/DEMUX bandwidth is larger than the modulated signal bandwidth, no distortion is acquired after multiplexing/demultiplexing processes. Nevertheless, it is not beneficial to use larger MUX/DEMUX bandwidths to avoid passing through more noise with the optical signal. Therefore, it is important to optimize the MUX/DEMUX bandwidth used.

Figure 3 shows the simulated BER performance of H 10 – 40 hybrid configuration at 60 GHz MUX/DEMUX bandwidth. The odd channels carry 10 Gbps data, while the even channels carry 40 Gbps data. It is clear that the BER performance differs from channel to channel for the same data rate. Table 2 illustrates a summary of the total differences between each group of 10G and 40G channels for different MUX/DEMUX bandwidths. The total performance difference among the same channels will be defined in this work as "range penalty". Table 2 also shows the "center received power" of each group of channels. These simulations were repeated for all configurations listed in Table 1. Figure 4 and Figure 5 show, respectively, the range penalty and received power center for different hybrid configurations.

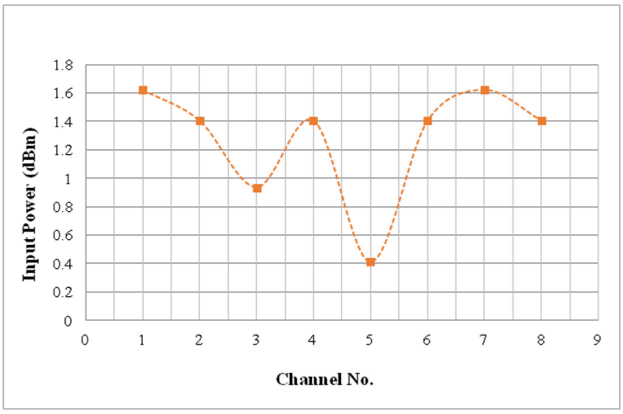
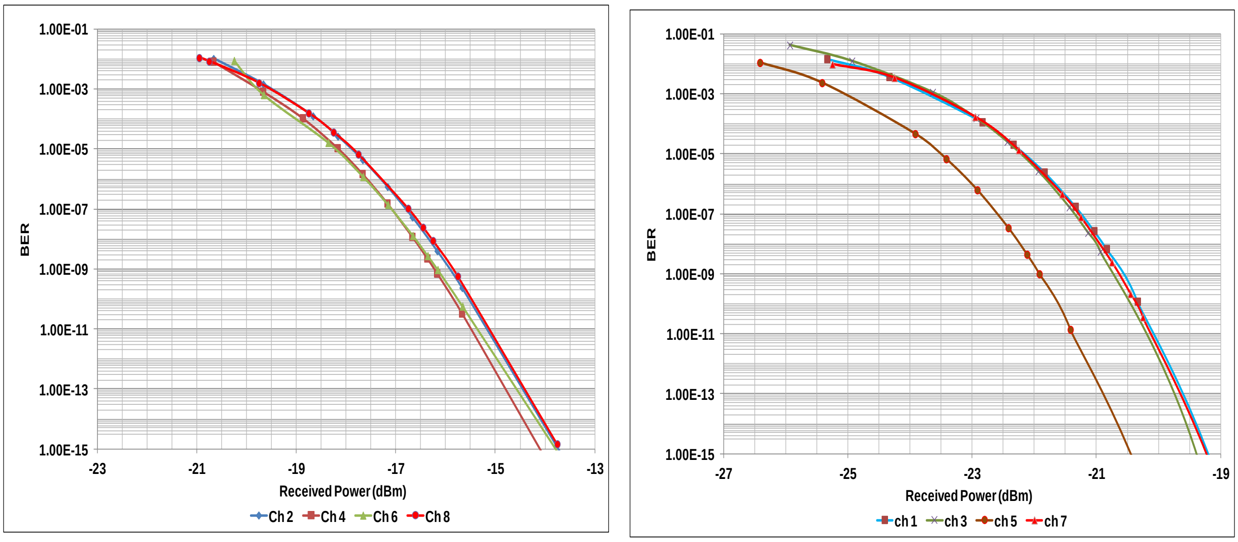


Figure 2. Channels' power levels at the output of the Mach-Zehnder modulator for H 10 – 40 hybrid configuration.

It is clear that each channel has different performance, which is mainly due to its wavelength and relative dispersion at that wavelength. Also, the power level of each wavelength is different, as shown in Figure 2. Therefore, the dispersion and non-linearity interaction during propagation in optical fiber will be different for each wavelength as explained in more detail in section 5.



(a) (b)

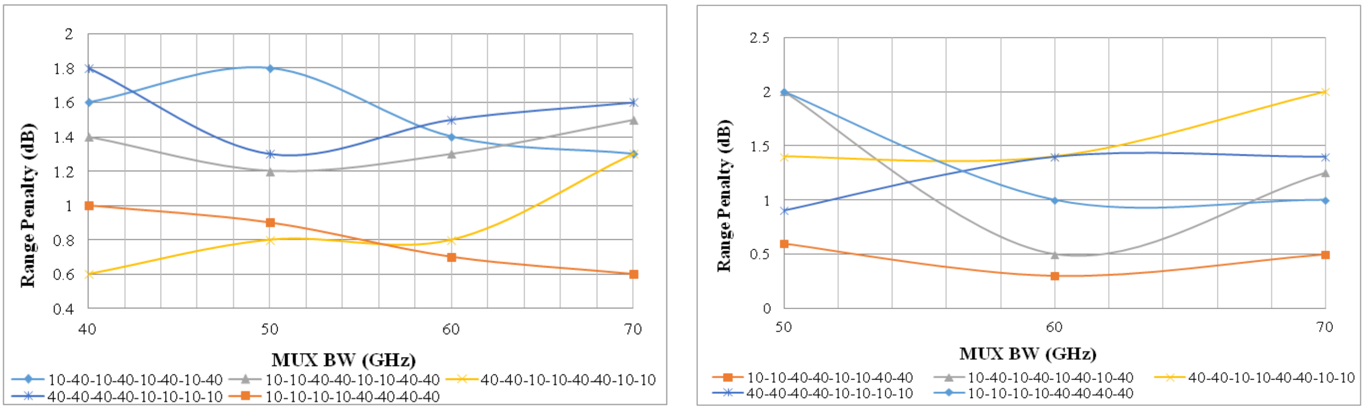
Figure 3. System performance of 8-channel 100-GHz spacing hybrid H 10 -40 configuration with NRZ modulated signals with 60 GHz MUX/DEMUX BW (a) 40 Gbps data rate (b) 10 Gbps data rate.

4. CIRCULATING LOOP SIMULATION

Figure 6 illustrates the block diagram of the circulating loop configuration used in the simulations to investigate the maximum propagating distance of signals for a selected hybrid optical communication system. The hybrid H 10 – 40 configuration is used in performance evaluation for NRZ and RZ pulse formats. The loop is made up of 50km of NZ-DSF fiber and 10km of DCF. Figure 7 and Figure 8 show the system performance of 10G and 40G channels propagating in the loop using RZ and NRZ pulses, respectively. It is clear that RZ pulse format outperforms NRZ pulse format. The maximum possible transmission distance for RZ pulses with a MUX/DEMUX BW of 60 GHz is approximately 400km (8 times 50km) which is characterized at BER of 1x10^{-12} and limited by the 40 Gbps channels, while the maximum possible transmission distance for NRZ pulses is about 200km (4 times 50km). The BER variation at high loop count shown in Figure 7 and Figure 8 is an artefact due to high BER values close to 10^{-2}. The MUX/DEMUX BW of 60 GHz is chosen in performance evaluation of pulse format in long distance hybrid rate data transmission, because it gives best performance for 40G data rate as shown in Figure 4b.

Table 2. Summary of system performance for H 10 – 40 hybrid configuration at 40, 50, 60 and 70 GHz MUX/DEMUX bandwidths at BER = 10^{-12}.

MUX/DEMUX BW GHz	System Performance			
	10 Gbps		**40 Gbps**	
	Range Penalty dB	Receiver Power Center dBm	Range Penalty dB	Receiver Power Center dBm
40	1.6	-20.70	Failed*	Failed*
50	1.8	-20.30	2.0	-13.0
60	1.4	-20.50	0.5	-15.0
70	1.4	-20.25	1.25	-14.75
* Failed, because signals cannot be detected without using forward error correction (FEC) capability in the system. FEC can correct errors of BER of 1×10^{-3} or lower.				



(a) (b)

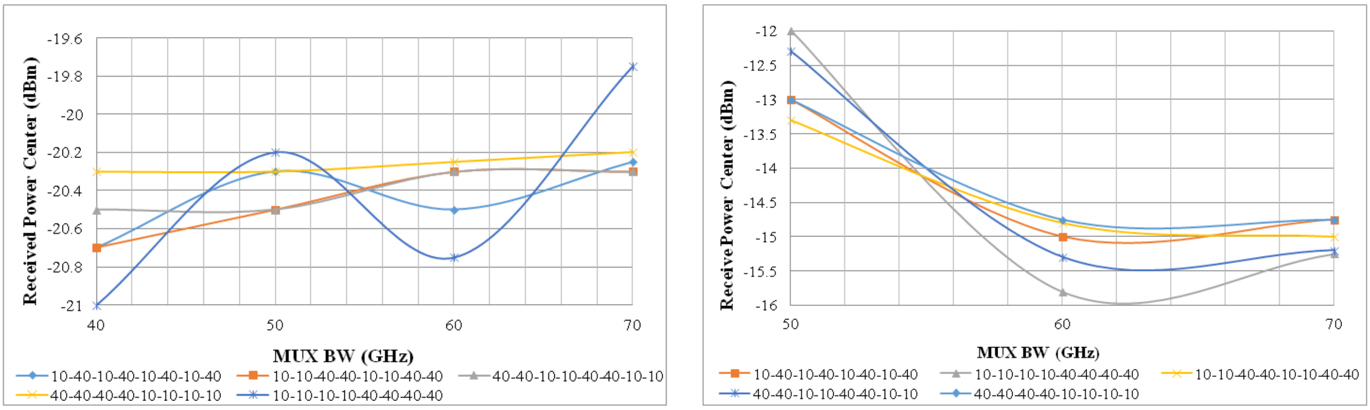
Figure 4. System performance range penalty summary at different MUX/DEMUX bandwidths for different hybrid configurations (a) 10 Gbps channels (b) 40 Gbps channels.

5. DISCUSSION

Non-linear Schrödinger equation governs signal propagation in optical fiber. It is given by:

$$\frac{\partial A}{\partial z}+\frac{\alpha}{2}A+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial T^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial T}=i\gamma[|A|^2A+\frac{i}{\omega_\circ}\frac{\partial}{\partial T}(|A|^2A)-T_R A\frac{\partial |A|^2}{\partial A}] \qquad (1)$$

where ($T = t - \beta_1 z$) is a normalizing parameter to reference the moving pulses in a retarded frame. β_1 is the inverse of group velocity (v_g), β_2 is the group velocity dispersion (GVD) parameter, β_3 is the third-order dispersion parameter, α is the fiber attenuation described in dB/km and A is the slowly varying amplitude of propagated pulse electric field along the fiber in the z direction. $|A|^2$ is the optical pulse power, T_R is the Raman time constant and the non-linear parameter γ is given by:



(a) (b)

Figure 5. Summary of system performance of received power center value at different MUX/DEMUX bandwidths for different hybrid configurations (a) 10 G bps channels (b) 40 Gbps channels.

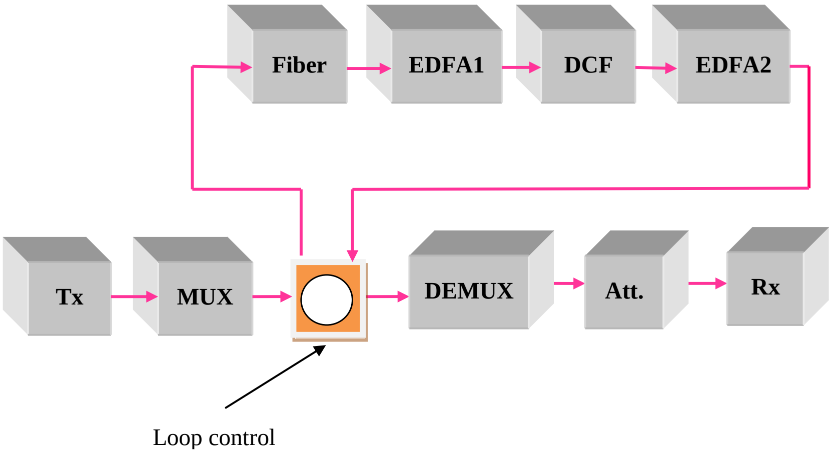


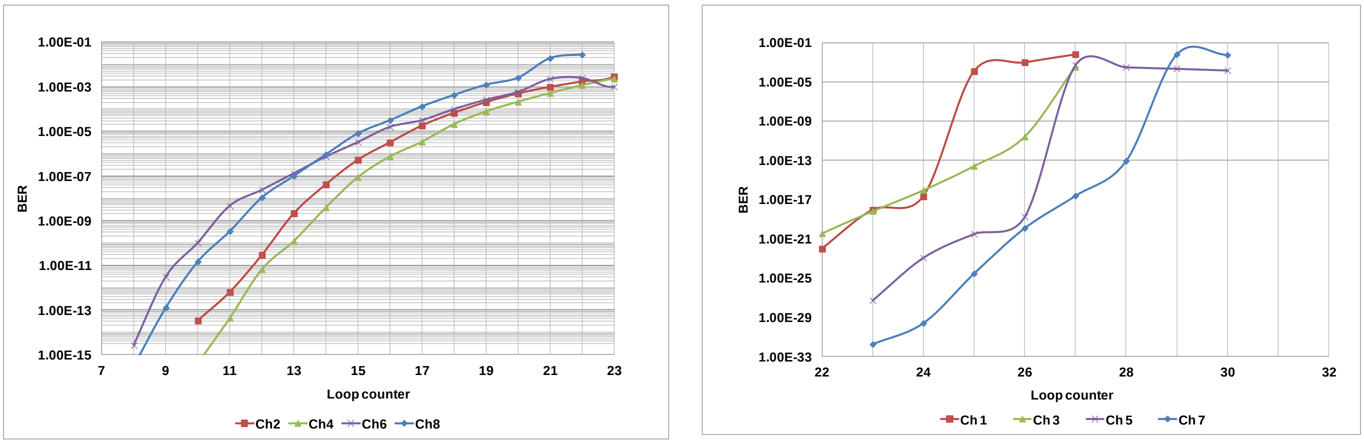
Figure 6. Block diagram of a circulating loop configuration used to investigate maximum propagation distance of signals in hybrid communication systems.

$$\gamma = \frac{n_2\,\omega_0}{c\,A_{eff}} \qquad (2)$$

where n_2 is the non-linear refractive index, A_{eff} is the effective core area, c is speed of light in vacuum and ω_o is related to the propagated optical signal center wavelength λ. The GVD parameter can be positive or negative, depending on whether λ is lower or higher than the fiber zero-dispersion wavelength λ_D. When λ is higher than λ_D, the GVD is negative and this regime is called anomalous-dispersion regime. On the other hand, the regime is called normal dispersion regime when GVD is positive ($\lambda < \lambda_D$). The commonly used fiber dispersion parameter D (ps/km.nm) is related to GVD by:

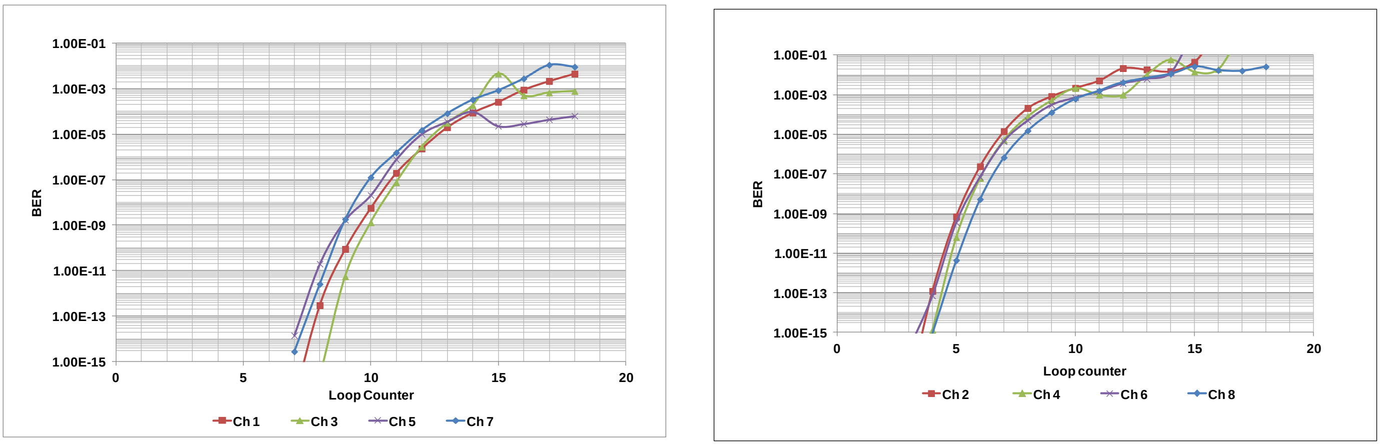
$$D = -\frac{2\pi c}{\lambda^2}\beta_2 \qquad (3)$$

Typically, the red-shifted (lower frequency) components of a propagated pulse travel slower than the blue-shifted (higher frequency) components in the anomalous-dispersion regime, causing the pulses to broaden in the time domain and compress in the wavelength domain. When the blue-shifted components surpass the red-shifted components, an inverse effect may occur, which causes compression in the time domain. On the other hand, the blue-shifted components travel slower than the red-shifted components in the normal dispersion regime, causing pulses to compress in the time domain and broaden in the wavelength domain.



(a) (b)

Figure 7. System performance for RZ modulated pulses of H 10 – 40 hybrid configuration propagated in a circulating loop (a) 10 Gbps channels (b) 40 Gbps channels.



(a) (b)

Figure 8. System performance for NRZ modulated pulses of H 10 – 40 hybrid configuration propagated in a circulating loop (a) 10 Gbps channels (b) 40 Gbps channels.

When optical pulses propagate in the optical fiber, they may encounter dispersion effect only, non-linearity effect only, none of these effects or both non-linearity and dispersion effects. In order to determine which effect occurs in the optical fiber, dispersion and non-linear lengths are defined as:

$$L_D = \frac{T_\circ^2}{\beta_2},\ L_{NL} = \frac{1}{\gamma P_\circ} \tag{4}$$

where T_o and P_o represent the propagated pulse width (1/e width) and peak power, respectively. When $L \ll L_\text{NL}$ and $L \ll L_D$, neither dispersion effect nor non-linear effect play a role in pulse evolution in the optical fiber. When $L \ll L_\text{NL}$, but $L \sim L_D$, the propagated pulses encounter dispersion only, while the non-linear effect in the fiber is negligible. On the other hand, when $L \sim L_\text{NL}$, but $L \ll L_D$, the dispersion term in Schrödinger non-linear equation will be ignored and the propagated pulses encounter non-linear effects during propagation. In the last case, when the fiber length is longer or comparable to both the non-linear and dispersion lengths, the evolution of pulses in the optical fiber will encounter both fiber dispersion and non-linearities.

The main non-linear effects that propagated DWDM signals encounter in optical fibers are self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). Other non-linear effects that signals experience in optical fibers are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The effect of SPM and XPM on propagated pulses is to broaden their wavelength content by causing non-linear phase shift. The non-linear intensity-dependent phase shift ϕ_{NL} is given by the following equation for two neighboring signals propagating in the fiber.

$$\emptyset_{NL} = n_2 k_0 L(|E_1|^2 + 2|E_2|^2) \tag{5}$$

where $|E_1|^2$ and $|E_2|^2$ are the intensities of a signal at a specific wavelength and its neighboring signal at another wavelength selected on ITU-grid. The first term in equation (5) is related to SPM and the second term is related to XPM. Each non-linear effect is triggered in the optical fiber when the propagated signal has a power level that exceeds a specific threshold. The first non-linear effect that optical signals run into is SBS, then SPM and XPM. However, FWM requires extra conditions beyond the power level threshold, which are related to phase and frequency matching of WDM signals propagating in the fiber [21]. The propagated pulses' format also affects the non-linear threshold due to its influence on the average power of the optical signal in the fiber. In addition, optical signal data rate plays a role in the fiber non-linear threshold and affects the sensitivity of propagated signal to dispersion. The higher the signal data rate, the more sensitive the signal propagated pulses to dispersion. NRZ pulses have higher average power compared to RZ pulses for the same data rate. Thus, they are more sensitive to non-linearity. On the other hand, RZ pulses are more sensitive to dispersion compared to NRZ pulses.

Propagated pulses in the optical fiber encounter broadening in the wavelength domain and compression in the time domain, because of SPM and XPM non-linearities. Thus, their effect is opposite to that of dispersion. However, it is too difficult to predict the behavior of dispersion and non-linearity interaction in optical fiber. Hence, numerical simulations are typically conducted in order to find the optimal regime of operation for each hybrid configuration.

Figure 9 and Figure 10 show the BER performance for single wavelength of H 10 - 40 hybrid configuration (Ch 2: 40 Gbps, -16.5 dBm) at different settings of dispersion and non-linearity. The BER parameter is calculated from Q-parameter using Optiwave optisys software. The BER performance curves *versus* dispersion values for different effective core areas are shown in Figure 9. BER performance curves versus effective area for different DCF lengths are illustrated in Figure 10. Note that increasing the fiber length does not necessarily give worst BER performance as shown in Figure 10, especially when going from 2.8km to 7.8km. Therefore, it is clear that there is an optimal regime of operation for each combination of A_{eff} and dispersion.

The large difference among each group of channels can be explained through the argument of interaction of fiber non-linearity and dispersion. The laser diode CW power level of each channel is set to 4 dBm. The power of each channel varies at the output of the external modulator due to its wavelength dependence. Figure 2 illustrates the output power per channel for the hybrid configuration H 10 – 40. The variation is over 1 dB. In addition to that, the dispersion of each channel is also different due to non-zero dispersion slope of SMF and DCF optical fibers. The dispersion slopes of SMF and DCF fibers are assumed 0.075 and - 0.3 ps/ (km.nm^2), respectively. Thus, the interaction of non-linearity and dispersion in the fiber transmission link is different for each channel as shown in Figure 9 and Figure 10. However, if the power level of all channels is the same, the non-linear effect for all channels will be relatively the same with minor differences due to the dependence of γ on frequency as described in Equation 2. The dispersion of each channel also varies slightly due to optical fibers' dispersion slopes. Thus, the BER performance of channel 5 is expected to be closer to the other channels shown in Figure 3b when its power level equals the power levels of other channels.

6. CONCLUSIONS

The possibility of transmitting 40G channels over 10G common equipment is investigated. Numerical simulations were conducted to investigate the effect of MUX/DEMUX bandwidth on system performance of hybrid 10G/40G optical communication systems. Different hybrid 10G/40G configurations were evaluated. It was found that the best MUX/DEMUX bandwidth, which could be used for different configurations, is 60 GHz. However, the configuration 10-10-40-40-10-10-40-40 has lower penalty for 40G channels for all investigated MUX/DEMUX bandwidths, while the configuration 40-40-10-10-40-40-10-10 has the best performance for 10G channels at 40GHz and 50GHz MUX/DEMUX bandwidths. The simulations showed also that it is difficult to predict the hybrid system performance for different configurations due to unpredictable interaction between dispersion and non-linearity in the optical fiber. It was also found that using RZ pulse format for both 10 Gbps and 40 Gbps modulated signals provides further signal propagation compared to using NRZ pulse format.

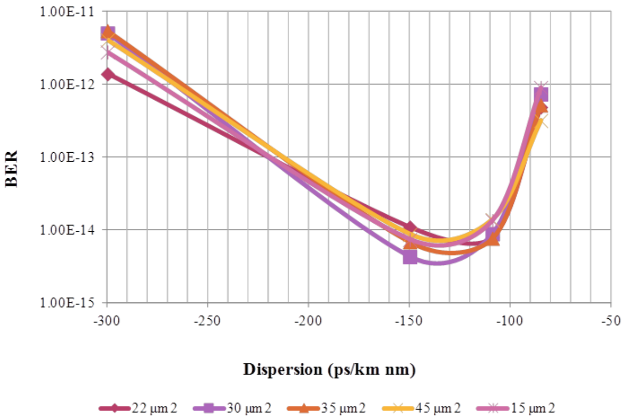


Figure 9. BER performance *versus* DCF dispersion for different A_{eff} (EDFA gain = 5 dB).

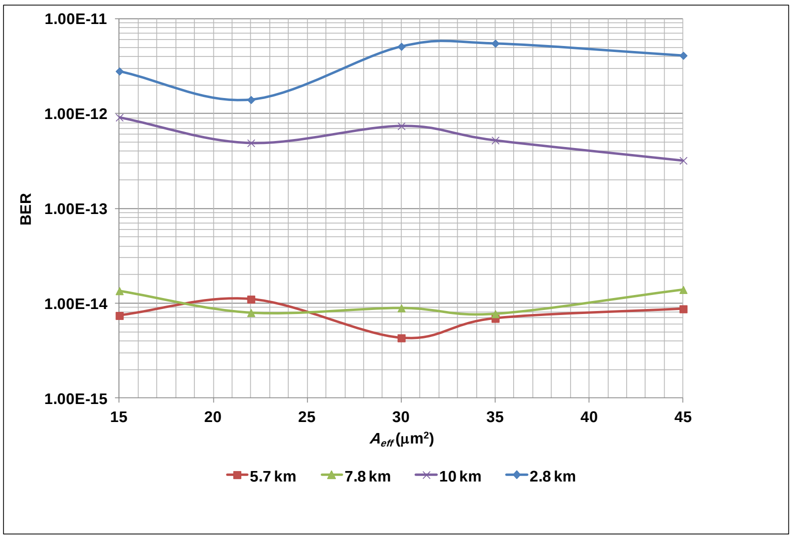


Figure 10. BER performance *versus* A_{eff} for different lengths of DCF (EDFA gain = 5 dB).

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ملخص البحث:

يحتاج كثير من أنظمة الاتصال الضوئية القائمة ذات السعة 10G الى تحديث لتصبح ملائمة لسعات أعلى (40G، 100G...)؛ من أجل تلبية الطلب المتزايد على نطاقات ترددية أعلى. غير أن كثيرين من المزودين بهذه الأنظمة في دول العالم الثالث تعوزهم الميزانية اللازمة لتغيير المعدات بالكامل في أنظمة الاتصال الضوئية القائمة. لذا، فإن من المهم دراسة أيّ المعدات يمكن الإبقاء عليها عند تحديث الأنظمة القائمة منخفضة السعة لرفع سعتها. فالسؤال الأساسي هُنا هو: ما المعدات التي تصلح للسعات المنخفضة والعالية على حدّ سواء؟

في هذه الورقة، يجري استقصاء أثر النطاق الترددي للمرسل المضاعف (MUX) وكاشف الإرسال المضاعف (DEMUX) على أداء أنظمة الاتصال الضوئية الهجينة (40G/10G)، علماً بأن هذه الأنظمة تسمح بإضافة قنوات جديدة بسعاتٍ أعلى الى المعدات القائمة ذات السعة 10G. وقد أجريت محاكاة رقمية على 8 قنوات متعاقبة على شبكة الاتحاد الدولي للاتصالات ذات النطاق الترددي 100 جيجاهيرتز تحمل كل منها بياناتٍ بمعدّل 10G أو 40G. وقد استخدمت قيم مختلفة للنطاق الترددي للمرسل المضاعف/ كاشف الإرسال المضاعف (40، 50، 60، 70 جيجاهيرتز) من أجل دراسة أداء كل تشكيلة من تشكيلات النظام الهجين. ووُجد أن النطاق الترددي الأمثل لجميع تشكيلات النظام المستقصاة هو (60 جيجاهيرتز). وقد جرى تقييم أداء النظام الهجين لكلّ من نمطَي النبضات: الرجوع الى الصفر (RZ)، وعدم الرجوع الى الصفر (NRZ). كذلك، تم استقصاء المدى الأقصى لتشكيلة هجينة منتقاة لكل من نمطَي النبضات: الرجوع الى الصفر، وعدم الرجوع الى الصفر.