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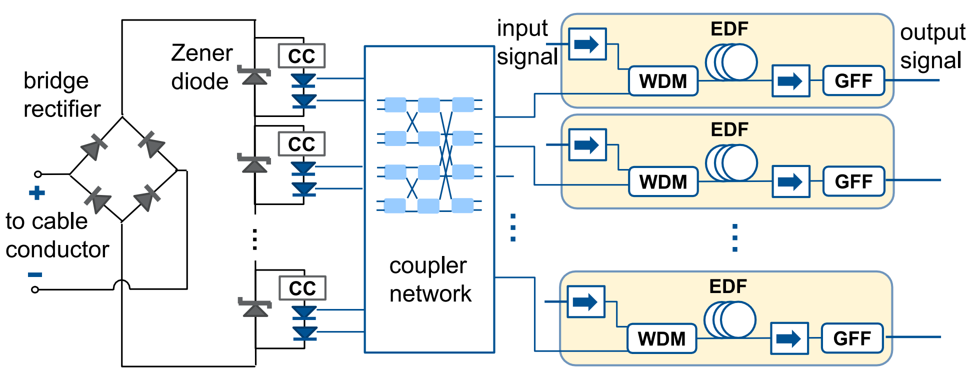

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Repeater Power Conversion Efficiency in Submarine Optical Communication Systems

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Abstract: In power-limited trans-oceanic submarine systems, the electrical-to-optical (E/O) power conversion efficiency determines the amount of optical signal power generated by repeaters, which governs the cable capacity. In contrast to conventional submarine systems, recent single mode fiber spatial division multiplexing (SDM) systems operate at a lower channel power and support a larger number of optical fibers. Moreover, pump sharing technology is used in SDM systems to enhance cable capacity and system reliability, where a group of pump lasers are combined to feed a group of fiber pairs. The repeater E/O power conversion efficiency is directly related with cable capacity, as well as capacity per power and cost per capacity analysis. Therefore, it is important to understand the characteristics of repeater E/O efficiency. We developed a model to analyze the repeater E/O efficiency in submarine SDM systems. Experimental measurement data of pump lasers and numerical simulation results of Erbium doped fiber amplifiers (EDFAs) were used as input information to the model to analyze repeater E/O efficiency in various system designs. Based on the E/O efficiency model results, we investigated cable capacity using the Gaussian noise (GN) model. Moreover, cable capacity per power was calculated and compared based on three different power metrics: (i) electrical supply power, (ii) pump optical power and (iii) EDFA output power. With the aid of the repeater E/O efficiency model, one can analyze the efficiency of submarine systems using the direct metric of cable capacity per electrical supply power.

Index Terms: Optic communications, power efficiency, pump sharing, spatial division multiplexing.

1. Introduction

The overall data capacity of trans-oceanic submarine systems is typically limited by the electrical power supply [1]–[6], up to ∼15–18 kW, beyond which reliability becomes a significant issue. The power is mainly dissipated by the cable conductor and repeaters, with equal power split in an ideal case. The product of repeater power consumption and electrical-to-optical conversion efficiency is the optical power generated by the repeater, which determines data capacity. Ref [7] showed that the overall E/O power conversion efficiency of a submarine repeater is typically on the order of ∼1%, a result of the combination of efficiency factors of the electrical driver circuitry, pump laser, Erbium doped fiber (EDF), and gain flattening filter (GFF), along with other factors such as pump ageing. To increase the efficiency of electrical power consumption, current submarine systems are evolving to spatial division multiplexing (SDM) system designs with increased number of fiber pairs (FPs) per cable and reduced optical launch power per channel. Due to the logarithmic dependence of data capacity on signal-to-noise ratio, it is generally beneficial to split optical power into parallel channels to achieve higher cable capacity in power limited systems. Therefore, such SDM designs can significantly improve the metric of total cable capacity per unit power [1], [2], [6], [8]–[16]. An important and related concept is pump farming or pump sharing, used in SDM systems to provide pump power to multiple amplifiers from a group of pump lasers [3]. SDM realization includes parallel single mode fiber systems, multi-core fiber systems, and multimode systems. In this paper, we consider signal mode fiber SDM systems, referred to as SDM_1 in Ref [3], [6]. As compared to conventional submarine systems, repeater E/O efficiency of SDM systems with pump sharing becomes more complicated depending on multiple system design variables such as the number of pumps, the number of fiber pairs, and channel launch power. It is therefore important to investigate the repeater power conversion efficiency in SDM systems with pump sharing for accurate estimation of cable capacity. In the absence of a detailed model of repeater E/O efficiency, cable capacity per power of SDM systems was analyzed indirectly in terms of pump optical power or EDFA optical power [6], [17].

In this paper, we extend the repeater E/O efficiency model in [7] to study SDM systems with pump sharing. Based on the repeater physical structure, the extended repeater E/O efficiency model is comprised of a detailed electrical power transfer formulation, experimental measurement data of pump laser efficiency, and numerical simulation results of EDFA conversion efficiency. Repeater E/O efficiency is analyzed in various SDM system configurations. It is shown that there exists an optimal range of pump power that provides maximum electrical power to pump power conversion efficiency. Also, there exists an optimal ratio between the number of pump lasers and the number of fiber pairs depending on the channel power that maximizes the repeater E/O efficiency. Moreover, we calculate cable capacity using a Gaussian noise (GN) model [18] that includes the generalized droop effect [19]–[22] and guided acoustic wave Brillouin scattering (GAWBS) noise [23]. With the aid of the repeater E/O efficiency model, we analyze the efficiency of submarine systems using the direct metric of cable capacity per electrical supply power and compare it with cable capacity per pump optical power and cable capacity per EDFA output power. The rest of the paper is organized as follows. Section 2 describes the repeater power conversion model. Section 3 describes input information to the model and repeater E/O efficiency results. Section 4 presents two system design examples employing the repeater power conversion efficiency model and compares cable capacity per power metrics. Section 5 draws conclusions.

2. Repeater Power Conversion Model

We present the repeater power conversion model in this section. A schematic diagram of a submarine repeater under bipolar power supply is shown in Fig. 1 [7], [24]. A diode bridge is used to support bi-directional powering and surge current control. For reliability concerns, each bridge diode is implemented with several individual components. Unipolar power supplies do not include the diode bridge rectifier. To stabilize the operation condition of pump lasers, Zener diodes and current control (CC) circuits are used for voltage and current control. In conventional submarine systems, each CC circuit controls a pair of pump lasers that are dedicated to one fiber pair (FP). Without losing generality, we assume the same configuration for repeater E/O efficiency analysis. Pump sharing technology combines a group of pump lasers to feed a group of fiber pairs, via a coupler network [3], [6]. We consider single mode fiber SDM systems, or SDM_1 [3], with one EDFA per fiber. In general, multiple sets of the components in Fig. 1 may be present in a repeater, depending on the total number of pumps and FPs. The overall repeater E/O efficiency will be the same as that of a subset if all subsets are identical.

Following [7] and Fig. 1, the overall repeater E/O conversion efficiency can be calculated as

$$\eta = \eta_{EE}\eta_{EO}\eta_{OO}\eta_{A}\alpha_{C}\alpha, \tag{1}$$

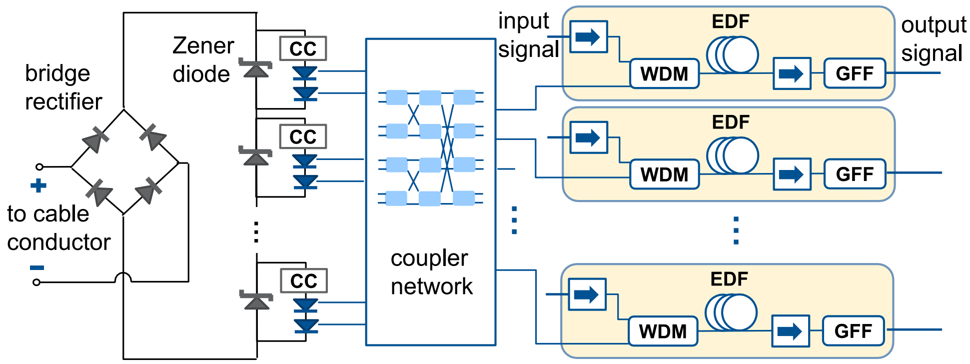

Fig. 1. Schematic diagram of a submarine repeater with pump sharing. CC: current control, WDM: wavelength division multiplexing, EDF: Erbium doped fiber, GFF: gain flattening filter.

where η_{EE} is the electrical to electrical driver efficiency, η_{EO} is the electrical power to pump optical power conversion efficiency, η_{OO} is the EDFA optical to optical power conversion efficiency, η_A is the factor accounting for pump ageing, α_C is the loss of the coupler network, α is the additional loss not included in the aforementioned factors such as optical power loss due to monitoring of pump lasers and EDFAs. The driver efficiency η_{EE} is comprised of power conversion factors of the diode bridge rectifier, Zener diodes and the current control circuits. The current-voltage characteristic of a diode is governed by the Shockley diode equation.

$$I_D = I_S\left[\exp\left(\frac{V_D}{nV_T}\right) - 1\right], \tag{2}$$

where I_D is the diode current, V_D is the diode voltage, I_S is the reverse bias saturation current, n is the quality factor, and V_T is the thermal voltage. $V_T = kT/q$, where k is the Boltzmann constant, T is the diode temperature, and q is the electron charge. The power dissipation of the diode bridge rectifier is

$$P_{DB} = 2M_D V_D I_D, \tag{3}$$

where the factor 2 indicates two diodes are forward biased in one bridge, and M_D is the redundancy factor due to reliability requirement. The diode bridge rectifier is only used in bipolar power supply systems. For unipolar power supplies, the power dissipation of (3) should be neglected. The power dissipation of a Zener diode is calculated by multiplying its current by the voltage drop

$$P_{ZD} = V_{ZD} I_{ZD}, \tag{4}$$

with

$$V_{ZD} = V_{CC} + 2V_{LD}, \tag{5}$$

where V_{CC} is the voltage drop of the current control circuit, and V_{LD} is the voltage drop across the pump laser which is obtained through pump laser characterization. The power dissipation of current control circuits depends on circuitry design based on bipolar transistors [25] or MOSFET transistors [26]. Typically, two pump lasers are connected in series with the cable conductor. The actual output power of each pump laser is monitored by a photodetector, which provides a feedback signal to adjust the current flowing into the pump laser. In the current control circuit, part of the electrical components passes a current close to the line current to provide power to pump lasers, while the other part of electrical components passes a differential current. The differential current is the fluctuation of current off from the desired current for a certain pump power due to environmental variations, which may be smaller in magnitude compared with the line current. With that in mind, we assume a phenomenological model of current control power dissipation for simplicity.

$$P_{CC} = Z_{CC} I_{LD}^2 + P_{CC0}, \tag{6}$$

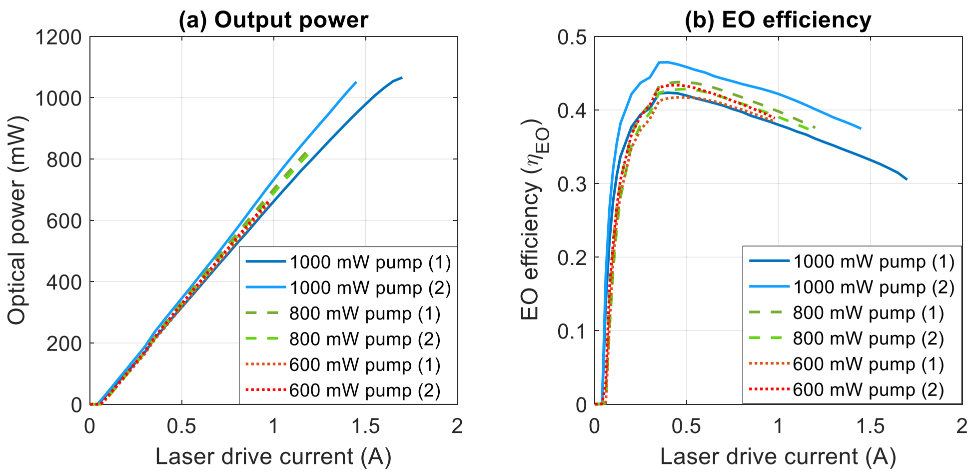

Fig. 2. Experimental data of 980 nm pump lasers (a) output power and (b) electrical to optical conversion efficiency.

where I_{LD} is the current of the pump laser, Z_{cc} is the effective impendence, and P_{cc0} accounts for the power consumption that is not dependent on the absolute magnitude of the pump laser current. The parameter value Z_{cc} significantly affects the power dissipation of current control circuits. We will examine the power dissipation for various values of Z_{cc} in Section 3. The driver efficiency η_{EE} is calculated as the ratio between actual electrical power applied to pump lasers to the total electrical power consumption.

$$\eta_{EE} = \frac{N_P \cdot P_{LD}}{P_{DB} + N_P/2 \cdot (P_{CC} + P_{ZD}) + N_P \cdot P_{LD}}, \tag{7}$$

where N_P is the number of pump lasers, P_{LD} is the electrical power dissipation of a pump laser. The pump efficiency η_{EO} can be obtained by pump laser characterization, which provides information of drive current I_{LD}, voltage V_{LD}, electrical power $P_{LD} = V_{LD}I_{LD}$, and optical output power $\hat{P}_p$. We use a circumflex marker to indicate optical power to avoid confusion. The EDFA efficiency η_{OO} can be obtained by EDFA experimental measurements or numerical simulations. We choose to use numerical simulation results since it provides the flexibility to optimize the EDF length for various system configurations. Experimental measurement data of pump lasers and simulation results of EDFAs will be discussed in Section 3. Finally, the coupler network loss is calculated as

$$a_C = a_1^K, \tag{8}$$

where α_1 is the insertion loss of a single coupler unit, and the number of coupler stages is

$$K = \log_2 \max\{N_P, 2N_{FP}\}. \tag{9}$$

Here N_{FP} is the number of fiber pairs. In (8), we assume that 2 × 2 couplers are used to build the coupler network [6]. (1–9) form the basis to calculate repeater E/O efficiency of various SDM system configurations.

3. Repeater Power Efficiency Results

We discuss input information and model results of repeater E/O efficiency in this section. We measured six high power and high efficiency 980 nm pump lasers. The maximum optical power ranges are 600 mW, 800 mW and 1000 mW. We measured two pump lasers of each type. The power vs. current and EO efficiency vs. current curves are shown in Fig. 2. All the six pump lasers have similar trend of efficiency versus current, as well as similar optimal drive current. We choose to use the average of the two 800 mW pump data for power efficiency analysis for the

TABLE 1
Parameters for Electrical Driver Efficiency (η_{EE}) Calculations

Parameter	Value	Parameter	Value	Parameter	Value
Quality factor, n	1	Saturation current, I_S	10^{-14} A	Effective impendence, Z_{CC}	2 Ω
Temperature, T	278 K	Redundancy factor, M_D	2	P_{CC0}	0.2 W

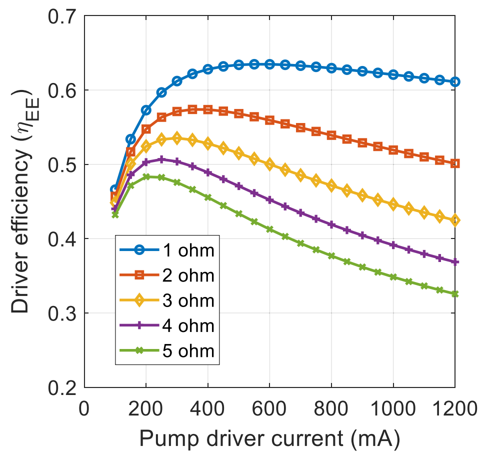

Fig. 3. Electrical driver efficiency versus pump driver current for 16 pump lasers.

rest of the paper. For the 800 mW pumps, the maximum EO efficiency is 0.43, achieved at 0.45 A drive current. The measurement data includes drive current I_{LD}, voltage V_{LD}, and optical output power $\hat{P}_p$. We calculate the electrical power dissipation as $P_{LD} = V_{LD} I_{LD}$. Power dissipation of temperature controller is not included here, since it is not present in submarine systems. Once given the required pump power, we can use the measurement data to map to corresponding pump EO efficiency, drive current and voltage. The drive current I_{LD} and voltage V_{LD} are then used for electrical drive efficiency η_{EE} calculations.

The electrical driver efficiency η_{EE} is calculated using (7), the pump laser measurement data, and the parameters in Table 1. One unknown parameter is the Zener diode current I_{ZD}. As a rule of thumb, a minimum of 10% of the total current should flow through the Zener diode in a voltage regulator circuit. Therefore, we assume that $I_{ZD} = I_{LD}$ / 9. Fig. 3 shows the driver efficiency as a function of pump driver current, assuming 16 pump lasers. As shown in (6), the effective impedance Z_{cc} significantly affects the power dissipation of the current control circuits. Different values of effective impedance are compared in Fig. 2. According to [7], conventional submarine repeaters have driver efficiency ~33%, and improved design with better DC-DC converter may achieve higher driver efficiency around 65%. For a typical feed current of 1 A, we observe that 5 Ω effective impendence may be representative for conventional repeaters, while a smaller effective impendence may be better for recent repeater designs with higher efficiency. For the rest of the paper, we assume 2 Ω effective impendence.

Next, we examine the conversion efficiency from electrical power to pump output power as $\eta_1 = \eta_{EE}\ \eta_{EO}\ \eta_A$. As shown in Fig. 1, the EDFA efficiency directly depends on pump power, but is not directly affected by electrical circuit efficiency. Therefore, it is simpler to investigate the power efficiency η_1 separately. Fig. 4 shows the power efficiency η_1 as a function of pump output power. Here we assume a pump ageing factor of 0.667 [7]. We observe that power efficiency η_1 reaches maximum value at approximately 300 mW pump power, independent of the number of pumps. Also, the power efficiency η_1 variation is small when the pump power is within 200 mW to 400 mW. This implies that to maximize repeater E/O efficiency, submarine systems should be designed to operate pump lasers at around 200 mW to 400 mW output power and adjust the number of pumps

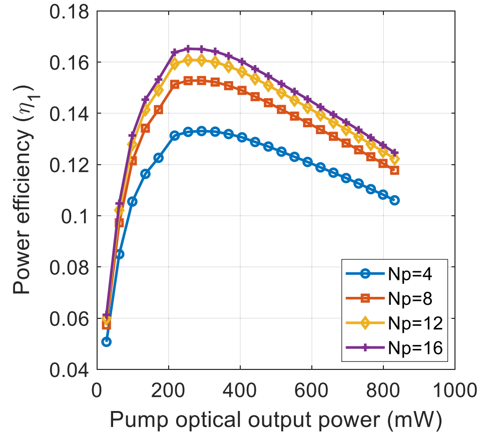

Fig. 4. Electrical to pump optical power conversion efficiency (η_1).

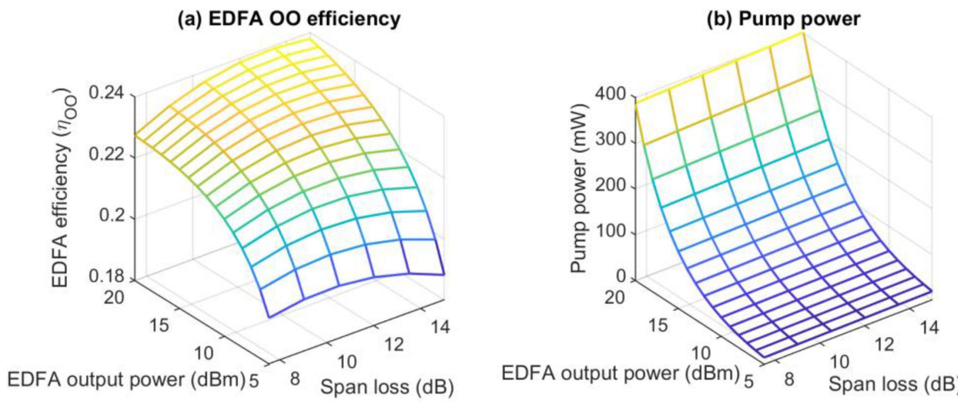

Fig. 5. EDFA simulation results (a) optical to optical conversion efficiency and (b) pump power.

according to the total pump power needed in EDFAs. We note that these optimal pump power values are obtained based on the 800 mW pump laser measurement data and expect the optimal values to change when the pump laser characteristics differ from the experimental data.

To study the EDFA optical to optical (OO) efficiency, we developed and validated a numerical model solving a group of rate equations of a two-level system [27]. Typical EDF parameters are used in the following simulations. We assume 0.2 dB WDM loss for both pump power and signal power, and 0.5 dB isolator loss. We assume an ideal gain flattening filter (GFF) profile to compensate for the gain spectrum, with an additional 0.5 dB loss for GFF manufacturing. The EDFA OO efficiency depends on the input signal power, pump power, span loss and EDF length. For system optimization, one may want to vary span length, fiber attenuation and EDFA output power as design parameters. Therefore, we simulated EDFA OO efficiency as functions of span loss and EDFA output power, while optimizing the EDF length to maximize OO efficiency for each case. Fig. 5 shows the simulation results of EDFA OO efficiency and the corresponding pump power. $\eta_{OO} = (\hat{P}_{out} - \hat{P}_{in})/\hat{P}_p$, where $\hat{P}_{in}$ and $\hat{P}_{out}$ are the input and output signal power respectively. It shows that the EDFA OO efficiency has a strong dependence on EDFA output power and a relatively weak dependence on span loss. The pump power data is used in the calculations of η_{EO} and η_1.

The overall repeater E/O efficiency can be calculated by combining the electrical circuit model, pump laser measurement data and EDFA simulation results, using the following procedure. Consider a submarine system with given channel power, span loss, total WDM channels and number

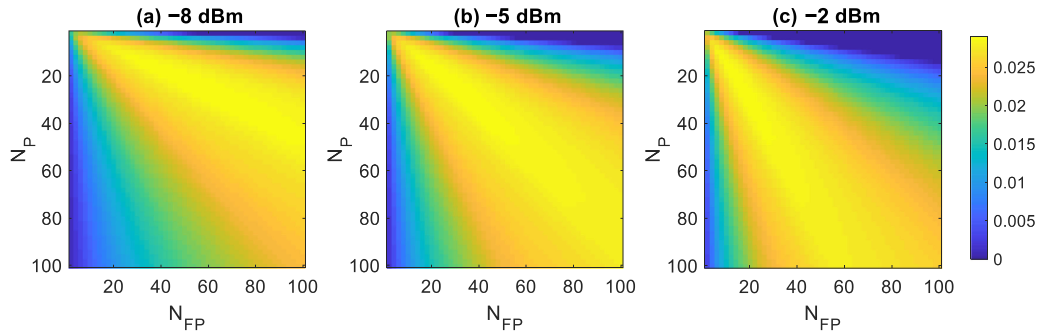

Fig. 6. Repeater E/O conversion efficiency for different channel launch power (a) −8 dBm, (b) −5 dBm and (c) −2 dBm.

TABLE 2
Transmission System Parameter

Parameter	Value	Parameter	Value	Parameter	Value
Distance	10,000 km	Fiber attenuation	0.150 dB/km	Max power supply	15 kV
Span length	80 km	Dispersion	20.2 ps/nm/km	Cable resistance	1 Ω/km
symbol rate	69 Gbaud	Effective area	115 μm^2	GAWBS coefficient	-60 dB/km
WDM channels, N_{ch}	60	EDFA noise figure	4.5 dB		

of fiber pairs. We can calculate the EDFA output power and then map to EDFA OO efficiency and pump power values based on the data in Fig. 5. The total required pump power is the pump power per fiber multiplying the number of fibers. Then, the pump power per pump laser is calculated as the total required pump power divided by the number of pumps, considering the coupler network loss. Using the pump power, the electrical driver efficiency can be calculated. If the number of pumps is a varying design parameter, we can choose a N_P value to maximize repeater E/O efficiency. This procedure calculates the repeater E/O efficiency as well as the repeater power consumption. In some system designs with fixed maximum repeater power and varying number of fiber pairs, we can use the same procedure to calculate the repeater E/O efficiency and repeater power for a wide range of the number of fiber pairs N_{FP}. And then choose the maximum number of N_{FP} that is supported by the fixed maximum repeater power. Examples of this case are given in Section 4.

Fig. 6 shows the repeater E/O conversion efficiency as functions of the number of pumps N_P and the number of fiber pairs N_{FP} for different channel power, assuming 12 dB span loss and 60 WDM channels. It shows that there exists an optimal ratio of N_{FP} to N_P depending on channel power. The optimal ratio values are 2.3, 1.2 and 0.6 for −8 dBm, −5 dBm and −2 dBm channel power, respectively. This is consistent with the discussion of power efficiency η_1 of Fig. 4. The pump power should be kept in a certain range to obtain maximum repeater E/O efficiency. As a result, when the channel power increases, the total required pump power increases and therefore the number of pumps increases.

4. System Design Applications

In this section, we discuss two system design examples using the repeater E/O efficiency model. The first example has fixed distance and varying channel launch power. System parameters are given in Table 2. Following the procedure of Section 3, the repeater EO efficiency is calculated for each channel launch power, where the maximum number of fiber pairs N_{FP} is found under the 15 kV power supply limit. The number of pumps N_P is used as a varying design parameter to maximize repeater E/O efficiency. We assume that both the repeaters and cable account for half of the total electrical power consumption. After the number of fiber pairs is calculated, we estimate

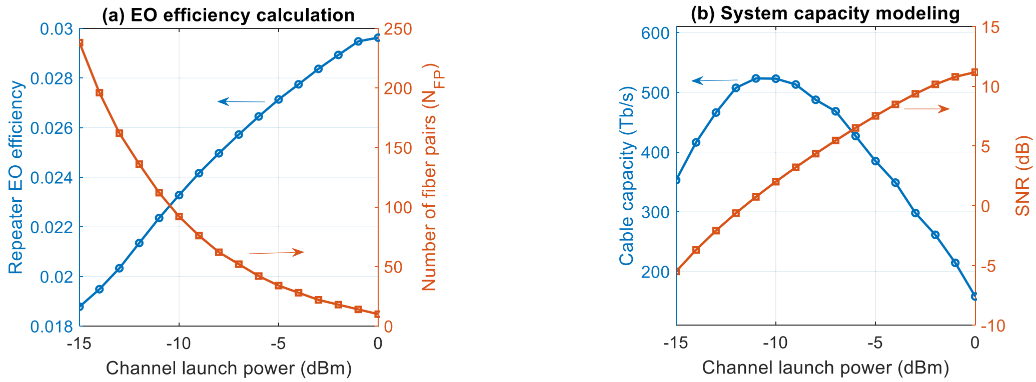

Fig. 7. Repeater electrical to optical conversion efficiency calculation and system capacity modeling results as functions of channel launch power.

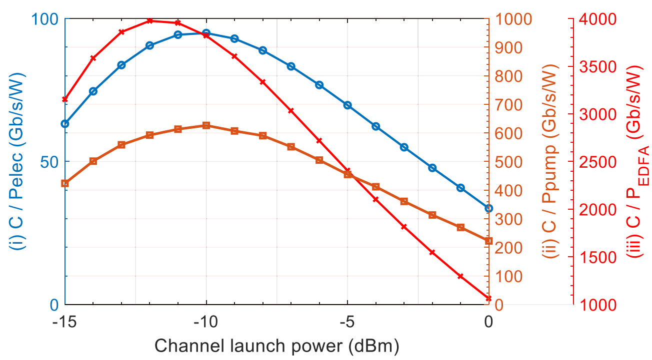

Fig. 8. Capacity per power versus channel launch power using three power metrics: (i) electrical power (blue circle), (ii) pump power (brown square), and (iii) EDFA output power (red cross).

cable capacity using a GN model that includes the generalized droop effect and GAWBS noise [18]–[23]. System modeling calculates link signal to noise ratio (SNR), which is used to calculate capacity as $C = N_{FP} \times N_{ch} \times 2 \times \text{symbol\_rate} \times \log_2(1 + SNR)$.

Fig. 7(a) shows that the repeater E/O efficiency increases with channel power, mainly due to the EDFA characteristics. As shown in Fig. 5, the EDFA OO efficiency increases with output power and hence channel launch power. The number of fiber pairs decreases with channel power due to fixed 15 kV power supply. The corresponding optimal values of the number of pumps N_P vary slightly from 28 to 25. Fig. 7(b) shows the cable capacity and link SNR versus channel power. The system power efficiency in terms of cable capacity per unit power is calculated using three different power metrics as shown in Fig. 8. The direct efficiency metric is the cable capacity per electrical power shown in a blue curve. As compared with the capacity per EDFA output power, the capacity per pump power has a more similar trend as the capacity per electrical power with the same optimal channel launch power at -10 dBm. This indicates that, in the absence of a repeater E/O efficiency model, capacity per pump power is a more accurate metric than capacity per EDFA power, consistent with the findings in [6]. Moreover, the optimal SNR values obtained using the capacity per electrical power and capacity per EDFA output power are 2.0 dB and -0.6 dB, respectively. These SNR values also agree quite well with published data in [6]. Although the capacity per pump power metric has similar trend and the same optimal SNR value as the direct capacity per electrical power metric, it shows different decreasing slope away from the optimal launch power. This may affect the analysis of cost per bit in searching of optimal launch power. Therefore, the repeater E/O efficiency model is valuable in submarine system design and cost per bit optimization.

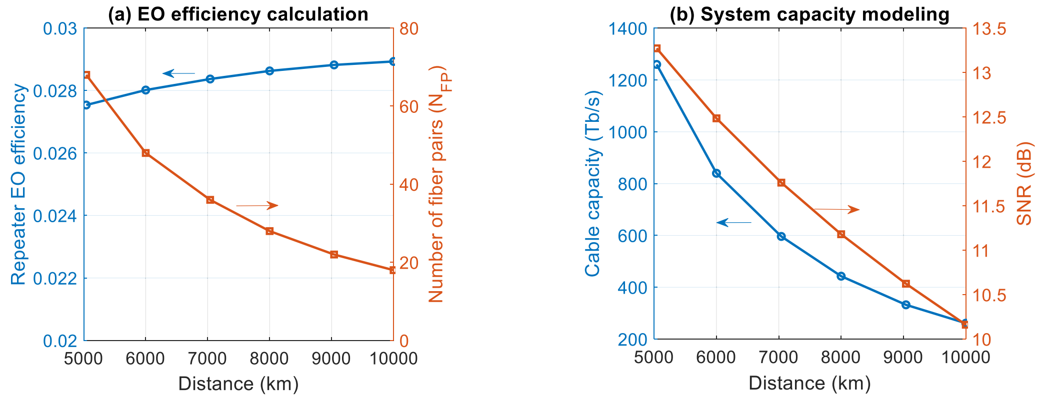

Fig. 9. Repeater electrical to optical conversion efficiency calculation and system capacity modeling results as functions of distance.

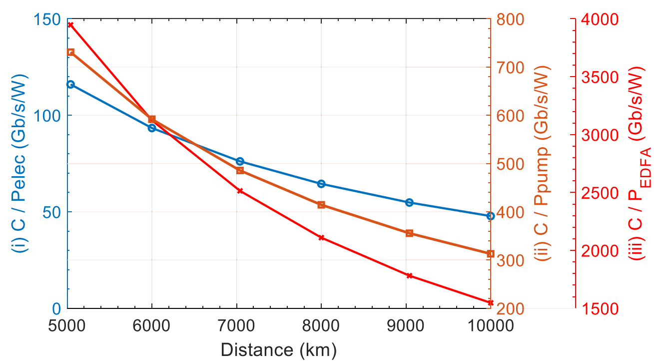

Fig. 10. Capacity per power versus distance using three different power metrics: (i) electrical power (blue circle), (ii) pump power (brown square), and (iii) EDFA output power (red cross).

The second system design example has fixed channel launch power and varying distance. All other parameters are the same as in Table 2. We choose −2 dBm channel power, which is 2.6 dB smaller than the nonlinear optimal channel power. Fig. 9 shows the repeater EO efficiency calculation and system capacity modeling results. The optimal values of the number of pumps N_P are {109, 76, 56, 43, 33, 28} when link distance increases from 5000 km to 10000 km. In contrast to the first example, the repeater EO efficiency only changes slightly with distance. Also, cable capacity per power are compared for the three different power metrics in Fig. 10. Significantly different slopes are observed for the three power metrics. However, as with the previous example and results in Fig. 8, the results in Fig. 10 also show better agreement of the pump power metric (than the EDFA output power metric) with the electrical power metric.

5. Conclusion

We have developed a model of repeater E/O efficiency for submarine systems with pump sharing, by analyzing the physical repeater structure including electrical circuits and optical components. Experimental measurement data of pump lasers and numerical simulation results of EDFA efficiency are used as input information to the model. The repeater E/O efficiency model facilitates submarine system design, such as accurate estimation of maximum number of fiber pairs under fixed electrical power supply. Using the repeater E/O efficiency model, we have analyzed a direct efficiency metric as cable capacity per electrical power for different system designs and compared them with two indirect metrics that are based on optical power. Submarine system design examples illustrated that E/O efficiency and system capacity are not necessarily optimized together, and that the pump power metric is more closely aligned with electrical power than the EDFA output power metric when estimating power efficiency. The repeater E/O efficiency is valuable for accurate cable capacity estimation and cost per bit optimization.

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