SUBMARINE CABLE CAPACITIES OF C+C AND C+L SYSTEMS

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Abstract: Recent research in submarine cable capacity within the constraint of electrical power feed limitations has shown that greater capacity can be realized through spatial division multiplexing (SDM) in which more fiber pairs carry channels with lower power and signal-to-noise ratio (SNR). This approach, sometimes called linear transmission, contrasts with traditional cable system designs in which channels are operated at or beyond the optimal nonlinear channel power in order to maximize individual channel SNR. Here we model the theoretical cable capacities achievable with C-band only (C+C) and C+L transmission systems with different optical fibers to understand the differences in capacity and the number of fiber pairs required to be accommodated in cable designs to attain the capacity levels predicted. We find that C+C systems provide higher maximum cable capacity than C+L systems by 35-40% or more for the same fiber type, when evaluated at the same SNR. Comparison of C+C transmission with fibers having standard G.652 effective area of ~82 μm^2 with C+L systems employing larger effective area fibers suggests that C+C transmission with the smaller effective area fibers can increase cable capacity by approximately 20-25%. This may be further increased by future attenuation reductions. The required number of fiber pairs depends on desired signal SNR, link length, and cable voltage, but 50 fiber pairs or more and linear transmission may be indicated in some cases where maximization of cable capacity is desired. However, if the goal is to maximize capacity per fiber, then nonlinear performance is important and large effective area fibers should be used.

1. INTRODUCTION

The topic of how to maximize the overall capacity of submarine cables within the constraints of limited electrical power delivery has recently become a subject of significant interest in the submarine systems community [1-7]. It has been shown that cable capacity can be increased significantly by lowering channel powers and thus channel SNR, and increasing spatial multiplicity in the cable [5,7]. Another recent study showed minimum cost/bit can be achieved with massive spatial division multiplexing [6]. Within the context of currently available single-mode and single-core optical fiber technology, increasing spatial multiplicity generally implies increasing the fiber pair count beyond the relatively small number of fiber pairs deployed in most cables to date (~8 fiber pairs or less). Another approach considered to enable greater cable capacity is to use wider fiber bandwidth such as C+L-band transmission instead of C-band only transmission, for the same number of fiber pairs.

In this work, we model and compare the maximum theoretical submarine cable capacity levels achievable using C-band only systems (C+C) and C+L systems. We follow the general approach of the analysis in [7] and estimate the maximum number of fiber pairs supported for the same electrical power constraint governed by the cable voltage supply design. We use the Gaussian noise (GN) formalism [8] to estimate channel signal-to-noise ratio (SNR), including detailed system losses for the two approaches to better estimate the relative maximum cable capacities supported. We find that the extra span losses incurred with C+L-band transmission systems limit their total capacity relative to C+C systems. We evaluate system lengths representing trans-Atlantic (6,600 km) and trans-Pacific (10,000 km), and compare the two system types in terms of capacity or complexity in several different ways. We find that as future systems trend toward higher spatial division multiplexing (SDM), i.e. fiber count, the advantages of C+C systems grow in terms of greater capacity and/or reduced complexity.

2. SYSTEM MODEL AND PARAMETERS

The maximum theoretical total cable capacity based on Shannon's theorem can be written as

$$C_{cable} = 2N_{FP}N_{ch}B_{sym}\log_2\left[1+SNR\left(\tilde{P}_{ch},L\right)\right] \quad (1)$$

where N_{FP} is the number of fiber pairs, N_{ch} is the number of channels in each fiber, B_{sym} is the symbol rate, and the channel SNR is a function of optical channel power $\tilde{P}_{ch}$, span length L, and the total link length. The SNR is calculated using the GN model, taking into account the "signal droop" effect [9] as well as impairments from spontaneous guided acoustic-wave Brillouin scattering (GAWBS) [10]. We assume a fixed cable DC voltage V_{PFE} from the power feed equipment, and optimal current flowing through the cable conductor to power the repeaters [1]. Within this framework, the number of fiber pairs supported by the fixed cable voltage depends on the optical channel power and several system parameters as

$$N_{fp} = floor\left[\frac{(1-\varepsilon)\eta V_{PFE}^2}{8N_{ch}\tilde{P}_{ch}N_{sp}\left(N_{sp}-1\right)LR_0}\right]. \quad (2)$$

In (2), η is the electrical-to-optical conversion efficiency in the optical amplifiers, ε is a fraction of electrical power consumed in the repeaters for control electronics and not converted into optical power, R_0 is cable conductor resistance, and N_{sp} is the number of spans in the link. Thus both N_{FP} and SNR depend on P_{ch}, with N_{FP} increasing and SNR decreasing with smaller channel powers. A theoretical maximum cable capacity occurs at low channel power with SNR ~2.4 dB [9]. This generally corresponds to larger fiber count and may be referred to as the SDM regime.

A schematic representation of one fiber pair in a submarine repeater is illustrated in Fig. 1 for C-band only (C+C) transmission. A separate optical amplifier amplifies the optical signals in each direction. For C+L system transmission, the repeater configuration is modified to provide separate amplification for the C and L bands, using a C/L bandsplitter to separate the bands before amplification, and then to combine them again after amplification, as shown in Fig. 2 for only one direction. Extra losses are associated with the C/L bandsplitters that must be considered when calculating the cable capacity. We have not considered other effects here such as Raman tilt in which C-band power is transferred to L-band channels and may be a significant challenge to manage in C+L systems to maintain equal capacity per wavelength.

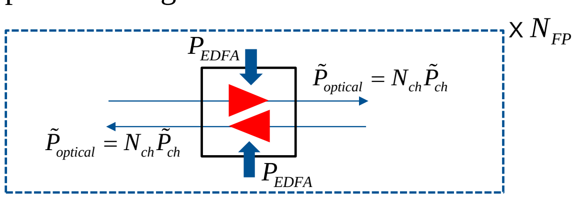


Fig. 1: C+C system repeater illustration.

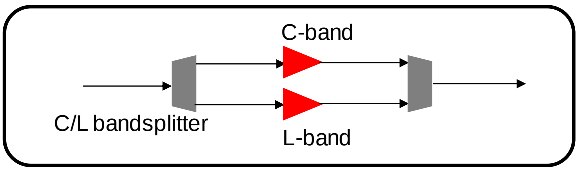


Fig. 2: Illustration of amplifier configuration in one direction for C+L system.

In this work, we consider two fiber types. The first fiber has ultra-low attenuation and very large effective area and is compliant with the G.654.D specification. This fiber type is currently widely deployed in submarine cables, and we consider it for both C+C and C+L systems. We also consider an ultra-low attenuation version of standard single-mode fiber, compliant with the G.652.B standard. This fiber type is evaluated only for C+C systems. The general fiber and system parameters used for the modelling and analysis here are given in Tables 1 and 2. The attenuation, effective area, and dispersion values given are assumed to be the average values across the C and L bands, respectively. We will refer to the two fiber types simply as G.654 and G.652 for the remainder of this work.

Parameter	**G.654.D C+L system (C/L)**	**G.654.D C+C system**	**G.652.B C+C system**
Attenuation (dB/km)	0.154/0.156	0.154	0.163
A_{eff} (μm^2)	150/154.5	150	82
Dispersion (ps/nm/km)	21/23.4	21	17
C/L bandsplitter loss (dB)	0.5/0.5		

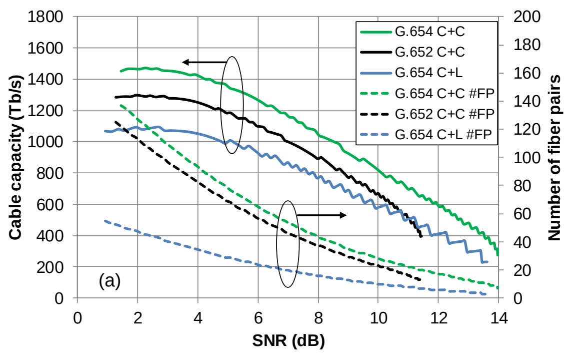
Table 1: Fiber parameters.

Parameter	**System value**
Link length (km)	6600, 10000
Symbol rate (Gbaud)	70
Number of channels per band	60
EDFA electrical-to-optical conversion efficiency η (%)	1.5
Control overhead ε (%)	10
Cable resistance R_0 (Ω/km)	1.0
PFE voltage (kV)	15
EDFA noise figure, C/L (dB)	5.0/5.5

Table 2: System parameters.

3. MODELING RESULTS

We first look at the modelling results predicted for total cable capacity and number of fiber pairs supported by the fixed cable voltage to produce that capacity, each as a function of SNR. The results for link lengths of 6,600 km and 10,000 km are shown in Fig. 3, each for a span length of 60 km. The data shows that for any given desired SNR value, the C+C system will provide greater cable capacity than the C+L system using the same fiber (G.654 as shown here). This is due primarily to the extra losses experienced in the C+L systems from the bandsplitters. We also observe that the G.652 C+C systems can offer greater cable capacity than the G.654 C+L systems, up to ~11 dB SNR for 6,600 km, and ~9 dB SNR for 10,000 km. Of course, the C+C systems achieve the higher capacity by enabling more than two times the number of fiber pairs at a given SNR value.



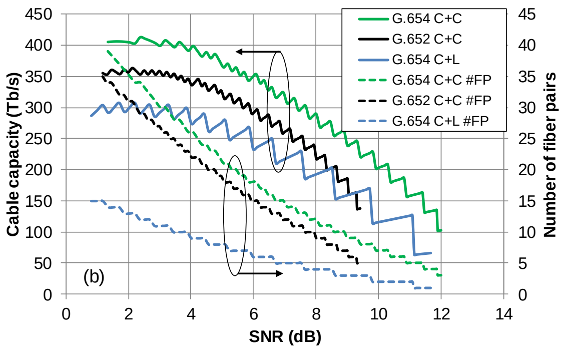


Fig. 3: Cable capacity and number of fiber pairs vs. SNR for a) 6,600 km system, and b) 10,000 km system.

We next evaluate the C+C and C+L systems on the basis of equal cable capacity in three different ways to understand relative system complexities in terms of transponder and component counts, and system requirements.

Case 1: Equal capacities, same span length, allow different SNRs.

To understand this comparison, we consider the model results for the 6,600 km system again, as shown in Fig. 4. In the figure, horizonal dash-dot lines are drawn in representing equal capacity levels. These correspond to G.654 C+L target SNR values of 3, 6, 8, and 10 dB. However, note that for these capacity levels, the SNR values for the C+C systems are higher, and therefore require fewer than 2x the fiber pairs of the C+L system. The relative number of fiber pairs required for the four capacity levels are shown in Fig. 5, along with the relative number of transponders and optical amplifiers.

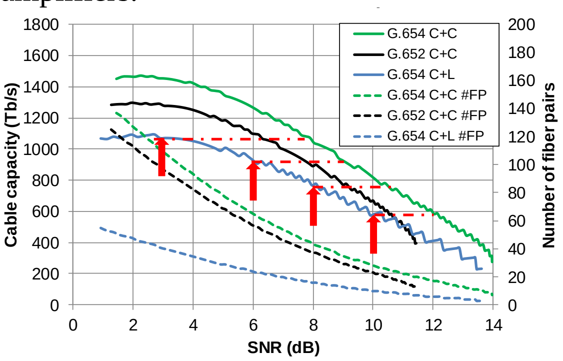


Fig. 4: Cable capacity and number of fiber pairs vs. SNR for 6,600 km system with four capacity levels illustrated.

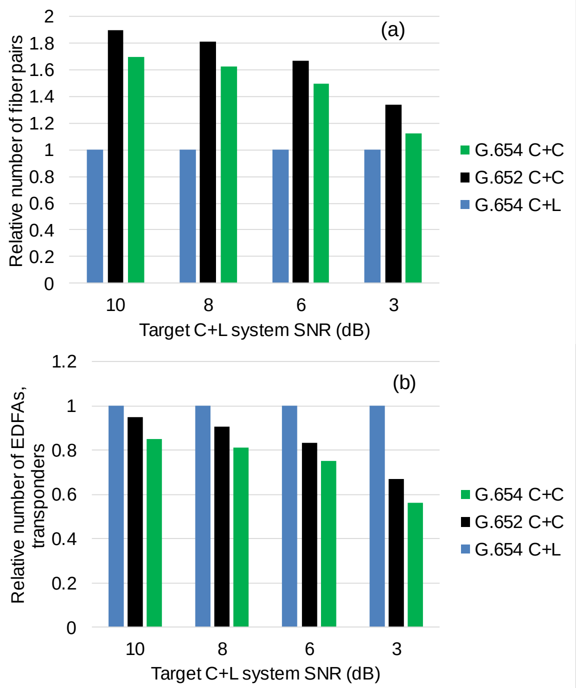


Fig. 5: 6,600 km link with 60 km spans. a) Relative number of fiber pairs required to achieve equal capacity. b) Relative number of transponders and EDFAs required.

The data in Fig. 5 shows that as systems are operated at lower SNR values (i.e. SDM systems), the relative number of fiber pairs for the G.654 C+C decreases until it is only about 12% more than the C+L system when the C+L system has target SNR of 3dB, or a cable capacity of almost 1100 Tb/s. This translates to the G.654 C+C system having 44% fewer transponders and EDFAs than the G.654 C+L system. For the G.652 C+C system, only 34% more fiber pairs (than G.654 C+L) are required for the same capacity, corresponding to 33% fewer transponders and EDFAs. The same trends hold for a 10,000 km link. In this case, for the C+L system target SNR of 3 dB, the G.654 C+C system with equal capacity has about 18% more fiber pairs, and 41% fewer transponders and EDFAs. The G.652 C+C system has 36% more fiber pairs and 32% fewer transponders and EDFAs.

Overall, it appears that C+C systems may be good candidates for a 1Pb/s cable in a trans-Atlantic length link.

Case 2: Equal capacities, same target SNR, different span lengths.

In the next case, we compare systems with equal capacities and target SNR values, but choose the maximum span lengths allowed for each system. The reference chosen for each target SNR is the G.654 C+L system with at least 60 km span length. That is, if a longer C+L span length provided the same capacity at the target SNR, we used it as the reference. An example is shown in Fig. 6 for a 6,600 km link with target SNR of 3 dB. The span length granularity was 5 km for this evaluation. In this case, one observes that the G.654 C+C and G.652 C+C systems with 85 km and 75 km span lengths, respectively, provide the same or greater capacity as the G.654 C+L system with 60 km span length.

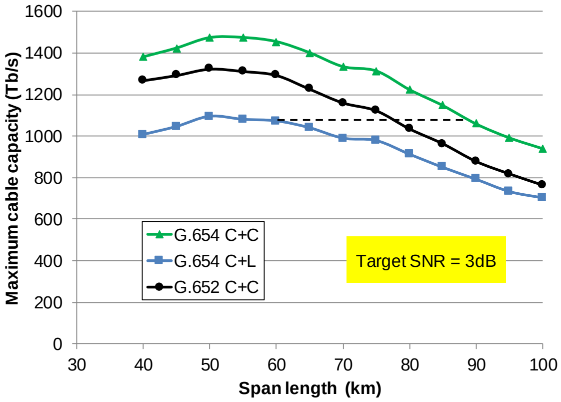


Fig. 6: Cable capacity as a function of span length for a target SNR value of 3 dB and a 6,600 km link.

Longer span lengths translate to fewer repeaters in the link, and thus likely lower cost. The relative number of repeaters needed by the three system types for 6,600 km and 10,000 km links are shown in Fig. 7 for different target SNR values. In all cases, the C+C systems required twice the number of fiber pairs as the C+L system since they provided the same capacity. For the 6,600 km link, both C+C systems require significantly fewer repeaters than the C+L system, with the G.654 C+C system having ~30% or more reduction. For the 10,000 km link, the G.654 C+C system provides the same capacity with up to 22% fewer repeaters. The G.652 C+C system only offers a reduction in the number of repeaters for smaller target SNR values of 3 and 6 dB, and actually requires more repeaters for higher SNR values in the 10,000 km link.

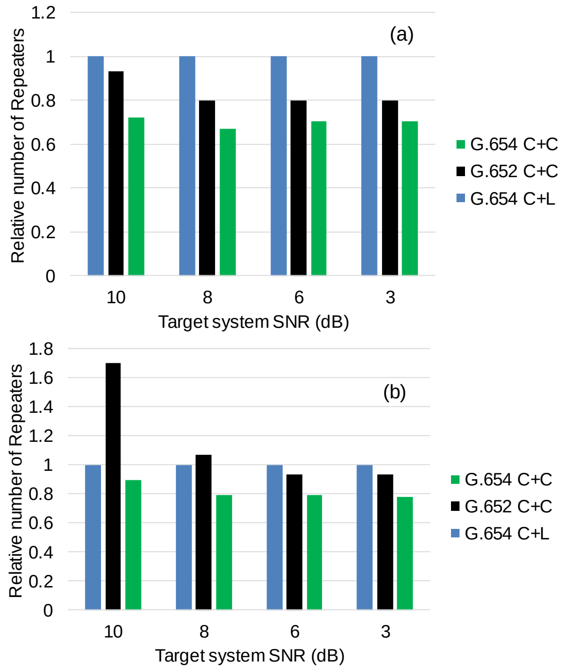
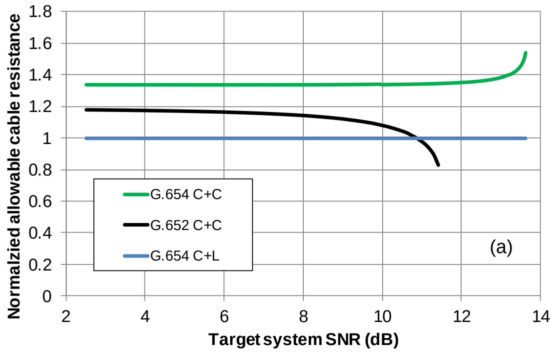


Fig. 7: Relative number of repeaters needed for equal capacity systems with same target SNR values for link lengths of a) 6,600 km and b) 10,000 km.

Case 3: Equal capacities, same target SNR, same span length, different cable resistance.

Another way to compare C+C and C+L systems on the basis of equal cable capacity is to evaluate the lower repeater powers required with the C+C systems. In this case, we use the capacity of the G.654 C+L system as the reference for a given target SNR value. This defines the required C+L repeater electrical power consumption for the SNR value. We then define the G.654 C+C and G.652 C+C systems to have the same cable capacity by using twice as many fiber pairs and the same channel SNR. For the target SNR, we find the required amplifier output powers, and thus the required repeater electrical powers to produce the same overall cable capacity as the C+L system using the GN model. Because of the extra losses in the C+L system mainly from the C/L bandsplitters, the C+C systems generally will have lower repeater electrical power consumption. Finally, we represent the differences in repeater powers by converting to allowable conductor resistance for the same total power consumption using Eq. 2 since this is a value that can be controlled in system design. The cable voltage is kept fixed at 15 kV for all systems. The results of this means of comparison are shown in Fig. 8 for both link lengths, each evaluated for 60 km spans.



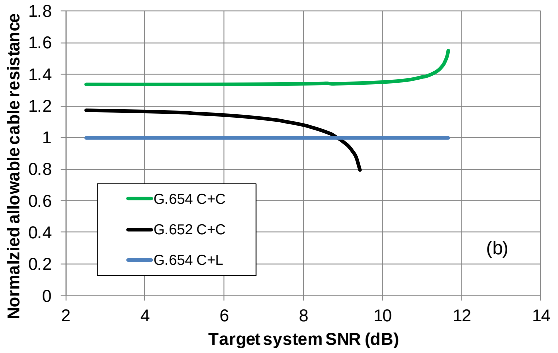


Fig. 8: Relative allowable cable conductor resistance for equal capacity systems with same target SNR values for link lengths of a) 6,600 km and b) 10,000 km. The span length for all systems is 60 km.

The results in Fig. 8 show that, compared to G.654 C+L systems, C+C systems built with the same G.654 fiber having the same total cable capacity enable the use of a cable conductor with at least 34% higher resistance for any target SNR value. The ability to use a higher resistance conductor to achieve the same capacity can reduce cable cost by use of less expensive conductor materials or reduced mass of the conductor. The tolerance in relative resistance allowance grows for very large SNR values. Even G.652 C+C systems enable a 17-18% increase in cable resistance relative to the C+L systems for high capacities (low SNR), but this increase diminishes with higher SNR and eventually disappears.

Case 4: Systems using maximum number of fiber pairs accommodated in cable design. Finally, we look at one more approach where the objective is to simply maximize the total cable capacity by using as many fiber pairs as can be physically accommodated in a cable design. Of course, this means operating the channels at lower SNRs in order to work within the fixed cable voltage. We expect that the number of fiber pairs will grow in time as cable designs evolve, so we look here at a range of values for the maximum number of fiber pairs from 20 to 50. The comparison then entails going back to the data shown in Fig. 3 and evaluating the capacity of each system for each value of maximum number of fiber pairs. Note that those will occur at different channel SNR values for each system. The results are given in Fig. 9 for both the 6,600 km and 10,000 km links.

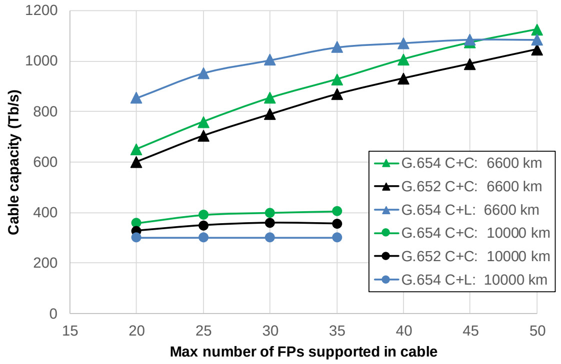


Fig. 9: Theoretical cable capacity as a function of maximum number of fiber pairs built in cable.

The results in Fig. 9 illustrate that for a trans-Atlantic link of 6,600 km, C+L systems built to use the maximum number of fiber pairs can offer a capacity advantage over similar C+C systems, at least up to approximately 45 fiber pairs. The C+L capacity advantage is about 30% for 20 fiber pairs compared to the C+C system using the same G.654 fiber, and decreases as the number of fiber pairs increases. However, one must note that the relatively small C+L capacity advantage comes at the price of a system with twice as many EDFAs and transponders as the corresponding C+C system.

On the other hand, the longer trans-Pacific 10,000 km link capacity offered by the G.654 C+L system is always smaller than the C+C systems using either the G.652 or G.654 fibers. This is because the maximum number of fiber pairs required by the C+L system is approximately 12 for a cable voltage of 15 kV, so cables that accommodate more fiber pairs do not offer greater capacity for a C+L system. For the G.654 C+C system, the maximum number of fiber pairs needed to maximize capacity is about 30-35, and it is about 25-30 for the G.652 C+C system.

4. CONCLUSIONS

We have examined theoretical submarine cable capacities of C+C and C+L transmission systems in the context of fixed cable voltage or electrical power supply. The C+L system was evaluated for a G.654 optical fiber with ultra-low loss and very large effective area, and the C+C systems were evaluated for the same G.654 fiber and for an ultra-low loss G.652 fiber with smaller effective area. We found that for the same target SNR value, the C+C systems offer a cable capacity advantage over the C+L system due to the extra losses in the C+L system. This capacity advantage is about 35% for the G.654 C+C system and ~20% for the G.652 system. We then looked at several different ways to compare the systems when evaluated for the same cable capacity. In case 1, we found that for equal span lengths, the C+C systems provided greater SNR values such that the C+C systems did not require twice as many fiber pairs to produce the same capacity, and that the relative number of fiber pairs needed by the C+C systems decreased with target SNR (and increasing cable capacity). This leads to significant savings in EDFAs and transponders for the C+C systems. In case 2, we demonstrated that another means of comparison with equal cable capacity allowed longer span lengths for the C+C systems and thus fewer repeaters in the cable for the same target SNR. The third case showed that higher allowable cable resistance values (and thus lower cable cost) could be used in C+C cables that had equal capacities to C+L cables due to the lower electrical power requirements. Finally, in the last case, we evaluated cable capacities when deploying the maximum number of fiber pairs that could be physically accommodated in a cable design. This comparison showed that 6,600 km C+L systems could provide larger capacity by ~30% or less, depending on maximum number of fiber pairs, but this required twice as many EDFAs and transponders. For 10,000 km systems, the C+C systems enabled higher cable capacity for larger numbers of fiber pairs, given a fixed 15 kV voltage.

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