Estimating the Techno-Economic Value of Hollow Core Fiber in Submarine Cables

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Abstract *We study the techno-economics of hollow core fibers (HCF) for submarine cable applications. The potential value of HCF is given in terms of maximum allowable fiber cost multiple relative to solid core fiber resulting in system cost/bit parity for different system and HCF characteristics.*

Introduction

Recent progress demonstrated in hollow core fiber in terms of attenuation reduction has generated significant interest in this technology as a future fiber for a wide number of applications [1-5]. In particular, HCF based on nested anti-resonant fiber (NANF) designs have shown great promise and recently demonstrated attenuation at 1550 nm on par with solid core fibers for the first time [4]. In addition to the potential for even further attenuation reduction to levels below silica fibers, HCF has other attributes that could offer significant benefits to long-haul transmission such as extremely high nonlinear tolerance, low chromatic dispersion, and potentially wider optical bandwidth [6]. All of these characteristics make HCF potentially attractive for future long-haul [7-9] and submarine cable deployments to enable greater capacity [10,11].

On the other hand, there are still many challenges facing HCF. Some of these include the existence of inter-modal interference (IMI) stemming from the existence and propagation of higher order modes, possibly higher splice losses and shorter distances between splices (spool length), and likely larger fiber outside diameter than silica core fibers. Another large unknown at this point is the cost of manufacturing HCF as large-scale production has not happened yet.

In this work, we seek to estimate the potential value of HCF in submarine cables as compared to silica core fiber (SCF). This is put in the context of the maximum allowable cost multiple relative to a SCF that produces cost/bit parity or reduction for HCF cables. A similar approach was applied recently in a cost sensitivity study of multicore fibers (MCF) in submarine cables [12]. In this context, the estimated cost multiples can be viewed as targets that HCF should meet for cables to at least maintain cost/bit parity even as larger cable capacities are enabled. The cost multiples estimated should not be interpreted as values that are achievable in practice.

System Parameters and Modeling Approach

Some general system parameters assumed for the study are given in Table 1. We considered a 7000 km trans-oceanic link length. The cable voltage was fixed at 18 kV and a low cable resistance value was considered to maximize electrical power availability. The SCF considered had attenuation of 0.148 dB/km and 125 μm^2 effective area. The baud rate and channel spacing were 100 Gbaud and 100 GHz. For the SCF, two optical bandwidths were considered of 5 THz (C-band) and 10 THz (C+L). For the HCF, we also considered wider bandwidths of 15 and 20 THz, assumed to extend down into the S-band. A range of electrical-to-optical (E-O) conversion efficiency values in the repeaters was evaluated from 2-5% for C-band EDFAs. L-band and S-band amplifiers were assumed to have reduced E-O efficiencies by about 40% relative to the C-band [13,14].

Table 1: General system parameters

Parameter	Value
Link length L (km)	7000
Cable voltage (kV)	18
Cable resistance (Ω/km)	0.5
Silica core fiber (SCF): Attenuation (dB/km) Effective area (μm^2)	 0.148 125
Symbol rate B (Gbaud)	100
Channel spacing (GHz)	100
Optical bandwidths (THz)	5 (C), 10 (C+L), 15, 20
E-O eff. in C-band (%)	2-5
Amplifier noise figure (NF) (dB)	5.0 (C-band) 5.5 (L-band) 6.0 (beyond C, L)

Three general cases are studied regarding HCF characteristics. These are described in Table 2. Case 1 was meant to represent characteristics close to, or slightly better than, HCF optical performance and system parameters demonstrated to date [4,15]. Case 2 is more forward-looking, mostly in terms of HCF attenuation and fiber outer diameter, and Case 3 represents near ideal attenuation, splice loss, and splice length characteristics. Case 2 is split into Cases 2a and 2b for two different HCF attenuation values of 0.10 and 0.05 dB/km, respectively. The maximum number of fiber pairs (FPs) able to be accommodated in current cable designs was based on the assumed fiber outside diameter. For Case 1, we assumed a larger HCF diameter of about 290 μm while for Cases 2 and 3 we assumed HCF diameters of 250 μm. For the SCF, we assumed a 200 μm diameter [16,17]. We assume a maximum FP number of 24 for a standard 250 μm diameter [18,19], and 18 and 36 FPs for 190 μm and 200 μm diameter fibers, respectively, by scaling to the same total fiber cross-section area. The nonlinear coefficient of HCF was about three orders of magnitude lower than that of the SCF [8-10] and nonlinearity for HCF was not a factor in these studies.

Table 2: HCF cases studied

	Case 1	**Case 2a, 2b**	**Case 3**
HCF atten. (dB/km)	0.15	0.10, 0.05	0.02
HCF-HCF splice loss (dB)	0.08	0.08	0.02
HCF-standard fiber splice loss (dB)	0.3	0.2	0.2
Distance between splices (km)	4	8	20
IMI (dB/km)	-56	-60	NA
Outside diameter (μm)/max #FPs	290/18	250/24	250/24
Max amplifier output power in 5 THz band (dBm)	27	27	27
SNR_m/gap-to-Shannon (dB)	20/3	25/2	25/2

The general system design approach used was to design each system for the minimum cost/bit subject to the maximum fiber pair number constraint [12,13,20]. This was accomplished by searching over span length and amplifier output power (and thus also number of fiber pairs) and choosing the system solution with the minimum cost/bit (cable capacity divided by total wet plant cost). We used estimates of the wet plant costs for fiber, cable, repeaters, and marine deployment in a similar manner to previous studies comparing SCF and MCF systems [12,13,20]. The channel generalized signal-to-noise ratio (GSNR) was calculated using the Gaussian Noise (GN) [21] and generalized signal droop models [22,23]. Attenuation and GSNR were assumed constant across all wavelengths, and cable capacity was calculated as

$$C_{cable} = 2BN_{fp}N_{ch}\log_2\left(1+\frac{GSNR}{\Gamma\cdot\left(1+\frac{GSNR}{SNR_m}\right)}\right) \quad (1)$$

where B is the symbol rate, Γ is the gap-to-Shannon, N_{fp} is number of fiber pairs, N_{ch} is number of channels, and SNR_m is the transponder SNR.

To determine an estimate for the potential value of HCF in the submarine system, we first assumed that the HCF cost/km was the same as the silica core fiber. We found the minimum cost/bit solutions for both fiber types for a given E-O efficiency value, and the corresponding cable capacities and number of fiber pairs. We then converted the difference in cost/bit between the fiber systems into an additional fiber value (in terms of cost/km) for HCF (assuming the HCF cost/bit was smaller than that of the SCF) as

$$HCF_{\text{cost,add}} = \frac{\left(\rho SCF_{\text{cost/bit}} - HCF_{\text{cost/bit}}\right)\cdot HCF_{capacity}}{2N_{fp,HCF}L} \quad (2)$$

where ρ is the desired fraction of the silica core fiber system cost/bit (e.g. ρ = 1 for parity, ρ = .85 for 15% cost/bit reduction). The allowable HCF cost multiple was then found as

$$\frac{HCF_{\text{cost/km}}}{SCF_{\text{cost/km}}} = \frac{\left(HCF_{\text{cost,add}} + SCF_{\text{cost/km}}\right)}{SCF_{\text{cost/km}}}. \quad (3)$$

Modeling Results

We first considered Case 1 for HCF which most closely corresponds to currently demonstrated fiber and system parameters. For this case, we did not find higher cable capacity using HCF than the SCF for any optical bandwidth considered using the minimum cost/bit criterion due to greater impairments (loss, IMI) and smaller number of FP. The HCF cost/bit was not lower than that of SCF assuming equal fiber cost, so HCF extra value does not apply in this case.

Case 2a: The results for this case are shown in Fig. 1 for the cable capacity (average of 4% and 5% E-O eff.) and estimated maximum HCF cost multiple. While C and C+L produce comparable cable capacities for SCF and HCF, the cable capacities for HCF with 15 and 20 THz bandwidth exceed that of SCF C+L. There is potential HCF value for all bandwidths due to the smaller number of fiber pairs deployed and a longer optimal span length (~130-140 km in this case). The 15 and 20 THz results cost multiple results for HCF were obtained by comparison to SCF C+L data. The error bars represent the range of E-O efficiency studied. The optimal SCF span length was about 90-100 km in most cases.

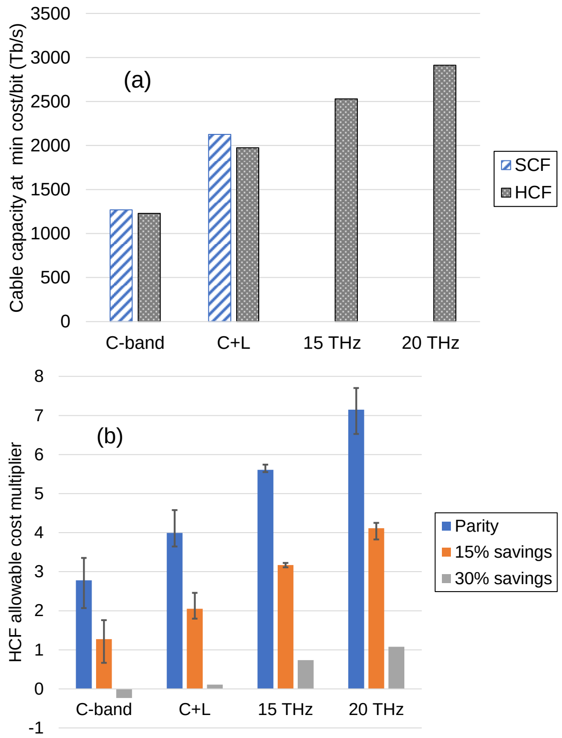
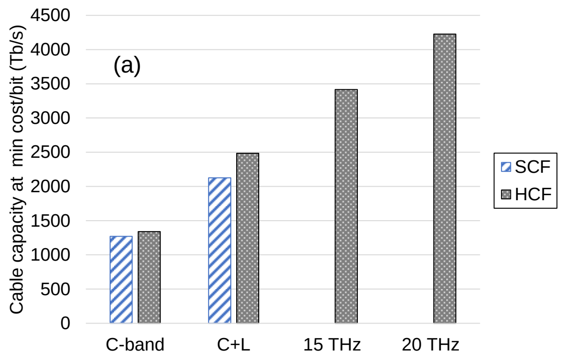


Fig. 1: Case 2a. a) Cable capacity values for minimum cost/bit systems, b) maximum HCF cost multiple.

Case 2b: The only difference for this case compared to Case 2a is the HCF attenuation, assumed to be 0.05 dB/km here. Results are shown in Fig. 2. Larger cable capacities are enabled with HCF and larger HCF cost multiples are estimated compared to 2a, ranging up to about 9x for C+L and 18x for 20 THz bandwidth. The optimal HCF span length was ~250 km.

Case 3: This last case assumed essentially ideal conditions for the HCF in terms of attenuation, splices, and elimination of IMI. Results in Fig. 3 suggest that such conditions would increase the maximum HCF cost multiple up as high as ~35-40x for 20 THz bandwidth and cable capacities about three times that of SCF C+L. The optimal HCF span length was ~700 km for this case. The high cost multiples suggested result from 7-8x fewer repeaters and fewer FPs.



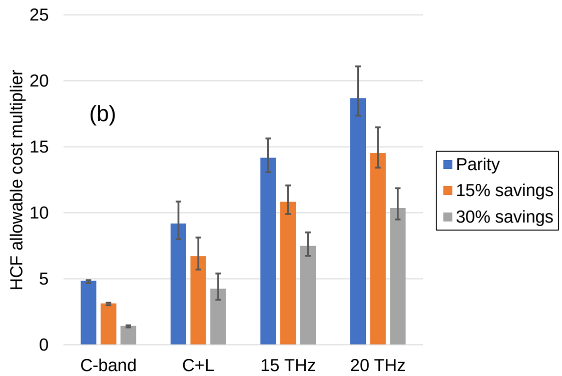


Fig. 2: Case 2b. a) Cable capacity values for minimum cost/bit systems, b) maximum HCF cost multiple.

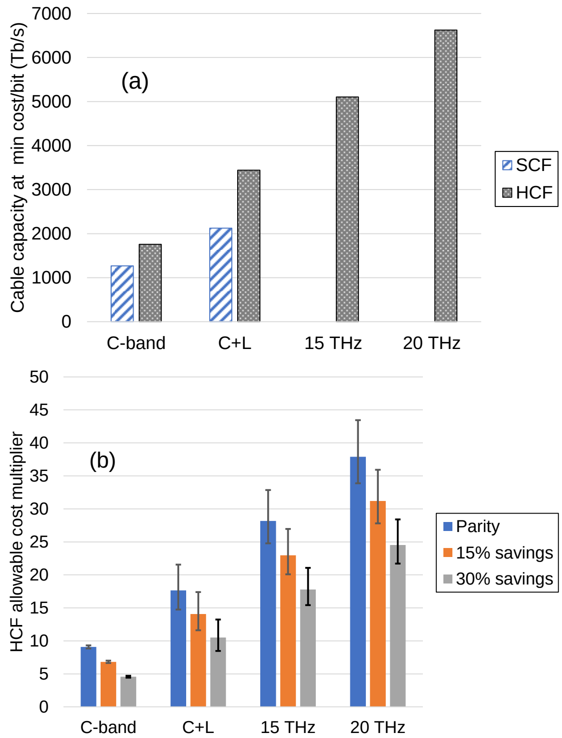


Fig. 3: Case 3. a) Cable capacity values for minimum cost/bit systems, b) maximum HCF cost multiple.

Summary and Conclusions

We have used an established cost/bit model to assess the potential future value of HCF in submarine cables for the first time. We evaluated several different cases and estimated the value in terms of the maximum allowable cost multiple of HCF to commercial SCF that produces cost/bit parity or reduction by enabling larger cable capacity and/or longer span lengths. Potentially larger optical bandwidths in HCF enhance the value. For the FP number constraints employed, we found the HCF attenuation may need to approach 0.10 or lower to produce significant value. Maximum allowable HCF cost multiples for the widest (20 THz) bandwidth were about 7x, 18x, and 37x for attenuations of 0.10, 0.05, and 0.02 dB/km, respectively.

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