Towards Zero-Crosstalk-Margin Operation of Spectrally-Spatially Flexible Optical Networks Using Heterogeneous Multicore Fibers

Anuj Agrawal†, Vimal Bhatia†, Shashi Prakash§
†Discipline of Electrical Engineering, Indian Institute of Technology (IIT) Indore, 453552 India
§Photonics Laboratory, Institute of Engineering and Technology, Devi Ahilya University, Indore, 452017 India
{phd1501202003, vbhatia}@iiti.ac.in, sprakash@ietdavv.edu.in

Abstract:
In spectrally-spatially flexible optical network (SS-FON), crosstalk (XT)-margin overprovisioning is unavoidable due to transmission reach granularity of modulation schemes. We show that heterogeneous multicore fibers of specific core designs can achieve zero-XT-margin. We also propose a core-type selection method to minimize XT-margin in SS-FONs.

OCIS codes: (060.4251) Networks, assignment and routing algorithms, (060.4265) Networks, wavelength routing.

1. Introduction

Spectrally-spatially flexible optical network (SS-FON) equipped with multicore fibers (MCFs) is a promising solution to meet the increasing bandwidth requirements [1,2]. Homogeneous (Hom)-MCFs (where all the cores have ideally the same physical design properties) have been widely researched in the recent years considering single-fiber-link transmission as well as multi-link transmission in mesh optical networks. However, heterogeneous (Het)-MCFs (where cores are designed with different physical properties) have shown promise for designing high-density, low intercore-crosstalk (XT), and bend-insensitive optical fibers [3,4]. In Het-MCFs, different XT-levels can be achieved by varying the core design properties in the correlation length (d)-dominant or bend-insensitive region [3,4].

Unallocated (U)-margins are unavoidable in optical networks due to the reach granularity of different modulation schemes (MSs) [5]. U-margins should be reduced to minimum possible levels to improve the network efficiency and cost. In SS-FONs, lightpaths are allocated while ensuring that the XT-levels do not exceed the maximum allowable or threshold XT (XT_{th}). Let XT_{μ} be the mean-XT of a lightpath. Due to the transmission reach or XT_{th} granularity of different MSs, lightpaths need to be allocated with lower XT-levels than XT_{th} [2] (i.e., $XT_{\mu} \leq XT_{th}$), which results in high U-margins for XT (hereafter referred as XT-margin (XT_{mar}), defined as $XT_{mar} = XT_{th} - XT_{\mu}, XT_{\mu} \leq XT_{th}$).

In this work, we show the advantages of Het-MCF design from the networking perspective towards zero-XT_{mar} operation of SS-FONs. We show that given a network topology and modulation scheme (MS), Het-MCFs can be designed to achieve zero-XT_{mar} operation of SS-FONs. We study several theoretical Het-MCFs designs, and analyze their effect on XT_{mar} of SS-FONs.

2. Proposed Method: XT-margin Minimization using Heterogeneous MCFs

Using the analytical model [1,2] based on coupled-power theory, XT_{μ} in a core of MCF is estimated as

$$XT_{\mu} = \frac{K - K\exp(-(K+1)hL)}{1 + K\exp(-(K+1)hL)}, \tag{1}$$

where, K is the number of adjacent cores, L is the fiber length, and h is a design parameter which represents the increase in XT per unit fiber length. In Het-MCFs, each core-type has different values of h depending on the core design parameters. Since Het-MCF designs may be trench-assisted or without-trench, the value of K and its effect on XT_{μ} may vary. Thus, we do not consider the effect of MCF design-types in this work, and focus on the advantages of having different types of cores (i.e., cores with different values of h), assuming a constant $K = 6$ (a typical value of K in a high-density hexagonal core-arrangement MCF [1]).

In d-dominant region, $h = 2\kappa^2/\Delta\beta^2 d$, where, κ is the coupling-coefficient, $\Delta\beta$ is the difference of propagation constants, and d is the correlation length. In [3,4], it is demonstrated that cores with different values of h can be obtained by varying the design parameters. Eq. (1) can be rewritten as

$$h = \frac{1}{(K+1)L} \ln \frac{K(1+XT_{\mu})}{K - XT_{\mu}}. \tag{2}$$

From Eq. (2), given the fiber length L (i.e., distance between origin o and target t nodes in a network) and the value of XT_{μ}, h can be obtained (assuming a constant K). As mentioned in [2] (including a margin of 7.69 dB), $XT_{th} = -21.7$ dB, $XT_{th} = -26.2$ dB, $XT_{th} = -28.7$ dB, and $XT_{th} = -32.7$ dB for BPSK, QPSK, 8-QAM, and 16-QAM, which corresponds to $XT_{th} = 0.0068$, $XT_{th} = 0.0024$, $XT_{th} = 0.00135$, and $XT_{th} = 0.000537$, respectively, in linear scale.

To establish a lightpath with zero-XT_{mar}, XT_{μ} should be equal to the XT_{th} corresponding to the MS chosen. Substituting XT_{μ} by XT_{th} in Eq. (2), the value of h required for zero-XT_{mar} (h_{zm}) lightpath establishment can be obtained as

$$h_{zm} = \frac{1}{(K+1)L} \ln \frac{K(1+XT_{th})}{K-XT_{th}}. \quad (3)$$

Thus, Het-MCFs with different values of h_{zm} can be designed to achieve zero-XT_{mar} operation of SS-FONs. Consider an example network of four nodes shown in Fig. 1(a). Assuming lightpath establishment using the shortest path, the fiber lengths (in km) for all possible node pairs in Fig. 1(a), namely, A-B, A-C, A-D, B-C, B-D, and C-D will be 100, 100, 140, 200, 100, and 100, respectively. Thus, there are three unique reach values required (100, 140, 200) for this network to establish lightpath between any of the nodes. On substituting $L = 100$ km, $L = 140$ km, and $L = 200$ km in Eq. (3) (and $XT_{th} = 0.00135$ corresponding to 8-QAM, which offers maximum reach of 223 km for $K = 6$ [2]), we get $h_{zm} = 2.25 \times 10^{-9} = h_a$, $h_{zm} = 1.606 \times 10^{-9} = h_b$, and $h_{zm} = 1.12 \times 10^{-9} = h_c$, respectively. Hence, for the example network shown in Fig. 1(a), if Het-MCFs having three different types of cores with the above obtained values of h_{zm} are used on all the links, zero-XT_{mar} operation can be achieved by establishing A-D lightpath through a core with h_b, B-C through a core with h_c, and the lightpaths between remaining node pairs through a core with h_a.

However, in real networks, the number of unique reach values required for different $o-t$ pairs is large. Hence, designing a MCF with various different core-types may not be possible. Moreover, in real network operations, alternate paths other than the shortest path can be used as well as core-switching can be done at intermediate nodes equipped with fully non-blocking reconfigurable add/drop multiplexers (FNB-ROADMs). XT_{mar} can also be reduced using precise-XT method [2], however, it is not preferable due to the dynamic and time-consuming XT-calculations involved.

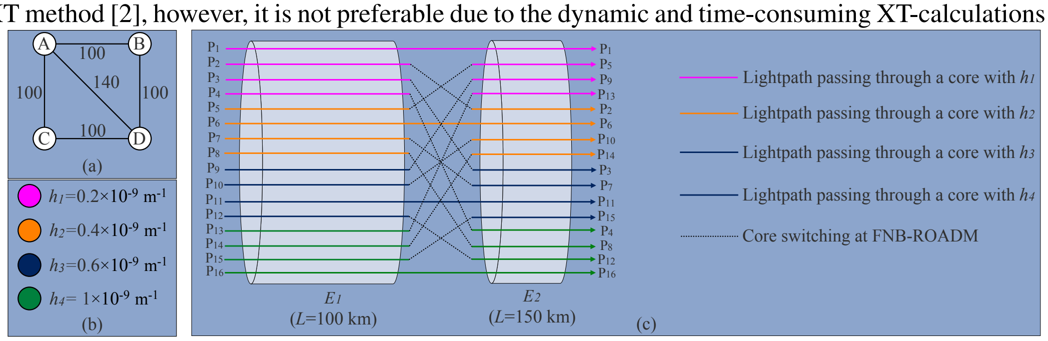


Fig. 1: (a) Example network (b) Four core-types considered in a Het-MCF (c) Possible paths for a 2-hop lightpath passing through E_1 and E_2 links of 100 and 150 km

Though it may not be possible to fabricate a Het-MCF with a large number of core-types, we show that SS-FONs equipped with Het-MCFs can achieve lower XT_{mar} than that with the Hom-MCFs, using the proposed Minimum-XT-margin (Min-XT_{mar}) offline core-type selection method described as follows. Consider a 2-hop lightpath request that passes through two fiber links equipped with Het-MCF having four different core-types as shown in Fig. 1(b). The possible combinations of core-type selection to establish lightpath using FNB-ROADM between two Het-MCF links are shown in Fig. 1(c). We calculate XT_{μ} for each path in Table 1 using Eq. (1), and the most efficeint MS is selected, ensuring $XT_{\mu} \leq XT_{th}$.

Table 1: XT_{mar} calculation of all possible paths for a 2-hop lightpath request shown in Fig. 1(c)

Path	$XT_{\mu}(E_1)$	$XT_{\mu}(E_2)$	$XT_{\mu}(P_1)$	MS	XT_{th}	$XT_{mar} = XT_{th} - XT_{\mu}(P_1)$
P_1 $[E_1 h_1 - E_2 h_1]$	0.00012	0.00018	0.0003	16-QAM	0.000537	0.000237
P_2 $[E_1 h_1 - E_2 h_2]$	0.00012	0.00036	0.00048	**16-QAM**	0.000537	**0.000057**
P_3 $[E_1 h_1 - E_2 h_3]$	0.00012	0.00054	0.00066	8-QAM	0.00135	0.00069
P_4 $[E_1 h_1 - E_2 h_4]$	0.00012	0.0009	0.00102	8-QAM	0.00135	0.00033
P_5 $[E_1 h_2 - E_2 h_1]$	0.00024	0.00018	0.00042	16-QAM	0.000537	0.000117
P_6 $[E_1 h_2 - E_2 h_2]$	0.00024	0.00036	0.0006	8-QAM	0.00135	0.00075
P_7 $[E_1 h_2 - E_2 h_3]$	0.00024	0.00054	0.00078	8-QAM	0.00135	0.00057
P_8 $[E_1 h_2 - E_2 h_4]$	0.00024	0.0009	0.00114	8-QAM	0.00135	0.00021
P_9 $[E_1 h_3 - E_2 h_1]$	0.00036	0.00018	0.00054	8-QAM	0.00135	0.00081
P_{10} $[E_1 h_3 - E_2 h_2]$	0.00036	0.00036	0.00072	8-QAM	0.00135	0.00063
P_{11} $[E_1 h_3 - E_2 h_3]$	0.00036	0.00054	0.0009	8-QAM	0.00135	0.00045
P_{12} $[E_1 h_3 - E_2 h_4]$	0.00036	0.0009	0.00126	**8-QAM**	0.00135	**0.00009**
P_{13} $[E_1 h_4 - E_2 h_1]$	0.0006	0.00018	0.00078	8-QAM	0.00135	0.00057
P_{14} $[E_1 h_4 - E_2 h_2]$	0.0006	0.00036	0.00096	8-QAM	0.00135	0.00039
P_{15} $[E_1 h_4 - E_2 h_3]$	0.0006	0.00054	0.00114	8-QAM	0.00135	0.00021
P_{16} $[E_1 h_4 - E_2 h_4]$	0.0006	0.0009	0.0015	QPSK	0.0024	0.0009

From Table 1, we observe that each path (including different core-types) offers different XT_{mar}, where path P_2 offers minimum XT_{mar} corresponding to 16-QAM, and P_{12} offers minimum XT_{mar} corresponding to 8-QAM. It should be noted that ideally the most efficient MS (i.e., 16-QAM among the four considered MSs) is chosen, however, if the spectrum of all the cores with h_1 and h_2 is occupied at a certain stage of network, lightpath establishment is attempted via h_3 and h_4 using 8-QAM. Thus, the XT_{mar} calculation using all the path combinations is useful. From Table 1, it can be observed that if Hom-MCF is used on E_1 and E_2 with either h_1, h_2, h_3, or h_4 (i.e., paths P_1, P_6, P_{11}, and P_{16}, respectively), the XT_{mar} values are higher than that possible using Het-MCF.

In the proposed Min-XT_{mar} method for core-type selection, we perform following three steps: 1. Obtain all possible paths for each $o-t$ pair in the network, 2. Calculate XT_{mar} for each path as obtained in Table 1, 3. Prioritize the obtained paths on the basis of most efficient MS first, and amongst the paths with same MS, they are prioritized in the order of decreasing values of XT_{mar}. If multiple paths have same MS and XT_{mar}, any one of them is chosen randomly. Thus, the priority order of the paths selected using the proposed method for Table 1 is $P_2 \rightarrow P_5 \rightarrow P_1 \rightarrow P_{12} \rightarrow P_8/P_{15} \rightarrow P_4 \rightarrow P_{14} \rightarrow P_{11} \rightarrow P_7/P_{13} \rightarrow P_{10} \rightarrow P_3 \rightarrow P_6 \rightarrow P_9 \rightarrow P_{16}$, which defines the core-type selection on different links between $o-t$.

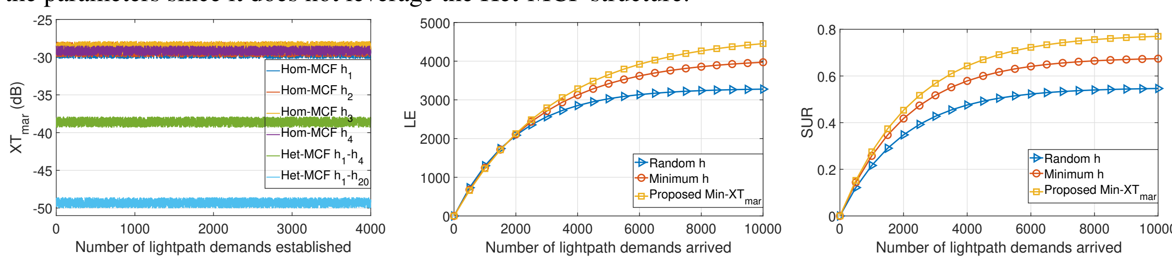
3. Simulation Results and Discussion

To analyze the compared methods, we perform spectrum allocation (SA) on the DT12 network topology [2] using incremental traffic model, where lightpath demands of infinite holding time with bit-rate requirements b (Gbps)= $\{100, 200, 500, 1000\}$ arrive randomly in the network. Simulation results in Fig. 2 show average values of XT_{mar}, spectrum utilization ratio (SUR), and the number of lightpaths established (LE) for 100 simulation runs, where in each run the arrival order of lightpath demands as well as their bit-rate requirements vary.

We consider a 20-core MCF on each link in DT12 network. In Fig. 2(a), we compare the XT_{mar} obtained for (i) Hom-MCFs considering different values of h (each of the 20 cores have same h), (ii) a Het-MCF with four different core-types shown in Fig. 1(b) (5 cores each with h_1, h_2, h_3, h_4), and (iii) a Het-MCF having 20 ($h_1 - h_{20}$) different core-types (each core has different $h \in [0.2 \times 10^{-9}, 10^{-9}]$). From Fig. 2, it is observed that Hom-MCF results in high XT_{mar}, irrespective of the value of h. Het-MCF with four core-types ($h_1 - h_4$) significantly improves the XT_{mar} by an average 9.36 dB, as compared to the Hom-MCFs. With the increase in the number of core-types, the XT_{mar} shifts towards zero, as observed from Fig. 2(a). This is due to the reason that the required numbers of unique reaches in DT12 can be achieved with the increase in the number of core-types, as explained in the previous section for Fig. 1(a).

In Fig. 2(b-c), we compare the proposed Min-XT_{mar} method with two different core-type selection schemes: (i) Random h, where core-type is selected randomly during SA, and (ii) Minimum h, where core-type with minimum value of h is selected first since it offers the minimum XT per unit length [3,4]. From Fig. 2(b), it is observed that the proposed method achieves higher LE as compared to both the methods due to XT_{mar} minimization, which inherently balances core-type selection (see Table 1). In contrast, using minimum h scheme, the cores that offer low XT per unit fiber length are occupied initially as the network load increases, and then the remaining core-types with higher h necessitates the selection of low-spectral-efficiency MSs to achieve the required transmission reaches.

From Fig. 2(c), we observe that the proposed method can utilize about 80% of the Het-MCF spectrum, since it performs core-type selection balancing. However, using minimum h scheme, as the network load increases, the cores with lower h cannot be utilized either (i) due to the reach consideration, i.e., no path available with $XT_\mu \leq XT_{th}$, or (ii) due to the spectrum continuity or contiguity constraints. Random h selection schemes performs the worst in terms of all the parameters since it does not leverage the Het-MCF structure.



(a) (b) (c)

Fig. 2: (a) XT_{mar} obtained using Hom-MCFs and Het-MCFs, and (b), (c) LE, SUR obtained using the proposed minimum-XT_{mar}, Random h, and Minimum h schemes.

4. Conclusion

We show that by varying the design parameters of cores of Het-MCFs, zero-XT_{mar} operation for a small network can be achieved. For big real networks, XT_{mar} can be reduced by increasing the number of core-types in Het-MCFs. Using the proposed Min-XT_{mar} core-type selection scheme, higher LE can be achieved as compared to the Random h selection, and Minimum h (i.e., core with lowest XT) selection schemes.

References

1. G. M. Saridis *et al.*, "Survey and evaluation of space division multiplexing: from technologies to optical networks," *IEEE Commun. Surv. Tut.*, vol. 17, no. 4, pp. 2136–2156, 2015.
2. M. Klinkowski and G. Zalewski, "Dynamic crosstalk-aware lightpath provisioning in spectrally-spatially flexible optical networks," *J. Opt. Commun. Netw.*, vol. 11, no. 5, pp. 213–225, 2019.
3. K. Saitoh and S. Matsuo, "Multicore fiber technology," *J. Lightw. Technol.*, vol. 34, no. 1, pp. 55–66, 2016.
4. Y. Amma *et al.*, "High-density multicore fiber with heterogeneous core arrangement," in *Proc. OFC*, 2015.
5. Y. Pointurier, "Design of low-margin optical networks," *J. Opt. Commun. Netw.*, vol. 9, no. 1, pp. A9–A17, 2017.