Assigning Counter-Propagating Cores in Multi-Core Fiber Optical Networks to Suppress Inter-Core Crosstalk and Inefficiency due to Bi-directional Traffic Asymmetry

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Abstract: We propose the assignment of Multi-Core Fiber (MCF) cores in a counter-propagating way to design an MCF optical network, which suppresses MCF inter-core crosstalk and reduces the capacity inefficiency caused by increasing asymmetry of bi-directional traffic. Simulation results demonstrate the effectiveness of our proposed approaches.
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1. Introduction

Modern fiber-optics communication technology over standard single-mode single core fibers is near its transmission capacity limit. To further increase the capacity, researchers are exploring Space-Division-Multiplexing (SDM) transmissions such as in Multi-Core Fiber (MCF)-based systems [1]. Most current studies on MCF-based optical networks assume a pair of MCFs on each link with optical signals transmitted in opposite directions in each [2] where the signals in all the cores are in the same direction. This symmetric network design increases capacity, but is limited in an MCF as the *inter-core crosstalk* degrades the signal between cores. Recent studies [3] experimentally demonstrated that counter propagation of the signals in neighboring cores of an MCF significantly suppresses the inter-core crosstalk. This motivates us to assign fiber cores in a counter-propagating way when planning an MCF optical network.

Meanwhile, new applications, such as video on demand and Virtual/Augmented Reality (VR/AR) tend to have highly asymmetric bi-directional traffic in the opposite directions of a flow, which leads to highly asymmetric traffic demand in the network [4]. However, almost all the current networks have been designed for symmetric traffic, provisioning the same capacity in both directions, and are not efficient for asymmetric flows. By allocating different numbers of cores in opposite directions, an MCF optical network with core counter-propagation can also reduce the inefficiency caused by the bi-directional traffic asymmetry.

We propose an interleaving core assignment strategy for an MCF optical network based on core counter-propagation. This largely avoids having neighboring cores with signals in the same direction (i.e., co-propagation), thereby reducing the inter-core crosstalk. Efficiency is also increased by using different numbers of counter-propagating cores in the opposite directions of each MCF, based on the actual bi-directional traffic demand. We evaluate the benefits of core counter-propagation to reduce the number of MCFs required and to suppress the inter-core crosstalk in the MCFs compared to a conventional symmetric network design. We also show how the proposed counter-propagating scheme improves network capacity efficiency for traffic with bi-directional asymmetry. An efficient core and spectrum assignment algorithm is proposed to achieve the highest benefit. Simulations verify the efficiency of the proposed counter-propagation scheme and the interleaving core assignment strategy.

2. MCF Core Counter-Propagation and Interleaving Core Assignment

Fig. 1 shows an example of a 7-core MCF, which has two modes to propagate optical signals in its cores. In an MCF optical network designed for bi-directionally symmetric traffic demands, the cores co-propagate signals as shown in Fig. 1(a), where all the optical signals are transmitted in the same direction. This can lead to significant inter-core crosstalk limiting its transmission capacity. To suppress this, the cores in an MCF can counter-propagate optical signals as shown in Fig. 1(b), whose effectiveness has been experimentally demonstrated in [3]. The best results from this counter-propagation mode are achieved by properly arranging the cores that are propagating in opposite directions. An interleaving core allocation, as shown, is the most efficient way for this.

The inter-core (co-propagating) crosstalk factor *CF* for a core is defined to be the number of other cores in the same MCF that are *directly* neighboring to the current core and transmitting optical channels of the same frequencies in the same direction as in the current core. Here *directly* neighboring cores are the ones with no other intervening core in the middle. In this study, we ignore the crosstalk between co-propagating cores that are not directly neighboring as it would be much less than that between directly neighboring co-propagating cores. In Fig. 1, cores 1 and 2 are examples of directly neighboring cores. For comparing the inter-core crosstalk between the core layouts in Fig. 1(a) and (b), we can calculate that the total inter-core crosstalk factor of MCF (a) as CF_{co}=24 and that of MCF (b) as $CF_{counter}$=6. Clearly, the counter-propagation significantly suppresses the inter-core crosstalk for an MCF.

In the context of an MCF optical network, Fig. 2 shows examples of MCF layout on a fiber link for the symmetric design and one based on counter-propagation. In Fig. 2(a), since each fiber link needs to support bi-directional traffic and no counter-propagation is allowed for the cores in an MCF, a pair of MCFs have to be deployed in opposite directions between nodes B and C. In contrast, using core counter-propagation in an MCF, only one MCF is needed between nodes B and C, where traffic in opposite directions is sent using a pair of counter-propagating cores. Moreover, in the symmetric design, the spectrum resources reserved in both directions would be the same and is set to be the larger of the values in the two directions. Thus, in Fig. 2(a), 8 frequency slots (FSs) are reserved in both the opposite MCFs. A design based on counter-propagating cores can flexibly allocate spectrum resources to match the actual demand. For example, with bi-directional traffic asymmetry, 8 FSs are allocated in the direction from C to B, but only 4 FSs are needed in the opposite direction. Unlike the example of Fig. 2(a), the core counter-propagation mode reduces 4 FSs and is more efficient for bi-directional asymmetric demand.

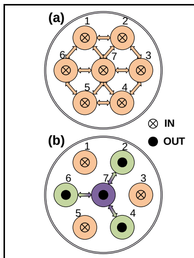

Fig. 1. Two modes.

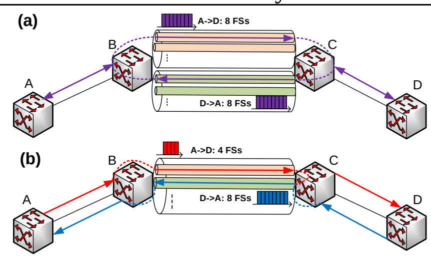

Fig. 2. MCFs in networks.

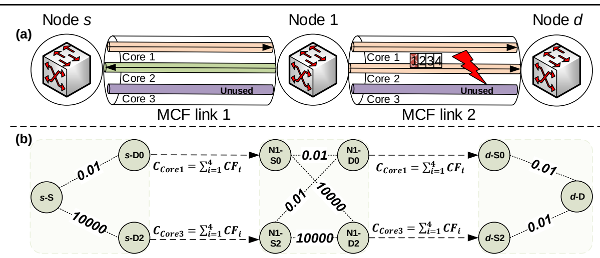

Fig. 3. Creating an auxiliary graph (AG).

3. Heuristic Algorithm

To benefit from the proposed core counter-propagation, we develop a heuristic algorithm to provision unidirectional optical channels for users considering the inter-core crosstalk factor of each FS. This aims to minimize both the MCFs required and the average channel-based inter-core crosstalk. The key idea of this algorithm is as follows.

Preparation for AG-based algorithm: Given an optical channel request that requires f FSs and is to be established along the shortest route between its source and destination nodes, we try each possible f-FS spectrum window (SW), (i.e., from FSs λ_i to λ_{i+f-1}, i=1,2,3…) along the route to first check whether each link can provide such a free SW. If there is any link that cannot provide such an SW, we record the total number l_i of such links for this SW; otherwise, $l_i = 0$. We then repeat the same process for the next f-FS SW (i.e., from FSs λ_{i+1} to λ_{i+f}) to find l_{i+1}. After scanning all the SWs, we find the smallest l_i as $l_{min} = \min_i l_i$. If $l_{min} = 0$, which means that at least one SW is eligible to establish the current optical channel along the route, then we implement an auxiliary graph (AG)-based algorithm to jointly assign the MCF core and spectrum along the route. We will introduce this AG-based algorithm later. Otherwise, if $l_{min} > 0$, we will find the first SW i^* whose $l_i = l_{min}$, i.e., $i^* = \operatorname{argmin}_i l_i$, and then add l_{min} MCFs on the links that lack SW i^*, which would ensure to add the *fewest* MCFs and enable the current route to be available on SW i^* on all the links. Based on this, we can then run the subsequent AG-based algorithm to jointly assign the MCF core and spectrum along the route.

AG-based algorithm: Given the knowledge that a route with MCF links is able to use a specific SW i to establish an optical channel, we use the example in Fig. 3 to illustrate the AG-based MCF core and spectrum assignment algorithm. Assume that the route traverses two MCF links as shown in Fig. 3(a). For this, we create an AG shown in Fig. 3(b). An MCF core that is not used yet or carries traffic in the direction from s to d and has available SW (e.g., from FSs 1 to 4) is mapped to a unidirectional *auxiliary link* connecting two *auxiliary nodes* (see the examples of core 3 in link 1 for the unused core and core 1 in link 1 for the other case). If an MCF core carries traffic in the opposite direction (e.g., core 2 in link 1) or is not available of the SW (e.g., core 2 in link 2, not available of FS 1), then no corresponding auxiliary link is set up. The cost of each auxiliary link on an MCF link is set as $c = \sum_{i=1\ldots f-1} CF_i$ where f is the total number of FSs in the SW and CF_i is the increase of inter-core crosstalk factor of FS i in the current MCF if the optical channel is established via the link. Next, to inter-connect MCF cores via a switch node, we add auxiliary links to fully connect auxiliary nodes on both sides as shown. The cost of each auxiliary link is set as follows. If its destination virtual node corresponds to an unused MCF core, then its cost is set to be large, e.g., 10^4, to avoid using this unused core before using up spectrum resources on the other used cores. Otherwise, the cost is set to be small, e.g., 0.01. For nodes s and d, auxiliary links are added similarly.

First-Fit (FF) vs. Least Cost (LC): Based on the AG created, the shortest path searching algorithm is run to find a path with the lowest cost for the current SW, c_i^{sw}. Next, we may implement two strategies, i.e., the first-fit (FF) strategy or the least cost (LC) strategy. The first one is to use the first eligible SW that has $c_i^{sw} < \infty$ to establish the optical channel. The second one needs to scan all the eligible SWs for the lowest cost one, i.e., $i^* = \operatorname{argmin}_i c_i^{sw}$.

4. Simulations and Performance Analyses

We evaluated the proposed strategy for the 11-node, 26-link COST239 and 14-node, 21-link NSFNET networks. A 7-core MCF was assumed for this simulation study though other types of MCFs are also possible. In each core of an MCF, there are a total of 320 FSs available, and the spectrum assignment for each optical channel is elastic as in the conventional elastic optical network (EON). A total of 500 bi-directional optical channel requests were simulated. Each request consists of two unidirectional optical channels between the node pair. The bandwidth of each unidirectional optical channel is independently assumed to follow a random distribution within a range of [5, 2*X*-5] FSs, where *X* is the average number of FSs required. Here, the number of FSs for each optical channel request can be derived from the actual bandwidth requirement between the corresponding node pair and the modulation format that can be used according to the distance or signal quality of the optical channel. To account for the asymmetry, we assigned a larger bandwidth to unidirectional optical channels whose source node index is larger than that of the destination node, and vice-versa in the other direction. We always used the shortest route based on the physical distance between each node pair for optical channel establishment. The AG-based algorithm was employed to choose the cores and spectrum windows for optical channels for the networks based on the core counter-propagation and the conventional symmetric designs.

Number of MCFs: We first evaluate how the total number of MCFs required (calculated as the sum of MCFs on each network link) changes with an increasing average number of FSs assigned to each unidirectional optical channel. The results for COST239 are shown in Fig. 4, where the legends of "Counter" and "Co" corresponds to the design cases of core counter-propagation and core co-propagation in each MCF, respectively. We use the legends of "FF" and "LC" to denote the core and spectrum selection strategies in the AG-based algorithm. The left *y*-axis shows the number of MCFs required. As expected, with the increase in the average number of FSs assigned to each channel, the number of MCFs increases, as more bandwidth is needed. Comparing the counter- and co-propagation cases, we see that the former significantly reduces the number of MCFs required by up to 39% and 42%, respectively for the FF and LC strategies. In addition, the LC strategy outperforms the FF strategy by more than 30% because it chooses the core and spectrum with the fewest unused cores and the least inter-core crosstalk.

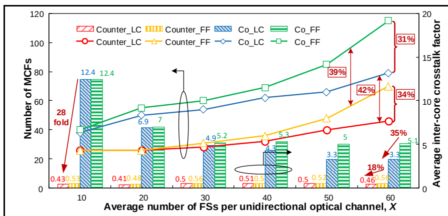

Fig. 4. Number of MCFs and inter-core crosstalk.

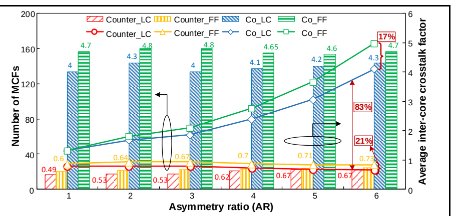

Fig. 5. Impact of traffic asymmetry ratio.

Inter-core crosstalk: Fig. 4 also compares the inter-core (co-propagating) crosstalk between different schemes (see the right *y*-axis). We use the average inter-core crosstalk factor per FS of each channel, calculated as $\overline{\boldsymbol{CF}} = \sum_{i\in L,f\in W} \boldsymbol{CF}_i^f / \sum_{d\in D} \boldsymbol{FS_d}$, to measure the inter-core crosstalk. $\boldsymbol{L}$ is the set of network links, $\boldsymbol{W}$ is the set of FSs in each core, and $\boldsymbol{D}$ is the set of unidirectional optical channels established. $\boldsymbol{CF}_i^f$ is the inter-core crosstalk factor of FS f in link i. $\boldsymbol{FS_d}$ is the number of FSs required by optical channel d. Compared to the co-propagation case, the counter-propagation case always shows lower inter-core crosstalk, reducing up to more than 28 fold under low traffic demand (e.g., *X*=10) for both FF and LC strategies. Also, the LC strategy shows a lower inter-core crosstalk than that of the FF strategy by choosing the core and spectrum with the lowest crosstalk.

Impact of asymmetry ratio (AR): We evaluate how the AR of bi-directional traffic demand impacts the benefit of core counter-propagation under *X*=15 for NSFNET (see Fig. 5). We see that with an increasing AR, the difference in the number of MCFs becomes more with counter-propagation performing much better than co-propagation, by up to 83%. A large difference in the inter-core crosstalk between the two schemes still maintains with a small increase in the inter-core crosstalk by the counter-propagation mode due to stronger traffic asymmetry.

5. Conclusion

We proposed the assignment of MCF cores in a counter-propagating way for optical channel establishment in an MCF optical network. An AG-based algorithm was proposed to choose the cores and spectrum windows for optical channels. Simulation results demonstrated the benefit of the proposed counter-propagation and interleaving core assignment scheme to not only reduce the number of MCFs, but also suppress the inter-core crosstalk significantly.

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