Polarity and Horizontal-Flipping Management in Multicore-Fiber-Based Optical Devices, Nodes, and Networks

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***Abstract*—We propose global core ID assignment in spatial channel networks employing multicore fibers (MCFs) and discuss how to define and manage the polarity and mirror-induced horizontal flipping for MCF-based optical devices.**

Keywords—spatial division multiplexing, multicore fiber, polarity, horizontal flipping, core selective switch, splitter

I. Introduction

If we assume that the volume of Internet traffic will continue to grow at a compound annual growth rate of 20% to 40%, an optical link with a capacity of approximately 1 Pb/s will be required around 2030. Since the theoretical capacity limit of a conventional single mode fiber (SMF) is less than approximately 100 Tb/s, we will most likely need more than ten single mode cores between adjacent optical nodes, which may be parallel SMFs or uncoupled multicore fiber(s) (MCF(s)) [1].

The spatial channel network (SCN) [2] was recently proposed as an optical network architecture to accommodate future Internet traffic in a scalable and economical manner by taking full advantage of the spatial and wavelength dimensions. In an SCN, the current optical layer evolves into hierarchical wavelength division multiplexing (WDM) and spatial division multiplexing (SDM) layers, while an optical node is decoupled into a spatial cross-connect (SXC) and a conventional wavelength cross-connect to form a hierarchical optical cross-connect. Here, a spatial channel (SCh) is a media channel in the SDM layer that is constructed by connecting cores in each SDM link (an MCF or parallel SMFs) on a route using SXCs.

In order to achieve SCNs in a scalable and economical way, a port modular SXC that is based on a novel MCF-based spatial optical switch referred to as a core selective switch (CSS) was recently proposed [2-4]. Here, a CSS is a one-input MCF and *N*-output MCF device where an optical signal launched into any core in the input MCF can be switched to a core that has the same cross-sectional core position of any output MCF in the MCF array. By connecting CSSs and other MCF-based spatial optical devices (MODs) such as a core selector (CS) and a core/port selector (CPS) in various ways using simple MCF wiring, a wide variety of connectivity flexibilities (*any-core-access*, *directionless*, and *contention-less*) can be achieved [3]. Here, a CS provides a functionality to connect an SMF core to any core in an MCF. A CPS has a functionality to connect an SMF core to any core in an MCF bundle. It should be emphasized that the CSS-based SXC approach does not necessarily presuppose the MCF link. When each SDM link comprises parallel SMFs, fan-in (FI) and fan-out (FO) devices are placed at ingress and egress MCF ports of the CSS-based SXC. Here, an FI (FO) device provides a functionality to multiplex (demultiplex) cores spatially in multiple SMFs (an MCF) into cores in an MCF (multiple SMFs).

It is understood that FI and FO devices and a CSS are counterparts of an arrayed waveguide grating and a wavelength selective switch in the SDM layer, respectively. However, there are two important differences between them in terms of resource management. The first difference comes from how resources (frequency slots in the WDM layer and cores in an MCF in the SDM layer) are represented. Since core resources in an MCF are represented by their three-dimensional position, different perspectives may result in different notations of cores. The second difference originates from the plane-mirror reflection that may exist in some MODs. For example, in the free-space-optics-based CSS reported in [4], a beam from an input MCF is targeted on the desired output MCF by controlling the tilt of a micro-electromechanical systems (MEMS) mirror. This causes the *horizontal flipping* in the core identification number (ID) of the MCF. Naturally, corresponding changes in frequency-slot notation do not happen in WDM devices unless intended as such.

Since MODs in each SXC in an SCN are controlled so as to establish an SCh by connecting cores in MCF links specified by a *global* core ID (GCID) in the SCN, which is given by a path computation element, it is very important to define the *polarity* (the nominal direction to be used) for each MOD and to manage the horizontal flipping on the route. As far as we know, MCF

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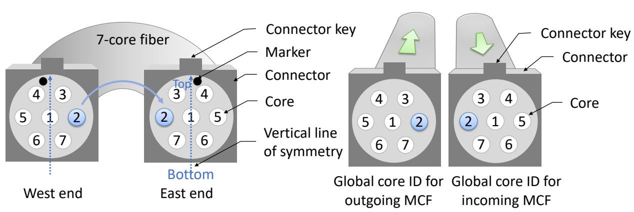
polarity was first discussed in [5] from the MCF link perspective. In this paper, we define the notation of core resources in MCFs in the SCN and discuss the polarity and horizontal-flipping management in SCNs at the device, node, and network levels.

II. Core ID Assignment in MCF

In general, core arrangement in an MCF is designed symmetrically to maximize the core density within the cladding. In order to identify each core, a marker is embedded at the position where the symmetry of core arrangement is broken. We suppose that (i) one line is selected from lines of symmetry in a core arrangement of an MCF and define it as the vertical line of symmetry, which is identified by the position relative to the marker. We also suppose that (ii) connector(s) are attached to the end of the MCF(s) of any MOD so that the connector key is placed on top of the vertical line of symmetry of the MCF. The *local* core ID (LCID) for an MCF or MOD is then determined as shown in Fig. 1.

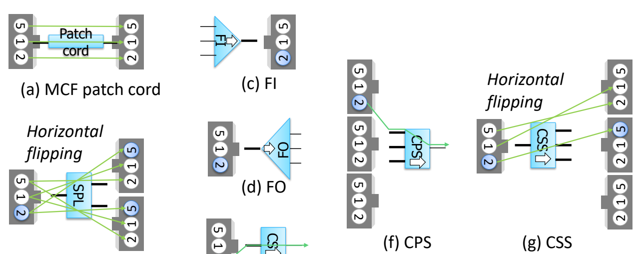
A. Polarity of MCF

Fig. 1(a) shows such a situation using a 7-core fiber (7-CF) patch cord as the simplest MOD. Note that if we assign core IDs



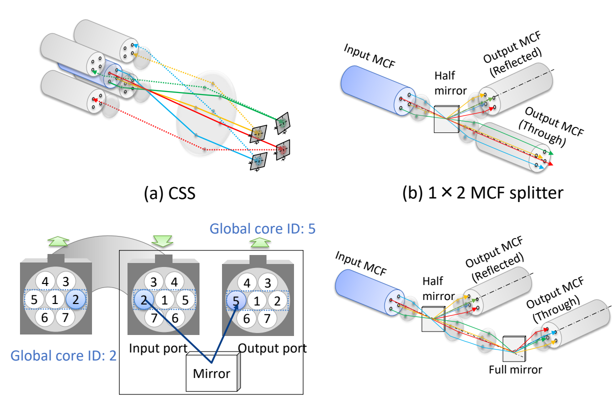
(a) Physical core ID assignment (b) Logical GCID based on signal direction

Fig. 1. Local and global core ID assignments for MCF and MOD.



(a) MCF patch cord (b) All-port flipped MCF splitter (c) FI (d) FO (e) CS (f) CPS (g) CSS

Fig. 2 Polarity and local core ID assignment definition.



(a) CSS (b) 1 × 2 MCF splitter (c) Horizontal flipping of global core ID (d) All-port flipped 1 × 2 MCF splitter

Fig. 3. Horizontal flipping in MODs with plane-mirror(s).

counterclockwise at the west end of the patch cord, core IDs and the marker position at the east end are placed in a horizontally flipped relationship with those at the west end. This means that strictly speaking, an MCF patch cord and even an MCF transmission line has a polarity in terms of the core arrangement in an MCF cross-section at each end. However, as discussed in [5], in practice, no polarity management of an MCF patch cord or transmission line is required thanks to the MCF line symmetry, which means that an MCF can be set without worrying about its direction. This makes it easier to manufacture/install MCF cables and to connect equipment with MCF patch cords. Instead, in order to achieve network-wide end-to-end core ID matching, we need to define a logical GCID for an MCF pair that links adjacent SXCs.

B. Global Core ID Assignment Based on Signal Direction

There are two possible methods for GCID assignment: one is based on the direction of the optical signals in a core, and the other is based on the polarity of each MCF pair in the network selected arbitrarily. Since both methods are logical ones, core IDs are assigned regardless of the location of the marker position relative to the connector key. Although both methods have their own advantages and disadvantages, in this paper, we employ the former, as indicated in Fig. 1(b), that requires no network-wide link polarity specification. In this method, depending on the signal direction, GCIDs are assigned in different arrangements, which are in a horizontally flipped relationship with each other, as shown in Fig. 1(b). As a result, an optical signal lunched into GCID #2 (C_2) for example is output from the core with the same GCID at the opposite end of the MCF link.

III. Polarity and Horizontal Flipping in MODs

A. Polarity of MODs

In addition to an MCF patch cord and transmission line, MODs that perform the same operations on each core, such as an MCF splitter, have no polarity in a practice sense. On the other hand, MODs that perform different operations, *e.g.,* core-by-core routing, on each core such as FI and FO devices, a CS, CPS, and CSS have polarity. For example, as can be understood from their names, FI and FO devices are designed with the intended orientation (polarity) in mind. In order to use MODs adequately to prevent network-wide core ID mismatch, we should define the polarity and the core ID assignment in MCF port(s) for each MOD (correspondence between core ID and core physical arrangement). Fig. 2 shows the definition of polarity and LCID assignment employed in this paper for various MODs (only the central three cores of a 7-CF are indicated for simplicity). The control signals to the CS, CPS, and CSS are set and the SMF ports of the FI and FO devices are labelled so that they operate as intended for the GCID of light propagating in the same direction as the polarity (normal (default) mode operation).

B. Horizontal Flipping in MODs

MODs with MCF input(s) and MCF output(s) that contain plane mirror(s) may cause *horizontal flipping* in the core ID of the MCF. One example is the free-space-optics-based CSS reported in [4] (Fig. 3(a)), where a beam from a core of the input MCF is targeted on the desired output MCF by controlling the tilt of a MEMS mirror corresponding to the input core ID.

Another example is a reflection port of an MCF splitter as shown in Fig. 3(b). In both cases, reflection at the plane mirror causes inversion of the beam direction resulting in the horizontal flipping from the viewpoint of the core ID arrangement as indicated in Fig. 3(c).

IV. Polarity and Horizontal Flipping Management

A. Device Level Management

So far, a wide variety of 1×8 CSSs supporting a 5-core fiber (5-CF), bundled three 5-CFs, and a 19-core fiber (19-CF) were prototyped using a MEMS mirror array [4,6]. It may be possible to build mechanisms into a CSS to recover the horizontal flipping; however, it increases loss, size, and complexity. Therefore, in terms of device-level horizontal flipping management, the minimum requirement may be that the flipping characteristics of all output port should be identical. Fig. 3(d) shows a device-level horizontal flipping management example. Here, the architecture of the MCF splitter shown in Fig. 3(b) is modified so that all output MCF ports exhibit horizontal flipping. Such an all-port flipped MCF splitter can be used instead of the ingress CSS in an SXC to reduce cost and improve reliability.

B. Node Level Management

As a node level management, the operation mode of each MOD in the SXC must be properly selected according to the polarity of the MOD with respect to the signal direction and the mirror-induced horizontal flipping in the MOD. This ensures that the core with a given GCID in an MCF link connected to an SXC port is cross-connected to the designated MCF link or added/dropped to the designated client-side SMF port.

1) MOD with Porality without Horizontal Flipping: If an FI device is used on the receiver side of an MCF transmission line instead of an FO device, which means that the FI is used in the opposite direction, an optical signal launched into a specific core is output from the wrong SMF port that corresponds to the core ID having the horizontally flipped relationship with the original core ID. A similar core ID mismatch occures when a CS or CPS is used in the opposite direction to its porality, which can be avoided by replacing the core ID with one in the horizontally flipped position. For example, if a CS is used in the opposite direction and required to select a core with GCID #2, the control signal to the CS should be set to C_5, not C_2. This is a simple polarity management rule for an MOD without horizontal flipping when it is used on its own. We refer to this as *inverse* mode operation as opposed to *normal* mode operation.

2) MOD with Polarity and Horizontal Flipping: The polarity and horizontal flipping of a CSS complicates the selection of its operation mode. The operation mode selection rule of a MOD with horizontal flippping and polarity when it is used on its own is shown in TABLE I.

3) Operation Mode Selection Considering Previous Stage Horizontal Flipping(s): Since MODs in each SXC in an SCN are controlled so as to establish an SCh specified by a GCID in the SCN, the operation mode of each of the MODs should be determined one by one, starting with the line-side MOD. In addtion, it should be noted that if an odd number of horizontal flippings occurres in the previous MODs, the later MOD must be added a core inversion so that the physical core positions of sdjacent MODs match. Fig. 4 shows the operation mode selection for a through SCh and add/drop SChs in an SXC with the any-core-access and directional connection flexibility. Here, the notation N(2) or I(2) means operating the MOD in normal or inverse mode for optical signal coming or outgoing through GCID #2 (C_2). The horizontal flipping in the through SCh can be canceled automatically by the ingress and egress CSSs and that in the add/drop SChs can be canceled by selecting the adequate operation mode for the CS on the client side.

TABLE I. Selection of Opetaion Mode for MODs with Holizontal Flipping and Polarity

		Position at which GCID specified	
		Input MCF port	Output MCF ports
Light direction in relation to MOD polarity	Same direction	Normal mode (Default setting)	Inverse mode (Due to horizontal flipping)
	Opposite direction	Inverse mode (Due to reverse use)	Normal mode (Reverse use is cancelled by horizontal flipping)

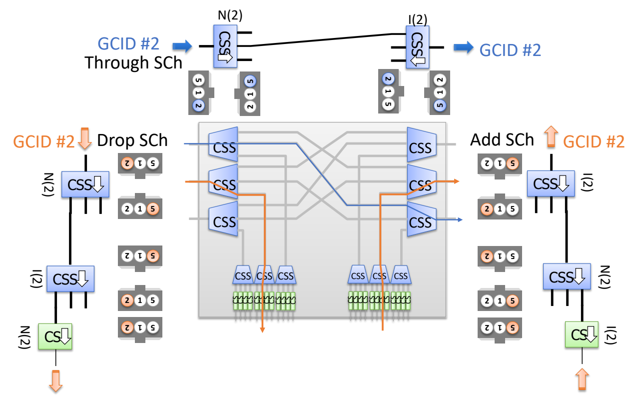


Fig. 4. Polarity and operation mode for CSS and CS when used in an SXC with any-core-access and directional connectivity.

C. Network Level Management

As the network level management, we should define the GCID assignment scheme for MCF links as described in Section IIB and monitor the end-to-end core ID matching.

V. Conclusions

In this paper, we proposed the GCID assignment in SCNs employing MCFs and discussed how to define the polarity and mirror-induced horizontal flipping for MODs. Then, we discussed the polarity and horizontal-flipping management at the device, node, and network levels.

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