FlyCast: Free-Space Optics Accelerating Multicast Communications in Physical Layer

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ABSTRACT

In this paper, we propose FlyCast, an architecture using the physical layer of free-space optics (FSO) to accelerate multicast communication. FlyCast leverages off-the-shelf devices (e.g. switchable mirror, beam splitter) to physically split the FSO beam to multi receivers on demand, which enables to build dynamical multicast trees in physical layer and accelerates multicast communications. We demonstrate the feasibility of FlyCast through our theoretical analysis and the proof-of-concept prototype.

CCS Concepts

•Networks → Hybrid networks; Data center networks;

Keywords

Data Center Network; Free Space Optics; Multicast

1. INTRODUCTION

One-to-many group communication is common in modern data centers running cloud and web-based applications, or high performance computing (HPC) applications. Those examples of cloud computing applications include publish-subscribe services, Hadoop using data replication for higher availability, network virtualization installing OS and application images on a group of virtual machines. High performance and scientific computing applications, often using MPI group communication extensively, have been examined and deployed in existing cloud computing infrastructures.

Multicast, an efficient mechanism for group communications, benefits the network by reducing bandwidth overhead and latency between group members, alleviating in hotspot or network congestion due to huge volume and high fan-out traffics. Traditional multicast solutions in cloud and HPC data center mainly is optimized and implemented on top of network, transport or upper layers [1], which suffer from suboptimal multicast trees and high complexity. Recently, hybrid network architecture that combines wireless (e.g. 60GHz, free-space optics) or optical space switches (OSS) to traditional wired electrical switches has been proposed to dynamically adapt to traffic demand .The physical layer broadcast media of wireless and optics have the nature of one-to-many communication, which are very suitable for group traffic pattern. Yu, et. al., utilizes the narrow-beam of 60GHz to construct a wired and wireless mixed multicast tree [4]. Xia, et. al., uses passive power splitters and OSS to set up a dynamical multicast tree, and the data is optically replicated from source to destinations [3].

Free-Space Optics (FSO) is an emerging technology with the advantage of free wiring and low latency in constructing flexible data center network [2]. Compared with 60GHz, it has the benefits of high bandwidth and low interference. Additionaly, with the switchable mirror (SM), it's more flexible and expandable than OSS. To the best of our knowledge, no existing equivalent work leverages the physical layer of FSO to accelerate multicast communication. In this paper, we propose an architecture named FlyCast, which utilizes commercial off-the-shelf devices (e.g. SM, beam splitter) to split the FSO beam to multi receivers on demand.

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2. THE ARCHITECTURE OF FLYCAST

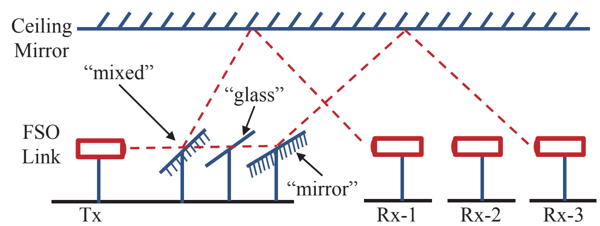

Figure 1: The Architecture of FlyCast

Our work is inspired by the Firefly, which exploits SMs to construct a flexible and fully FSO interconnected network [2]. Each FSO device is equipped with multiple SMs. The SMs are made up of a special liquid crystal material which can be electrically controlled to rapidly switch between pure-reflection (mirror), half-reflection (mixed) and total transparent (glass) states. Firefly dynamically establishes the link by switching one of the SMs to mirror state, while leaving the rest in glass state. The Firefly only supports one-to-one communication. However, FlyCast makes use of the mixed state of SMs to optically duplicate data to multiple receivers, as shown in Fig. 1. The glass state (e.g. 2nd SM) means that the related terminal does not receive the data, meanwhile there exist receivers at behind. On the contrary, the SM with mirror state (e.g. 3rd SM) steers all the received beam to the related receiver. When both the related terminal and followed terminals can receive data, the SM leaves in mixed state (e.g. 1st SM). Hence, the source can simultaneously send data to Rx-1 and Rx-3 at line-rate.

Next, we will use a motivating example to show what kind benefits of FlyCast delivers, as shown in Fig.2. We assume that every Top-of-Rack (ToR) switch has two ports and each port is equipped with two SMs (links with same color mean that the SMs share the common FSO), and the dynamical topology is shown as Fig. 2(a). The runtime topology can be changed between Fig. 2 (b) and (c) by the controller. When ToR A sends the same data to ToR E and C, no matter what routing paths are used or how to change the states of SMs according to Firefly, it needs at least three hops to complete the multicast communication. In this scenario, using the physical layer of FSO, ToR A can simultaneously send data to C and E via one hop, as shown in Fig. 2(d) and (e).

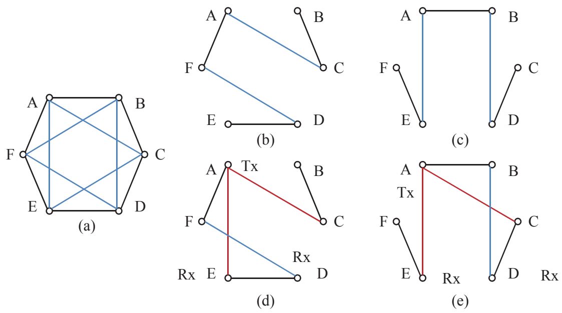

Figure 2: An Example of the Advantage of FlyCast

Traditional distributed multicast routing protocols are difficult to realize in the asymmetric network. The FlyCast performs routing protocol in the control plane of software-defined networking (SDN) architecture. Moreover, the controller manages the joining and leaving of group members through interacting with the applications, and the SDN switches should support multicast rules. Given the group members, network controller runs the control algorithm to compute network topology and adjust the states of SMs. The problem of computing network topology turns into building a directed Steiner tree with additional constraints. Though it is a NP-hard problem, there exist solutions based on approximation algorithms. However, edges sharing the same port are conflicted, we have to modify the existing approaches to construct multicast trees. For the direct edge <a, b> chosen as the subset of the multicast tree, we will prune the other edges connected to b except <b, a>, thus guaranteeing the in-degree of successors at most 1.

3. THE FEASIBILITY OF FLYCAST

The signal of FSO will be degraded when passing through a beam splitter. Let l denote the transmittance (from 0.5 to 0.9) and let S/N denote the signal-noise ratio of the initial FSO. From Eq. 1 we can find out that the degradation of FSO signal is determined by the transmittance.

$$10\lg(l * S/N) = 10\lg(S/N) + 10\lg(l) \tag{1}$$

Only the power of last received signal R_k and R_{k+1} which passes through k beam splitters are greater than the transceivers' receiver sensitivity, all data can be recovered correctly.

$$Max : k, subjectto :$$

$$R_k, R_{k+1} > B \tag{2}$$

$$R_{k+1} = A - n * k \tag{3}$$

$$R_k = A - n * (k-1) - m \tag{4}$$

$$n = -10\lg(l) \tag{5}$$

$$m = -10\lg(1-l) \tag{6}$$

The calculation process is as follows: Let A denote the output power of the transceiver and B denote the receiver sensitivity. Eq. 2 to Eq. 4 guarantee that the reflected and passed signal are stronger than the receiver sensitivity. The degradations of signal under different transmittances are described in Eq. 5 and Eq. 6. The goal is to maximize the number of beam splitters.

The transceiver has a maximum output power of 4dBm and a receiver sensitivity of -15dBm. Fig. 3 illustrates the relationship between the transmittances and number of beam splitters. Note that the initial FSO can be split up to 20 times with the transmittance of 0.9. Though the transmittance of SM in mixed state is about 0.5, the SM can be replaced with continuous switchable glass or MEMS-based mirrors and beam splitters with different transmittances.

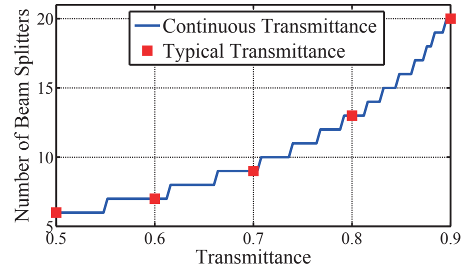

Figure 3: The Number of Beam Splitters under Different Transmittances

Furthermore, we develop a proof-of-concept prototype to validate the result of above theoretical analysis, as shown in Fig. 4. We test the signal loss from one to three beam splitters with the transmittance of 0.5. Considering the misalignment of collimator and the number of beam splitters, the signal loss is consistent with the theoretical value (3dBm), as shown in Tab. 1.

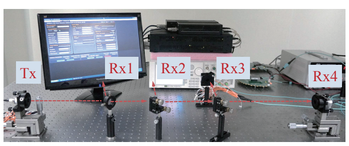

Figure 4: The Prototype of FlyCast

Num	Loss
1	3.22
2	2.76
3	3.17

Table 1: Signal Loss

4. ACKNOWLEDGMENTS

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