Current and Next-Generation Passive Optical Networks Monitoring Solution

Maged Abdullah Esmail, *Student Member, IEEE, OSA* and Habib Fathallah[1], *Member, IEEE, OSA*
Electrical Engineering Department
Prince Sultan Advanced Technologies Research Institute (PSATRI)/ STC-Chair
King Saud University, Riyadh, Saudi Arabia
Email: mesmail@ksu.edu.sa, hfathallah@ksu.edu.sa

***Abstract*— In order to enable new services that require high data rates over longer distances, the optical fiber substitutes the copper cable step by step in the access network area. Time division multiplexed Passive optical network (TDM-PON) is a fast emerging architecture that uses passive components only between the customer and the central office. PON operators need a monitoring system for the physical layer to guarantee high service quality. This monitoring system is necessary during the fiber installation, final testing, regular operation of the network, and for fault localization. In this paper, we present our monitoring system based on optical coding for PON maintenance. This system has almost all the monitoring features required by a network operator. We explained the design and the principle operation of the technique. Moreover, we presents a management and protection solution for long-reach PON networks. Our system design achieves high reliability performance with almost half the cost if full network protection is used.**

***Index Terms*—PON, FTTH, physical layer, fault detection, fault location, monitoring, OTDR, next generation access.**

I. Introduction

Passive optical networks (PONs) are the most emerging class of fiber access systems in the world today. PON based Fiber-to-the-Home (FTTH) is a network technology that has been recognized as the ultimate solution for providing various communication and multimedia services. This deploys optical fiber cable directly to the home or business to deliver triple-play services, high speed internet access, digital cable television, online gaming, etc. [1]. This worldwide acceleration is largely due to both, the considerable decrease in capital expenditure (CapEx) of introducing FTTH connectivity, and its "future proof" nature in meeting ever increasing user bandwidth requirements [2]. For instance, in February 2010, Google announced the plans to build an experimental Gbps FTTH network to households in North America for testing out new concepts in technologies and applications. Worldwide, FTTH deployment had surpassed thirty million users in 2009 and is still continuing to grow at a rapid pace [3].

The time division multiplexing PON (TDM-PON), one among several architectures that can be used in FTTH networks, is widely chosen by operators and it is expected that the next generation 10Gbit TDM-PON will be the most promising system among several technologies [4]. TDM PON bandwidth supply is growing faster than subscriber bandwidth demand, and TDM-PON will deliver future ultra-high speed services far more efficiently than WDM-PON for years to come [5].

PON technologies are advancing to increase the data rate to 10 Gbps in parallel with increasing the number of customers to 128 and more. This huge amount of information carried by the PON needs a practical, cost-effective surveillance and management system which is a key factor to continue developing these networks. PON physical layer fault monitoring has been receiving increasing attention in the last years where proposals from researchers have emerged. This attention leads to the ITU-T L.66 (2007) Recommendation which standardizes the criteria for in-service maintenance of PONs. It reserves the U-band (1625–1675 nm) for maintenance and lists several methods to implement PON in-service maintenance functions.

In this paper we will report on our proposed solution for PON monitoring. We first study the preferred features for any monitoring system to be adopted by a network operator. According to these features, we describe our monitoring system which is based on optical coding. We show how optical coding can be applied for the current and next generation of PONs. Since monitoring information is collected by the active components in addition to the physical layer monitoring system, we show how we can integrate our system with the current protocols to produce more effective monitoring system. Finally we discuss the open issues that still need more research to develop the PON maintenance.

In Section II we study the required features by a network operator to adopt a monitoring technique. Section III and IV describes our optical coding based system for monitoring the current deployed or next-generation PON (NG-PON). In section V we describe the integration of our system with the higher layer protocols and finally we discuss the open issues in section VI.

II. Monitoring Required Features

There are some features that should be achieved by a fully monitoring system. *Centralized* monitoring system enables the

[1]Habib is also an adjunct professor with the Electrical and Computer Engineering Department of Laval University (Quebec, Canada).

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network management system (NMS) in the central office (CO) to remotely and completely collect the monitoring information of the network without customer collaboration or collecting part of the information by the optical network terminal (ONT). The possibility to monitor the network *automatically* enables the operator to collect monitoring information and detect faults without dispatching technicians to the field. This feature reduces the operational expenditure (OpEx) and measurement time. It is desirable for the monitoring system to be *transparent* to the data in the C and L bands. Hence, data transmission and receiving can work in parallel with the monitoring system without interruption. Achieving the *demarcation function* is an important feature for any network operator. This function allows the operator to differentiate between his responsibilities and the customer responsibilities.

In principle, using *single wavelength* for network monitoring saves the bandwidth and decreases the cost of the system. The ability to monitor high network *capacity* (64, 128 and beyond) makes the technique applicable for NG-PON. *Fault detection* is the first objective of any monitoring system. It allows the NMS to identify which branch in the network is faulty. The second objective is *fault localization*. This feature determines the exact location of a fault within the faulty branch. Hence, it decreases the OpEx. Using *power supply in the field* between the CO and the ONUs is inconsistent with the key principle of PONs. It also increases the OpEx since this power supply is used to supply active components which are more susceptible to faults than passive components. The monitoring technique *cost* is a critical feature for any service operator. This is mainly because the PON market is cost sensitive especially for the components not shared by the customers (components between the PSC and the customers). Hence, the monitoring technique cost should be low even if it has full monitoring capability. Another important feature that comes in parallel with cost is network *reliability*. Technique *complexity* limits its applicability. The technique should use simple components that are easy to design, manufacture and install. This ensures that the technique will be adopted by the industry. This includes for example, the constraint of using different fiber for each branch or fixing the length of each fiber branch. This constraint puts impractical limitations when it comes to real implementation. *Scalability* feature is the ability of the monitoring technique to handle growing number of customers and network infrastructure change in graceful manner. *Customer independence* is preferable because it makes the maintenance easier and improves customer satisfaction. *Cascading* remote nodes (RNs) should not be an obstacle for the monitoring system.

III. PON MONITORING

We proposed a modified optical code-division-multiplexing (OCDM) scheme for centralized monitoring of PONs in [6]. This scheme is based on using an optical encoder called Ring encoder shown in Fig. 1. The encoder consists of simple, passive and inexpensive components (a 100% reflectivity FBG, a coupler and a patch cord). One encoder is installed at the end of each branch as an ID for it. The encoder is capable to generate a unique multi-level optical orthogonal code (ML-OOC) using a pulse transmitted from the CO. The NMS in the CO holds the monitoring equipments. It basically includes a transmitter, a detector and decoders to decode the received optical codes (OCs).

The system principle operation is simple. The monitoring transmitter sends a short duration pulse from the U-band. This pulse propagates through the feeder and then splits to M subpulses where M is the number of branches connected to the power splitter and combiner (PSC_1). The subpulse that propagates to PSC_2 is again split to K subpulses equal the number of branches connected to PSC_2. All the subpulses from PSC_1 and PSC_2 continue their propagation till they become close to the ONT where a wavelength selector (WS) is

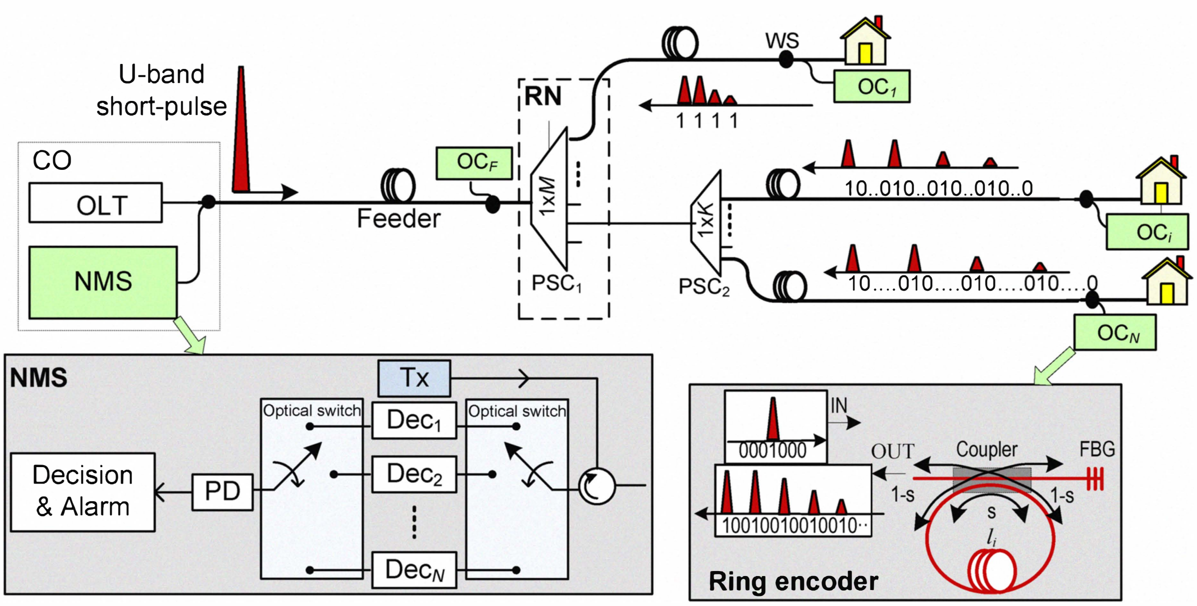

Fig. 1. PON based on Ring encoder for network monitoring.

used to separate the monitoring subpulse from the data toward the Ring encoder. The Ring encoder uses the subpulse to generate and ML-OOC and sends it back toward the CO. Once this code is received, the NMS uses a decoder to decode it and determine the status of the branch assigned with this code.

In this proposed monitoring system, no active components are placed in the field (*no power supply in the field and high reliability*) and no intelligent module is embedded inside the customer's ONT to collect monitoring information (*Centralized and customer independence*) and the system is able to collect the monitoring information *automatically* without technicians dispatching. This approach uses time-domain optical codes (single *wavelength*) and decodes them using decoders without need to use tunable OTDR or filters (*simple* and low *cost*). The passive encoders are placed outside the home before the customer premises equipment (*demarcation function*). This technique supports high network *capacity* and it is flexible with network infrastructure change (*scalability*) where only extra optical encoders are needed to be installed without change in the network infrastructure. Transmitting the monitoring pulse in the U-band and using WSs makes the technique *transparent* to the data. Using two or more PSCs is not an obstacle for this technique (*Cascading*). As each branch has its own ID (optical code), *fault detection* feature is achieved by the NMS.

IV. NEXT-GENERATION PON (NG-PON) MONITORING

NG-PON with high bandwidth is a natural path forward to satisfy the demand for high data rate requirments and for network operators to develop further valuable access services. Increasing the number of customers to 128, 256 and beyond, in addition to increasing bandwidth up to multi-hundred Mbps (or Gbps) per customer is among the requirements of NG-PONs [7]. However, most of the currently available or proposed monitoring techniques have constraints to approach this level of customers [6]. Furthermore, the high splitting ratio (128, 256) introduces severe degradation to the monitoring signal which may lead to losing the monitoring information.

The NG-PON architecture includes TDM-PON, WDM-PON and hybrid TDM over WDM-PON. They all require to develop an adequate monitoring system that can be installed on any PON regardless of its architecture. Recently, there has been increasing interest in extended-reach networks which offer the potential to reduce bandwidth transport costs by enabling the direct connection of access networks and inner core networks, thereby eliminating the costs of the electronic interface between the access and the outer core/metro backhaul network (all optical networks). These networks are called Long-reach passive optical networks (LR-PONs) [8]. LR-PON extends the PONs span from the traditional 20km span up to 100 km and beyond by exploiting optical amplifiers to composite for the large loss and wavelength division multiplexing (WDM) technologies to support more customers. The increased range and number of optical access-metro nodes, compounds the need for operation, administration, and management (OAM) technologies, particularly fault management.

In [9], we proposed a fault management and protection solution for ring-and-spur LR-PON. This solution is based on using OCs as IDs for the fiber segments between the RNs as shows in Fig. 2(a) (square boxes). Instead of installing optical encoders in the entire network (ring and TDM access networks), optical encoders are only installed in the ring to manage and protect the faults occurs within it. Fault detection is achieved by the encoders and ring duplicating is used for network protection as shown in Fig. 2(a). We found that LR-PON protection by ring duplication reduces the cost of full network to almost half as compared to full network protection with high reliability performance 99.9972%.

The RN is designed using passive components to decrease the CapEx and OpEx, and is able to forward the upstream data to both rings for network protection purpose (see Fig. 2(b)). The principle operation of the system is simple. First the NMS sends a monitoring pulse (west) and each encoder couples part of the pulse, generate a code and reflects it back to the CO. Each segment is identified by an OC connected to its end. Once a fault occurs in specific segment, the ID's OC is missed and the NMS will generate an alarm which is used then to

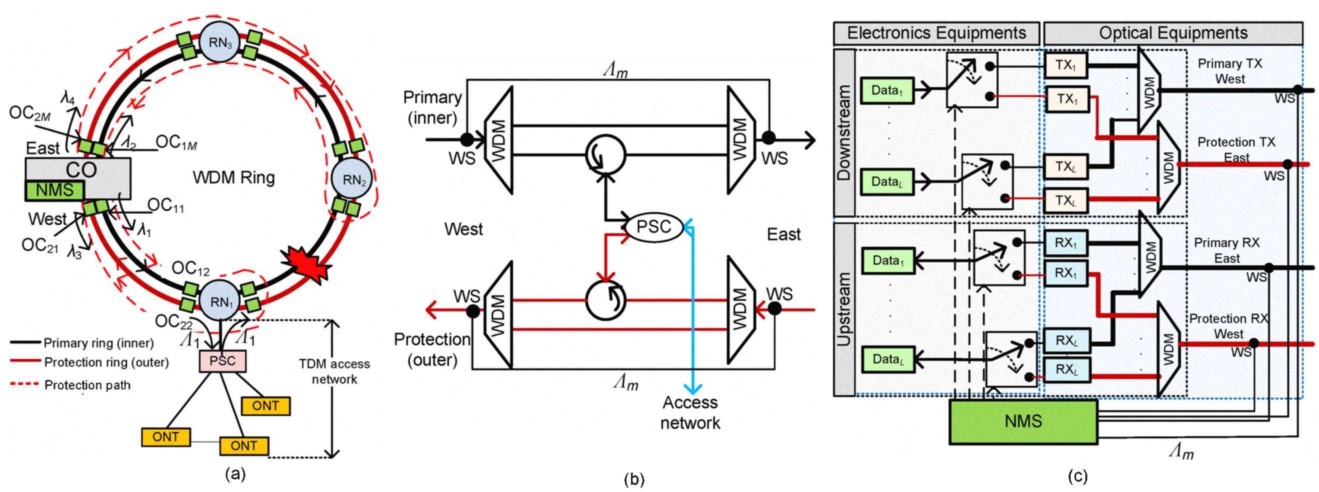

Fig. 2. Double ring LR-PON protection: (a) Ring design (OCs shown in squares), (b) RN architecture and (c) OLT architecture.

initiate the protection process. The protection process controls the operation of the optical switches located in the CO (see Fig. 2(c)) to transmit and receive data through the healthy segments of the double ring.

The optical encoder consists of simple, inexpensive and passive components (FBGs, WSs PSCs, patch cords) which reduce the NMS cost as shown in Fig. 3. It is designed in a manner to generate a code and send it to any side of the ring; hence it is called symmetrical optical encoder (SOC).

V. Optical Coding Based Monitoring System Integration with Higher Layer Protocols

Higher layer protocols and applications are widely used today by network operators to supervise access, metro and long haul transmission system. ITU-T G.984.2 (Amendment 2) and G.984.3 are two standards developed for GPON maintenance. ITU-T G.984.2 (Amendment 2) (2008) Recommendation describes some physical layer measurements to provide the G-PON system with a basic optical layer supervision capability. The method of obtaining these measurements is left to implementation choice. These measurements based on monitoring the transceivers, i.e. active components (OLT and ONT). The measurements include the transmitted and received power, temperature, voltage and laser bias current. The OLT and ONT communicate each allowing the operator to monitor, administrate and troubleshoot the network. For example, if the optical power level at the receiver is lower than a threshold, a message is sent to the opposite transmitter to increase the laser power.

G.984.3 (2008) Recommendation describes the operation, administration and maintenance (OAM) functions installed in the OLT and ONU. The alarms defined in this Recommendation include mechanisms to detect link failure and monitor the health and performance of links.

Although the measurements based on the active equipments (OLT and ONT) and the higher layer protocols provide a solution for physical layer monitoring and supervision in PON, their performance is still limited, insufficient and expensive for the network operator. Recall that one among the most important goals of ongoing research is to better optimize the finding of faults and avoid expensive dispatching of technicians and truck rolls in the field for each service interruption. In the following, we highlight the major shortages of using active components measurements and higher layer protocols to monitor the PON's physical layer:

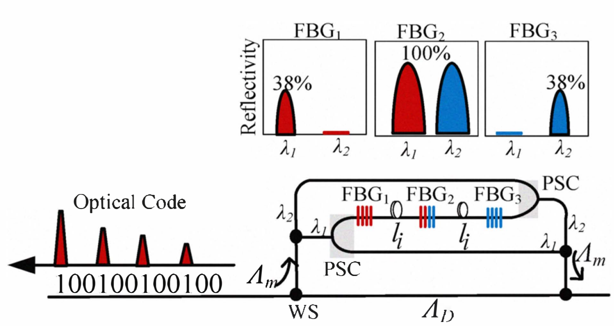

Fig. 3. FBG symmetrical optical encoder (FBG-SOE).

1- Technicians are required in the field to localize faults: Faulty branches are detected from measuring the signal quality without determining their exact location. To localize the faults, technicians should be dispatched in the field to make OTDR measurments.
2- No preventive fault detection leading to error rate degradation and data loss: In case of data degradation detected through an increasing in bit error rate (BER). In this case, the signal is already affected and none of the higher layer parameters can identify the main source of problem. Signal degradations between the transmitter and the receiver could be detected in an earlier stage before bit error detection and correction takes place. Therefore it is recommended that fault detection takes place at the layer closest to the failure, which is the physical layer for optical networks [10].
3- To use higher layer protocols, a special numerical algorithm and additional processor capacity at the endpoints of the network (OLT/ONUs) are required to collect data about the signal quality, process it and then transmit it to the central office to take decisions. This increases the complexity, cost and repairing time.
4- Higher layer protocols need to depend on the ONT equipments (which belong to the customer in some companies) in collecting monitoring information which is not preferred for the service provider.
5- In case of an ONU fault, relocating or switching off scenarios, the monitoring information from these terminals will be lost. This makes the CO confused about the real status of the branched fiber that is connected to this customer which can be taken as fiber cut whereas it is not. Then the service provider has to dispatch technicians to fix a problem that is under the customer responsibility. This induces loss of money for avoidable OpEx.

For these reasons, using active equipments measurements and higher layer protocols to monitor the physical layer of PONs is inefficient. However, an optical layer monitoring system can be integrated with the active equipments measurements and higher layer protocols to produce an efficient and complete monitoring system. This integration enables the service provider to monitor the active equipments in addition to the health characteristics of each fiber segment in the network. Table I shows some OLT alarms defined in G.984.3 Recommendation related to the physical layer where we can integrate them with the gathered monitoring information collected by our optical coding based monitoring system to end up with more effective monitoring system.

VI. Open Issues and Future Directions of Research in PON Monitoring

PON monitoring still does not have full and cost-effective monitoring capability system. Most of the monitoring techniques which are reliable and cost-effective (Optical coding is one among them) misses the fault localization feature which is a primary task for any monitoring technique. This missed feature leads us to divide the monitoring

TABLE I

OLT PHYSICAL LAYER RELATED ALARMS IN ITU-T G.984.3 RECOMMENDATION THAT WE CAN INTEGRATE WITH OUR MONITORING SYSTEM.

G.984.3 physical layer monitoring parameters			**Integrated physical layer monitoring system parameters**
Alarm Type		Detection Conditon in G.984.3	Expected role optical coding based monitoring system
LOS_i	Loss of signal for ONU_i	No valid optical signal from the i^{th} ONU when it was expected during 4 consecutive non-contiguous allocations to that ONU.	Loss of signal could originate from a fault in the branch or another source (e.g. ONU_i itself faulty). The OLT cannot determine the exact source of fault. Our system confirms if the specific branch is interrupted or there is another problem.
LOS	Loss of signal	The OLT did not receive any expected transmissions in the upstream (complete PON failure) for 4 consecutive frames.	There is no monitoring signal detected form any branch. Interruption of all ONUs signals is probable only when the fault occurs in the feeder or the RN. The OLT cannot determine the exact source of fault. Our system can determine if the loss is due to feeder problem or splitter problem.
SF_i	Signal fail of ONU_i	When the upstream BER of ONUi becomes $\geq 10^{-Y}$, this state is entered. Y is configurable in the range of 3 to 8.	In this case, the OLT cannot identify the cause of the BER degradation. Our system will help the OLT to fix the source if this originated from the fiber health or the ONU_i itself.
SD_i	Signal degraded of ONU_i	When the upstream BER of ONU_i becomes $\geq 10^{-X}$, this state is entered. X is configurable in the range of 4 to 9, but must be higher than Y (the SF_i threshold).	Similarly, in this case, the OLT cannot identify the cause of the BER degradation. Our system will assist the OLT to fix the source of the problem.

procedure into two main steps. First step, fault detection to determine the faulty branch among the different branches in PON. This is achieved by using optical coding technique. After completion this step and identifying the faulty branch, the second step is accomplished by dispatching technicans to the faulty branch location in the field and injecting an OTDR to exactly determine the location of fault. However, dispatching technicians increases the OpEx of the network. This issue requires more research to design a centralized monitoring technique with full capability, i.e. a technique that perform fault detection and localization from the CO without need for dispatching technicians.

Integrating the physical layer monitoring system with the measurments gathered by the active components and the alarms generated by the higher layer protocols needs more research and standarization to end up with more effective surveillance system. In this paper, we proposed a mangement and protection solution for one architecture of LR-PON. The different LR-PON architectures and the other types of NG-PON such as TDM-PON and WDM-PON are other open research areas.

VII. CONCLUSION

As the fiber progresses towards the home, TDM-PON maintenance is very important, to develop a reliable network and minimize the down time and OpEx. Although there is an increasing need to use efficient monitoring system for the physical layer in TDM-PONs, there is no standardized monitoring system that satisfies the PON operators' requirements till now. The lack of a centralized, comprehensive, efficient and inexpensive solution for the PON physical layer monitoring inspired us to propose new technique based on optical coding. We have presented our technique as a solution for the current deployed and for next-generation PON. Our technique uses passive, simple and inexpensive optical coding. This technique has almost all the features required by the network operator to use it as a monitoring system. We show also how we can integrate our system with the measurements collected by the active equipments and higher layer protocols to produce a more effective monitoring system.

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REFERENCES

[1] I. Heard, "Availability and cost estimation of secured FTTH architectures," in *Proceedings of International Conf. on Opt. Net. Design and Modeling* , Vilanova i la Geltru, March, 2008, pp. 1-6.

[2] K. Yuksel, V. Moeyaert, M. Wuilpart and P. Megret, "Optical layer monitoring in Passive Optical Networking (PONs): A review," *Transparent Optical Networks Conf.*, vol. 1, Athens, 2008, pp. 92-98.

[3] M. Yuang, C. Lam, H. Kuwahara and A. Willner, "Next-Generation Broadband Optical Access Network Technologies," *IEEE Journal on Selected Areas in Comm.*, vol. 28, no. 6, pp. 769 - 772, Aug. 2010.

[4] M. Tsubokawa and K. Kumozaki, "Evolution of Next Generation Access," *IEEE Globecom*, New Orleans, Dec., 2008, pp. 1 - 3.

[5] E. Harstead, "Future bandwidth demand favors TDM PON, not WDM PON," in *Proceedings of OFC/NFOE)*, Los Angeles , 2011, pp. 1 - 3.

[6] M. Esmail and H. Fathallah, "Novel Coding for PON Fault Identification," *IEEE Communications Letters*, vol. 15, no. 6, pp. 677 - 679, June 2011.

[7] J. Kani, *et al.*, "Next-Generation PON—Part I: Technology Roadmap and General Requirements," *IEEE Communication Magazine*, vol. 47, no. 11, pp. 43 - 49, Nov 2009.

[8] G. Talli, *et. al*, "Integrated Metro and Access Network: PIEMAN," in the *12th European Conference on Networks and Optical Communications*, Kista, Sweden, 2007.

[9] M. Esmail and H. Fathallah, "Long Reach PON Fault Management and Protection System," in *Proceedings of Access Networks and In-house Communications Conference (ANIC)*, Toronto, Canada, June, 2011.

[10] M. Maier, *Optical Switching Networks*, 1st ed. New York, USA: Cambridge University Press, 2008.