OCDMA and Optical Coding: Principles, Applications, and Challenges

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ABSTRACT

We survey the current trends in OCDMA and optical coding through their applications. Although a prerequisite for OCDMA, optical coding distinguishes itself from OCDMA through major applications where codes are not applied to data and carry network-level information other than user identity. After introducing the principles of coding, we discuss OCDMA and its applications, particularly OCDMA PON. Optical coding and its applications are then reviewed.

INTRODUCTION

Interest in optical code division multiple access (OCDMA) has been steadily growing during recent decades [1]. That trend is accelerating due to fiber penetration in the first mile and the establishment of passive optical network (PON) technology as a pragmatic solution for residential access [2]. In OCDMA, an optical code (OC) represents a user address and signs each transmitted data bit. We define *optical coding* as the process by which a code is inscribed into, and extracted from, an optical signal. Although a prerequisite for OCDMA, optical coding boasts a wide range of novel and promising applications, such as OC label switching.

Most previous reviews of OCDMA focus on physical-layer implementations and present an overview of networking applications. In addition, to our knowledge, none of the prior reviews of OCDMA address optical coding as a separate field with its distinctive applications. This work is an overview of both OCDMA and optical coding through their major applications. We give a summary of principles common to optical coding and OCDMA. OCDMA and its applications, particularly PON, are examined. The main advantages, challenges, and tradeoffs of OCDMA as a PON candidate technology are briefly listed. Then, we introduce optical coding and its prominent applications. We conclude with a discussion of future trends.

PRINCIPLES OF CODING IN THE OPTICAL DOMAIN

OCDM is a multiplexing procedure by which each communication channel is distinguished by a specific optical code rather than a wavelength or time-slot. An encoding operation optically transforms each data bit before transmission. At the receiver, the reverse decoding operation is required to recover the original data. The encoding and decoding operations alone constitute optical coding. OCDMA is the use of OCDM technology to arbitrate channel access among multiple network nodes in a distributed fashion.

Encoding involves multiplying the data bit by a code sequence either in the time domain, the wavelength domain, or a combination of both. The latter method is called two-dimensional coding (2D-coding) [3]. Figure 1 illustrates the three coding principles. In a time-encoded signal, the bit is split into smaller time components called chips. Time-domain coding that manipulates the phase of the optical signal is usually *bipolar* and requires phase-accurate coherent sources. Alternatively, *positive* encoding manipulates the power of the optical signal but not its phase and typically uses incoherent sources [1, 4]. In wavelength-domain coding, transmitted bits consist of a unique subset of wavelengths forming the code. 2D-coding combines both wavelength selection and time spreading. A data bit is encoded as consecutive chips of different wavelengths, the unique wavelength sequence constituting the code. Decoding consists of applying the reverse time/wavelength operations. Regardless of the coding domain, the coding operation broadens the spectrum of the data signal, hence the designation of *spread spectrum*. Note that encoding can also be performed in the space-domain, whereby the code determines the positions of chips within a dense fiber array or a multicore fiber [5].

An OCDMA local area network (LAN) is based on a broadcast medium. Signals from different encoders are coupled and each decoder receives the sum of the encoded signals. If a given encoder transmits a signal, only the decoder with the same code is capable of recovering it. Unwanted signals appear as noise to the decoder and are called multiple-access interference (MAI). MAI is the principal source of noise in OCDMA and is the limiting factor to system performance. In a well-designed OCDMA LAN where MAI is overcome, users can successfully communicate asynchronously and regardless of network traffic.

Decoding a signal encoded by the same

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code represents a logical auto-correlation of a single code. Otherwise, the operation represents a cross-correlation between two different codes. Code design aims at generating codes with high auto-correlation and low cross-correlation properties. More particular requirements on code design arise from the use of specific transmission media or components. Various code families have been proposed to address such requirements [6]. Code length is an important feature of code and system design. A larger code length improves correlation properties among codes, hence raising system performance in terms of MAI, bit error rate (BER), and throughput.

A vast array of physical-layer methods have been proposed to implement optical coding. This gives rise to alternative classifications using component characteristics rather than the coding dimension. For instance, employing incoherent versus coherent light sources is often used to classify OCDMA systems because that choice has important cost and performance implications [7]. Note that the choice of coherent sources does not always imply that chips are phase rather than power modulated [1]. In addition, whether the encoding occurs in fiber, in a planar lightwave circuit (PLC), or in an out-of-fiber external device has an important impact on system design. Table 1 presents different classifications for the encoding techniques listed in [4].

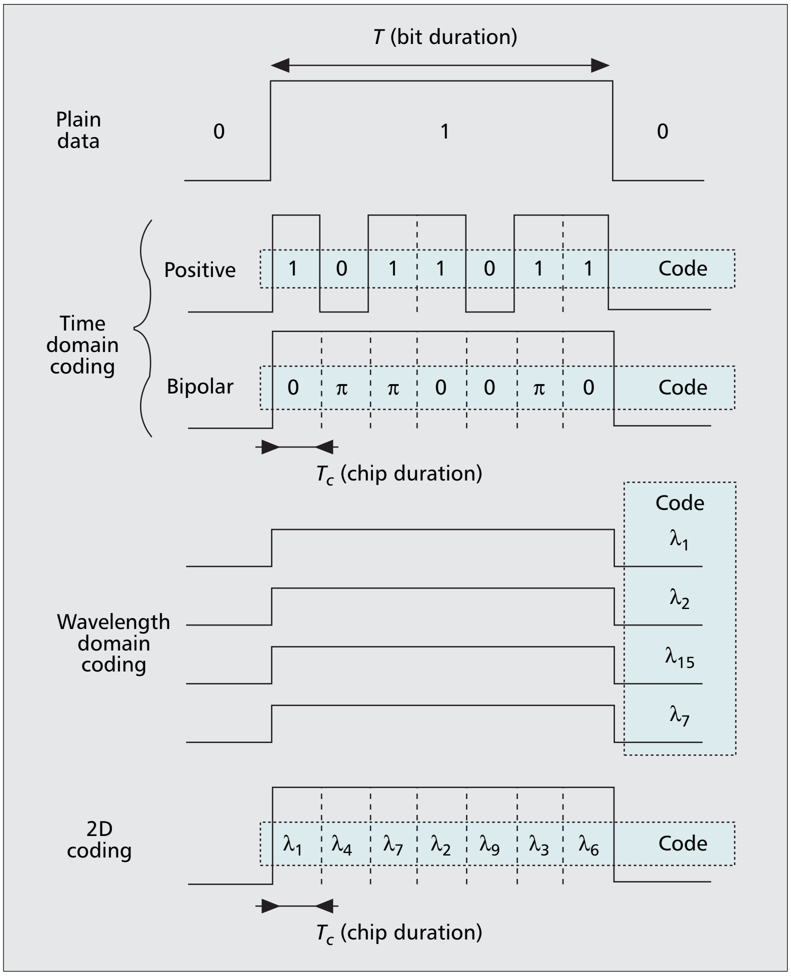

Figure 1. *Optical coding dimensions.*

Throughout this work, we distinguish multiplexing techniques (xDM) from multiple access (xDMA). The former focus on transport, and the latter denotes distributed access methods, as mentioned previously for OCDM and OCDMA. For example, in an OCDMA-over-wavelength-division multiplexing (OCDMA/WDM) network, all nodes require an OCDMA transceiver. Each wavelength is used as a medium for a number of OCDMA channels [6].

OCDMA AND ITS APPLICATIONS: CODES AS USER ADDRESSES

OCDMA is based on the principle that codes are mapped to the identities or addresses of users following a code-user relation. Accordingly, OCDMA was initially proposed to implement ultrafast asynchronous broadcast LAN.

FROM LAN TO PON

LAN and PON contender techniques include TDMA, SCMA, and WDMA, denoting time-, subcarrier-, and wavelength-division multiple access respectively [2]. In TDMA, a time slot is allocated to each user statically or dynamically. TDMA already is deployed in two forms: asynchronous transfer mode PON (with various extensions) and Ethernet PON (EPON). In WDMA, each user has a specific wavelength. Both TDMA and WDMA benefit from the maturity of electrical multiplexing and optical transmission gained in backbone networks. TDMA/WDM is proposed as a viable extension to TDMA that achieves dynamic bandwidth allocation (DBA) on multiple wavelengths [8]. In SCMA, microwave channels are multiplexed electrically, and the composite signal modulates the optical carrier. SCMA is commonly used in hybrid fiber-coax networks to carry broadcast community access television (CATV) channels. SCMA/WDM has notable applications in radio-over-fiber networks [2].

The combination of three potential advantages makes OCDMA attractive from a networking perspective. First, OCDMA offers a larger channel count than the spectral division of WDMA. Second, asynchronous transmission simplifies access control to the medium compared to TDMA. Finally, multi-class traffic can be implemented by using different code lengths simultaneously. The motivation for LAN implementation of OCDMA is reinforced by the expectancy that LAN traffic patterns, characterized by burstiness, favor a technique where a large number of users may gain access provided fewer are statistically active at the same time.

With its considerable channel count, dense WDM (DWDM) may surpass OCDMA by offering enough channels for LAN applications in addition to simpler implementations. Access environments, however, require even larger channel counts than LAN and stand to benefit from the simplicity of asynchronous transmission and quality of service (QoS) differentiation, hence the transition of the focus of OCDMA research to access network PON.

Coding domain	Encoding device	Chip modulation	Source	Medium
Time	Fiber delay lines	Power, phase	Coherent, incoherent	In-fiber, PLC
	Mach-Zehnder interferometer	Phase	Coherent	External
	External phase modulator	Phase	Coherent	External
	Phase modulator and Local oscillator	Phase	Coherent	External
	PLC w/delay and phase modulators	Phase	Coherent	PLC
	Segmented fiber grating	Phase	Coherent	In-fiber
	Uniform Bragg grating	Phase	Coherent	In-fiber
Wavelength	Liquid crystal modulator	Phase, power	Coherent	External
	Broadband source	Power	Incoherent	In-fiber
	AWG and phase-plates	Phase	Coherent	PLC
	Superstructured Bragg grating	Phase	Coherent	In-fiber
	AWG and holograms	Phase	Coherent	External
2D	Fiber Bragg grating	Power	Incoherent	In-fiber
	Integrated laser source-encoder	Phase, power	Incoherent	PLC
Space	Holograms	Power	Incoherent	External

■ **Table 1.** *Various classifications of the encoding techniques listed in [4].*

OCDMA FOR ACCESS NETWORKS

OCDMA is viewed as a candidate technology for future PON access networks [2, 3, 6, 7]. An OCDMA PON uses a tree topology with passive power splitters. Each optical network unit (ONU) contains an encoder and decoder with unique fixed codes. The optical line terminal (OLT) may contain all encoder-decoder pairs required for communication with each ONU [6] or a smaller number of tunable encoder-decoders. In contrast to LAN, OCDMA PON are not fully broadcast systems, because the signal transmitted by an ONU never reaches other ONU. Hybrid OCDMA/WDM systems have been proposed [6]. More ambitious contributions introduce mapping universal IP addresses to OCDMA codes [9].

OCDMA POTENTIAL STRENGTHS

OCDMA has considerable potential on the networking level. A well-designed OCDMA access network eliminates channel contention. In other words, provided interference is controlled, an upstream or downstream connection can be established asynchronously with no collisions or blocking. The networking implications are substantial. The following is a brief description of the main assets OCDMA exhibits from a networking perspective:

- Network operation and management are greatly simplified. Ideally, no channel control mechanism (such as a Medium Access Control protocol) is required to avoid collisions or allocate bandwidth. No synchronization scheme or scheduling algorithm is required, eliminating an important source of processing and overhead in TDMA-based systems. In addition, ONU are not required to report the instantaneous bandwidth requirements to the OLT, thereby reducing round-trip walk time and delay.
- OCDMA supports a larger number of users than TDMA or WDMA, especially 2D-OCDMA systems where codes exploit both time and wavelength dimensions. It is possible for an even larger number of codes to be assigned in OCDMA if an access protocol is used.
- OCDMA offers the same virtual topology as WDMA, using a simpler network configuration. Like WDMA, OCDMA offers a virtual point-to-point topology over a physical tree architecture. However, to achieve this, WDMA requires an in-field WDM multiplexer or individual wavelength filters at the ONU. OCDMA requires the cheaper power-splitter but incurs the larger power losses associated.
- OCDMA access systems may accommodate additional users with less cost and complexity. A new TDMA or WDMA user reduces free bandwidth irreversibly, thus requiring changes to bandwidth allocation. For instance, for every new user added in TDMA, the OLT may be required to run the admission control procedure to protect bandwidth previously guaranteed under ONU service-level agreements (SLA). In OCDMA, adding a user does not reduce the bandwidth of other users. By virtue of its inher-

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ent bandwidth and quality fairness, OCDMA avoids the complexity of measures such as admission control.

- OCDMA, like WDMA, exhibits transparency. ONU can operate at lower speeds than the OLT, use different bit rates, formats, and protocols, and undergo upgrades independently. In TDMA, ONU require high-speed transceivers and queuing to enable them to communicate with the OLT, regardless of their input data speed.
- OCDMA offers all-optical granularity. Unlike WDMA and TDMA/WDM, OCDMA can accommodate a large number of low bit-rate users on the same optical medium. Moreover, using multi-rate OCDMA techniques, low- and high-bitrate channels can be provisioned on the same OCDMA network. Such aspects correspond to access traffic patterns and are highly desirable as they eliminate electronic grooming.
- ODMA is particularly suited for symmetrical access network operation, with OLT and ONU transmitting at multi-gigabit rates. ATM PON design was conducted on the assumption that downstream traffic largely exceeds upstream traffic [2]. Kitayama et al. argue that the growing peer-to-peer nature of applications will generate sizeable symmetrical traffic. OCDMA offers the capability to support high-speed symmetrical traffic for a larger number of ONU than WDMA. They propose an OCDMA/WDM system serving up to 512 ONU, each having symmetrical traffic ranging from 2.5 to 10 Gb/s [6]. Current EPON implementations use 1 Gb/s in both upstream and downstream directions.
- Finally, OCDMA exhibits higher levels of security; whereas TDMA and WDMA require encryption at the electrical level.

At the physical layer, OCDMA also presents important advantages. Unlike wavelengths in WDMA, well-designed OCDMA codes yield channels with inherent bandwidth and signal quality fairness. Special codes also can be designed to make OCDMA robust in hostile conditions, such as wavelength drifts, without additional equipment [1].

OCDMA IMPLEMENTATION CHALLENGES AND TRADEOFFS

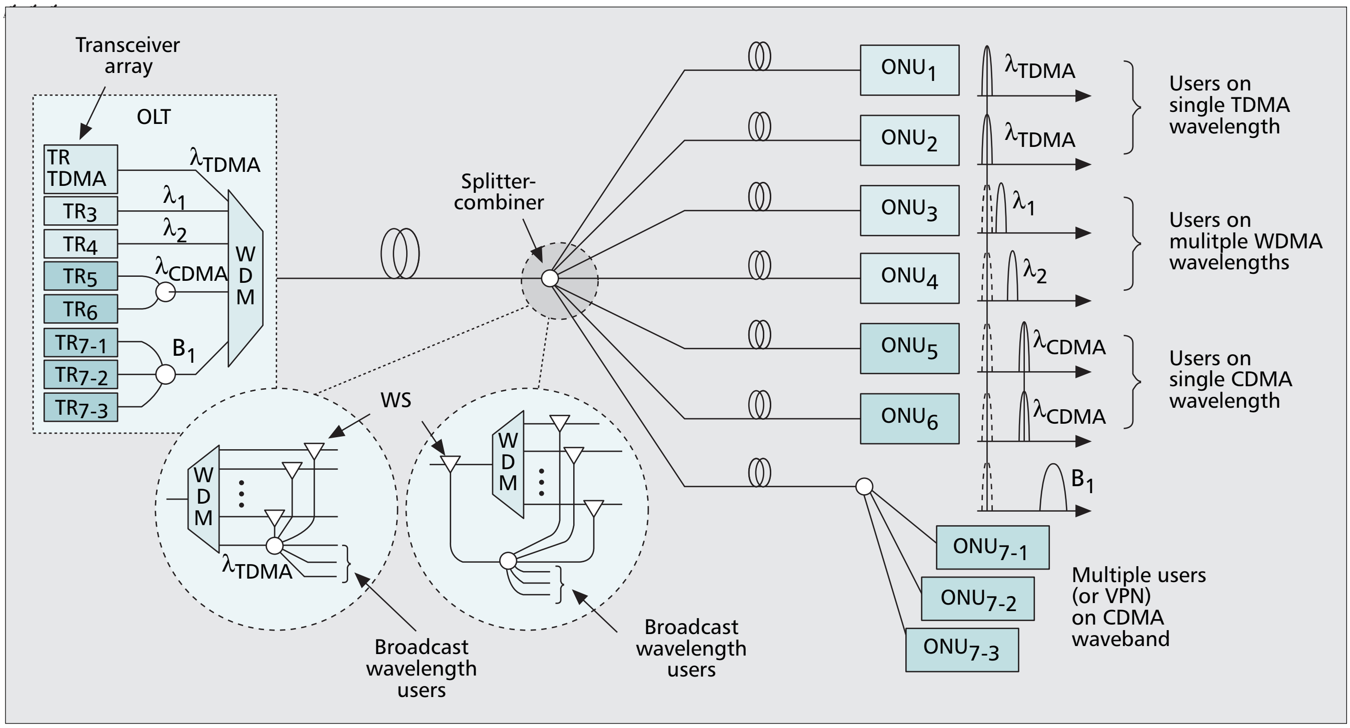
The main barriers to OCDMA deployment reside in the physical layer. OCDMA implementations span a large array of disparate optical and optoelectronic component technologies [1, 7]. Most of those techniques are experimental. The following is a discussion of the major physical layer impairments of OCDMA and related tradeoffs:

- In OCDMA, MAI exacerbates two major types of noise: beat noise and shot noise. WDMA and TDMA do not suffer as much from those physical impairments [3]. At the photodetector, MAI translates into shot noise that limits system scalability in terms of number of ONU. Beat noise is generated optically between pulses with close wavelengths and is a major source of noise for most OCDMA systems [3, 6].
- Component cost and complexity are key issues in OCDMA system design. For instance, the tunability of encoders and decoders presents a significant challenge compared to tunability of WDMA transceivers. In addition, currently available broadband light sources required for spectral or 2D-OCDMA operation are either expensive or do not offer enough intensity [3]. One proposed solution is a single centralized broadband source at the OLT similar to the concept of colorless ONU in WDMA [7].
- OCDMA is limited in network reach by dispersion due to the high encoded signal bit rate and high power budget required [2].
- The authors in [7] survey all existing coherent and incoherent OCDMA and WDMA testbeds and compare their performance in terms of bit rate per channel and maximum number of users. The use of coherent sources (lasers) in OCDMA yields higher performance, but lasers are more costly and sensitive than incoherent light sources, such as amplified spontaneous emission (ASE) from optical amplifiers or super-luminescent diodes (SLD). The cost of maintaining coherent transceivers in distributed locations (i.e., the access environment) is higher for both WDMA and OCDMA. On the other hand, employing incoherent sources produces simpler and cheaper configurations, albeit lower performance.
- Owing to its spread-spectrum nature, spectral efficiency in OCDMA is theoretically lower than for WDMA, especially in incoherent systems. A related "perception-barrier" [3] to OCDMA consists in the non-acceptance of the tradeoff between spectral efficiency and the higher-level advantages offered by OCDMA. Stok et al. argue that the optical medium calls for such a tradeoff due to its large available bandwidth. There is little research that includes the effect of OCDMA strengths such as bursty traffic and reduced delay and protocol overhead on its spectral efficiency.

GRADUAL EVOLUTION PATHS TOWARD OCDMA PON

OCDMA PON propositions suffer from a lack of transitional models that take into account legacy systems. Entire OCDMA networking systems usually are presented as bulk replacement alternatives. However, many design issues must be demonstrated if OCDMA access PON are to emerge. Beyond OCDMA transceiver operation, research must control noise sources and MAI to achieve acceptable BER levels. PON architecture must incorporate accurate power budgeting in accordance with ONU distance, bit rate, and QoS class. Network planning must provision codes for new users and insure that power budgeting is adaptive to user addition or retrieval. Most importantly, resulting transceiver OLT and ONU devices must be manufactured and deployed at acceptable costs.

We believe that to become viable, serious propositions must include the gradual migration paths from WDMA to OCDMA as is the case presently from TDMA to WDMA [8]. Such migration paths offer partial implementations that postpone some of the research elements required for full OCDMA PON. The following scenarios outline possible and gradual OCDMA upgrades.



■ **Figure 2.** *Hybrid OCDMA-WDMA-TDMA PON architecture.*

Serving New Areas with the Same PON — Adding a PON fiber leg carrying a new wavelength or waveband may serve a cluster of OCDMA users rather than a single WDMA user. The new ONU are equipped with OCDMA transceivers, and the OLT harbors an array of OCDMA transceivers corresponding to the OCDMA user codes.

Serving New Local Users with OCDMA — Adding new PON users may be achieved by replacing an existing WDMA channel by a number of OCDMA channels multiplexed over the same wavelength and serving more than one end-user. At the OLT and ONU, the WDMA receivers are replaced by a power splitter and one OCDMA transceiver for each new user. This scenario may apply to local community networks or enterprise virtual private networks (VPN), using electronic aggregation over a single WDMA channel and upgrading to optical multi-class and multi-rate networks. At the ONU end, fiber may be extended from the splitter to reach remote premises.

Figure 2 illustrates possible evolution scenarios. The shaded ONU and transceivers (TR) use OCDMA. The splitter-combiner may be replaced by various architectures employing WDM multiplexers and wavelength/waveband selectors (WS). WS devices are passive WDM multiplexers with lower wavelength granularity and are typically used to separate data and signaling wavebands [10]. To maintain broadcast signals in the WDM multiplexer configurations, the broadcast wavelengths (TDMA, OCDMA) must be separated from the point-to-point wavelengths (WDMA) so as to split their power among all users. WS devices separate or merge the broadcast signals. Note that the PON configuration in Fig. 2 allows both TDMA and WDMA ONU to remain untouched and co-exist with the OCDMA upgrade of individual ONU, including the potential use of the legacy TDMA wavelength for broadcast services [8].

OTHER OCDMA APPLICATIONS

Due to its advantages, OCDMA was proposed to support a number of other applications. Some of them are briefly described in the following paragraphs.

Metro-Level Optical VPN — A wavelength-routing metropolitan optical network may provide lightpaths for VPN connections. These links carry a multitude of OCDMA signals that are multiplexed and demultiplexed at the end-points. The primary goal of a VPN is to provide secure data links over an insecure platform. The OCDMA signals provide enhanced security and can be decoded only at the corresponding end point. The use of OCDMA for all-optical VPN simplifies network design by replacing electronic multiplexing and grooming with optical splitting and combining. Light-tree capabilities at the metropolitan network level can be used to enable the establishment of multipoint VPN.

Image Transmission — Image transmission using TDM requires the encoding of images as pixel streams and multiplexing the streams of different users at the source node using parallel-to-serial conversion. At the destination node, individual user pixel streams must be separated using serial-to-parallel conversion before recovering the images from pixel values. OCDMA has been proposed to remove the *bottleneck-prone* [5] parallel-to-serial and serial-to-parallel conversions: pixel streams are transmitted simultaneous-

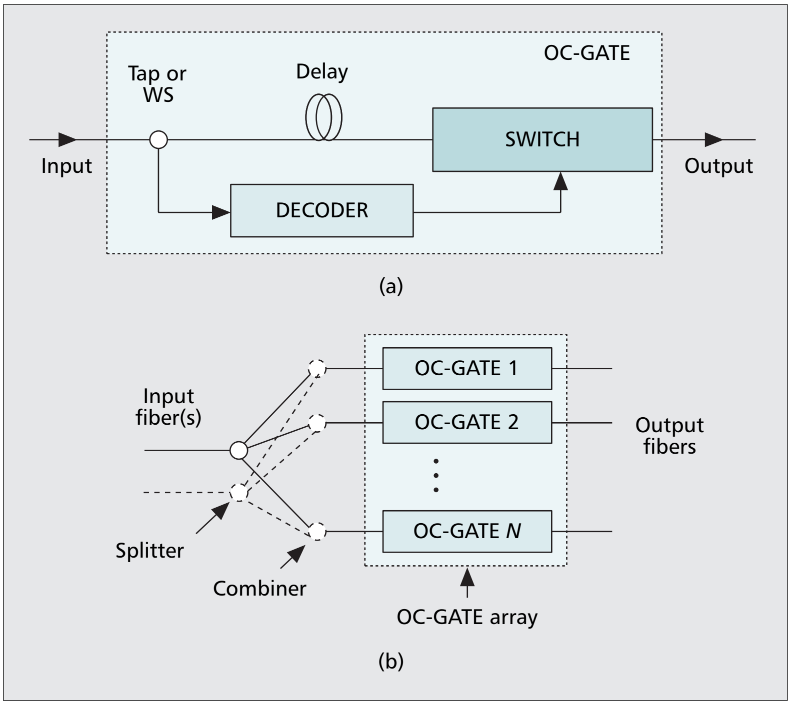


Figure 3. *OC label switch architecture.*

ly over user-specific code-channels. The implementation of OCDMA with multiple service levels for this application was introduced in [5].

Radio-Over-Fiber — Radio-over-fiber enables a fiber access network to connect wireless base-stations. Due to the OCDMA large channel count, the mapping of individual radio channels to OCDMA channels for multiplexing and transport to the core network has been proposed in [11].

OPTICAL CODING AND ITS APPLICATIONS: INFORMATION-BEARING CODEWORDS

In optical coding, codes may correspond to network-layer information other than user identity. In a typical example of this *code-information* relation, codes denote optical paths in multiprotocol label switching (MPLS). Codes can also represent optical control and signaling messages in optical burst switching (OBS), network fault detection, and maintenance. In such applications, optical coding achieves a form of optical information processing. It brings network-layer operations to the optical medium, further reducing the burden of electronic processing. OC processing rates are limited only by the speed of light in the encoding/decoding device. The following sections describe the most important applications of optical coding.

ALL-OPTICAL SWITCHING AND LABEL ROUTING

OC label switching is among the most promising implementations of optical coding. In an OC label-switched network, optically-encoded pulses are added to fixed-length packets as headers that specify the route or label-switched path (LSP).

In an OC label switch (OCLS), each output port is controlled by a header-sensitive switching device called an optical code gate (OC-gate). OC-gates allow through only packets with a specific header (OC-label).

Figure 3a depicts a simplified OC-gate architecture. The OC-label is tapped at the OC-gate input and fed to the OC-gate decoder while the packet enters a delay line. If the OC-label matches the decoder, the resulting optical pulse triggers an on-off electro-optical switch in time to allow the packet through. Only packets with an OC-label correlating with the decoder can cross the OC-gate. The switch maintains the optical path open for the duration of one packet.

In an OCLS, packet power is split among router outputs, as shown in Fig. 3b. Only the output with the same code as the OC-label forwards the packet, thus completing the switching process. In a more integrated approach, the OC-label may be tapped at the label switch input and fed to an array of decoders, each of which controls a specific output [12, 13]. Although this architecture uses one common delay line for all outputs, we preferred to introduce individual OC-gates , to their expected versatility, particularly for optical network control and signaling.

The OC-gate array in Fig. 3b may be duplicated for each input fiber on a separate switching plane [12] or reused by more than one input fiber (dashed connections). Amplification and pulse reshaping stages can also be required. OC-labels may be in-band [12] or out-of-band [13] with the optical packet. Out-of-band labels are simpler to implement, because they can be easily stripped using WS devices or be transmitted alongside the packet rather than prior to it [13].

OPTICAL CONTROL SIGNALING AND OBS

Optical coding benefits from the fact that more information can be packed all-optically in a coded pulse than in a wavelength assignment. We use the term *codeword* to designate a pulse encoded in a unique code and corresponding to a specific piece of information or set of commands. Like an OC-label, a codeword can carry photonic signaling information such as the status of links and equipment for maintenance, the availability of communication channels such as wavelength lightpaths, and control commands for dynamic switches. OC-gate-like devices enable the photonic processing of codewords at optical speeds. Condensing relevant information in a codeword inserted in a control packet is an alternative to electronic processing of an optical control packet. In addition to the elimination of electronic processing time, codewords reduce control packet overhead. The mapping of codes to relevant values (quantities or commands) requires the provision of enough codes to span the entire set of information values. Longer codes enable condensing more information in a single codeword.

OBS offers an interesting application of control codewords. In OBS, data to be transmitted is arranged in large bursts rather than packets. A control packet is sent prior to a data burst to insure that the switch resources are reserved and the switching fabric is configured to forward the arriving burst along the route. An important system parameter for OBS is the delay between the arrival times of the control packet and the data burst, called the offset time.

Kitayama and Murata propose an OBS network that uses the just-enough-time (JET) signaling protocol [12]. The control packet is required to contain only two relevant pieces of information: burst length and offset time. Time-duration values are mapped onto unique codewords inserted into the control packet. The offset time seen by each OBS-switch decreases as the burst progresses along its path. Therefore, at each switch, the codeword is processed by a decoder array and swapped for a new updated codeword. If the lightpath is unavailable, a non-acknowledgement (NCK) message is sent back to the destination via the reverse path. The advantages of this implementation include lower control-packet processing latency, greatly reduced offset time, and lower control packet loss [12].

NETWORK MONITORING AND OC-OTDR

The goal of optical time-domain reflectometry (OTDR) technology is to monitor fiber plant quality and detect faults, particularly fiber cuts. It is based on the emission of out-of-band optical pulses and the analysis of resulting reflections. Pulse reflection analysis reveals the position of cuts, as well as any optical devices causing unusual reflection losses such as faulty connectors. OTDR has found wide-scale applications in WDM backbone point-to-point links. In PON, a pulse emitted downstream may generate reflections at any of the PON branches. The localization of an eventual faulty branch is impossible, unless upstream OTDR is performed at each ONU.

Fathallah and Rusch proposed a resourceful way of identifying the branch provenance of pulse reflections using optical coding [10]. Each branch is equipped with encoder devices (Fig. 4). Each of those devices encodes the emitted pulse using a specific code that identifies the network branch. An optical switch and decoder array are required at the central office to select the monitored branch. Waveband separators break up the monitoring waveband from the data waveband at the ONU and the OLT [10]. Using remote pulse encoding, downstream OTDR identifies the location of cuts or defective devices in a PON.

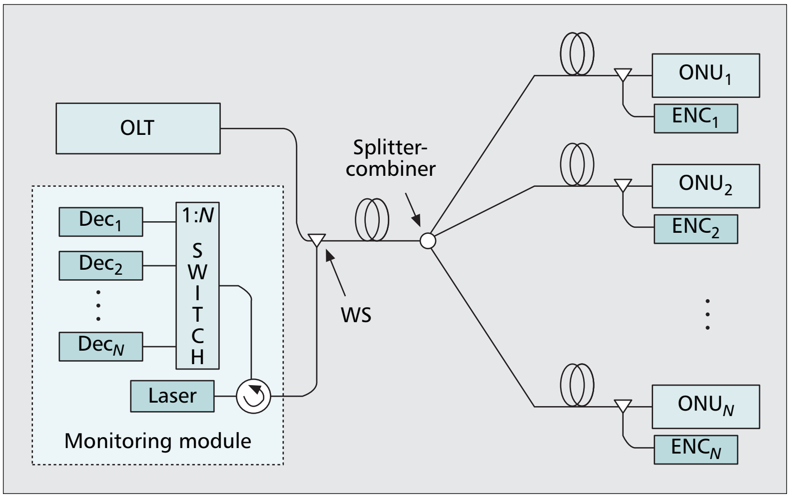


Figure 4. *4 OC-OTDR monitoring system [10].*

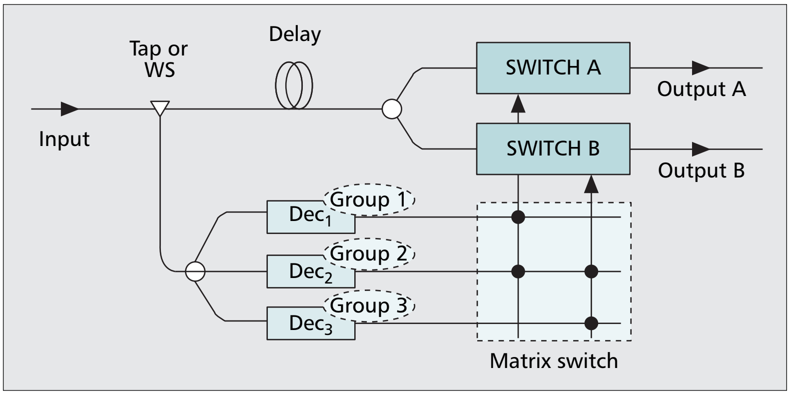


Figure 5. *OC-multicast switch architecture [14].*

ALL-OPTICAL MULTICASTING

OC label switching may be extended to implement a multicast (MC) tree network where optical codes denote MC groups as well as individual end-users [14]. The network topology considered is a tree where MC-enabled OC label switches reside at each node except the end nodes. Packets are labeled with OC pulses corresponding to their MC group. Figure 5 illustrates the architecture of an OC-MC switch.

Node switches tap the OC-label and split it among a set of decoders representing the MC groups while the packet goes through a delay line. Using an electrical matrix switch, group decoders can activate more than one on-off switch. That process results in the release of more than one copy of the data packet towards the corresponding end-nodes, if required. In the example of Fig. 5, a packet addressed to group-2 is forwarded through both output paths, whereas packets addressed to groups other than group-1, -2, or -3 are discarded.

This method achieves high-speed multicasting. The use of OC instead of wavelengths improves scalability by enabling more MC groups [14]. The major downside is large and cumbersome MC switches.

CONCLUSION

When it comes to OCDMA, it is difficult to generalize. The advantages stated are often specific to particular technologies, techniques, or components, thus implying drawbacks and tradeoffs. For instance, the cheapness of incoherent light sources implies a limit on the network reach (due to dispersion), BER, and user bandwidth. Although this work attempts to synthesize and address the common aspects of OCDMA, a better understanding requires an in-depth study of each OCDMA technique such as [1].

It seems impossible to predict with certainty whether OCDMA will conquer the access network in the same way as CDMA has become the standard in wireless communications. If the development of the Ethernet is any indication, successful deployment is related to the initial simplicity and efficiency of a given solution. Therefore, OCDMA requires significant component development in the short term to become viable. With the rapid expansion of photonics, this cannot be excluded. However, other paths can prove simpler to implement. One such path may be space-division multiplexing (SDM), which relies solely on advanced space-switching techniques.

Although optical coding requires mature photonic encoder and decoder technology, it avoids the more elaborate system design issues required for OCDMA to emerge. For instance, encoded pulses that serve as device triggers, network information carriers, or monitoring signals, may use lower bit rates than data [10]. This alleviates some of the physical boundaries challenging OCDMA deployment such as dispersion and beat noise. Therefore, optical coding techniques are expected to continue developing independently from OCDMA.

The use of optical coding for ultrafast optoelectronic device control can be further generalized. The applications mentioned previously encode information using single codewords. An alignment of multiple codewords (different OC) may be used to represent more information. The use of single- or multiple-codewords as ultrafast control is not limited to telecommunications applications and forms a step towards optical information processors.

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BIOGRAPHIES

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It seems impossible to predict with certainty whether OCDMA will conquer the access network in the same way as CDMA has become the standard in wireless. If the development of the Ethernet is any indication, successful deployment is related to the initial simplicity and efficiency of a given solution.