The Role of Optical CDMA in Access Networks

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ABSTRACT

We investigate the possible role of optical CDMA (O-CDMA) in future access networks. We begin with a short review of the O-CDMA technique for those unfamiliar with the technology. Next, we investigate in detail those characteristics of O-CDMA that make it an attractive technology for application in metro access networks: fairness, flexibility, simplified network control and management, service differentiation, and increased security. Although O-CDMA has many favorable attributes, it also has several actual or perceived drawbacks. We discuss the technical, economic, and perception barriers that may have limited the widescale deployment of O-CDMA access networks. We try to determine which of these drawbacks may be surmountable in the near future and which may be true "show-stoppers."

INTRODUCTION

Optical code-division multiple access (O-CDMA) combines the large bandwidth of the fiber medium with the flexibility of the CDMA technique to achieve high-speed connectivity. CDMA was originally investigated in the context of radio frequency communications systems, and was first applied to the optical domain in the mid-1980s [1, 2]. These researchers sought to use the excess bandwidth in single-mode fibers to achieve random asynchronous operation without the need for a centralized network controller.

In an O-CDMA system, each bit is divided up into n time periods, called chips. By sending a short optical pulse during some chip intervals, but not others, an optical signature sequence, or codeword, can be created. Each user on the O-CDMA system has a unique signature sequence. The encoder of each transmitter represents each 1 bit by sending the signature sequence; however, a binary 0 bit is not encoded and is represented using an all-zero sequence. Since each bit is represented by a pattern of lit and unlit chips, the bandwidth of the data stream is increased. O-CDMA is therefore a spread-spectrum technology.

The O-CDMA encoded data is then sent to the $N \times N$ star coupler (in a local area network) or a $1 \times N$ coupler (in an access network) and broadcast to all nodes. The crosstalk between different users sharing the common fiber channel, known as the multiple access interference (MAI), is usually the dominant source of bit errors in an O-CDMA system; therefore, intelligent design of the codeword sequences is important to reduce the contribution of MAI to the total received signal.

An alternative approach, which reduces the demands on the electronic hardware, is to spread the optical orthogonal codes in both the temporal and wavelength domains simultaneously. Instead of viewing each wavelength as a separate channel that can support a set of optical orthogonal codes, the time chips and wavelength channels can be viewed as the axes of a two-dimensional codeword. Figure 1 demonstrates how the multiwavelength (or two-dimensional) optical CDMA scheme compares to conventional wavelength-division multiple access (WDMA) and time-division multiple access (TDMA) approaches.

OPTICAL CDMA FOR ACCESS NETWORKS

In a data communication system, the access (or distribution) network directly interfaces with the customers' premises and is responsible for delivering and collecting traffic [3]. This access network should employ a multiple access technology that is fair, flexible and inherently secure. In this section, we discuss why O-CDMA may be a suitable candidate for deployment in these access networks.

FAIR DIVISION OF BANDWIDTH

Optical CDMA provides a way for many active users to share the optical bandwidth in a fair manner. Through the use of optical codes with some degree of time domain spreading, the number of active users can be made much larger than the number of available wavelengths. The bandwidth of the fiber medium is partitioned

Adding a new user on an optical CDMA system is as easy as assigning a new code, assuming that the extra (unused) codes were provisioned when the network was deployed. If no free codes were available, the system could be upgraded to support more users by increasing the amount of time-or wavelength-domain spreading.

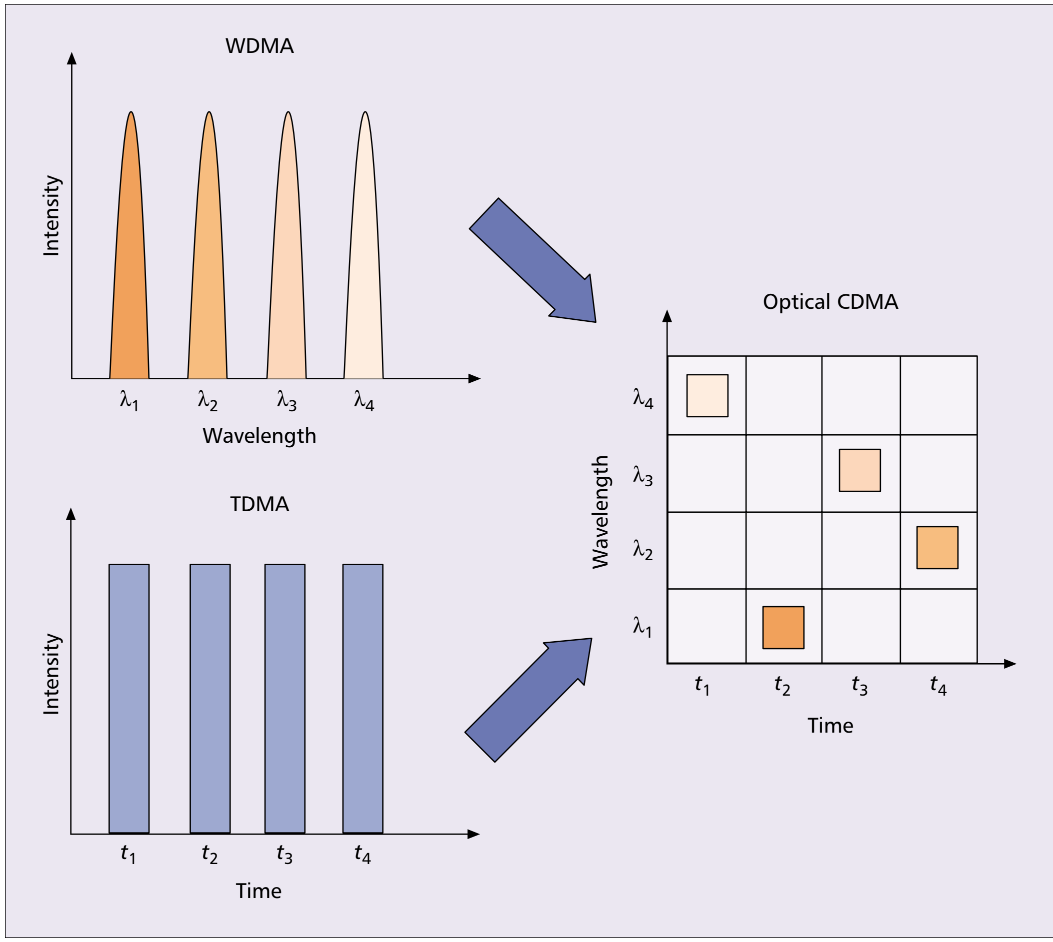

Figure 1. *The relation of optical CDMA to wavelength- and time-division multiple access.*

into a number of virtual channels, one for each station on the network. The large number of parallel channels eliminates channel contention; however, we pay the price of increased crosstalk with the addition of each active user. All users on the network have access to an equal portion of the shared bandwidth, and one user cannot block access to the channel for any other user (if we ignore contention for a common receiver); therefore, O-CDMA networks achieve the ideal in network fairness.

FLEXIBILITY

Second, O-CDMA systems have the potential to be very flexible. As shown in Fig. 1, two-dimensional O-CDMA codes that use both time and wavelength domain encoding have been developed. In addition to having favorable cross-correlation and autocorrelation characteristics, these two-dimensional codes allow a network designer to tailor the spreading to the particular system under design. The aspect ratio of the 2D codewords is not fixed; therefore, to achieve a specified BER more wavelength spreading may be desirable in a system with a high channel count while additional time-domain spreading may be performed in a system with a low channel count. In O-CDMA, performance can also be traded for robustness. Fathallah and Rusch [4] have shown that through appropriate code design, O-CDMA could be used in hostile noncontrollable environments. By sacrificing capacity, in terms of the maximum number of users that can be supported, the wavelength drifts due to temperature fluctuations could be controlled entirely through the use of robust codes. This eliminated the need for complex, expensive frequency control loops to manage wavelength drift.

NETWORK CONTROL AND MANAGEMENT

Third, the use of O-CDMA entails simplified network control and management. If the optical codes are designed such that the non-shifted autocorrelation peak is large and the shifted autocorrelation peak is minimized, each receiver is able to operate asynchronously without the need for a global clock signal. Since the number of unique codes is equal to the number of stations on the network, there is no need for a centralized node (or a complex protocol) to arbitrate channel contentions.

Adding a new user on an O-CDMA system is as easy as assigning a new code, assuming that the extra (unused) codes were provisioned when the network was deployed. If no free codes were available, the system could be upgraded to support more users by increasing the amount of time- or wavelength-domain spreading. The amount of coding overhead could also be increased if it were determined that quality of service (QoS) contracts for the bit error rate were being violated.

Service Differentiation

Next, O-CDMA offers the possibility of offering differentiated service or QoS at the physical layer. Through the use of multirate O-CDMA codes [5, 6], different service classes for multimedia traffic can be defined. Low-rate codes could be used for email and file transfer while high-rate codes could be used for the transfer of audio and video information.

In a previous paper [7] we proposed the provisioning of QoS at the physical layer through dynamic coding. Should the network detect high MAI levels that compromise previous QoS guarantees, new signature sequences could be allocated to all nodes to satisfy both new and existing QoS contracts. As shown in Fig. 2, each node could be equipped with a simple and inexpensive photodiode that measures the total energy on the channel, plus some code generation logic. Should the average MAI power increase beyond a predetermined threshold, each node would switch to a new signature sequence to maintain the desired QoS parameters. Each node would be assigned a distinct signature sequence for each of the possible code sets that may be encountered to avoid having two nodes transmit with the same address code.

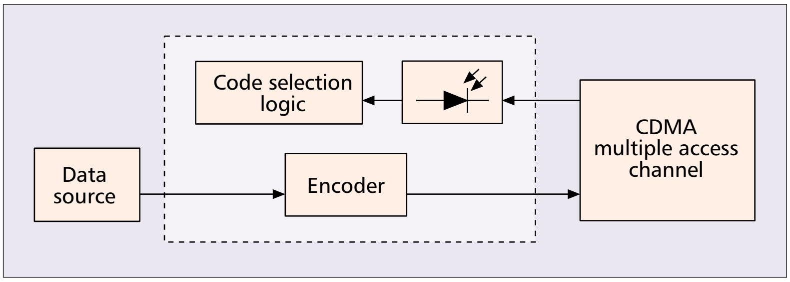

Figure 2. *A dynamic encoder that adjusts the signature sequence based on the total network traffic.*

Security

Finally, optical CDMA would offer an advantage that current access networks do not offer: inherent security. Tančevski *et al.* have shown that in a system with 41 wavelengths and 961 time chips available for spreading, it would take an eavesdropper 1350 years to examine all possible combinations, under the assumption that 10^7 codes could be examined per second [8]. Clearly, this is a better scenario that current hybrid fiber coax (HFC) access networks where a shared medium allows one user's (probably unencrypted) data to be read by many possible eavesdroppers.

Technological Barriers to Acceptance

Although O-CDMA has many characteristics that make it a promising technology for access networks, there are still many drawbacks (both real and perceived) that limit its widescale deployment. In this section we discuss the technological barriers to acceptance. In later sections we consider both cost and perception issues that have held back O-CDMA.

Shot and Beat Noise

In a recent paper [9] entitled "To Spread or Not to Spread: The Myths of Optical CDMA," Cedric F. Lam of AT&T Laboratories summarized several of the technological barriers to CDMA acceptance. He listed cumulative shot noise and optical beat noise as the major physical channel impairments that limit the performance of O-CDMA. These noise sources do not exist to the same extent in WDMA systems since the energy intended for a given receiver is confined to a single wavelength channel. In O-CDMA, the bandwidth is shared; it is the optical power from other users on the same wavelength channels that leads to the beat and shot noise. The shot noise builds as the square root of the received optical power, proportional to the number of active users in an O-CDMA system; therefore, shot noise can limit the scalability of O-CDMA systems. Optical beat noise has been shown [10] to be the dominant source of noise in some O-CDMA systems.

Forward Error Correction

Lam addresses the fact that optical beat noise in O-CDMA systems can be canceled through clever control of the optical phase coherence [9]; however, the cumulative shot noise cannot. Rather than rely on control of the optical phase (which is complex and expensive), a better approach may be to add forward error correction (FEC). Lam states that FEC is expensive and impractical since the electronics necessary for error correction must run at the speed of optical transport [9]. This may apply to high-capacity backbone links, but the modest per-user rate of access networks may render FEC cost-effective.

In the future, access networks will be used to deliver multiple high-definition television (HDTV) broadcasts to the home, requiring a data rate on the order of 1 Gb/s. At these high data rates, the signal processing necessary for FEC becomes onerous using today's hardware. Even if we do not rely on the fact that Moore's law will double processing speeds every 18 months, these higher data rates may still be manageable. One solution would be to limit the maximum number of users on an O-CDMA access system, without changing the amount of coding overhead. This approach is equivalent to making the cells smaller in RF cellular networks. Controlling the MAI in this way would allow a 10^{-9} error rate at 1 Gb/s per user, *without* the need for FEC. The downside is an increased cost per user since the subscriber base must be smaller.

Another approach would be to implement the FEC encoding/decoding using optical, rather than electronic, processing. It may be possible to design FEC codes that would rely solely on those signal processing operations that could be implemented in optics such as addition, splitting, multiplexing, demultiplexing, Fourier transforms, and wavelength conversion. The electronic bottleneck would be removed, allowing the FEC coding to run at very high data rates.

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COST BARRIERS

Currently, we believe that the biggest barrier to the widescale deployment of O-CDMA systems is cost. This issue is not specific to O-CDMA; other access technologies such as WDMA are also constrained by the need for expensive optical hardware. In this section we discuss those cost issues that are unique to O-CDMA, such as the need for all-optical encoding/decoding hardware and broadband light sources.

ENCODING AND DECODING HARDWARE

The head-end of an optical CDMA access network, as well as the terminals at the users' premises, would need to be able to generate arbitrary 2D codewords. In the literature, these O-CDMA encoders have been demonstrated using tunable fiber Bragg gratings (FBGs) [11, 12]. The tunability is achieved with piezoelectric devices that strain FBGs and shift the center frequencies of the gratings, hence changing the pattern of the code. Although these systems take advantage of optical hardware to avoid the need for electronics running at the chip rate, they are both expensive and bulky. The center frequency of FBGs also has a temperature dependence; therefore, either robust encoding [4] or wavelength control loops would be required to mitigate this effect. These solutions either limit performance or increase complexity, which is reflected in a higher overall cost.

BROADBAND LIGHT SOURCE

In addition to the encoding hardware, a light source capable of generating a large number of wavelengths would also be required at the customers' premises. There are several different methods of generating this broadband light: filtering the output of a broadband light-emitting diode (LED), spectrally slicing the amplified spontaneous emission (ASE) of an erbium-doped fiber amplifier (EDFA), or combining the output of a number of laser diodes tuned to distinct wavelengths. The broadband LED is the cheapest option, but the light generated may not have a high enough intensity for O-CDMA applications. Both the laser diode array and the EDFA options have the required power but are currently expensive.

A solution may be to install a single powerful broadband light source at the head-end. The multiwavelength light could be distributed by fiber to all nodes on the network for use in encoding data on the return path. In this way, each node would only require encoding/decoding hardware, not a dedicated broadband source. To further reduce the cost and improve performance of the head-end source, a multiwavelength fiber laser [13] that can generate a large number of wavelengths (on the order of 15) may be preferred.

THE PROMISE OF INTEGRATION

The long-term solution to the cost problem will be monolithic or hybrid integration. If an array of tunable lasers could be integrated on the same substrate as a waveguide-based encoder and modulator, costs as well as size would drop rapidly, while reliability and robustness would improve. Lee *et al.* [14] as well as Babich and Young [15] have proposed and simulated a design for a planar lightwave circuit that could perform all-optical spectral encoding. These designs rely on arrayed waveguide grating (AWG) technology, which is suitable for integration and can scale to a large number of wavelengths. Although O-CDMA systems using discrete AWGs have been built [16], we are unaware of any demonstration of a planar lightwave circuit that can perform O-CDMA encoding/decoding. It is therefore not easy to judge the feasibility of such integration technology.

PERCEPTION BARRIERS

VITERBI'S VIEW

The final barrier to the acceptance of O-CDMA in access or local area networks is the perception of the technology as inefficient, exotic, or difficult to commercialize. This view of O-CDMA is taken by Lam [9], who quotes A. J. Viterbi to support his argument: "Treating bandwidth as an inexpensive commodity and processing as expensive is bucking the powerful trend … Transmission bandwidth will always be at a premium … The mystique of spread spectrum communication is such that commercial enterprises, as well as academics, are often attracted by the novelty and cleverness of the technique. Also in small artificially aided markets, there may be temporary economic advantages. In the long run …we must stand back and question the wisdom of squandering a precious resource such as bandwidth for reasons of expediency." [17] Although Viterbi's words may apply well to satellite systems (the original context of the quote), we do not believe that they hold for O-CDMA networks. In RF systems, the limited amount of spectrum available is constrained by regulatory bodies (e.g., the FCC in the United States). Since this bandwidth is a precious and expensive resource, it makes sense to use as much processing as possible to compress the spectrum required for a given application. With data rates in wireless networks typically less than 1 Gb/s, ample digital signal processing power is available. Therefore, in the radio world, bandwidth is scarce while processing is plentiful.

In optical networks, the exact opposite is true. In the telecommunications transmission windows, a single optical fiber offers a usable bandwidth that is a factor of 100 greater than the entire terrestrial frequency spectrum, from kilometer waves to the satellite band. Clearly, in optical access networks where the number of active nodes will be on the order of hundreds to thousands and data rates will hover around 1 Gb/s, there is no shortage of bandwidth. With electronics currently operating at speeds on the order of tens of gigahertz, it is clear that in optics bandwidth is plentiful while processing is scarce.

"INEFFICIENT" OPTICAL CDMA

Optical CDMA compensates for the scarcity of processing power by throwing more bandwidth at the problem. The "inefficient" use of spectrum by O-CDMA is really an attempt to perform processing functions in the optical, rather than electrical, domain. Competing optical access technologies, such as WDMA, that do not employ spectral spreading may appear to use bandwidth more efficiently; however, other factors should be included in these efficiency calculations. For example, WDMA will require a method to mediate channel access to avoid wavelength contention. Contention-based media access schemes such as carrier sense multiple access with collision detection (CSMA/CD) are difficult to implement and have the drawback of nondeterministic service [18]. Time sharing could also be used to avoid contention; however, this requires synchronization among the nodes and may need a more complex protocol, especially if dynamic slot assignment is used [18]. Through spectral spreading, O-CDMA addresses these channel control problems without the need for complex protocols or extensive electronic processing.

CONCLUSIONS

In this article we have considered both the benefits and drawbacks of optical CDMA technology, in the context of local area and access networks. O-CDMA has many characteristics such as fair bandwidth sharing and intrinsic security that make the technology appealing for application in access. Unfortunately, the relatively high cost of the encoding and decoding hardware may limit the deployment of O-CDMA access networks. We believe that additional processing, in the form of forward error correction, together with progress in optoelectronic integration may deliver O-CDMA from its technological and cost drawbacks. The most severe barrier to O-CDMA deployment in the future may be the perception of the optical networking community that the technology is both exotic and inefficient.

REFERENCES

[1] J. Y. Hui, "Pattern Code Modulation and Optical Decoding — A Novel Code-Division Multiplexing Technique for Multifiber Network," *IEEE JSAC*, vol. SAC-3, no. 6, Nov. 1985, pp. 916–27.

[2] J. A. Salehi, "Code Division Multiple-Access Techniques in Optical Fiber Networks — Part I: Fundamental Principles," *IEEE Trans. Commun.*, vol. 37, no. 8, Aug. 1989, pp. 824–33.

[3] A. A. Saleh and J. M. Simmons, "Architectural Principles of Optical Regional and Metropolitan Access Networks," *J. Lightwave Tech.*, vol. 17, no. 12, Dec. 1999, pp. 2431–48.

[4] H. Fathallah and L. A. Rusch, "Robust Optical FFH-CDMA Communications: Coding in Place of Frequency and Temperature Controls," *J. Lightwave Tech.*, vol. 17, no. 8, Aug. 1999, pp. 1284–93.

[5] E. Inaty, P. Fortier, and L. A. Rusch, "SIR Performance Evaluation of a Multirate OFFH-CDMA System," *IEEE Commun. Lett.*, vol. 5, no. 5, May 2001, pp. 224–26.

[6] E. Inaty *et al.*, "Multirate Optical Fast Frequency Hopping CDMA System Using Power Control," *IEEE J. Lightwave Tech.*, vol. 20, no. 2, Feb. 2002, pp. 166–77.

[7] A. Stok and E. H. Sargent, "Lighting the Local Network: Optical Code Division Multiple Access and Quality of Service Provisioning," *IEEE Network*, vol. 14, no. 6, Nov./Dec. 2000, pp. 42–46.

[8] L. Tančevski and I. Andonovic, "Hybrid Wavelength Hopping/Time Spreading Schemes for Use in Massive Optical Networks with Increased Security," *J. Lightwave Tech.*, vol. 14, no. 12, Dec. 1996, pp. 2636–47.

[9] C. F. Lam, "To Spread or Not to Spread: The Myths of Optical CDMA," *IEEE LEOS 2000 Annual Mtg.*, 2000, vol. 2, pp. 810–11.

[10] L. Tančevski and L. A. Rusch, "Impact of The Beat Noise on The Performance of 2-D Optical CDMA Systems," *IEEE Commun. Lett.*, vol. 4, no. 8, Aug. 2000, pp. 264–66.

[11] H. Fathallah, L. A. Rusch, and S. LaRochelle, "Passive Optical Fast Frequency-hop CDMA Communications System," *J. Lightwave Tech.*, vol. 17, no. 3, Mar. 1999, pp. 397–405.

[12] L. R. Chen, "Flexible Fiber Bragg Grating Encoder/decoder for Hybrid Wavelength-time Optical CDMA," *IEEE Photon. Tech. Lett.*, vol. 13, no. 11, Nov. 2001, pp. 1233–35.

[13] T. Miyazaki *et al.*, "A Multiwavelength Fiber Ring-Laser Employing a Pair of Silica-Based Arrayed-Waveguide-Gratings," *IEEE Photon. Tech. Lett.*, vol. 9, no. 7, July 1997, pp. 910–12.

[14] C.-H. Lee *et al.*, "Planar Lightwave Circuit Design for Programmable Complementary Spectral Keying Encoder and Decoder," *Elect. Lett.*, vol. 35, 1999, pp. 1813–15.

[15] C. D. Babich and J. F. Young, "Performance Modeling of a Planar Waveguide Based Spectral Encoding System," *IEEE LEOS 1999 Annual Mtg.*, 1999, vol. 2, pp. 523–24.

[16] C. F. Lam, D. T. K. Tong, M. C. Wu, and E. Yablonovic, "Experimental Demonstration of Bipolar Optical CDMA System Using a Balanced Transmitter and Complementary Spectral Encoding," *IEEE Photon. Tech. Lett.*, vol. 10, no. 10, Oct. 1998, pp. 1504–6.

[17] A. J. Viterbi, "When Not To Spread Spectrum: A Sequel," *IEEE Commun. Mag.*, vol. 23, no. 4, Apr. 1985, pp. 12–17.

[18] G. Kramer and G. Pesavento, "Ethernet Passive Optical Network (EPON): Building a Next-Generation Optical Access Network," *IEEE Commun. Mag.*, vol. 40, no. 2, Feb. 2002, pp. 66–73.

BIOGRAPHIES

ANDREW STOK (andrew.stok@utoronto.ca) received a B.Sc. degree in engineering physics from Queen's University, Kingston, Canada, in 1998. In March 2000 he received an M.A.Sc. degree in photonics from the Department of Electrical and Computer Engineering at the University of Toronto. He is currently pursuing a Ph.D. degree in photonics from the same department. His research interests include the theory, design, and development of optical networks, with a focus on optical code-division multiple access technology.

EDWARD H. SARGENT (ted.sargent@utoronto.ca) holds the Nortel Networks Canada Research Chair in Emerging Technologies at the University of Toronto. In 2002 he won the IEEE Canada Outstanding Engineer Award for "for groundbreaking research in applying new phenomena and materials from nanotechnology towards transforming fibre-optic communications systems into agile optical networks." In 2001 the Canada Research Chairs Foundation wrote that Ted Sargent has "...shown that a new kind of photonic macrocrystal — one which harnesses nature's underlying drive toward symmetry — will transform how communication networks are built. He works with novel materials that can be induced to organize themselves into specific arrays and patterns, spaced no further apart than the microscopic wavelength of the light which passed through them. He has also developed the photonic heterostructure." In 1999 Canada's Natural Sciences and Engineering Research Council award Ted Sargent its Silver Medal, writing in its citation: "This work shed light for the very first time on the essential physical mechanisms that underlie the operation of the lateral current laser. The groundbreaking research proved that it is possible to build and interconnect these laser devices using standard semiconductor fabrication techniques, thereby opening up an avenue for making laser light the driving force of future microchips." The Switzerland-based Chorafas Foundation, which awards scientific prizes worldwide for outstanding research in the engineering sciences, humanities and social sciences, medicine, and the natural science, wrote: "Dr. Sargent proved that it is possible to harness the combined power of photons and electrons to make new, integrated, functionally sophisticated devices and circuits to enable the fibre-optic networks of the future." In awarding Ted Sargent the Premier's Research Excellence Award of Ontario, the award committee wrote: "Dr. Sargent is innovating revolutionary ways to send, display, and acquire information using light. He developed the theory and demonstrated the realization of the lateral current injection laser, a new semiconductor laser with the potential to enable the integration of many optoelectronic devices onto a single platform."

The most severe barrier to O-CDMA deployment in the future may be the perception of the optical networking community that the technology is both exotic and inefficient.