Jagdeep Shah

OPTICAL CDMA

To provide multiple access, fiber-optic networks use a combination of time-division multiplexing and wavelength-division multiplexing. This is in contrast to RF wireless networks, in which code-division multiplexing is becoming the dominant multiple access technique. In code-division multiple access (CDMA), a user is assigned a unique code composed of some combination of time slot, wavelength and other parameters. Yet to be applied outside the lab, optical code-division multiple access (optical CDMA) appears to hold promise for the future. The author describes work supported by the Defense Advanced Research Projects Agency (DARPA) under a program aimed at realizing an optical CDMA network.

Multiple access techniques allow multiple users to access limited-bandwidth communication networks. There are three major multiple access techniques deployed across the electromagnetic spectrum. In time-division multiple access (TDMA), a user is assigned a specific time slot within a bit period, the inverse of the bit rate at which the network is operating. The shortest time slot is determined by the network bandwidth. The number of simultaneous users on an optical network may also be increased substantially by use of multiple wavelengths (wavelength-division multiple access, or WDMA).

To provide access to a large number of simultaneous users, today's optical networks use a combination of WDMA and TDMA, operating at the highest available electronic modulation speed. The third multiple access technique, code-division multiple access (CDMA), assigns each user a code rather than a time slot and/or wavelength. The code is comprised of a combination of time slots, wavelength (or frequency) and other parameters, such as polarization. Because it offers a number of significant advantages, CDMA has become, or is slated to become, the dominant multiple access technique for RF wireless (mobile telephone) networks around the world. While there have been a number of investigations of various properties of CDMA in the optical domain, at present, no networks based on optical CDMA exist.

The Defense Advanced Research Projects Agency (DARPA) has recently initiated a program, O-CDMA, to demonstrate technology for an advanced network based on optical CDMA. The program has three components: advanced encoding and decoding hardware; coding algorithms and schemes; network architecture, simulation and applications. Although the primary emphasis is on the development of advanced encoding and decoding hardware, the other two components of the program are essential because they provide cross-validation and allow systems issues to be addressed. It is expected that this comprehensive approach will enable rapid progress toward an advanced optical network based on CDMA. In this article I discuss the goals of the program and the technology that will be developed within the framework it provides.

The basic ideas behind code-division multiplexing have been described in the literature[1] and are illustrated in Fig. 1.

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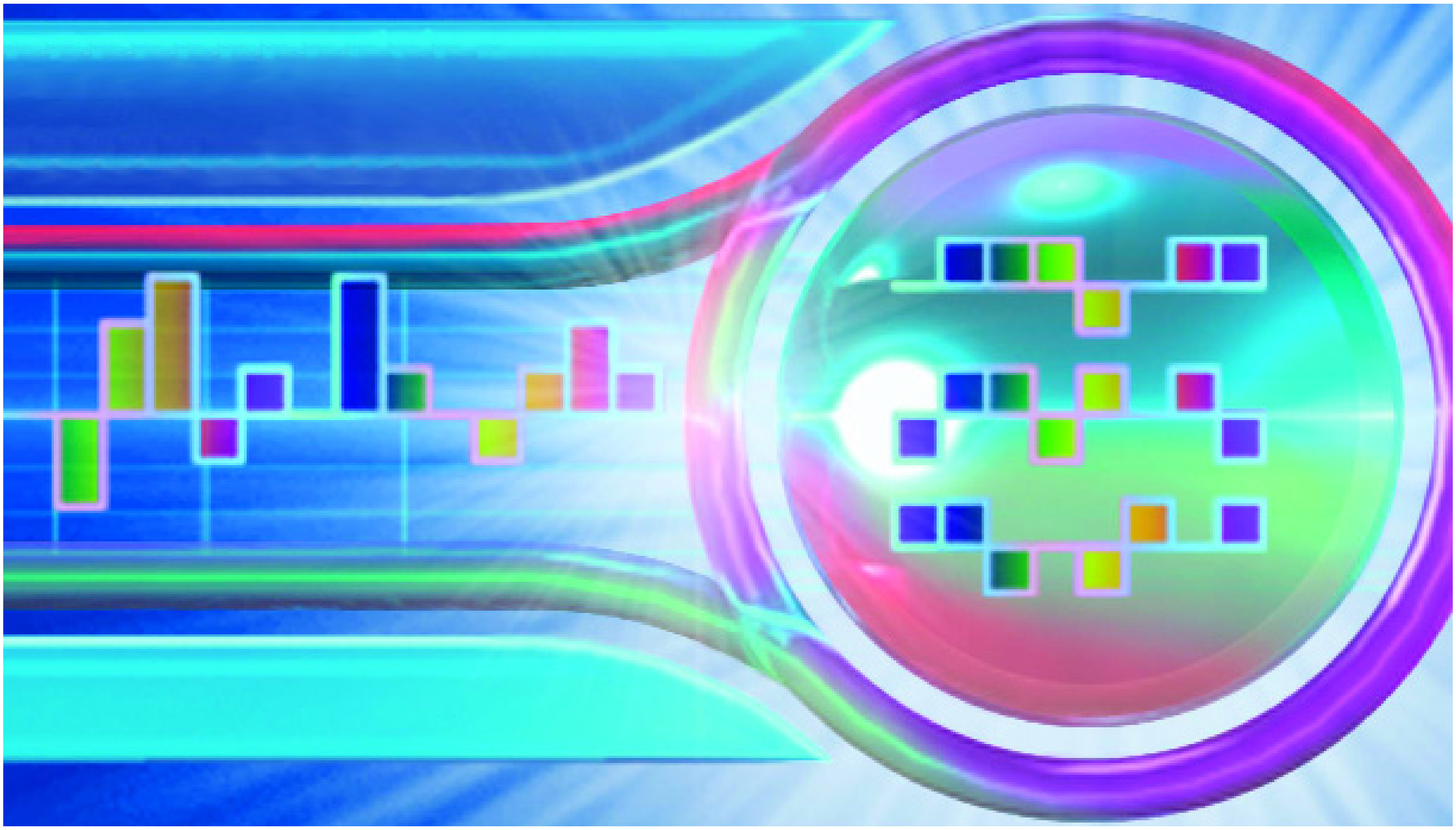

In a digital optical network, data are represented by a series of "1s" (the presence of signal) and "0s" (the absence of signal). In general, a "1" is represented by a pulse of duration T_S ($<T_B$, the bit period), with a spectral width of $\Delta\upsilon_S$. In a WDMA system, a given data stream may be centered at any one of N frequencies υ_N, corresponding to wavelengths λ_N. In a CDMA system, the simplest conceptual code is a temporal one in which the bit period T_B is divided into M temporal chips of duration T_C ($=T_B/M$), and a well-defined subset of these M chips is populated for a given code. A pulse of width T_C occupies a much broader spectrum of width $\Delta\upsilon_C(=M\Delta\upsilon_S)$. Another possibility is a spectral code for which a well-defined subset of M spectral chips (each of spectral width $\Delta\upsilon_S$) is populated for a given code. These one-dimensional (1D) codes are illustrated in Figs. 1(b) and 1(c). One can also devise multidimensional codes combining temporal, spectral and other properties (e.g., polarization) of the optical field. For example, a 2D temporal-spectral code is composed of a combination of time and spectral chips [see Fig. 1(d)]. Multidimensional codes can clearly accommodate a larger

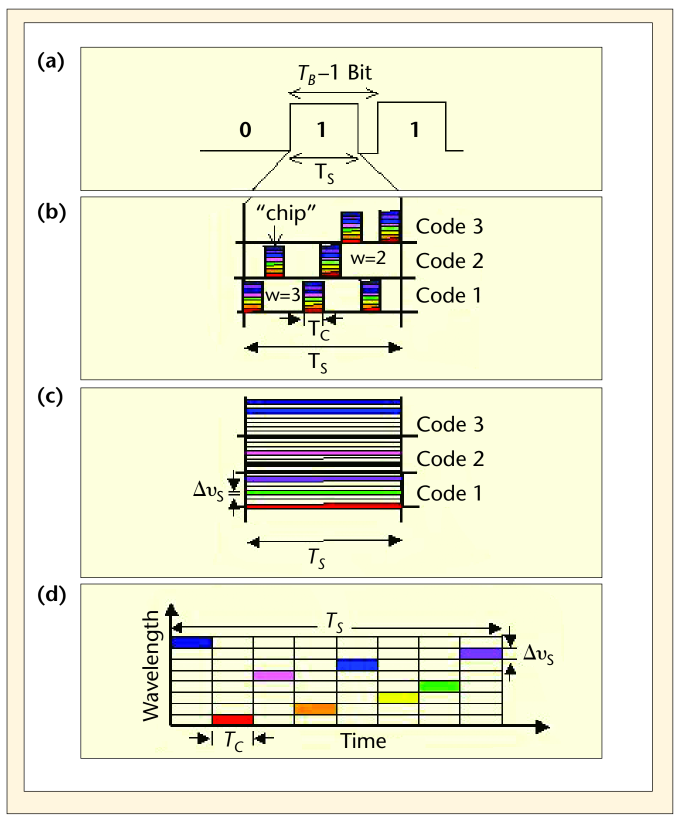

Figure 1. Schematic illustration of 1D and 2D optical CDMA codes. (a) Data stream; (b) 1D temporal codes, temporal chips T_C, M=8, w=2 or 3; (c) 1D spectral codes, spectral chips $\Delta\upsilon_S$, M=8; (d) 2D spectral-temporal code, 8 temporal and 8 spectral chips.

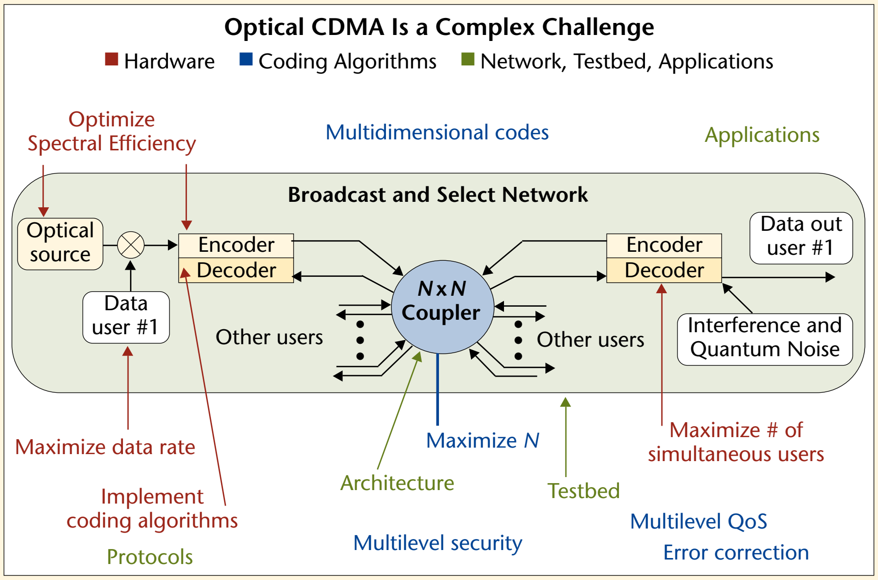

Figure 2. The area enclosed in the light blue box illustrates a conceptual optical CDMA network (assumed to be an N x N star). Realization of such a network is a complex challenge based on three major components: hardware (red), coding algorithms (blue) and validation [network architecture, simulations and applications (green)].

number of users in a network. Optical code-division multiplexing concepts were described in a recent *Optics & Photonics News* article[2] and other reviews.[3-6]

RF wireless CDMA for mobile communications

RF wireless CDMA communications use an RF carrier frequency, typically in the ~1 GHz (10^9 Hz) range and a bit rate ~100 kbit/s. The typical bit period of T_B= 500 ns is divided into a few thousand temporal chips ($M \sim 10^3$), and a 1D temporal code in which a subset of the M chips is populated and assigned to a user. Because the spectrum of the typical subnanosecond chip duration is much wider than that of the communication bit rate, the technique is also known as the spread-spectrum technique.

In a CDMA system, the user transmits encoded information and the intended receiver has a decoder tuned to decode the assigned code. The decoder also receives signals transmitted by other users using different codes and must discriminate against such information. The ability of the decoder to discriminate is assured if the codes are orthogonal or, in other words, if they have a large autocorrelation and zero cross-correlation.

The orthogonality of codes is a very important property. Coding schemes with a large number of orthogonal codes lead to a large cardinality, i.e., a large number of potential users, for the CDMA system. The large value of M and the bipolar codes in the RF domain allow a large number of orthogonal codes and hence a large cardinality.

In RF communication systems, CDMA provides a number of substantial advantages.[1] These include: a more efficient use of the spectrum; improved multipath interference rejection; easier allocation of frequencies; and no hard limit on the number of users. These and other advantages are rapidly making CDMA the dominant technology in mobile telephony around the world. The next generation of wireless technology, third-generation (3G) wireless, will be dominated by CDMA worldwide.

Potential benefits of optical CDMA

Not all the benefits of CDMA in the RF wireless domain apply to CDMA in the optical domain. Multipath interference, for example, is not expected to be important in fiber-optic networks. In addition, optical CDMA faces unique challenges of its own, as discussed below. While these will be difficult to overcome, advanced optical networks based on CDMA hold the promise of significant benefits. These include: format-independent physical layer security; low probability of detection, interception and jamming; covert communication overlaying on existing WDM networks; decentralized network control, leading to increased reliability and survivability; and contention-free networks providing uncoordinated access.

Challenges for optical CDMA systems

Two major differences between the RF and the optical domain are in the carrier frequency and the bit rate. The typical optical carrier frequency (~ 200 THz, or 2 x 10^{14} Hz) is 200,000 times higher than the typical RF frequency, while the bit rate in today's optical networks is 10 Gbit/s, 5000 times higher than in an RF CDMA. These differences produce some unique challenges for CDMA in the optical domain.

These challenges can best be illustrated by means of a conceptual network for optical CDMA. For the sake of simplicity, consider the star network illustrated in Fig. 2. It has N user stations, each equipped with a tunable encoder and a tunable decoder. Any user can communicate with any other user if the two agree on a code for communication. The transmitting user encodes the information and broadcasts it to all the other users. Only the intended receiver knows the code and can decode the signal by proper tuning of the decoder at the receiving station.

A major challenge is to maximize the cardinality of the system, the number N. In the simplest case, cardinality is limited by the maximum number of orthogonal codes. The small bit period in the optical domain (~ 100 ps) may limit M, the number of temporal chips in a bit. Furthermore, in contrast to RF wireless communication, optical communication relies primarily on incoherent coding, i.e., on modulation of the intensity of the optical signal rather than its amplitude and phase. If incoherent codes are used in an optical CDMA system, the resulting unipolar codes and the small M may severely limit the cardinality, and hence the practicality, of the system. Maximizing cardinality requires not only new coding algorithms or schemes but also the development of the hardware—encoders and decoders—necessary to implement them.

The conceptual network shown in Fig. 2 illustrates another major challenge for developers of an optical CDMA system. Because the transmitted signal is split N ways, an intended receiver receives only $1/N$ of the signal intended for that receiver—along with signals from all other transmitters, with different codes, not intended for that receiver. Thus, the unwanted signal is $\approx N$ times stronger than the signal carrying the correct information. An optical communication system is ultimately limited by quantum noise proportional to the square root of the total number of photons incident on the detector. Therefore, even if the decoder is able to reject all the signals not intended for it, the noise from the unintended signals may be so large that it limits the maximum number of users simultaneously transmitting signals in an optical CDMA network. The challenge is to design a system and develop corresponding hardware that maximizes the number of simultaneous users on the network.

Unlike the situation in TDMA or WDMA systems, in CDMA systems there is no hard limit on the number of simultaneous users. Increasing the number of simultaneous users results in larger multiple access interference and hence degrades the performance of the system. Any discussion of the maximum number of simultaneous users must therefore be accompanied by discussion of the acceptable signal-to-noise ratio, which is related to the bit-error rate (BER). One challenge is therefore to demonstrate a system with an acceptable BER that can accommodate a large number of simultaneous users.

Another challenge is to maximize the spectral efficiency of the optical CDMA system. Current WDM/TDM-based optical communication systems operate at 10 Gbit/s and use 100 GHz of spectrum for each wavelength. This corresponds to a spectral efficiency of 0.1 bits/s/Hz. Future development of the technology may increase the efficiency to 0.4 bits/s/Hz by increasing the bit rate to 40 Gbit/s with the same spectral bandwidth. Can an optical CDMA system do as well in terms of spectral efficiency? Can it do better? In today's optical communication systems the cost of transmitting a single bit of information has continuously decreased, but this trend may be difficult to sustain. This factor makes increasing spectral efficiency an important goal.

These challenges relate primarily to developing appropriate coding schemes and hardware. There are other challenges related to network architecture, control and management. To provide a "reality check" in coding and hardware development, it is important to address these issues at an early stage. The future of optical CDMA systems will depend on how well these formidable challenges are met.

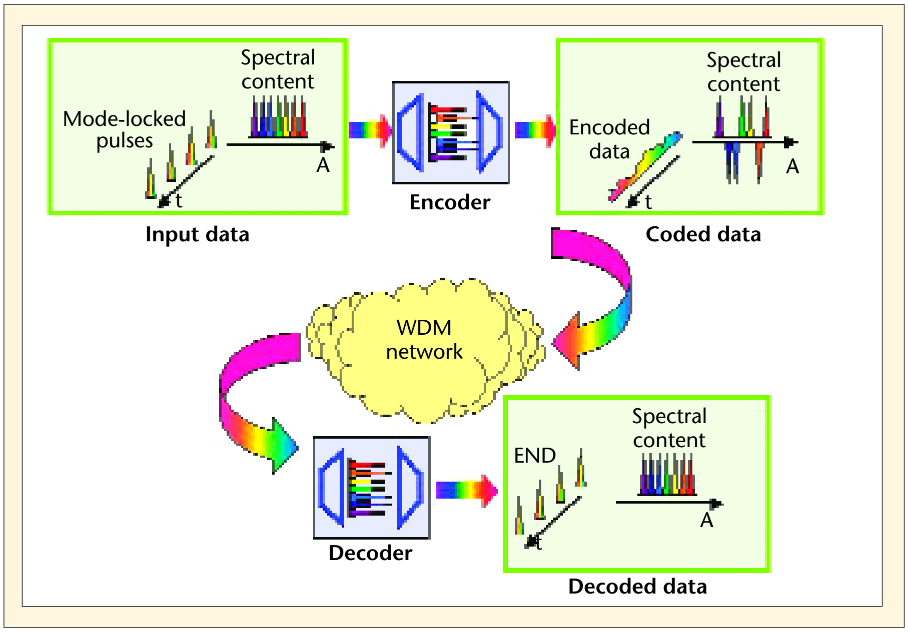

Figure 3. Schematic illustrating the coherent optical CDMA architecture, using mode-locked pulses as frequency bins, to be investigated by the Telcordia team.

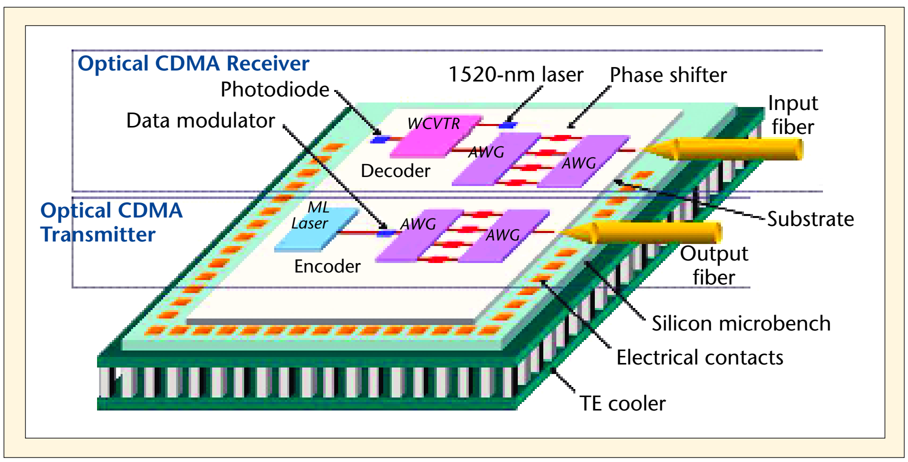

Figure 4. Schematic of the optical CDMA transceiver chip, packaged on a silicon-microbench platform, as proposed by the UC Davis team. (The package casing is omitted for easy viewing.) This chip incorporates advanced optoelectronic technologies including; ultrafast mode-locked lasers; arrayed-wavelength-grating multiplexers; phase modulators; and asymmetric wavelength converters. The chip dimensions are expected to be 4 x 4 x 1 cm^3.

DARPA's O-CDMA Program

Although the challenges facing optical CDMA systems are significant, the potential benefits are equally so. Since the mid-1980s, researchers have devoted considerable effort to developing coding algorithms, encoder and decoder hardware. While much progress has been made toward understanding the fundamental issues, a concerted effort to develop technology for an advanced optical CDMA communication system has not yet been made. The DARPA O-CDMA program will mount such a focused effort. As discussed earlier, coding schemes that maximize cardinality are of little practical value if the corresponding hardware cannot be developed. Similarly, elegant hardware that cannot be used to implement the desired coding algorithms is of little practical value. Finally, potential applications, network architecture, control and management must be considered in parallel with the coding and hardware effort. DARPA's O-CDMA program encompasses all three areas, placing emphasis on validation of each by the others and on development of all system components in harmony.

The DARPA O-CDMA program is an approximately $30 million, four-year project with well-defined goals and intermediate milestones at 18 months. The program has five teams led by Princeton University, Telcordia Technologies, University of California-Davis, University of California-Los Angeles and the University of Southern California. Each team will use a variety of approaches to investigate hardware, coding and network issues. MIT Lincoln Laboratory will set up a testbed to test hardware developed by the five teams. Researchers there will also develop network simulations based on the test results. A different group at Telcordia will conduct a network control and management study to help focus the program. The goals of DARPA's O-CDMA program include experimental demonstration of a multiuser optical CDMA system operating at 10 Gbit/s per user with a BER < 10^{-9}, and a demonstration that the system would provide such performance when scaled to 100 simultaneous users and 1000 potential users. An additional goal is to maximize the spectral efficiency of the system. The teams have proposed different approaches to achieving these goals.

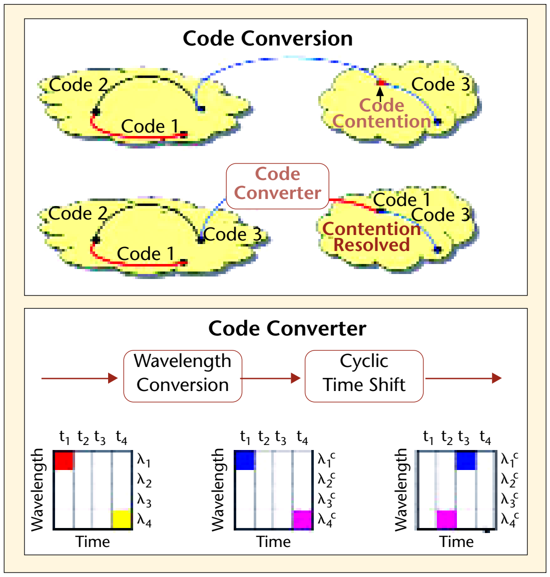

Figure 5. The USC team will investigate the architecture of interconnected LANs. The upper box illustrates the concept of code conversion and re-use for interconnected LANs. The lower box illustrates how wavelength conversion and time slot interchanging can be applied to code conversion.

The program will investigate many different coding approaches, including spectral phase coding, spectral intensity coding and fast and slow frequency hopping. Encoding technologies to be investigated include spatial light modulators, InP phase and intensity modulators, microresonators and fast electronics. Different approaches to decoders include coherent detection with or without local oscillators, incoherent bipolar detection and gated detection. Different multidimensional, multilength and multiweight coding algorithms will be investigated. Multilevel security and various network architecture, protocols, simulation and management issues will be examined. The researchers also plan to explore potential applications for an optical CDMA communication system.

Technologies to be developed

The Princeton team, comprised of Princeton, Hofstra, Telcordia and Kambrook Technical Associates, will investigate optical CDMA based on fast frequency hopping incoherent coding schemes, in which a different wavelength (frequency) is assigned to a different temporal chip within a bit period. They will use scalable and reconfigurable fiber-based delays and balanced detection of unipolar codes. Because of the asynchronous nature of optical CDMA systems, to resolve the correlation functions properly, the balanced detector must operate at the temporal chip rate ($1/T_C$). For data rates of 10 Gbit/s, the bandwidth requirement would be several hundred GHz. The use of a balanced detector directly at such a chip rate is not possible because commercial photodetectors can only operate at rates of up to 60 GHz. To overcome this problem, the Princeton team will use a terahertz optical asymmetric demultiplexer (TOAD) to perform optical sampling at the expected positions of the autocorrelation peaks. TOAD acts as an all-optical demultiplexer or an "AND" gate. The sampled signals from the true and complement correlators are then photodetected and subtracted by the balanced detector. Although the balanced detector is still unable to resolve the details of the two correlators' output, it can see the difference in energy between the autocorrelation peak and cross-correlation functions over one chip (per bit period) because of the sampling. The Princeton team will also investigate multilength, multiweight coding schemes for providing differentiated services and multilevel security.

The Telcordia team, comprised of Telcordia, the University of Central Florida School of Optics (CREOL) and Essex Corp., will focus on optical CDMA systems that can overlay existing WDM systems. The attainment of the O-CDMA program goal of 10 Gbit/s per user would also enable delivery of high-bandwidth applications (Gigabit Ethernet, uncompressed HDTV, multimedia services) to a large number of end users. The Telcordia team will investigate an optical CDMA system based on spectrally efficient hierarchical wave-banding architecture by use of spectral content of a mode-locked laser source as a set of ultradense WDM carriers within a tunable window. Along with additional security, this optical CDMA system is expected to provide spectral efficiency comparable to or higher than the corresponding WDM system.

These ideas are illustrated in Fig. 3. The output of a mode-locked laser operating at a repetition rate of 10 GHz consists of a series of pulses separated by 100 ps. The output spectrum consists of a series of spectral lines separated by 10 GHz within a spectral envelope the width of which is determined by the width of the mode-locked pulses. (A 4-ps Gaussian pulsewidth corresponds to a spectral width of about 100 GHz). To spatially separate various spectral lines, the output of the mode-locked laser is passed through an encoder consisting of an optical demultiplexer. The output then passes through a phase modulator that modulates the phase of the individual spectral lines, followed by a multiplexer that combines the modulated spectral lines. The coded pulse consists of the same spectral components as the input, but with a different phase relationship (equivalent to a broad pulse in the temporal domain) between them. The code is then inserted into the WDM network. At the destination, a decoder with a complementary code rephases the various spectral components and regenerates the original short pulse.

The University of California-Davis team, consisting of UC Davis and Lawrence Livermore National Laboratory (LLNL), will also investigate the spectral coding approach, but with significant differences. Instead of modulating the phase of an individual spectral line, this team plans to modulate either the intensity or the phase of a group of spectral lines using fast InP modulators. The use of extremely fast InP modulators will allow reconfiguration of the encoders and decoders on ~ 10 ns time scales. They will also use a different detection scheme based on threshold detection.

Furthermore, they will fabricate a complete optical CDMA transmitter and receiver module on a single chip, as illustrated in Fig. 4. They will also investigate various approaches to coding algorithms and forward error correction. The system will be demonstrated using a laboratory testbed and the UC Davis network.

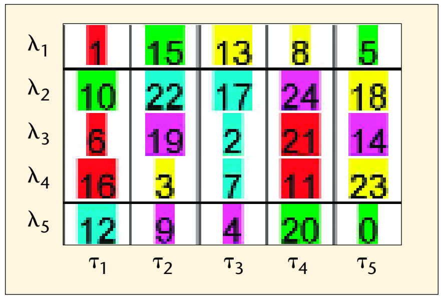

Figure 6. Illustration of the UCLA encoding scheme using a 5 x 5 matrix (i.e., L = 5 wavelengths, N = 5 bits).

The University of Southern California (USC) has assembled a vertically integrated research team to solve the user-code bottleneck caused by the requirement of extremely short temporal chips. Their work involves examination of the complete system, including: new network architectures and protocols; optimized scrambling codes; robust system implementations; and rapidly reconfigurable encoding by use of microresonator device arrays. In addition to investigating 2D wavelength-time codes, they will consider the architecture of interconnected local area networks (LANs) [Fig. 5]. The USC researchers will develop code converters using wavelength switching and time-slot interchanging so that different LANs can use the same codes. They will also investigate how to provide variable quality of service (QoS) and variable quality of security (QoSec).

UCLA has assembled a vertically integrated team to investigate a totally different approach to coding and hardware. In contrast to the approach of dividing a bit period into M temporal chips, the UCLA approach creates a "macro-bit" made of N (= a large number) bits. A single code quasi-randomly fills the L x N matrix. In the UCLA scheme, a code can occupy multiple wavelengths in a single bit-time slot and leave other bit-time slots empty to provide extra security. The total number of squares occupied by a code always equals N, the number of bits in a macro-bit. The L x N matrix is filled with numbers that are algorithmically generated from a seed. The numbers are pointers that prevent bit-level collisions. Figure 6 illustrates the concept for a 5 x 5 matrix.

According to the scheme, the code for the ith user is given by the boxes occupied by the number i modulo 5. For example, the code for the first user is given by the boxes occupied by numbers 1, 6, 11, 16 and 21, boxes indicated by red (Fig. 6). Other codes are also color-coded. Note that bit slot 1 is occupied by three wavelengths, bit slot 4 is occupied by two wavelengths, and other bit slots are empty for the code for user 1. In this scheme, the code pattern changes every macro-bit and thus provides considerably enhanced security. This novel coding scheme will be implemented by use of a chirped broadband light source, an encoder consisting of a 1 x K splitter followed by K electronic delays and K electro-absorption modulators, followed by a K x 1 combiner and delay-to-wavelength converter. The new coding scheme and hardware using fast electronics are two particularly interesting aspects of the UCLA program.

Summary

Optical CDMA faces many complex and formidable challenges but also offers a number of potential benefits. Three diverse areas—coding algorithms, hardware to implement them and network architecture and applications—must be addressed in a comprehensive manner. The goal of the DARPA program is to demonstrate technology for an advanced optical network that supports a large number of simultaneous users at a very high bit-rate per user with very low bit-error rates, large cardinality and high spectral efficiency.

Jagdeep Shah (jshah@darpa.mil) is program manager in the Microsystems Technology Office at the Defense Advanced Research Projects Agency, Arlington, Virginia.

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