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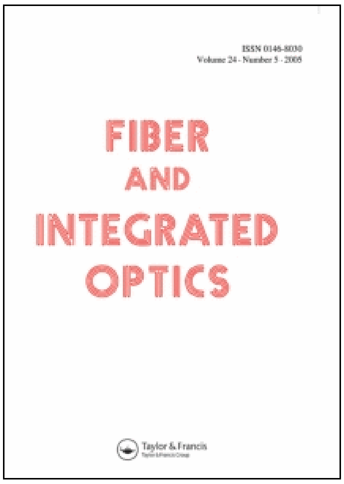

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Photonic code-division multiple-access communications

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Photonic Code-Division Multiple-Access Communications

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Photonic code-division multiple access schemes have been proposed since the 1970s. Although there are many published proposals for new coding schemes, there are many less experimental verifications of these schemes, even fewer reports of successful data transmission, and no commercial systems. We attempt to explain the key factors that have led to the current state-of-the-art. In so doing, we describe the fundamental principles of matched filtering and noise in photonic CDMA schemes. We survey important developments and show how various schemes are related. We review recent experimental advances and compare the published experimental and theoretical performance for different schemes. We discuss the current major issues and likely future directions.

Keywords code-division multiple access, coherence multiplexing, optical communications, optical networks, photonics

Code-division multiple access (CDMA) techniques have been proposed for optical communications for over twenty years. Over this period, there has been no shortage of new approaches and theoretical performance analyses. There have also been many proof-of-concept experiments, although a good deal fewer than proposals. However, despite the demonstrable success of CDMA as a communication technique in the radio, microwave, and millimeter wave bands [1], there are

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currently no commercial optical communication systems that use CDMA, and the field remains outside the mainstream in optical communications research. In this review, we explore the reasons behind this lack of success and describe fundamental issues in photonic CDMA that underpin the obtainable level of performance. We describe recent experiments that, for the first time, demonstrate limits on what is achievable. Those limits, and what sets them, have yet to be widely appreciated by the contemporary research community.

CDMA is a technique to provide multiaccess communications by the assignment of unique codes to users. Coding allows users to share the same frequency band and to operate asynchronously. The combination of these two attractive features distinguishes CDMA from time-division and frequency-division techniques. Other attractive features claimed for CDMA in optical communications include low delay access suited to bursty local-area network traffic, efficiency in allocating bandwidth only as required, soft capacity, and security.

Photonic CDMA schemes are CDMA schemes in which coding and decoding operations are embedded in the optical domain. In this article, we review the field of photonic CDMA with emphasis on elucidating the underlying fundamental principles; establishing the main limitations, features, and interrelationships between important schemes; and surveying the main accomplishments. We include chronological background and, where appropriate, discuss key early developments in related areas. We compare the published theoretical and experimental performance of photonic CDMA schemes and examine current outstanding issues.

Fundamentals

In this section, we review the fundamental principles of operation of photonic CDMA schemes. We consider a broadcast CDMA network, shown schematically in Figure 1, in which signals from all transmitters are distributed to every receiver using a star coupler. Each user receives all transmitted information but is able to extract the signal of one transmitter from a background of multiple-user interference using prior knowledge of the coding employed. The inset of Figure 1 illustrates the process of data transmission in a photonic CDMA scheme. Encoding and decoding are performed in the optical domain, which has the potential to provide aggregate capacities exceeding those available with electronic-based coding, and has been a motivation behind much of the work in photonic CDMA.

The difference in *signal-to-noise ratio* (SNR) at the output and input of the decoder is known as the process gain [2] and is a measure of the capacity of the network to support multiple users. A feature of CDMA schemes is that the transmitted signal bandwidth greatly exceeds the baseband data bandwidth. In *radio frequency* (RF) systems, this is a direct consequence of encoding each bit, and the ratio of the transmitted signal bandwidth to the data bandwidth can be equated to the process gain. In photonic CDMA schemes, however, as we shall see later, there is no simple rule of thumb to relate process gain and signal bandwidth.

Any combination of spatial, temporal, frequency, and polarization information can, in principle, be used for coding in photonic CDMA. There are several fundamentally different approaches to the design of decoders for photonic schemes. We distinguish between incoherent techniques that assume linear addition of optical intensity and coherent techniques that utilize coherent superposition of fields. Coherent techniques require setting and controlling optical delays on the

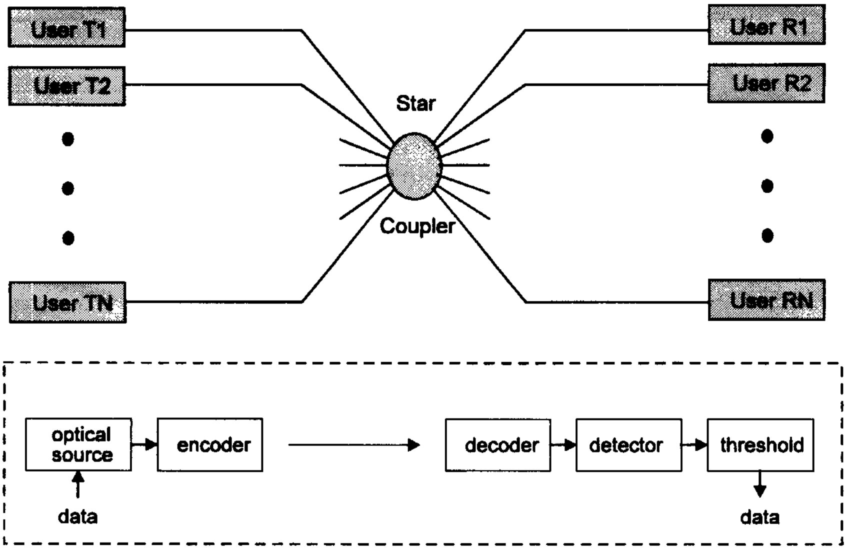


Figure 1. Photonic CDMA broadcast network. Inset: process of data transmission based on all-optical encoding and decoding.

scale of the optical wavelength in order to achieve the correct phases of superposed fields. Perceived difficulties of the coherent approach have led to an emphasis on incoherent approaches. However, this review describes recent work that clearly illustrates the practical potential of coherent approaches.

Matched Filtering

A receiver in a CDMA system must recover a desired signal from background multiple-user interference that constitutes additive noise. This is best achieved by a decoder that maximizes the SNR of the desired signal. If the background noise is white, a well-known result is that the SNR is maximized by a matched filter, which has an impulse response $h_{\mathrm{dec}}(t)$ equal to the time-reversed complex conjugate of the desired signal $f(t)$ delayed by an arbitrary time interval τ_m [3], i.e.,

$$h(t) = f^*(\tau_m - t) \tag{1}$$

Optical matched filtering based on Eq. (1) has been applied to CDMA, using spectral phase coding to perform spreading and despreading of a transform-limited optical pulse [4]. We discuss this scheme in more detail later in the section entitled Spread-Time and Spread-Spectrum Schemes.

To design a matched filter, complete knowledge of the signal to be detected is required. However, this information is often not available for optical signals used in photonic CDMA schemes. For example, the optical field of a light-emitting diode is stochastic and only statistical information is available. Given a stochastic input, the best filter is one that minimizes the mean-square-error estimate of the transmitted signal [5]. If the encoder response is fully known and the additive noise is white and has a much larger power-spectral density than the signal to be observed, which approximates envisaged CDMA environments, it can be shown [5] that the best filter is one that is matched to the encoder. The decoder, thus, requires an impulse response equal to the time-reversed complex conjugate of the encoder impulse response, i.e.,

$$h_{\text{dec}}(t) = h^*_{\text{enc}}(\tau_m - t) \tag{2}$$

and is a suboptimal matched filter except when the input is a transform-limited optical signal. Schemes based on Eq. (2) that employ unbalanced Mach–Zehnder interferometers and *continuous-wave* (CW) sources have been termed coherence multiplexing and are discussed in the next section. CDMA schemes based on Eq. (2) that employ pulsed sources and decoders consisting of cascaded 2 × 2 couplers interconnected by delays [6, 7] have also been pursued, and are discussed the section entitled Spread-Time and Spread-Spectrum Schemes.

The majority of photonic CDMA schemes, however, are incoherent, where filtering is performed on a power basis by time-averaging over the optical phase. Assuming that all optical signals at the decoder output are incoherent, the total signal is produced by summing the intensities of individual components. In this case, the decoder impulse response can be specified by

$$|h_{\text{dec}}(t)|^2 \cong |h_{\text{enc}}(\tau_m - t)|^2 \tag{3}$$

i.e., the magnitude of the impulse response is the time-reverse of the encoder and independent of the signal waveform. To ensure that signals do not interfere coherently at the decoder output, a mismatch in delays between encoder and decoder that exceeds the source coherence time response is required, hence the approximation in Eq. (3).

Optical Mixing Noise

Most RF schemes are based on linear envelope detection of incoming signals after mixing with a stored reference code. The process gain is typically limited by crosstalk arising from the imperfect orthogonality between codes, represented mathematically by finite crosscorrelations. By contrast, photonic CDMA schemes use square-law photodetection in which all incident fields are mixed. The resulting mixing (beat) products, not present in linear RF systems, generate baseband electrical noise if the fields occupy the same optical bandwidth. This optical beat noise often severely limits the performance of photonic CDMA systems and often exceeds crosstalk since it scales with the square of the number of detected fields, which is proportional to the number of users, whereas, the total crosscorrelation between codes scales with the number of users. Low crosscorrelation between codes is a prerequisite for good performance of photonic CDMA schemes; however, the maximum achievable total network capacity, defined as the product of the number of users and the per user bit rate, is fundamentally limited by optical beat noise. Strategies for reducing optical beat noise include using sources with broad linewidths to reduce the fraction of optical beat noise falling within the receiver bandwidth, using differential detection, and using time gating. The first two are discussed in the next section. Time gating is discussed in the following subsection.

Time-Gates

Many photonic CDMA schemes utilize short optical pulses and are based on a spread-time approach. In spread-time approaches, data is transmitted as a pulse

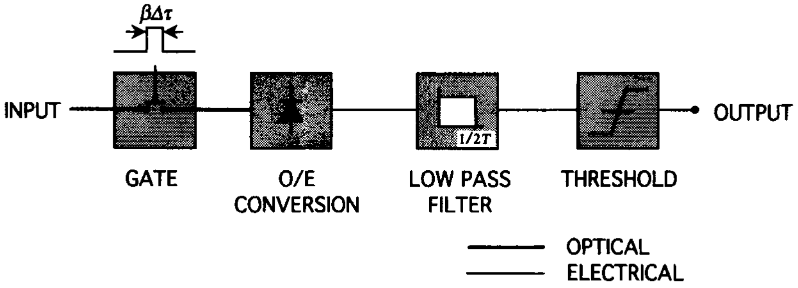


Figure 2. Time-gated receiver.

much shorter than a bit period that is converted (spread) by an encoder into a low-level, high-rate code (chip) sequence. Matched decoding despreads the signal by reconstructing the original pulse, whereas unmatched signals remain spread in time. Discrimination is achieved by thresholding the chip-resolved output. In a given bit period, information from the desired transmitter is contained ideally in a single chip period $\Delta\tau$ containing the reconstructed pulse, whereas multiple-access noise is spread randomly over the full bit period T. Discrimination can be enhanced by a time-gate clocked to sample only the signal-bearing fraction of each bit, thereby rejecting signals that fall outside the gated interval. The time-gate is analogous to a bandpass filter in spread-spectrum CDMA schemes. Many analyses of the performance of spread-time schemes assume use of an ideal time-gate.

The improvement in SNR under time gating is given by the ratio of the bit period to the time window $T/\beta\Delta\tau$ where β is the number of chips for which the gate is open. Time gating is effective in reducing any noise in the received optical signal including multiple-user shot noise, crosstalk, and optical beat noise. The time-gate may be placed, in principle, before or after the detector without affecting the SNR. Placing it before the detector, as shown in Figure 2, has the advantage of reducing the minimum detector bandwidth required from $1/2\Delta\tau$ to $1/2T$.

Dispersion

The basic requirement of CDMA that each user employ a transmitted signal bandwidth greater than the data bandwidth has the potential to impose a trade-off between process gain and dispersion penalty. In fact, the majority of photonic CDMA schemes proposed to date use large optical bandwidths that impose very significant limits on transmission distance. In schemes based on short optical pulses, dispersion also impacts on process gain. To date, there have been no studies of the impact of dispersion on photonic CDMA schemes, despite its obvious importance. In the next section, we quantify the impact of dispersion on coherence multiplexing. The stringent limits set by dispersion will probably limit future applications of CDMA to local-area and access networks requiring relatively short lengths of fiber, i.e., a few kilometers.

Security

The feature of intrinsic security is often quoted as a major advantage of photonic CDMA approaches, however, this has not been substantiated. Code sequences provide some protection against casual observers; however, it is recognized in RF networks that coding is not synonymous with security [2], a point often overlooked in papers on photonic CDMA. A certain degree of security in a CDMA network is provided by high levels of traffic, since signals that overlap in optical bandwidth also overlap in time, and some knowledge of the code sequences will be required to extract any data. However, high levels of traffic cannot be guaranteed in photonic CDMA networks. For schemes employing an *amplitude-shift key* (ASK) data format, a tapped signal could be read without the need for decoding if only one transmitter was active, and the security derived from several users simultaneously active is not compelling. We expect that to provide sufficient justification for implementation, a CDMA network would require inherent security and not rely on high-traffic levels.

Several desirable features for secure photonic CDMA schemes may be identified. First, a modulation format other than ASK is required. Second, it is preferable to use schemes that utilize coding of optical fields since these schemes are inherently more secure than schemes based on intensity. In the latter case, it would be possible to detect a signal, record the transmission, and later decode electronically. In contrast, when the code information is embedded in the optical field, decoding must occur in real time. Third, it is desirable to utilize a large number of coding parameters to increase the difficulty of exhaustively searching for the correct code. We describe a scheme that has these features later the section entitled Spectral Coding Methods and Security.

Coherence Multiplexing

The first coherent optical CDMA proposal emerged in the mid-1970s. In 1975, Cielo and Delisle [8] proposed and demonstrated that the optical spectrum of a broadband, CW thermal source could be modulated in an unbalanced Michelson interferometer and the modulation signal could be recovered using a matched unbalanced interferometer. In 1976, Cielo and Delisle went on to propose and demonstrate the use of the same scheme for multiplexing of communication signals [9]. Their work was taken up in the early 1980s and extended by Goedgebuer and coworkers [10–12]. Cielo and Delisle's papers were published in French and not widely noted. Several other groups also published, apparently independently, similar concepts for application to communications [13] and to sensors [14, 15]. The scheme became known as path-difference multiplexing or coherence multiplexing. Coherence multiplexing has not generally been categorized as a photonic CDMA scheme. However, coherence multiplexing makes use of a coherent matched filter and, importantly, has the defining features of CDMA—shared signal bandwidth and asynchronous operation. We will further show in this article that the operation of coherence multiplexing is closely related to a number of other CDMA schemes.

Coherence multiplexing, as implemented in a CDMA broadcast network, is illustrated in Figure 3. *Encoders* (ENC) and *decoders* (DEC) consist of interferometers with path delay imbalances substantially greater than the coherence-times τ_c of the sources. The differential delay in each interferometer is used to address the channels. Digital data is applied to the encoder by $\pm \pi/2$ *phase-shift keying* (PSK) one arm using a phase modulator. This does not produce an intensity modulation at the output of the encoder since the fields from the two paths combine incoherently. Decoding is achieved by matching the differential delays of the

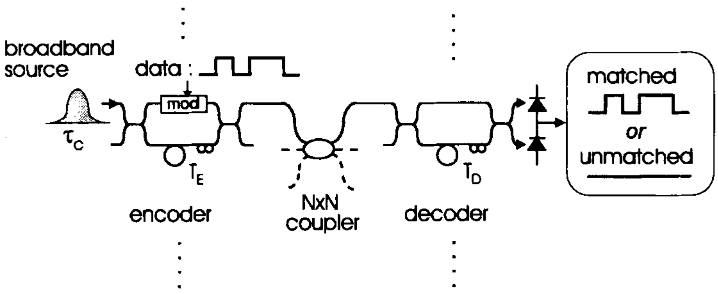


Figure 3. Photonic CDMA network employing coherence multiplexing (mod: phase modulator).

decoder T_D and encoder T_E to significantly less than the source coherence-time, i.e., $|T_D - T_E| \ll \tau_c$. Fields from two of the four available paths from the input to the output are then correlated. These two fields, one of which has been phase modulated with the data, interfere coherently and the data is recovered as an intensity modulation. When the delays of the decoder and encoder are unmatched by more than several coherence-times, i.e., when $|T_D - T_E|$ is greater than a few times τ_c, the fields remain substantially uncorrelated and negligible coherent interference takes place. Signals from these unmatched encoders are, therefore, not recovered. The differences between all encoder delays must significantly exceed the source coherence-time to prevent crosstalk between channels. It is desirable to use sources with broad linewidths since this allows short interferometer delays to be used and also reduces the detected optical beat noise. The network is, in principle, reconfigured by switching the encoder and/or decoder delays.

Apart from practical constraints placed on the power budget by available source power, receiver sensitivity, and splitting losses, the number of users that can be supported at a given bit rate is severely limited by the optical beat noise generated in the network [16]. The generation of optical beat noise in coherence-multiplexed systems has been studied theoretically by Wentworth [17] and by Chu and Dickey [18].

The highest capacity demonstrated to date in any optical CDMA network is 4 Gbit/s in a four-channel coherence-multiplexed system, with each channel having a capacity of 1 Gbit/s [19]. The experimental configuration of this demonstration is shown in Figure 4. The interferometers were constructed from standard single-mode fiber, and the source was an erbium-doped fiber amplifier that produced polarized amplified spontaneous emission with a coherence-time of 390 fs. The receiver had a measured bandwidth of 750 MHz. Conventional coherence-multiplexing systems use detection from only one decoder output. With single-ended detection, and all four channels operational, a floor in the BER was observed at 10^{-6}. This observation is the first experimental verification of the impact of optical beat noise in limiting the transmission capacity of a coherence-multiplexed system. However, using differential detection of both decoder outputs, the BER floor was not observed. These measurements of BER [19] are shown in Figure 5*a*. Using differential detection, a BER of around 10^{-11} could be achieved with all four channels operational.

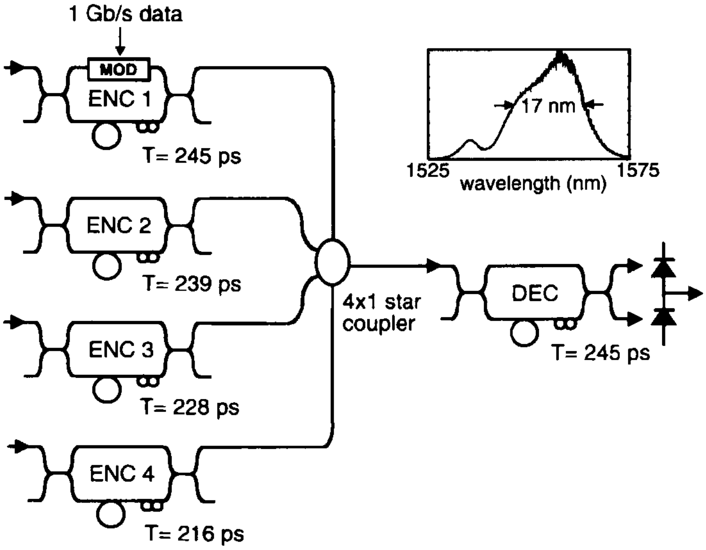
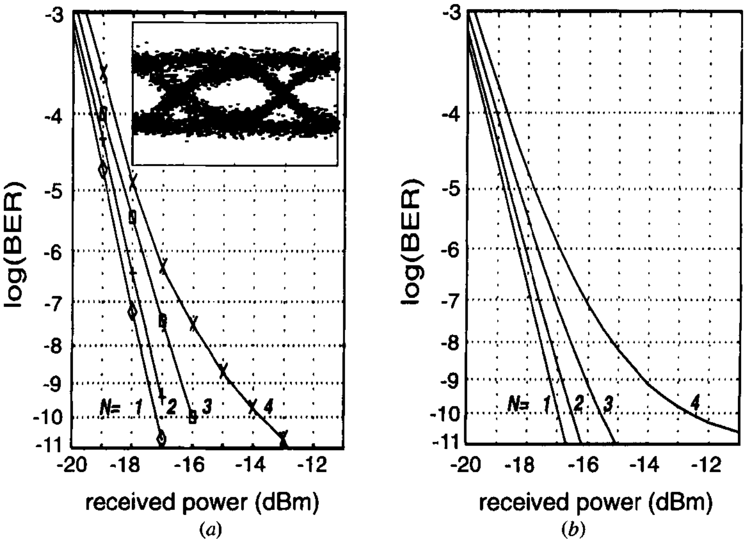


Figure 4. Experimental configuration [ENC 1, encoder (matched to decoder); ENC 2–4, encoders; DEC, decoder; MOD, $LiNbO_3$ phase modulator]. Inset: source spectrum.



(*a*) (*b*)

Figure 5. *a* Measured and *b* theoretically estimated BER performance of a 1-Gbit/s per-user coherence-multiplexed system for one-, two-, three-, and four-channel operation. Inset: measured eye-diagram with four-channel operation.

Using the theory in [17] and accounting for the effects of differential detection [20], the SNR limited by the optical beat noise is given by [21]

$$\mathrm{SNR}_{\mathrm{OBN}} = \frac{1}{\tau_c \cdot B_e \cdot (4N^2 + 2N + 1)} \approx \frac{1}{4\tau_c \cdot B_e \cdot N^2} \tag{4}$$

where N is the number of channels and B_e is the receiver bandwidth. The theory assumes that all sources are polarized and have thermal characteristics and identical spectra. We used Eq. (4) to estimate theoretically the BER performance of the experimental demonstration [21]. In calculating the BERs, we assumed that the optical beat noise had a Gaussian probability density function, thus BER $\approx Q(\sqrt{\mathrm{SNR}})$. This is a reasonable approximation because the receiver bandwidth is far smaller than the source linewidth. We also assumed that the contribution from shot noise is negligible compared to receiver noise, which was the case in our receiver. The theoretically estimated BERs for one-, two-, three-, and four-channel operation are plotted in Figure 5*b* and show close agreement with the experimental results. This is the first comparison of theoretical and experimental transmission performance in photonic CDMA schemes.

An important characteristic of coherence-multiplexed systems, and with many other optical CDMA systems, is that the optical beat noise increases linearly with the receiver bandwidth and quadratically with the number of channels, as indicated by Eq. (4). Therefore, the total network capacity, which is given approximately by $2B_eN = 1/(2\tau_c\mathrm{SNR}_{\mathrm{OBN}}N)$, decreases linearly with the number of users in the network, as noted by Healy [16] and Chu and Dickey [18]. Maximum capacity is, thus, obtained in networks with small numbers of users.

We have used Eq. (4) to estimate the value of the BER floors in systems having bit rates of 40 Mbit/s, 155 Mbit/s, 622 Mbit/s, and 1244 Mbit/s per user [21]. These are plotted against the number of users in Figure 6. These predictions assume a receiver bandwidth equal to half the bit rate and use the measured coherence-time of the source [21]. Figure 6 shows, for example, that in a network with a channel capacity of 155 Mbit/s per user, a BER floor at 10^{-9} will be reached with approximately 15 users.

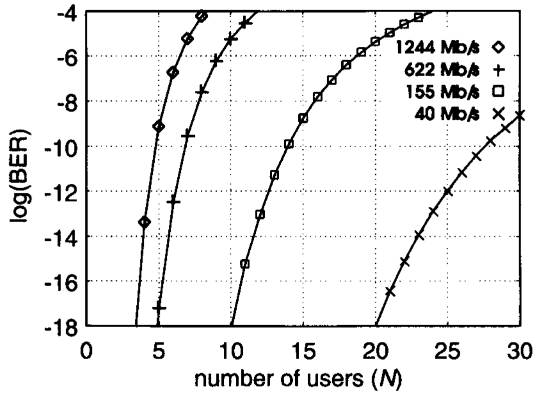


Figure 6. Calculated BER floors versus number of users (N) for systems with data rates of 40, 155, 622, and 1244 Mbit/s per user.

Capacity can be improved by increasing the linewidth of the source (see Eq. (4)), however, a broader linewidth source reduces the transmission distance as a result of fiber dispersion in the transmission path. This trade-off between optical beat noise and dispersion gives rise to an optimum source linewidth. Assuming a source with Gaussian lineshape and FWHM $\Delta\lambda$, then transmission at a bit rate B over a distance L of fiber with dispersion D will close the eye-opening in the received signal by a factor approximately equal to $1 - 5.16B^2L^2\sigma^2D^2$, where $\sigma = 0.42\Delta\lambda$ [22]. Using this expression, together with Eq. (4), we find that the linewidth that gives a maximum $\mathrm{SNR}_{\mathrm{OBN}}$ is $\Delta\lambda_{\mathrm{opt}} \approx 0.46(BLD)^{-1}$. From this, we can estimate the maximum number of users that can be supported at a BER of 10^{-9} for transmission at a channel bit rate B and transmission distance L. These results are plotted in Figure 7 as N^2B against BL for a system at 1550 nm operating in standard fiber with $D = 16$ ps/nm/km. We find, for example, that a system operating at 40 Mbit/s over 12 km would achieve maximum capacity with a (Gaussian) source width of 60 nm. At this optimum source linewidth, we see from Figure 7 that approximately 50 users could be supported.

The significant recent progress made on coherence multiplexing means that it is, by far, the most developed photonic CDMA scheme. Coherence multiplexing is the only approach to reach gigabit per second data rates and to reach multi-gigabit per second fundamental capacities. A further recent advance is the demonstration of the feasibility of integrating encoders and decoders by Hauden et al. [23]. The most noticeably outstanding issue, in common with several other approaches, is the need for switchable delays that will enable the network addresses to be reconfigured. In the next section, we review closely related approaches that avoid the need for switchable delays.

Spectral Coding Methods and Security

In this section, we review CDMA schemes that use broadband CW sources and perform coding directly in the optical frequency domain. In these schemes, the spectrum is divided into M slices and encoded by an M-element user code. We compare several schemes and point out their relationships with each other and with coherence multiplexing.

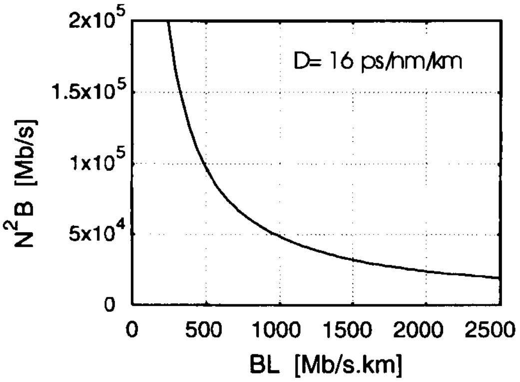


Figure 7. Estimate of the maximum total capacity (at a BER of 10^{-9}) in a coherence-multiplexed system for transmission in standard fiber ($D = 16$ ps/nm/km) using the optimum source linewidth $\Delta\lambda_{\mathrm{opt}}$.

Griffin and Sampson [24] first proposed spectral coding of broadband CW light and several similar independent proposals followed [25, 26]. Griffin and Sampson proposed a so-called coherence coding scheme based on binary coding of the phase of each of M spectral slices using a mask and grating arrangement placed in one arm of an unbalanced Mach–Zehnder (MZ) interferometer. The arrangement is shown schematically in Figure 8. The transfer function $|H_{\text{enc}}(f)|^2$ for the encoder in this scheme is given by

$$|H_{\text{enc}}(f)|^2 = \frac{1}{2}\{1 + \cos[2\pi f\tau + \phi(f)]\} \tag{5}$$

where $\phi(f)$ represents the applied coding sequence, with value 0 or π, and f is the optical frequency. The transfer function describes an output spectrum modulated by a binary code that replicates the spatial coding of the phase mask. A matched decoder in this scheme comprises an identical interferometer and phase mask. The scheme is, in essence, a generalized version of coherence multiplexing [27]. The dispersive element in the encoder modifies the coherence function of the transmitted signal, hence the term coherence coding. The dispersive element allows the use of identical delays for all encoders and decoders but requires differential detection to provide discrimination against crosstalk.

There have been several schemes independently proposed that provide the functionality of coherence coding but do not involve an interferometric en/decoder. Kavehrad and Zaccarin [28, 29] proposed spectrally encoding a broadband CW source by placing a spatial amplitude mask in a dispersive arrangement identical to that shown schematically in Figure 8. The encoder response in this case may be cast in the form

$$|H_{\text{enc}}(f)|^2 = \cos[\phi(f)] \tag{6}$$

where $\phi(f)$ assumes values of 0 or $\pi/2$. For decoding, two masks with complementary codes are used and combined with differential detection to provide high process gain. Nguyen et al. [30] have also proposed a similar scheme employing a more complex encoder that switches between two amplitude masks, thereby transmitting data symbols as complementary spectral codes. The decoder is the same as that used in [28].

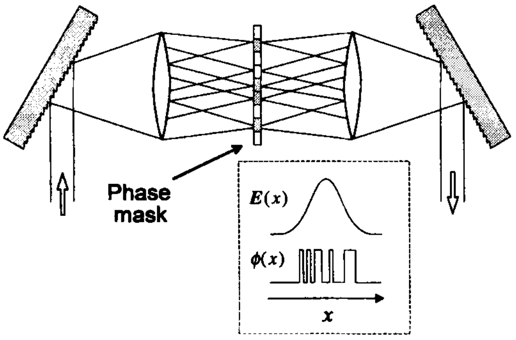


Figure 8. Grating and mask arrangement to perform spectral coding. Inset: typical spatial variation of field amplitude and code variable.

The similarity between coherence coding and spectral amplitude coding is apparent from a comparison of Eqs. (5) and (6). When the interferometer delay is set to $\tau = 0$, the encoder transfer functions are identical. Kavehrad and Zaccarin's scheme employs ASK to transmit data. For coherence coding, ASK can be employed, however, phase-shift keying (PSK) applied to one arm of the interferometer is also possible. PSK produces complementary spectra for transmission of symbols one and zero identical to those produced in the scheme of Nguyen et al.

Spectral coding provides several attractive features. The mapping of the physical mask pattern to an optical spectral code allows a wide range of codes to be employed. The code sequences may be reconfigured electronically, for example, using a liquid crystal array to implement the spatial phase mask, relieving the difficulties associated with switchable optical delays. Implementation using guided-wave devices is also possible [27, 31]. A major advantage, shared with coherence multiplexing, is that the temporal response of transmitted symbols is largely unaffected by the spectral coding, allowing the detector to operate at speeds comensurate with the baseband data rate rather than at the far higher chip rates that characterize spread-time approaches. This feature distinguishes the spectral coding schemes discussed above from the spread-time scheme of Weiner et al. [4] that proposed direct spectral manipulation of transform-limited pulses.

The fundamental similarity of spectral phase and amplitude encoding schemes suggests that system performance will be similar. Analysis of crosstalk for each of the schemes [27, 28, 30] indicates that a large number of users could potentially be supported. However, Griffin and Sampson [27] recognized that system performance would be constrained by optical mixing noise. The analysis of optical beat noise outlined in the previous section for coherence multiplexing is also valid for coherence coding, and so the performance limits presented in that section apply. Kavehrad and Zaccharin [28, 29] and Nguyen et al. [30] did not take into account optical beat noise, and performance estimates were unrealistically high. Smith et al. [32] subsequently highlighted this deficiency and provided more realistic estimates of performance. They gave an optical beat noise-limited SNR of

$$\mathrm{SNR} \approx \frac{1}{\tau_c B_e N^2} \tag{7}$$

where the terms are the same as in Eq. (4). A comparison with Eq. (4) suggests that an ideal spectral amplitude encoding network can potentially support twice the number of users as one using coherence coding. This difference arises because optical beat noise is determined by the number of paths; and for coherence coding there are four paths per user, whereas, for spectral amplitude coding schemes there is only one path. The analysis in [32] that leads to Eq. (7) assumes ideal operation in a system having a rectangular spectrum subdivided into slices without any "dead space" between. In practice, for all spectral coding schemes, the source bandwidth will not be able to be used with 100% efficiency due to finite roll-off of the filtering, reducing capacity. This has yet to be considered in detail.

The first experimental verification of spectral encoding schemes employed coherence coding at a data rate of 10 Mbit/s [33]. The experiment employed a pair of 15-element phase masks patterned with an m-sequence code. Reconfiguration and rejection of an unmatched signal were demonstrated by manually translating the decoder phase mask. More recently, data transmission using spectral amplitude encoding has been demonstrated [34], although at a data rate of only 10 Kbit/s. The basic operation of spectral masking has been extensively demonstrated, together with electronic reconfiguration, for encoding picosecond pulses [35]. The feasibility of encoding a broadband source using an acousto-optic modulator has also been demonstrated [31].

The security aspects of point-to-point links that employ schemes closely related to coherence coding have previously been considered [25]. Coherence coding satisfies the key requirements outlined in the section entitled Fundamentals and appears to offer the best prospect of a secure CDMA network. However, thorough investigations of security in photonic CDMA networks have not been reported, and therefore, claims of high security remain speculative. Smith et al. [32] have pointed out that, given the need for a spectral encoding device, much higher aggregate capacities can be achieved by assigning a single slice to a given user, i.e., using spectrum-sliced wavelength-division multiplexing. This avoids the optical beat noise between users by eliminating the spectral overlap, greatly increasing performance. This is a compelling argument and requires that spectral coding schemes be justified on other grounds, namely, security.

Spread-Time and Spread-Spectrum Schemes

In this section, we review two classes of spread-time approaches to photonic CDMA based, respectively, on incoherent and coherent matched filtering. We also review optical spread-spectrum approaches.

Incoherent Matched Filtering

Incoherent matched filtering using optical fiber delay lines was first proposed and demonstrated in the 1970s as a means of processing microwave and RF signals [36–39]. In the early to mid-1980s, work on incoherent fiber optic signal processing was systematized and extended to single-mode fibers by Moslehi et al., and Jackson and Shaw [40, 41]. Fiber optic signal processing of baseband microwave and RF signals has continued to attract interest, although, with the exception of phased array radar [42, 43], convincing applications have not yet emerged. In the early 1980s, proposals emerged of so-called incoherent photonic CDMA schemes [44–56]. In 1983, Davies and Shaar [44] proposed a time-hopped CDMA scheme based on incoherent matched filtering of short optical pulses. Shaar and Davies [45] were the first to propose special sequences for use in incoherent CDMA. In 1986, Prucnal et al. [46] proposed using these sequences in an incoherent CDMA scheme based on code generation and filtering of short optical pulses using single-mode optical fiber delay lines. There subsequently followed many publications on schemes [47, 48] closely related to the scheme in [46], on code design [49, 50], and on performance analysis [51–56]. Proposals of new schemes for incoherent CDMA and analysis of their performance continue to be an active area of research. However, despite the emphasis given to these schemes in the literature, experimental confirmation of even modest performance is lacking. More surprisingly, given the apparent level of interest, their published theoretical performance is poor. Simple arguments can be constructed to show that this low performance is fundamental and cannot be significantly improved. In the following, we discuss both fundamental and practical problems with spread-time CDMA schemes based on incoherent matched filtering.

Incoherent matched filtering schemes operate as outlined in the section entitled Fundamentals. A short optical pulse, with duration much less than the data bit period, is transmitted through a network of optical delays and is transformed into a low-level, high-rate pulse train that constitutes the transmitter code sequence. At the receiver, a filtering operation is performed on the intensity of incident signals by an optical delay network acting as a decoder. Only a signal that is matched to the decoder is despread in time, with a concomitant increase in peak level compared to unmatched signals, and can be discriminated by a threshold device.

In order to evaluate the process gain for such schemes, consider an input optical pulse that is encoded as a sequence of n pulses, each of equal magnitude. Decoding involves splitting the encoded signal n ways, applying appropriate time delays and recombining the n components, each composed of n pulses, giving a total of n^2 pulses at the output. The peak signal contains n pulses and, assuming incoherent superposition, contains only $1/n$ of the signal power received. Thus, the process gain for these schemes is n, which equates to the number of "1" chips in the code sequence. This low process gain means that the performance of incoherent schemes is dominated by crosstalk between codes. Crosstalk is determined by the number of pulses from different users that are coincident. In order to obtain acceptable performance with low process gain, accidental coincidences must be minimized. This requires that sparse sequences be used. A great deal of research has been invested in the design of suitable sparse unipolar codes, e.g., [48–50]. A second consequence of low process gain is that time-gated detection is essential for adequate performance [51]. Poor overall performance is manifested either as high bit error rates due to high levels of crosstalk or low total network capacities due to excessively long sequence lengths. Specific examples of performance are given in the next section, however, the dependence of the total capacity on key system parameters can be determined by simple arguments [57]. Consider prime sequences [45] as typical examples of suitable codes. Prime sequences are a family of n codes containing n "1"s in a code of length n^2. The bit period is, therefore, of order n^2 chips, and the scheme accommodates n users. The aggregate capacity, therefore, scales according to $n \cdot (1/n^2\Delta\tau) = 1/n\Delta\tau$ where $\Delta\tau$ is the chip duration. Thus, the aggregate capacity of these schemes scales inversely with number of users and is a small fraction of the chip rate.

Several methods to reduce crosstalk in incoherent matched filtering schemes have been proposed. A scheme based on nonlinear optical thresholding before decoding has been proposed [51]. Brandt-Pearce and Aazhang [58] proposed that knowledge of code properties can be utilized to improve signal estimation through multiuser detection. A number of approaches have also been proposed to achieve a bipolar characteristic with incoherent detection, with potential improvement in capacity [53, 59–61]. Application of these various schemes may improve the performance of incoherent systems where throughput is limited to modest values. However, reduced crosstalk will require analyses of these schemes to take into account optical mixing between signals from multiple users. To date, this has been neglected and, furthermore, no specification on the bandwidth of the optical signals required to fulfill this assumption has been published. We speculate that any coding or detection improvement for an incoherent system will only achieve modest gains before optical mixing effects dominate.

Choice of a source of suitable optical pulses is a major practical issue in incoherent matched filtering that has received little attention. Incoherent superposition is a basic premise of these schemes and, to be achieved, requires the use of pulses with a high time-bandwidth product and an optical bandwidth considerably greater than the detection bandwidth. Specifically, use of mode-locked lasers is ruled out since the pulses they produce are close to transform-limited. A rule of thumb for obtaining incoherent superposition is that the pulses should have a time-bandwidth product of at least n times the transform limit, where n is the number of "1" chips in a code. This ensures that an approximate incoherent sum for the matched peak is obtained by offsetting in time each pulse by one coherence-time. The only practical sources of pulses with high time-bandwidth products suitable for use in communication systems are gain-switched Fabry–Perot semiconductor lasers that produce pulsewidths of around 20 ps and time-bandwidth products in the range of fifty or so [62]. However, the performance of an incoherent scheme based on 20 ps chips is very unattractive, as discussed in the next section.

Reconfiguration to address different network users in incoherent matched filtering schemes requires switchable delay lines. The slow emergence of suitable devices is a major impediment to achieving full network functionality. State-of-the-art is discussed further in the section entitled Outstanding Issues.

Several approaches based on combining spatial coding with incoherent matched filtering have been proposed [63, 64]. Mendez et al. recently made some progress toward a network demonstration [65]. These approaches ameliorate some of the problems discussed by increasing spatial diversity. However, it is not clear yet that they offer any particular advantages. Several other groups have also proposed the use of spatial variables in incoherent CDMA schemes [66, 67].

Given the severe fundamental and practical problems faced by incoherent matched filtering, we do not anticipate any significant developments in this field in the near future. However, it would seem reasonable to expect that future theoretical work takes into account at least some of the issues raised above.

Coherent Matched Filtering

In this section, we briefly describe coherent matched filtering, give some background, and review the experimental progress made to date. We make a comparison between the potential performance of coherent matched filtering and coherence multiplexing.

Coherent optical processing of baseband signals was first demonstrated by Davies and James [68] in 1984 in the form of an optical transversal filter. More recently, substantial progress has been made in the development of planar lightwave circuits for coherent transversal filters [69–71] and for optical domain filtering [72] and dispersion compensation [73]. These developments have shown the practicality in integrated form of networks of delays stabilized relative to the optical carrier phase. Filtering based on planar lightwave circuits has, to date, utilized the frequency response in processing CW optical inputs. Use of the impulse response in coherent matched filtering was first proposed and demonstrated in 1989 by Marhic and Chang [6], who described coding and coherent decoding of short optical pulses in optical lattice[1,2] networks that are interconnected using both network ports. The authors went on to demonstrate encoding and remote decoding in a single-stage lattice network [74]. Marhic and Chang indicated that optical phase and coupling fraction of the 2 × 2 couplers were potential coding variables but gave no details of how multiple access was to be achieved. Independently, Sampson and Jackson [7] proposed in 1990 encoding and coherent decoding in multistage lattice networks that are interconnected by a single network port. The authors proposed a multiaccess scheme on the basis of coherent interference of matched signals and incoherent interference of unmatched signals. Encoding, remote decoding, and data transmission in the presence of a simulated interfering user were demonstrated in 1992 [75]. Syms et al. [76] independently proposed waveguide structures for encoding and coherent matched filtering in 1991. They proposed applying their matched filtering scheme to spread-spectrum communications but did not give details of how to achieve multiple access.

Coherent matched filtering is described in detail in [74] and [77]. The scheme is based on time spreading and operates in a very similar fashion to incoherent matched filtering previously described. The principal difference is that, for coherent matched filtering, the code sequence is despread coherently to reconstruct the original pulse. This process is indicated schematically in Figure 9 based on optical lattice networks interconnected via a single port. The principle advantage of the coherent approach is that, for an encoder that produces n pulses, the coherently decoded signal has an intensity n times greater than an incoherent superposition, with the added advantage that this intensity is a fixed fraction of the total energy, independent of n. Interconnection of lattice network encoders and decoders via both ports [74] provides, in principle, perfect reconstruction of the input pulse at the output; whereas, interconnection via a single port [77] imparts a 6-dB loss and small side lobes are present in the reconstructed pulse. Use of both ports to perform two-channel matched filtering is advantageous in principle, however in practice, it is unlikely to be feasible. Transmission using two distinct fibers is impractical due to the large relative phase excursions that would be encountered. Transmission of both channels as orthogonal polarization states in single-mode fiber [74] could be implemented. However, adaptive polarization control would be required at the decoder input as well as phase control to account for propagation delay between the two channels. Given this level of complexity, single-channel matched filtering would appear to be the more practical approach.

Sampson and Griffin proposed and demonstrated two CDMA schemes based on single-channel coherent matched filtering. The first scheme uses incoherent unmatched decoding [7] and requires that the delays of all encoders and decoders are chosen to minimize coincidences of optical pulses that fall within a coherence-time. The resulting incoherent superpositions have intensities that are lower than the matched peak response by at least a factor n, the number of pulses generated

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[1] The terms "ladder" and "lattice" have both been used in the literature to describe networks consisting of coupled Mach–Zehnder interferometers.

[2] The first optical lattice network for matched filtering is attributed to Marom [38]. However, Marom's network differed significantly from the ladder networks considered more recently. Marom's network consisted of multimode fibers weakly coupled at suitable points using asymmetric fused fiber couplers to form a tapped bus structure.

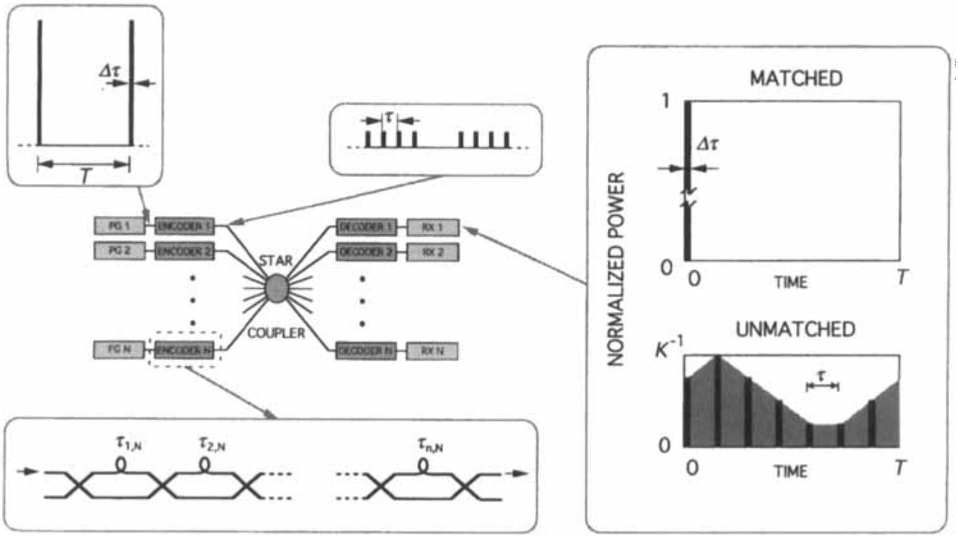

Figure 9. Photonic CDMA broadcast network employing coherent matched filtering. Ideal forms for matched and unmatched decoded sequences are shown and assume a given value of delay between users. Shading of the envelope of the unmatched sequence is an aid to the eye [PG, pulse generator; RX, receiver].

in an encoder [77]. The process gain of this scheme can be further enhanced by using differential detection to reject incoherent signals that are common to both decoder outputs. The second approach [78] uses coherent unmatched decoding in which all encoder and decoder delays are equal to within an optical wavelength, and optical phase is used as the coding variable. In optical phase coding, all interference is coherent, which has generally been avoided in photonic CDMA schemes, with the exception of the ultrashort pulse coding scheme to be discussed later in this section. Figure 10 shows schematically how optical phase coding may be achieved in practice. A master network is used to which all encoders and decoders are locked. Optical phase coding has the attractive features of a single design for all encoders and decoders and reconfiguration via electronic control of optical phase.

Lattice network approaches have not been studied as extensively as coherence multiplexing. The principles of operation of both CDMA schemes just discussed have been experimentally demonstrated [7, 78]. For the scheme based on incoherent unmatched decoding, data transmission using two-stage lattice networks including a simulated interfering user has been demonstrated [75]. The choice of codes necessary to achieve incoherent unmatched decoding in practice has been examined [77]. Sampson et al. found that delay coincidences are difficult to avoid but showed that codes with very low crosstalk can still be chosen. It has also been shown that codes can be designed for coherent unmatched decoding that reduce coherent crosstalk to low levels [78]; however, the resulting coherent crosstalk has complex structure, and it has not been verified that low bit error rates can be achieved with this approach. An estimate of the performance of coherent matched filtering schemes is given in the next section.

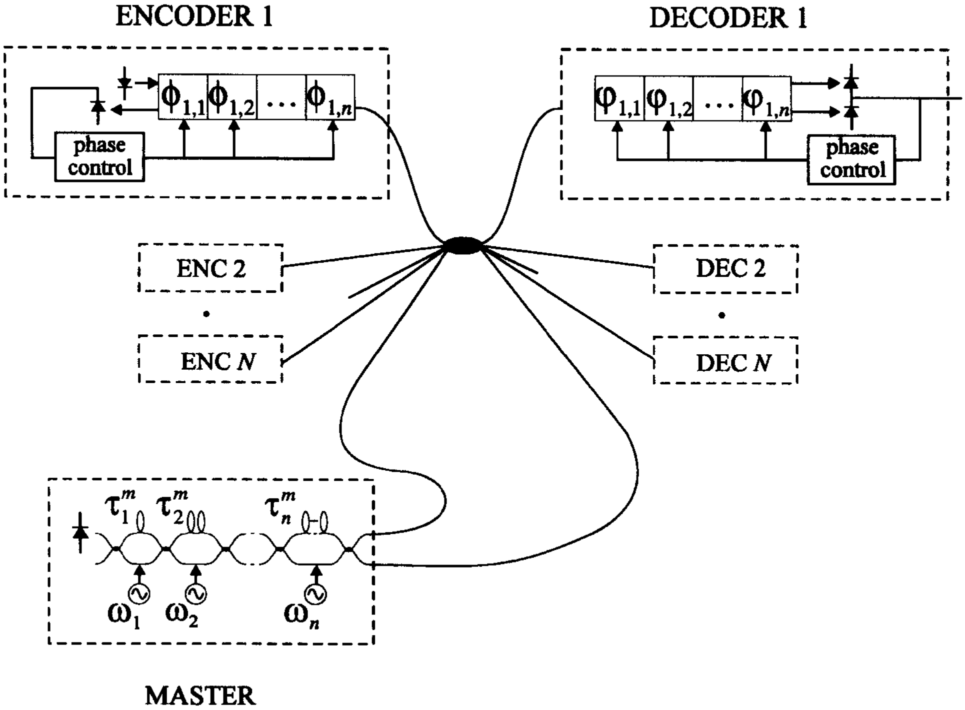

Figure 10. Photonic CDMA broadcast network employing optical phase coding in multiple-stage lattice networks. A master encoder provides global optical phase control.

Coherent matched filtering using short optical pulses has an important potential advantage over coherence multiplexing with CW sources. As discussed previously, time-gating the signal-bearing pulse can be used to reduce optical beat noise that sets severe limits on the performance of coherence multiplexing. However, the use of pulses also introduces crosstalk by virtue of the asynchronous arrival times of unmatched pulses. In coherence multiplexed systems, incoherent crosstalk contributes a CW background light level and so is easily removed by AC coupling at the receiver. In coherent matched filtering systems, incoherent crosstalk is reduced using lattice networks with multiple stages in order to spread the unmatched pulses more uniformly and using differential detection. Sampson et al. [77] showed crosstalk can be reduced to low levels; however, a detailed analysis of the limits on performance of pulsed coherent matched filtering schemes due to optical beat noise has not been performed to date. This is an important area for future work.

Weiner et al. [4] in 1988 proposed a novel coherent approach based on time spreading and despreading of ultrashort optical pulses. They demonstrated pulse spreading and despreading using the same grating and mask arrangement shown in Figure 8. Their scheme represents true optical matched filtering because it is based on transform-limited optical pulses. A similar scheme was also proposed independently [79]. Salehi and Weiner [80] went on to analyze the potential performance of their approach, however, no experimental demonstration of remote decoding or data transmission has been published to date. Their coherent ultrashort pulse scheme has both fundamental and practical problems. Fundamentally, the impact of chromatic dispersion is severe and has two aspects. First, the scheme requires the use of femtosecond pulses, which are sensitive to broadening by dispersion. Pulse broadening by a certain ratio reduces process gain by the same ratio since the basis of the scheme is time spreading. However, the impact of dispersion cannot be reduced by using longer pulses because this also reduces process gain since the maximum time spread achievable by an encoder is limited by practical details to the range 10 ps to 100 ps. Second, since frequency-dependent phase is the basis for encoding, chromatic dispersion in optical fibers also acts to encode the signal. Therefore, a decoder must compensate for the combined effects of a possibly unknown length of fiber and a known encoder. This feature places severe constraints on the design of a practical CDMA network. Alternatively, the scheme places strict and unrealistic requirements on both linear and higher order dispersion in optical fibers, as Weiner and Salehi discuss in [81]. Another major practical problem is how to achieve ultrafast thresholding, which, to date, has not been demonstrated in practical form [81].

Salehi and Paek [82] proposed using coherent spatial matched filtering for photonic CDMA. Their scheme is based on spatial encoding and holographic decoding. In [82], the authors point out the enormous potential process gain and present a free-space proof-of-principle experiment. However, the scheme requires transmission of spatial information and, therefore, cannot be used in combination with transmission over a single-mode optical fiber. This dramatically reduces the potential usefulness of their scheme.

Spread Optical Spectrum

Direct-sequence optical spread spectrum was proposed in 1988 [83, 84]. This approach is the optical equivalent of direct-sequence spread spectrum in the RF domain. In spread optical spectrum, a narrowband optical carrier is spread by a high-rate sequence driving an electro-optic modulator and also despread using an electro-optic modulator. At the outset, it was realized that the limit on the modulation bandwidth of electro-optic modulators limited process gain and so placed severe restrictions on performance [83]. This limitation has sometimes been subsequently overlooked [85]. The limitation of spread optical spectrum CDMA schemes can be readily appreciated from simple arguments. First, a reasonable upper limit on chip rates based on cost and current performance is 10 Gbit/s. The ratio of the chip rate B_C to the bit rate B is approximately the process gain of the scheme. The SNR is given approximately by $B_C/N \cdot B$. If we assume an SNR of 50, sufficient to achieve low error rate, then the aggregate capacity of the scheme is 200 Mbit/s. Such low capacities make the scheme uncompetitive with even current commercial TDMA technology such as FDDI and fast ethernet. To avoid this limitation but retain the benefits of CDMA, Foschini and Vanucci [83] considered combining CDMA with WDM in a high-capacity network. To our knowledge, this work has not been carried beyond a feasibility study [86]. An interesting related application of direct-sequence spread optical spectrum is to switching [87]. The colocation of encoding and decoding electro-optic modulators permits the use of nondeterministic, analogue spreading and despreading signals. In [87], the authors use Gaussian noise, which they claim gives about an order of magnitude increase in aggregate capacity.

Performance Comparison

In this section, we compare the published performance of various schemes. We first consider theoretical performance and then experimental performance.

Theoretical Performance

We have chosen to compare the published performance of four different schemes. They are coherence multiplexing [21], coherent matched filtering of short pulses [77], ultrashort pulse spectral phase coding [80], and incoherent matched filtering of short pulses [51]. These schemes, in our view, represent the most promising approaches reported to date. Coherence multiplexing is also representative of the class of schemes based on spectral coding. Our purpose here is to provide some quantitative indication of likely achievable performance. However, the basis for comparison is complex and dependent on many factors, and therefore, the reader is advised to exercise caution in the interpretation of the results to follow.

In Table 1, we give a range of parameters for each scheme. The parameters chip period, bit rate, number of users, and total capacity are self-explanatory. The parameter "bandwidth utility" is defined as the ratio of the total capacity to the optical bandwidth employed. For a TDMA scheme employing transform-limited pulses, the bandwidth utility is equal to one. The parameter "time utility" is defined as the ratio of the total capacity of the scheme to the total capacity of a TDMA scheme based on the same chip period. After surveying published results,

Table 1
Published theoretical performance of several CDMA schemes

Scheme	Ref.	Chip period (ps)	Bit rate (Mbit/s)	Number of users	Total capacity (Gbit/s)	Bandwidth utility	Time utility
Coherence multiplexing	Pendock et al. [21]	–	40	30	1.2	0.0006	–
Coherence multiplexing	Pendock et al. [21]	–	622	7	4.3	0.002	–
Coherent matched filtering	Sampson et al. [77]	20	500	18	9	0.007	0.18
Ultrashort pulse coding	Weiner et al. [80]	0.1	800	20	16	0.004	0.0016
Ultrashort pulse coding	Weiner et al. [80]	1	80	20	1.6	0.004	0.0016
Incoherent matched filtering	Salehi et al. [51]	1	500	10	5	0.001	0.005
Incoherent matched filtering	Salehi et al. [51]	20	25	10	0.25	0.001	0.005

we have chosen to assume numbers of users of around 20 for operation at bit rates in the range of tens to hundreds of megabits per second at a bit error rate of 10^{-9}. We have not included an assessment of link length in Table 1 because it is not included in the published analyses. We note that it is not straightforward to evaluate the impact of dispersion on schemes based on pulses because the process gain is affected by dispersion.

The performance figures for coherence multiplexing in Table 1 are somewhat conservative, as the analysis in [21] assumes a modest optical bandwidth of 17 nm at a center wavelength of 1550 nm, and considers the worst case when all polarizations are aligned. For coherent matched filtering, the results assume use of a time-gate with 20-ps response time and are based on four-stage lattice networks and single-ended detection. The estimates of the performance of coherent matched filtering in Table 1 are subject to significant uncertainties. The estimates are based on published average variances due to crosstalk [77] and do not take into account optical beat noise. Improved performance can be expected using differential detection, although no data has been published to date. For the ultrashort pulse scheme, we assume chip durations (pulsewidths) of either 100 fs or 1 ps. The choice of pulsewidth represents a trade-off between dispersion-limited link length and process gain. However, emergence in the near future of a time-gate with 100-fs response time, as required by this scheme, in a form suitable for use in a communication system appears unlikely. Therefore, the performance figures at 100 fs are unlikely to be achievable. For incoherent matched filtering, we have assumed pulsewidths of 1 ps and 20 ps in order to provide meaningful comparison with the other schemes. We have assumed the optical bandwidth to exceed the transform-limited bandwidth by a factor equal to the number of "1"s in the chip sequences used, as discussed in the previous section. The performance figures for 1-ps pulsewidths are unlikely to be achievable because, as pointed out in the previous section, an appropriate source of incoherent 1-ps pulses is currently lacking.

The theoretical total capacities of the chosen CDMA schemes that support a modest few tens of users are poor compared to current electronic TDM transmission systems at 10 Gbit/s and emerging WDM transmission technologies at 20 Gbit/s and beyond. There exists some potential for improvement of coherent matched filtering, although this has yet to be convincingly demonstrated.

Experimental Performance

There are very few experimental verifications compared to the number of proposals and analyses of photonic CDMA schemes. Of the experimental verifications, there are even fewer that report measurement of bit error rates or assess in some way the quality of transmission. In this section, we restrict ourselves to a survey of experimental results that report measured bit error rates.

Table 2 gives the per user bit rates, numbers of channels, and bit error rates in published experimental demonstrations of photonic CDMA schemes. Prucnal et al. [46] performed the first demonstration of data transmission in photonic CDMA. Their experimental implementation was, however, not completely optical, as they used electronic encoding and all-optical decoding. The bit rate used was a modest 3.125 Mbit/s, and the chip rate was 100 Mbit/s. They simulated two additional interfering users and reported average measured bit error rates in the range 10^{-2} to 10^{-6}. Furthermore, they noted a significant disadvantage of incoherent schemes that measured bit error rates were markedly different from the average value depending on the precise sequences chosen. Hamel et al. [88] demonstrated the simultaneous transmission of two analogue television channels over a 3.5-km fiber link using coherence multiplexing. They measured crosstalk of -20 dB, however, gave no other performance data on the fidelity of the channels. Vethanayagam and MacDonald [89] used a novel incoherent approach to achieving bipolar electrical processing with unipolar optical inputs. They used a partially photonic implementation with electronic encoding and all-optical decoding. The bit rate was 50 Mbit/s, and the chip rate was 800 Mbit/s. They performed a two-channel experiment and gave plots of bit error rate versus received optical power that showed no signs of an error rate floor. However, the lowest bit error rate reported was 10^{-7} due to insufficient optical power at the receiver. Following the work reported in [65], Mendez et al. [90] reported a bit error rate of 2×10^{-9} at a data rate of 155 Mbit/s for a four-channel space- and time-coded incoherent CDMA demonstration. They indicated that the bit error rate was limited by multiple-access interference, i.e., by crosstalk.

The first gigabit per second photonic CDMA demonstration was reported by Pendock et al. [91] in 1995. Pendock et al. demonstrated two 1-Gbit/s channel coherence-multiplexed transmission over an 11-km fiber link. Significant features of this experiment are the use of an erbium-doped fiber amplifier as a source and a data transmission scheme using amplitude modulation and differential detection.

Table 2
Published experimental performance of photonic CDMA schemes

Scheme	Ref.	Channels	Data rate (Mbit/s)	Bit error rate	Link length (km)
Incoherent matched filtering	Prucnal et al. 1986 [46]	3	3.125	10^{-2}–10^{-6}	–
Coherence multiplexing	Hamel et al. 1987 [88]	2	Analog TV	–	3.5
Incoherent matched filtering	Vethanayagam et al. 1991 [89]	2	50	10^{-7}	–
Coherent matched filtering	Griffin et al. 1992 [75]	2	69	10^{-10}	–
Space and time addressed	Mendez et al. 1994 [90]	4	155	2×10^{-9}	–
Coherence multiplexing	Pendock et al. 1995 [91]	2	1000	$< 10^{-9}$	11
Coherence multiplexing	Pendock et al. 1995 [19]	4	1000	$< 10^{-9}$	8

Pendock and Sampson reported improved performance in [19], demonstrating four channels each with a capacity of 1 Gbit/s in transmission over an 8-km fiber link as described earlier in this article.

Outstanding Issues

There remain substantial uncertainties over the viability of photonic CDMA. It seems likely that achievable capacities will be limited of the order of a few tens of gigabits per second to optical beat noise, although the performance of schemes based on incoherent matched filtering and spread optical spectrum are likely to be much lower. A common feature of the highest performance schemes is utilization of broad optical bandwidths. Broad optical bandwidths in combination with dispersion produce pulse broadening that restricts link lengths to typically a few kilometers. Dispersion can be compensated, however, compensation of broadband signals would appear to be beyond the capability of current technologies [81].

It is appropriate to examine the range of likely applications in light of these fundamental restrictions on performance. Consider, first, applications requiring large numbers of network nodes. Given that photonic CDMA is not an appropriate technology for long distance, high bit rate transmission, such applications fall into the categories of metropolitan-area, local-area, and access networks. Total capacities of photonic CDMA techniques that are capable of supporting many tens of nodes are low. For example, the capacities of coherence multiplexing and incoherent matched filtering scale inversely with the number of users. Such schemes accommodating many low bit rate (few megabits per second) users must be compared with electronic TDMA schemes that are currently commercially available, such as FDDI, which has a total capacity of 100 Mbit/s. Given the level of complexity of photonic CDMA schemes, it appears unlikely that costs could be sufficiently reduced to make photonic CDMA schemes competitive in this application area. A possible exception to this is broadband customer access networks, where, for example, spectrum-sliced WDM systems are currently receiving some attention [92]. At higher bit rates of hundreds of megabits per second to gigabits per second, several schemes appear capable of supporting a few tens of users. Such schemes may find specific application in short-distance networks such as intercomputer networks. The impetus for such networks may come from the aspect of security if it can be established that such schemes can realize a security advantage over conventional approaches. In theory, it is possible to combine photonic CDMA with other multiplexing techniques in order to improve performance. However, in general, other techniques can achieve higher capacities, and therefore, use of CDMA must convey some other advantage. Given the additional complexity inherent in combined approaches, we believe it is unlikely that these approaches will be taken up.

In light of the above, we predict that photonic CDMA will be, at best, a niche technology satisfying as yet unforeseen networking applications. However, in order to arrive at that point, several significant technical obstacles that we shall now discuss remain to be overcome. Many schemes require a time-gate in order to discriminate sufficiently against noise. High-speed operation of time-gates has been successfully demonstrated in several optical TDMA systems, for example, using $LiNbO_3$ electro-optic switches [93]. However, the use of time-gates in CDMA has yet to be demonstrated experimentally. Also, the acquisition of the necessary timing information at the start of each new transmission is an important topic yet to be investigated.

The issue of network reconfiguration remains outstanding. This is particularly so for time-addressed schemes for which devices to change time delays that are necessary to reconfigure codes have yet to emerge. To date, space-switched lattice delay lines are the most promising technology [94, 95]. However, their current performance does not come close to what would be required to support a few tens of users. Coherent schemes require changes in delays in multiples of a few typically subpicosecond coherence-times. Therefore, there may exist the scope to reconfigure using alternative short-range delay technologies [96]. The only experimental demonstrations of reconfiguration in a CDMA scheme were reported by Griffin et al. in [33] and [78], as discussed previously. Spectral coding schemes have the best potential to provide electronic reconfiguration using a liquid crystal phase mask [35], also as discussed earlier.

Conclusion

In the introduction, attractive features of CDMA for optical communications were claimed to include asynchronous, low-delay access suited to bursty local-area network traffic, efficiency in allocating bandwidth only as required, soft capacity, and security. Despite the recent substantial experimental advances that we have reported here, the current state-of-the-art is a long way from meaningfully testing the veracity of these claims. Photonic CDMA will remain for the foreseeable future bound up in trying to assess and demonstrate limits on total capacities that make feasible its consideration for next generation lightwave networks. Given the pace of change and levels of performance in other competing technologies, the future of photonic CDMA is not bright. We predict that, at best, niche applications may emerge that take advantage of the potential security of some schemes.

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