A FEASIBLE ARCHITECTURE FOR HIGH-SPEED SYNCHRONOUS CDMA DISTRIBUTION NETWORK USING OPTICAL PROCESSING

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Abstract—In this paper, we propose a feasible architecture to implement tunable all-optical synchronous CDMA networks. Such a network is simply based on single rapidly tunable optical delay-lines and requires only a small number of electro-optic switches. Fast coding and decoding algorithms for synchronous prime-sequence codes are described. By using the proposed technique, all-optical synchronous CDMA networks can be constructed by integrated optics and can achieve a very high processing speed.

I. INTRODUCTION

Optical code-division multiple-access (CDMA) attracts a lot of interests recently and is a promising technique for future all-optical networks. By using optical signal processing to remove the bottleneck at the electro-optic/opto-electronic interface, optical CDMA (OCDMA) networks could potentially offer an ultrahigh throughput, in excess of 100 Gbit/s [1]-[3]. To have OCDMA possible for networking/switching applications, rapidly tunable schemes are highly required. Recently, research on programmable OCDMA networks has been carried out [3][4], in which optical lattices are used as programmable encoders and decoders to optically generate and correlate OCDMA sequences, respectively. Such encoders and decoders, however, are not suitable for prime-sequence codes [3][4]. On the other hand, OCDMA can only support a limited number of simultaneous users and subscribers because of asynchronism. To further increase the network capacity while maintain secure data communications in fiber optic networks, synchronous OCDMA can be employed at the expense of transmission scheduling and network synchronization [2][5]. For example, future military command and control communications may require synchronous OCDMA to ensure the high-speed secure access to various tactical systems in the base. Moreover, synchronous OCDMA can be employed in conjunction with optical time-division multiple-access (OTDMA) to support multi-rate services in a given network as pointed out in [5]. Thus, this can be potentially useful for the Broadband Integrated Services Digital Networks (BISDN's).

In this paper, we present a feasible architecture for fully tunable synchronous OCDMA distribution networks using prime-sequence codes. The proposed network uses single tunable optical delay-lines, of which the number of electro-optic switches is proportional to the logarithm (base 2) of a given prime number. Thus, using this scheme allows to construct high-capacity OCDMA networks in a feasible way with the potential of very-low coding power loss. The proposed technique is especially useful for a network where all the transmitters are fully tunable over the whole channels and receivers are fixed. Furthermore, we present a two-wavelength scheme to effectively resolve the clock distribution and frame synchronization in a large-scale synchronous OCDMA network. Thus, this self-synchronization OCDMA can be used to implement a distribution network where all transmitters are synchronized at the transmitting end while receivers can be inserted at different locations, as shown in Figure 1.

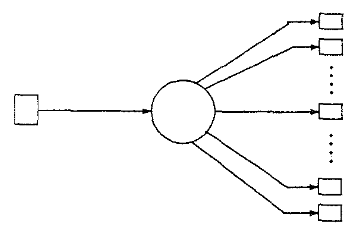

Figure 1: A distribution network.

II. SYNCHRONOUS PRIME-SEQUENCE CODES

To implement a fully tunable OCDMA network, the selection of optical address code sequences is important, because it affects both the network reconfiguration time and the complexity of tunable encoders/decoders. Although the optical orthogonal codes (OOC's) designed in [6] can have a better property of cross- and auto-correlations than prime-sequence codes [1], much more complex algorithms are required to produce OOC's. In contrast, the generation of prime-sequence codes are extremely simple, which only needs to perform the operation of modulo multiplication as will be shown in (1). Thus, the use of prime-sequence codes in OCDMA networks can ensure a very fast reconfiguration time. Moreover, a prime-sequence code has the perfect grouping characteristic [7], i.e., every codeword is subdivided into P equal-length subsequences of which each contains only one pulse. This characteristic can be used to significantly reduce the cost of fully tunable OCDMA encoders. In this paper, we focus on synchronous prime-sequence codes and their application to OCDMA networks.

For a given prime number P, the number of codewords in the prime-sequence code is equal to P and so is the number of total subscribers in an asynchronous OCDMA network [1].

A synchronous prime-sequence code has P^2 distinct codewords of length $L = P^2$ and weight P, which is derived from a set of prime sequences, $S_i = (s_{i0}, s_{i1}, \cdots, s_{ij}, \cdots, s_{i(P-1)})$, where s_{ij} is expressed as

$$s_{ij} = i \cdot j \quad (\text{modulo } P) \tag{1}$$

here $i, j \in \text{GF}(P)$ – Galois field of a prime number P [1]. The k-th synchronous prime sequence in a given group i, $S_i(k)$, is then obtained by left-rotating the elements of the i-th prime sequence by k times, where $k \in \text{GF}(P)$ [5], such that

$$S_i(k) = (s_{i0}(k), \cdots, s_{ij}(k), \cdots, s_{i(P-1)}(k)) , \quad \text{for } i, j \in \text{GF}(P) \tag{2}$$

is constructed according to the following rules:

1. For all $k = 0$,

$$s_{ij}(0) = s_{ij} \tag{3}$$

2. For $k \geq 1$,

$$s_{i(j-1)}(k) = s_{ij}(k-1) , \qquad \text{if } i \geq 1 \tag{4}$$

$$s_{0j}(k) = P - k , \qquad \text{if } i = 0 \tag{5}$$

where $s_{i(-1)}(k) \triangleq s_{i(P-1)}(k)$.

The P^2 codewords of the synchronous prime-sequence (S-PS) code, $C_i(k) = (c_{i0}(k), c_{i1}(k), \cdots, c_{im}(k), \cdots, c_{i(L-1)})$, are thus generated by

$$c_{im}(k) = \begin{cases} 1 , & \text{for } m = s_{ij}(k) + jP, \\ & \text{where } j \in GF(P) \\ 0 , & \text{otherwise} \end{cases} \tag{6}$$

Since the code cardinality determines the network size in OCDMA, P^2 users can now be supported by the synchronous prime-sequence code, as compared to P users in the original asynchronous prime-sequence code with the same L. For $P = 5$, the obtained synchronous prime sequences are given in Table 1, and the corresponding 25 codewords are also listed there.

As shown in (6), all the P ONE's (i.e., pulses) of each $C_i(k)$ are assigned to P individual subsequences of equal length P. The position of the ONE in the j-th subsequence is specified by $s_{ij}(k)$ given in (3)-(5), while the remaining $P-1$ slots of the subsequence are filled with ZERO's (i.e., no pulses). Benefiting from these grouping characteristics, rapidly tunable synchronous OCDMA encoders and decoders can be easily designed, based on single tunable optical delay-lines [7][8].

Table 1: Synchronous Prime Sequences and the Mapped S-PS Codewords for $P = 5$

Group i	Number k	S-PS $S_i(k)$	Mapped Codewords $C_i(k)$
0	0	00000	(10000 10000 10000 10000 10000)
	1	44444	(00001 00001 00001 00001 00001)
	2	33333	(00010 00010 00010 00010 00010)
	3	22222	(00100 00100 00100 00100 00100)
	4	11111	(01000 01000 01000 01000 01000)
1	0	01234	(10000 01000 00100 00010 00001)
	1	12340	(01000 00100 00010 00001 10000)
	2	23401	(00100 00010 00001 10000 01000)
	3	34012	(00010 00001 10000 01000 00100)
	4	40123	(00001 10000 01000 00100 00010)
2	0	02413	(10000 00100 00001 01000 00010)
	1	24130	(00100 00001 01000 00010 10000)
	2	41302	(00001 01000 00010 10000 00100)
	3	13024	(01000 00010 10000 00100 00001)
	4	30241	(00010 10000 00100 00001 01000)
3	0	03142	(10000 00010 01000 00001 00100)
	1	31420	(00010 01000 00001 00100 10000)
	2	14203	(01000 00001 00100 10000 00010)
	3	42031	(00001 00100 10000 00010 01000)
	4	20314	(00100 10000 00010 01000 00001)
4	0	04321	(10000 00001 00010 00100 01000)
	1	43210	(00001 00010 00100 01000 10000)
	2	32104	(00010 00100 01000 10000 00001)
	3	21043	(00100 01000 10000 00001 00010)
	4	10432	(01000 10000 00001 00010 00100)

III. OPTICAL ARCHITECTURE FOR SYNCHRONOUS OCDMA DISTRIBUTION NETWORKS

Figure 2 shows the proposed architecture for an all-optical CDMA network using synchronous prime-sequence (PS) code. Two mode-locked lasers are synchronized by a common clock at the transmitting end and are used to generate two streams of ultrashort optical pulses having width $\tau = T/L$ but different repetition rates and wavelengths. The optical sampling signal of wavelength λ_1 has a rate P/T, while the optical clock signal of λ_2 has a rate $1/T$, where T is the data bit period and P is a prime number (equal to code weight). This is a two-wavelength scheme, and it can be used in both synchronous OCDMA and OTDMA networks to effectively solve the problem associated with data-frame synchronization at each receiver, especially in a large-scale distribution network. At the i'-th optical transmitter ($i' = 1, 2, \ldots, P^2$), the stream of optical sampling pulses is then fed into an OCDMA encoder based on a single rapidly tunable optical delay-line as will be discussed in Section III-A. The OCDMA encoder further generates an intended synchronous PS codeword $C_i(k)$ used as a destination address of the desired receiver when the current data bit is "1"; otherwise no optical codeword should be resulted at the encoder, which can be realized by simply removing the P optical sampling pulses within this data frame from the encoder output. Thus, the original electrical data bits are optically encoded with the destination address $C_i(k)$ of a desired user.

A wavelength-insensitive, passive optical star coupler is employed to combine all the encoded short pulse streams of λ_1 together with optical clock signal of λ_2. Then, the two-wavelength signals are broadcast to every optical receiver in the network. At the receiver, an OCDMA decoder is required to extract the desired data message from a given transmitter. Finally, a high-speed electrical threshold detector is used after the wideband photodiode (PD) to threshold-detect the main peak (equal to P in the normalized case) of the expected auto-correlation function, which is always at the last time slot of each data frame. Therefore, the electrical data which were sent from the desired transmitter are now recovered at a receiver.

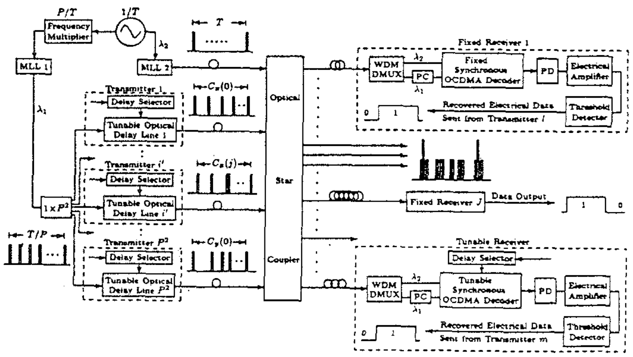

Figure 2: Proposed architecture for an all-optical synchronous CDMA network. MLL: mode-locked laser. DMUX: demultiplexer. PC: phase compensator.

A. *Transmitter Design*

In a distribution network, fully tunable transmitters should be used. As shown in Figure 2, at each transmitter the optical sampling pulses are available to a single rapidly tunable optical delay-line which only comprises M stages of electro-optic (EO) switches [7][8]

$$M = \lceil \log_2 P \rceil + 1 \tag{7}$$

The block diagram of a single tunable optical delay-line is illustrated in Figure 3. At the l-th stage, a differential time delay $\Delta\tau_l$ is then given by

$$\Delta\tau_l = 2^{l-1}\tau \tag{8}$$

where $l = \{1, 2, \ldots, \lceil \log_2 P \rceil\}$ and P is a prime number.

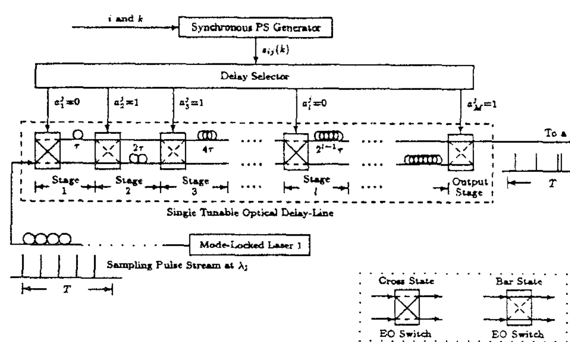

Figure 3: Architecture of an OCDMA encoder for synchronous PS codes.

In this configuration, any time delay of an integer multiple of $\tau = T/L$ can be generated by routing an incoming pulse to proper optical paths through setting the (bar or cross) states of the EO switches. At a given transmitter, the information (i.e., the values of i and k) that specifies the destination address sequence $S_i(k)$ of the desired receiver is made available to a synchronous PS generator whenever an electrical data bit "1" is issued. The synchronous PS generator consecutively transmits the corresponding P synchronous prime-sequence elements $s_{ij}(k)$'s, each for T/P seconds, to an electrical delay selector. The selector in turn maps each $s_{ij}(k)$ into a binary delay control sequence $(a_1^j a_2^j a_3^j \cdots a_{\lceil \log_2 P \rceil + 1}^j)$. The mapping is achieved by setting the l-th EO switch of the tunable optical delay-line to either the cross state, as $a_l^j = 0$, or the bar state, as $a_l^j = 1$, for all $l = \{1, 2, \ldots, \lceil \log_2 P \rceil\}$, such that the desired delay (i.e., $s_{ij}(k)\tau$) can be generated. For example, let $P = 5$ and $s_{ij}(k) = 3$, the required binary delay control sequence should be (0010), which sets the switches at stages 1, 2, and 4 (i.e., the output stage) to the cross state and the remaining one switch to the bar state, to generate a time delay of 3τ as shown in Figure 3 [7]. For the case of data bit 0, no optical pulses are actually transmitted and this can be achieved by setting the last EO switch such that the P optical clock pulses within the data frame simply exit from the unintended output. Note that this coding scheme has a major advantage that no extra EO modulator is required to gate the sampling pulse stream before each tunable OCDMA encoder.

During the generation of a synchronous PS codeword, the state of each EO switch needs to be changed in every T/P seconds and must be stable before the arrival of the next sampling pulse. Therefore, the processing speed of the controlling electronics has to be a factor of P faster than that of those used in the all-parallel or parallel-serial coding scheme [2][7]. On the other hand, the proposed coding technique eliminates the cost and extra power loss imposed by passive power splitters and combiners used in References [2][7], and can be feasibly constructed by integrated optics with potentially very low power loss. We assume that the speed of electronics is limited to 20 Gbit/s at the present time, then the maximum allowed data rate of users is equal to ~ 1.5 Gbit/s for $P = 13$, which is sufficient to support 1 Gbit/s HDTV or image services. Although the electronic processing speed limits the maximum data rate for a given P at the OCDMA encoders using a single tunable optical delay-line, the chip rate (i.e., $1/\tau$) of the encoders can be still ultrahigh, which is determined only by the width τ of optical pulses generated by the mode-locked lasers. In addition, only 5 EO switches are needed in this encoder to tune over the $P^2 = 169$ channels. Therefore, the use of the proposed encoder allows the construction of a low-cost and high-capacity optical fiber network with the fixed receiver-assignment OCDMA scheme, which is attractive to continuous-type applications.

B. *Clock Distribution and Frame Synchronization*

Since the synchronous OCDMA scheme is used, the frame-synchronization information is very important to each receiver. As pointed out in the above, the receiver will perform the correlation operation to create a main peak of the expected auto-correlation function only at the last time slot per data frame and then threshold-detects that peak to recover the original electrical data bit "1". In this case, the conventional optical phase-locked loops can not be used to obtain the correct frame-synchronization signal at each receiver, even if they can operate up to 100 Gbit/s using ultrafast nonlinear optical effects in laser amplifiers or fibers (e.g., optical gain modulation, four-wave mixing) [9][10]. This is because the recovered clock stream of ultrashort optical pulses has a phase difference with respect to the first time slot of an OCDMA data frame at each receiver. This phase difference is normally unknown for the *real-time signal processing*, otherwise some post-processing methods should be used to ensure the correct frame synchronization at receivers. However, such methods cause the throughput bottleneck which in turn crashs down ultra-high-speed communications in the synchronous OCDMA network. To effectively solve this problem, we propose to use a two-wavelength scheme for the distribution of optical clock signal (i.e., frame-synchronization information) along with OCDMA signal through the common fiber to each receiver, as shown in Figure 2.

The use of a two-wavelength scheme has several advantages. For example, this can effectively distribute optical clock at λ_2 with OCDMA signal at λ_1 by using wavelength-division multiplexing (WDM). The separation of both signals is also easy at each receiver, using a WDM demultiplexer. Then the feasible phase compensation between two-wavelength lights of different propagation speeds is achieved by independently processing the optical clock and OCDMA signals. For large-size or multistage networks, the two-wavelength scheme is more suitable than the separate-fiber scheme which requires very precise length control of fibers [2]. Assume that the OCDMA signal has a faster propagation speed than the clock. The former will arrive at the decoder earlier than the latter, and therefore, a phase difference between two signals is resulted. An all-optical phase compensator (PC), which can be actually a fixed optical delay line, is then used to adjust the phase of OCDMA signal such that the optical clock pulse will ride atop the last time slot per data frame at a 2×1 coupler of the OCDMA decoder as shown in Figures 2, 4, and 5.

C. *Receiver Design*

At each OCDMA receiver, the arriving synchronous prime-sequence codewords are correlated by a fixed optical decoder for the fixed receiver-assignment OCDMA scheme. The block diagram of a fixed decoder for codeword $C_i(k)$ is shown in Figure 4. An autocorrelation function with its highest peak located at the last time slot of a data frame is generated when the address sequence $C_i(k)$ passes through the decoder completely; otherwise, low cross-correlation functions are resulted. Because of the coding property of the synchronous PS code, the transmissions of all users have to be synchronized by a common clock, and each receiver needs to know exactly the end (i.e., the last slot) of each data frame. On the other hand, the cumulative effect of the cross-correlation functions outside the last slot per data frame can be as strong as the autocorrelation peak and causes errors in data recovery [5], because multiple users can simultaneously transmit their data messages in a synchronous OCDMA network. To solve these problems at the decoder, an ultrashort optical clock stream with width τ is used to ride atop the last slot per data frame (i.e., the expected position of the autocorrelation peak). This clock stream is generated from the mode-locked laser of wavelength λ_2 at the transmitting end, having a repetition rate of $1/T$ (see Figure 2). The clock signal is then synchronized with each data frame through an appropriate phase compensation, achieved by using a propagation-speed compensator (i.e., phase compensator) as just discussed in Section III-B. Finally, the synchronized optical pulse (i.e., a clock pulse atop the autocorrelation peak) is converted into the electrical one by a wideband photodiode and is then threshold-detected. A data bit 1 is thus recovered. However, the clock pulse alone (i.e., without the autocorrelation peak) simply results in a data bit 0.

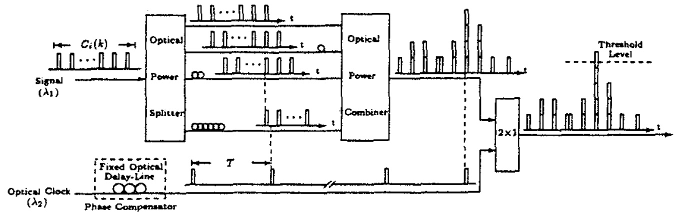

Figure 4: Block diagram of a fixed optical decoder for codeword $C_i(k)$.

For some applications, fully tunable OCDMA decoders are required at some of the receivers. The proposed tunable decoder is illustrated in Figure 5, of which the tunable part is still based on the single tunable optical delay-line used in the encoder. Similar to the operation of the encoder, when a user wants to extract the data encoded with the binary address sequence $C_i(k)$, the consecutive elements $s_{ij}(k)$'s of the corresponding synchronous prime-sequence $S_i(k)$ are issued to the delay selector, which will send the mapped binary delay control-sequence $(b_1^j b_2^j b_3^j \cdots b_{\lceil log_2 P \rceil+1}^j)$ to correctly set the states of the EO switches before the arrival of the j-th subsequence in $C_i(k)$. The desired delay of $(P-1-s_{ij}(k))\tau$ is now generated such that the ONE in the j-th subsequence of $C_i(k)$ can be delayed to the last time slot of the subsequence. The followed $1 \times P$ EO switch array, which is arranged in a binary-tree structure as shown in Figure 6, then selects the j-th fixed optical delay-line to obtain a delay of $(P-j-1)P\tau$ for the j-th subsequence. In this way, all P pulses of $C_i(k)$ will alway arrive at the last time slot of the data frame and, in turn, results an autocorrelation peak at that position when they are recombined at the combiner. Finally, the optical clock stream is employed such that a clock pulse always rides atop the last slot of each frame to ensure its coincidence with the autocorrelation peak (see Figure 5), if such a peak exists.

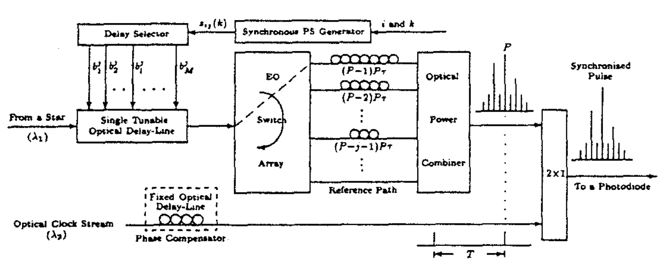

Figure 5: The proposed rapidly tunable OCDMA decoder for synchronous PS codes.

The operation speed of the proposed decoders is now limited by that of the electronics in both the delay selector and EO switches. Code sequences with non-separating pulses (i.e., with zero-slot separation), as shown in Group 1 of Table 1, mainly limit the speed of the proposed decoders to that of the states of the art electronics can provide (i.e., about 20 Gbit/s nowadays), although such pulses only exist in a few synchronous PS codewords [5]. To alleviate this speed restriction, one simple method is to either use RZ pulses or eliminate those codewords with non-separating pulses (e.g., removing P codewords in Group $i = 1$). Thus, the network throughput can be doubled without increasing the processing speed of electronics. Using a similar technique, the throughput can be improved k times by removing the kP codewords in Groups $i = \{1, 2, \ldots, k\}$ $(k < P)$. Even so, the number of remaining usable codewords is still large for a higher P. A more efficient method is to remove one of two non-separating pulses and two small-separation pulses from the corresponding codewords (e.g., in Groups 1 and 2 of Table 1) and then to remove one pulse from the remaining codewords in a synchronous PS code. Note that codewords $C_2(0)$ and $C_2(4)$ in Table 1 should be eliminated, because there are simultaneously 4 one-slot-separating pulses. In this way, the code cardinality is only slightly reduced, so is the number of total users.

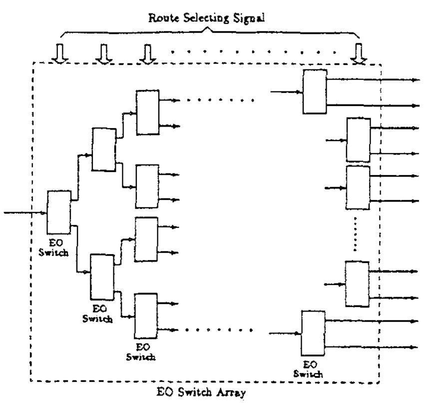

Figure 6: Block diagram of a $1 \times P$ EO switch array comprising 1×2 EO switches.

For simplicity, we assume that the power losses of EO switches are negligible. The number of EO switches (N_d) and the total power loss (P_d) for the proposed decoder are given by $N_d \leq \lceil \log_2 P \rceil + \sum_{x=0}^{m-1} 2^x + 1$ and $P_d = 10 \log_{10} P$, respectively, where m is bounded by $2^{m-1} < P < 2^m$. For example, for 169 users, at most 20 EO switches are required by a tunable decoder (see Figures 5 and 6) with total power loss of 11.1 dB. As shown in Figure 6, 17 EO switches could be enough in principle if allowing the unequal-amplitude optical pulses at the output of a 2×1 combiner or assuming zero loss for a $1 \times P$ EO switch array. Alternative scheme for implementing a $1 \times P$ EO switch array is to use a passive $1 \times P$ optical splitter and P EO switches, at the expense of higher power loss and larger device size.

IV. CONCLUSIONS

We have proposed a novel architecture for fully tunable optical CDMA networks using synchronous prime-sequence (PS) codes. Since the coding and decoding schemes are simple and systematic, both the encoders and decoders can be easily implemented with integrated optics; thus resulting in low-loss and high-capacity optical CDMA networks. The use of proposed encoder can efficiently realize the function of EO modulation and optical coding. The proposed network can operate at an ultrahigh rate, without using very high-speed electronics, by carefully selecting those codewords with certain pulse-separations or removing one pulse from all the codewords and so on, as discussed in the above. Thus, it is expected that a feasible synchronous OCDMA network using fixed-receiver assignment scheme can be efficiently implemented. Furthermore, the combination of error-correction codes with the synchronous PS code in OCDMA systems can ensure both high performance and low system cost [11]. The proposed network architecture is expected to be attractive for various applications, such as future military command and control systems requiring high-speed secure access. Furthermore, synchronous OCDMA can be used in conjunction with OTDMA to support multi-rate services in a given network [5], which can be potentially used in BISDN's.

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