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High Capacity Optical Networks Using OCDMA and OTDM Techniques

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Here is an overview of new techniques being explored for future generations of optical communications networks, using new photonic processing techniuqes instead of electronic signal processing

Significant technological advances have been a constant in the recent development in optical communication systems. Low attenuation fiber optics, high spectral purity lasers and optical amplifiers, among others, are devices that have allowed the transporting of hundreds of gigabits per second in thousands of kilometers, in a more reliable, secure and efficient manner, compared to radiofrequency (RF) systems. This transporting capacity provides enough data for the growing demand on new communication services.

However, the electronic devices available today have become a limiting factor for the use of optical systems, even through the use of advanced digital signal processing techniques. Withh the development of photonic devices, it is expected to have completely optical signal processing. If so, the electronic limitation will be greatly reduced, allowing the use of new multiple access technologies and, consequently, delivering a much higher data multiplexing rate than nowadays.

In this new scenario, it will be possible to build ultra-high bandwidth, simple and reliable optical networks, at low operational expenses, no matter the format of the information [1].

Before these systems enter into commercial operation, some problems must be solved, as the difficulty to obtain synchronization—which must be extremely precise—needed to realize the information routing inside the network without any optical-electrical conversion.

In order to transmit information through long distances using wavelength division multiplexing (WDM), it is necessary to amplify the optical signal. As the power density in the fiber increases, it starts to behave non-linearly causing signal deterioration. Thus, the number of channels inside the fiber must be reduced [2].

In light of these difficulties, research is underway on various methods to make optical signal processing possible in WDM networks. Recently, efforts have been concentrated in two promising technologies: optical code division multiple access (OCDMA) and optical time division multiple access (OTDM). The first uses the spread spectrum technique, also used in mobile phone systems. The second one is a light pulse multiplexing technique which intercalates, in time, many lower bit rate signals.

This paper has the goal of presenting the OCDMA and OTDM techniques, considering their specific characteristics, peculiarities, technical challenges and research situation. Therefore, initially we revise the classical CDMA philosophy, pointing out the fundamentals of spread spectrum and the orthogonal codes that cause the spectrum to be spread. Next we explain how CDMA can be implemented in optical communication. Research fields of greater importance, whose goals are to solve problems encountered in making this technique realizable, are presented and discussed. We conclude with introductions to TDM and OTDM. Some architecture proposals are discussed for the optical case, listing its deficiencies and implementation problems that, consequently, bring up new research interests in this area.

Code Division Multiple Access

The spread spectrum technique is the basic principle used in CDMA (Code Division Multiple Access). Each user's transceiver in the system uses a different spreading code. To visualize the basic process used in CDMA, consider a system with four users transmitting signals in the same frequency band, as shown in Figure 1. The signals are transmitted with the same power, even though they are presented one above the other in the figure. If there where no time multiplexing, all users would transmit at the same time. To make this possible, a special code is designated to each user (signal), and this code distinguishes one signal from the others. The receiver recovers the desired signal by means of correlation between the received signal and the code that is applied at the transmitter. The desired signal is then filtered and the other signals, now with lower power, appear to the receiver as noise [3].

A spread spectrum signal must have two special characteristics: the bandwidth is much bigger than the bandwidth of the signal that contains the information; and it is generated from an independent modulation signal, that has to be known by the receiver in order to be recovered. This independent signal, in the CDMA case, is each user's individual spreading code [4].

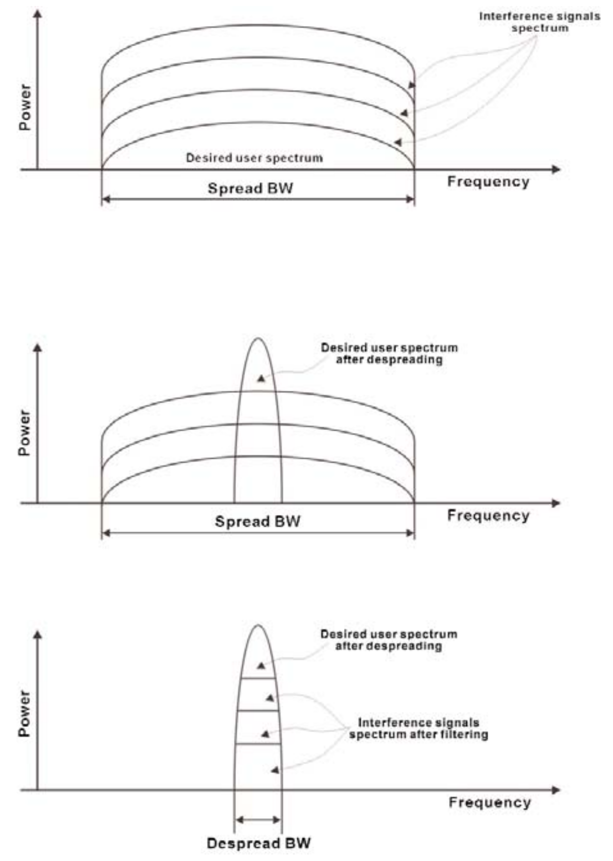

Figure 1 · CDMA technique. (a) Signals from four users, spread by the use of the spreading code, in the same frequency band; (b) Desired signal is despread; (c) Signals after filtering.

Effects Derived from Spectrum Spreading

The transmission capacity, C, of a channel is obtained by the Shannon-Hartly law, expressed as

$$C = B \cdot \log_2\left(1+\frac{P}{N}\right) \qquad (1)$$

where B and P, respectively, are the bandwidth and signal power, and N is the noise power.

Thus, fixing the power and increasing the signal bandwidth, the channel capacity also increases. In CDMA, the system capacity is determined by choosing the demanded Signal/Noise power, P/N, for each user or by the spreading gain, i.e., by an increase of the bandwidth B in equation 1. The noise signals to be considered include thermal noise, interference due to multiple access and, most importantly, interference from other users.

Originally proposed for military purposes, spectral spreading was used initially for sigilous communications, since spread signals have excellent rejection to intentional jamming [2]. On the other hand, the use of pseudo-random codes to generate the transmitted signal makes the information recovery process more complex. The reason is that, in order to decode the signal, it is necessary to apply the same code used on the transmitted signal.

Among the advantages of the use of spectrum spreading are: improvement in the transmitted signal's immunity against multipath distortion; rejection to strong narrowbandinterference; low transmitting power (low energy consumption); and simpler service planning, since all users use the same transmitting and the same receiving frequency.

This type of transmission technique has been used successfully in radio communications. In optical systems, it is expected to use CDMA in a shared optical medium local network (LAN), and in local access networks [2].

Direct Sequence Spread Spectrum

Consider the information to be transmitted, *m(t)*, to be a train of random pulses as in

$$m(t) = \sum_{\substack{k=-\infty \\ 0\le\alpha\le T_b}}^{\infty} a_k p(t - kT_b - \alpha) \qquad (2)$$

in which T_b is the width of each pulse, delayed by kT_b seconds, and a_k is a random weighting variable, Figure 2.

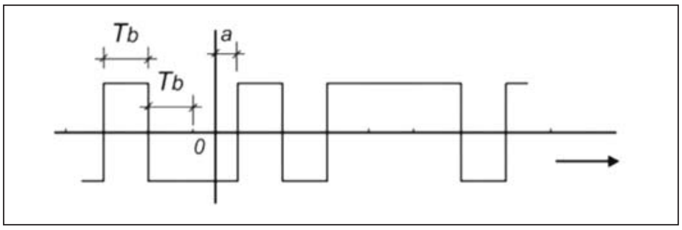

Figure 2 · **Pulse train (bits) of a signal *m(t)* as defined in Equation 2.**

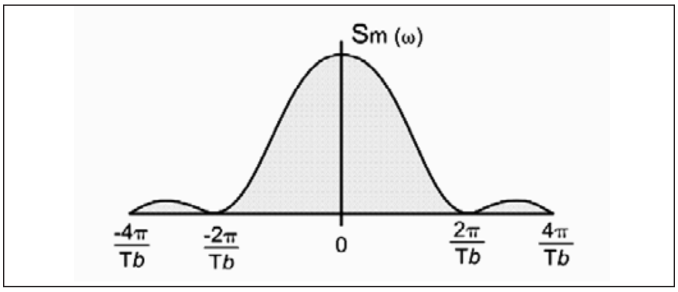

Figure 3 · **Spectrum of the signal shown in Figure 2.**

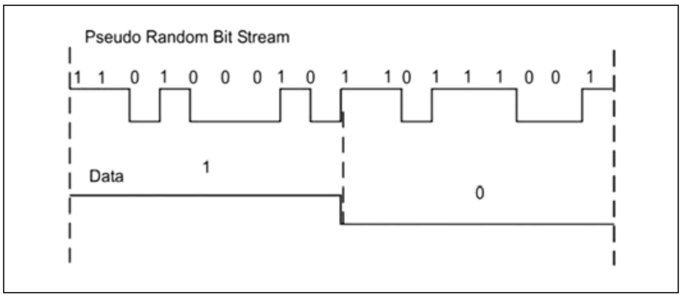

Figure 4 · **Pseudo-noise sequence used in DSSS to spread a signal intended for transmission.**

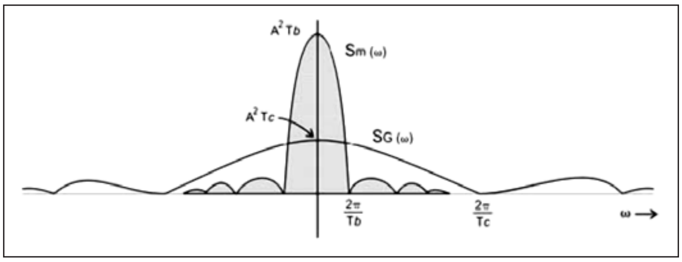

Figure 5 · **The spectrum of a PN sequence—S_G(ω)—, whose chip rate is much higher than other signal's bit rate—*m(t)*—, has a much wider bandwidth.**

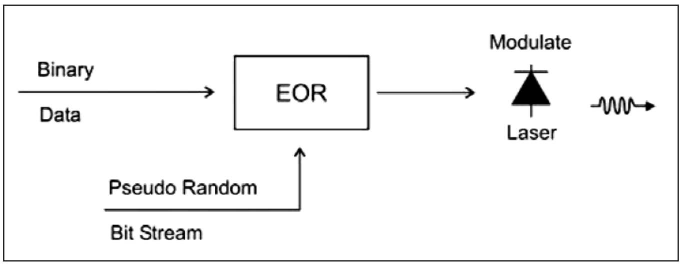

Figure 6 · **Basic CDMA transmitter diagram, in which the spread signal modulates a laser source. (Adapted from (2).)**

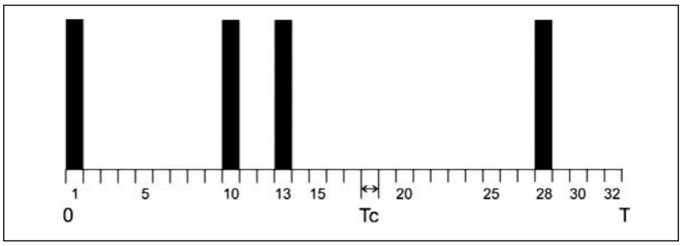

Figure 7 · **Optical code represented by light pulses in the chip positions 1, 10, 13 and 28.**

This signal's spectrum is shown in Figure 3.

The information signal's spectrum spreading by means of the use of the Direct Sequence Spread Spectrum (DSSS) technique consists in multiplying *m(t)* by a signal of the same shape as *m(t)*, but at a much higher bit rate. The signal with these characteristics is called Pseudo-random (PN) sequence (Figure 4). Figure 5 compares the spectrum of *m(t)* and the PN sequence, respectively, S_m(ω) and S_G(ω). One can observe that S_G(ω) has a much wider bandwidth than the information's spectrum.

The bits in the PN sequence are called chips. The ratio between the bit rate of the information signal and the chip rate is defined as the spreading ratio, or the processing gain. In optical systems, on-off modulation of the PN sequence can be realized by means of an EOR (exclusive OR) operation of the signal and the data pulse train. This new sequence can modulate an optical carrier, Figure 6.

Despreading is obtained by multiplying the receiver signal by the same PN sequence used in the generation of the spread signal, delayed by a period of T_d seconds, relative to the delay suffered by the signal propagation in the communication channel. Therefore, it is essential to maintain a synchronism between transmitters and receivers.

Optical CDMA

At first, optical CDMA (OCDMA) or fiber optic CDMA (FO-CDMA) was proposed considering that the optical fiber has an available bandwidth in the order of 25 THz for information transmission. However, the processing capacity of electronic devices used in the electric-optic-electric conversion reduces the throughput of data in an optical network. This problem can be minimized if both signal spreading and correlation are realized in the optical domain [5]. Having this as a goal, research on OCDMA has focused on the development of compatible pseudo-random sequences and on device projects able to process optically those sequences.

In this sense, Salehi proposes a class of optical orthogonal codes (OOC) [6, 7]. The basic difference between OOC and codes used in RF systems is in the polarity of the PN sequences. Bipolar signals, levels +1 or –1, used in conventional spread spectrum systems are unrealizable in optical systems.

The OOK (On-Off keying) technique is the simplest form of modulating light in order to generate OOC codes. Figure 7 illustrates a 32 chips-per-bit optical code with 4 active chips. Alternatively, this code can be presented by means of an optical disc as shown in Figure 8, in which the disc perimeter is equivalent to a bit period (T_b) and each chip period (T_c) corresponds to a disc sector equal to $2\pi T_c/T_b$ [6]. This representation is useful to make an analogy to maximum autocorrelation values, Figure 9a, and with sequence shifting, by rotating the disc, Figure 9b.

If many users are simultaneously connected, the use of OOC, along with a non-linearity optical limiter, minimizes the interference caused by multiple signals on the desired signal. This way, the performance of the optical system improves and a number up to five times greater of users can access the system, maintaining a constant BER [7].

In relation to optical processing devices, in some models are proposed for transmitter and receiver architecture that work, in theory, for bipolar OCDMA systems [5]. At the transmitter, a laser generates ultra-fast pulses that are split and sent through distinct paths. At the receiver end, the pulses are recombined and transformed in electrical pulses. Even though it uses optical processing, this proposal still has a limitation due to the noise presented in the optical-to-electrical conversion in the final decision stage of the receiver.

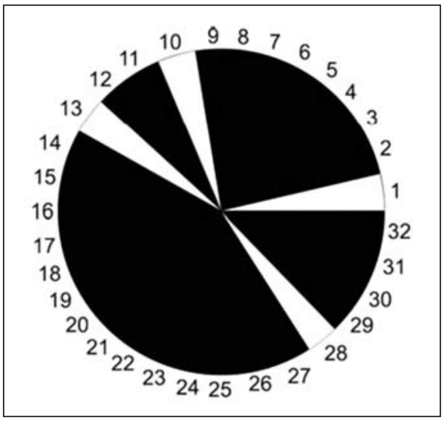

Figure 8 · Alternative representation of Fig. 7's optical code.

Research groups in Canada, United States and England have also developed studies involving OOCs and optical processing of information [8, 9, 10].

A particularly interesting characteristic of the CDMA technique is the efficient asynchronous transmission. In the case of local area networks (LAN), that use a mechanism of bursty transmissions in a shared medium, the OCDMA technique allows the implementation of access to these LANs at high bit rates and with a better cost-benefit relationship. A practical system for such proposal would have the following aspects different from a standard CDMA RF system [2]: the bit coding would be unipolar; the bit 1 is determined by a PN sequence; the bit 0 is not transmitted.

Time Division Multiplexing

Figure 10 illustrates the time division multiplexing (TDM) technique applied to four signals. In this technique, each signal transmits one bit at a time. Thus, in the situation shown in Figure 10, the output signal has a throughput four times greater than that of each input signal. Due to the characteristic of time division, the input signals must be synchronized with the output signal. The receivers must also be syncronized in order to recover the information des-

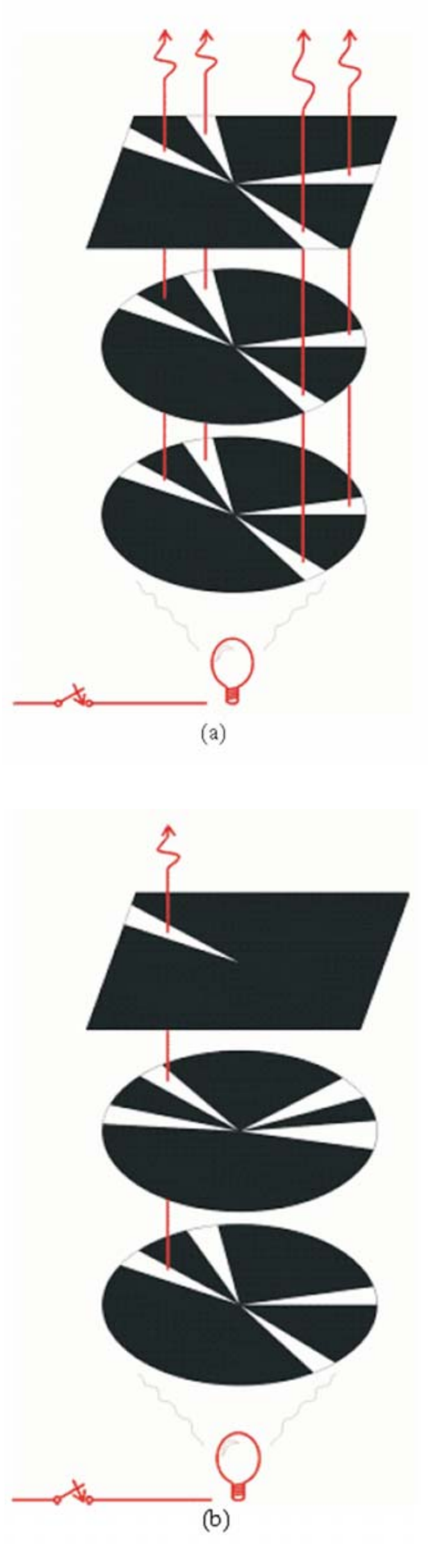

Figure 9 · Autocorrelation demonstration of a disk representing an optical PN sequence. (a) peak value. (b) autocorrelation with some shifting in the sequence.

tined to each one of them.

The Public Switched Tele-phone Network (PSTN) uses this technique in the digitalization and transmission processes for voice signals. In this case, each voice signal is digitized in the PCM format at a rate of 64 kbps. In mobile telephony, systems such as IS-136 (TDMA) and GSM use the TDM technique along with frequency multiplexing.

Optical TDM

Most optical communication services already use TDM, but the multiplexing is realized electrically and the transmission devices process a single bit stream [2]. SDH and SONET are examples for electronic TDM transmitted over a single optical carrier.

Researches have been made on optical processing in order to transmit data at a rate up to 160 Gbps. Due to the high bit rate, some of these works have focused on routing and synchronization technologies for faster signals [11].

Transmissions at 40 Gbps per channel are already achievable by means of WDM [16]. Getting to rates of 160 Gbps per channel, it is possible to reach either greater throughput, or fewer transmitters and fibers can be used, Figure 11. Recent studies have described technologies able to process data faster than 1 Tbps, thanks to the use of solitons [12].

OTDM systems have been implemented in the third optical window (1.55 µm) due to the disponibility of erbium doped fiber amplifiers (EDFA). These devices allow long distance links to be viable using shifted dispersion fibers, minimizing the chromatic dispersion problem [16].

Implementation methods for OTDM systems have been proposed using fibers with special manufacturing characteristics [13], combination of time-delayed pulses by fibers with different lengths [2] or solitons [12]. Several companies and research groups have presented their solutions, such as the Fraunhofer Heinrich-Hertz-Institute [14] and the Freeband Kennisimplus [15].

Figure 12 shows one of these different possible configurations for OTDM, proposed in [2]. In this solution, each time slot is divided in four time intervals, in which are inserted RZ-coded bits. This way, at the beginning of each time slot, the laser produces a pulse during 1/8 of a period of that slot. Mode-locking and self-pulsating lasers have been proposed to generate this optical pulse. This kind of laser creates very fast pulses spaced in a regular way by means of a modulated current applied on it. What differentiates it from regular lasers, that also generate light pulses reproducing the input current, is the existence of a special chemical substance that acts as a "saturable absorber." This substance releases light pulses when the laser is in a saturated state and absorbs light whenever the polarization level is lower [2].

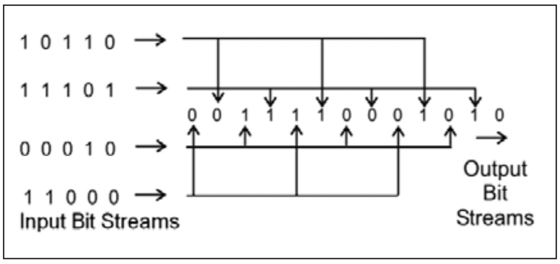

Figure 10 · Time Division Multiplexing (TDM).

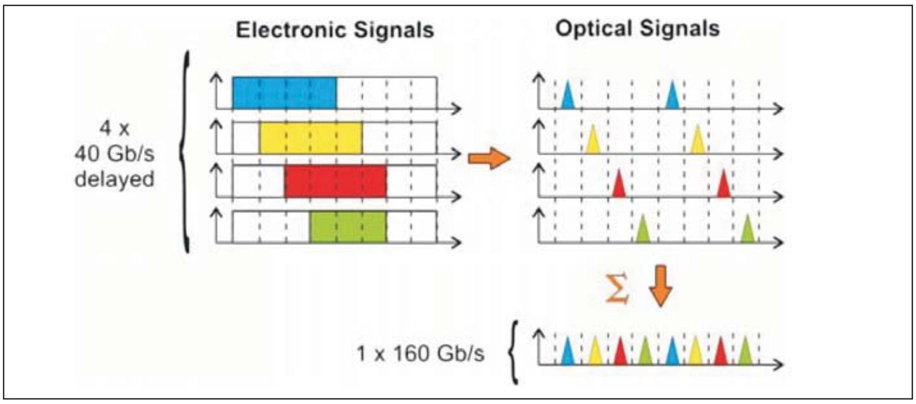

Figure 11 · Transmission bit rate optimization using OTDM.

The signal generated in the laser passes through a 1:4 power splitter. Three signals are then delayed by fibers with different physical lengths. Then, the pulses are modulated separately with the respective information. The modulated signals are then recombined and amplified for transmission. One can observe that, in this kind of solution, only one transmitter is used.

The demultiplexing process must be realized optically in order to avoid electronic limitations. The optical extraction of data can be made using Nonlinear Optical Loop Mirror (NOLM). This device works as a AND logical gate that, by means of control pulses, selects every *n*th pulse, Figure 13.

An Add/Drop type of multiplexer is capable of receiving or substituting a particular channel, intercalated in time, without interfering with the other signals. The greatest challenge in the OTDM demultiplexing process is the synchronization between the receiver and the input signal.

Conclusion

In this paper, we discussed the OCDMA and the OTDM techniques, which try to increase the optical communication systems capacity. Given the current needs and tendencies in this area, the positive aspects of each technique were detailed, considering the basic working points, not forgetting the difficulties encountered in the implementation of such technologies. We showed that the main problem in increasing the transmission rates is the electronic processing limitation. Therefore, the research work has focused on the development of equipment and devices able to process the signals optically.

For OCDMA, the use of special orthogonal codes at high rates causes the transmitted signal's spectrum to be spread. However, some difficulties are still found in relation to receivers, at the moment of converting the optical signal to electrical, at the final decision stage.

By using optical time division, it is considered possible to transmit data at bit rates over 1 Tbps, using very narrow pulses [11]. However, OTDM has serious problems especially in regard to synchronization and dispersion compensation. In the matter of application of this technique in local area networks, there is still a problem on the routing of the information without having to rely on electronic processing.

Finally, the OCDM and OTDM technologies, currently in research, development and testing stage, are capable of increasing significantly the transmission rates of operational optical systems. Particularly, in the photonic area these studies and development efforts have created a basis for the concretization of ultra-fast networks, independent of the information format and that are able to get all the way to the final user (fiber-in-the-home).

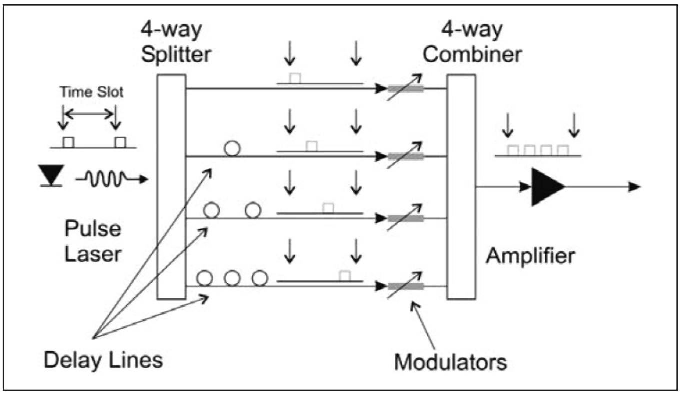

Figure 12 · OTDM configuration using splitters and delay lines to multiplex 4 independent streams.

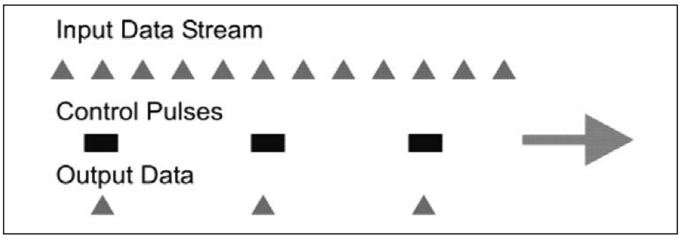

Figure 13 · Extraction of one channel in an OTDM stream using control pulses.

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