Comparative Study of Multiencoding Schemes for OCDM Using a Single Multiport Optical Encoder/Decoder

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***Abstract*—We analyse the performance of multicode shift keying modulation in an optical code-division multiplexing network scenario and demonstrate the effectiveness of using a single multiport optical encoder/decoder as a source coding element. We assign a set of codes to each user, and numerically evaluate the system performances, in terms of bit-error rate and spectral efficiency.**

***Index Terms*—Arrayed waveguide grating, fiber-optics communication, M-ary transmission, multiple-access networks, optical code-division multiple-access.**

I. Introduction

Optical code-division-multiplexing (OCDM) techniques are currently receiving much research interest due to their unique features of providing flexible asynchronous interconnections between a large number of active users in high bit-rate local access networks [1]. Many different coding techniques have been proposed in time and frequency domains, and recently multicode OCDM has been demonstrated to increase the transmission data rate, the spectral efficiency, and the system confidentiality [2]–[4]. In this scheme, m bits are encoded into $M = 2^m$ codewords, so that if K users access the network, at least $M \cdot K$ encoder/decoders (E/Ds) are required [5].

In the present letter, we investigate the performance of a single multiport E/D in a multicode OCDM network: the device has N ports and it is able to generate/process N phase-shifted keying codes of the same code family, simultaneously [6]. We can increase N up to 100 or more, but the code length increases proportionally, liming the maximum data bit rate, which is inversely proportional to the chip time interval $B_{\max} = 1/(\Delta\tau \cdot N)$ [7]. In all the numerical simulations, we assume that N has a fixed value, so that the maximum number of users K has to satisfy the condition to $K \leqslant \lfloor N/M \rfloor$, where $\lfloor x \rfloor$ denotes the floor function, i.e., the largest integer $\leqslant x$. We analyze three different cases, the multicode OCDM and two schemes of M-ary coding, and evaluate the system performance in terms of bit-error rate (BER) as a function of the number of simultaneous users, and the corresponding spectral efficiency.

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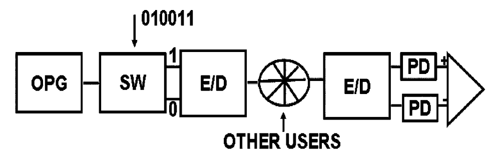

Fig. 1. CSK-OCDM system with balanced detection (OPG: Optical pulse generator. SW: Switch. PD: Photodetector).

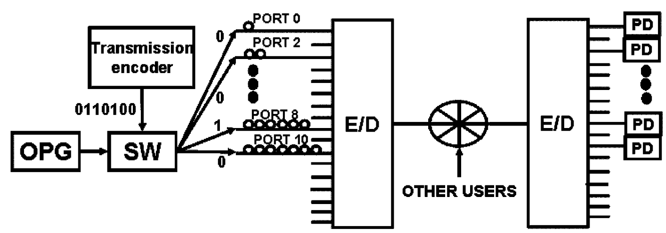

Fig. 2. Multicode OCDM system. (OPG: Optical pulse generator. SW: Switch. PD: Photodetector).

The simplest implementation of multicode transmission is the $M = 2$ case, where each bit from each user is encoded; this modulation format is also known as code-shift keying (CSK). Fig. 1 illustrates the schematic of the CSK-OCDM transmitter and receiver [8]: the serial stream of bits from a single user are switched to two different ports of a multiport encoder, according to their values. In this way, the bit "0" is encoded by a waveform orthogonal to that one used for the bit "1". Opposite to standard ON–OFF keying (OOK) OCDM techniques, in CSK systems, both bits "0" and "1" are encoded by different codes, so that an eavesdroppers cannot break the system by a simple power detection. All the users access two different ports of the multiport E/D, and balanced detection reduces the multiple access interference (MAI) noise; furthermore, the requirements for real-time estimation of the number of active users and the dynamic threshold level setting can be relaxed with a fix threshold level at zero.

II. Multicode OCDM

The scheme of Fig. 2 extends the CSK encoding format to the case $M > 2$: the switch routes each bit of the serial stream from

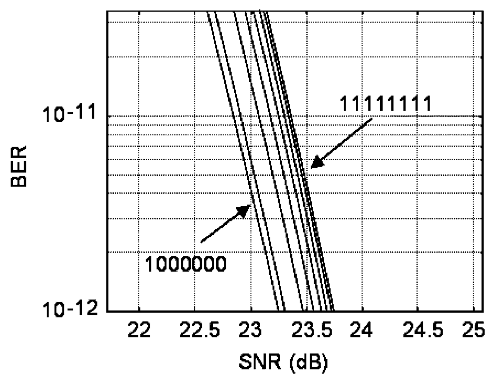

Fig. 3. BER for different data streams from a single user.

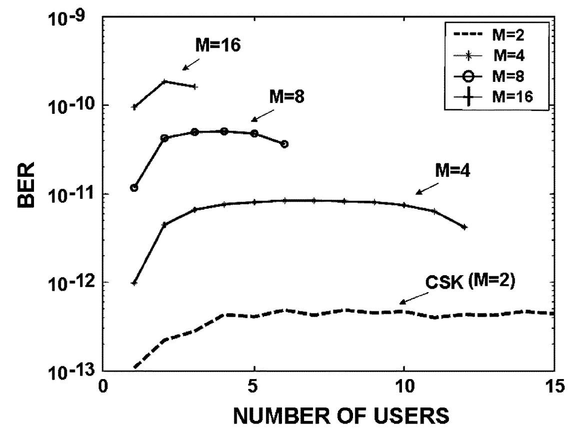

Fig. 4. BER in a multicode OCDM transmission (SNR = 24 dB for $M = 4, 8, 16$; SNR = 22 dB for $M = 2$).

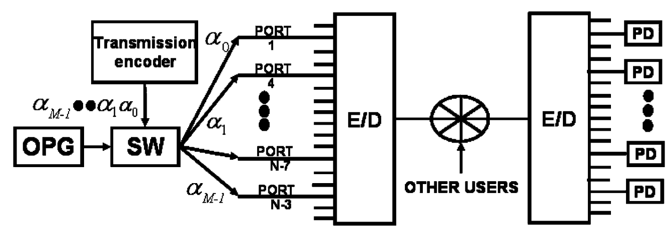

Fig. 5. M-ary OCDM system (OPG: Optical pulse generator. SW: Switch. PD: Photodetector).

a single user to delay lines connected to M different ports of the encoder, which compensate for the bit time interval. In this case, all the codes are generated simultaneously, and the maximum bit rate is $1/N \cdot \Delta\tau$. This is a new encoding scheme where each user simultaneously transmits M codes, corresponding to the bits of a data sequence. The system confidentiality is highly improved, and the spectral efficiency remains unchanged. It is also possible to remove the delays, or to change their values, to avoid code overlap in time; in the last case, the ratio between the auto- and cross-correlation functions r_K is very high, and the system performance is enhanced, but the maximum data bit rate is reduced. This technique can also be used to increase the code cardinality, using a pulse position coding. However, in this section, we will investigate the system performance in the worst-case condition, when all the codes are generated simultaneously, and the pulse position coding will be discussed only for the M-ary coding case. The corresponding BER can be evaluated as described in [9] for an M-ary orthogonal signal

$$\mathrm{BER}(K) = 1 - \frac{1}{4}\prod_{i=1}^{n}\mathrm{erfc}\left[\sqrt{\frac{\mathrm{SNR}}{8}}\left(\frac{1}{r_K}-1\right)\right] \times \prod_{i=1}^{M-n}\left\{1+\mathrm{erf}\left[\sqrt{\frac{\mathrm{SNR}}{8}}\left(1-\frac{1}{r_K}\right)\right]\right\} \quad (1)$$

where $r_k = \mathrm{CCP}_k/\mathrm{ACP}$ is the ratio between the auto- and cross-correlation peaks, and n is the number of bits "1" in each stream [6]. We evaluate the code performance in different OCDM architectures and we take only the MAI noise into account, since the beat noise depends on the photodetector integration time and the receiver architecture [10], although in an actual OCDM network, each user can access the network independently, with a different bit rate. To evaluate the system performance, we consider the worst-case condition when the MAI noise is maximum, i.e., all the users access synchronously to the network, with the same bit rate, using different sets of codes generated by the same device.

In Fig. 3, the BER is shown for a data stream from a single user considering the same configuration of Fig. 2, and in Fig. 4, the BER is plotted for different numbers of simultaneous users: four cases have been considered from $M = 2$ (CSK modulation) to $M = 16$. We observe that if M increases, the BER increases and the maximum number of users decreases as N/M, where N is the number of ports of the E/D. CSK ($M = 2$) modulation presents better performance, with respect to the other multicode schemes; in this case, the error probability has been calculated as

$$\mathrm{BER}(K) = \mathrm{erfc}\left[\frac{\sqrt{\mathrm{SNR}}}{2}\left(1-\frac{1}{r_K}\right)\right] \quad (2)$$

having used a balanced detection scheme [8].

III. M-ARY OCDM

In an M-ary transmission, the serial bit stream from each user is mapped into a source alphabet α_k with M determinations, each of them is associated to a different encoder port (Fig. 5). This scheme is distinct from the multicode scheme in that only a single code is generated for the M-bit sequence. In this case, the BER for equally likely symbols can be calculated as

$$\mathrm{BER}(K) = \frac{M}{2(M-1)}P_e(K) \quad (3)$$

where $P_e(K)$ is the error probability of a single symbol [9], which can be evaluated by setting $n = 1$ into (1).

The BER for the M-ary transmission versus the number of users is plotted in Fig. 6, and we observe that both the BER and the maximum number of users decrease by increasing M.

IV. PULSE POSITIONING M-ARY ENCODING

Since the number of ports of the E/D is fixed, the number of codes that can be generated cannot be increased to accommodate a larger number of users. However, the code cardinality can be enhanced by using the pulse position coding [11]. In an M-ary transmission, each pulse is driven into a different port, at any of Q different time intervals; at the receiver, a time gating allows us to distinguish different codes. The maximum bit rate

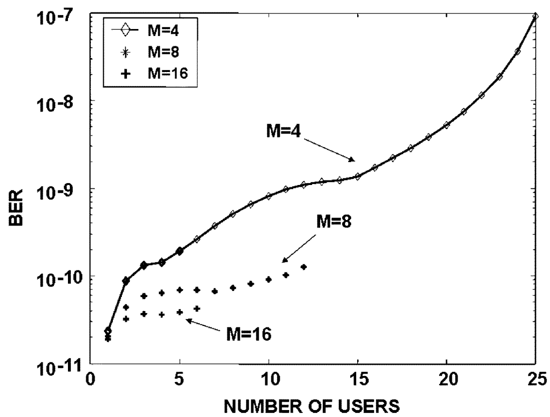

Fig. 6. BER in an M-ary OCDM transmission (SNR $= 24$ dB).

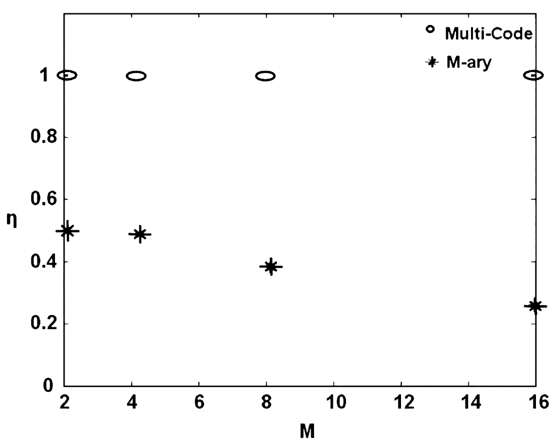

Fig. 7. Spectral efficiency for multicode and M-ary encoding formats.

is reduced by a factor Q, and the maximum number of users is increased proportionally $K \leqslant \lfloor N \cdot Q/M \rfloor$.

V. Spectral Efficiency

To evaluate the spectral efficiency, we start from the definition $\eta = K \cdot B/\Delta f$, (b/s/Hz), where B is the data bit rate and Δf is the minimum bandwidth of the modulated signal. For the multiport E/D, the minimum bandwidth is $\Delta f = 1/\Delta\tau$ [5]. The encoded data bit rate depends on the modulation format, and it cannot exceed the code length, i.e., $B < \Delta f/N$.

In the case of OOK-OCDM, the maximum number of users equates the number of device ports $(N = K)$, so that $\eta \leqslant 1$.

In the cases of CSK and multicode OCDM transmission, the maximum number of users is $\lfloor N/M \rfloor$ but the user bit rate can also be multiplied by M, so that the upper-bound for the spectral efficiency is still one. In the case of M-ary transmission, the upper bound can be calculated as $\eta \leqslant \log_2 M/M$ (Fig. 7), since the maximum user bit rate can be increased of $\log_2 M$. In the case of pulse position encoding, the bit rate decreases with Q, and the maximum number of users increases with Q, so that the spectral efficiency remains unchanged.

VI. Conclusion

M-ary and multicode encoding schemes can enhance the system confidentiality of an OCDM network, as well as the spectral efficiency. Different techniques have been proposed in the literature, considering different code families; in all the cases, the code cardinality has been supposed very large, so that a fixed number of users can use different sets of codes. However, all these methods require a very complex hardware, with a number of different E/Ds that equates the overall number of orthogonal codes.

In the present letter, we investigated the effectiveness of using a single multiport E/D in a multiencoding OCDM network. We assume that the number of codes that the device can generate/process is fixed, so that in the M-ary case, the spectral efficiency is reduced by a factor of $\log_2 M/M$, with respect to the standard OOK-OCDM. On the other hand, for multicode OCDM, the spectral efficiency is maximum.

We numerically investigate the system performance for various modulation formats, and we show that the BER increases with M, in the case of multicode modulation, and decreases in the M-ary case. Moreover, in the M-ary case, the BER increases with the number of users, whereas it remains practically constant for the multicode modulation. This different behavior stems from the fact that in the numerical simulations, we considered only MAI noise, which increases with the number of the encoder ports that are simultaneously used. In multicode modulation, a single user transmits over a set of different ports, whereas a single port is used by each user in the M-ary case.

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