Average Power Reduction Techniques for Multiple-Subcarrier Intensity-Modulated Optical Signals

Roy You and Joseph M. Kahn, *Fellow, IEEE*

***Abstract*—We describe two classes of simple, effective techniques for reducing the average optical power requirement in intensity-modulated optical systems using multiple BPSK or QPSK subcarriers. The first class of techniques involves block coding between the information bits to be transmitted and the symbol amplitudes modulated onto the subcarriers in order to increase the minimum value of the multiple-subcarrier electrical waveform. The second class of techniques involves replacing the fixed dc bias by a bias signal that varies on a symbol-by-symbol basis. These two classes of techniques can be applied separately or in tandem. The reduction in power requirement increases with the number of subcarriers and, with eight subcarriers, can be as high as about 3.6 dB and 3.2 dB with BPSK and QPSK, respectively. The techniques described here are applicable as long as all subcarriers originate from a single transmitter and are symbol-synchronized.**

***Index Terms*—Intensity modulation, optical communication, subcarrier multiplexing.**

I. Introduction

In electrical and RF communication systems, multicarrier modulation (MCM), in which multiple digital streams are modulated onto carriers at different frequencies, permits transmission with minimal intersymbol interference (ISI) on frequency-selective channels [1]. Electrical MCM systems frequently use tens to hundreds of carriers. On electrical channels, the average-power requirement of a MCM system is approximately the same as a single-carrier system, assuming ISI is not present. Electrical MCM systems employing a large number of carriers have the drawback of a high peak-to-average power ratio (PAR), which can lead to nonlinear distortion and clipping in systems with peak-power limitations. Several techniques for reducing the PAR in electrical MCM systems have been proposed [2]–[5].

On optical communication channels, multiple-subcarrier modulation (MSM) involves modulation of multiple digital and/or analog information sources onto different electrical subcarriers, which are then modulated onto a single optical carrier [6], [7]. The MSM electrical signal may be modulated onto the optical carrier using intensity, frequency, or phase modulation. Most current practical MSM systems use intensity modulation (IM) with direct detection (DD), owing to its simple implementation. MSM permits asynchronous multiplexing of numerous, possibly heterogeneous information streams, and permits a receiver to demodulate only the streams of interest. For this reason, MSM with IM/DD is widely used in optical fiber distribution of video signals [6].

The main drawback of MSM with IM/DD is poor optical average power efficiency. This arises because the MSM electrical signal is a sum of modulated sinusoids, and thus takes on both negative and positive values. Optical intensity (instantaneous power) must be nonnegative. Hence, a dc bias must be added to the MSM electrical signal in order to modulate it onto the intensity of an optical carrier. As the number of subcarriers increases, the minimum value of the MSM electrical signal decreases (becomes more negative), and the required dc bias increases. Since the average optical power is proportional to this dc bias, the optical average-power efficiency worsens as the number of subcarriers increases [6], [7]. It is worth noting that the peak-to-average optical power ratio of a MSM IM signal is about two, independent of the number of subcarriers.

Optical fiber MSM IM/DD systems typically use tens to hundreds of subcarriers [6]. In an effort to reduce the optical average power requirement, often the bias is reduced to the point that some clipping occurs. Techniques intended to reduce the impact of clipping noise in optical fiber MSM systems have been investigated [8], [9].

Optical wireless (OW) transmission with IM/DD is an attractive option for high-speed indoor and outdoor links [7], [10], [11]. MSM with has been considered for use in IM/DD OW systems, because the use of several narrow-band subcarriers promises to minimize ISI on multipath channels [7], [12], and because MSM can provide immunity to fluorescent-light noise near dc [13]. In most applications of OW, particularly those using portable transmitters, eye safety and power consumption limit the available average optical power. This dictates that in MSM systems, the number of subcarriers should be kept small, e.g., under ten.

In this paper, we discuss two classes of techniques for reducing the optical average power requirement in IM/DD MSM systems using BPSK or QPSK digital modulation. The first class of techniques involves block coding between the information bits to be transmitted and the symbol amplitudes modulated onto subcarriers, in order to increase the minimum

Paper approved for publication by O. K. Tonguz, the Editor for Optical Transmission Systems of the IEEE Communications Society. Manuscript received October 15, 1999; revised June 15, 2000. This work was supported by the National Science Foundation under Grant ECS-9710065 and by the Sharp Corporation. This work was presented in part at IEEE International Conference on Communications, New Orleans, LA, June 18–22, 2000.

The authors are with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720 USA (e-mail: jmk@eecs.berkeley.edu).

Publisher Item Identifier S 0090-6778(01)10624-0.

value of the MSM electrical waveform, and thus decrease the bias that must be added to it. These techniques are somewhat analogous to those used for PAR reduction in MCM electrical systems [2]–[5]. The second class of techniques involves replacing the fixed dc bias by a bias signal that varies on a symbol-by-symbol basis. During each symbol, the minimum bias required to achieve nonnegativity is utilized. The use of a symbol-by-symbol bias for a single quadrature amplitude-modulated subcarrier has been considered in [14]. The two classes of techniques proposed here can be applied separately or in tandem. They are effective and easy to implement, but do require that all subcarriers originate from a single transmitter and that all subcarriers be synchronized at the symbol level. When the number of subcarriers is small, as in OW applications, the computations required to implement the proposed techniques can be performed off-line and implemented via table lookup. By contrast, in MCM electrical systems using a large number of carriers, PAR reduction techniques often require that computations be performed on a real-time basis; see, e.g., [4].

The remainder of this paper is organized as follows. The IM/DD channel model is described in Section II. Our techniques for power-efficient MSM transmission are presented in Section III, and their performance is evaluated and compared to existing techniques in Section IV. Concluding remarks are given in Section V.

II. IM/DD Optical Channel Model

Indoor OW channels with IM/DD can be described by [7]

$$y(t) = rx(t) \otimes h(t) + n(t) \quad (1)$$

where the symbol $\otimes$ represents convolution. The channel input $x(t)$ is the transmitted optical intensity, which must be nonnegative

$$x(t) \geq 0. \quad (2)$$

The average optical power P is given by the mean value of $x(t)$ as

$$P = E[x(t)] \quad (3)$$

in contrast to electrical channels, where the average power is the mean value of $x^2(t)$. The channel output $y(t)$ is the received photocurrent. Here, r is the photodetector responsivity. The channel is a fixed, linear system having impulse response $h(t)$ and frequency response $H(j\omega)$. In this study, we will neglect multipath distortion, so that $h(t) = H(j0)\delta(t)$, where $\delta(t)$ is an impulse function. In OW systems with IM/DD, receiver thermal noise and intense ambient shot noise can be modeled as Gaussian and independent of the transmitted signal. We will model the noise $n(t)$ as Gaussian, independent of $x(t)$, and white, with two-sided power spectral density (PSD) N_0. The results obtained here are applicable also to fiber-optic channels provided that dispersion is negligible and the noise is white, Gaussian, and independent of the transmitted optical signal.

III. Power-Efficient Multiple-Subcarrier Transmission Scheme

Fig. 1(a) and (b) depict the transmitter and receiver design used in the proposed MSM transmission scheme with QPSK. The transmitter and receiver are identical for BPSK, except that all sine branches are omitted. Referring to Fig. 1(a), the transmitter uses a set of N subcarrier frequencies $\{\omega_n, n = 1, \ldots, N\}$. During each symbol interval, of duration T, it transmits a vector of K information bits $\boldsymbol{x}^{(m)} = (x_1^{(m)}, \ldots, x_K^{(m)})$, $m \in \{1, \ldots, M\}$, where $M = 2^K$. A block coder maps $\boldsymbol{x}^{(m)}$ to a corresponding vector of symbol amplitudes, $\boldsymbol{a}^{(m)}$. For QPSK, each such vector is of the form

$$\boldsymbol{a}^{(m)} = \left(a_{1c}^{(m)}, a_{1s}^{(m)}, \ldots, a_{Nc}^{(m)}, a_{Ns}^{(m)}\right) \quad (4)$$

where $a_{nc}^{(m)} \in \{-1, 1\}$, $a_{ns}^{(m)} \in \{-1, 1\}$, $n = 1, \ldots, N$. Similarly, for BPSK

$$\boldsymbol{a}^{(m)} = \left(a_{1c}^{(m)}, \ldots, a_{Nc}^{(m)}\right) \quad (5)$$

where $a_{nc}^{(m)} \in \{-1, 1\}$, $n = 1, \ldots, N$. Defining a pulse shape $g(t)$, the MSM electrical signal for QPSK is

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{n=1}^{N} \left[a_{nc}^{(m^i)} \cos\omega_n t + a_{ns}^{(m^i)} \sin\omega_n t\right] g(t - iT). \quad (6)$$

The MSM electrical signal for BPSK is identical to (6), except that the sine terms are omitted.

Since $s(t)$ can be positive or negative, the transmitter adds a baseband bias signal $b(t)$

$$b(t) = b_0 + \sum_i b\left(\boldsymbol{a}^{(m_i)}; \left\{\boldsymbol{a}^{(m_j)}, j \neq i\right\}\right) g(t - iT). \quad (7)$$

In general, $b(t)$ is the sum of a constant b_0 and a baseband pulse-amplitude modulation (PAM) signal corresponding to the second term in (7). In this baseband PAM signal, the amplitude of symbol i depends, in general, both on $\boldsymbol{a}^{(m_i)}$, the vector of subcarrier amplitudes for symbol i, and on $\{\boldsymbol{a}^{(m_j)}, j \neq i\}$, the vectors in past and future symbols. The bias $b(t)$ is chosen so that $x(t) = A[s(t) + b(t)] \geq 0$, where A is a nonnegative scale factor. The average optical power is

$$P = AE[s(t)] + AE[b(t)]. \quad (8)$$

With the proper choice of T, $\{\omega_n, n = 1, \ldots, N\}$, and $g(t)$, each of the subcarriers is orthogonal to the others and to the time-varying bias signal $b(t)$.

Fig. 1(b) shows the receiver used under the proposed MSM techniques with QPSK; for BPSK, the receiver is identical, but omits the sine branches. Like a standard QPSK MSM receiver, the receiver of Fig. 1(b) uses a bank of hard decision devices to obtain a vector of detected symbol amplitudes, $\hat{\boldsymbol{a}} = \{\hat{a}_{1c}, \hat{a}_{1s}, \ldots, \hat{a}_{Nc}, \hat{a}_{Ns}\}$. In the receiver of Fig. 1(b),

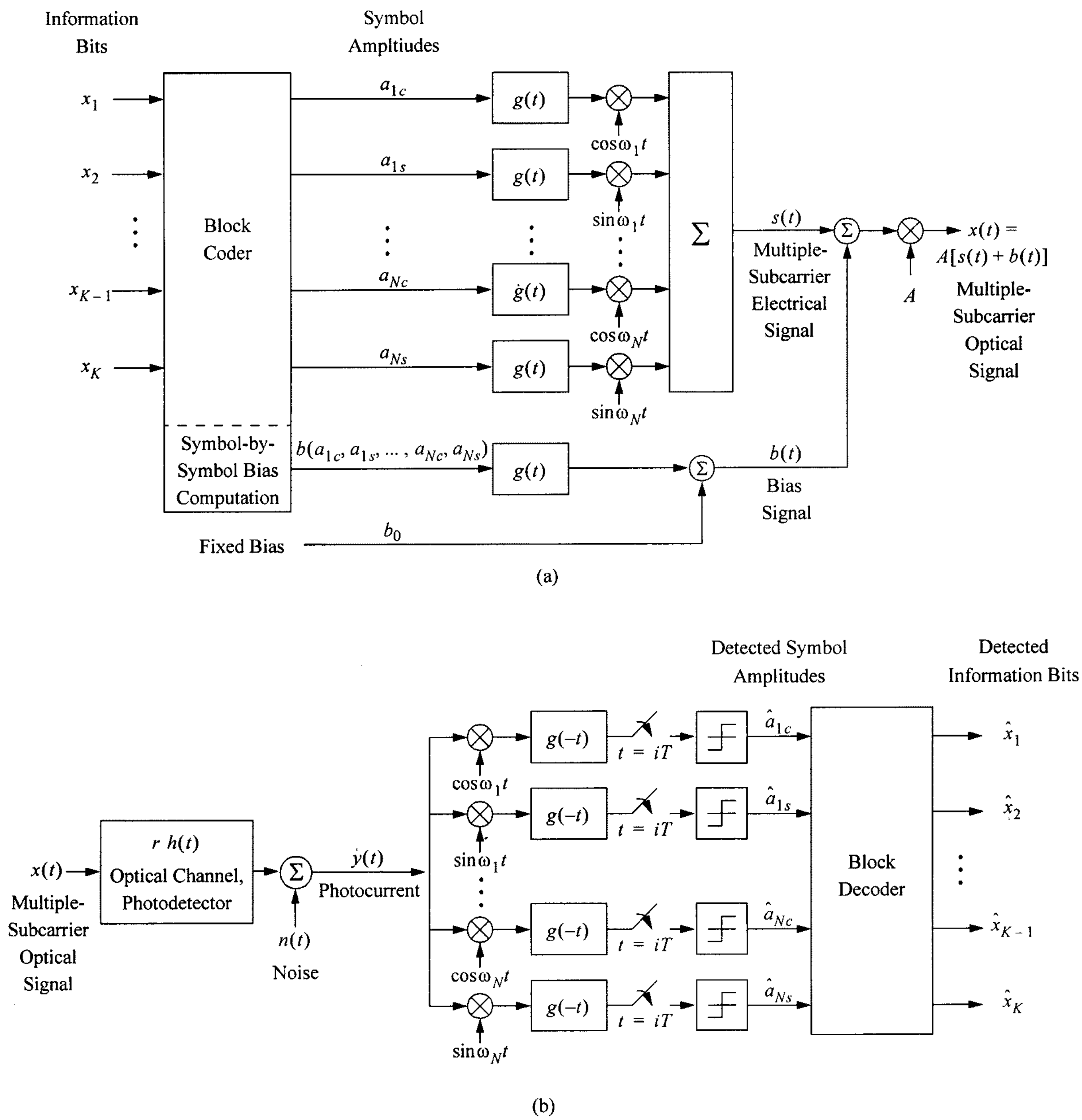

Fig. 1. Power-efficient multiple-subcarrier modulation scheme: (a) transmitter and (b) channel and receiver. QPSK modulation is assumed in this figure. For simplicity, we suppress the possible dependence of the baseband PAM amplitude b on past and future symbols.

however, a hard-decision block decoder maps the vector $\hat{\boldsymbol{a}}$ to a vector of detected information bits, $\hat{\boldsymbol{x}} = (\hat{x}_1, \ldots, \hat{x}_K)$.

In the remainder of this paper, unless otherwise noted, we consider a rectangular transmit pulse shape

$$g(t) = \begin{cases} 1, & 0 \le t < T \\ 0, & t < 0, \, t \ge T. \end{cases} \tag{9}$$

There are two reasons for this choice. In IM/DD optical systems, the rectangular pulse yields high average-power efficiency [7]. Also, choosing the rectangular pulse makes it very straightforward to design the block code and bias signal to minimize the transmit power requirement. In (7), the baseband PAM amplitude in symbol i depends only on $\boldsymbol{a}^{(m_i)}$ and not on $\{\boldsymbol{a}^{(m_j)}, j \neq i\}$, so that we let $b(\boldsymbol{a}^{(m_i)}; \{\boldsymbol{a}^{(m_j)}, j \neq i\}) \to b(\boldsymbol{a}^{(m_i)})$. In order to guarantee that the subcarriers and time-varying bias signal are mutually orthogonal, we choose $\{\omega_n\}$, the set of subcarrier frequencies to have an integral number of cycles per symbol interval. We consider both "dense" and "coarse" packing of subcarrier frequencies, which are described by

$$\omega_n = n\frac{2\pi}{T} \quad \text{(dense packing)} \tag{10}$$

and

$$\omega_n = n\frac{4\pi}{T} \quad \text{(coarse packing)} \tag{11}$$

respectively, where $n = 1, \ldots, N$. With our choices of $g(t)$ and $\{\omega_n\}$, $E[s(t)] = 0$, regardless of how we choose the signal set $\{\boldsymbol{a}^{(m)}\}$. Hence, (8) simplifies to

$$P = AE[b(t)]. \tag{12}$$

In evaluating the average transmit power requirement, we will often consider the minimum value of the MSM electrical signal described by $\boldsymbol{a}^{(m)}$ over the symbol interval

$$s_{\min}^{(m)} = \min_{\substack{t \\ 0 \le t \le T}} \sum_{n=1}^{N} \left[a_{nc}^{(m)} \cos \omega_n t + a_{ns}^{(m)} \sin \omega_n t \right]. \quad (13)$$

For BPSK, the sine terms are omitted in the expression for $s_{\min}^{(m)}$.

We now describe various options for the design of the block code and of the bias signal.

A. Block Code

In this subsection, we consider how to design the block code utilized in the transmitter, which is shown in Fig. 1(a). This code maps $\boldsymbol{x}^{(m)}$, the vector of K information bits to be transmitted, to $\boldsymbol{a}^{(m)}$, the vector of symbol amplitudes modulated onto the N subcarriers. Recall that $m \in \{1, \ldots, M\}$, where $M = 2^K$.

1) Normal Block Code: Under this block code, all N subcarriers are used for transmission of information bits. Hence, $K = 2N$, $M = 2^{2N}$ for QPSK and $K = N$, $M = 2^N$ for BPSK. Each information bit can be mapped independently to the corresponding symbol amplitude, i.e., a component of the vector $\boldsymbol{a}^{(m)}$. At the receiver, each detected symbol amplitude, i.e., each component of the vector $\hat{\boldsymbol{a}}$, can be mapped independently to an information bit. If the MSM signal conveys multiple, independent bit streams to different users on different subcarrier frequencies, each user's receiver only needs to demodulate those subcarriers conveying the desired bit streams.

2) Reserved-Subcarrier Block Code: The reserved-subcarrier block code is similar in spirit, though not implementation, to the technique described in [4]. Under this block code, $L > 0$, subcarrier frequencies are reserved with the goal of maximizing the minimum value of the MSM electrical signal $s(t)$, thereby minimizing the average optical power P. Hence, in this case, $K = 2(N - L)$, $M = 2^{2(N-L)}$ for QPSK and $K = N - L$, $M = 2^{(N-L)}$ for BPSK. In reserved-subcarrier block coding, we define a set of reserved subcarriers

$$S = \{n_1, n_2, \ldots, n_L\}, \qquad n_i \in \{1, \ldots, N\}. \quad (14)$$

The block code is described as follows. We encode an information bit vector $\boldsymbol{x}^{(m)}$ by freely choosing the symbol amplitudes on the unreserved subcarriers

$$\left\{ a_{nc}^{(m)}, a_{ns}^{(m)}, n \notin S \right\}. \quad (15)$$

We then choose the symbol amplitudes on the reserved subcarriers to maximize $s_{\min}^{(m)}$, the minimum value of the MSM electrical signal over the symbol interval

$$\left\{ a_{nc}^{(m)}, a_{ns}^{(m)}, n \in S \right\} = \underset{\{a_{nc}^{(m)}, a_{ns}^{(m)}, n \in S\}}{\arg\max} \left[s_{\min}^{(m)} \right]. \quad (16)$$

For each choice of N, L, and biasing technique, there exists an optimal set of reserved subcarriers, though this set is often not unique. Under reserved-subcarrier block coding, each user's receiver only needs to demodulate those subcarriers conveying the desired bit streams.

3) Minimum-Power Block Code: Minimum-power block coding is similar to the technique described in [2]. Under this block code, no fixed set of subcarriers are reserved, but the throughput is equivalent to that obtained when L subcarrier frequencies are reserved. Hence, it may be said that $L > 0$ subcarrier frequencies are "effectively reserved" for maximizing the minimum value of the MSM electrical signal $s(t)$. Under the minimum-power block code, $K = 2(N - L)$, $M = 2^{2(N-L)}$ for QPSK and $K = N - L$, $M = 2^{(N-L)}$ for BPSK. To describe this block code, we first sort all possible vectors of symbol amplitudes in order of decreasing $s_{\min}^{(m)}$. For QPSK, we have

$$s_{\min}^{(m)} \ge s_{\min}^{(m+1)}, \qquad m = 1, \ldots, 2^{2N} - 1. \quad (17)$$

For BPSK, this ordering holds for $m = 1, \ldots, 2^N - 1$. The signal set uses the first M vectors $\{\boldsymbol{a}^{(m)} m = 1, \ldots, M\}$, which have maximum $s_{\min}^{(m)}$. This represents the optimal choice of signal set for a given N and L, independent of the biasing technique. For a given N, L, and biasing technique, the optical average power requirement under minimum-power block coding always lower-bounds the average power requirement under the reserved-subcarrier block coding. The major drawback of minimum-power block coding is that, in general, each receiver needs to demodulate all of the subcarriers, even to extract only a subset of the transmitted information bits.

B. Baseband Bias Signal

In this subsection, we consider how to design the bias signal $b(t)$. The bias signal $b(t)$ must be chosen so that when it is added to the MSM electrical signal $s(t)$, the sum is nonnegative, i.e., $x(t) = A[s(t) + b(t)] \ge 0$, where A is a nonnegative scale factor. It is convenient to break $b(t)$ into the sum of a constant and a baseband PAM signal, as indicated in (7).

1) Fixed Bias: When using a fixed bias signal, we set $b(\boldsymbol{a}^{(m)}) = 0, \forall m$, and we use a fixed bias b_0. With an arbitrary pulse shape $g(t)$, the smallest allowable b_0 is given by

$$b_0 = -\min_t s(t) \quad (18)$$

and the average optical power is

$$P = Ab_0. \quad (19)$$

For the rectangular $g(t)$ assumed here, the smallest allowable fixed bias is given by

$$b_0 = -\min_{\{\boldsymbol{a}^{(m)}, m=1, \ldots, M\}} \left[s_{\min}^{(m)} \right]. \quad (20)$$

Note that when using fixed bias with reserved-subcarrier block coding, the average transmit power is minimized if we choose S, the set of reserved subcarriers, to minimize b_0.

2) Time-Varying Bias: With a time-varying bias, $b(t)$ is chosen to be of the form (7), i.e., the sum of a constant and a baseband PAM signal. For an arbitrary pulse shape $g(t)$, to minimize the average optical power P, it may be necessary to use both terms. In this case, using (8), the average transmitted optical power is

$$P = AE[s(t)] + Ab_0 + AE\left[b\left(\boldsymbol{a}^{(m)} \right) \right] T^{-1} \int_{-\infty}^{\infty} g(t)\, dt. \quad (21)$$

With a rectangular $g(t)$, the baseband PAM component of $b(t)$ is piecewise constant and can describe the dc component of $b(t)$ even when we set $b_0 = 0$. Hence, with rectangular $g(t)$ and time-varying bias, we will choose $b_0 = 0$. The smallest allowable symbol-by-symbol bias is given by

$$b\left(\boldsymbol{a}^{(m)}\right) = -s_{\min}^{(m)}. \tag{22}$$

Using (12), we find the average transmit power to be

$$P = AE\left[b\left(\boldsymbol{a}^{(m)}\right)\right]. \tag{23}$$

Note that when using time-varying bias with reserved-subcarrier block coding, the average transmit power is minimized if we choose S, the set of reserved subcarriers, to minimize $E[b(\boldsymbol{a}^{(m)})]$.

IV. Performance Evaluation

In this section, we evaluate the bandwidth and power requirements of the proposed MSM block coding and biasing schemes, comparing them to ON–OFF keying (OOK). For each scheme, R_b represents the information bit rate, B represents the total electrical bandwidth required at the receiver, and P_b represents the probability of information bit error.

We first consider a reference system using OOK with rectangular pulses of duration T [described by (9)] and symbol rate $1/T$. Following [7], we have $R_b = 1/T$, $B = 1/T$, and $P_b = Q(\sqrt{r^2 P^2 T/N_0})$, where $Q(x)$ is the Gaussian Q function [15]. For OOK, the bandwidth requirement B is taken to equal the first null in the PSD of the transmitted signal.

For the proposed MSM scheme, with either dense or coarse frequency packing, the information bit rates are given by

$$R_b = \frac{N-L}{T} \qquad \text{(BPSK)} \tag{24}$$

and

$$R_b = \frac{2(N-L)}{T} \qquad \text{(QPSK)}. \tag{25}$$

With either BPSK or QPSK, the electrical bandwidth requirements are given by

$$B = \frac{N+1}{T} \qquad \text{(dense packing)} \tag{26}$$

and

$$B = \frac{2N+1}{T} \qquad \text{(coarse packing)}. \tag{27}$$

These values of B correspond to the first null in the PSD of the MSM signal $s(t)$ above the highest subcarrier frequency.

In the proposed MSM scheme, $\boldsymbol{x}^{(m)}$, a vector of K information bits, is mapped to $\boldsymbol{a}^{(m)}$, a vector of symbol amplitudes. Assuming an additive white Gaussian noise (AWGN) channel and the hard-decision receiver shown in Fig. 1(b), $\boldsymbol{a}^{(m)}$ is transmitted through a binary symmetric channel characterized by the crossover probability

$$p = P(\hat{a}_{nc} \neq a_{nc}) = P(\hat{a}_{ns} \neq a_{ns}) \tag{28}$$

$n = 1, \ldots, N$. This definition of p holds for QPSK; for BPSK, the definition should omit the term $P(\hat{a}_{ns} \neq a_{ns})$. It is easily shown that

$$p = Q\left(\sqrt{\frac{r^2 A^2 T}{2N_0}}\right) \qquad \text{(BPSK or QPSK)}. \tag{29}$$

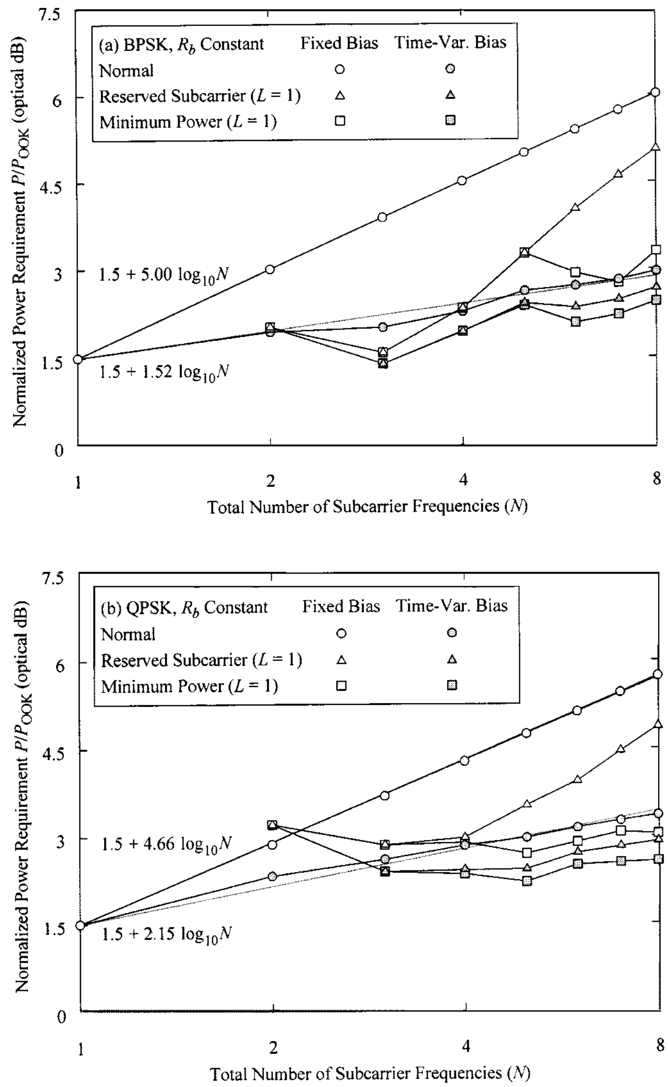

Fig. 2. Normalized optical power requirement versus number of subcarriers for various block-coding and biasing schemes. These results assume a rectangular transmit pulse $g(t)$ and are valid for either $\omega_n = n2\pi/T$ or $\omega_n = n4\pi/T$. The normalized power requirement is the power required by a scheme divided by the power required by OOK, assuming a fixed bit rate R_b. Solid lines connect the actual power requirements at different N. Dashed lines represent linear least-squares fits to the power requirements for normal block coding, corresponding to the analytical expressions given. (a) BPSK. (b) QPSK.

While (29) depends explicitly on the amplitude scaling factor A, we would like to relate p to the average optical power P and to N and L. As shown by (12), P is proportional to A, and P depends on N, L, and the choice of block coding and biasing schemes via its dependence on $E[b(t)]$. The probability of information bit error is given by

$$P_b = \frac{1}{K}\sum_{k=1}^{K} P(\hat{x}_k \neq x_k). \tag{30}$$

The relationship between P_b and p depends on the block code [the choice of $\{\boldsymbol{a}^{(m)}, m = 1, \ldots, M\}$] and on the mapping between $\{\boldsymbol{x}^{(m)}\}$ and $\{\boldsymbol{a}^{(m)}\}$. In the proposed scheme, the block code is designed to minimize $P = AE[b(t)]$ subject to fixed A and not necessarily to minimize P_b subject to fixed A (i.e.,

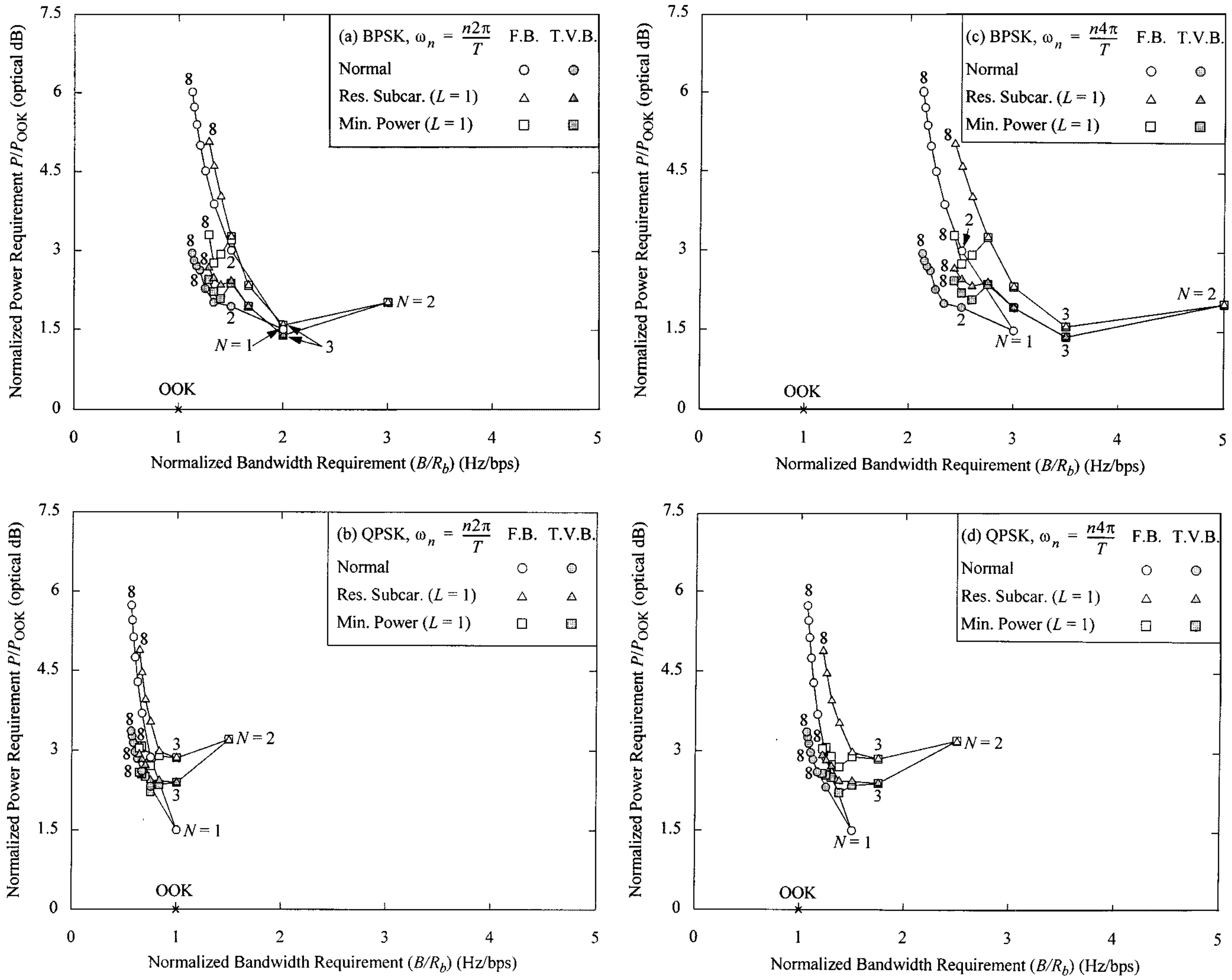

Fig. 3. Normalized optical power requirement versus normalized bandwidth requirement for various block coding and biasing schemes. These results assume a rectangular transmit pulse $g(t)$. The normalized power requirement is the power required by a scheme divided by the power required by OOK, assuming a fixed bit rate R_b. (a) BPSK, $\omega_n = n2\pi/T$. (b) QPSK, $\omega_n = n2\pi/T$. (c) BPSK, $\omega_n = n4\pi/T$. (d) QPSK, $\omega_n = n4\pi/T$.

fixed p). Nonetheless, given any block code, it is always possible to choose the mapping between $\{\boldsymbol{x}^{(m)}\}$ and $\{\boldsymbol{a}^{(m)}\}$ so that $P_b \leq p$.[1] In evaluating the proposed MSM schemes, we assume conservatively that

$$P_b = p \qquad \text{(BPSK or QPSK)}. \tag{31}$$

In comparing various modulation techniques, we consider the normalized bandwidth requirement B/R_b and the normalized power requirement P/P_{OOK}, which represents the average optical power required by a particular scheme to achieve an arbitrary specified BER compared to that required by OOK to achieve the same BER, assuming a fixed bit rate R_b.[2]

[1]For simplicity, consider BPSK and arbitrary N. When $L = 0$, the codewords (i.e., the $\{\boldsymbol{a}^{(m)}\}$) lie on the 2^N vertices of an N-dimensional hypercube. When $L > 0$, the worst-case block code has its codewords on the 2^{N-L} vertices of a hypercube of dimension $N - L$. This occurs when the symbol amplitudes on L subcarriers are identical for all codewords. For this worst-case block code, $P_b = p$, assuming Gray coding between the $\{\boldsymbol{x}^{(m)}\}$ and $\{\boldsymbol{a}^{(m)}\}$. For any other block code, it is possible to find a mapping such that $P_b \leq p$. Similar arguments can be used in the case of QPSK to justify the assertion that $P_b \leq p$.

[2]We actually consider $10\,\log_{10}(P/P_{\text{OOK}})$, which has units of optical decibels.

Fig. 2 presents the normalized power requirement versus the total number of subcarrier frequencies N for various MSM schemes with BPSK and QPSK. In Fig. 2(a), we see that BPSK, with normal block coding and fixed bias, has a normalized power requirement of $1.5 + 5.00\,\log_{10} N$, while normal block coding and time-varying bias lowers this to approximately $1.5 + 1.52\,\log_{10} N$. For $N = 8$, this amounts to a power savings of about 3.0 dB. For $N \geq 3$, reserved-subcarrier block coding with time-varying bias and minimum-power block coding with time-varying bias are the best-performing techniques. The latter offers power savings up to about 0.6 dB more than normal block coding with time-varying bias.

Referring to Fig. 2(b), we see that QPSK, with normal block coding and fixed bias, has a normalized power requirement of about $1.5 + 4.66\,\log_{10} N$. Normal block coding and time-varying bias lowers this to about $1.5 + 2.15\,\log_{10} N$, which represents a power savings of about 2.4 dB when $N = 8$. For $N \geq 3$, reserved-subcarrier block coding with time-varying bias and minimum-power block coding with time-varying bias are the best-performing techniques, and the latter offers power

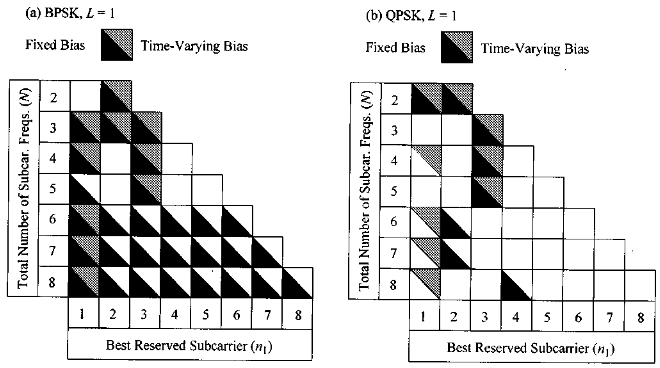

Fig. 4. Choice of best reserved subcarrier under reserved-subcarrier block coding with $L = 1$, with fixed or time-varying bias. These results assume a rectangular transmit pulse $g(t)$, and are valid for either $\omega_n = n2\pi/T$ or $\omega_n = n4\pi/T$. In many cases, the best reserved subcarrier is not unique. (a) BPSK. (b) QPSK.

savings up to about 0.8 dB more than normal block coding with time-varying bias.

In Fig. 3, we plot the normalized power requirement versus the normalized bandwidth requirement for all of the block-coding and biasing schemes, comparing these to OOK. Fig. 3(a) and (b) consider the dense frequency packing with BPSK and QPSK, respectively, while Fig. 3(c) and (d) consider the coarse frequency packing with BPSK and QPSK, respectively. Fig. 3 illustrates the bandwidth expansion ratio incurred by reserved-subcarrier or minimum-power block codings, which is $N/(N-L)$. With $L = 1$, at $N = 2$, this ratio is 2, while at $N = 8$, it is only 8/7. In applications where bandwidth is at a premium, when N is small, it may be most attractive to use normal block coding with time-varying bias. As N increases, it becomes increasingly attractive to use the other two block codings with time-varying bias.

Fig. 4 indicates the best subcarrier to reserve with fixed bias or time-varying bias, for various N, considering reserved-subcarrier block coding with $L = 1$. In Fig. 4(a), we see that, for BPSK with fixed bias, for most N, there are several equivalent best reserved subcarriers. By contrast, with time-varying bias, for most N, the best reserved subcarrier is unique, and it is best to reserve subcarrier 1. In Fig. 4(b), we see that, for QPSK with fixed or time-varying bias, for most N, the best reserved subcarrier is unique. With time-varying bias, for most N, it is best to reserve subcarrier 1.

V. Concluding Remarks

We have described two classes of simple, effective techniques for reducing the average optical power requirement in MSM IM/DD systems using BPSK or QPSK modulation. The first class of techniques involves block coding between the information bits to be transmitted and the symbol amplitudes modulated onto the subcarriers, in order to increase the minimum value of the MSM electrical waveform. This class of techniques increases the bandwidth required for transmission at a given bit rate, but the bandwidth expansion ratio decreases as the number of subcarriers increases. The second class of techniques replaces the fixed dc bias by a time-varying bias signal and does not entail a bandwidth expansion. These two classes of techniques can be applied separately or together. When the number of subcarriers is small, the computation required to implement the proposed techniques can be performed off-line and implemented via table lookup. The proposed techniques yield a reduction in average power requirement that increases with the number of subcarriers. With eight subcarriers, this reduction can be as high as about 3.6 and 3.2 dB with BPSK and QPSK, respectively. These two classes of techniques are applicable as long as all subcarriers originate from a single transmitter and are symbol-synchronized.

Several problems remain for future study. These include: 1) block coding and time-varying biasing techniques for nonrectangular transmit pulse shapes; 2) efficient implementation of the proposed techniques when the number of subcarriers becomes large, and table lookup becomes impractical; 3) obtaining analytical bounds on the transmit power requirements with block coding and/or time-varying bias; 4) design of block codes that minimize the transmit power required to achieve a specified information bit-error probability; 5) utilizing information contained in the time-varying bias signal to enhance detection efficiency [14]; and 6) possible impairment caused by a time-varying bias signal on channels exhibiting memory or nonlinearity.

Acknowledgment

The authors would like to thank V. Anantharam for discussions on analytical bounds for the transmit power requirement.

References

[1] J. A. C. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Commun. Mag.*, vol. 28, pp. 5–14, May 1990.

[2] S. Fragiacomo, C. Matrakidis, and J. J. O'Reilly, "Multicarrier transmission peak-to-average power reduction using simple block code," *Electron. Lett.*, vol. 34, no. 10, pp. 953–954, May 1998.

[3] R. van Nee and A. de Wild, "Reducing the peak-to-average power ratio of OFDM," in *Proc. 1998 IEEE Conf. on Vehic. Technol.*, Ottawa, ON, Canada, May 18–21, 1998, pp. 2072–2076.

[4] J. Tellado and J. M. Cioffi, "Efficient algorithms for reducing PAR in multicarrier systems," in *Proc. 1998 IEEE Intl. Symp. on Info. Thy.*, New York, NY, Aug. 16–21, 1998, p. 191.

[5] D. Wulich and L. Goldfeld, "Reduction of peak factor in orthogonal multicarrier modulation by amplitude limiting and coding," *IEEE on Commun.*, vol. 47, pp. 18–21, Jan. 1999.

[6] T. E. Darcie, "Subcarrier multiplexing for lightwave networks and video distribution systems," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 1240–1248, Sept. 1990.

[7] J. R. Barry, *Wireless Infrared Communications*. Boston, MA: Kluwer, 1994.

[8] Q. Pan and R. J. Green, "Preclipping AM/QAM hybrid lightwave systems with bandstop filtering," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 1079–1081, Aug. 1996.

[9] Q. Shi, "Error performance of OFDM-QAM in subcarrier multiplexed fiber-optic transmission," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 845–847, June 1997.

[10] F. R. Gfeller and U. H. Bapst, "Wireless in-house data communication via diffuse infrared radiation," *Proc. IEEE*, vol. 67, pp. 1474–1486, Nov. 1979.

[11] D. J. T. Heatley, D. R. Wisely, I. Neild, and P. Cochrane, "Optical wireless: The story so far," *IEEE Commun. Mag.*, vol. 36, pp. 72–74, 79–82, Dec. 1998.

[12] J. B. Carruthers and J. M. Kahn, "Multiple-subcarrier modulation for nondirected wireless infrared communication," *IEEE J. Select. Areas Commun.*, vol. 14, pp. 538–546, Apr. 1996.

[13] R. Narasimhan, M. D. Audeh, and J. M. Kahn, "Effect of electronic-ballast fluorescent lighting on wireless infrared links," *Proc. Inst. Elect. Eng.*, pt. J, vol. 143, pp. 347–354, Dec. 1996.
[14] S. Hranilovic and D. A. Johns, "A multilevel modulation scheme for high-speed wireless infrared communications," in *Proc. IEEE Int. Symp. Circuits and Systems*, Orlando, FL, May 30–June 2, 1999.
[15] J. G. Proakis, *Digital Communications*, 3rd ed. New York: McGraw-Hill, 1995.

Roy You received the B.S. degree from the University of California at Berkeley in 1997. He is currently working toward the Ph.D. degree in communications at the same university.

His research interests include digital communication, optical communication systems, and information theory.

Joseph M. Kahn (M'90–SM'98–F'00) received the A.B., M.A., and Ph.D. degrees in physics from the University of California at Berkeley (UC Berkeley) in 1981, 1983, and 1986, respectively.

He is a Professor in the Department of Electrical Engineering and Computer Sciences at UC Berkeley. In 2000, he co-founded StrataLight Communications, Inc., where he is currently Chief Scientist. From 1987 to 1990, he was a Member of Technical Staff in the Lightwave Communications Research Department of At&T Bell Laboratories, where he performed research on multi-gigabit-per-second coherent optical fiber transmission systems, setting several world records for receiver sensitivity. He joined the faculty of UC Berkeley in 1990. His current research interests include wireless communication using antenna arrays, free-space optical communication, optical fiber communication, and wireless communication for networks of sensors based on micro-electromechanical systems.

Prof. Kahn received the National Science Foundation Presidential Young Investigator Award in 1991. He is a member of the IEEE Communications Society, the IEEE Information Theory Society, and the IEEE Lasers and Electro-Optics Society. From 1993–2000, he served as a Technical Editor of *IEEE Personal Communications Magazine.*