Data-aided channel estimation and frequency domain equalization of minimum-shift keying in optical transmission systems

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We demonstrate a digital optical communication system based on minimum shift keying (MSK) signal transmission with coherent detection. 5-Gb/s MSK signal can transmit over a 160-km standard single mode fiber (SSMF) without phase compensation. At the receiver, we use data-aided channel estimation and frequency domain equalization (FDE) techniques in the digital signal processing (DSP) algorithm, then analyze its performance characteristics compared with quadrature phase shift keying (QPSK) format. The simulation results show that the MSK format will be a potential candidate for next-generation access network.

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With the emergence of bandwidth-hungry services such as high-definition (HD) television streaming, cloud computing, interactive HD online gaming, the bit rate requirement of the next generation short reach optical fiber system is increasing step by step. Unlike long haul and metro networks where expense can be shared by a large number of users, access applications desire low-capital expenditures and low-operational expenditures expense. However, the performance of the traditional modulation formats in access network, such as on off keying (OOK), will seriously deteriorate because of the fiber dispersion and nonlinear impairment. The need for increasing spectral efficiency in fiber optic networks has prompted researchers to examine some advanced modulation formats[1,2]. It is well known that minimum shift keying (MSK) is a special format of continuous phase modulation (CPM). It has the property of decaying fast side-lobe and reduces the effects such as inter-carrier interference (ICI)[3]. MSK has a higher spectral efficiency at the same bit rate and better dispersion tolerance than OOK[4]. Besides, the power spectrum of MSK signal does not have peak value, thus resulting much smaller nonlinear than OOK signal. Recently, optical MSK has received much attention. Some researchers focused on the transmitter by using specially designed modulators to generate optical MSK signal[5−10]and multi-amplitude minimum shift keying (MAMSK) signal[11,12]. In addition, some demodulation schemes have proposed[13,14]. The fiber dispersion can be compensated by dispersion compensation fiber (DCF). Due to the large attenuation of these compensation components, some additional amplifiers are needed to compensate for the loss. However, the amplified spontaneous emission (ASE) noises from these amplifiers will reduce the transmission distance. Meanwhile, it brings about the accumulation of noises. In contrast, the electrical field equalization has some advantages such as high flexibility, low cost and programmable strongly.

In this letter, we demonstrate a digital optical communication system based on MSK signal transmission with coherent detection. 5-Gb/s MSK signal transmit over a 160-km standard single mode fiber (SSMF) without phase compensation. At the receiver, optical signal is mixed with a local oscillator (LO), then down-converted and processed by off-line digital signal processing (DSP) algorithm. We use data-aided channel estimation and frequency domain equalization (FDE) techniques to compensate fiber dispersion and nonlinearity in the electric field. We analyze its performance characteristics compared with quadrature phase shift keying (QPSK) format.

A block-based transmission approach to CPM enables FDE for binary schemes effectively[15,16]. Therefore, we consider a block-based communication system in the letter. The block structure of the MSK signal imposes several restrictions at the transmitter, including insertion of a cycle prefix (CP) and tail symbols. In Fig. 1, a binary data stream feeds a symbol mapper, associating in a one-to-one fashion each group of 1 bit with a channel symbol belonging to a binary amplitude-shift keying (ASK) constellation $\mathbf{x} = \{\pm 1\}$[17]. The symbol stream is divided into non-overlapping blocks, each consisting of two sub-blocks, the first of length $(N - N_p - K)$, and the second of length N_p. N_p is the CP ,which equals or exceeds the maximum expected channel length. K is the length of tail symbols[18]. Tail symbols are unique to CPM, as it ensures that the initial phase state of the CP matches the initial phase state of the final N_p symbols of the block.

The data blocks $\left\{a^{(l)}\right\}$ after parallel-to-series conversion, feed a continuous phase modulator to generate the baseband MSK signal

$$s_{\text{base}}(t) = \sqrt{\frac{2E_{\text{s}}}{T_{\text{s}}}} \exp[j\psi(t; a^{(l)})], \qquad (1)$$

where T_{s} is the symbol interval, E_{s} is the average transmitted energy per symbol. $\psi\left(t; a^{(l)}\right)$ is the titled-phase of MSK signal[19].

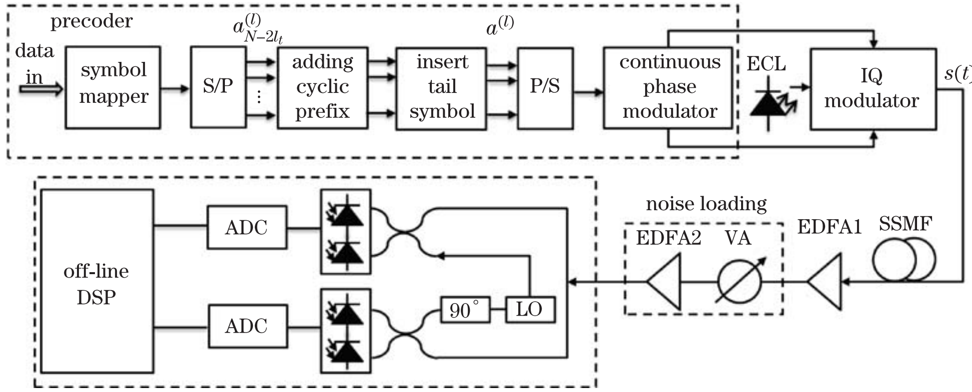

Fig. 1. Block diagram of the digital communication system. EDFA: erbium doped fiber amplifier, VA: variable attenuator, LO: local oscillator, ADC: analog to digital converter.

Subsequently, the baseband signals are fed into the quadrature modulator (QM) by an optical carrier with a frequency of f_c

$$s(t)=\sqrt{\frac{2E_\mathrm{s}}{T_\mathrm{s}}}\exp\left\{\mathrm{j}\left[2\pi f_c t+\psi\left(t;a^{(l)}\right)+\varphi\right]\right\}, \quad (2)$$

where φ denotes the phase noise.

The optical MSK signal is launched into a 160-km SSMF and pre-amplified by EDFA1 to 4 dBm. The noise loading circuit is used to adjust the optical signal to noise ratio (OSNR) to the desired level (in a reference optical bandwidth of 0.1 nm). At the receiver, implementation a MSK receiver is notably more complex than receivers for other phase modulation schemes like QPSK. A coherent optical receiver (see Fig. 1) is utilized[20]. The optical MSK signal is coupled with the LO by the 90-degree hybrid coupler, then down-converted and stored for processing off-line in MATLAB[21]. All subsequent processing is handled by DSP. The proposed MSK receiver architecture is based on the linear decomposition of the MSK signal, a technique first proposed for binary formats by Laurent[22]. Through linear decomposition, the MSK signal is described as a superposition of complex-valued pulse amplitude modulation (PAM) waveforms, which enables the use of linear demodulation techniques such as channel equalization. These PAM pulses are multiplied by data dependent complex-valued coefficients, called pseudo-symbols, which exhibit a temporal correlation to maintain the continuity and restricted progression of phase states.

The MSK signal after Laurent decomposition can be approximated as

$$s(t)\approx\sqrt{\frac{2E_\mathrm{s}}{T_\mathrm{s}}}\sum_{n=0}^{N-1}a_n\mathrm{c}_0(t-nT_\mathrm{s}), \quad (3)$$

where $\alpha_{n,0}=\sum\limits_{m=0}^{n}x_m$. Let $a_n=\exp\left(\mathrm{j}\pi h\sum\limits_{m=0}^{n}x_m\right)$,

$$c_0(t)=\begin{cases}\sin\dfrac{\pi t}{2T_\mathrm{s}}, & 0\leqslant t\leqslant 2T_\mathrm{s}\\ 0, & \text{otherwise}\end{cases}. \quad (4)$$

The received baseband signal is therefore

$$r(t)=\sum_n s(t)h(t-nT_\mathrm{s}/2)+z(t), \quad (5)$$

where $z(t)$ is zero-mean complex additive white Gaussian noise (AWGN) with variance N_0.

The illustration of DSP algorithm for digital coherent receiver is shown in Fig. 2. Initially, the blocks of MSK symbols are send to its own synchronization module, which capture the synchronized signal to pinpoint the start of FFT window and separate the training symbols and data symbols. Here, we utilize the non-periodic auto-correlation property of the Golay complementary pair[23,24]. The proposed timing metric has the impulsive peak at the correct timing point.

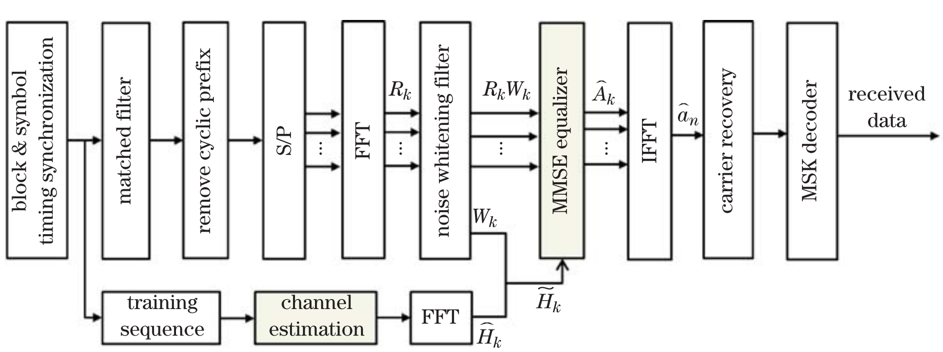

Fig. 2. The illustration of DSP algorithm for digital coherent receiver. FFT: fast fourier transformation; IFFT: inverse fast fourier transformation.

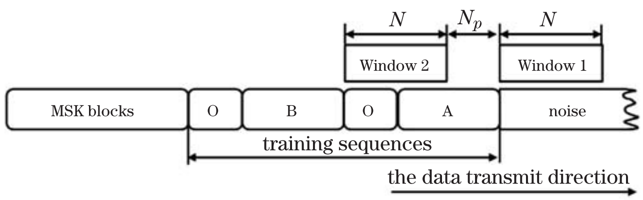

Fig. 3. Synchronization model of MSK system.

The proposed preamble can be given by[25]

$$S = [\mathbf{A}\ \ \mathbf{O}\ \ \mathbf{B}\ \ \mathbf{O}],$$

where **A** and **B** are Golay complementary pair of length N, **O** is the zero-value sequence of length N_p equals or exceeds the maximum expected channel coherent time.

Adopt double slide windows spaced N, the non-periodic cross-correlation with Golay sequence **A** in the window 1 and **B** in the window 2 are performed at the receiver at time m. We can obtain a sharp peak by the amplified signal energy with the average ratio of signal energy. Thus the value of m that corresponds to maximum value of the timing metric is the timing offset estimate

$$\hat{\varepsilon} = \arg\max_m (Z(m)). \tag{6}$$

Channel estimation is an important procedure in optical transmission systems. With accurate channel response estimation, the physical impairments of the fiber transmission such as chromatic dispersion can be obtained, and subsequent channel equalization can be performed to restore the signal. In this letter, we use combined time-domain synchronization and channel estimation algorithm. By utilizing the non-periodic autocorrelation property of the Golay complementary pair, we can get amplified $2N$ time domain channel impulse response sample taps in the initial synchronization module, without matrix inversion and other complex operations. Figure 4 presents structure diagram of joint synchronization and channel estimation algorithm. The symbol timing synchronization of the signal $\hat{h}_{\text{syn}}(n)$ is an enlarged of $2N$ time-domain channel tap impulse response, the $\hat{h}_{\text{syn}}(n)$ divided by $2N$, then through N-point FFT module, to obtain the frequency-domain channel estimation values of the optical transmission channel.

Then data symbols through a real-valued matched filter $c_0(t)$[18], we obtain the received sequence $\boldsymbol{r} = \{r_n\}$,

$$\begin{aligned} r_n &= \int_{-\infty}^{+\infty} r(t) c_0(t) \mathrm{d}t \\ &= \int_{-\infty}^{+\infty} \Big(\sum_n s_n h(t - nT_{\mathrm{s}}/2) + z(t) \Big) c_0(t) \mathrm{d}t \\ &= \sum_n s_{n-l} h_l + z_n. \end{aligned} \tag{7}$$

After removing the CP, we have

$$r_n = \sum_0^{N-1} s_{(n-l)_N} h_l + z_n = h_n \otimes s_n + z_n, \tag{8}$$

where $\otimes$ indicates circular convolution,

$$s_n = \int_{-\infty}^{+\infty} s(t)\, c_0(t - nT_{\mathrm{s}})\, \mathrm{d}t. \tag{9}$$

According to Eqs. (3) and (9), we can obtain

$$\begin{aligned} s_n &= \int_{-\infty}^{+\infty} s(t)\, c_0(t - nT_{\mathrm{s}})\, \mathrm{d}t \\ &= \int_{-\infty}^{+\infty} \left(\sum_{m=0}^{N-1} e^{j\frac{\pi}{2}\alpha_{n,0}} c_0(t - mT_{\mathrm{s}}) \right) c_0(t - nT_{\mathrm{s}})\, \mathrm{d}t \\ &= \sum_{l=0}^{2L-1} e^{j\frac{\pi}{2}\alpha_{n-l,0}} \int_{-\infty}^{+\infty} c_0(t + lT_{\mathrm{s}})\, c_0(t)\, \mathrm{d}t \\ &= \sum_{l=0}^{2L-1} e^{j\frac{\pi}{2}\alpha_{n-l,0}} c(0,0;l) \underline{\underline{L=1}} \\ &\cdot \sum_{l=0}^{1} e^{j\frac{\pi}{2}\alpha_{n-l,0}} c(0,0;l). \end{aligned} \tag{10}$$

Here the correlation factor $c(0,0;l)$ is defined as

$$c(0,0;l) : \left(1, \frac{1}{\pi}, 0, \cdots, 0, \frac{1}{\pi}\right), \quad l = 0, 1. \tag{11}$$

According to Eqs. (8) and (10) above, the overall channel can be modeled as a concatenation of two filters, with impulse response $c(0,0;l) * \hat{h}_n$, when this MSK signal is transmitted over the optical channel as defined in Eq. (5). After removing the CP from the received samples and taking a fast Fourier transform (FFT), we have

$$R_k = A_k C_k \widehat{H} + Z_k, \tag{12}$$

where $e^{j\frac{\pi}{2}\alpha_{n,0}} \xrightarrow{\text{DFT}} A_k$. Note that the noise is correlated, and a noise-whitening filter is needed before the minimum mean square error (MMSE) equalizer. The frequency response of the noise-whitening filter is $W_k = 1/\sqrt{C_k}$, and MMSE equalizer is

$$\widetilde{H}_k = \frac{\widehat{H}_k^* C_k W_k}{|\widehat{H}_k C_k W_k|^2 + N_0}. \tag{13}$$

The equalized signal is

$$\begin{aligned} \widetilde{A}_k &= R_k W_k \widetilde{H}_k = R_k \frac{\widehat{H}_k^*}{|\widehat{H}_k|^2 C_k + N_0} \\ &= \frac{\widehat{H}_k^* C_k}{|\widehat{H}_k|^2 C_k + N_0} A_k + \frac{\widehat{H}_k^*}{|\widehat{H}_k|^2 C_k + N_0} Z_k. \end{aligned} \tag{14}$$

Subsequently, the IFFT modules are used to return the time-domain for processing the symbols.

Due to the asynchrony between transmit and receive lasers, the received data constellation suffers from a rotation, which would bring a huge degradation[26]. We employ the data-aided channel equalization techniques while not blind equalization. At the receiver, we must find the starting point of the training sequence, then extracting it for channel estimation. Therefore, the frequency synchronization must be completed before channel equalization. In this letter, we only consider the impact of phase noise which caused by line-width of LO. Assuming the frequency of the signal and the LO are consistent in our simulation. The Viterbi-Viterbi algorithm[27,28] is used to eliminate phase noise. After the carrier recovery signal is obtain, MSK decoder block is utilized to demodulate the received MSK signal[18].

In order to verify the system, the numerical simulations are performed based on the Optisystem software. The laser is operating at a wavelength of 1552.52 nm with a line-width of 100 kHz. The MSK signal is generated offline by a MATLAB program with parameters as follows. A binary data stream feeds a symbol mapper. The symbol stream is divided into non-overlapping blocks. A frame consists of 110 data blocks and 2 training blocks. The training blocks use the Golay complementary pair as the training sequence to capture the synchronized signal and estimate the fiber transform function. The block length is 256. It is including 254 information bits and 2 tail symbols. The CP length is 32. The length of transmitted data block $a^{(l)}$ with guard interval is 288. The data block $\{a^{(l)}\}$, after parallel-to-series conversion, feed a continuous phase modulator to generate the baseband MSK signals. Subsequently, the baseband signals are fed into the IQ modulator before being launched into SSMF, and SSMF with a dispersion parameter of 16.75 ps/nm/km is considered for transmission purposes. Then the optical MSK signal is pre-amplified by EDFA1 to 4dBm. The noise loading circuit is used to adjust the OSNR to the desired level (in a reference optical bandwidth of 0.1 nm).

At the receiver, a coherent receiver is utilized. The captured signal was mixed with a LO and down-converted, then further processed by offline DSP. Initially, the blocks of MSK symbols are send to its own synchronization module, which capture the synchronized signal to pinpoint the start of FFT window and separate the training symbols and data symbols. Then data symbols through the matched filter remove CP. Estimate the transfer function of the optical transport channel by joint time-domain synchronization and channel estimation. Equalize the received signal through a MMSE equalizer operating in the frequency domain to decrease the linear distortion. Therefore, the IFFT and FFT functional modules are essential. Subsequently, feed the frequency-domain signal into an IFFT block to get a time-domain MSK signal. Then, eliminate the phase noise, which caused by laser. Finally, MSK decoder block is utilized to demodulate the received MSK signal.

Figure 5 shows the relationship between the BER and the OSNR over different fiber length. As can be seen from Fig. 5, the system performance is close over different fiber length, which is substantially determined by the OSNR. For comparison, QPSK signals are transmitted over the same configuration, and processed by a FDE of equal length as that of the MSK receiver. Note that differential encoded QPSK is shown in Fig. 5. In practice, the carrier phase is extracted from the received signal by performing some nonlinear operation that introduces a phase ambiguity. The phase ambiguity problem resulting from the estimation of the carrier phase can be overcome by encoding the information in phase differences between successive signal transmissions as opposed to absolute phase encoding. Instead, the received signal in any given signaling interval is compared to the phase of the received signal from the preceding signaling interval. Therefore, the use of differential encoding is highly preferred to reduce susceptibility to phase ambiguities. Differential encoding does not apply to MSK since the symbols already depend on the previous phase state. For the 5-Gb/s MSK signal, there is a 0.5 dB improvement at a BER of 1×10^{-4} after 80-km SSMF transmission. In fact, the MSK format has continuous phase, which can effectively reduce the signal bandwidth. Therefore, it has greater dispersion tolerance and more concentrated energy over the fiber transmission. Figure 6 shows the relationship of required OSNR at BER=10^{-3} versus chromatic dispersion. The simulation results show that MSK has better dispersion tolerance before 1675 ps/nm, comparing with QPSK.

Figure 7 illustrates the relationship between the BER and the OSNR over 40-km uncompensated fiber as MSK and QPSK are 10 Gb/s. With the further speed increasing, the performance of QPSK has a 1.5-dB improvement at a BER of 1×10^{-4} after 40-km SSMF transmission. Although MSK have high spectral efficiency, it is at the expense of sacrificing the minimum reach compared to QPSK format. The simulation results reveal that MSK modulation format achieve better performance in low speed and short reach optical transmission compared with QPSK format.

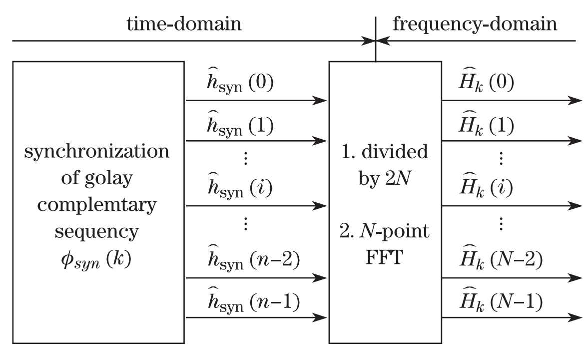

Fig. 4. Joint synchronization and channel estimation algorithm structure diagram.

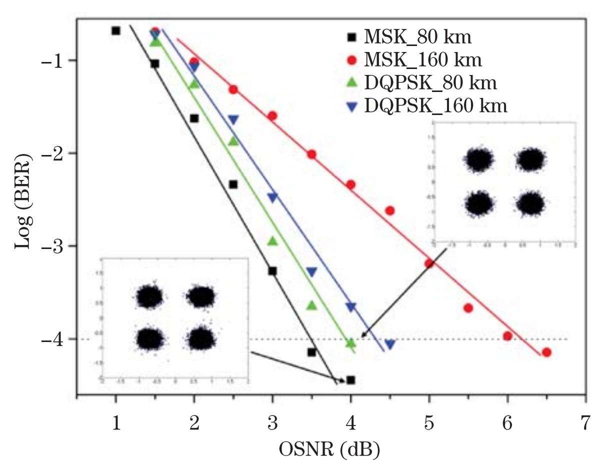

Fig. 5. (Color online) BER curves OSNR for different length fiber links of MSK and differential quadrature phase shift keving (DQPSK) format.

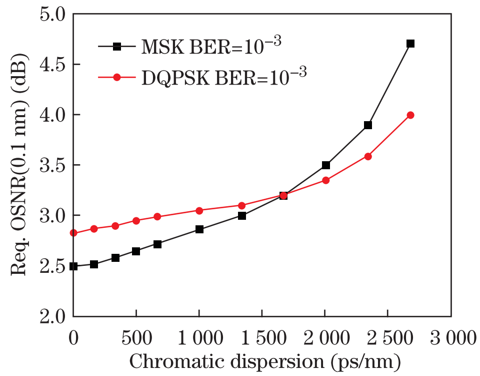

Fig. 6. (Color online) Required OSNR at BER=10^{-3} versus chromatic dispersion (ps/nm).

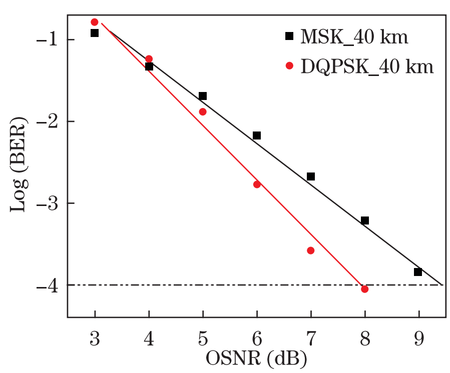

Fig. 7. (Color online) BER versus the OSNR over 40-km uncompensated fiber link in 10 Gbps.

In conclusion, we demonstrate a digital optical communication system based on MSK signal transmission with coherent detection. In the simulation, 5-Gb/s MSK signal is transmitted over 160-km SSMF. The received signals processed by DSP algorithm off-line, including the timing synchronization, channel estimation, frequency domain equalization, and carrier phase recovery. We analyze its performance characteristics compared with QPSK format. Comparing BER of these received signal in different OSNR before and after transmission over fiber links. The simulation results show that, MSK modulation format achieve better performance in low rate and short reach optical transmission. It could be a potential candidate for the next-generation access network to improving the spectrum efficiency.

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