A novel symbol overlapping FFH-OCDMA system

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Received September 25, 2003

A novel symbol overlapping optical fast frequency-hop code-division multiple access (FFH-OCDMA) system is proposed, and its bit error rate (BER) performance is investigated under consideration of avalanche photonic diode (APD) noise and thermal noise. An experimental symbol overlapping (SO) FFH-OCDMA testbed is developed and some experimental results are given. The theoretical and experimental results show that the system is apt to implement and has larger throughput.

OCIS code: 060.2330.

Optical code-division multiple access (OCDMA) is a highly flexible spread spectrum access scheme and has been paid much attention[1−6]. Among methods proposed to achieve passive optical CDMA, the optical fast frequency-hop CDMA (FFH-OCDMA) system is one of the most promising schemes.

In the traditional FFH-OCDMA system[6], each data bit is spread into a frequency-hop sequence which takes one bit duration in the way of on/off keying, and for consecutive dataflow, symbols of neighber bits are adjacent but not overlapped. In transmitters and receivers, electronic ultra-short pulse compression and stretching are involved, respectively, and the user data bit rate is far less than the available modulation rate of light source. Based on the properties of FFH-OCDMA system that the decoder can realign the corresponding frequency-hop sequence into a single pulse, i.e. no side lobe exists in auto-convolution output of codes, we proposed a symbol overlapping (SO) FFH-OCDMA system.

In the SO-FFH-OCDMA system, similar to that of traditional FFH-OCDMA system, optical encoders and decoders shown in Fig. 1 are made up of fiber Bragg gratings (FBGs), fiber delay lines and optical circulators. The length of fiber delay line between FBGs is $cT/2n_{\text{eff}}$, which corresponds to the pulse round trip propagation time T, but not $cT_c/2n_{\text{eff}}$ of traditional FFH-OCDMA system. Here c is light velocity in vacuum, T is the bit duration, and n_{eff} is the effective group index of fiber, T_c is the chip duration. In traditional FFH-OCDMA system, there exists a relationship of $T = NT_c$, but in our system, there is an equation $T = T_c$. In the encoder, the broadband source (e.g. EDFA/ASE source) is directly modulated by data bits. A frequency-hop sequence, which contains N pulses at different wavelength, spreads to N bit durations. The spread spectrum symbols of neighbor bits are temporally overlapped, so we call it symbol overlapping FFH-OCDMA system. The detailed signaling scheme of SO-FFH-OCDMA system is shown in Fig. 2. For the transmitter and receiver, no pulse compression and stretching process is required, and the system is easy to implement. In SO-FFH-OCDMA systems, one-coincidence sequences[7] are used as address codes.

We considered a SO-FFH-OCDMA system in which K active users share the same fiber-optic medium in a star architecture. Via on/off keying, each information bit from user k is encoded into a code sequence

$$c_k(t) = \sum_{j=1}^{N} d_{k,j} p_j(t - jT), \qquad (1)$$

where N is the code length, $d_{k,j}$ ($d_{k,j} \in \{0,1\}$), for $1 \le j \le N$, is the jth chip value of the kth user's code and T is the bit duration. The chip signaling waveform $p_j(t)$, for $1 \le j \le N$, is assumed to be rectangular with unit energy. The received signal of each user is the sum of all the active users' transmitted signals stemming from $(-N+1)$th to $(N-1)$th bits:

$$r(t) = \sum_{k=1}^{K} \sum_{n=-N+1}^{N-1} b_{k,n} c_k(t - nT - \tau_k), \qquad (2)$$

where $b_{k,i}$ ($b_{k,i} \in \{0,1\}$) and τ_k ($0 \le \tau_k \le T$) for $k = 1, \cdots, K$, are the kth user's ith information bit and time delay, respectively. The receiver applies a matched filter

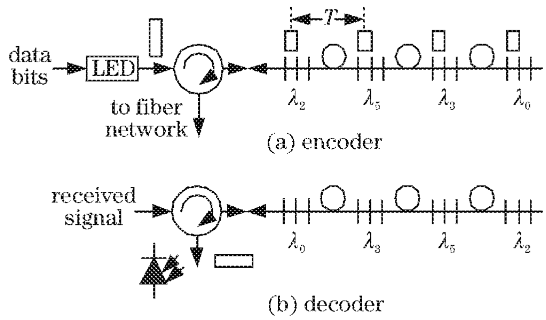

Fig. 1. En/decoder of proposed SO-FFH-OCDMA system.

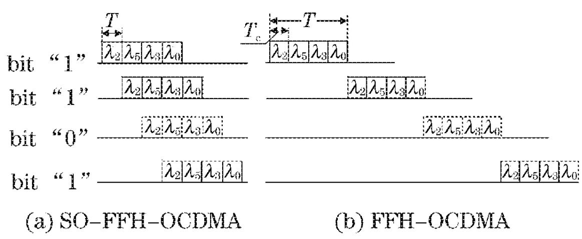

Fig. 2. Comparision of signaling scheme between SO-FFH-OCDMA system and FFH-OCDMA system.

to the received signal to extract the desired user's bit stream. For notational simplicity, assume that the desired user's signal is denoted by $k=1$ and $\tau_1=0$. The correlation output of matched filter is thus:

$$\begin{aligned} y &= \int_0^T c_1(t)r(t)\mathrm{d}t \\ &= b_{1,0}N + \sum_{k=2}^{K}\sum_{n=-N+1}^{N-1} b_{k,n}c_1(t)c_k(t-nT-\tau_k) \\ &= b_{1,0}N + \sum_{k=2}^{K}\sum_{s=-N+1}^{N-1} b_{k,s}R_{1,k}(s) = b_{1,0}N + I, \end{aligned} \quad (3)$$

where $R_{1,k}(s)$ is the cross-correlation function between kth and desired user's codes at the time shift s. I denotes multiple access interference (MAI) with the desired user. According to features of one-coincidence sequences[7], for any code k, $R_{1,k}(s)$ equals to 1 when and only when s is a certain value s_k in $[-n+1, n-1]$. So $I = \sum_{k=2}^{k=K} b_{k,s_k}$. Statisically, it is obvious that the random variable I is binomially distributed

$$p_I(I) = \sum_{k=0}^{K-1} \binom{K-1}{k} p^k (1-p)^{K-1-k} \delta(I-k). \quad (4)$$

Assuming the Poisson distribution, the average number of photons absorbed by an avalanche photonic diode (APD) detector from an incident optical field over an interval $(t, t+T)$ is $\lambda_s T$, where $\lambda_s = \eta p_W / h\nu$ represents the photon absorption rate due to a mark transmission in the desired user sequence. Here p_W is the received light power, η is the quantum efficiency of APD, h is Plank's constant, and ν is the optical frequency. Taken into account the APD noise and thermal noise, for given I and the desired user's bit "1" transmission, the conditional probability density function (PDF) of the accumulated output of the desired user is

$$p_Y(y|I, b_{1,0}=1) = \frac{1}{\sqrt{2\pi}\sigma_{I,1}} \mathrm{e}^{-(y-\mu_{I,1})^2/2\sigma_{I,1}^2}, \quad (5)$$

where the mean $\mu_{I,1}$ and the variance $\sigma_{I,1}^2$ are respectively

$$\mu_{I,1} = GT\left[(N+I)\lambda_s + I_\mathrm{b}/\mathrm{e}\right] + TI_\mathrm{s}/\mathrm{e}, \quad (6)$$

$$\sigma_{I,1}^2 = G^2 F_\mathrm{e} T[(N+I)\lambda_s + I_\mathrm{b}/\mathrm{e}] + TI_\mathrm{s}/\mathrm{e} + \sigma_\mathrm{th}^2, \quad (7)$$

where G is the average APD gain, I_s is the APD surface leakage current, σ_th^2 is the variance of thermal noise written as $\sigma_\mathrm{th}^2 = 2k_\mathrm{B}T_\mathrm{r}T/(\mathrm{e}^2 R_\mathrm{L})$, k_B is Boltzmann's constant, T_r is the receiver noise temperature, F_e is the excess noise factor given by $F_\mathrm{e} = k_\mathrm{eff}G + (2-1/G)(1-k_\mathrm{eff})$, k_eff is the APD effective ionization ratio, R_L is the receiver load resistor, and I_b is the APD bulk leakage current.

Similarly, for "0" transmission and given I, the conditional PDF of the accumulated output of the desired user is

$$p_Y(y|I, b_{1,0}=0) = \frac{1}{\sqrt{2\pi}\sigma_{I,0}} \mathrm{e}^{-(y-\mu_{I,0})^2/2\sigma_{I,0}^2}, \quad (8)$$

where $\mu_{I,0}$ and $\sigma_{I,0}^2$ are respectively

$$\mu_{I,0} = GT[I\lambda_s + I_\mathrm{b}/\mathrm{e}] + TI_\mathrm{s}/\mathrm{e}, \quad (9)$$

$$\sigma_{I,0}^2 = G^2 F_\mathrm{e} T[I\lambda_s + I_\mathrm{b}/\mathrm{e}] + TI_\mathrm{s}/\mathrm{e} + \sigma_\mathrm{th}^2. \quad (10)$$

So the system's probability of error for equiprobable data is given by

$$\begin{aligned} p_\mathrm{e} &= \frac{1}{2}\sum_{I=0}^{K-1} p_I(I)\left\{\Pr(y \geq Th|I, b_{1,0}=0) + \Pr(y \leq Th|I, b_{1,0}=1)\right\} \\ &= \frac{1}{2}\sum_{I=0}^{K-1} \binom{K-1}{I} \left(\frac{1}{2}\right)^{K-1} \left\{\int_{Th}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_{I,0}} \mathrm{e}^{-(y-\mu_{I,0})^2/2\sigma_{I,0}^2}\mathrm{d}y + \int_0^{Th} \frac{1}{\sqrt{2\pi}\sigma_{I,1}} \mathrm{e}^{-(y-\mu_{I,1})^2/2\sigma 1}\mathrm{d}y\right\}. \end{aligned} \quad (11)$$

For K active users, the threshold Th is selected as $Th = GT[(N+K-1)\lambda_s/2 + I_\mathrm{b}/\mathrm{e}] + TI_\mathrm{s}/\mathrm{e}$. Similarly, for traditional FFH-OCDMA system, one has

$$p_\mathrm{e} = \frac{1}{2}\sum_{I=0}^{K-1} \binom{K-1}{I} \left(\frac{1}{2N}\right)^I \left(\frac{2N-1}{2N}\right)^{K-1-I} \left\{\int_{Th}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_{I,0}} \mathrm{e}^{-(y-\mu_{I,0})^2/2\sigma_{I,0}^2}\mathrm{d}y + \int_0^{Th} \frac{1}{\sqrt{2\pi}\sigma_{I,1}} \mathrm{e}^{-(y-\mu_{I,1})^2/2\sigma_{I,1}^2}\mathrm{d}y\right\}, \quad (12)$$

where the threshold is selected as $Th = GT[(N/2 + (K-1)/2N)\lambda_s + I_\mathrm{b}/\mathrm{e}] + TI_\mathrm{s}/\mathrm{e}$.

We calculated probability of error for SO-FFH-OCDMA system and Fathallah's FFH-OCDMA system versus received power for different number of active users with $N=12$, and the results are shown in Fig. 3. The DS-OCDMA system's probability of error is calculated in the same way as Ref. [8]. The code length of DS-OCDMA system is selected to be nearly equal to the product of N and q[6]. Here q equals to 19. In consideration of typical receiver and APD detector, these values of parameters used during calculation are selected as shown in Table 1.

As shown in Fig. 3, when $K > N$, the bit error rate (BER) of SO-FFH-OCDMA system is 3 to 4 orders of magnitude greater than that of FFH-OCDMA system. This is because that in SO-FFH-OCDMA system, there are many symbols overlap within single bit duration, and the signal interference ratio is relatively lower

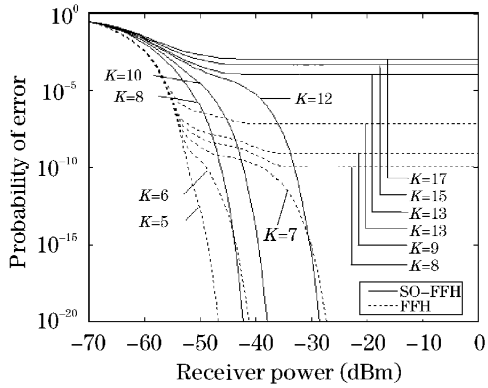

Fig. 3. Probability of error of SO-FFH-OCDMA system and traditional FFH-OCDMA system versus received power.

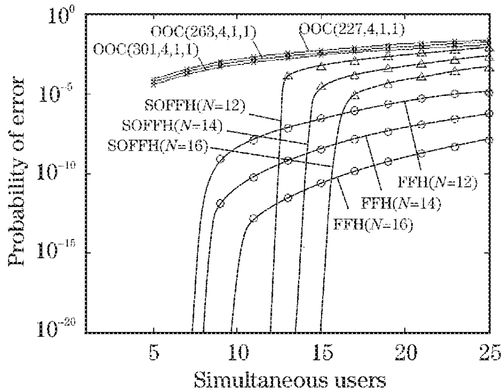

Fig. 4. Comparison of SO-FFH-OCDMA system, traditional FFH-OCDMA system, and DS-OCDMA system.

Table 1. Parameters for Analysis

Parameter	Value
Light Wavelength λ	1.55 μm
APD Quantum Efficiency η	0.6
Average APD Gain G	100
APD Effective Ionization Ratio k_{eff}	0.02
APD Bulk Leakage Current I_{b}	0.1 nA
APD Surface Leakage Current $\mathrm{I_s}$	10 nA
Data Bit Rate $1/T$	500 Mb/s
Receiver Noise Temperature T_{r}	300 K
Receiver Load Resistor R_{L}	1030 Ω

than that of traditional FFH-OCDMA system. So the maximal number of active users in SO-FFH-OCDMA system is equal to the codelength N. Whereas, the FFH-OCDMA system shows better performance when $K > N$, and the maximal number of active users is more than N.

However, when the number of active users K is no more than N, the probability of error for SO-FFH-OCDMA is lower than that of FFH-OCDMA system, and the system shows error-free. Both the BER curve of SO-FFH-OCDMA system and that of FFH-OCDMA system show significant transition at $K = N$ and $K = \lfloor N/2+1 \rfloor$, respectively. This is thanks to the error asymmetry of these two incoherent systems, and different decision thresholds of the two OCDMA systems[9]. In detail, if both the APD noise and thermal noise are neglected, Eq. (11) and its decision threshold may be simplified as $p_{\mathrm{e}} = \frac{1}{2}\sum_{I=1}^{K-1}\begin{pmatrix} K-1 \\ I \end{pmatrix}\left(\frac{1}{2}\right)^{K-1}\delta(I > Th)$ and $Th = (N+K-1)/2$. When $K \leq N$, there exists an inequation $\max(I) = K-1 < Th$, so $p_{\mathrm{e}} = 0$. This is consistent with obvious fact that when $K \leq N$, possible maximum interference (i.e. $K-1$) is less than the auto-correlation output of the desired user (i.e. N). For the traditional FFH-OCDMA system, Eq. (12) and its decision threshold may be simplified as $p_{\mathrm{e}} = \frac{1}{2}\sum_{I=1}^{K-1}\begin{pmatrix} K-1 \\ I \end{pmatrix}\left(\frac{1}{2N}\right)^{I}\left(\frac{2N-1}{2N}\right)^{K-1-I}\delta(I > Th)$ and $Th = (N/2+(K-1))/2N$, so when $K \leq N/2+1$, the possible maximum interference is less than the threshold, and the system is error-free. So SO-FFH-OCDMA system can accommodate nearly twice many error-free users as FFH-OCDMA system.

The probability of error for SO-FFH-OCDMA system, FFH-OCDMA system, and non-coherent DS-OCDMA system using optical orthogonal code (OOC) versus K are also calculated with $p_W = -20$ dBm, and the results are shown in Fig. 4. The SO-FFH-OCDMA system has less probability of error than DS-OCDMA system with the same code length. The system turns out preferable in networks with less users and higher user bit rates.

Given the maximum modulation rate of light source M, the maximal user data bit rate in SO-FFH-OCDMA system is M, while that in traditional FFH-OCDMA systems is M/N. So the user data bit rate in the SO-FFH-OCDMA system is improved N times. In SO-FFH-OCDMA systems, the maximal number of active users is N, so the gross throughput of the system is $N \cdot M$. Whereas, the cardinality (i.e. the maximal number of codes) of a $N \times q$ ($q > N$) codeset is q, so the maximal gross throughput of FFH-OCDMA system is qM/N. Generally speaking, one has $q \ll N^2$, so SO-FFH-OCDMA system has much larger throughput than traditional FFH-OCDMA system. If q is selected to be nearly equal to N, the SO-FFH-OCDMA system's throughput is nearly equal to that of wavelength division multiplexing (WDM) system (i.e. qM). Due to its simplicity, feasibility, and robustness, SO-FFH-OCDMA system is attractive, and it may challenge WDM technology in access networks.

In order to demonstrate the practicability of the scheme, we developed a SO-FFH-OCDMA test-bed, as shown in Fig. 5. A codeset of $N = 6$, $q = 11$ is used in the system. The length of fiber delay line corresponds to the data bit rate of 120 Mb/s (i.e. 850 mm) for full symbol overlapping operation. Non-return zero (NRZ) pulse signal from a pulse generator directly modulates LEDs of encoders, and the spread spectrum signals of all users are fed into the fiber via optical coupler. An erbium-doped fiber amplifier (EDFA) was used in the optical line to compensate for the loss caused by couplers and fibers. The received optical power is about −34.5 dBm. The optical reflective spectra of encoder and decoder

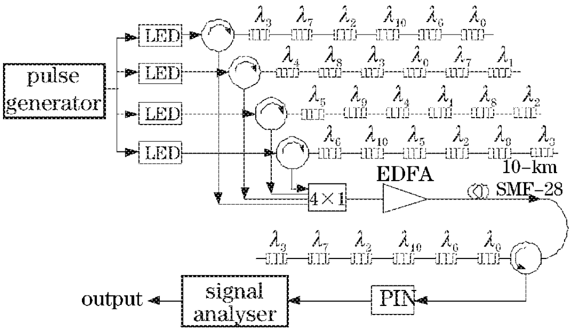

Fig. 5. Diagram of 4-user SO-FFH-OCDMA test-bed.

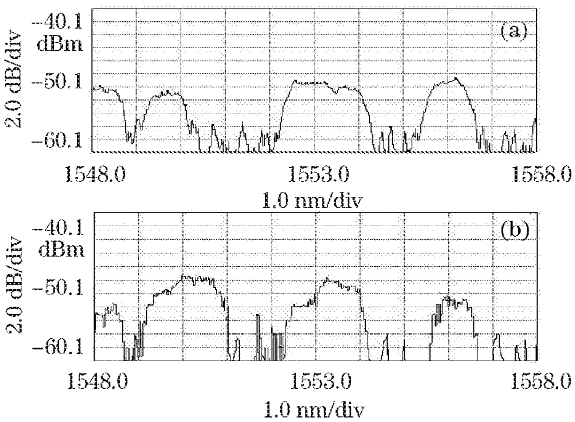

Fig. 6. The optical spectra of encoder (a) and decoder (b).

are shown in Fig. 6. The length error of fiber delay lines is less than 100 mm.

In principle, for the SO-FFH-OCDMA system, the transceivers of users may operate at arbitrary rate below 120 Mb/s. So we adjust the data bitrates of transceiver from 120 to 20 Mb/s. The waveforms of both decoded signal (above) and output of pulse generator (below) at the bit rate 120 and 80 Mb/s are shown in Fig. 7. At both user bit rates the system shows good decoding performance. So the symbol overlapping scheme is successful to achieve the function of multiple access.

However, when the modulation rate of data bit ($1/T$) in the test-bed is more than $c/(2n_{\text{eff}}L)$, i.e. 120 Mb/s, the decoding performance abruptly degrades so that data extraction is impossible, this can be called over-overlapping. Here, L is the length of fiber delay lines in codec. The phenomenon may be due to interference between two consecutive symbols, i.e. the pulses (chip) with same wavelength in consecutive symbols will be partly overlapped. So the maximal modulation rate of SO-FFH-OCDMA system is $c/(2n_{\text{eff}}L)$.

In conclusion, we have proposed a novel symbol overlapping FFH-OCDMA system that can be easy to implement. Theoretical analysis and experiment show that in the system, the user data bit rate and gross throughput of the system increase significantly, as compared with traditional FFH-OCDMA system. The system can accommodate nearly twice many error-free users as FFH-OCDMA system. Due to the MAI, the maximal number of active users in the system is equal to the code length, less than traditional FFH-OCDMA system. Due to the interference between adjacent symbols, the upper limit of user data bit rate in the system is in inverse proportion to the round trip propagation delay of fiber delay lines in the codec. The scheme is apt to applications with less users and high user data bit rate.

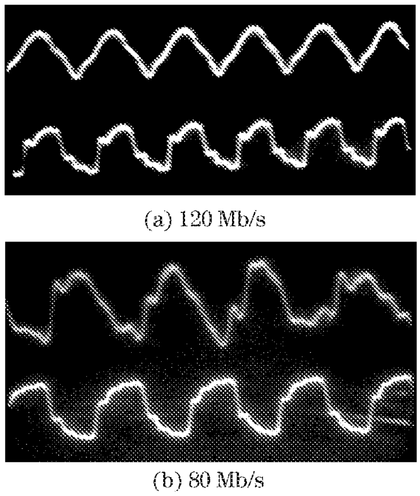

Fig. 7. The waveform of decoder output in SO-FFH-OCDMA test-bed at different bit rates.

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