INVITED PAPER Special Section on Photonic Technologies for Access Networks

Future Optical Access Network and Spectral M-Ary ASK OCDM as Its Key Technology

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SUMMARY This paper presents spectral multi-level (M-ary) amplitude shift keying (ASK) optical code-division-multiplexing (OCDM) as a key technology for future optical access network. A novel transmitter configuration to achieve flexible scalability that is required in future optical access network is proposed. The transmitter employs pre-biasing circuits and dummy data input. Pre-biasing circuits enable us to achieve high tolerance to multiple access interference by compensating for the nonlinearity of the M-ary ASK and increase the number of multiplexed binary data streams. By inputting the dummy data into the transmitter so that the total number of multiplexed binary data streams including those that actually accommodate users/services and the dummy streams remains constant, the number of users/services can be increased up to the total number of data streams without changing the parameters for pre-biasing. Therefore, the proposed transmitter can flexibly enhance the scalability of the spectral M-ary ASK OCDM. The formulas for calculating the bit error rate characteristics are described when using the conventional and proposed transmitters. The feasibility of the proposed transmitter is verified theoretically using the established formulas.

key words: *optical access network, optical code-division-multiplexing, M-ary ASK, pre-biasing*

1. Introduction

Fiber-to-the-x (FTTx) services have been widely provided mainly over passive optical network (PON) systems such as Gigabit Ethernet PONs (GE-PONs) and Gigabit-capable PONs (G-PONs). To broaden the bandwidth, 10-Gbit/s-class PON systems based on time-division-multiplexing (TDM) technologies have been actively investigated and have already been standardized in IEEE 802.3av [1]. In the future, we will need to meet the ever growing demand for bandwidth per user, which is expected to exceed the gigabit per second level, while considering other system requirements such as scalability, operational flexibility, reliability, cost effectiveness, and coexistence with the existing systems.

Optical code-division-multiplexing (OCDM) is a promising candidate for constructing such future optical access networks. In OCDM access networks where unique codes are assigned to individual users/services, a level of bandwidth per user can be offered that far exceeds the TDM based systems. Moreover, inherent characteristics of OCDM such as low latency, soft capacity on demand, and physical layer security are also attractive [2]. One issue that must be addressed concerning OCDM is that advanced optical/electrical devices are needed for en/decoding, which are functions peculiar to OCDM. This complicates the transmitter and receiver configurations. Another is mitigating the signal interference beat noise and multiple access interference (MAI) that severely limit the number of multiplexed binary data streams. In order for OCDM-based systems to coexist with the existing systems in the same fiber infrastructure, users/services must be efficiently accommodated within a limited wavelength band.

For point-to-multipoint applications, we recently proposed spectral multi-level (M-ary) amplitude shift keying (ASK) OCDM where each frequency component is individually intensity modulated with M-ary data based on electrical-domain spatial code spreading [3]. In this scheme, advanced optical en/decoders such as the 16-level phase-shifted superstructured fiber Bragg grating (SSFBG) [4], spatial light phase modulator [5], or ring resonator based spectral phase encoder [6] are not required. Furthermore, due to the spatial code-spreading scheme, there is no need for high-speed electrical en/decoders operating at the chip rate (= data rate × code length) unlike the methods that employ temporal code spreading in the electrical domain [7], [8]. Therefore, bandwidth-guaranteed services that exceed the gigabit per second level can be provided using practical transmitter and receiver configurations.

Spectral M-ary ASK OCDM is also promising in terms of the tolerance to the noises particular to OCDM. Since code multiplexing is performed in the electrical domain, it is completely free from signal interference beat noise. Moreover, in the ideal case where the intensity levels of the M-ary ASK optical signals comprising the OCDM signal are linear to the corresponding symbol values, MAI can be simply removed without optical thresholding [5] and time gating [5], [6] at the decoder. The nonlinearity at the M-ary ASK, however, induces incomplete elimination of the MAI.

In this paper, we first clarify the requirements for future optical access network. Next, as a key technology for such network, spectral M-ary ASK OCDM is presented and its issue is described. To enhance the scalability flexibly, we propose a novel transmitter configuration where pre-biasing circuits and dummy data input are employed. By pre-biasing the M-ary data, i.e., adjusting the voltage levels of the M-ary data, to compensate for the nonlinearity of the modulator, ASK optical signals that have equally spaced intensity levels are generated and the MAI can simply be removed at the receiver. In addition, dummy data are input into the trans-

Manuscript received November 6, 2009.
Manuscript revised February 8, 2010.
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DOI: 10.1587/transele.E93.C.1139

mitter so that the total number of multiplexed data streams remains constant regardless of the number of actually accommodated users/services. This allows the parameters for pre-biasing such as the voltage difference between neighboring levels to remain the same regardless of the number of users/services. As a result, new users/services can be flexibly installed without changing the active transmitter. The feasibility of the proposed transmitter is verified through theoretical analysis using the formulas we establish.

2. Future Optical Access Network

2.1 Trends in Optical Access Network

Figure 1 shows the technology trends in optical access network. FTTx services have been provided mainly over PON systems. So far, PON systems based on TDM technology such as Synchronous Transfer Mode PONs (STM-PONs), Broadband PONs (B-PONs), and GE-PONs have been deployed. The bandwidth has been steadily broadened with the progress of high-speed electrical device technologies and 10G-EPON is a promising candidate for the next generation access system due to its compatibility with the existing TDM based systems. In the future, since the demand for guaranteed bandwidth per user is expected to exceed the limitation of TDM, future optical access network based on new technologies such as OCDM [3]–[8], dense wavelength-division-multiplexing (DWDM) [9], frequency-division-multiplexing (FDM) which requires no optical filter for demultiplexing super dense WDM signal by employing coherent detection [10], and orthogonal frequency-division-multiplexing (OFDM) [11] is considered as a key.

2.2 Requirements for Future Optical Access Network

The bandwidth per user is expected to keep on broadening and to exceed the gigabit per second level to meet the demands for wide-bandwidth services with low latency such as high quality interactive video conferencing based on uncompressed high-definition video streams, and Giga-byte-class digital file transfer on peer-to-peer basis. On the contrary, future optical access network must have flexibility to accommodate diverse services promptly. Reliability is becoming other concern that must be addressed since robustness and security are strongly demanded to be enhanced from the views of operators and users, respectively.

For smooth migration from the existing systems, coexistence of different systems on the same optical distribution network is desirable. It is not to say that cost effectiveness is also crucial.

3. Spectral M-Ary ASK OCDM

In OCDM access networks where unique codes are assigned to individual users/services, a level of bandwidth per user can be offered that far exceeds the TDM based systems. Moreover, low latency, soft capacity on demand, and physical layer security are offered [2].

Spectral M-ary ASK OCDM [3] is attractive due to its practical transmitter and receiver configurations and high tolerance to the noises peculiar to OCDM. In this section, as a key technology for future access network, the configuration is reviewed and its issue is described. Next, to flexibly enhance the scalability, a novel transmitter configuration is proposed and its feasibility is confirmed through theoretical analysis.

3.1 Configuration

Figure 2 shows the configuration for the conventional spectral M-ary ASK OCDM based on electrical-domain spatial code spreading [3]. An OCDM transmitter (Tx) is connected to a number of OCDM receivers (Rxs) through a power splitter. The transmitter comprises a binary/M-ary converter, laser diodes (LDs), intensity modulators (MODs), and a multiplexer. An OCDM signal, for which the frequency components are individually intensity modulated with the M-ary data, is launched to the receivers.

The binary/M-ary converter generates M-ary data, $D'_1(t)$~$D'_K(t)$, by multiplexing the binary data, $D_1(t)$ ~ $D_N(t)$, based on spatial code spreading. Term K is the length of the orthogonal codes assigned to the spatial encoders in the binary/M-ary converter and term N represents the number of accommodated users/services. M-ary data #k, $D'_k(t)$, is expressed as

$$D'_k(t) = \sum_{n=1}^{N} D_n(t) \cdot c_{n,k} \quad (k = 1, 2, \cdots, K) \tag{1}$$

where $c_{n,k}$ is the k_{th} chip of code #n ($n = 1, 2, \cdots, N$).

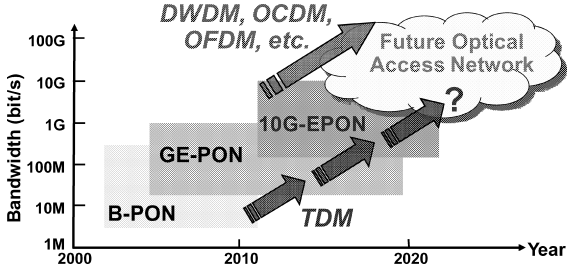

Fig. 1 Trends in optical access network.

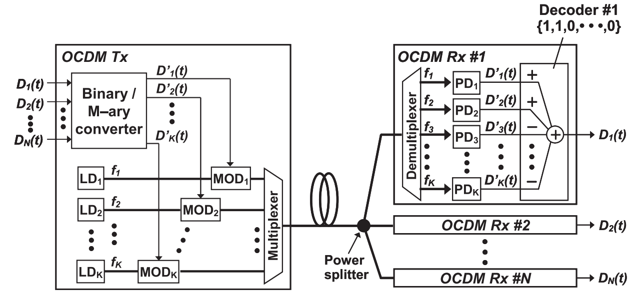

Fig. 2 Configuration for spectral M-ary ASK OCDM.

MODs generate M-ary ASK optical signals, for which the intensities are linear to the symbol values of the M-ary data applied to each modulator. The multiplexer combines M-ary ASK optical signals from all MODs, and outputs an OCDM signal.

The OCDM Rx comprises a demultiplexer, photodetectors (PDs), and a decoder. Demultiplexed frequency components are detected at each PD. The M-ary data generated at the binary/M-ary converter, $D'_1(t) \sim D'_K(t)$, are demodulated. Since code multiplexing is performed in the electrical domain on the transmitter side, it is clear that no beat noise is generated at all, unlike conventional OCDM in the optical domain. The M-ary data from the PDs are added or subtracted according to the orthogonal code assigned to the decoder and the desired data are extracted. Assuming the voltage levels of the M-ary data are linear to the symbol values, MAI can be eliminated due to the orthogonality of the code.

This configuration has the following features. The first feature is that no complicated optical devices are necessary. No optical en/decoders are used. No optical thresholding or time gating is employed at the receivers to mitigate beat noise and MAI. The second feature is that since electrical en/decoders need only to operate at the data rate due to spatial code spreading, high-speed electrical en/decoders that operate at the chip rate are not required. Therefore, practical transmitter and receiver configurations can be used to achieve a bandwidth per user that exceeds the gigabit per second level.

3.2 Issue

When the length of the orthogonal codes, i.e., the number of frequencies comprising the OCDM signal, is fixed at K, the maximum number of multiplexed binary data streams with the code length of K must be increased to accommodate efficiently users/services within the limited wavelength band. To achieve this, since spectral M-ary ASK OCDM is inherently free from signal interference beat noise, the major issue is the suppression of MAI. For complete MAI elimination, the M-ary data from the PDs must satisfy the following requirements. The first is that the voltage levels must be linear to the symbol values for the respective M-ary data. In other words, each voltage level must be equally spaced. The second is that the voltage difference between neighboring levels must be the same for all the M-ary data. Assuming that the responsivity of the PDs is linear against the input optical power, the intensity levels of the M-ary ASK optical signals must be equally spaced to satisfy the first requirement.

The $LiNbO_3$ (LN) modulator is a promising candidate for the intensity modulator due to its stability, wide bandwidth, and mature integration technologies with other functional devices based on planar lightwave circuits (PLCs) [12]. However, due to the nonlinearity of its modulation characteristics that originate from the Mach-Zehnder interferometer (MZI) configuration, generated M-ary ASK optical signals have unequally spaced intensity levels as indicated in Fig. 3. This results in incomplete elimination of MAI and the receiver sensitivity degrades as the number of accommodated users/services, N, increases. In Fig. 3, $T(V)$ represents the transmittance when the applied voltage to the modulator is V.

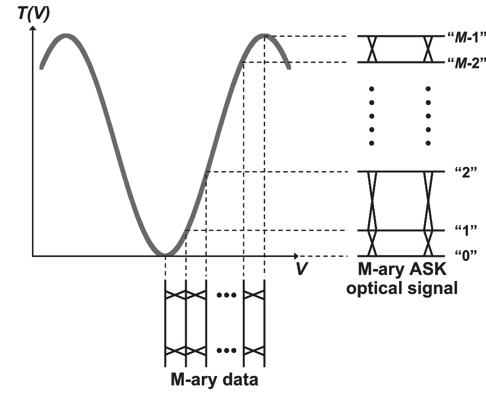

Fig. 3 M-ary ASK using LN intensity modulator.

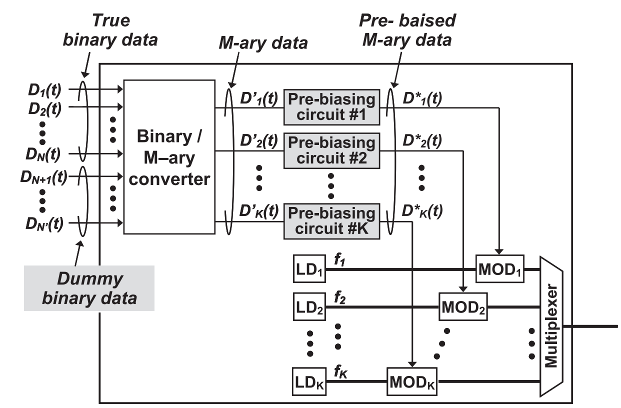

Fig. 4 Proposed transmitter configuration employing pre-biasing circuits and dummy data input.

3.3 Proposed Transmitter Employing Pre-Biasing Circuits and Dummy Data Input

As explained in the previous section, it is crucial to generate M-ary ASK optical signals that have equally spaced intensity levels. To satisfy this requirement using LN intensity modulators, we must compensate for the nonlinearity of the modulation characteristics.

Figure 4 shows the proposed transmitter configuration. Dummy binary data, $D_{N+1}(t) \sim D_{N'}(t)$, are input to the binary/M-ary converter so that the number of binary data streams including both true data and dummy data remains at the constant value of N'. True data are the desired data for some of the receivers. Here, all of the input data are bit synchronized. Value N' is the maximum number of binary data streams that can be multiplexed when the orthogonal codes with the length of K are assigned to the spatial encoders in the binary/M-ary converter. When the number

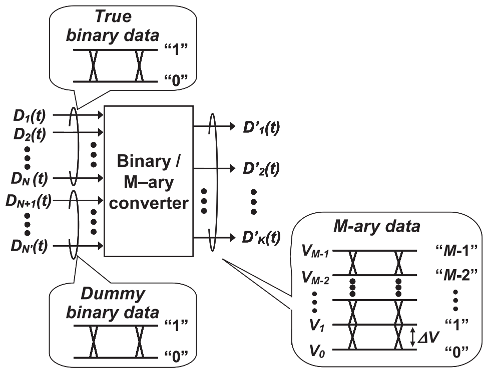

Fig. 5 M-ary data generation at binary/M-ary converter employing dummy data input.

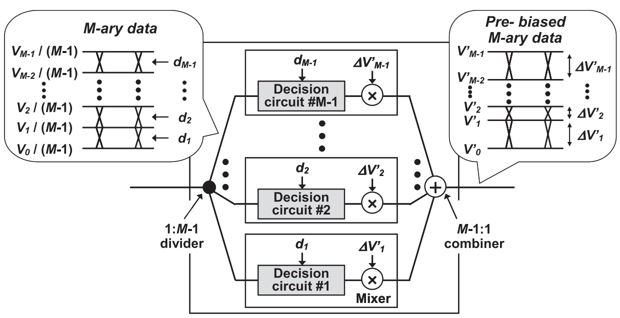

Fig. 6 Pre-biasing circuit.

of multiplexed true data streams, N, equals N', no dummy data are needed. In addition, pre-biasing circuits are connected to each output port of the binary/M-ary converter. The pre-biasing circuits adjust the intensity levels of the M-ary data, $D'_1(t) \sim D'_K(t)$, and launch pre-biased M-ary data, $D^*_1(t) \sim D^*_K(t)$ to the MODs.

Figure 5 illustrates M-ary data generation with the input of dummy binary data that have amplitudes that are equal to those of the true binary data. Assuming that the dummy binary data have no correlation with any true binary data, the maximum symbol values, "$M-1$," and the peak-to-peak voltages of the M-ary data remain constant regardless of the value of N. The m_{th} voltage level corresponding to the symbol value of "$m-1$," V_{m-1}, is fixed as follows.

$$V_{m-1} = V_0 + (m-1) \cdot \Delta V \quad (m = 1, 2, \cdots, M) \tag{2}$$

where V_0 represents the voltage level at the symbol value of "0," and ΔV is the voltage difference between the neighboring symbol values.

Figure 6 shows the configuration of the pre-biasing circuit comprising a $1 : M-1$ divider, pairs of decision circuits and mixers, and a $M-1 : 1$ combiner. The decision circuit outputs binary data by thresholding the incoming M-ary data. The threshold voltage at the h_{th} decision circuit, d_h ($h = 1, 2, \cdots, M-1$), is set between $V_{h-1}/(M-1)$ and $V_h/(M-1)$. Since each voltage level is fixed as in Eq. (2) from the effect of inputting the dummy data, d_h is independent of the number of true data streams, N. At the mixers, the amplitudes of the binary data from the decision circuits

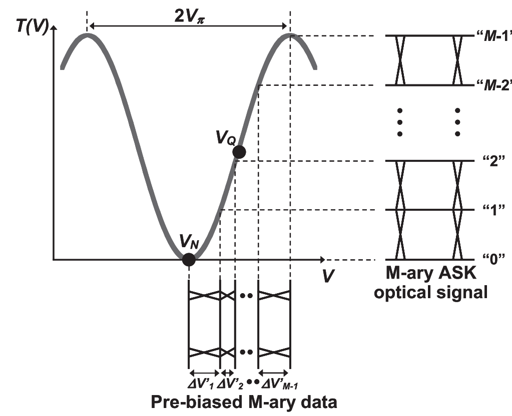

Fig. 7 M-ary ASK using LN intensity modulator with pre-biasing.

are controlled by multiplying the binary data with DC signals, the voltages for which are $\Delta V'_1 \sim \Delta V'_{M-1}$ in order. The output from the mixers is combined and the pre-biased M-ary data are generated. The m_{th} voltage level, V'_{m-1}, is given as

$$V'_{m-1} = V'_0 + \sum_{h=1}^{m-1} \Delta V'_h \quad (m = 2, 3, \cdots, M) \tag{3}$$

where V'_0 represents the voltage level at the symbol value of "0." As expressed in Eq. (4), the values of $\Delta V'_1 \sim \Delta V'_{M-1}$ are set so that the peak-to-peak voltage of the pre-biased M-ary data is the half-wavelength voltage of the LN intensity modulators, V_π.

$$V_\pi = \sum_{h=1}^{M-1} \Delta V'_h. \tag{4}$$

Equation (5) expresses the transmittance of single-drive LN intensity modulators, $T(V)$, as a function of the applied voltage to the electrode, V. The extinction ratio is assumed to be infinite.

$$T(V) \propto \sin^2 \frac{V - V_N}{2V_\pi} \pi \tag{5}$$

where V_N is the voltage that minimizes $T(V)$. By biasing the modulator so that the middle voltage of the pre-biased M-ary data equals the positive slope quadrature point, V_Q, and setting $\Delta V'_h$ as given in Eq. (6), the desired M-ary ASK optical signals can be obtained (Fig. 7).

$$\Delta V'_h = \frac{2V_\pi}{\pi} \left(\sin^{-1} \sqrt{\frac{h}{M-1}} - \sin^{-1} \sqrt{\frac{h-1}{M-1}} \right)$$
$$(h = 1, 2, \cdots, M-1) \tag{6}$$

Here, the maximum symbol values, "$M-1$," are not varied corresponding to the change in N due to the input of dummy data to the binary/M-ary converter. As a result, while N increases or decreases, there is no need to reset the values for $\Delta V'_1 \sim \Delta V'_{M-1}$. Since the threshold voltages, $d_1 \sim d_{M-1}$, are also fixed as mentioned previously, none of the parameters for pre-biasing need to be changed regardless

Table 1 Definition of i when D_1 is the desired data.

i	$(D_1, D_2, D_3, \bullet\bullet\bullet\bullet\bullet, D_{N-1}, D_N)$	
1	(0, 0, 0, ●●●●●, 0, 0)	$D_1 = 0$
2	(0, 0, 0, ●●●●●, 0, 1)	
3	(0, 0, 0, ●●●●●, 1, 0)	
⋮	⋮	
2^{N-1}	(0, 1, 1, ●●●●●, 1, 1)	
$2^{N-1}+1$	(1, 0, 0, ●●●●●, 0, 0)	$D_1 = 1$
$2^{N-1}+2$	(1, 0, 0, ●●●●●, 0, 1)	
$2^{N-1}+3$	(1, 0, 0, ●●●●●, 1, 0)	
⋮	⋮	
2^N	(1, 1, 1, ●●●●●, 1, 1)	

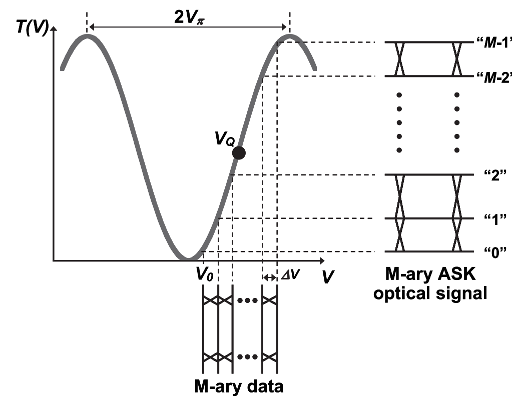

Fig. 8 M-ary ASK model for conventional transmitter.

of the number of true data streams. Therefore, the proposed transmitter can flexibly enhance the scalability of the spectral M-ary ASK OCDM.

3.4 Theoretical Analysis

The performance of spectral M-ary ASK OCDM is analyzed theoretically when employing the conventional and proposed transmitters. First, the bit error rate (BER) is formulated for both cases. Next, the effect of the proposed transmitter is evaluated using the established formula. Finally, a configuration of future access network based on specral M-ary ASK OCDM is presented.

3.4.1 Formula for BER Characteristics

(a) Conventional Transmitter

When the mark ratios of binary data, $D_1(t)$~$D_N(t)$, are 1/2, the BER is derived from the following equation.

$$\begin{aligned} BER &= \frac{1}{2^N}\cdot\left(\sum_{i=1}^{2^{N-1}}\frac{1}{\sqrt{2\pi}}\int_{\frac{d-S(i)}{\sigma(i)}}^{\infty}\exp\left(-\frac{t^2}{2}\right)dt \right.\\ &\qquad \left. +\sum_{i=2^{N-1}+1}^{2^N}\frac{1}{\sqrt{2\pi}}\int_{\frac{S(i)-d}{\sigma(i)}}^{\infty}\exp\left(-\frac{t^2}{2}\right)dt\right)\\ &= \frac{1}{2^N}\cdot\left(\sum_{i=1}^{2^{N-1}}\frac{1}{2}\cdot erfc\left(\frac{d-S(i)}{\sqrt{2}\sigma(i)}\right)\right.\\ &\qquad \left. +\sum_{i=2^{N-1}+1}^{2^N}\frac{1}{2}\cdot erfc\left(\frac{S(i)-d}{\sqrt{2}\sigma(i)}\right)\right) \end{aligned} \tag{7}$$

The terms are error probabilities when the desired binary data are space and mark in order. Term i represents the combinations of symbol values of $D_1(t) \sim D_N(t)$. Table 1 gives the definition of i when $D_1(t)$ is the desired data. Terms $S(i)$ and $\sigma^2(i)$ correspond to the signal amplitude level and the total noise variance at the decoder output, respectively. The decision level, d, is set at the middle amplitude level of the output signal from the decoder.

When $P_k(i)$ is the instant optical power of the k_{th} frequency component where the combination of the symbol values of $D_1(t) \sim D_N(t)$ corresponds to i, $S(i)$ is given as

$$S(i) = R\cdot\sum_{k=1}^{K}(2c_{n,k}-1)\cdot P_k(i) \tag{8}$$

where $c_{n,k}$ is the k_{th} chip of code #n, and R is the responsivity of the PDs. Equation (8) expresses that the k_{th} input are added or subtracted depending on the values of $c_{n,k}$, {1} or {0}, at decoder #n. Meanwhile, $\sigma^2(i)$ is expressed as follows.

$$\sigma^2(i) = \sigma_{shot}^2 + \sigma_{circuit}^2 = 2eR\cdot\sum_{k=1}^{K}P_k(i)\cdot B_e + \sigma_{circuit}^2 \tag{9}$$

where e is the electron charge, and B_e is the electrical bandwidth of the receiver. The terms represent the shot noise and the thermal noise in order.

The voltage difference between the neighboring symbol levels of the M-ary data is fixed at, ΔV, regardless of the value of N. Voltage ΔV is determined so that the peak-to-peak voltage of the M-ary data equals V_π when N is maximum with the code length of K. The modulators are biased so that the middle voltage of the M-ary data equals the positive slope quadrature point, V_Q, as shown in Fig. 8, and $P_k(i)$ is expressed using the average input power into each PD, P, as

$$P_k(i) = P\cdot\frac{T(V_0 + M(i)\cdot\Delta V)}{T(V_Q)} \tag{10}$$

where V_0 is the voltage corresponding to the symbol value of "0," and $M(i)$ is the symbol value when the combination of the symbol values of $D_1(t)$~$D_N(t)$ corresponds to i. By substituting Eqs. (8) ~ (10) into Eq. (7), the BER characteristics against P when the conventional transmitter is used are obtained.

(b) Proposed Transmitter

When the mark ratios of both true binary data, $D_1(t) \sim D_N(t)$, and dummy binary data, $D_{N+1}(t) \sim D_{N'}(t)$, are 1/2, the BER is derived from Eq. (7). Due to the dummy data input, the maximum symbol values, "$M-1$" keep constant regardless of the number of true data stream, N. Since the

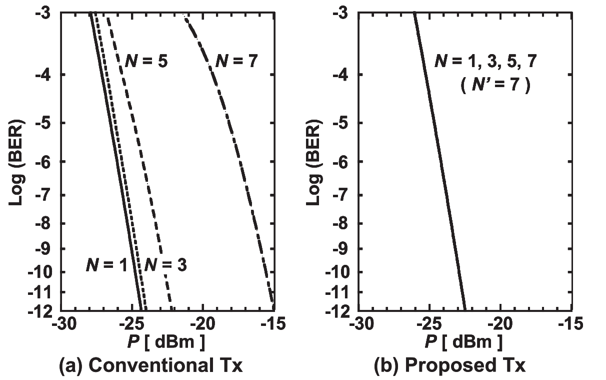

Fig. 9 BER characteristics at 1.25 Gbit/s against average optical power per wavelength, P, when $K = 8$.

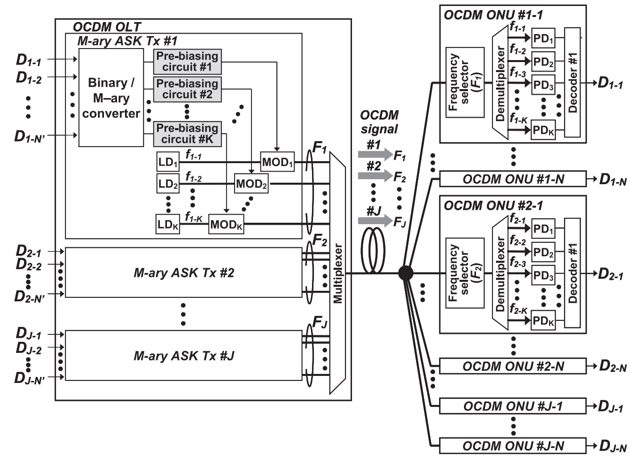

Fig. 10 Future optical access network based on spectral M-ary ASK OCDM.

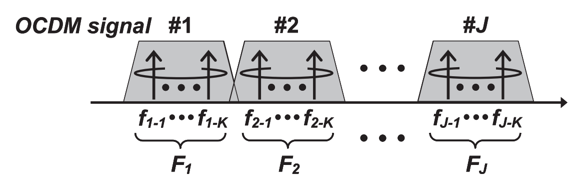

Fig. 11 Frequency allocation.

peak-to-peak voltages of the pre-biased M-ary data are V_π as described in the previous session, the instant optical power of the k_{th} frequency component, $P'_k(i)$, is expressed as follows

$$P'_k(i) = 2P \cdot \frac{M(i)}{M-1} \tag{11}$$

By substituting Eqs. (8), (9), and (11) into Eq. (7), the BER characteristics against P when the proposed transmitter is used are obtained.

3.4.2 Performance Evaluation

The BER characteristics at the data rate of 1.25 Gbit/s are calculated for cases employing the conventional and proposed transmitters. As orthogonal codes, Hadamard codes with the length, K, of eight are used. This means that the number of multiplexed binary data streams which equals that of accommodated users/services, N, can increase up to seven ($= K - 1$) for the conventional transmitter. With the increase of N, M becomes larger. When N is seven, M takes maximum value five. For the proposed transmitter, on the other hand, the number of multiplexed binary data stream, N', is always seven ($= K - 1$) regardless of that of accommodated users/services, N, due to the dummy data input. Therefore, M remains constant at five while N varies from 1 to 7.

Figure 9 shows the results. In the case of the conventional transmitter, the BER deteriorates as N increases mainly due to the MAI that originates from the nonlinearity of M-ary ASK. On the contrary, the BER remains unchanged regardless of the value of N due to the effect of inputting dummy data. When the number of multiplexed users/services is seven, the receiver sensitivity for the BER of 1×10^{-12} is higher by 7.6 dB compared to the case using the conventional transmitter.

3.4.3 Application Area

Figure 10 shows a configuration of future access network based on specral M-ary ASK OCDM. One OCDM optical line terminal (OLT) comprising M-ary ASK transmitters and a multiplexer is connected to OCDM optical network units (ONUs). The j_{th} ($j = 1, 2, \cdots, J$) transmitter corresponds to ONU $\#j-1 \sim \#j-N$ and launches pre-biased M-ary ASK optical signals which frequencies range from f_{j-1} to f_{j-K} within the j_{th} frequency band, F_j. Here, J is the total number of M-ary ASK transmitters. N can increase up to the maximum number of multiplexed binary data streams, N', with the code length of K. The multiplexer combines M-ary ASK optical signals from all the transmitters and simultaneously generates spectral M-ary ASK OCDM signals $\#1 \sim \#J$ which frequency allocations are shown in Fig. 11.

The ONUs are the same configuration as that of the OCDM Rxs in Fig. 2 excluding a frequency selector placed ahead of the demultiplexer. The frequency selector in ONU $\#j$-1 $\sim \#j-N$ passes only the desired OCDM signal $\#j$. With tunable frequency selector and reconfigurable electrical decoder according to the assigned orthogonal codes, a single kind of ONU can be used for all ONUs.

Maximum number of accommodated users/services is $J \times N'$. For example, assuming J of five and the use of Hadamard codes with K of eight corresponding to N' of seven ($= K - 1$), the number of users/services can exceed 32 which is the number of branches in current GE-PON.

Under the above assumption, the acceptable transmission loss for the BER of under 10^{-12} is calculated using the obtained BER characteristics in the previous section. The power of each frequency component at the OLT end is 5 dBm assuming that of the LD output is 15 dBm and the total loss in the OLT is 10 dB. The total loss is derived considering the loss in the Mod of 7 dB including modulation loss and that in the demultiplexer of 3 dB.

From Fig. 9(b), the minimum power of each frequency component at PD input for the BER of under 10^{-12} is -22.6 dBm. Therefore, assuming the losses in frequency selector and demultiplexer are 2 and 3 dB, respectively, the transmission loss of 22.6 dB is allowed. This value can be expanded with the use of avalanche photo-diode and/or optical amplifier.

4. Conclusion

We proposed a novel transmitter configuration that provides spectral M-ary ASK OCDM with flexible scalability. Due to the pre-biasing circuits and the dummy data input, the number of accommodated users/services can be increased flexibly without changing the active transmitter. The feasibility of the proposed transmitter is verified theoretically using the formulas we established. The transmitter enables us to realize flexibly scalable future optical access networks where diverse bandwidth-guaranteed services of over the gigabit per second level are expected to be demanded and the total throughput that far exceeds the limitation of TDM based systems is required.

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