A Novel Energy Efficient Transmission Scheme for Short-Range Data Communication

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ABSTRACT

Two, three, and four channels Mapping Multiplexing Technique (MMT) is demonstrated to increase the data capacity of multilevel intensity modulated transmission formats to 2, 3 and 4 bits per symbol with a substantial reduction in energy consumption. The paper outline the N-channel MMT design metrics consideration influence on the performance enhancement of higher order amplitude modulated systems in terms of energy efficiency and signal to noise ratio per bit.

Keywords: digital data Communication, energy efficiency, multilevel signalling.

1 INTRODUCTION

The ability to transfer guided light by the aid of fiber optic communication technology shapes the backbone of the whole internet and data transmission industry. Data centers are experiencing a rapid increase in the amount of network traffic that they have to sustain due to cloud computing and scaling with the processing speed of CMOS technology[1]. Recently, IEEE 802.3bm Task Force (TF) have investigated the technical performance and feasibility for 4-PAM, 8-PAM and 16-PAM multilevel formats on Single Mode Fiber (SMF) to be standardized to the existing 100 GBASE-LR4[2]. The reports demonstrated the deployment practicality of 4-PAM, and 8-PAM in the context of being an upper boundary limit for the modulation order due to the exponential increase in penalties with the increment in the M-PAM number of levels in the presence of impairments [3].

Higher order amplitude modulated formats such as 4, 8 and 16-PAM modulation format are of practical interest to expand the capacity for optical interconnects. Fig. 1 shows the exponential increase in the data traffic for metropolitan networks compared to the longhaul networks where the estimated growth factor will be 2x times and by 2018 it will account for 62% of the global IP traffic demand[4]. In metropolitan networks, one of the significant IP consumers are data centers where the data centers traffic demand will reach 8.6 zettabyte by 2018. On the other side, as more and more data centers and processing cores are on demand, as the power consumption is becoming a challenging issue. Greenpeace's Make IT Green report [5], estimates that the global demand for electricity from data centers was around 330bn kWh in 2007. This demand is projected to triple by 2020 (more than 1000bn kWh). Hence, it is desirable to meet this demand by simultaneously reducing the energy consumption per bit which will reflect a lower cost per transported bit of information.

It is the interest of this paper to present a two, three, and four channel Mapping Multiplexing Technique (MMT) in order to increase the data capacity of multilevel intensity modulated transmission formats to 2, 3 and 4 bits per symbol with a reduction in power penalty[6-7]. It is verified based upon the findings of extensive theoretical and empirical research that, MMT is able to offer reduced average energy consumption per bit and per symbol.

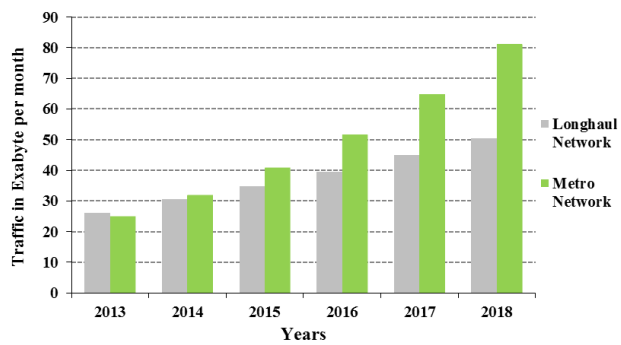

Fig. 1 Global IP data traffic growth for metropolitan and longhaul networks [4].

2 MMT STRUCTURE MODEL

Fig. 2 depicts the waveform structure and the constellation diagram for a 4-channel MMT system; the MMT symbol can be translated to two time independent consecutives one-dimensional constellation. The MMT transmitter multiplexes the data from N-channels using MMT mapping algorithm [6-7]. Each channel is composed of 50% RZ-OOK bit stream, which will be mapped to a unique MMT symbol. The mapper modulator unit generates two consecutive slot waveforms in the form of $X_K = [x_{k,\Delta 1}(t_i), x_{k,\Delta 2}(t_{i+1})]$.

The MMT waveform generator can be expressed mathematically as

$$x_{k,\Delta S}(A_{m,\Delta S},t) = \begin{cases} A_{m,\Delta S}\, W_{T_{sym}}(t-\frac{(S-1)}{2}) & for\ \ (S-1)\frac{T_{sym}}{2} \le t \le \frac{S.T_{sym}}{2} \\ 0 & otherwise \end{cases} \quad (1)$$

where each k represents a MMT symbol from a total of X_K symbols, $W_{T_{sym}}$ is the MMT symbol duration and ΔS is the slot index where $\Delta S = \{\Delta 1, \Delta 2\}$.

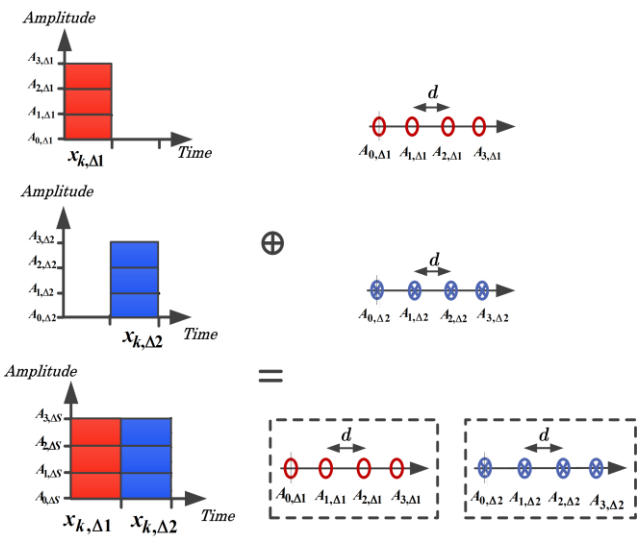

Fig. 2 A waveform representation for the Euclidean superposition of a 4-channel MMT signal with its corresponding constellation.

3 ENERGY MODEL

The energy efficiency has been widely investigated for optical communication systems [8]. The average energy per bit is a useful measurement peculiarity to evaluate energy consumption for advanced modulation schemes since it can be scaled to highlight the energy consumption in different networks. In addition, an energy efficient modulation scheme has a direct impact on optical communication as it can be rendered for a longer fiber reach and/or a reduction in transceiver launched power.

3.1 Average Energy for MMT symbol

The MMT $X_k(t)$ signal waveform can be represented by

$$X_k(t) = x_{k,\Delta 1}(t) + x_{k,\Delta 2}(t) \quad (2)$$

by substitution in Eq. (2) into Eq. (1) $X_k(t)$ will be

$$X_k(t) = \begin{cases} x_{k,\Delta 1}(t) = A_{m,\Delta 1} W_{T_{sym}}(t), & 0 \le t \le \frac{1}{2}T_{sym} \\ x_{k,\Delta 2}(t) = A_{m,\Delta 2} W_{T_{sym}}(t-\frac{1}{2}), & \frac{1}{2}T_{sym} \le t \le T_{sym} \end{cases} \quad (3)$$

where $W_{T_{sym}}(t)$ is the MMT pulse duration, $A_{m,\Delta 1}$ and $A_{m,\Delta 2}$ denote the set of amplitude levels associated with slots $\Delta 1$ and $\Delta 2$, respectively. The amplitude value per slot ΔS can be expressed as

$$A_{m,\Delta S} = (m)d \qquad , m = \{0,1,....,(M_{\Delta S}-1)\} \quad (4)$$

where d is the minimum Euclidean distance between adjacent signal points.

The energy in MMT symbol $X_K(t)$ can be expressed as

$$E_K = \int_{-\infty}^{\infty} A^2{}_{m,\Delta S}\, W_{T_{sym}}(t-\frac{\Delta S-1}{2})dt$$

$$= \int_0^{\frac{T_{sym}}{2}} A^2{}_{m,\Delta 1} W(t)dt + \int_{\frac{T_{sym}}{2}}^{T_{sym}} A^2{}_{m,\Delta 2} W(t-\frac{1}{2})dt$$

$$= (A^2{}_{m,\Delta 1} + A^2{}_{m,\Delta 2})\ \xi_T \quad (5)$$

where ξ_T is the unit energy associated with pulse duration T_{sym}, since the MMT symbol is composed of two slots. As shown in Fig. 2 (the graphical representation for a 4-channel MMT) the MMT symbol can be translated to two time independent consecutives one dimensional constellation [6-7].

The MMT average energy can be interpreted as the superposition of a two consecutive non-overlapping one dimensional constellation, which can be referred as a method of Euclidian superposition.

The average energy per slot ΔS can be expressed by

$$E_{avg,\Delta S} = \frac{\xi_T}{2M_{\Delta S}} \sum_{i=0}^{M_{\Delta S}-1} A^2{}_{i,\Delta S} = \frac{d^2\xi_T}{12}(M_{\Delta S}-1)(2M_{\Delta S}-1) \quad (6)$$

where $M_{\Delta S}$, ($M_{\Delta S} = \{2^1, 2^2, ..., 2^{\ell_{\Delta S}}\}$) represents the number of each slot level.

The average energy per MMT symbol is

$$E_{avg} = \frac{d^2\xi_T}{M_{\Delta 1}M_{\Delta 2}} \sum_{i=0}^{M_{\Delta 1}-1} \sum_{j=0}^{M_{\Delta 2}-1} (A^2{}_{i,\Delta 1} + A^2{}_{j,\Delta 2})$$

$$= \frac{d^2\xi_T}{6}[(M_{\Delta 1}-1)(2M_{\Delta 1}-1) + (M_{\Delta 2}-1)(2M_{\Delta 2}-1)] \quad (7)$$

For an equivalent number of levels per slot where ($M_{\Delta 1} = M_{\Delta 2} = M_{\Delta}$), then

$$E_{avg} = \frac{d^2\xi_T}{3}(M_{\Delta}-1)(2M_{\Delta}-1) \quad (8)$$

Table 1: Average energy comparison between 2-, 3- and 4-Channel MMT and 4-, 8- and 16-PAM

Scheme	Average Energy Formula(E_{avg})	2 Bits/symbol	3 Bits/symbol	4 Bits/symbol
N-channel MMT	$=[(M_{\Delta 1}-1)(2M_{\Delta 1}-1)+(M_{\Delta 2}-1)(2M_{\Delta 2}-1)]\frac{d^2\xi_T}{6}$	$d^2\xi_T$	$4d^2\xi_T$	$7d^2\xi_T$
M-PAM	$=(M^2-1)\times\frac{d^2\xi_T}{12}$	$1.25d^2\xi_T$	$5.25d^2\xi_T$	$21.25d^2\xi_T$
Scheme	**Average Energy Per Bit Formula($E_{avg/bit}$)**	**2 Bits/symbol**	**3 Bits/symbol**	**4 Bits/symbol**
N-channel MMT	$=[(M_{\Delta 1}-1)(2M_{\Delta 1}-1)+(M_{\Delta 2}-1)(2M_{\Delta 2}-1)]\times\frac{d^2\xi_T}{6\log_2(M_{\Delta 1}M_{\Delta 2})}$	$0.5d^2\xi_T$	$\cong 1.33d^2\xi_T$	$1.75d^2\xi_T$
M-PAM	$=(M^2-1)\times\frac{d^2\xi_T}{12\log_2(M)}$	$0.625d^2\xi_T$	$1.75d^2\xi_T$	$\cong 5.31d^2\xi_T$

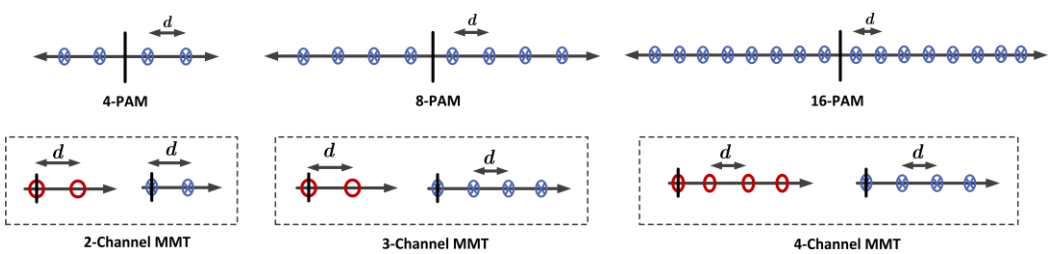

Fig. 3 Signal space constellation for 4, 8, and16-PAM and 2,3, and 4-channel MMT.

3.2 N-Channel MMT and M-PAM Energy Efficiency Comparison

Table 1 shows the comparison between MMT and M-PAM systems in terms of average energy per symbol and per bit for transmission of 2, 3 and 4 bits/symbol. The average energy for each technique can be calculated by taking the average energy per symbol in the constellation diagram shown in Fig. 3. The average symbol energy of each resultant MMT signal depends on the superposition of the allocation ratio of energies for the squared amplitude of waveform $|x_{k,\Delta 1}|^2$ and $|x_{k,\Delta 2}|^2$ modulated signals, denoted by $E_{avg,\Delta 1}$ and $E_{avg,\Delta 2}$, respectively. Assuming AWGN, the minimum Euclidean distance d considered a good quantification for the signal error probability [9].

With respect to the energy required per bit, MMT with 2, 3 and 4 bits/symbol can offer around 25%, 32% and 203% ($5.31d^2\xi_T \rightarrow 1.75d^2\xi_T$) increase in theoretical bit rate transmission compared to its equivalent 2, 4 and16-PAM, respectively. Note that, it is adequate to evaluate the MMT energy efficiency with M-PAM modulation formats by employing the same minimum Euclidean distance d for both. The more energy efficient transmission scheme can be translated as the one which minimizes the energy, whether average energy or average energy per bit, while keeping the Euclidean distance constant [9].

Fig. 4 shows a graphical analysis in the form of a comparison between 2,3 and 4 bits per symbol transmission using MMT and PAM technique in terms of the amount of energy per bit (in joule per bit) at various bit rates.

For energy constrained systems, transmission of 2, 3 and 4 bits per symbol using MMT system merit 20%, 24% and 67% energy per bit reduction in comparison to 2, 4 and 16-PAM modulation format, respectively. The performance levels of these results can be associated with the signal to noise ratio per bit at a given symbol error rate. Also, the increase in the data rate is associated with the decrease in overall amount of energy per bit since its dependent upon the bit duration. Hence, the increase in data rate is favorable from an energy efficiency perspective.

4 THEORETICAL SYMBOL ERROR PROBABILITY

Under the assumptions that the noise is additive, white and stationary, a theoretical lower bound model for the Symbol Error Probability (SEP) is developed for N-Channel MMT, based upon the MMT waveform. Assuming that all symbols M_s are equipropable, the symbol error rate can be derived through

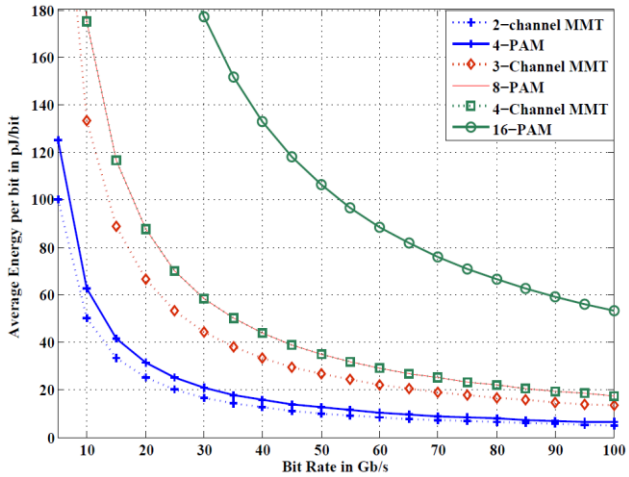

Fig. 4 Bit rate versus average energy per bit for 4,8, and16-PAM and 2, 3, and 4-channel MMT.

$$SEP = \frac{1}{M_s}\sum_{m=1}^{M_s} P[error|m\,sent] \quad (9)$$

where M_s is the number of level per symbol and P is the propability of receiving symbol with error, given that symbol m have been sent. The SEP is dependent upon the number of levels per slot and on the minimum euclidean distance.

The minimum euclidean distance is derived and expressed with respect to the average energy per bit as

$$d = \sqrt{\frac{6\log_2(M_{\Delta1}M_{\Delta2})}{[(M_{\Delta1}-1)(2M_{\Delta1}-1)+(M_{\Delta2}-1)(2M_{\Delta2}-1)]}.E_{avg/bit}} \quad (10)$$

The $\frac{E_{avg/bit}}{N_o}$ is equivelent to the signal to noise ratio per bit (SNR per bit) and can be expressed as

$$SER = \frac{[2(M_{\Delta1}-2)+2(M_{\Delta2}-2)+4]}{M_{\Delta1}M_{\Delta2}} * Q\left(\sqrt{\frac{6\log_2(M_{\Delta1}M_{\Delta2})}{[(M_{\Delta1}-1)(2M_{\Delta1}-1)+(M_{\Delta2}-1)(2M_{\Delta2}-1)]}.\frac{E_{avg/bit}}{N_0}}\right) \quad (11)$$

Where $Q(.)$ is the integral of the Gaussian probability density function with zero mean and power spectral density= $\frac{1}{2}N_0$, defined by $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{(\frac{-y^2}{2})}dy$.

Fig. 5 illustrates the exact theoretical difference in SNR per bit between 4, 8, and 16-PAM and 2, 3, and 4-channel MMT obtained from Eq. (11). At SEP=10^{-9} , the difference between 2-channel MMT and 4-PAM is around 3.8 dB, and

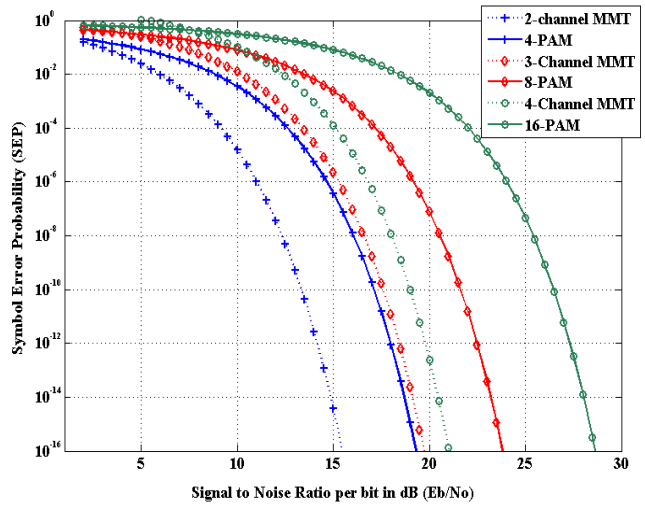

Fig. 5 Signal to noise ratio per bit versus symbol error probability for 4, 8, and 16-PAM and 2, 3, and 4-channel MMT.

between 3-channel MMT and 8-PAM is around 4 dB, while the difference between 4-Channel MMT and 16-PAM is around 7.4 dB. These results highlight the SNR per bit advantage of the N-Channel MMT schemes over M-PAM formats to further support the performance consideration in the proposed schemes.

5 CONCLUSION

In this paper, we proposed and discussed the transmission of 2, 3 and 4 bits/symbol utilizing MMT transmission system as an energy efficient alternatives to M-PAM systems, with possible future application in metro and short-haul networks. The results show a clear advantage of the proposed MMT technique over PAM in terms of energy efficiency and SNR per bit.

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