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100 Gb/s Ethernet over multimode fiber based on MIMO with spatial pre-coding

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Abstract: We propose a novel MIMO scheme over multimode fiber, acting as a distributed random code generator fed by spatial codes, using silicon photonics in the transmitter and maximum-likelihood electronic detection in the receiver.

***Index Terms*— Optical MIMO, Maximum likelihood decoding, Integrated Optics, Phase shift keying (PSK), Optical fiber communication.**

I. Introduction

In light of the large-scale proliferation of 10 GbE (10G-BASE-SR) optical transmission in datacom applications, interest has recently peaked in extending the 802.3 suite of standards to 100 GbE over Multi Mode Fiber (MMF), currently envisioned to be realized by means of CWDM technology. Here we explore an alternative optical Multiple-Input-Multiple-Output (MIMO) transmission architecture for short-range 100 GbE over MMF, based on the paradigm that the MMF channel matrix random nature provides a unique opportunity to generate and manipulate random codes, reliably conveying vast amounts of information, in parallel over a single MMF interconnect. In this paper we extend and further improve the performance of our recently proposed novel optical technique [1] for massive parallel transmission over MMF. In effect we convert the fiber into an extended random code generator providing a closer-to-ideal novel opto-electronic realization of Shanon's mathematical construct of *random* coding [2].

Our approach capitalizes on the statistical multi-path characteristics of the MMF propagation modes [3,4], as further clarified in our recent research [**Error! Bookmark not defined.**] pertaining to MMF channel models over relatively short distances, accounting for intermodal coupling but not for intermodal dispersion. This paper builds upon those MMF MIMO models, as well as upon our initial random coding concept [1], substantially improving the BER performance of our configuration. The latter is based on the new insight that spatial coding [5] applied at the input of the optical MIMO system exerts a beneficial effect upon the quality of the random codes generated at the output side. Further to the novel optical realization of the communication-theoretic concepts of spatially coded signaling, the opto-electronic feasibility of our system is made possible at this juncture by advances in opto-electronic components, in particular silicon photonics [6], using potentially simpler optics, eliminating the multiple CWDM sources in favor of a single CW laser coupled to a silicon-based array of high-speed PSK waveguide modulators.

II. Concept and System Architecture

Consider a multimode fiber configured as a MIMO system, randomly coupling n_T modulated sources at its input and terminated in n_R detectors at its output (Fig. 1). The transmitter opto-electronic structure comprises n_T optical input ports synchronously modulated by binary PSK, each at bitrate $T^{-1} = 12.5\,\text{Gb/s}$ (10 GbE + 2.5 Gb/s overhead), injecting the optical field complex amplitudes into the MMF, randomly coupled to the propagation modes of the MMF. The multiple PSK modulated optical sources are realized as silicon-based plasma-effect modulators – a recently emerging technology amenable to compact integration.

In each symbol interval T, a k-bit message, $\mathbf{m} \equiv m_1 m_2 ... m_k \in \mathbf{Z}_2^k$ (with $\mathbf{Z}_2 \equiv \{0,1\}$), selected out of a space of $M = 2^k = 2^{10}$ messages, is initially encoded as an n_T-dim. binary bitstring $\mathbf{g} \equiv g_1 g_2 ... g_{n_R} \in \mathbf{Z}_2^{n_R}$ with $n_T \geq k+1$, selected out of a Gilbert-Varshamov code $\mathcal{G}$ of specified minimum distance as discussed below. The input binary codewords are then mapped into bipolar complex field vectors $\underset{\sim}{\mathbf{E}}^s$, with phase-modulated elements $\pm A$ respectively launched into the fiber input ports,. The complex field vector incident at the n_R detectors is $\underset{\sim}{\mathbf{E}}^d = \mathbf{H}\underset{\sim}{\mathbf{E}}^s$, with $\mathbf{H}$ the MMF random channel matrix of size $n_R D \times n_T$ and D the number of speckle/modal optical Degrees of Freedom (DOF) at each detector. Upon optical detection, the components of the received field are absolute-squared, summed over the DOFs and one-bit quantized with thresholds B_i selected offline such that $\Pr\{c_i = 1\} = 0.5$

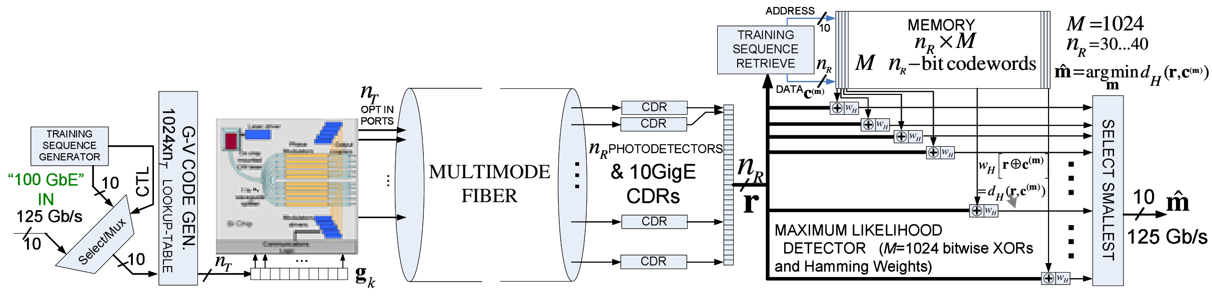


Fig. 1. 100 Gbps MIMO over MMF with random coding naturally generated by MMF channel matrix statistics, assisted by G-V precoding.

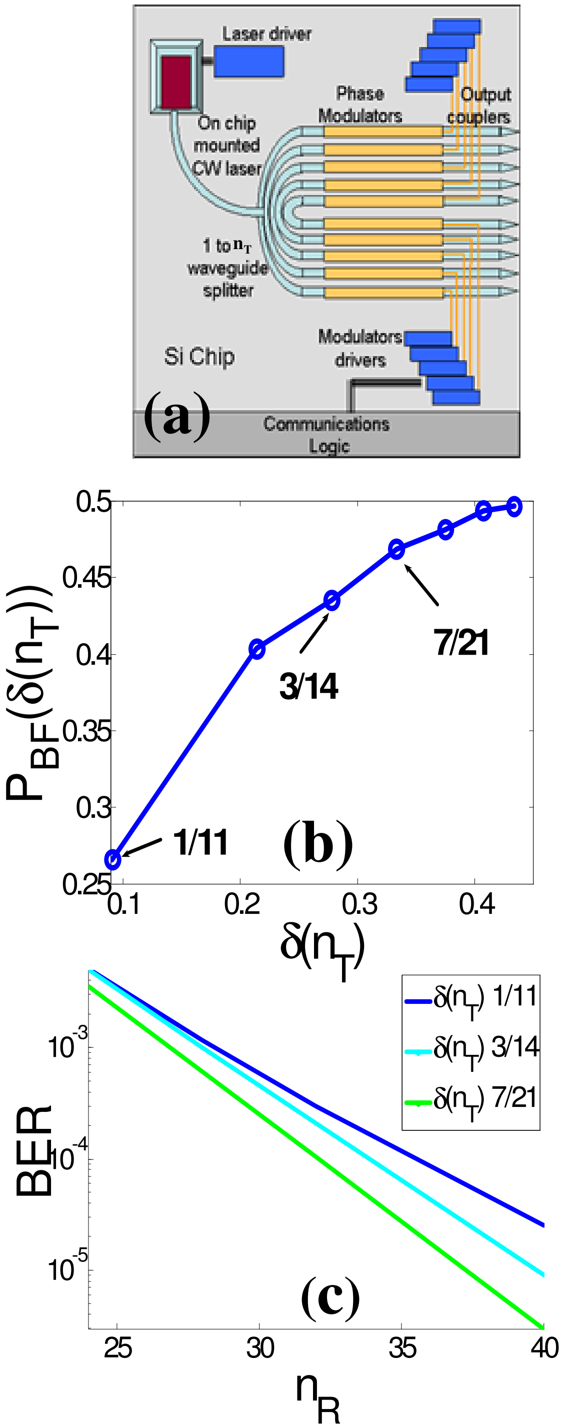
The detected n_R-bit codewords $\mathbf{c} = c_1 c_2 ... c_{n_R}$ form realizations of a random code $\mathbb{C} \subset \mathbf{Z}_2^{n_R}$ of size M . As the channel matrix $\mathbf{H}$ is random, so will be the code $\mathbb{C}[\mathbf{H}]$. End-to-end, we have synthesized a coded vector binary channel, $\mathbf{r} = \mathbf{c} \oplus \boldsymbol{\varepsilon}$, $\mathbf{c} \in \mathbb{C}[\mathbf{H}]$, with $\boldsymbol{\varepsilon}$ the error vector induced by the thermal noise.

The receiver side electronic ML processing and the channel matrix estimation procedure illustrated in Fig. 1, were discussed in [1]. The main novelty here consists in the introduction of a transmit-side spatial code $\mathbb{G}$, resulting in improved performance of the receive-side "Shanon" random code $\mathbb{C}$. Notice that in the initial proposal [1] the input vectors $\mathbf{m}$ were *uncoded*, using the minimum number of physical input ports $n_T = k+1 = 11$ (including a reference input to remove PSK phase ambiguity). It was shown that *the fiber acts as a distributed random code generator*, with the modal fluctuations naturally generating random codewords $\mathbf{c} \in \mathbb{C}$ at the fiber output, however the code joint statistics was outside the designer's control.

Here we significantly improve system performance by deliberately introducing spatial coding redundancy at the *input* side, replacing the uncoded input messages of [1] with a spatial code, $\mathbb{G}$, requiring to increase the number of input ports to $n_T > k+1$ in excess of the minimum necessary to carry the M messages. Such novel application of a controlled spatial redundancy at the input side embeds our k-dim. transmission message subspace into a higher n_T-dim space. Coupled with the natural random coding effect induced by the fluctuations of channel matrix, $\mathbf{H}$, this architectural modification is shown here to substantially *reduce the correlation* between the randomly generated codewords at the fiber output, generating a code $\mathbb{C}$ with nearly independent codewords, hence improving BER and/or link budget.

To be effective, the input spatial code introduced here requires that its codewords be sufficiently spread apart, i.e. their minimum normalized Hamming distance, $\delta(n_T) \equiv \min_{\mathbf{g},\mathbf{g}'} d_H(\mathbf{g},\mathbf{g}')/n_T$, be equal to a substantial fraction, of the max possible distance n_T. Let $p_{BF}(\delta) \equiv \Pr\{[c_\mathbf{m} \oplus c_{\mathbf{m}'}]_\beta = 1\}$ be the prob. of a bit flip (BF) in any bit position between two output codewords, s.t $d_H(\mathbf{g},\mathbf{g}')/n_T = \delta(n_T)$. The simulation presented in Fig. 2(a) demonstrates that $p_{BF}(\delta(n_T)) \to 0.5$ i.e. a perfect random code is asymptotically attained upon increasing $\delta(n_T)$. Fig. 2(b) shows the Gilbert-Varshamov Sphere-Packing bound on $\delta(n_T)$ [5]. Finally, Fig.2(c) evaluates BER vs. the output detectors count, indicating that the error rate performance is successively improved upon increasing $\delta(n_T)$, over the three analyzed cases $\delta(n_T) = 1/11,\ 3/14,\ 7/21$.

We conclude that the random codes naturally induced by the MMF channel matrix statistics, further assisted by spatial input coding with specified minimum distance, as proposed and analyzed here for the first time, enable ultra-high bitrate parallel transmission of 100 GbE, with manageable complexity, of n_T independently modulated signals all superimposed into the MMF at the same wavelength,



Fig, 2. (a) Optoelectronic multi-port phase modulator (n_T = 11, 14, 21 ports) based on Si photonics. (b) Bit-flip prob. vs. normalized min. distance $\delta(n_T)$ defined as Hamm. distance over n_T .(c)BER performance for three systems with $\delta(n_T)$ = 1/11, 3/14, 7/21 assuming raw per bit error prob. P_ε = 0.01 .

REFERENCES

1 . M.Greenberg, M. Nazarathy, M. Orenstein, CLEO 2007. .

2 C.E. Shannon, Bell Sys. Tech. J., **27**, 379-423 and 623-656, (1948).

3 Y.Yadin, M.Orenstein, J.Lightwave Technol. **24**,380-386 (2006).

4. M.Greenberg, M. Nazarathy, M. Orenstein LEOS 2006 WX5.

5. R. G. Gallager, "Information theory and reliable communication", New York, Wiley, 1968.

6. Xu, B. Schmidt, J. Shakya, M. Lipson , Optics Express **14**, 9430-9435 (2006).