Modeling and experiments for reliable operation of single-mode transceivers over multimode fiber

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Abstract: We define metrics to predict the transmission performance of SMF transceivers over MMF links at 40Gbps and 100Gbps based on simulation and experiments.
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1. Introduction

Several campus networks using legacy OM1 or OM2 deployed several decades ago in military bases, schools and many other commercial premises, are still in operation. They run typically at data rates between 100 Mbps (100BASE-FX) to 1 Gbps (1000BASE-SX/LX/LH) for distances between 100m to 2 km. Although there is a need to upgrade the networks to higher data rates, for some legacy infrastructure there are considerable challenges. Often, the cost of deploying new optical fiber is prohibitively expensive. For others, the deployment process itself is too disruptive to ongoing operations.

Recently developments of efficient mode field adapters (MFAs), that optimize the coupling between fundamental modes of SMF and MMF can provide a significantly faster and less expensive upgrade path for those legacy networks to data rates of hundreds or thousands of times faster. Although, 40G and 100G transmission from single-mode 1300 nm transceivers over MMF using MFAs has been reported [1-2], the reliability of these hybrid networks needs further evaluation.

In this paper, we theoretically and experimentally investigate the causes of the performance degradation of single-mode signals over MMF, including the high modal dispersion of MMF at 1300 nm, the effect of coupling losses, and multi-path interference (MPI). Our theoretical model compares the effect of data rate, e.g., 10Gbps vs 25Gbps per lane and the impact of the error correction codes.

For experimental validation of our findings, 40GBASE-LR4 and MSA 100G CWDM4 transceivers operating over OM1 and OM2 fiber are tested.

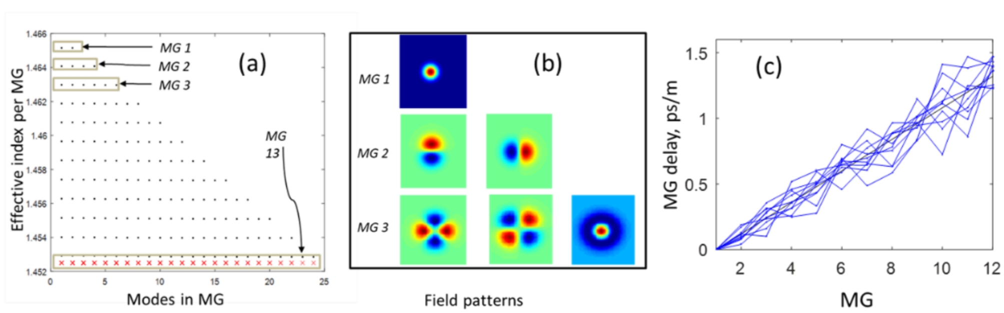

Fig. 1 Modeled MMFs showing; (a) effective indices, (b) intensity patters, MG1 or LP01, MG2 or LP11s and MG3 and, (c) mode group delays

2. Channel Modeling: theoretical background and results

Reliable SM transceiver (xcvr) operation over MMF requires MFAs that optimize the coupling to one mode or MG in the MMF. MFAs could consist of tapered fibers or waveguides, lens adaptors, or spatial mode converters. In this investigation we use MFAs based on multi-plane light conversion (MLP), which can provide optimized conversion from the SMF or SM transceiver to the MMF's fundamental mode [3-4].

A 50-micron grade-index MMF has ~380 propagating modes grouped in 19 mode groups (MGs) in the 850 nm window, and less than 150 propagating modes grouped in about 12 mode groups at 1300 nm. Fig.1 shows; (a) the propagation constant of some of the mode field patterns, (b) and MG of these modes computed using FIMWAVE for the mode profiles and, (c) a modified Wentzel–Kramers–Brillouin (WKB) method [5] for the propagation constant and group delays.

Fig. 2 shows the modeled channel where the xcvr parameters such as laser RIN, rise time, and optical modulation amplitude (OMA) among others are obtained from IEEE link models or multi source agreement (MSA) such as in the case of 100G CWDM4. In the modeled channel, a SMF connects the transceiver to the MFA input. The output of the MFA ideally excites only the MMF fundamental mode as shown in Fig. 2 before C3. The light passes through connector C3 and depending on the losses, different degrees of mode mixing can be produced.

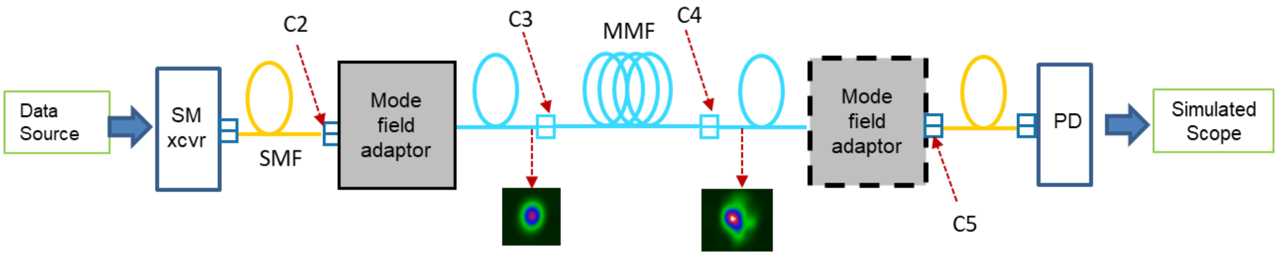

Fig. 2 Modeled channel.

The coupling ratio resultant can be obtained from the overlap integral of the MMF normalized field amplitude patterns, $\psi_{Gi}(r,\phi)$ and at the field amplitude patterns of a SMF with core radius, R, given by,

$$c(R,\Delta x,\Delta y)_{g,i} = \int_y\int_x \psi_{g,i}(x,y)\psi_{g=1,i=1}(R,x-\Delta x,y-\Delta y)dxdy,$$

where i is the index of the modes that are included in the mode group, MG = g, Δx and Δy represent the lateral misalignments of the connectors. The value of the total coupled power in each MG, g is given by,

$$P_g = \sum_i \left|c_{g,i}(R_{Tx},\Delta x,\Delta y)\right|^2.$$

Fig. 3 shows the coupling power as a function of the connector offset up to 7 um, which is typically associated with a 0.75 dB loss for an encircle flux compliant launch condition.

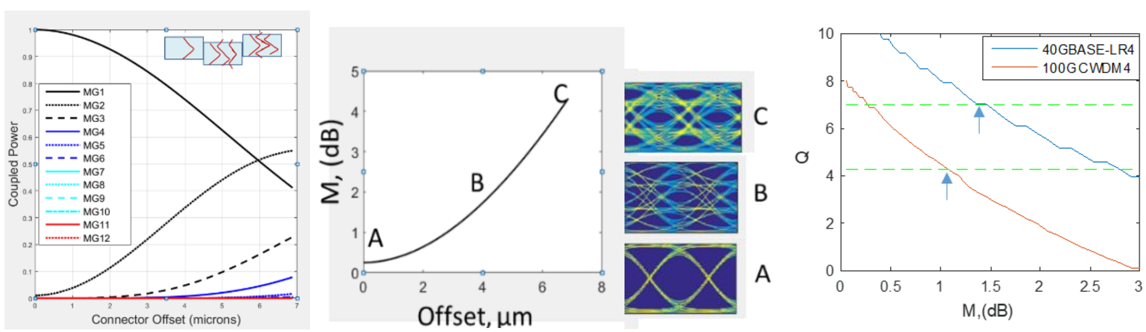

Fig. 3 (a) Coupled power in the fundamental mode vs connector offset., (b) M as a function of offset, (c) eye diagrams for different M values. (d) Simulation result for 40GBASE-LR-4 and 100G CWDM. Green lines indicate the Q values limits (7.03 and 4.26) for both applications.

A metric to evaluate the performance of the channel is the ratio of power in the fundamental mode, g=1 to the total optical power in the fiber,

$$P_t,\ \ M=-10\log_{10}(P_g/P_t)$$

Fig. 3(b) shows the variation of M as a function of radial offset between connectors. The simulated normalized eye diagrams for different M values are shown in part (c) of the same figure. Along the fiber between the two connectors, C3 and C4, the model assumes that there are not macro or micro bends introducing more mode coupling. After C4, part of the light traveling in MG>1, coupling back to the fundamental mode (Fig. 2). Due to the high coherence length of SM lasers this coupling back to the fundamental mode introduces dispersion and interference in the signal. The Q factor as a function of M, for 40GBASe-LR4 and 100G CWDM-4 for an OM2 channel of 500m is shown in fig. 3(d).

This graph indicates that for both systems to operate free of error, it should operate with M< 1.5 dB. It shows that 40GBASE-LR can produce higher Q factors due to the lower base data rate (more robust to modal dispersion). However, due to the higher Q factor requirement for BER <1E-12 the advantage is not as significant. So far, the model assumes that the fiber in the channel is not moved, bent or twisted.

3. Experimental

Modeling using the worst-case parameters for 40G and 100G transceivers, shows the advantages of running the lower speed since slower signals are less affected by dispersion. Experiments implementing the modeled channels support these results. For example, Fig. 4 shows that for 40G operation $M < 1.8$ dB, whereas for 100G operation $M < 1.3$ dB. However, the model assumes that the fiber in the channel is stationary. More experiments on the same channels producing small bending and twist in the fibers shows the opposite result. Under those conditions, the 40G channels become significantly more sensitivity to perturbations, increasing BER from <1E-12 to 1E-10 or higher, causing it to fail the BER requirement. Whereas, for the 100G channel the lowest BER started around 1E-11 and increased up to 1E-7, still significantly higher than the required BER < 5E-5.

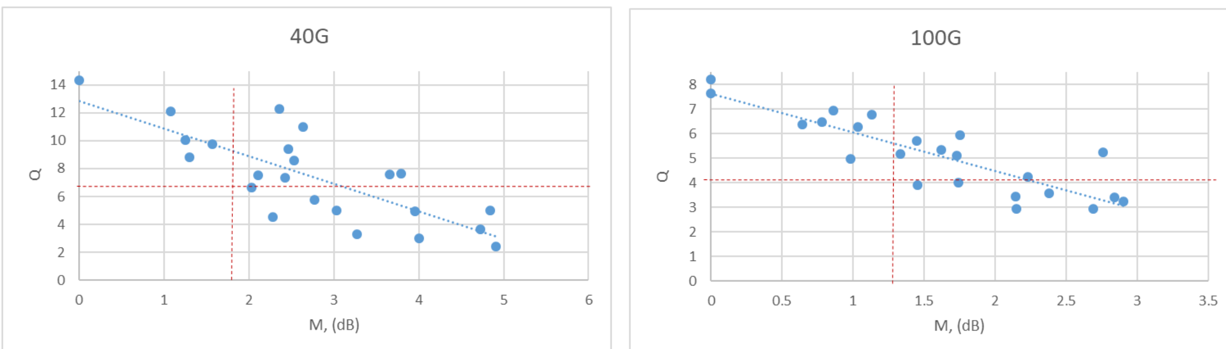

Fig. 4 Experiment to measure Q vs M for (a) 40GBASE-SR4 and(b)100G CWDM4 (c) worst BER of the application when fiber is subject to small macro bend or twist.

4. Discussion, Summary, and Conclusions

The use of SM transceivers for transmission over MMF can provide significant advantages in brownfield upgrades. The demonstration of channels up to 2 km operating at 40Gbps has been previously shown in OFC 2019. In this work, we go beyond previous results, evaluating hero implementations to study the factors that can impact the reliability of the link for potential higher speeds of interest for future network upgrades. A metric, M, that quantifies the power in the fundamental mode vs. the higher order modes compares the performance of different transceivers operating at different data rates. We divided our study into quasi-stationary (channel under test fixed) and transient effects (macro bend or twist). Modeling shows that for quasi-stationary cases, 40GBASE-SR4 which does not use FEC has advantages over 100G CDWM. Both applications can work up to 500 meters for $M < 1.3$, which is feasible with a good quality MFA and low-loss connectivity in the channel. However, even under those conditions, a bend or twist in the fiber can increase M, where for a small fraction of time the higher-order modes beyond $g > 2$ can be excited. If the fiber has core imperfections the increase in mode group delays from $g = 1$ to $g > 2$ a significant number of errors can be produced. The 40GBASE-SR xcvr without FEC cannot operate under those conditions. However, the errors can be easily corrected by the FEC producing a stable channel. This study indicates that the most robust upgrade path for $M < 1.3$, is to use 100G xcvrs with FEC instead of 40G without FEC. The cost difference between these transceivers or switches is small compared with the cost of replacing the cabling infrastructure.

5. References

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