

0.6Tb/s-km Multimode Fibre Feasibility-Experiment using 40-Channel DWDM over Quadrature-Subcarrier Channels

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Abstract: We describe the complete implementation of a 204Gb/s throughput quadrature-subcarrier system for standard within-building 50 μ m multimode fibre applications. The simultaneous transmission of 40 DWDM channels, utilizing in-phase and quadrature 2.55Gb/s subcarrier signals, is shown to be feasible. Complete data and carrier synchronization was provided by a zero-latency, pilot-tone based, phase-locked-loop scheme operating at 5.1GHz.

Index Terms: microwave photonics, optoelectronics, multimode fibre, optical networking

1. Introduction

As customer demand for bandwidth continues to increase, the move towards Tb/s-km Ethernet is becoming more urgent. Applications are expected to embrace both local and metropolitan area networks, and will undoubtedly be internet and data-transfer driven. The majority of within-building legacy links employ multimode fibre (MMF), with typical link lengths around 300m. However, metro links will require significantly greater distances, perhaps up to several km's, while maintaining many Gb/s bandwidth. Previous work (now standardized) has included transmission at the Gb-E rate of 1.25Gb/s over 550m of MMF with long-wavelength (1300nm) laser sources, and over 275m at 850nm [1]. Realization of higher transmission rates and lengths requires techniques capable of overcoming both modal bandwidth and noise limitation problems, e.g. [2]. It is well known that basic WDM techniques and multi-level coding yield improvements in the bandwidth capacity product of MMF links [3], and also that subcarrier multiplexing (SCM) can provide capacity enhancement in single and multi-user networks [4]. This latter advantage is achieved in MMF by using relatively flat regions of its response outside the

nominal modal bandwidth [5]. In this paper, we describe for the first time the comprehensive combination of 2×2.55Gb/s in-phase and quadrature (I&Q) electrical SCM, with 40×DWDM 100GHz ITU-grid channels in the 1550nm window, to demonstrate the feasibility of 204Gb/s throughput over 3km of 50μm GRIN MMF. This system also features complete zero-latency carrier extraction and data synchronization based on a phase-locked loop (PLL) operating at 5.1GHz.

2. Experimental set-up

The experimental setup is shown in figure 1. It comprises a 2×2.55Gb/s conventional I&Q modulator with the additional feature of pilot-tone injection at the receiver 5.1GHz PLL centre frequency, and prescaler-locking of the input data to half the pilot-tone frequency. This setup simulates the transmission of nominal STM-16 SDH/Sonet data. A 40-channel DWDM MMF link provided the overall 204Gb/s capacity. At the transmission end, two pattern generators produced 2^7-1 pseudo-random binary sequences (PRBS's), each at a bit rate of 2.55Gb/s. Conventionally, a 90° hybrid split the 5.1GHz subcarrier into I&Q signals, and two data channels were used to modulate each of these quadrature subcarriers. A particular feature is the re-injection of the 5.1GHz carrier signal, at the point where the quadrature signals are combined to provide a pilot-tone for use at the receiving end. After broadband amplification, this composite signal was passed to a 12GHz-bandwidth Mach-Zehnder (MZ) modulator, which simultaneously controlled the intensities of ten representative frequency-stabilized lasers and additional wavelength-tunable channels, which had all been combined in a commercially-available 40-channel arrayed-waveguide grating (AWG). By this means, all 40 channels on the ITU grid could be used for data transfer. The single-mode fibre (SMF) MZ output was centre-launched into MMF spans ranging from 300m to 3km. Prior experiments had shown that the MMF bandwidth under these conditions was sufficient for transmission of the SCM data over the entire 3km length, as shown in figure 2. Power losses were incurred at various points in the optical system, including 8.5dB loss at the MZ modulator, and up to 9dB in the AWG. At the receiver end, each of the possible 40 channels was wavelength-selected using an electronically-tuned

monochromator, which introduced a further loss of up to 10dB. Use of an erbium-doped fibre amplifier (EDFA) was necessary in this early work, but it is anticipated that more advanced optical components will substantially reduce these losses, and obviate the need for an EDFA. The multi-mode output of the monochromator was passed to a MMF-pigtailed 12GHz-bandwidth PIN photodiode and, after further amplification, passed to the receiver subsystem. As shown in figure 1, this consisted of a 3-way splitter, which divided the signal between the 5.1GHz carrier recovery (CR) PLL, and the two arms of the I&Q demodulator. The PLL output provided the conventional quadrature reference for baseband down-conversion of the subcarrier signals, and also provided direct zero-latency synchronization of the data sequences by means of a further divide-by-two prescaler. By this means, acquisition of the optical signal by the receiver subsystem guarantees synchronization of the data. The demodulated I&Q signals were then passed via 1.87GHz 3dB-bandwidth lowpass filters to two data receivers, which were synchronized by the carrier-locked prescaler output signal. Initial experiments over 300m explored both 10 simultaneous and selected individual wavelengths over the entire ITU grid. When demultiplexed using the monochromator, error-free operation was obtained in every case. Adjacent channel interference effects were investigated and no discernible penalty observed. Subsequently, the MMF link length was increased to 3km, necessitating extra amplification. As an EDFA was readily available, this was used to provide the required broadband gain. Naturally, bandpass electrical amplifiers could have been used had they been available. In addition, many of the components exhibited losses in excess of their specified values. We would expect an optimized link not to require an EDFA. Clearly, with a fully-populated 40-laser array, our experimental link offers 204Gb/s data throughput over 3km. Additional experiments are now in progress to investigate performance for MMF lengths up to 10km.

3. Experimental results

Figure 3a illustrates the recovered eye diagrams for the quadrature channels at 2.55Gb/s each, over 300m in both electrical (back-to-back) and optical domains. As may be seen, the eye diagrams are well-

rendered, and error-free operation was obtained, as might be expected. Subsequently, the MMF length was increased to 3km, and clean eye diagrams again obtained, as shown in figure 3a.

4. Conclusions

We have demonstrated the feasibility of 204Gb/s transmission over 3km of 50 μ m MMF, using 40 \times DWDM channels on the ITU grid. Complete carrier and data synchronization was provided by the use of a pilot-tone, in conjunction with a demodulating PLL and prescaler. In all cases, error-free operation was obtained. Parallel transmission of data and carrier signals should provide skew-free operation in many Ethernet applications with zero-latency. In addition, we believe this to be the highest capacity and length product (0.6Tb/s-km) reported for any single MMF link to date.

5. References

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Figure Captions

Figure 1. Experimental set-up for the transmission of 204Gb/s over 3km MMF

Figure 2: Transfer functions for 300m MMF transmission link (left) and 3km MMF transmission link (right).

Figure 3: Representative recovered I&Q eye diagrams for electrical circuit at wavelengths of 1558.17 nm and 1557.36 nm, a) over 300m, b) over 3km of MMF.

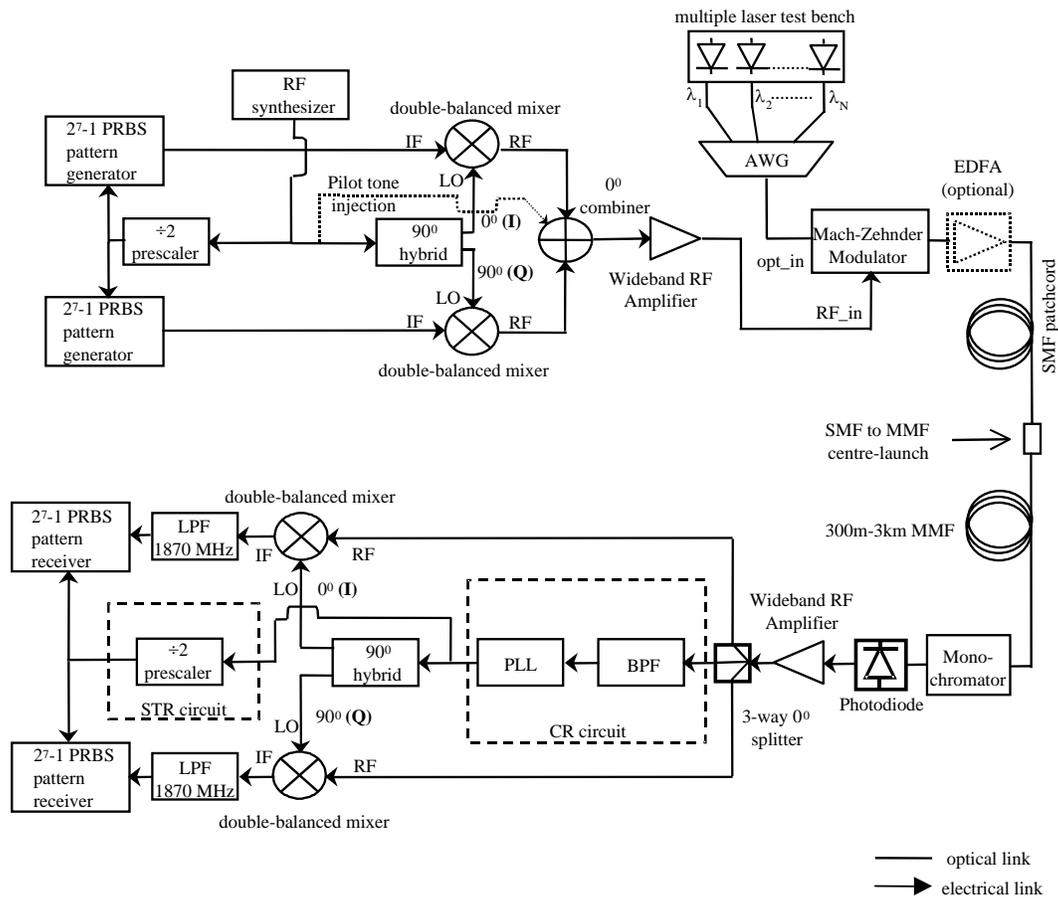


Figure 1

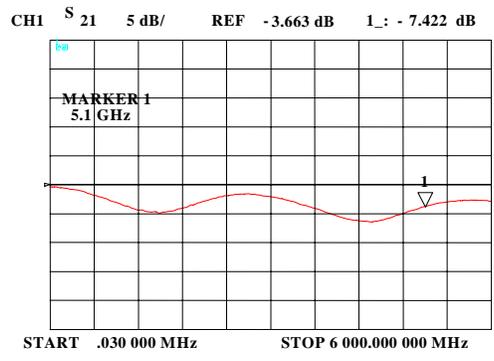
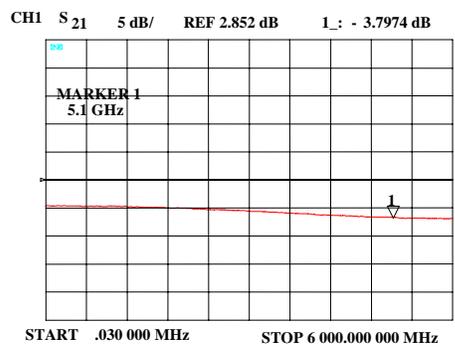
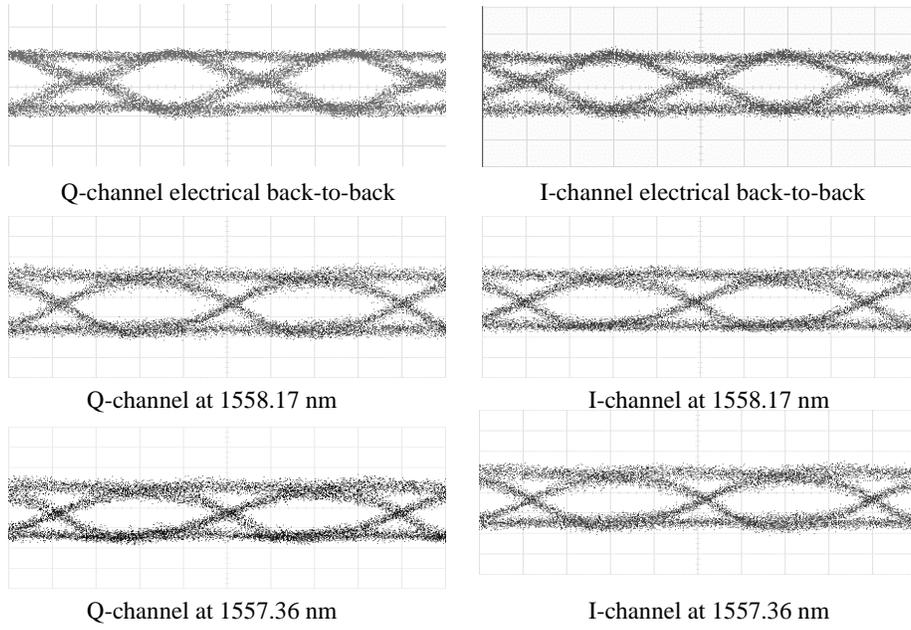
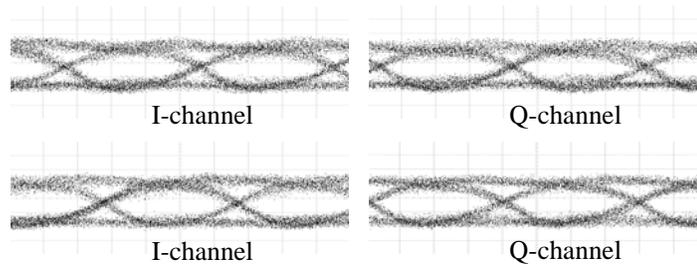


Figure 2



50mV/div ,100ps/div in all cases

Figure 3a



50mV/div ,100ps/div in all cases

Figure 3b