TuV 4:30 pm–6:00 pm

Ballroom E

Subcarrier Modulation

Sheryl L. Woodward, *AT&T, USA, Presider*

TuV1 **4:30 pm**

A complete 5 Gb/s throughput quadrature subcarrier system featuring zero-latency carrier and data synchronization

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1. Introduction

The growing demand for more advanced local area networks (LANs), capable of accommodating higher capacity services, has led to a parallel increasing demand for low-cost, greater speed, backbone links to support these networks. Development of higher transmission rate links would require the application of new techniques that will upgrade the existing interconnects capacity, for reasons of cost and reliability. Many installed potential links in LANs employ 62.5 µm core diameter multimode fibre (MMF) with typical link lengths of 300 m.

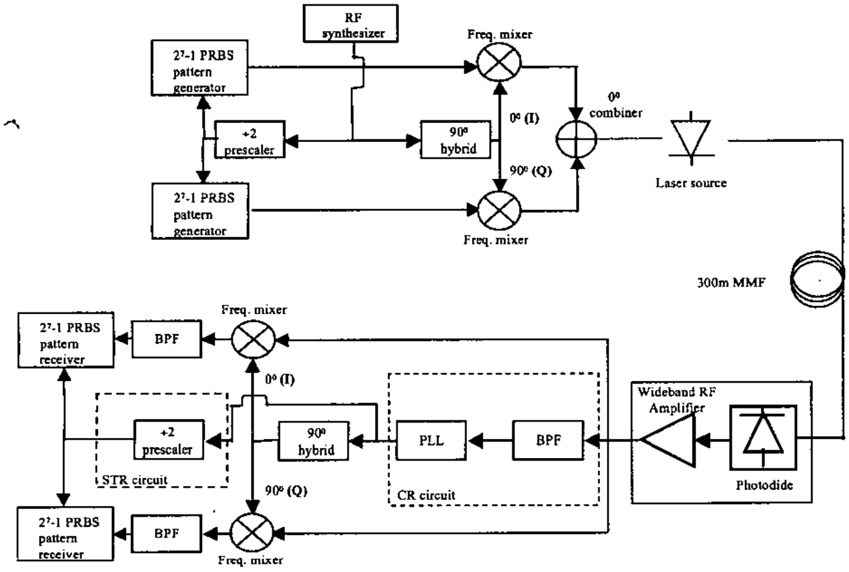
Transmission at the gigabit ethernet rate of 1.25 Gb/s is being demonstrated over 550 m of 62.5 µm MMF for long wavelength (1300 nm) laser sources and over 275 m at the short operating wavelength of 850 nm.[1] In order to be able to realize higher transmission rates it is essential to employ techniques capable of overcoming the modal bandwidth limitation of the fibre.[2] Wavelength division multiplexing (WDM) and multilevel coding have demonstrated high capacity performance over MMF links.[3]

Subcarrier multiplexing (SCM) is another technique capable of providing high capacity links to a large number of users.[4] In conjunction with MMF, it takes advantage of the relatively flat regions of the fibre response outside its modal bandwidth range by transmitting several narrowband channels in the passband region of the fibre, instead of a single broadband channel in its baseband. Baseband information signals in a SCM system modulate different subcarriers at high frequencies using any of the widely applied digital modulation schemes. Only the desired narrowband channels have to be demodulated in the receiver resulting in an increase in the receiver sensitivity, implying higher data rates or number of users. Previous complete system experiments employing SCM have demonstrated the transmission of 1 Gb/s channels and a single 2.5 Gb/s channel over 500 m[5] and 300 m[6] of MMF respectively.

2. Experimental set-up

The experimental set-up of the I&Q transmission system is illustrated in figure 1. In the modulator, the pattern generators produce two $2^7{-}1$ pseudorandom bit sequences (PRBS) at a bit rate of 2.5 Gb/s each. The subcarrier, at the frequency of 5.1 GHz, is split to produce the inphase and quadrature signals, through a 90° hybrid, necessary for modulation into the double balanced mixers and to provide, through a divide-by-2 prescaler, the required external clock rate to drive the pattern generators. This novel technique offers the advantage of simple symbol timing recovery (STR) circuits in the demodulator as the transmission clock is synchronized to the carrier frequency. Once the carrier signal is extracted only the same type of prescaler is necessary to perform timing recovery.

The modulated signals are combined and transmitted through 300 m of 62.5 µm MMF. After transmission through the fibre, the signal is detected using a photodiode and amplified into a 34 dB wideband RF amplifier before it is applied to the demodulation network. The I&Q waveform is split to provide the two modulated patterns ready for demodulation into the same specification double balanced mixers as the input and a third signal that is applied through the carrier recovery (CR) circuit to extract the subcarrier frequency. The extracted carrier in turn is split two ways, into the second divide-by-2 prescaler for timing extraction due to the configuration in the system's modulator and into the second 90° hybrid that provides the quadrature subcarriers for demodulation. The demodulated patterns are filtered into two flat delay 1870 MHz low pass filters (LPFs) to remove double frequency components due to the demodulation process and also filter any out of band noise.



TuV1 **Fig. 1.** Experimental set-up for the I&Q, 5 Gb/s transmission system.

2.1 carrier recovery (CR) circuit

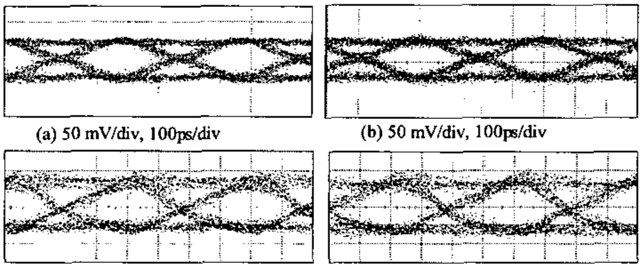
The CR circuit comprises a narrow bandwidth (40 MHz) bandpass filter (BPF) and a phase locked loop (PLL). The PLL consists of a double balanced mixer operating as a phase detector, an operational amplifier network as the loop filter (LF) and a voltage controlled oscillator (VCO) in a loop configuration. The phase detector compares the frequency and phase of the bandlimited RF signal at the input of the PLL and the output signal from the VCO. It produces an error signal that is filtered and amplified in the loop filter. Because the LF determines the performance of the PLL, a second-order loop is designed in our system for improved stability.[5] The output of the filter controls the VCO output frequency, driving it in every cycle towards the direction of reducing its frequency and phase difference with respect the RF signal into to the PLL.

When the frequency of the VCO output is within the lock-in range of the PLL, the feedback nature of the loop forces the VCO output frequency to lock to that of the RF signal, maintaining a fixed phase relationship between them. More subtly the PLL attenuates any data signal components within its lock-in range. The spectrum line of the input signal to the PLL at the subcarrier frequency must be at least 2 dB to 3 dB higher than the spectral lines either side of it in order for the loop to acquire lock. Because the modulation format followed in the modulator is that of double-sideband suppressed-carrier amplitude modulated (DSB-SC-AM) signals, a small DC component is added on one of the pseudorandom sequences by offsetting the corresponding pattern generator.

3. Experimental results

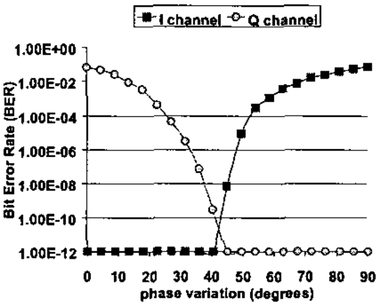
SCM offers the advantage of transmitting several channels independent of each other over the same link. In combination with the spectrally efficient I&Q modulation scheme, an aggregate capacity SCM link of 5 Gb/s is demonstrated. Figure 2 shows the recovered eye diagrams for the quadrature channels at 2.5 Gb/s each for the back-to-back (electrical) and over 300 m of MMF system configurations.

In applications where phase modulation is involved, the phase relationship between the channels is a crucial parameter. In an I&Q modulator-demodulator (MODEM), isolation between the LO and RF ports of the double balanced mixers must be high in order to prevent any signals reflected back and interfere with the phase relationship of the subcarriers produced in the 90° hybrids. For that reason buffer amplifiers had to be used between the hybrid outputs and the LO


(a) 50 mV/div, 100ps/div (b) 50 mV/div, 100ps/div

(c) 50 mV/div, 100ps/div (d) 50 mV/div, 100ps/div

TuV1 Fig. 2. Recovered I and Q eye diagrams: (a) back-back Q channel, (b) back-back I channel, (c) recovered channel after 300 m of MMF, (d) recovered I channel after 300 m MMF.



TuV1 Fig. 3. Bit error rate versus phase variation between the I and Q channels.

ports of the mixers, both for modulation and demodulation. Figure 3 illustrates the achieved bit error rates (BERs) of the channels with phase variation between the 0° and 90° range, indicating the importance of phase balance for an error free transmission.

4. Conclusions

We have demonstrated a complete quadrature subcarrier system with 5 Gb/s throughput suitable for within-building multimode fibre applications. By using a 5.1 GHz pilot tone and referencing the data to a prescaled version of the carrier, a zero-latency synchronisation scheme has been realised which is scaleable to higher date rates and upgrades to existing infrastructure.

References

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TuV2 **4:45 pm**

A 20 Gb/s per wavelength subcarrier multiplexed optical transmission system

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1. Introduction

This paper introduces a subcarrier multiplexed (SCM) optical transport system[1,2] which enables 20 Gb/s per wavelength, which represents the highest capacity commercial SCM system demonstrated to date. The system provides OC-3 (622 Mb/s) to OC-48 (2.5 Gb/s) granularity; each individual subcarrier transports independent traffic, enabling multi-service and protocol transparency (per subcarrier). Thus, it is suited to meet the diverse requirements of the metro environment. Performance is shown after 2 × 82 km spans of dispersion compensated SMF. BER < 10^{-15} is maintained and results suggest that more spans can be supported with this technology.

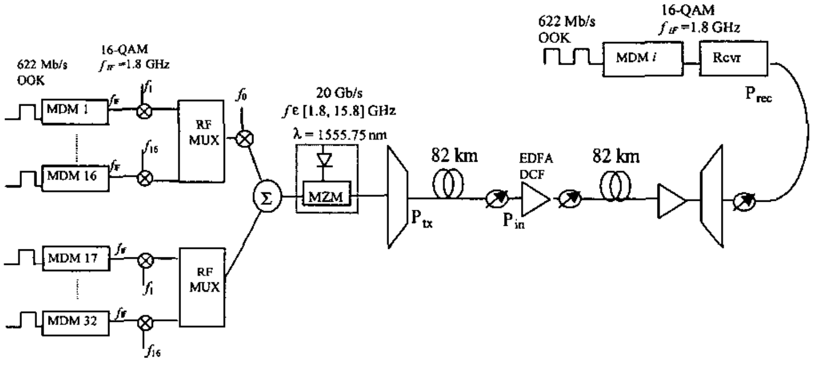
2. Experiment

The transmission link is diagrammed in Fig. 1. Thirty-two OOK OC-12 (622 Mb/s) signals are received by 2 sets of 16 high-speed modems. The modems convert each baseband OOK signal to 16-QAM format[3] with FEC. Each channel is upconverted from an intermediate frequency (f_{IF}) to a frequency between 9.8 GHz (f_1) and 15.8 GHz (f_{16}). One set of 16 subcarriers (SC) is then block down converted (via f_0) to a low frequency band extending from 1.8 GHz to 7.8 GHz. The resulting contiguous subcarrier bands drive a Mach-Zender modulator (MZM) to provide an aggregate 20 Gb/s optical signal. Following transmission an inverse operation is performed at the receiver to recover original baseband OOK signals.

Three transmission cases are considered: (1) attenuation only (no fiber), (2) single 82 km SMF span, and (3) 2 × 82 km SMF spans. In all cases, optical power launched into the fiber (P_{tx}) is +4.5 dBm at 1555.75 nm (ITU channel 27) and received power (P_{rec}) is −10 dBm. An EDFA is used to preamplify the received signal, and in all cases variable optical attenuators (VOA's) are positioned to control EDFA input power (P_{in}) and received optical power. The transmission link employs Corning SMF-28 optical fiber and Corning dispersion compensating fiber (DCF) modules. Signals are passed through a 100 GHz multiplexor (transmit side)-demultiplexor (receive side) pair to account for the impact of filter roll-off and to reject ASE at the receiver.[4] The link performance metric is Symbol Energy-to-Noise Density ratio (E_s/N_o).

Single 82 km Span

First a single 82 km SMF span with optical preamplifier was studied. Fiber loss (including connectors) is 19.5 dB, VOA insertion loss is 1.0 dB so that $P_{in} = -16$ dBm (for 0 dB attenuation at EDFA input). A DCF (9 dB passive loss) was placed at preamplifier midstage, and EDFA input power was varied (using VOA) to study the impact of additional transmission loss. Fig. 2a compares E_s/N_o versus EDFA input power (P_{in}) for case 1 (no fiber) and case 2 (82 km SMF). Fig. 2b plots theoretical (solid curve) and measured (points) BER versus E_s/N_o—data agree to within 0.5 dB. No additional noise impairments are observed for $E_s/N_o > 12$ dB, therefore, agreement between theory and experiment is preserved. Given this agreement, and including an additional 1.0 dB



TuV2 Fig. 1. Schematic of 2 × 82 km SCM transmission link. MZM and MDM represent the Mach-Zender modulator and high-speed modem, respectively.