Lemma 2:

$$\sigma_S^2(\ell_S, k_S) = (1-\varepsilon)^2\mathcal{G}_+(\ell_S) + 2\varepsilon(1-\varepsilon)\mathcal{H}_+(\ell_S) + \varepsilon^2\mathcal{G}_+(\ell_S+1) \quad (9)$$

where $\mathcal{G}_+(\ell)$ and $\mathcal{H}_+(\ell)$ are given by $\mathcal{G}_+(\ell) = (\mathcal{G}^E(\ell) + \mathcal{G}^O(\ell))/2$ and $\mathcal{H}_+(\ell) = (\mathcal{H}^E(\ell) + \mathcal{H}^O(\ell))/2$, where

$$\mathcal{G}^{E/O}(\ell) = \frac{1}{N}E[R_N^{E/O}(\ell;\ \mathbf{X},\mathbf{X})^2] - \frac{1}{N}E[R_N^{E/O}(\ell;\ \mathbf{X},\mathbf{X})]^2$$

$$\mathcal{H}^{E/O}(\ell) = \frac{1}{N}E[R_N^{E/O}(\ell;\ \mathbf{X},\mathbf{X})R_N^{E/O}(\ell+1,\mathbf{X},\mathbf{X})] - \frac{1}{N}E[R_N^{E/O}(\ell;\ \mathbf{X},\mathbf{X})]\cdot E[R_N^{E/O}(\ell+1,\mathbf{X},\mathbf{X})]$$

The calculations for $\mathcal{G}_+(\ell_S)$ and $\mathcal{H}_+(\ell_S)$ are rather cumbersome [7], but we give the simple expressions for large N as

$$\mathcal{G}_+(\ell_S) \simeq \frac{1+\lambda^2}{1-\lambda^2} - \left(2\ell_S + \frac{1+\lambda^2}{1-\lambda^2}\right)\lambda^{2\ell_S}$$

and

$$\mathcal{H}_+(\ell_S) \simeq \frac{2\lambda}{1-\lambda^2} - \left((2\ell_S+1) + \frac{1+\lambda^2}{1-\lambda^2}\right)\lambda^{2\ell_S+1}$$

for $0 \le \ell_S \le \lfloor (N-1)/2 \rfloor$, which imply that the variance of self-interferences depends on ℓ_S even for large N. The variance of cross-interference differs in this respect. The expression for $\lfloor (N-1)/2 \rfloor < \ell_S < N$ is obtained using relations $\mathcal{G}_+(\ell_S) = \mathcal{G}_+(N-\ell_S)$ and $\mathcal{H}_+(\ell_S) = \mathcal{H}_+(N-\ell_S-1)$.

More precisely, if we concentrate on a nearly synchronised correlator, i.e. $\ell_S = 0$ or $N-1$, we get $\sigma_S^2(0, k_S) = \varepsilon^2(1-\lambda^2)$ and $\sigma_S^2(N-1, k_S) = (1-\varepsilon)^2(1-\lambda^2)$; whereas in the case of $0 < \ell_S < \lfloor (N-1)/2 \rfloor$, as ℓ_S increases, the minimum and the maximum value of $\sigma_S^2(\ell_S, k_S)$ asymptotically approach to $(1/2)\cdot(1+\lambda)/(1-\lambda)$, and $(1+\lambda^2)/(1-\lambda^2)$, when $\varepsilon = \frac{1}{2}$ and $\varepsilon = 0$, respectively. Thus its averaged value over K_S is given by $(2/3)\cdot(1+\lambda+\lambda^2)/(1-\lambda^2)$ which is identical to the normalised variance of cross-interference in an asynchronous state, where K_S denotes the random number for k_S taking values in a set $\{0, 1, \ldots, M-1\}$ with its uniform probability. The above explicit expression for variances implies that time-averaging of variances on delay parameters, i.e. l_S, k_S as done in almost all of several previously published references [1–6] may loose information about synchronisation achievement. On the contrary, designers of rake receivers would rather utilise these expressions.

Note that since $(1/\sqrt{N})S^{(i)_p}(\ell_S, k_S)|_{\ell_S} = 0$ tends to Gaussian distribution with mean $\sqrt{N}(1-\varepsilon'(1-\lambda))$ and variance $\sigma_T^2(\prime,\lambda) = (J-1)\sigma_2 + \sigma_2^S + (N_0/2)$, the BER of the nearly synchronised correlator with its time delay $\varepsilon' = \varepsilon$ for $\ell_S = 0$ and $\varepsilon' = 1-\varepsilon$ for $\ell_S = N-1$, is estimated by

$$P_e(\varepsilon';\lambda) = Q\left(\frac{\sqrt{N}(1-\varepsilon'(1-\lambda))}{\sigma_T(\varepsilon',\lambda)}\right) \quad (10)$$

where

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}}\exp\left[-\frac{\omega^2}{2}\right]\mathrm{d}\omega$$

$$\sigma_S^2 = \varepsilon'^2(1-\lambda^2)$$

$$\sigma^2 = \frac{2}{3}\cdot\frac{1+\lambda+\lambda^2}{1-\lambda^2}$$

and N_0 denotes variance of channel noise. Hence we get the expected BER:

$$\overline{P_e}(\lambda) = 2\int_0^{1/2} P_e(\varepsilon';\lambda)\,\mathrm{d}\varepsilon'$$

Lastly, note that since the classic LFSR-based SS codes are assumed to be approximately identified with sequences of i.i.d. binary random variables, SS codes generated by Markov chains show great promise.

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Demonstration of 20 Gbit/s subcarrier multiplexed transmission system

F.A. Flood

A 20 Gbit/s subcarrier multiplexed (SCM) optical transmission system is presented. To date, this represents the highest aggregate bit rate SCM transmission that has been demonstrated. Results show that the bit error rate (BER) is less than 10^{-12} for a link loss of 29.5 dB, which corresponds to 118 km single mode fibre (SMF). Furthermore, excellent performance is demonstrated after transmission over 82 km of dispersion compensated SMF. Results suggest that the system can support transmission over multiple spans of optical fibre.

Introduction: Metropolitan area networks (MAN) must accommodate requirements of both long haul and access systems. That is, these networks require high transport capacity (≥10 Gbit/s per wavelength); in addition, they must provide transparent support of multiple protocols with low cost scalability [1]. Traditional SONET time-division multiplexed (TDM) technology, which was designed for voice traffic, does not satisfy the needs of an increasingly data-centric metro environment. This Letter introduces a lightwave efficient network solution (LENS), a high-speed (20 Gbit/s per wavelength) subcarrier multiplexed optical transport system. The LENS system is compatible with DWDM and is uniquely suited to meet the needs of the metro environment. The system is described briefly and performance is shown after transmission over 82 km of dispersion compensated SMF. BER $<10^{-12}$ is easily achieved and results indicate the transmission over multiple 80 km to 100 km fibre spans is practical. This is the highest capacity SCM system demonstrated to date [2, 3].

Experimental results: The transmission link is shown in Fig. 1. Each of 32 high-speed modems converts a 622 Mbit/s (OC-12) OOK baseband signal to 16-QAM format at an intermediate carrier frequency (f_{IF}) of 1.8 GHz. The modems apply two types of forward error correction (FEC): Reed–Solomon block code (176/160) and trellis code (4/3), in addition to raised cosine ($\alpha = 0.2$) pulse shaping [4]. Accounting for FEC and pulse shaping, the 16-QAM format provides a 50% reduction in signal bandwidth so that the IF signal bandwidth is 320 MHz (i.e. symbol rate $R_s = 320$Mbit/s). Each of the 32 digital IF subcarriers is uniquely upconverted and arranged into two contiguous bands (16 channels per band) with frequencies from 1.8 GHz to 8 GHz (lower band) and 9.0 GHz to 16 GHz (upper band). These two subcarrier bands are combined to modulate a CW optical carrier at an aggregate 20 Gbit/s bit rate. The receiver performs an inverse operation to recover original OOK baseband OC-12 signals. In this experiment, +4.5 dBm is launched into the optical fibre (P_{TX}) at a wavelength of 1555.75 km (ITU channel 27). Optical attenuators are placed at the input and output of the optical preamplifier in order to control amplifier input power (P_{in}) and received optical power (P_{rec}), respectively. The system performance metric is the ratio: energy per symbol/noise power density (E_s/N_0), which is related to bit error rate (BER) as shown in Fig. 2 (accounting for FEC and pulse shaping). Thus BER < 10^{-12} requires E_s/N_0 > 12 dB – this defines the minimum acceptable performance.

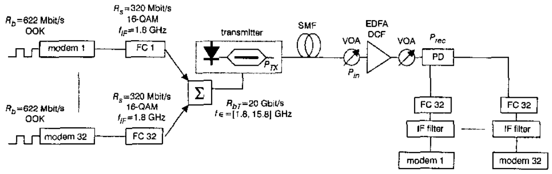

Fig. 1 *Schematic diagram of 20 Gbit/s SCM transmission link*
FC ≡ frequency converter

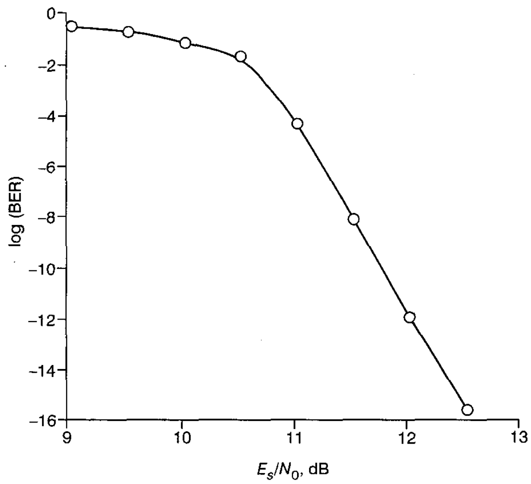

Fig. 2 *Relationship between BER and E_s/N_0 for 16-QAM signal with Reed–Solomon FEC (176/160), trellis code FEC (4/3), and raised-cosine pulse shaping ($\alpha = 0.2$)*

Two cases have been considered: (i) attenuation only (baseline) and (ii) attenuation with dispersion (dispersion compensated SMF). First, the optical fibre was removed so that only attenuation is considered. Link performance is measured against EDFA input power (P_{in}) while received optical power (P_{rec}) was fixed at −10 dBm (optimum value). Performance is measured starting from $P_{in} = -16$ dBm which is equivalent to 82 km SMF loss (assuming 0.25 dB/km fibre attenuation). Results are shown in Fig. 3. Because of the large number of subcarriers, only the minimum and maximum values in lower band (channels 1 through 16) and upper band (channels 17 through 32) are shown – performance of all other channels will fall within this range. Individual subcarriers were not equalised, which accounts for the 5 dB to 6 dB spread in E_s/N_0 values. The equalisation process trades off E_s/N_0 between the high performance and low performance channels, so that E_s/N_0 values for all channels in the equalised system will fall approximately midway between curves shown in Fig. 3. Data indicate that even this non-optimised system can support an extra 9 dB (36 km) of attenuation beyond 82 km SMF loss. That is, BER < 10^{-12} is maintained for 118 km optical fibre attenuation (without dispersion).

Next, 82 km of SMF was inserted and a dispersion compensating fibre (DCF) was placed at the EDFA midstage. Link performance was measured for $P_{in} = -16$ dBm and $P_{rec} = -10$ dBm. Fig. 4 shows E_s/N_0 values against subcarrier channel for case 1 (no fibre) and case 2 (82 km SMF with DCF). Again, the variation in subcarrier performance occurs because no attempt was made to equalise individual subcarrier powers. Even for this non-optimised system, BER is maintained well below 10^{-12} after 82 km of SMF. Compared to the baseline performance, dispersion compensated SMF is observed to degrade performance by a maximum 2.5 dB. Two phenomena contribute to the observed performance degradation. First, the DCF introduces a 10 dB passive loss at the EDFA midstage – this increases the preamplifier noise figure. Secondly, the DCF does not perfectly compensate for dispersion; this explains the preferential performance degradation at higher frequencies. If care is taken to match the SFM and DCF lengths and if subcarriers are properly equalised, these data indicate that the LENS system can support multiple 80 km to 100 km fibre spans.

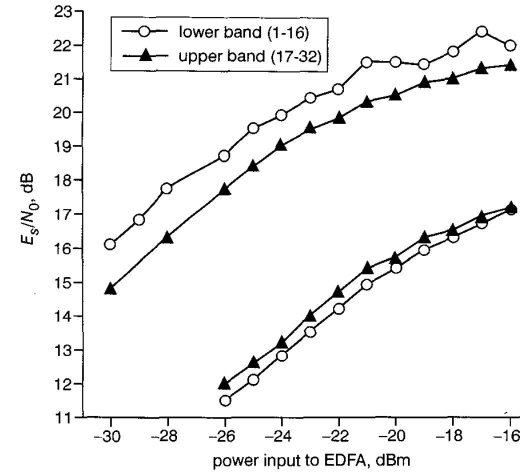

Fig. 3 *Baseline link performance without SMF (i.e. attenuation only)*
Best and worst case channels in lower (channels 1 through 16) and upper (channels 17 through 32) subcarrier bands. $P_{TX} = +4.5$ dBm and $P_{rec} = -10$ dBm

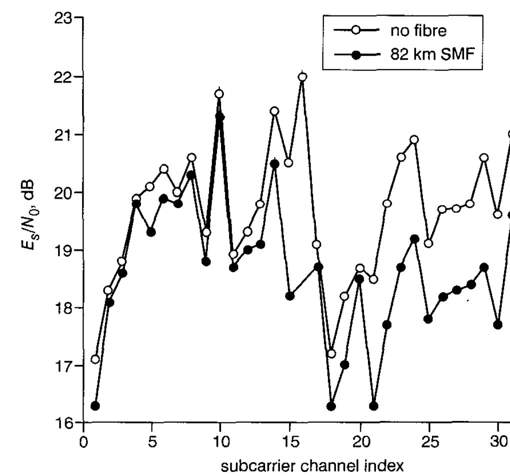

Fig. 4 *Performance of all 32 subcarriers after 82 km of dispersion compensated SMF is compared with baseline performance (attenuation only)*
$P_{TX} = +4.5$ dBm, $P_{in} = -16$ dBm and $P_{rec} = -10$ dBm.

Conclusion: A 20 Gbit/s SCM lightwave transmission system is presented. Excellent performance (i.e. BER < 10^{-12}) is demonstrated after 82 km of dispersion compensated SMF. This is the highest aggregate bit rate SCM system demonstrated to date. Results indicate that transmission over 118 km of SMF is permissible if dispersion is properly compensated, and that transmission over multiple 80 km fibre spans is practical.

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Enhancement of system performance in directly modulated metro-WDM systems by a spectral filtering method

Sung-Bum Park and Chang-Hee Lee

A numerical demonstration is presented of the reduction of both the chirp-induced dispersion penalty and the extinction ratio penalty in directly modulated metro-wavelength-division multiplexed (WDM) transmission systems by a spectral filtering method. The pre-filtering method suppresses nonlinear effects and gives better performance.

Introduction: Metro-wavelength-division multiplexed (WDM) systems have attracted considerable attention recently as a cost-effective upgrade of optical transmission systems to high capacity. A direct modulation scheme is suitable for these systems instead of an expensive external modulation scheme. In directly modulated multi-gigabit transmission systems, however, the chirp-induced broadening of optical spectrum limits the transmission distance. To increase the transmission distance of directly modulated signals, a spectral filtering method had been proposed [1, 2]. In this Letter, we apply the spectral filtering method to enhance system performance of directly modulated metro-WDM systems. The chirp-induced dispersion penalty and the extinction ratio penalty are suppressed effectively by using the proposed method. Spectral filtering at the transmitter side reduces the penalty caused by nonlinear effects.

Simulation conditions: The schematic diagram of directly modulated WDM systems is shown in Fig. 1. Each span length is 120 km. The optical booster amplifier can be eliminated when we use high power laser diodes (LDs).

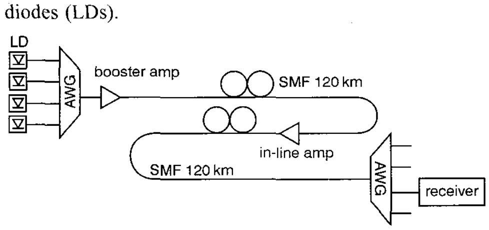

Fig. 1 *Schematic diagram of WDM transmission system*

The optical intensity and chirp of the directly modulated distributed feedback (DFB) LD were obtained by solving the rate equation [3]. The modulation signal is 2.5 Gbit/s pseudorandom binary sequence of $2^6 - 1$. The bias current is adjusted to be 1.3 times the threshold current and the extinction ratio is set to 10 dB. The spectral width of the directly modulated LD is 0.18 nm at −20 dB points from the peak. An arrayed-waveguide grating (AWG) is used as the spectral filter and MUX/DMUX. In this Letter, pre-filtering means the spectral filter at the transmitter side and post-filtering means that at the receiver side. The dispersion coefficient and the loss of the optical fibre are 17 ps/nm/km and 0.22 dB/km, respectively. For the receiver, we assume a third-order Butterworth filter with a 3 dB bandwidth of 0.65 times the bit rate. The optical transmitter output pulses in Fig. 2*b* show the increase in the extinction ratio and the reduction in the relaxation oscillation peaks when a spectral filter with a 3 dB bandwidth of 10 GHz is used [2].

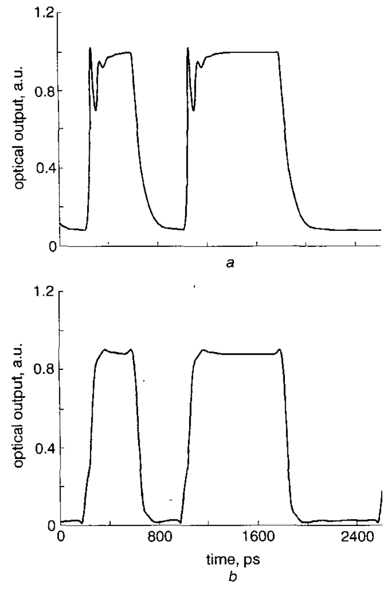

Fig. 2 *Optical output pulses at transmitter side*
a Without spectral filtering *b* With spectral filtering

Simulation results: Fig. 3 shows the bit error rate (BER) curves by varying the spectral filter bandwidth after 240 km transmission. The maximum improvement of BER power penalty is approximately 3 dB when the bandwidth of spectral filter is 8 GHz, which depends on the linewidth of the LD. This considerable improvement of the power penalty comes from the increase in the extinction ratio [3] and the decrease in the chirp-induced dispersion penalty. As the spectral filter bandwidth decreases from the optimum value, the power penalty starts to increase. This penalty increase is caused by the excess filtering of 'mark' pulse energy by the spectral filter.

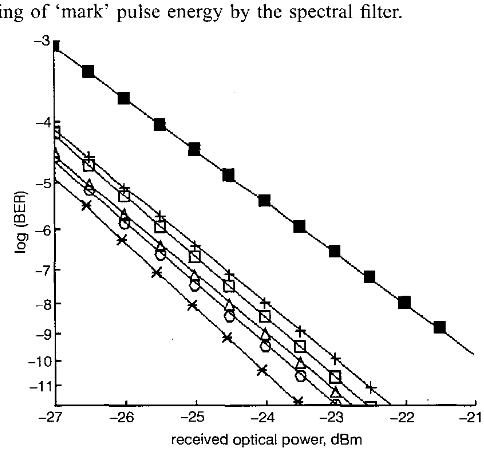

Fig. 3 *Calculated BER curves against spectral filter bandwidth after 240 km transmission*

■ without spectral filter
□ for spectral filter bandwidth of 4 GHz (at 240 km)
* for spectral filter bandwidth of 8 GHz (at 0 km)
○ for spectral filter bandwidth of 8 GHz (at 240 km)
△ for spectral filter bandwidth of 12 GHz (at 240 km)
+ for spectral filter bandwidth of 20 GHz (at 240 km)

In linear transmission systems, the improvement of system performance is independent of the location of the spectral filter. However, it may change when we consider the nonlinear effects in the optical fibre. To investigate the optical nonlinear effects in the fibre, the nonlinear Schrodinger equation is numerically solved by the split-step Fourier method [4].

In the case of post-filtering, we use only an AWG with an 8 GHz bandwidth at the receiver side and substitute a coupler for an AWG at the transmitter side. For the pre-filtering scheme, AWGs were used both