Error rate degradation due to switch crosstalk in large modular switched optical networks

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The characteristics of the maximum number of nodes \( N \) (which coincides with the number of frequencies) as functions of \( R_b \) and \( F \) are shown in Fig. 5. For example, for \( F \) is 100, the limitation of \( N \) is 30 for the \( R_b \) of less than 3 Gb/s. If more than 30 frequencies are required to the proposed network, finesse of FFP filters must be increased more than 100. On the other hand, \( B_{\text{amp}} \) of more than 50 nm is required for the \( R_b \) of higher than 10 Gb/s.

V. CONCLUSION

A logical star ring network based on OFDM-ADM employing a FFP filter and an optical circulator is proposed. Focusing on the crosstalk, the maximum number of nodes for the \( 1 \times N \) ring network was estimated concerning with the finesse of the FFP filter and the bandwidth of optical amplifiers. The criterion of total crosstalk was estimated to be \(-11.7 \text{ dB} \) based on 100 GHz spaced, 622 Mb/s, three-channel IM-DD transmission experiment. As a result, the limitation of \( N \) was estimated to be 30 for the \( R_b \) of less than 3 Gb/s, which is mainly determined by the finesse of 100.

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REFERENCES

ttronic interface is designed for specific multiplexing schemes and bit rates. Therefore, post installation changes will be expensive. Optical technologies may be employed to provide the required capacity and flexibility. Until now, advanced optical techniques for time switching and frequency switching are still immature compared to the electronic counterparts, whereas optical space switching and wavelength division multiplexing (WDM) [1] provide attractive solutions to some of the improved networking functions required.

**OPTICAL NETWORK ARCHITECTURE**

A schematic architecture for an optical core network is shown in Fig. 1. The optical nodes are linked in a mesh configuration where transmission in opposite directions in the network is carried over two separate subnetworks. Optical isolators are assumed to eliminate problems caused by optical reflections. An optical path through the network will typically comprise a number of fiber transmission sections interconnected by optical network nodes incorporating optical space switches, optical amplifiers and WDM components. This network forms a high capacity optical transport layer of simple functionality with access to an electronic transport layer of limited bandwidth capable of providing a number of network management functions, drop-insert of new channels, etc. The optical network is constructed in a modular fashion where each module consists of a network node and a length of fiber. If operation of the single network elements is independent of the overall network architecture, this approach allows simple overall network configuration and ease of upgrade and extensions.

In Fig. 2 a single network module (building block) is illustrated along with a schematic of an optical path through the network. An optical building block comprises wavelength selective elements for improved capacity and flexibility, amplifiers for signal level restoration, a splitter and a small switch for path protection, an optical cross-point switch matrix, and a length of fiber for network node interconnection. The signals at the input and at the output of a network building block must be maintained at the same level.

**OPTICAL NETWORK MODEL**

The dimension of the network is limited by a number of effects such as optical crosstalk, amplifier spontaneous emission, laser saturation, fiber nonlinearities, reflections, jitter accumulation, and signal bandwidth narrowing caused by filter concatenation. To get an appreciation of the limits to the number of building blocks that can be cascaded, a statistical model for the bit-error-rate (BER) at the receiver has been developed. Only the degradation caused by amplifier noise, receiver noise and switch crosstalk is considered. The crosstalk is assumed to appear as background light at the receiver [4]. The BER may then be evaluated for each possible crosstalk level, \( r \), at the receiver. We get

\[
\text{BER} = \sum_{i=0}^{R} \frac{1}{2} \left( \frac{1}{2} \right)^i \left( \int_{Q_i} \exp\left(-y^2/2\right)dy + \int_{Q_i}^\infty \exp\left(-y^2/2\right)dy \right) P_B\{r = i\}
\]
### Table 1

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Wavelength</th>
<th>1.55 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIN receiver</td>
<td>Equivalent input noise</td>
<td>3.2 pA/√Hz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1 GHz</td>
<td></td>
</tr>
<tr>
<td>Responsivity</td>
<td>0.85 A/W</td>
<td></td>
</tr>
<tr>
<td>WDM mux/demux</td>
<td>Number of channels</td>
<td>Variable 1-32</td>
</tr>
<tr>
<td>Loss</td>
<td>4 dB</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>Protection switch</td>
<td>Size</td>
<td>2 x 2</td>
</tr>
<tr>
<td>Loss</td>
<td>6 dB</td>
<td></td>
</tr>
<tr>
<td>Crosstalk per crosspoint</td>
<td>-20 dB</td>
<td></td>
</tr>
<tr>
<td>Crosspoint switch</td>
<td>Size</td>
<td>8 x 8</td>
</tr>
<tr>
<td>Loss</td>
<td>10 dB</td>
<td></td>
</tr>
<tr>
<td>Crosstalk per crosspoint</td>
<td>-20 dB</td>
<td></td>
</tr>
<tr>
<td>Amplifier</td>
<td>Gain</td>
<td>18 dB</td>
</tr>
<tr>
<td>Aggregate input power</td>
<td>-17 dBm</td>
<td></td>
</tr>
<tr>
<td>Spon. emission factor</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Coupling loss</td>
<td>0 dB</td>
<td></td>
</tr>
<tr>
<td>Fibre</td>
<td>Loss</td>
<td>9 dB</td>
</tr>
<tr>
<td>Maximum power in fibre</td>
<td>-2 dBm</td>
<td></td>
</tr>
<tr>
<td>Splitter</td>
<td>Loss</td>
<td>3 dB</td>
</tr>
</tbody>
</table>

The modular optical network shown in Fig. 2 has been simulated using this model. The network parameters used are given in Table I. The network performance has been modelled for two different switch matrix configurations [5]. The Benes structure is characterised by poor overall crosstalk suppression but requires only $2 \log_2 N$-1 crosspoint stages for a $N \times N$ switch. The active splitter/active combiner tree structure features good crosstalk performance using $2 \log_2 N$ crosspoint stages, however, the insertion loss is slightly increased. The Benes architecture is rearrangeable nonblocking and the tree architecture is strictly nonblocking. The performance of the two different network configurations is compared in Fig. 3 and 4. The aggregate number of crosspoint stages, $R$, is found by adding the number of stages for the individual switches along the path, see Fig. 2. The BER is calculated from (3). Further, the statistical crosstalk model is compared to a simplified on-off model where the system crosstalk with equal probability takes on the values 0 and $R_1$ only.

The significant difference in the number of cascaded network blocks, 37 and 16, respectively, for a system with 16 wavelengths, at a BER of $10^{-9}$, is caused by the higher crosstalk suppression of the tree switch architecture. For this architecture the crosstalk will not affect the system performance even for a large number of concatenated network blocks.

The insertion loss of the blocks is assumed to be adjusted to 0 dB. However, the optical components may have an insertion loss depending on the polarisation state that cannot be compensated for. The influence of a 0.1 dB polarisation dependent loss for each switch crosspoint is illustrated in Fig. 5 and Fig. 6. This results in an overall insertion loss of 0.6 dB for network blocks based on the Benes switch matrix compared with 0.8 dB for the tree architecture based modules. For a system with 16 wavelength channels the maximum number of cascaded networks blocks is now 6-7 blocks for both switch architectures at a BER of $10^{-9}$.
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Fig. 5. Calculated BER for a modular optical network with active/active tree switch matrices. The number of wavelength channels, \( W \), is 1, 2, 4, 8, 16, or 32. The influence of a 0.1 dB polarization sensitivity per switch crosspoint is included.

In large networks \( (R \text{ large}) \) the level of the total crosstalk at the receiver is approximately Gaussian distributed with a variance of \( (R_I)^2/4R \). Hence, the signal-to-noise-and-crosstalk-ratio can be defined as

\[
S/N_{X} = 20 \log \left( \frac{I_{1} - I_{0}}{1/2 \left( \sqrt{\sigma_{I}^{2} + (R_I)^2/4R} + \sqrt{\sigma_{I}^{2} + (R_I)^2/4R} \right)} \right).
\]

(5)

Now, a \( S \) / \( N_{X} \) ratio of 21.6 dB corresponds to a BER of \( 10^{-9} \). Over the range \( 10^{-4} < \text{BER} < 10^{-12} \) the estimates of the BER derived from the \( S / N_{X} \) ratio approach are within 50% of the above numerical results obtained by the network model. This accuracy may in practice be sufficient to get an appreciation of the parameters limiting the network performance.

CONCLUSIONS

A switched optical network architecture based on optical modules linked in a mesh configuration has been presented and a model of this network has been developed. The importance of keeping the polarization dependent insertion loss of the modules as low as possible is illustrated and the trade off between this requirement and the need for low crosstalk is analyzed. The modular networking approach with it’s high capacity and increased flexibility makes it a promising solution for use in future transparent optical networks.

REFERENCES


