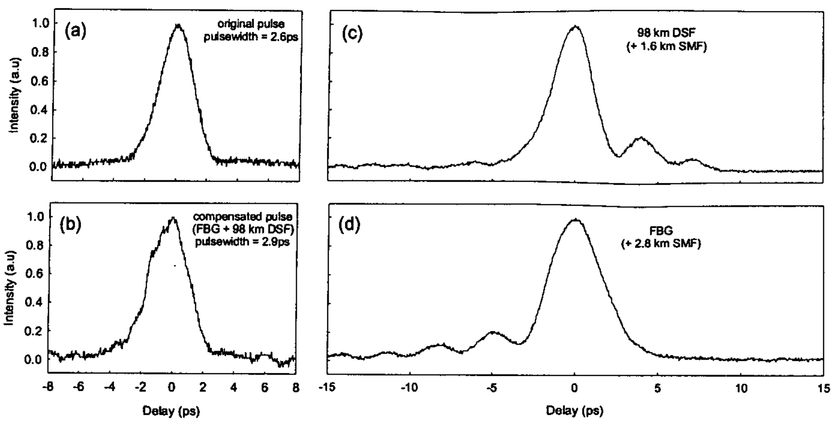


CThO2 **Fig. 3.** Cross-correlation traces: (a) original pulse, (b) TOD compensated pulse (98 km DSF and chirped FBG), (c) pulse propagated through 98 km DSF only, and (d) pulse propagated through the chirped FBG only.

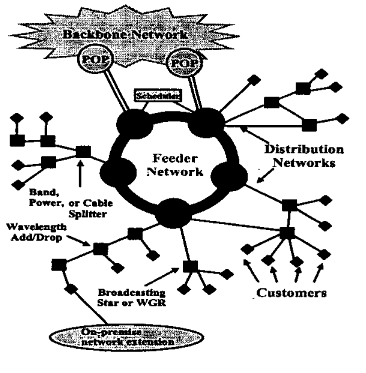
access networks, in particular the ONRAMP Consortium's hierarchical metropolitan-area access network. This comprises of several distribution networks sharing the resources of each feeder network that descends from the backbone (see Fig. 1)

The number of users supportable is the principal design metric; in seeking architectures that maximize this metric, since fiber to the end user is less of a shared medium, bandwidth can be readily traded for lower cost. A passive distribution bus, broadcast ring etc. cannot support more than a few dozen users because of the typical losses encountered by a signal channel in the lightpath.[2]

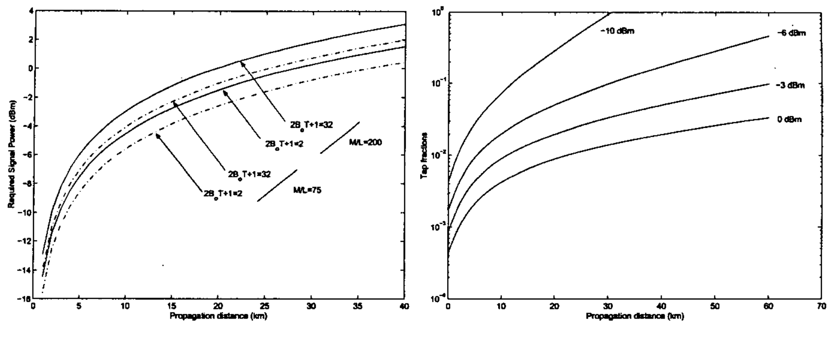
In this paper, we propose the use of remotely pumped erbium-doped fiber amplifiers (EDFAs) in particular layout geometries to increase the number of users by two or three orders of magnitude *without adding substantially to the cost.*[3] Sections of erbium-doped fiber of appropriately chosen length and doping concentration are inserted at suitable locations along the length of undoped single-mode fiber. The pump sources can be maintained at the feeder network access nodes, simplifying deployment, network management-and-control and ensuring that no component physically in the distribution network needs an electrical power supply.

We have carried out detailed calculations,[3] introducing two different analyses based on established rate-equations models of EDFAs, for several upstream and downstream architectures. The first approach was used to calculate numerically the number of users in a particular two-level distribution tree to be implemented by ONRAMP. The second model is a mean-field approximation to and extension of the former, with the benefit of closed-form expressions for several figures-of-merit.[4] We can then optimize design parameters, e.g. the sequence of tap fractions (fraction of signal power extracted by a particular user from the signal lightpath for detection). Because of accumulated amplified spontaneous emission from sections of erbium-doped fibers that act as amplifiers and decreasing pump power with propagation distance, the optimum sequence of tap fractions, which begin at a small number because of high signal-to-noise ratio at the head-end of the network and, by definition, terminating at 1 for the last receiver in a network, is not a simple relationship. Moreover, for a given network architecture, there exists a maximum "receiver density" (number of users per unit length) and a maximum length of fiber run for a given normalized input signal power. This is shown in Fig. 2(a) for a suboptimal (uniform) tap sequence. The optimal non-uniform sequence of optimal tap fractions at a sub-maximum receiver density (100 per km) is shown in Fig. 2(b) and represents a substantial improvement. Practical implementations can be designed, for example, as a "staircase approximation" to the latter and yields a number of users somewhat less than the theoretical maximum.

This work was funded by DARPA under the ONRAMP Consortium.



CThO4 **Fig. 1.** Hierarchical structure for the ONRAMP access network.



CThO4 **Fig. 2.** (a)The maximum length of erbium-doped fiber that can be supported by a given normalized input signal power (or vice versa), for space-time bandwidth product dimensionality factor as defined in[5] equal to 2 and 32, and for 75 and 200 users per kilometer, using uniform tap fractions. (b) Optimal (unequal) sequence of tap fractions v/s distance along a 10 Gb/s fiber network for users spaced apart by 10 m, and input signal power -10 dBm to 0 dBm.

References

1. Vincent W.S. Chan, K.L. Hall, E. Modiano and K.A. Rauschenbach, "Architectures and technologies for high-speed optical data networks", *IEEE Journal of Lightwave Technology,* 16, 12, pp. 2146–2169, 1998.
2. Vincent W.S. Chan, Serena Chan and Shayan Mookherjea, "Optical Distribution Networks" in *Proceedings of OptiComm 2000,* Session 4: Transport and Access, Dallas, TX, October 2000.
3. Shayan Mookherjea, *Optical Distribution Networks: Signal-to-noise Ratio Optimization and Distributed Erbium-doped Fiber Amplifiers,* Master of Science thesis, Massachusetts Institute of Technology, Cambridge, MA, June 2000.
4. Shayan Mookherjea, "Remotely-pumped optical distribution networks: a distributed amplifier model," submitted to *IEEE Journal of Lightwave Technology,* June 2000.
5. P.A. Humblet and M. Azizoglu, "On the bit error rate of lightwave systems with optical amplifiers," *IEEE Journal of Lightwave Technology,* 9, 11, pp. 1576–1582, 1991.

CThO5 **3:45 pm**

On the effects of ASE noise models on turbo code decoder performance in optical fiber transmissions

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1. Introduction

Turbo codes (TC) have been shown to be the most powerful forward error correction (FEC) code achieving near Shannon limit performance.[1] As FEC codes become a practical solution in improving system capacity in fiber communications, the application of TC in fiber transmissions begins to attract research interest.[2]

While the Gaussian approximation of the amplified spontaneous emission (ASE) noise is widely used in the study of fiber transmission systems, and there exist standard TC for Gaussian channels, we show in this paper that the Gaussian approximation underestimates the achievable performance of TC in real fiber transmission systems. To take the full advantage of TC, the more accurate noise statistics and binary asymmetric channel (BAC) model should be used for setting threshold and in the Bahl, Cocke, Jelinek, and Raviv (BCJR) decoding algorithm.[3]

In addition, for simplicity, the fiber channel with dominant ASE noise is usually approximated as a binary symmetric channel (BSC). We have shown that the BSC model overestimates the Shannon limit in.[4] In this paper, we show that this approximation also leads to suboptimal threshold settings, and underestimates the performance of *punctured* TC.

2. Modification of the BCJR Decoding Algorithm

The BCJR algorithm is a recursive algorithm for maximum a posteriori probability decoding of the received noisy code word. The key to the BCJR algorithm is to decompose the a posteriori probability into three factors, α_{k-1}, γ_k, and β_k, relating the decision at time k to the previous, current, and future observations, respectively. As the key factor, γ_k is defined as a function of the PDFs of the received signals. Both α_{k-1} and β_k can be computed recursively as a function of γ_k. Hence, the performance of the BCJR algorithm highly depends on the accuracy of the noise model.

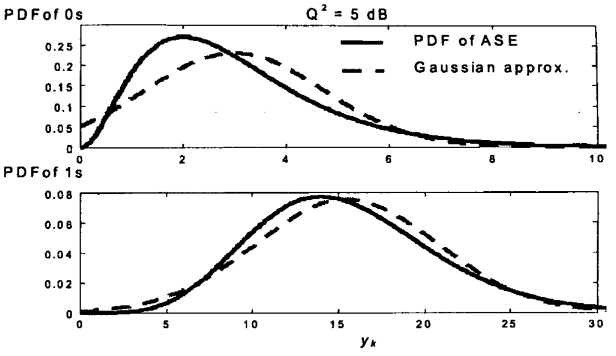
As shown in Figure 1, the differences between the PDFs of the ASE noise[4] and Gaussian noise with the same mean and variance are not negligible, especially at low Q. Hence, the performance of the TC can be significantly improved by deriving a new formula for γ_k using the ASE noise model[5,6] instead of the standard formula using the Gaussian noise model. Moreover, when punctured TC are used, the accuracy of the noise model is even more acute because the threshold values required to completely eliminate the effect of the missing punctured bits in the decoder are very sensitive to the noise model.

With the BSC approximation, the probability density ratio at the incorrect threshold increases exponentially with Q, while the ideal value should be 1. Thus, for punctured TC, the BSC model performs even worse with higher Q.

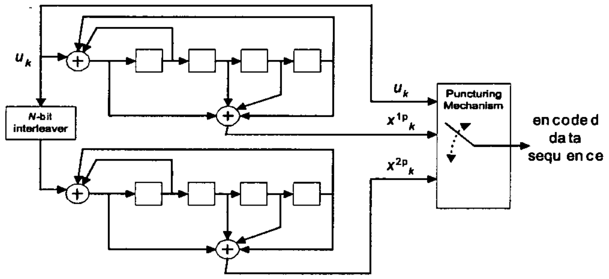
3. Simulations and Conclusions

In our simulations, we used a (31, 27, 400) convolutional Turbo encoder (Figure 2). The results plotted in Figure 3 show that our modified TC decoder can achieve more than 2 dB extra coding gain as compared to the TC decoder based on Gaussian approximations. It is also shown that the rate 3/4 punctured TC based on the BSC model performs worse than the uncoded case.

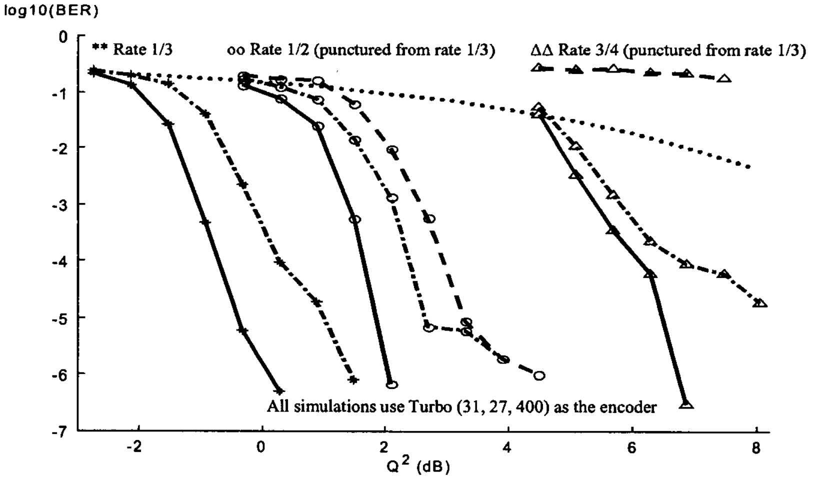
We will also be investigating incorporation of more accurate noise statistics as described in[7] to our derivations.



CThO5 Fig. 1. Comparison of the PDFs of the ASE noise and Gaussian noise with the same mean and variance



CThO5 Fig. 2. (31, 27, *N*) TC encoder structure



CThO5 Fig. 3. BER comparison of the Turbo code decoder based on ASE noise model (solid), Gaussian noise + BAC model (dashdot), Gaussian noise + BSC model (dashed) of the fiber transmission system, and the uncoded data (dotted)

Reference

1. C. Berrou, A. Glavieux, and P. Thitimajshima, *Proc. 1993 Int. Conf. Comm.*, pp. 1064–1070.
2. O. Aitsab, and V. Lemaire, *Optical Fiber Communications Conf. 2000, Tech. Digest*, ThS5-1-3, Baltimore, MD, 2000.
3. L.R. Bahl, J. Cocke, F. Jelinek, and J. Raviv, *IEEE Trans. on Info. Theory*, pp. 284–287, March 1974.
4. Y. Cai, *et al.*, submitted to *Optical Fiber Communications Conf. 2001*, Anaheim, CA, March 2001.
5. P.A. Humblet and M. Azizoglu, *Journal of Lightwave Technology*, vol. 9, no. 11, pp. 1576–1582, November 1991.
6. D. Marcuse, *Journal of Lightwave Technology*, vol. 8, no. 12, pp. 1816–1823, December 1990.
7. R. Holzlöhner, *et al.*, submitted to *Optical Fiber Communications Conf. 2001*, Anaheim, CA, March 2001.