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TR2014-084 September 2014

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European Conference on Optical Communications (ECOC 2014)

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Introduction

Superchannels (SCs) are attracting increasing attention these days, as a means to increase spectral efficiency[1−3]. Superchannels, however, experience non-uniform interferences from fiber nonlinearity and inter-carrier interference (ICI). One of the methods to balance the penalty is to adjust the launch power[2], however, changing the power of one sub-channel affects other subchannels through fiber nonlinearity and ICI. Therefore, optimizing the power levels of all subchannels will require significant effort. The use of rate-adaptive forward error correction (FEC) has been proposed[4−6] so that the capacity can be optimized depending on the signal-to-noise ratio (SNR) of the channel, while not affecting the power level, or the spectral width. In this paper, we investigate a method of adjusting FEC code rate per subchannel, and show that the capacity increases compared to the conventional case in which the identical FEC code rate is used across the entire SC. Effect of power allocation will also be investigated.

Models

We treat amplified spontaneous emissions (ASE), nonlinear interference (NLI) due to fiber nonlinearity, and ICI as the additive white Gaussian noise sources. We used 32GBd subchannels with root raised cosine (RRC) shaping with a roll-off parameter of 0.1[7], which is typically used for balancing the timing jitter requirements and spectral density. We then calculated the capacity divided by the subchannel spacing, as shown in Fig. 1, where OSNR is changed. ICI is treated as an additional additive Gaussian noise. Depending on the OSNR, the capacity reaches maximum with the channel spacing ratio of 1.04-1.05. This means that as OSNR becomes lower, the contribution from ICI becomes less important, and the channel spacing can be narrower. To maximize the spectral efficiency, for 32GBd subchannel, we chose a subchannel spacing of 33.25GHz (ratio of 1.04). In this case, effective OSNR caused by ICI is 29.3dB in the edge subchannels, and 26.3dB in the rest of the subchannels. We then calculate NLI. An uncompensated 80km non-zero dispersion shifted fiber (NZDSF) link with 10 spans is assumed. The Gaussian Noise (GN) model[8] was used to estimate the noise caused by fiber nonlinearity. The dispersion parameter of 3.9 ps/nm/km, and the nonlinearity factor of 1.6 /W/km were used. Figure 2 shows the calculated OSNR caused by NLI when the number of subchannels is changed from 1 to 11, and the subchannel power levels are flat at 0dBm. This does not include ASE nor ICI. Note that the whole curves shift down or up by 3dB, when the subchannel power is changed by +/-1dB, according to the GN model. The center channels always have the lower OSNR than the edge channels, and the largest difference is 1.55dB, when the number of sub-channels is 11. In the case of SSMF, the difference is 1.11dB with 11 subchannels.

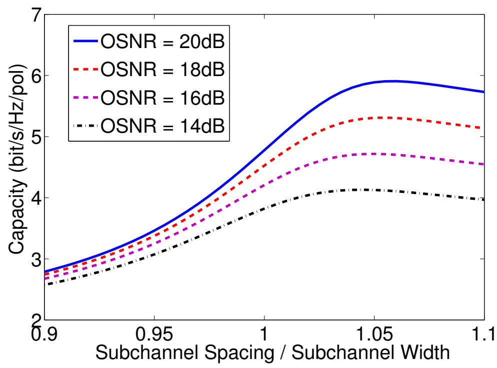

Fig. 1: Capacity as a function of the ratio of channel spacing to Nyquist channel width, when OSNR is given.

Subchannel power can have some variation,

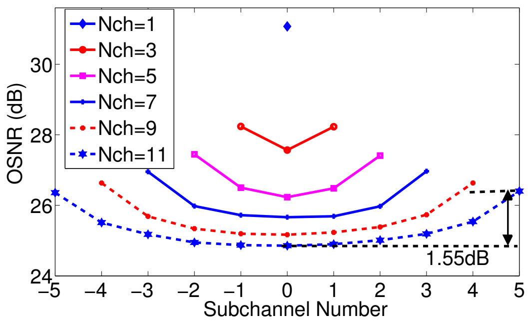

Fig. 2: OSNR caused by NLI for 10 spans of 80km NZDSF.

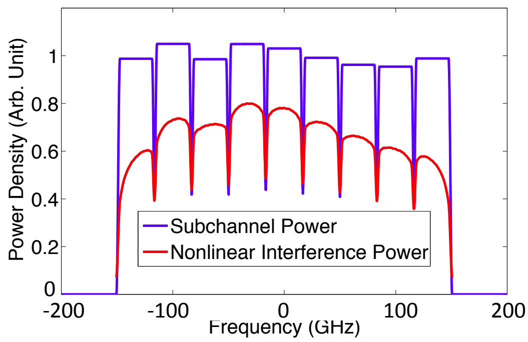

Fig. 3: Noise power density in the presence of subchannel power variations of 0.2dB SD.

caused by various factors in the transmitters and optical filters. We modeled the power variation with Gaussian distribution having 0.2dB standard deviations (SD). The top curve of Fig. 3 shows the subchannel power, and bottom curve shows the NLI calculated by the GN model, exhibiting the signature of the subchannel power distribution.

Channel capacity

Figure 4 is the channel capacity $log_2(1 + SNR)$, where the SNR is calculated by taking into account the ASE, NLI, ICI, and power variations (0.2dB SD) with 3 or 9 channels. A link of 10 spans of 80km NZDSF is used, and Erbium Doped Fiber Amplifier (EDFA) noise figure of 4.0 was assumed. Note that the channel capacity is the one approached by using very high-order modulation with the optimum FEC code rate. Conventional cases use the same FEC code rate and the overall capacity is limited by the worst SNR subchannel. Per-channel rate-adaptive FEC (our proposed method) means FEC code rate is adjusted for each subchannel such that each subchannel achieves the maximum capacity. The overall channel capacity is an average of the subchannel capacities.

Table 1 summarizes compared to the conventional case, per-channel rate-adaptive FEC has 3.8% and 3.1% higher capacity, in the case of 3 and 9 channels, respectively. The nonlinear

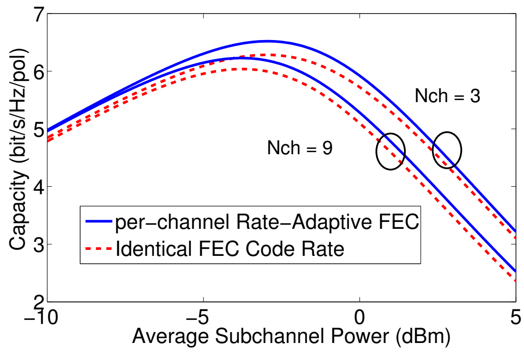

Fig. 4: Channel capacity vs. average subchannel power, when two FEC schemes are used. The link is 10 spans × 80km NZDSF, and ASE, NLI, ICI, and power variations were all considered

power threshold is 0.23 dB and 0.32 dB higher, respectively. Full SC FEC means that all the received signals are combined into a large single FEC decoder (or parallel FEC decoders exchanging the information with each other), so the capacity is determined by the total SNR (i.e., total SC power divided by the total noise power). Note that full SC FEC is difficult to achieve with the current technology, so it is encouraging that per-channel rate-adaptive FEC performs slightly better than the full SC FEC. When similar calculation was conducted for SSMF cases, due to smaller nonlinearity, the power at maximum capacity shifts higher. Near or below the peak capacity, the difference between the conventional (identical FEC code rate) case and the per-channel variable FEC is dominated by the ICI.

		3ch		9ch	
Factors	FEC	Max Capacity (b/s/Hz/pol)	Increase (%)	Max Capacity (b/s/Hz/pol)	Increase (%)
ASE + NLI	Identical FEC Code Rate	6.750	Baseline	6.487	Baselline
	Rate-Adaptive	6.796	0.68	6.538	0.79
	Full SC FEC	6.795	0.67	6.537	0.77
ASE + NLI + ICI	Identical FEC Code Rate	6.353	Baseline	6.150	Baseline
	Rate-Adaptive	6.515	2.55	6.228	1.27
	Full SC FEC	6.510	2.48	6.224	1.20
ASE + NLI + ICI + Pwr Var.	Identical FEC Code Rate	6.283	Baseline	6.039	Baseline
	Rate-Adaptive	6.520	3.77	6.228	3.12
	Full SC FEC	6.517	3.72	6.209	2.81

Tab. 1: Calculated maximum capacity, with 10 spans × 80km NZDSF

Power allocation

How to allocate power among the subchannels affects the channel capacity. We compared the following four scenarios.

1. Baseline case

   The subchannel power is flat, and identical

FEC code rate is used. This is the conventional method.

2. Identical BER
   Liu et al. adjusted subchannel power levels such that all channels meet the same bit error ratio (BER)[2]. In our calculation with 3 subchannels, we adjust the power such that all the subchannels have the same SNR at the peak of the capacity, and found that center channel with 0.9dB higher than side subchannels. In this case the identical FEC code rate is used. Note that when multiple SCs exist in the system, this relatively large power adjustment may affect other SCs through NLI.
3. Flat power/per-channel rate-adaptive FEC
   Per-channel rate-adaptive FEC improves the peak capacity, as we have discussed so far.
4. Water-filling
   In wireless communications, water-filling algorithm is widely used, in which higher SNR channels will have higher power[9]. This means that side subchannels will have higher power than the center subchannels. To our knowledge, nobody has considered water-filling algorithm for SCs. Since changing the power level affects nonlinear effects, we numerically changed the power distribution to obtain the highest capacity, and found that side subchannel power higher than the center channel by 0.6dB gave best results.

Figure 5 shows the comparison of the peak capacity of the 3-channel case for the four scenarios. This shows that adjusting the subchannel power to achieve the same SNR (BER) is effective, but the rate-adaptive FEC with/without power allocations offers even higher throughput. Note that water-filling algorithm only works with per-channel rate-adaptive FECs.

Discussions

Various schemes of rate-adaptive LDPC codes have been proposed[10–12]. In addition, studies on the combination of block codes and LDPC codes are made[5,13], in which block codes have fine granularity. We have limited the discussions to the SCs, however, rate-adaptive FEC with fine granularity can also be effective for non-SC networks where there are large variations in OSNR[14].

Conclusions

We have theoretically investigated the application of per-channel rate-adaptive FEC for SCs. When there are variations among subchannel SNRs, rate-adaptive FEC can absorb the variation effectively and increase the total capacity and nonlinear threshold power. We also investigated the power allocation scheme, and found that increasing the subchannel power whose SNR is higher, which is analogous to the water-filling algorithm, is more effective than the conventional method of flattening the BER/SNR.

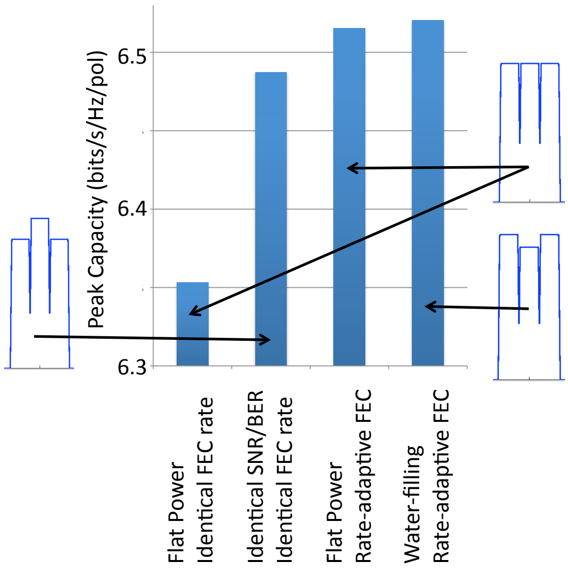

Fig. 5: Peak channel capacity vs 4 combinations of FEC scheme and power allocation, for 10 spans of 80km NZDSF link with 3 subchannels

Acknowledgements

This work was in part supported by the Lambda Reach project of the National Institute of Information and Communications Technology (NICT), as part of a program of the Ministry of Internal Affairs and Communications (MIC) of Japan.

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