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Concatenated SD-Hamming and KP4 Codes in DCN PAM4 4×200 Gbps/lane

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Abstract *We experimentally demonstrate the feasibility of serially concatenated soft-decision Hamming codes and KP4 FEC as a backward-compatible solution for 200 Gbsps/lane for IM/DD DCN applications.©2022 The Author(s)*

Introduction

Intensity modulation with direct detection (IM/DD) offers a cost and power-effective solution to the exponential growth of data traffic in data centre networks (DCN). Hard decision (HD) FEC based on Reed Solomon codes has been standardized in 100GBASE-KP4 for its simplicity and ability to meet the output bit error rate (BER) target of 10^{-13} at a net coding gain of 6.4 dB. However, for 200 Gbps/lane optical PHY specifications, legacy HD FEC alone does not meet the requirements resulting from the severely band-limited channel and the need for low-power DSP[1].

A possible end-to-end solution is to replace the KP4 FEC in favour of an HD FEC with lower rate. The end-to-end solution is attractive in the mid to long term in conjunction with the transition towards a 200G attachment unit interface (AUI). However, in the short term, it would break compatibility with current 100G AUI implementations.

A second option is to segment the channel into optical and electrical segments and design a new soft-decision (SD) channel code for the optical part. SD FEC provides additional coding gain at the expense of more complex decoders. This additional complexity translates into increased area on chip, power consumption and latency. The disadvantage would be the additional high-latency decoding and encoding that take place on the attachment unit (e.g. the pluggable module) to terminate the KP4 FEC.

The more appealing alternative pursued in this work is to serially concatenate a low-complexity and low-latency SD high-rate inner code with the legacy outer KP4 code. The objective of the inner code is to provide a sufficient reduction of the BER that meets the decoding threshold of the powerful outer code. The latter scheme would be backwards compatible and transparent at the current KP4 interface.

We examine the interplay of baud rate, code rate, DSP and interleaving based on an experimental evaluation with state-of-the-art components and demonstrate the feasibility of the serially concatenated scheme for 200 Gbps/lane and possible pitfalls.

Concatenated Codes for DCN

Serially concatenated codes were proposed for long-haul optical transport networks (OTN), where a powerful inner coder is used for error correction, and a weaker outer code is employed to remove the error floor exhibited by most SD FEC solutions[2]. An alternative concatenation scheme, where a weak inner code is concatenated with a powerful outer code is presented in[3],[4]. The latter technique allows to adapt a powerful HD code to a soft decision channel with relatively low additional complexity and latency. The inner code should thus be able to reduce the BER to below the KP4 threshold of $2.2 \cdot 10^{-4}$, process log-likelihood ratios (LLRs) and allow for low-complexity parallelized decoders.

Similar to[5],[6] we adopt low-overhead extended Hamming codes with Chase decoding. The choice for Hamming codes is motivated by the relative simplicity and low latency of the hardware decoder implementation, as well as by a good performance as an error reducing interface.

For a baud rate of 106 Gbaud and a target net bit rate of 200 Gbps we can employ the HD RS(544,514) (KP4), which results in a net rate of 200.3 Gbps. For 112 Gbaud, we employ an extended Hamming(128,120) code concatenated with KP4 with a resulting net rate of 199.8 Gbps, and finally for 119 Gbaud we use an extended Hamming(64,57) and KP4 with a net rate of 200.2 Gbps.

System Setup

Figure 1 shows the experimental setup. The transmitter operates at $106, 112$ or 119 Gbaud.

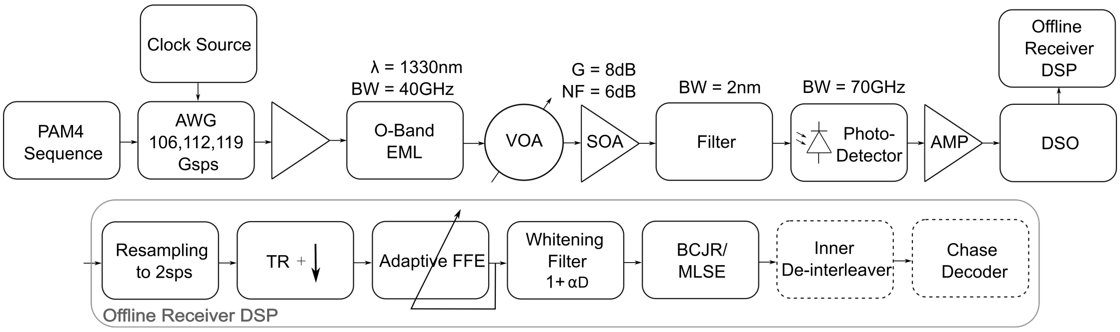

Fig. 1: Experimental IM/DD setup with offline DSP

The Gray-mapped PAM4 waveform originating from long pseudo-random bit sequences (PRBSs) is generated by an AWG operating without pulse shaping at 1 sps. After an EML modulator, a variable optical attenuator (VOA) allows to control the received optical power (ROP). An SOA, optical filter and a PIN PD with an amplifier complete the receiver setup. The waveforms are captured by a digital storage oscilloscope (DSO) and digitized at 256 Gsps. The ROP is adjusted in steps of 1 dB in the interval -6 dBm to 0 dBm.

The offline DSP performs downsampling, timing recovery, full response adaptive equalization with an LMS Volterra equalizer, and BCJR equalization with a 4-state trellis. The BCJR outputs bit-wise LLRs for the two bit levels of the PAM4 constellation. For the 106 Gbaud rate with only the KP4 channel code, the BCJR with 4 states is replaced with a hard-output MLSE with 4 states. Although not explored here in depth, a non-negligible part of implementation complexity and latency is determined by equalization, with BCJR dominating MLSE. Timing recovery works at 2 sps, and adaptive and sequence equalization at 1 sps.

We evaluate the system performance considering both linear and non-linear equalization. For the linear case we employ an adaptive LMS feed-forward equalizer with 141 taps. For non-linear equalization we use an adaptive LMS feed-forward Volterra equalizer with 141 linear taps, 9 second-order non-linear taps and 9 non-linear third order taps (for more details see[7]). Although non-linear equalization has a much higher footprint and power consumption, it is sometimes employed in state-of-the-art products and thus relevant for our investigation.

For the evaluation of post-FEC error rates we rely on the KP4 threshold for HD, under the assumption that enough interleaving is provided between inner and outer code. For SD-Hamming we follow the methods presented in[8],[9]. Basically, the transmitter sends long PRBS sequences instead of codewords, to ensure that relevant error patterns are present in the channel. At the receiver a combination of scramblers and random interleavers is used to decode for the all-zero codeword as well as create novel codewords from the same recorded sequence. We generate a different finite depth random interleaver per codeword, and we adjust this depth to assess improvements in performance with a given latency budget.

Figure 2 shows the empirical probability of symbol burst errors up to length 10 for ROP=-4 dBm at 112 Gbaud after BCJR with linear and non-linear adaptive equalizers, extracted from a sequence of 10^6 symbols. These error patterns can be broken up and distributed among multiple codewords by symbol-wise inner de-interleavers inserted between BCJR and the Chase decoders. The choice of interleaver structure and depth is important under a latency constraint. We choose random interleaving as a universal option that delivers an average behaviour over many possible interleaver structures. Our simulations generate 4000 such random realizations and the BER is reported as an average over these realizations.

The Hamming Chase decoder considers 5 least reliable bit positions for flipping and can flip up to 5 bits at a time. This decoder will not approach ML performance, but delivers a benchmark for pragmatic, low-complexity implementation. We note that in our experiments increasing the number of candidates for bit-flipping only provided with diminishing returns, while increasing the interleaver depth turned out to bring outsized benefits.

Experimental Results

Figure 3 shows the receiver optical power (ROP) for which BER=$2.2 \cdot 10^{-4}$ is achieved before the KP4 decoder for all three scenarios considered, where channel shortening before BCJR/MLSE is

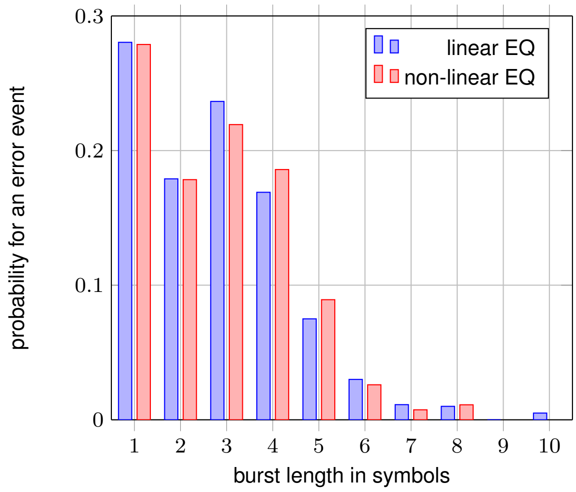

Fig. 2: Empirical symbol error burst distribution for 112 Gbaud with linear and non-linear adaptive equalization

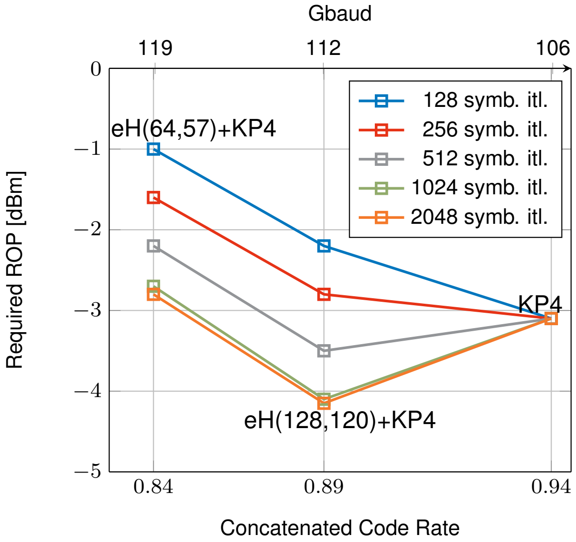

Fig. 3: Rate vs ROP for Concatenated Code with Linear Adaptive FFE equalizer

done with a linear adaptive equalizer. The highest sensitivity is achieved at 112 Gbaud with extended Hamming(128,120) and a random interleaver of depth 2048. We note that the depth of the interleaver has a strong impact on the performance of the concatenated scheme. In agreement with the empirical error burst statistics from Figure 2, a symbol interleaver with depth larger than 8 codewords provides best interleaving results. We note that at a rate of 112 Gbaud, a (random) interleaver/de-interleaver pair of 1024 symbols introduces a latency of 18.28 ns. If we consider 500 m single-mode fiber, and ask that the transceiver latency is at most 10% of the propagation time (2.45 µs), this interleaver consumes 7% of the total transceiver latency budget. For an interleaving depth of 256 or fewer symbols, 106 Gbaud with hard-output MLSE, ideal outer symbol interleaver and legacy KP4 achieves the best sensitivity of -3.1 dBm. Decimal values of ROP are obtained by linear interpolation between neighbouring points allowed by the ROP resolution of our experimental setup.

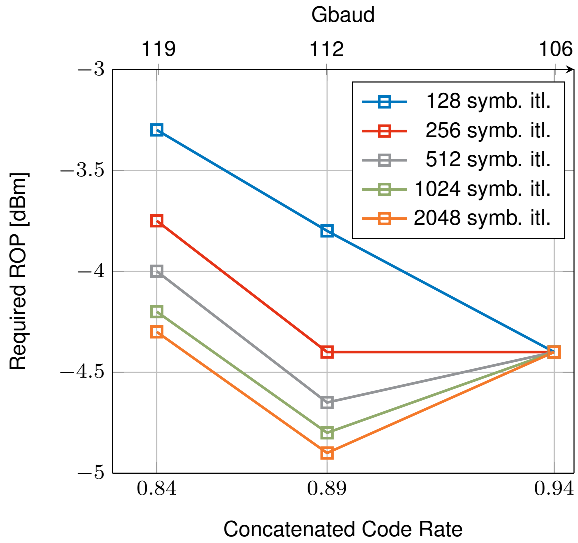

Fig. 4: Rate vs ROP for Concatenated Code with Non-Linear Adaptive FFE equalizer

Figure 4 shows the receiver optical power (ROP) for which BER=$2.2 \cdot 10^{-4}$ is achieved before the KP4 decoder for all three scenarios considered, with non-linear adaptive equalization. The non-linear FFE equalizer has only a quantitative impact on the performance, i.e. better sensitivity is achieved, but the relative order is almost identical to that depicted in figure 3. Nonlinear equalization provides an extra ROP gain of 0.7 dB at 112 Gbaud with an interleaver depth of 2048 symbols.

Conclusion

We evaluated the feasibility of a pragmatic low-complexity, low-latency concatenated coding scheme to support 200 Gbps optics with KP4 backward compatibility. We observed from experimental evaluations with state-of-the-art components that for a fixed target net bit rate, there are optimal choices of inner code rates, interleaver depth and line baud rates that deliver optimum receiver sensitivity. In particular, with linear adaptive equalization, at a rate of 112 Gbaud, with extended Hamming(128,120) + KP4, we gain 1.05 dB compared with 106 Gbaud and KP4, when the interleaver length is 2048 symbols. With non-linear equalization the gain in ROP reduces to 0.5 dB.

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