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First Experimental Verification of Improved Decoding of Staircase Codes using Marked Bits

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Abstract: Experimental validation for improved staircase decoding via marked bits is shown for the first time. Using a single-span hybrid-amplified recirculating loop experiment, we demonstrate reach increases of up to 240 km.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications

1. Introduction

High-performance hard-decision forward error correction (HD-FEC) is a promising alternative for next-generation high-speed FEC for fiber optics. Compared to soft-decision FEC, HD-FEC offers a low-complexity low-power-consumption hardware implementation. One of the most popular families of HD-FEC codes are staircase codes (SCCs) [1], which offer an improvement of 0.42 dB in terms of net coding gain compared to the best code from [2] (ITU-T G.975.1). SCCs are used as an outer code in the draft agreement for 400 Gb/s OTN [3].

SCCs are decoded iteratively via bounded-distance decoding (BDD) for their component codes, which are very often Bose-Chaudhuri-Hocquenghem (BCH) codes. BDD is very simple, however, its error correcting capability is limited to $t = \lfloor \frac{d_0-1}{2} \rfloor$ errors, where d_0 is the minimum Hamming distance. Sometimes, BDD will erroneously decode a received sequence with more than t errors, a situation known as a *miscorrection*. Miscorrections are highly undesirable and are known to degrade the performance of iterative BDD by introducing additional errors into the iterative decoding process. Miscorrection detection based on zero-syndrome codeword was originally proposed in [4]. Later, [5] proposed the idea of anchor codewords and [6] used channel reliabilities for product codes.

Recently, a simple algorithm to improve the decoding of SCCs was proposed in [7]. This hybrid algorithm relies on the idea of using soft information (log-likelihood ratios, LLRs) from the channel to mark highly reliable bits (HRBs) and highly unreliable bits (HUBs). Unlike previous methods, the algorithm in [7] improves the miscorrection-detection capability of the SCC decoder *and* increases the effective error-correcting capability of BDD. The algorithm is very simple as it only requires modifications to the decoding structure of the last block of each decoding window. Furthermore, no soft information needs to be stored nor tracked during the decoding process.

One of the key assumptions in the algorithm of [7] is the use of a threshold δ which differentiates regular bits from HRBs. Due to the use of soft information, the algorithm is sensitive to the exact noise statistics, and thus, the optimum value of δ depends on the channel under consideration. Numerical results for the AWGN in [7] show that the optimum threshold is $\delta = 10$. The optimum value of δ for the nonlinear optical fiber channel is unknown. In this paper, we evaluate the performance of SCCs with the improved decoding via marked bits in a hybrid-amplified recirculating loop experiment. In addition, we investigate the optimum threshold δ , which is found to be much smaller than the one for the AWGN channel. It is shown that the SCC decoding with the optimized LLR threshold can provide steeper waterfall performance curves and achieve a reach increase of up to 240 km.

2. Staircase Codes and Decoding via Marked Bits

Standard decoding of SCCs is performed using a sliding window, wherein BDD is used to iteratively decode each component code. The BDD output $\hat{c}$ depends on the hamming distance between the received sequence r and the transmitted codeword c , denoted as $d_H(r, c)$. Three possible cases exist: If $d_H(r, c) \leq t$, BDD yields the correct codeword c . If $d_H(r, c) > t$ and the received sequence r is not close to another transmitted codeword, BDD will declare a failure. In the third case, $d_H(r, c) > t$, but there is another codeword $\tilde{c}$ that satisfies $d_H(r, \tilde{c}) \leq t$. In this case BDD will mistakenly decode r as $\tilde{c} \neq c$, a situation called *miscorrection*. In practice, BDD is often a syndrome-based decoder that uses syndromes to estimate the error pattern e , where $\hat{c} = r \oplus e$. If the syndrome is zero, no errors are present.

The decoder proposed in [7] uses a hybrid fashion by marking bits to improve the standard decoding of SCCs. Using the received symbol, a log-likelihood ratio (LLR) λ is calculated for each coded bit. Then, a threshold δ is set to mark the bits with $|\lambda| \geq \delta$. These bits are marked as HRBs. The algorithm also marks $d_0 - t - 1$ bits with the smallest $|\lambda|$ value in each codeword as HUBs. The intuition behind this bit marking is that HRBs can help detect miscorrections and that HUBs can be used as potential candidates for bit flipping. The latter can help the decoder to deal with both miscorrections and decoding failures.

The proposed algorithm of [7] is shown in Fig. 1 (left). During the decoding process, if BDD indicates decoding success, miscorrection detection is conducted. This detection step checks that BDD will not flip bits that are either marked as HRBs or that belong to a zero-syndrome codeword. To handle miscorrections, the most HUB will be flipped. To handle decoding failures, the $d_0 - w_H(e) - t$ most unreliable HUBs will be flipped, where $w_H(e)$ is the Hamming weight of the error pattern e . The objective of the bit flipping operation ($r \rightarrow r'$) is to try to flip erroneous bits, which will make $d_H(r', c) = t$. In this case, BDD will give the correct codeword. The last step is to conduct miscorrection detection one more time to check if the bit flipping indeed gave the desired result (see Fig. 1 (left)).

Fig. 1: Improved decoding via marked bits (left) and simulation results for AWGN channel and 2-PAM (right).

Fig. 1 (right) shows simulation results for the AWGN channel with 2-PAM and three SCCs. The component codes are BCH codes with parameters (n, k, t) , where n is the codeword length, k is the number of information bits, and t the error-correcting capability. The code rate of the SCC is $R = 2k/n - 1$. We consider three SCC rates: $R = 0.92, 0.87, 0.83$, generated by (shortened) BCH codes $(504, 485, 2)$, $(256, 239, 2)$ and $(228, 209, 2)$. The decoding window size is 9, and the maximum number of iterations is 7. The optimum LLR threshold is $\delta = 10$. Compared to standard SCC decoding, the proposed algorithm can achieve up to 0.3 dB SNR gain.

3. Transmission Experiment: Setup and Results

As shown on Fig. 2, a single-channel dual-polarization 25 GBaud 8-QAM signal is modulated onto a <100 kHz linewidth external-cavity laser (ECL) at 1550.12 nm using a 100 GSa/s digital-to-analog converter (DAC) and a dual-polarization Mach-Zehnder IQ-Modulator (DP-MZM). Using acousto-optical modulators (AOM), the signal is looped over a span consisting of 75 km of standard single-mode fiber (SSMF) and an optical filter to eliminate out-of-band noise. The optical signal is amplified using a hybrid scheme consisting of both lumped EDFA and distributed backward-pumped Raman amplification. Intradynic reception is performed using a 90° -hybrid, balanced photo-detector (BPD) and an 80 GSa/s four-channel real-time oscilloscope. IQ-imbalance compensation, resampling, chromatic-dispersion compensation and equalization are performed using offline processing. By sweeping the signal power from -10 dBm to 0 dBm using a variable optical attenuator (VOA), the optimal launch power was found to be -5 dBm.

The transmitted symbols are generated using a pseudo-random sequence of length 2^{15} . This sequence is transmitted over the recirculating loop and 18 sequences per polarization are captured. This gives a database with $3 \cdot 2 \cdot 18 \cdot 2^{15}$ code bits (for 8-QAM). FEC encoding was applied to a random sequence of information bits and a scrambler was used as described in [8] so that the scrambled codeword coincides with the transmitted sequence. At the receiver, the

Fig. 2: Experimental setup.

signs of the LLRs were changed depending on the scrambling sequence. To accurately investigate post-FEC BER, the database was randomly interleaved 1,000 times. For each random interleaving sequence, FEC encoding was applied to a new randomly generated data sequence.

Post-FEC BER results for the standard decoding and the decoding via marked bits are presented in Fig. 3 (left). When comparing the results for standard decoding (circles), we observe that SCCs with larger code rates lead to a steeper waterfall performance. This comes from the fact that the steepness of the post-FEC BER curves in the waterfall region is determined by the size of the SCC block. For the codes in this paper, the SCC block sizes are 63504, 16384 and 12996 bits for $R = 0.92, 0.87, 0.83$, resp. This effect can also be observed in Fig. 1 (right).

For each code rate, Fig. 3 (left) shows results using a fixed LLR threshold $\delta = 10$ (white triangles). This value of δ is optimal for the AWGN channel [7]. The performance gain offered by decoding with marked bits and $\delta = 10$ is limited, particularly for post-FEC BER below 10^{-6} and for $R = 0.87$. This is due to an incorrect selection of δ . Fig. 3 (right) shows an optimization of the LLR threshold δ for different code rates and different transmission distances. From this figure it is clear that $\delta = 10$ is too high for the optical channel. To obtain the best performance, the optimum threshold δ should be chosen depending on the code rate of SCCs (shown with filled markers).

Fig. 3: Left: Post-FEC BER of standard SCC decoding and improved decoding via marked bits. Right: Post-FEC BER vs. LLR threshold δ for different number of spans (optimum values shown with filled markers).

The results in in Fig. 3 (left) for the optimized decoding via marked bits (solid markers) were obtained using optimum values of δ for each transmission distance and code rate. We observe that the optimized hybrid decoding algorithm provides reach extensions of 210 km, 240 km and 230 km for code rates 0.92, 0.87 and 0.83, resp. The gains due to the optimization of δ seem to decrease for larger code rates.

4. Conclusions

We have experimentally shown that the performance of staircase codes can be significantly improved by marking bits. The full gains can be achieved in an optical transmission system if the decoder design is re-optimized. An increase in transmission distance of up to 240 km was demonstrated, showing the potential of hybrid HD-FEC schemes.

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