Addendum to "Feedforward Carrier Recovery for Coherent Optical Communications"

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***Abstract*—In a previous paper [1], we noted when the transmitted signal constellations has rotational symmetry, laser phase noise can be mitigated using non-data-aided (NDA) feedforward (FF) carrier recovery. The structures of a FF carrier recovery unit and a NDA soft-decision phase estimator were shown in Fig. 3 and 4(a), respectively. We have found that in an NDA FF carrier recovery unit, the order of the linear filter and phase estimator can be exchanged in a manner not possible with a decision-directed (DD) FF carrier recovery unit. We show that this alternative NDA (ANDA) FF carrier recovery unit exhibits better immunity to cycle slips compared to standard NDA.**

I. Introduction

An NDA FF carrier recovery unit for M-ary phase-shift keying (M-PSK) is shown in Fig. 1(a). The input signal is raised to the M-th power to remove data modulation. A soft-decision estimate of the instantaneous phase is obtained by finding its argument with phase unwrapping. The soft-decision phases ψ_k are then passed through a Wiener filter $W_{hd}(z)$ whose output $\theta_{k-\Delta}$ is the minimum mean square error (MMSE) estimate of the carrier phase (with delay Δ).

It is possible to exchange the order of the linear filter and the phase-unwrapped argument function (Fig. 1(b)). The resulting structure is similar to that reported in [2]. This alternative NDA (ANDA) structure has the same linearized mathematical model as the standard NDA structure. The analysis of its performance is the same as Section III of [1]. The optimum coefficients for $W_{sd}(z)$ in Fig. 1(b) are therefore the same as for $W_{hd}(z)$ in Fig. 1(a) of [1].

The ANDA structure has better immunity to cycle slips than the NDA structure at low SNR and high laser phase noise, due to the nonlinear behavior of the phase unwrapper. In the standard NDA configuration, a noisy input $z_k = y_k^M$ is passed to the $\arg\{\cdot\}$ function, which makes the unwrapped phase susceptible to cycle slips. By performing the filtering first, the $\arg\{\cdot\}$ function operates on a signal with less angular uncertainty, so cycle slips are less likely. In Section III-F of [1], we found that differential bit-encoding is needed to prevent catastrophic receiver failure when the target BER is 10^{-3}. Differential bit-encoding is undesirable for two reasons: (i) it increases the raw BER by a constant factor, (ii) it precludes the use of powerful soft-decision coding using low-density parity check (LDPC) or Turbo codes.

Manuscript received January 06, 2009. Current version published July 01, 2009. This work was sponsored by Naval Research Laboratory award N00173-06-1-G035 and by Army Research Laboratory contract W911-QX-O6-C-0101 via a subcontract from CeLight, Inc.

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Digital Object Identifier 10.1109/JLT.2008.929416

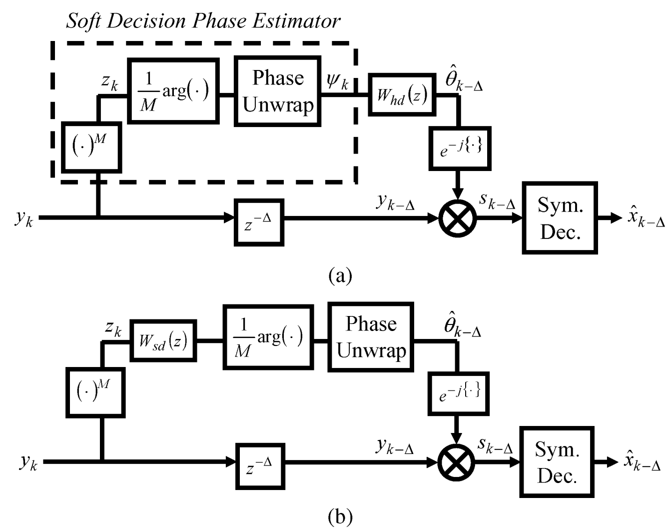

Fig. 1 Feedforward (FF) carrier recovery unit for M-PSK using (a) non-data aided (NDA), and (b) alternative non-data aided (ANDA) designs.

Fig. 2(a), (b) show the simulated BER vs. SNR performance of NDA and ANDA with and without differential bit-encoding for QPSK at a linewidth of $\Delta\nu T_b = 5 \times 10^{-5}$. Our simulation used 2^{22} random symbols, and the filter length L was determined using a 95% impulse energy criterion (Section III-C of [1]). We observe that ANDA without differential bit-encoding can operate without cycle slips at up to $\mathrm{BER} = 10^{-2}$, and its performance is close to the AWGN limit. In contrast, cycle slipping is a persistent phenomenon for NDA without differential bit-encoding, causing the simulated BER to be 0.5 for all simulated SNR values.

ANDA is a useful alternative because any residual cycle slips (with probability of occurrence less than 2^{-22}) can be mitigated by periodically inserting known training symbols. Suppose we inserted a training symbol after every B transmitted symbols. If a cycle slip occurred, the training symbol will be detected with a rotation that is an integer multiple of 90 degrees [1]. The receiver can use this knowledge to correctly detect all subsequent symbols. Therefore, a cycle slip will cause a burst error of at most $B - 1$ symbols, if the slip event occurred at the beginning of the block.

Suppose in addition to inserting periodic training symbols, the receiver also employed bit interleaving. Let the interleaver depth be K blocks by Bb bits, where b is the number of bits per symbol. Interleaving will disperse the burst error bits so the net effect of cycle slipping is to increase the net BER. Provided

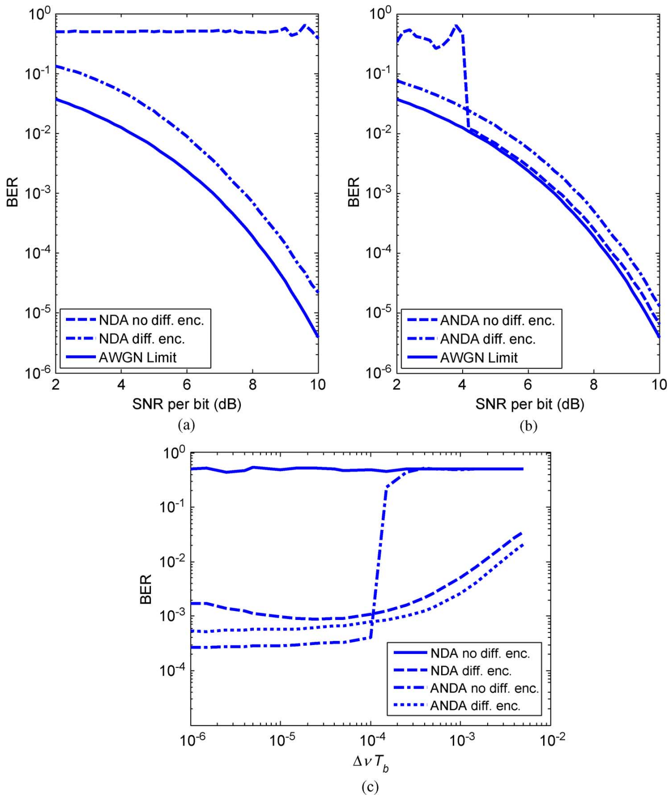

Fig. 2 Simulation results for FF carrier recovery with and without differential bit-encoding using an NDA and ANDA structure. (a−b) BER versus SNR at a linewidth of ΔνTb = 5×10−5, (c) BER versus linewidth at an SNR of 7.8 dB per bit.

the BER increase is small compared to the target BER, all errors can be still corrected by an outer forward error correction (FEC) code. The key parameter is therefore the probability of a cycle slip within a block, which is BP_{slip}, where P_{slip} is the probability that a cycle slip occurs at a given symbol. Our goal is to ensure $BP_{slip} \ll BER_{t\arg et}$. We observe in Fig. 2(b) that cycle slips disappeared when the raw BER is below $\sim 10^{-2}$. Over many simulations, we found that the SNR at which cycle slips begin to appear was always similar. We can state with confidence that $P_{slip} < 2^{-22} < 10^{-6}$ when the raw BER is below 10^{-2}. Furthermore, as cycle slips are a highly nonlinear phenomenon, $P_{slip}(SNR)$ should fall much faster than the $\mathrm{erfc}(\cdot)$ function for raw BER. An equivalent "threshold" effect is well known in FM radio, for example.

In modern systems employing FEC, $BER_{t\arg et}$ is usually around 10^{-3}. Even assuming a highly pessimistic P_{slip} of 10^{-6}, we can choose the block length B to be 100 to ensure the cycle-slips-induced BER increase is $10^{-4} < 10^{-3}$. The choice of interleaver memory depth K is arbitrary as long as it is greater than $1/BP_{slip}$ to ensure a burst error is distributed amongst enough bits. For the case considered here, K should exceed 10,000.

In Fig. 2(c), we fixed the SNR per bit at 7.8 dB (1 dB above the AWGN limit at a target BER of 10^{-3}), and the performances of NDA and ANDA versus linewidth are shown with and without differential bit-encoding. ANDA without differential-bit encoding operated without cycle slips at linewidths up to $\Delta\nu T_b = 10^{-4}$, and is almost the same as the linewidth tolerance for NDA with differential bit-encoding reported in Table III of [1]. In contrast, cycle slips are persistent for NDA without differential-bit encoding at all simulated linewidths.

II. Conclusions

By exchanging the order of the phase estimator and linear filter, we have proposed an alternative non-data aided (NDA) feedforward (FF) carrier recovery structure that has greater immunity to cycle slipping than the standard NDA structure. As the probability of cycle slipping is sufficiently low for ANDA, the insertion of periodic training symbols in conjunction with bit interleaving is sufficient for correcting burst errors due to cycle slips. Differential bit-encoding is unnecessary. This enables the use of soft-decision coding.

References

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