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Algorithms for Optical QAM Detection

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Abstract **— This paper presents a linewidth-tolerant carrier phase estimation algorithm for synchronous optical QAM transmission systems. The 2-stage structure of the algorithm allows a flexible and hardware-efficient implementation for arbitrary QAM constellations.**

Index Terms **— Optical communication, quadrature amplitude modulation, synchronous detection.**

I. Introduction

A key element for the success of coherent receivers is the possibility to realize them with low-cost DFB lasers. For QPSK and other phase modulation schemes a multitude of algorithms exist that provide a high phase noise tolerance [1,2]. However, all these algorithms fail when applied to most higher-order QAM constellations, because these constellations don't have equidistant phases. Additionally it has been shown that decision-directed carrier recovery is also not an option for higher-order QAM constellations due to the inevitable feedback delay in practical systems [3].

In this publication we review a novel feed-forward carrier recovery algorithm for arbitrary QAM constellations which promises a phase noise tolerance that is sufficient to realize coherent higher-order QAM receivers with DFB lasers [3]. In addition we propose an extension of the algorithm that allows to significantly reduce the required hardware effort while preserving the phase noise tolerance.

II. Feed-forward Carrier Phase Estimation

Fig. 1 shows the block diagram of the feedforward QAM carrier recovery scheme [3]. The input signal $\underline{Y}_k$ of the coherent receiver is sampled at the symbol rate, and perfect clock recovery and equalization are assumed. To recover the carrier phase in a pure feedforward approach the received signal $\underline{Y}_k$ is rotated by B equidistant test carrier phase angles φ_b with

$$\varphi_b = \left(\frac{b}{B} - \frac{1}{2}\right) \cdot \gamma\,,\ b \in \{0, 1, ..., B-1\}, \qquad (1)$$

where γ is the symmetry angle of the QAM constellation. For square QAM constellations $\gamma = \pi/2$ holds. Without rotational symmetry $\gamma = 2\pi$ must be used.

Then all rotated symbols are fed into a decision circuit and the squared distance $|d_{k,b}|^2$

$$\left|d_{k,b}\right|^2 = \left|\underline{Y}_k e^{-j\varphi_b} - \hat{\underline{X}}_{k,b}\right|^2, \qquad \hat{\underline{X}}_{k,b} = \left\lfloor \underline{Y}_k e^{-j\varphi_b} \right\rfloor_D \qquad (2)$$

to the closest constellation point is calculated in the complex plane. $\lfloor . \rfloor_D$ denotes the output of the decision device.

In order to remove noise, for each b the distances of $2N+1$ consecutive symbols rotated by the same test carrier phase angle φ_b are summed up,

$$s_{k,b} = \sum_{n=-N}^{N} \left|d_{k-n,b}\right|^2 . \qquad (3)$$

The optimum value of the filter halfwidth N depends on the laser linewidth times symbol rate product.

After filtering the optimum phase angle for symbol k is determined by searching that $b = b_{k,min}$ which provides the minimum sum $s_{k,b}$ of distance squares. As the decoding was already executed in (2), the decoded output symbol $\hat{\underline{X}}_k$ can be selected from the $\hat{\underline{X}}_{k,b}$ by a switch controlled by the index $b_{k,min}$ of the minimum distance sum.

Due to the possible rotational symmetry of the QAM constellation and the resulting m-fold ambiguity of the recovered phase with $m = 2\pi/\gamma$, the receiver may not be able uniquely assign the recovered symbol to the corresponding bits. This problem can be resolved either by using framing information [4] or by applying differential coding [5].

III. Two-stage Carrier Recovery

Although a possible hardware efficient implementation of the QAM carrier recovery algorithm has been proposed in [3], the required hardware effort is still significant. The main reason for this is that B parallel blocks are required to test the different phase values. An efficient approach to reduce the hardware effort is therefore to reduce the number of required parallel blocks. However, a reduction of the number of test carrier angles within the test interval reduces the precision of the carrier recovery and thus the receiver sensitivity. Hence the

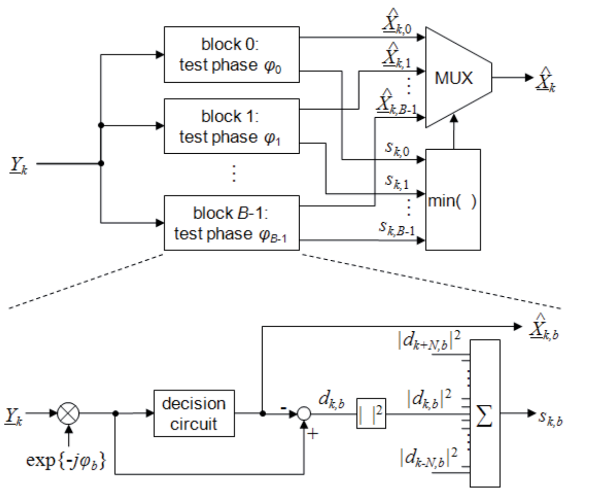

Fig. 1. Feed-forward QAM carrier recovery

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only way is to reduce the test interval for the carrier recovery.

A possible solution is to use a 2-stage carrier phase estimator (Fig. 2) as proposed in [6]. The 1st stage phase estimator is used to generate a rough phase estimate $\tilde{\varphi}_k$ of the carrier phase. Possible estimator algorithms are Viterbi & Viterbi carrier recovery, decision-directed carrier recovery or any other approach. The best suitable algorithm depends on the applied QAM constellation and the required phase noise tolerance.

Although these algorithms fail to provide a precise estimate of the carrier phase, they can significantly reduce the interval in which the actual carrier phase has to be expected. In section II the test interval for the QAM carrier recovery algorithm depends on the symmetry angle of the QAM constellation, e.g. $\gamma = \pi/2$ for square QAM. If the QAM carrier recovery is used as 2nd stage estimator in the 2-stage receiver the test interval depends on the accuracy of the first stage estimator, which can be significantly lower than the symmetry angle of the QAM constellation. Therefore the number of required test carrier angles B and hence the hardware effort can be significantly reduced without sacrificing the linewidth tolerance.

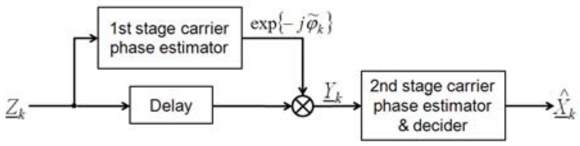

Fig. 2. Two-stage carrier phase estimator structure

IV. Simulation Results for Square 16-QAM

The 2-stage carrier recovery is tested in a Matlab simulation of a coherent square 16-QAM transmission system. The linewidth times symbol duration product and the optical signal to noise ratio (OSNR) are selected to be $\Delta f \cdot T_S = 10^{-4}$ and 20 dB, respectively. The filter halfwidth is $N = 8$.

As 1st stage carrier recovery a feed-forward block phase estimator with variable block length L using the Viterbi&Viterbi (V&V) algorithm and a decision-directed algorithm with a variable feedback delay of Δk symbols are considered.

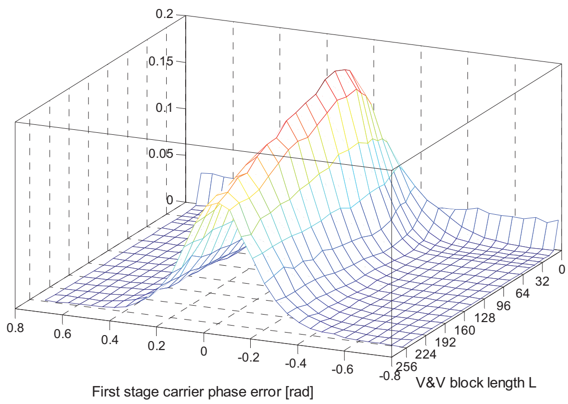

Fig. 3. First stage phase estimator accuracy using Viterbi&Viterbi feed-forward carrier recovery

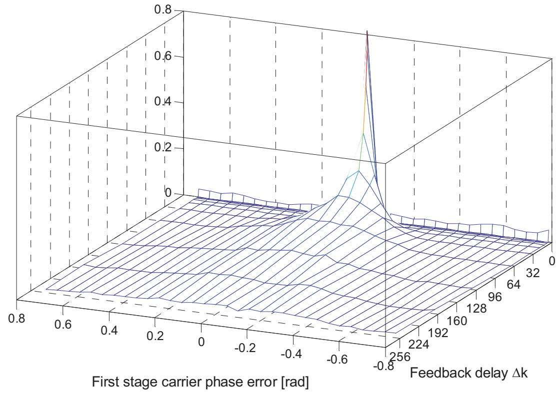

Fig. 4. First stage phase estimator accuracy using decision-directed carrier recovery

Figs. 3 and 4 show the achieved accuracy of the two considered 1st stage estimators for different block lengths L and different feedback delays Δk, respectively. The optimum block for the V&V estimator is $L = 32$. It allows to reduce the test interval of the 2nd stage estimator by a factor of 2 to [-π/8, π/8].

For small feedback delays the decision-directed estimator does not even require the 2nd stage estimator. But the estimator efficiency reduces rapidly with increasing feedback delay, and for $\Delta k > 128$ the estimator completely fails. As feedback delays below 128 symbols are not realistic in practical systems, decision-directed carrier recovery is not suitable for 1st stage carrier phase estimation with 16-QAM.

V. Conclusion

We have presented a phase noise tolerant 2-stage carrier recovery concept for arbitrary QAM constellations. Two possible 1st stage estimators have been evaluated for 16-QAM receivers. The Viterbi&Viterbi carrier recovery in the 1st stage halves the test interval needed for the 2nd stage estimator.

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