PLL-free coherent optical QPSK Transmission with realtime digital phase estimation using DFB Lasers

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Outline

- Properties of coherent optical QPSK transmission
- Description of Receiver
- Measurement Results
- Conclusions
Properties of synchronous optical QPSK

- **4 bit/symbol** (with added polarization division multiplex)
  - lower cost per bit
- Symbol rate: 40 Gbaud may suffer from nonlinear phase noise. 10 Gbaud (= 4 x 10 Gbit/s) is perfect for evolutionary retrofitting of 40 Gbit/s transponders into existing 10 Gbit/s WDM systems.
- Electrical received signals are proportional to optical fields: „Optical equalization of CD and PMD in the electrical domain“ becomes possible.
- **DFB lasers** are a must, since external cavity lasers are too costly and space-consuming.
  - Possible for synchronous QPSK with feed-forward carrier recovery
Demodulation of the QPSK signal

\[ E_S \propto c e^{j(\omega_S t + \varphi_S)} \]
\[ E_{LO} \propto e^{j(\omega_{LO} t + \varphi_{LO})} \]

Setting of 90° hybrid:
\[ (l_{11} - l_{21}) - (l_{12} - l_{22}) = \frac{\lambda}{4} \]

\[ X = \text{Re}\{X\} + j \text{Im}\{X\} = ce^{j\varphi'} \]

\[ \varphi' = (\omega_S - \omega_{LO})t + (\varphi_S - \varphi_{LO}) \]

Automatic frequency control & carrier recovery needed!
Analog carrier recovery

\[ X \propto c \cdot e^{j\phi} \]

\[ \text{delay} \]

\[ \text{demodulator} \rightarrow D \]

\[ \text{frequency multipliers} \]

\[ X^4 \]

\[ \text{filter} \]

\[ Y \]

\[ Z \]

\[ C \]

\[ C^* \propto e^{-j\phi} \]

\[ \text{regenerative frequency dividers} \]

- Frequency multiplication by a factor of 4 removes QPSK modulation
- Lowpass filtering of frequency-quadrupled carrier: in analog multipliers (Gilbert cells) and adders included, filter design part of circuit design
- Frequency division of baseband intradyne signals by a factor of 4, using two regenerative frequency dividers: \( e^{j\omega t} = e^{j2\omega t} \cdot e^{-j\omega t} \)
Digital carrier recovery

Differential encoding of angle quadrant number in transmitter

LO $E_{LO}$ | Mod. 1 | Mod. 2 | Mod. M | RX

TX | $E_S$ | $l_{11}$ | $l_{12}$ | $l_{21}$ | $l_{22}$ | $E_{TX}E_{LO}^*$

Re $X$ | Im $X$

Content of each Module (logical unit):

- Phase determination for the received modulated signal $\psi = \text{arc}(X)$: LUT
- Estimation of phase $\phi$ for the unmodulated IF carrier, based on $X$ or $\psi$
- Delay element for $\psi$ that compensates for phase estimation time (feedforward approach, avoids feedback loop problems)
- Demodulation and differential decoding, based on angles $\phi$, $\psi$ and data from logical preceding module
Random QPSK Data is generated and differentially encoded
Physical behaviour of the optical transmission subsystem is modeled
BER statistics collected after Digital Signal Processing (DSP)
Compare different Phase recovery concepts with identical input data
Simulation results (log BER vs. SNR curves)

- **Theory**: Curve is obtained without use of the simulation model
- **Ideal Phase Recovery**: Use real IF phase from physical model
- **Original Concept**: IEEE PTL, Vol. 17, 2005, pp. 887-889
- **NCF**: Nonlinear Complex Filter, best results, high effort
- **SMLPA**: Selective Maximum Likelihood Phase Approximation, 2nd best results, low effort, **chosen for implementation**
Frequency estimation for Automatic LO frequency control

- Quadrant jump numbers are generated for each pair of subsequent estimated phase angles, necessary for correct differential decoding.
- Possible values (0, 1, -1) can be interpreted as a raw estimation of instantaneous phase change velocity.
- Sum of quadrant jump numbers from 16 modules yields an estimated LO frequency.
- Sum is PWM modulated for external automatic frequency control: single output pin.
- Coarse frequency control, no OPLL.

Inconsistency between estimated IF phase and (most likely) physical course is detected and encoded for differential decoding as a quadrant jump number $n_j$. 

In the diagram:
- Quadrant jump numbers $n_j(i_0)$, where $i_0$ is the index of the chosen course.
- Physical course transitions are indicated.
- The sum of quadrant jump numbers from 16 modules yields an estimated LO frequency.
Signal processing component development

- 10 Gsps analog digital converter
- 0.25µm SiGe technology
- 5 bit Gray coded differential outputs

- Digital signal processing ASIC
- 120 nm CMOS technology
- Divide 10 GHz clock from ADC down to CMOS clock of 625 MHz
- 1:8 demultiplexer (full custom design)
- 8:16 demultiplexer, carrier and data recovery with standard cells, VHDL code verified on FPGA in experiment
Intradyne transmission results, using DFB lasers with $\Delta f < 2$ MHz (specified)

- Measured BER (I & Q averaged): $1.7 \cdot 10^{-5}$ floor
- Constant for preamplifier input power $>-37$ dBm
- Detection (PRBS synchronization) possible up to $-51$ dBm
- BER floor within capability of FEC (7%) $\Rightarrow 1.3$ Gb/s net data rate
A BER of $1.7 \cdot 10^{-5}$ was achieved, which is the lowest BER ever reported for real-time synchronous QPSK transmission with DFB lasers.

Additional phase noise tolerance (factor 2) applies for polarization division multiplex.
Realtime coherent QPSK transmission setup with FPGA

- Data rate: 700 Mbaud (1.4 Gb/s)
- Manual polarization control
- Commercial 5 bit ADCs, clocked at 700 MHz
- Automatic LO frequency control implemented
- Noisy optical front ends, much too wide optical filter (~20 GHz)
Outlook: Polarization multiplex, polarization control

- Combination of Phase and Data recovery based on Selective Maximum Likelihood Phase Approximation (SMLPA) with Polarization Control successfully simulated
- VHDL implementation on FPGA ready for subsequent experiments in extended testbed
Conclusions

- **Realtime coherent QPSK transmission with DFB lasers**
- BER floor of $1.7 \times 10^{-5}$ at 700 Mbaud (1.4 Gb/s)
- Phase noise should be unproblematic at 10 Gbaud.
- $4 \times 10$ Gb/s synchronous QPSK transmission systems with polarization division multiplex can be developed, using DFB lasers.

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[http://ont.upb.de/synQPSK](http://ont.upb.de/synQPSK)

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