Christian-Albrechts-Universität zu Kiel

Introducing Flexibility into the Network Using Multidimensional Constellations

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- **Transmission reach for ≈28 Gbaud PDM M-QAM modulation formats**
  - coherent detection
  - 50 GHz WDM grid

format	data rate	transmission reach
4-QAM	112 Gb/s	> 3000 km [1]
16-QAM	224 Gb/s	≈ 700 km [2]

≈7 dB; corresponds well to S/N loss in AWGN channel

[1]: G. Charlet et al., JLT, pp. 153-157, 2009.
[2]: M.Gunkel, ITG-Workshop, July 2012.

Introduction (2)

- **Transmission reach for ≈28 Gbaud PDM M-QAM modulation formats**
  - coherent detection
  - 50 GHz WDM grid

format	data rate	transmission reach
4-QAM	112 Gb/s	> 3000 km [1]
8-QAM	168 Gb/s	≈ 1500 km
16-QAM	224 Gb/s	≈ 700 km [2]
32-QAM	280 Gb/s	< 400 km

- **Very rough resolution of interplay of spectral efficiency and reach!**
- **Flexible transparent optical networks will benefit from higher resolution**

[1]: G. Charlet et al., JLT, pp. 153-157, 2009.
[2]: M.Gunkel, ITG-Workshop, July 2012.

Introduction (3)

- **Options to tune spectral efficiency vs. reach**
  - implement FEC with variable overhead
    - balance net data rate vs. parity information (i.e. error correction capability)
    - pros/cons:

      \+ very high resultion of spectral efficiency vs. reach

      – high effort, all possible schemes need to be implemented on chip
  - implement modulation formats with fractional numbers of bits/symbol
    - example: map 5 bits onto 2 symbols of 6-PSK each

      $\Rightarrow$4-dimensional constellation
    - pros/cons:

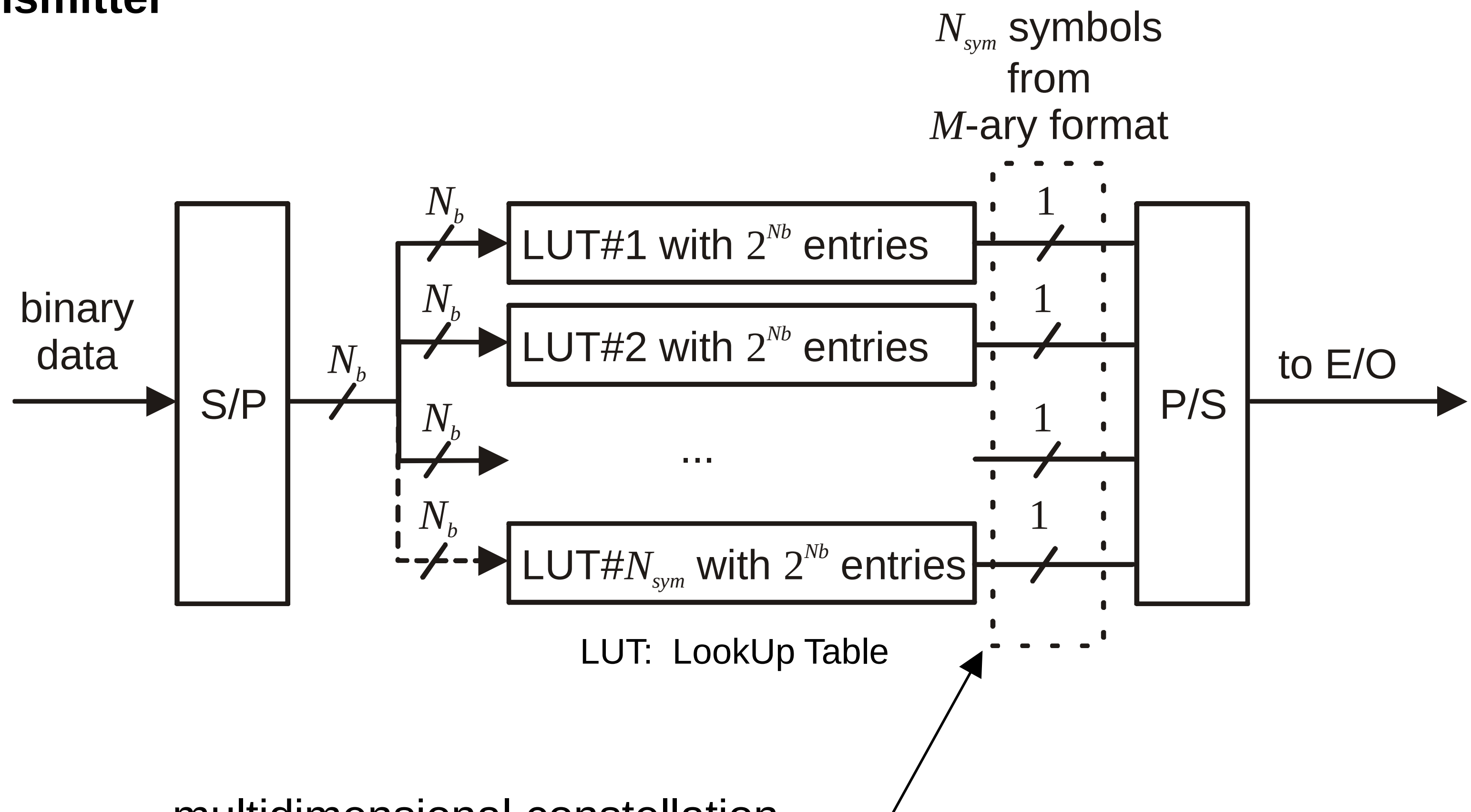
      – scheme optimization is challenging (only pre-implementation effort!)

      \+ very low effort using look-up tables of only a few dozens of entries

Outline

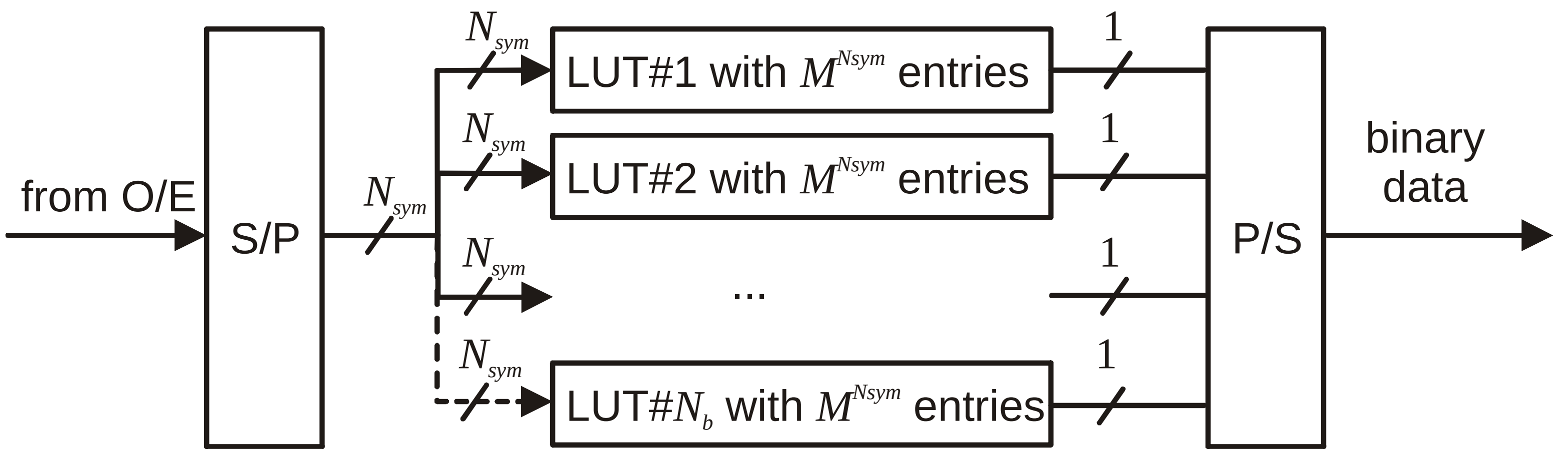
- **Basic principle of multidimensional constellations**
- **Literature**
- **Challenges**
- **Theoretical results for AWGN channel**
  - ASK-based constellation for real channel (e.g. IM/DD)
  - PSK-based constellation for compl. channel (IQ-modulation/coherent detection)
- **Experimental proof of concept with optical IM/DD channel**

- **Transmitter**



multidimensional constellation
- N_{sym} dimensions for real M-ary format (e.g. ASK)
- $2N_{sym}$ dimensions for complex M-ary format (e.g. PSK, QAM)

- **Receiver**



LUT: LookUp Table

Literature

- **1980: 3-PSK with number of bits per symbol N_b/N_{sym}=3/2**
  - J.R.Pierce, *IEEE Transactions on Communications*, pp. 1098-1099, 1980
- **1982: coded modulation (G.Ungerböck)**
  - channel coding and modulation are combined
- **mid of 1980s (L.-F.Wei, G.D.Forney)**
  - improvement of coded modulation using multidimensional constellations
- **1989: thorough investigation into multidim. constellations by Forney et al.**
  - focus:
    - coded modulation
    - maximization of power efficiency
- **focus here: flexible tuning of spectral efficiency**

Literature (2)

- **1997: fractional numbers of bits per symbol using multi-dimensional cross-QAM (e.g. 32-QAM, 128-QAM)**
  - E.A.Gelblum, *IEEE Transactions on Inform. Theory*, pp. 335-341, 1997
  - general approach for high orders
- **here: simple approach for (relatively) low orders**
- **2008: DPSK-3ASK for optical communications (M.Eiselt, B.Teipen)**
  - number of bits per symbol N_b/N_{sym}=5/2
  - ASK-part:
    - mapping of N_b=3 bits onto N_{sym}=2 symbols

    $\Rightarrow$ number of bits per symbol N_b/N_{sym}=3/2
- **here: higher resolution using real and complex formats**

Literature (3)

- **2012: Flexibility of spectral efficiency is considered as enabling technology for 400 G WDM transmission on 50 GHz grid**
  - X.Zhou et al., *IEEE JLT*, early access article, 2012
  - fractional numbers of bits per symbol is considered as one option

- **Optimization of constellation**
  - determine M such that a sufficient number of groups of symbols is provided

    example:
    - N_b=3 bits $\Rightarrow 2^3=8$ combinations
    - N_{sym}=2 symbols $\Rightarrow M^2$ combinations $\Rightarrow M=3$ results in 9 combinations

    $\Rightarrow$ 3-ary format required (e.g 3-ASK or 3-PSK)
  - eliminate M^{Nsym}-2^{Nb} redundant symbol groups to maximize power efficiency
- **Optimization of coding (i.e. mapping of bit vector onto symbols groups)**
  - Gray coding only possible for $N_{sym}=1$
  - find coding such that bit errors are minimized
  - current approach: brute force optimization based on $(2^{Nb})!$ possible schemes
- **All these challenges are pre-implementation issues!!!**

Theory: ASK-Based Constellations

- **Analytical result for AWGN-channel for arbitrary values for N_b and N_{sym}**

needs to be minimized by optimization of coding

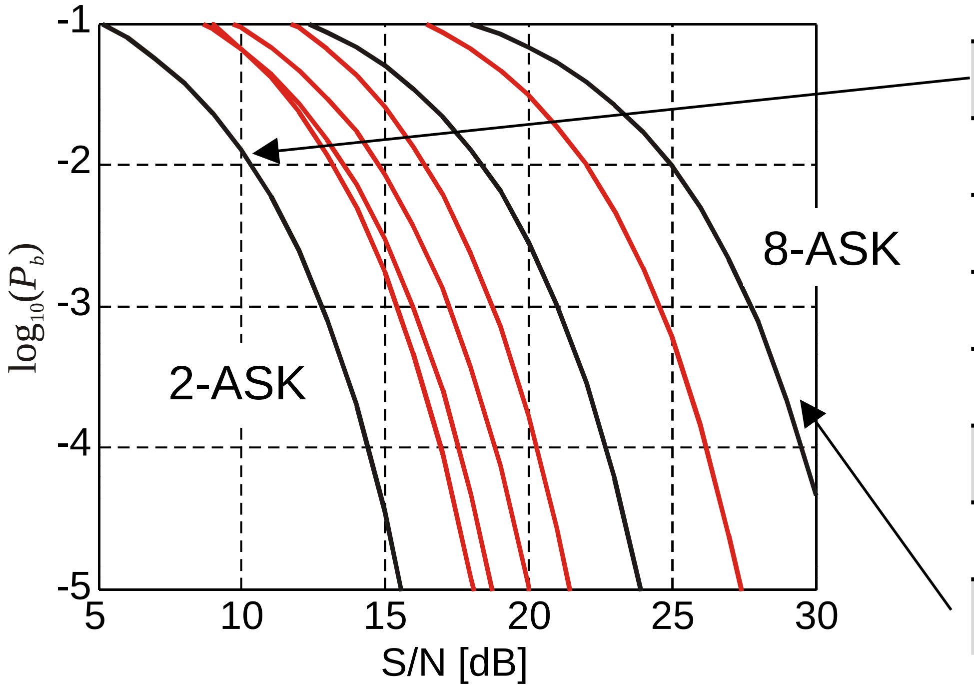
d_{min}^2/S needs to be maximized by optimization of constellation

$$P_b = \frac{G_p \cdot \sum_{m=1}^{2^{N_b}} N_N(m)}{2N_b \cdot 2^{N_b}} erfc\left(\sqrt{\frac{d_{\min}^2}{8N}}\right)$$

- $G_p>1$: Gray penalty
- d_{min}: minimum distance between symbol groups in N_{sym}-dimensional space
- $N_N(m)$: number of neighbors of m^{th} symbol group
- N: variance of noise
- S: signal power

Theory: ASK-Based Constellations (2)

- **Bit error probability for unipolar symbols**



N_b	N_{sym}	N_b/N_{sym}	M	G_p
1	1	1	2	1
5	4	1.25	3	1.45
4	3	1.33	3	1.09
3	2	1.5	3	1.14
5	3	1.6	4	1.35
2	1	2	4	1
5	2	2.5	6	1.27
3	1	3	8	1

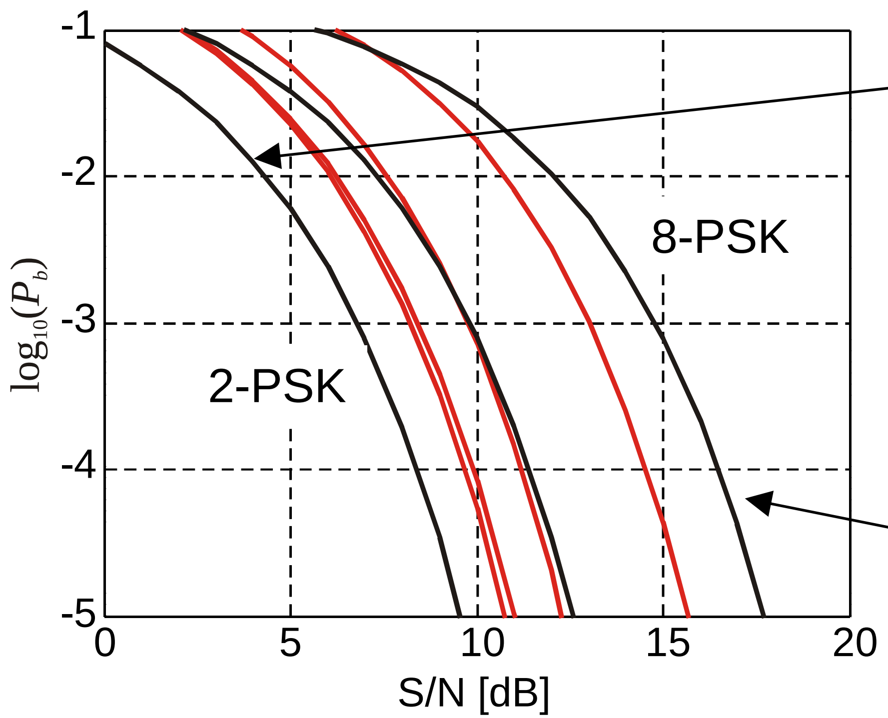
- **Formats with fractional numbers of bits per symbol increase resolution**

Theory: PSK-Based Constellations

- **Analytical result for AWGN-channel**

$$P_b = \frac{G_p N_{sym}}{N_b} erfc\left[\sin\left(\frac{\pi}{M}\right)\sqrt{\frac{S_0}{N}}\right]$$

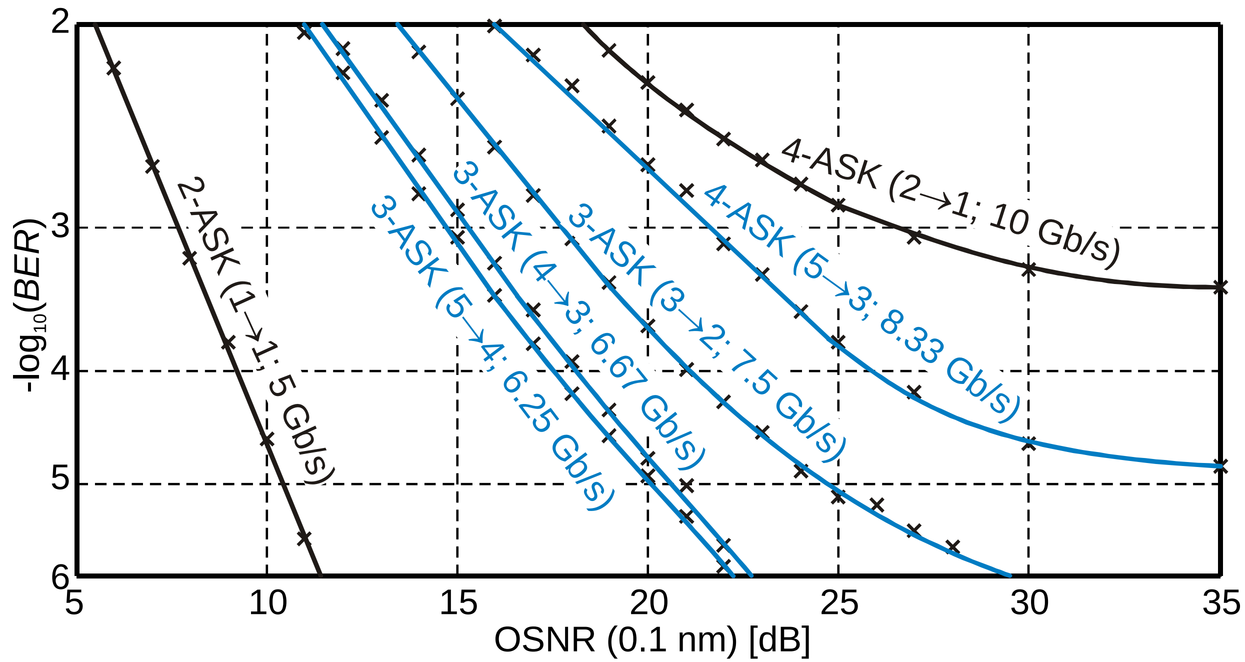
square of radius of PSK-circle



N_b	N_{sym}	N_b/N_{sym}	M	G_p
1	1	1	2	1
4	3	1.33	3	1.26
3	2	1.5	3	1.31
5	3	1.6	4	1.63
2	1	2	4	1
5	2	2.5	6	1.66
3	1	3	8	1

Experimental Proof of Concept

- **Multilevel ASK**
- **IM/DD**
- **Symbol rate: 5 Gbaud**
- **Optical back-to-back**



- **Performance of multilevel transmission (error floor at $P_b \approx 5 \cdot 10^{-4}$) suffers from**
  - limited quality of multilevel signal generation
  - limited linearity of components for optical E/O and O/E
- **Proof of concept has been shown**

Summary

- **Multidimensional constellations offer**
  - increased flexibility of interplay between spectral efficiency and reach
  - low implementation complexity
- **Theoretical results and an experimental proof-of-concept for**
  - M-ASK intended for use in IM/DD
  - M-PSK intended for use in IQ-modulation / coherent detection
- **Realization using M-QAM**
  - is expected to be feasible as well
  - requires smarter algorithms for optimization of
    - constellation
    - coding

    than those that are currently in use