PLSK vs. DPSK in Four-Wave Mixing Crosstalk

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What is PLSK (also referred to as PolSK)?
- One state of polarization (say vertical) corresponds to a "1", while the orthogonal polarization state (say horizontal) corresponds to a "0"
- Relative orthogonality is important for detection

Advantages of PLSK scheme
- Reduced sensitivity to nonlinear effects
- 3-dB improvement in receiver sensitivity over IM/DD

Commercially available from www.jgkb.com
PLSK Receivers

Type A
- Simple
- Requires polarization control
- Only for binary PLSK


Type B
- Complicated (requires differential detection and polarization cubes)
- Full extraction of Stokes parameters

Type C
- No differential detection
- Full extraction of Stokes parameters
- Needs four arms and post-processing
• What are PSK and DPSK?
  – The phase shift keying (PSK) scheme utilizes the phase of carrier waves as the information bearing parameter
  – The DPSK scheme transmits information through the phase difference of adjacent symbols (0: zero phase shift, 1: phase shift)

• Advantages of DPSK scheme
  – Reduced sensitivity to nonlinear effects
  – 3-dB improvement in receiver sensitivity over IM/DD
DPSK Transmitters

RZ DPSK Transmitter (double stage)

NRZ DPSK Transmitter (single stage)

Incoming carrier → Modulated carrier
DPSK Receiver

Modulated carrier

Asymmetric Mach-Zehnder Interferometer

Additional delay (equivalent to one bit time slot)

Demodulated signal

0 1
Problem Statement

• Hypothesis
  – For eavesdropping through FWM in a transmission fiber, using PLSK format leads to a loss of distinction between a “1” and a “0” due to the $\lambda$-dependent polarization scrambling
  – Since FWM is a phase conjugation process, the phase and DPSK format information is preserved, despite the polarization scrambling

• To prove the hypothesis
  – We simulated the generation of a FWM sideband and examined the power distribution over the two polarization axes and the orthogonality between the “1” and “0” signals along the length of the fiber
Simulation Procedures

- Coupled wave equations for FWM

\[
\frac{\partial E_{k,p}}{\partial z} = i \cdot \frac{D_p D_f}{3} \left[ D_p D_f E_{j,p} E_{j,p}^* E_{k,p} + 2 \cdot E_{j,p}^* E_{k,p} E_{l,p} \right]
\]

- Six coupled wave equations were solved by Runge-Kutta method
  - Three waves: pump, signal, conjugate, two orthogonal SOPs: x and y
  - Einstein summation \((j,k,l = p,s,c, p = x,y)\) over all possible combinations
- Degeneracy factors
  - \(D_p = 3\) when all three waves are co-polarized, otherwise \(D_p = 1\)
  - \(D_f = 2\) when all three waves are different in frequency, otherwise \(D_f = 1\)
- Nonlinear effects by weak conjugate wave onto pump and signals were ignored
- To accelerate the nonlinear effects, high pump (14.7 dBm) and signal (10 dBm) power were assumed
• SMF-28 type fiber
  – Fused silica, 4 micron core radius, $g = 2.2 \text{ km}^{-1}\text{W}^{-1}$

• Polarization characteristics
  – Birefringence $\sim 10^{-7}$
  – Random polarization mode coupling
    » Mean coupling length $L_c = 100 \text{ m}$
    » Birefringence axis rotation: random within $\pm \pi/8 \text{ rad}$

– Explicit reports on the $g$-dependence of polarization mode coupling (manifest by PMD) were not found from literature searches
– Random couplings for all three waves were assumed
– Ensemble average over 200 samples taken to obtain results
• Assumptions for simulations: *Worst-case scenario*
  – Perfectly phase matched case considered
  – Signal and pump are co-polarized (for “1”) at input

• Calculated growth of conjugate waves

  – Signal and pump were co-polarized along the x-axis
  – Due to the random polarization coupling, an orthogonally polarized y-component was generated at the conjugate wavelength
  – In 4.5 km, the two components become approximately equalized in power


• Degradation of Orthogonality

  – Two originally orthogonal signals were propagated under FWM
  – Even though the two corresponding conjugate waves have equal amount of power in both axes, they can still be decoded if they were orthogonal
  – Simulation results show that the wavelength-dependent polarization scrambling, in combination with FWM, randomizes and degrades the orthogonality

\[
\begin{align*}
\text{Conjugate #1 (C1)} & \\
\text{x-polarized pump} & \\
\text{Signal #1} & \\
\text{x-polarized} & \\
\text{Signal #2} & \\
\text{y-polarized} & \\
\text{Conjugate #2 (C2)} & \\
\end{align*}
\]

\[
\begin{align*}
\text{\begin{array}{c}
\text{C1} \cdot & \text{C2}^* \\
\text{\mid C1\mid \cdot \mid C2\mid} \\
\end{array}}
\end{align*}
\]

\[
\begin{align*}
\text{Propagation Distance [m]} & \\
0 & \\
1000 & \\
2000 & \\
3000 & \\
4000 & \\
0.0 & \\
0.2 & \\
0.4 & \\
0.6 & \\
0.8 & \\
1.0 & \\
\end{align*}
\]
Readability of FWM-generated Conjugate Wave

- **Case 1: DPSK**
  - No phase scrambling due to FWM, just conjugation
  - Readability = Conversion efficiency for one component

- **Case 2: PLSK**
  - The readability of the conjugated signal decreases as the power contrast between the two polarization component reduces
  - Readability is defined as:

\[
\text{Readability} = \frac{P_{cx}}{P_{sx,\text{ini}}^0} \cdot \frac{P_{cx}}{P_{cy}^0}
\]
Summary

• PLSK and DPSK
  – Both schemes mitigate nonlinear effects and boost receiver sensitivity
  – Transmitters for both schemes have comparable complexity
  – PLSK receivers are more complex than DPSK counterparts

• In case of eavesdropping using FWM
  – PLSK exhibits significantly lower readability beyond ~1km
  – DPSK was not affected due to the lack of phase scrambling mechanisms

• Main cause of the readability degradation in PLSK
  – Wavelength-dependent polarization scrambling

• Preliminary results so far. Future work includes
  – Clarifying the wavelength dependence of polarization scrambling
  – PMD-impact on the performance of PLSK scheme