Soliton Molecules and Optical Rogue Waves

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Part IV

State-of-the-Art Optical Telecommunication:

Soliton Molecules etc.
amplitude modulation: sidebands

[Diagram showing amplitude modulation with sidebands]

“Gimme your bandwidth!”
Coding of Data in Optical Format

This most straightforward coding is known as OOK, as for On-Off Keying, which transmits one bit per clock period.

\[ T = \text{clock period} \]

bit sequence: 0 1 0 1 1 1 0

This diagram illustrates how the bit sequence is encoded in the optical format, with peaks representing '1' and no peak representing '0'.
WDM  wavelength division multiplex
    each bitstream is modulated onto its own carrier frequency

TDM  time division multiplex
    bit streams are combined, result is modulated onto carrier

How to multiplex several data streams into one
Coding of Data in Optical Format

"Configuration space" for analog amplitude modulation as considered by Shannon

\[ C = B \cdot \log_2 \left( 1 + \frac{S}{N} \right) \]

C: capacity, B: bandwidth, n: number of symbols

Coding of Data in Optical Format

On-off-keying:

Data-carrying capacity subject to Shannon limit

Claude E. Shannon: *A Mathematical Theory of Communication*
The Bell System Tech. J. 27 (1948)

\[ C = B \log_2(n) \]

* C: capacity, B: bandwidth, n: number of symbols

with \( n = 2 \) and \( B \approx 40 \) THz \( \Rightarrow C \approx 40 \) Tbits

The Shannon limit for binary signals has been reached
Historical development of data rates in telecommunication

- Classic copper cable: ca. 15% per year
- Microwaves, beacons, satellites: ca. 20% per year
- Optics: lasers and fibers

For comparison: Moore's Law
Global Fixed Internet Traffic Volume
Hero experiments, and the Limit to Growth:
Data rates and distances achieved over single fiber

Binary coding is no longer up to the task

source: http://web.physik.uni-rostock.de/optik/
Internet data traffic volume at German switch „DE-CIX“
as of July 2014

Global IP traffic in 2014 estimated as $8 \cdot 10^{20}$ Bytes/a

Fiber-optic data transmission these days carries an enormous volume

2 Tbits / second
$10^{19}$ Bytes/a
Where there is data, it can be tapped. And it is being done.

Note: World production of hard disks currently estimated at $10^{20}$ Bytes/a
TransAtlantic Telephone Cable 14

in service since 2001
cost 1.3 billion US$
length 15 000 km
data rate 1 Tbit/s

Bude (Cornwall) pop. 9242
Coding of Data in Optical Format

\[ C = B \cdot \log_2 \left(1 + \frac{S}{N}\right) \]

C: capacity, B: bandwidth, n: number of symbols
Coding of Data in Optical Format

Advanced coding formats combine phase and amplitude modulation:
this is known as QAM (as in quadrature-phase and amplitude modulation)

32-QAM: Measured configuration diagramm

Akihide Sano et al. (21 authors),
„409-Tb/s + 409-Tb/s crosstalk suppressed bidirectional MCF transmission over 450 km using propagation-direction interleaving“

transmits 5 bits per clock period
Fiber – any glass – is a nonlinear material. This is a given.

Conventional wisdom: \textit{nonlinearity} is bad.
Mainstream approach: keep signal power low

$\Rightarrow$
- nonlinear effects are avoided
- signal-to-noise ratio issue at detection site
- limited configuration space volume

This approach will eventually run into a bottleneck
Now enter... solitons
The fundamental soliton

\[ \gamma > 0, \quad \beta_2 < 0 \quad {\text{(anomalous dispersion)}} \]

\[
A(z, T) = \sqrt{P_1} \ \text{sech} \left( \frac{T}{T_0} \right) \ e^{i\gamma P_1 z/2}
\]

with

\[
P_1 T_0^2 = \frac{|\beta_2|}{\gamma}
\]

\(z:\) position, \(P_1:\) peak power
\(T:\) time (in comoving frame) \(T_0:\) pulse duration

\(z\) dependence only in phase \(\Rightarrow |A|^2\) is independent of \(z\)
\(T\) dependence only in envelope \(\Rightarrow\) constant phase profile

Solitons are the natural bits of optical data transmission

First commercial deployments: 2001
experiment simulating long-distance transmission in the lab

LF Mollenauer et al. 1991
If the soliton has excess power, it becomes narrower
⇒ it becomes spectrally wider and suffers more loss in the filter.

Filtered line is self-correcting!
sketch to explain Gordon-Haus jitter

experimental result for ultralong distance soliton transmission

LF Mollenauer et al. 1990
- solitons can rearrange themselves and adapt to the next filter
- for linear waves the line becomes opaque
Dispersion Management

fiber with periodically alternating dispersion

Periodically alternating dispersion is advantageous for wavelength division multiplexing:

- Low path-average dispersion affords low soliton power
- High local dispersion destroys phase matching for four wave mixing
- More technical benefits...

\[ S = \frac{(\beta_+ - \bar{\beta})L_+ + (\beta_- - \bar{\beta}_2)L_-}{\tau^2} \]
Can solitons exist in dispersion-managed fibers?

Discovery of the DM soliton 1997-98 by five groups almost simultaneously


propagation of a DM soliton

propagation of a DM soliton, sampled once every dispersion period
Now enter... soliton molecules
Stable soliton compound
(exists only in DM fibers)

input pulse:

stroboscopic view:

see also:
Maruta et al: IEEE JSTQE 2002

M. Stratmann, T. Pagel, FM: PRL 95, 143902 (2005)
First experiment to demonstrate soliton compounds

M. Stratmann, T. Pagel, FM, PRL 95, 143902 (2005)
return to equilibrium separation: experimental data

stable equilibrium separation like for nuclei in a diatomic molecule „soliton molecules“

M. Stratmann, T. Pagel, FM: PRL 95, 143902 (2005)
binding mechanism understood

- local forces at different positions inside the double pulse result from the relative phases present in these positions
- integration across whole profile, weighted with local power, yields local net effect
- global net effect is found from integration over a dispersion map period
- this approach pioneered by J. P. Gordon and L. F. Mollenauer

Perturbation treatment:
Improved experimental setup

- Pulse shaper with spatial light modulator can control both amplitude and phase.
- Flip mirrors (FM) allow comparison of input/output.
- Auto/cross-correlator with spectral dispersion acquires pulse shapes.
FROG: Frequency-Resolved Optical Gating
R. Trebino et al. 1997

Autocorrelation with spectral dispersion, and a sophisticated reconstruction algorithm allows to obtain both amplitude and phase profile.
Improved experimental setup

Fiber types used:
• OFS Fitel TrueWave SRS $\beta_2 = -5.159 \text{ ps}^2/\text{km}$ 24 m segments
• OFS Fitel TrueWave RS $\beta_2 = +4.259 \text{ ps}^2/\text{km}$ 22 m segments

Length of dispersion period 46 m
Completed DM fiber line:
10 periods, total length 460 m

Compare with typical commercial system:
40 Gbit/s (25 ps clock period) uses $\tau = 7.5 \text{ ps}$
This experiment:
Pulse duration scaled down by factor of 30
Length scale scaled down by factor of 900
Experiment corresponds to system with total length 410 km

Typical pulse energies here $\approx 10 \text{ pJ}$ (scaled: 0.3 pJ)

Fiber line has 20 splices, thus power loss of 1.55 dB
Systematic tests

Evaluation of autocorrelation traces to locate equilibrium

2-soliton molecule

3-soliton molecule

Auxiliary lines indicate: input sep. equal to output sep.
Systematic tests

Evaluation of cross correlation traces to study power and phase dependence of molecule formation

2-molecule

Measured cross correlation FROG data yield relative positions and velocities
Systematic tests

Evaluation of cross correlation traces to study power and phase dependence of molecule formation

3-molecule

bisector (locus in absence of interaction)

stable equilibrium!
Single soliton, 2-molecule, and 3-molecule

- Loss reduces overall power
- Power oscillates between pulses – imbalance

All symbols could be generated and transmitted successfully
Solitons Beyond Binary: Possibility of Fibre-Optic Transmission of Two Bits per Clock Period

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Today massive streams of short light pulses are sent down optical fibers and internet traffic. The fiber’s data-carrying rate is by and large limited by the available bandwidth (≈ 30 THz) and by a fact that in coding a logical One is represented by a pulse, and a logical Zero by

0
1
2
3
4 Symbols = 2 bits/clock

Physical Review A 87, 043834 (2013)

Two-soliton and three-soliton molecules in optical fibers

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(Received 12 February 2013; published 25 April 2013)

An experimental study of bound states of two solitons and of three solitons in dispersion-managed fibers is presented. The existence regime and stability of such soliton molecules is investigated. With a programmable pulse shaper we can flexibly shape launch signals; received signals are detected in amplitude and phase, and in relative position and velocity. An equilibrium separation is demonstrated for both two-soliton and three-soliton soliton molecules. It is also shown that stable molecules are possible only with antiphase pulses. Both types of soliton molecule are viable for transmission in the same fiber, at the same wavelength. Together with single solitons this opens the possibility of quaternary data transmission in a soliton-based format.

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I. INTRODUCTION

Today’s telephone and internet traffic is accommodated by massive streams of short light pulses passing through optical fibers. To keep up with the ever-increasing demand by data-hungry applications, the data-carrying capacity of fibers 40 Gbits/s channels. However, the demand grows so rapidly that one is now faced with a “capacity crunch” [5]. Economic considerations favor the continued use of existing (legacy) fibers. But then the only option for further improvement is to find coding schemes which go beyond the binary format.
Higher-order equilibrium states

Several authors have suggested that more than a single equilibrium separation exists:

• A. Maruta, T. Inoue, Y. Nonaka, Y. Yoshika, IEEE J. Selected Topics Quant. El. 8, 640 (2002)
• M. Shkarayev, M. G. Stepanov, Physica D 238, 840 (2009)

What do we know about the equilibrium separation?

In Phys. Rev. A 78, 063817 (2008) we had used a perturbative ansatz assuming Gaussian pulses

⇒ Interaction induces frequency shifts which cause velocities ⇒ effective 'force'

⇒ Existence of an equilibrium could be established

That approximation is not very good at
  ... very small separations (perturbation not small)
  ... large separations (pulse tails not Gaussian)

In a modified ansatz we now used actual pulse shapes (determined numerically) improved validity at larger separations!

Higher-order equilibrium states

- Hierarchy of equilibrium states
- Alternatingly stable / unstable for both in-phase and opposite-phase pulses
- Globally lowest separation state is for opposite phase pulses, and is always stable
- With increasing separation, the binding energy decreases
- Hierarchy truncated at radiative background level

Circles mark stable equilibrium positions:
- opposite-phase pulses
- in-phase pulses

Unstable equilibria not highlighted

Higher-order equilibrium states

- Opposite phase pulse pairs: lowest state is stable
- In phase pulse pairs: lowest state is unstable
- More states are not observed due to radiative background

Beyond-Binary Coding with Soliton Molecules

Transmits two bits of information per time step

- Enhances data-carrying capacity of fiber twofold
- Can be combined with other advanced schemes

Nonlinearity taken into account from outset

- No need to keep signal power very low
- Improved robustness against perturbations

Works with legacy fibers

- Avoids to introduce large-core or multicore fibers

Experiments under way to test...

- In-line amplification with Er-doped fiber
- Collision behavior
Next steps I: Induce collisions

- Carve structures from laser pulses with pulse shaper
- Can simultaneously generate pulses with different frequency and timing
- By dispersion, that amounts to nonzero relative propagation velocities

⇒ Pulses are set on collision course!
   Collision point can be: at fiber end, or before, or beyond
Next steps I: Induce collisions
cooperation: Maria Lubs

Simulation results for simplest case: NLSE soliton collisions in standard fiber

Frequency difference corresponds to relative velocity
Data as seen at fiber end (fixed position)
Next steps I: Induce collisions
cooperation: Maria Lubs

Corresponding experimental data
Next steps II: Introduce gain cooperation: Jan Froh

Gain in Er-doped fiber to compensate all loss
Dispersion landscape minimally disrupted
Resulting fiber line $\approx$ twice as long

- Dispersion values of all fibers have been measured (white-light interferometry)
- Required fiber lengths have been determined
- Gain has been verified, final assembly completed, first data taken
- Evaluation in progress
Take-away messages:

• Optical fiber beats all other data conduits due to large bandwidth and low loss.
• Traffic growth used to be exponential; may show first signs of slowing growth.

  Possible reasons:
  * number of users begins to saturate
  * binary coding hits limit; quest for nonbinary coding is on
  * efficiency does not keep up, rising expense

• Linear coding schemes run into new bottlenecks.
• Soliton concept is elegant, and can be quaternary.

stay tuned....