100 GbE Passive Optical Access Networks

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Supervised by: Dr. Seb Savory

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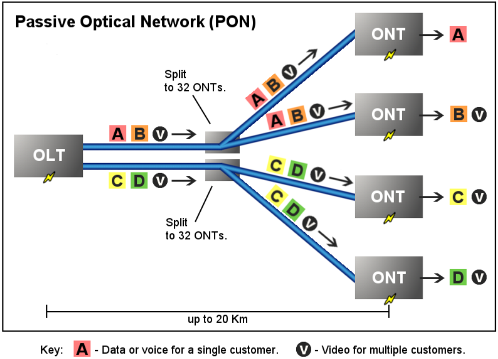
- Point-to-multipoint
- Unpowered beam splitter
- "Everything sent to everyone"



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Need for high-speed (100 Gb/s) PON

- Fibre-to-the-home?
- Well-served by 1 Gb/s PON, mature (mass deployment $>$ 1 decade)

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- Fibre-to-the-home?
- Well-served by 1 Gb/s PON, mature (mass deployment $>$ 1 decade)
- Reuse existing fibres in other applications
- Mobile
  - Increase density in cell sites $\rightarrow$ PON to deliver backhaul
  - Possible 5G fronthaul: radio receivers sample RF signals and relay them to centralized location for processing

Direct detection vs coherent receivers

- Direct detection receiver
  - Single photodiode with amplifier
  - Rx current $\propto$ received optical power (Phase information lost)
  - On-off keying (mainly)
- Coherent receiver
  - $\propto$ real and imaginary parts of received electrical field
  - Polarization-division multiplexing
  - Phase-shift keying, quadrature amplitude modulation

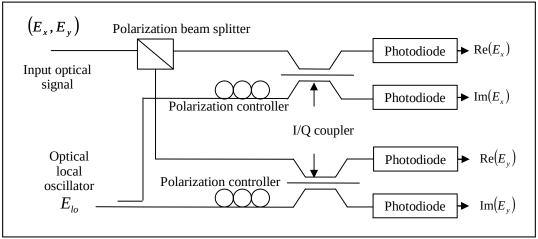


Image credit: Seb J. Savory, "Digital filters for coherent optical receivers," 2008.

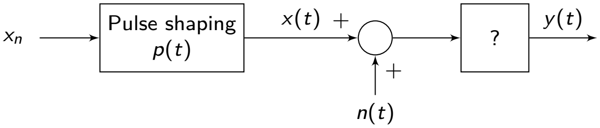
Aims of this project

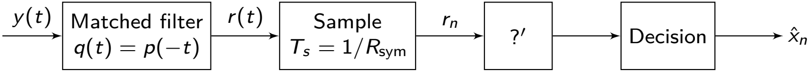
- Build simulation models for optical networks with coherent receivers
- Use DSP to correct for fibre effects
- Simulate different options for achieving 100 Gb/s
- Experimentally validate simulation results
- Evaluate feasibility to use in PONs

Simulations performed thus far

QPSK with symbol rate 25 GBd over AWGN channel

- Chromatic dispersion
- Adaptive equalizer
- Phase noise (laser linewidth)





Chromatic dispersion

- Group speed of light varies with wavelength
- Modelled as linear system, impulse response:

$$g(z,t) = \sqrt{\frac{c}{\mathrm{j}D\lambda^2 z}} \exp\left(\mathrm{j}\frac{\pi c}{D\lambda^2 z} t^2\right)$$

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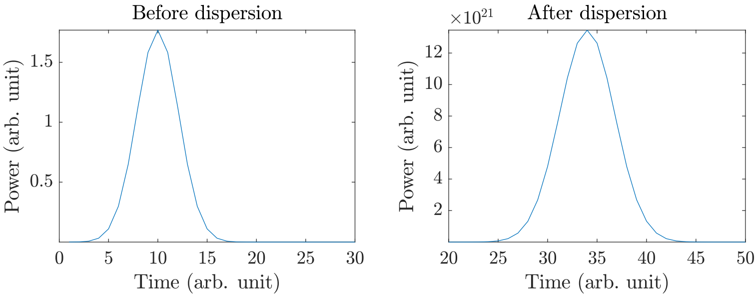

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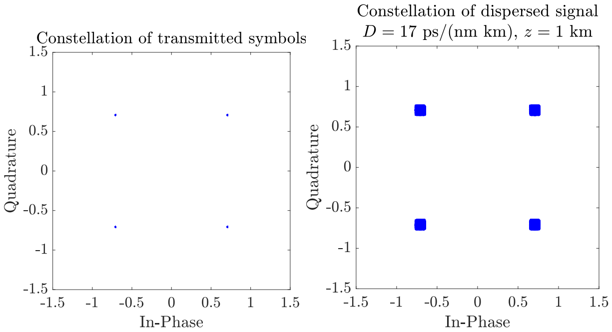

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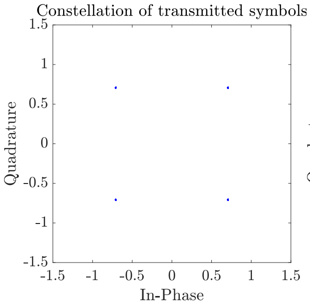

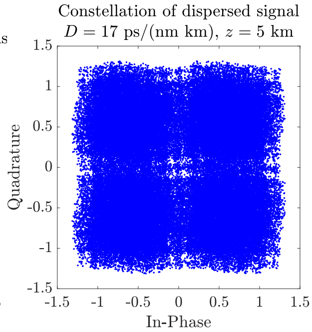

Chromatic dispersion compensation

$$g_{\mathrm{c}}(z, t) = \sqrt{\frac{c}{\mathrm{j}(-D)\lambda^2 z}} \exp\left(\mathrm{j}\frac{\pi c}{(-D)\lambda^2 z} t^2\right)$$

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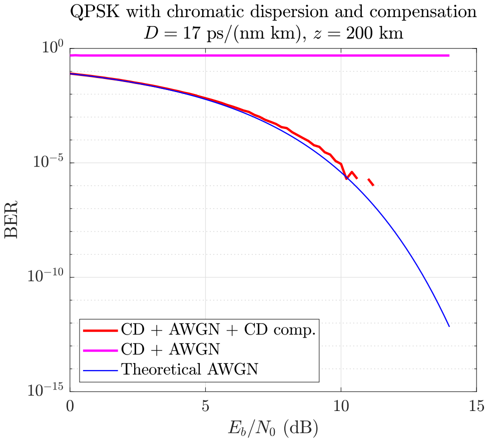

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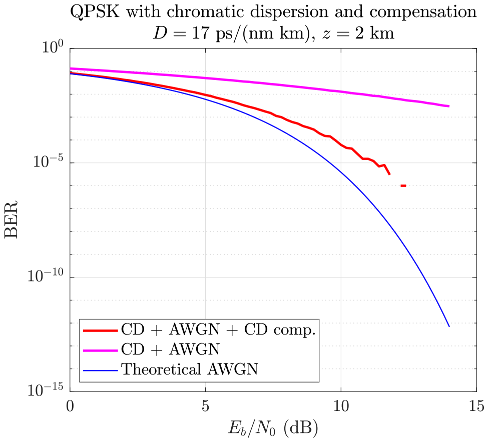
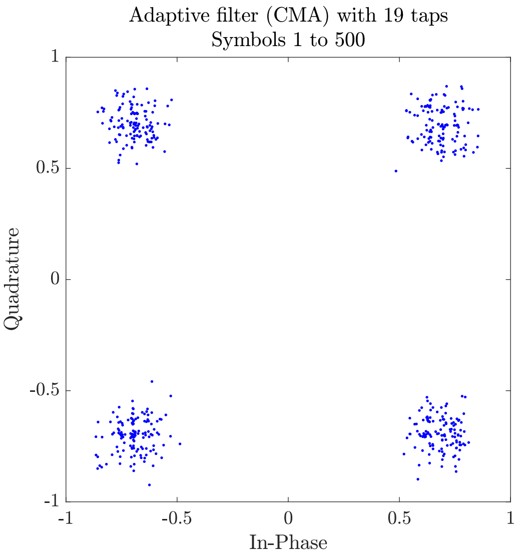


Adaptive equalizer

- Error of previous symbol fed back to change filter tap weights
- Can correct for static and time-varying effects
- Constant modulus algorithm (CMA)
- For PSK, magnitude of transmitted symbols is constant (unity)
- Error signal is distance of received signal from unit circle

Adaptive equalizer: convergence



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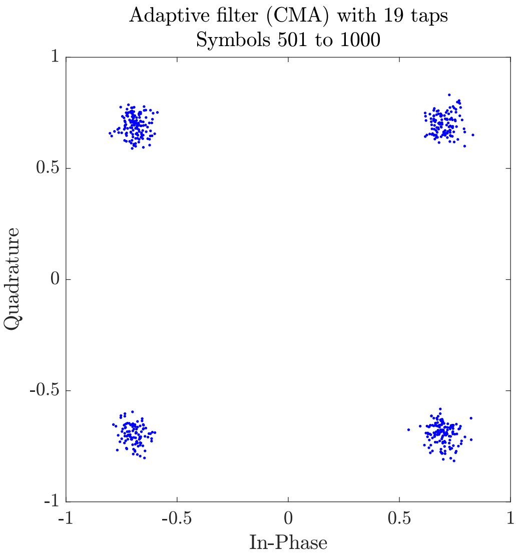

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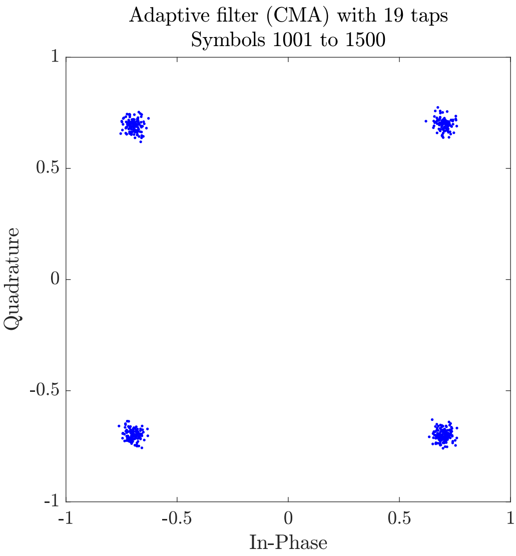

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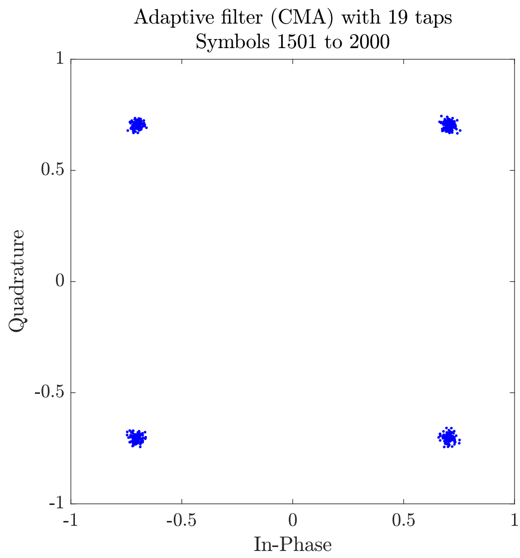

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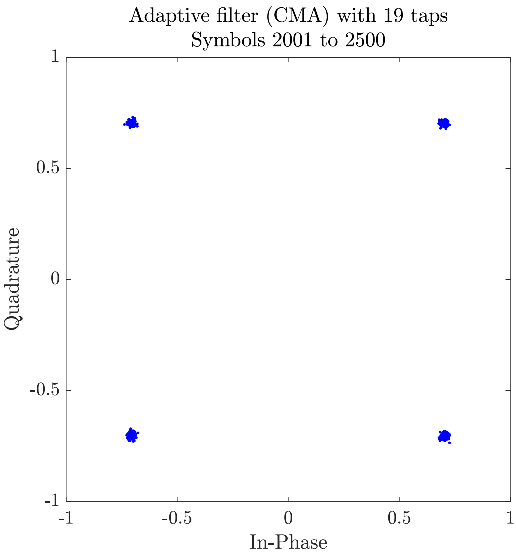

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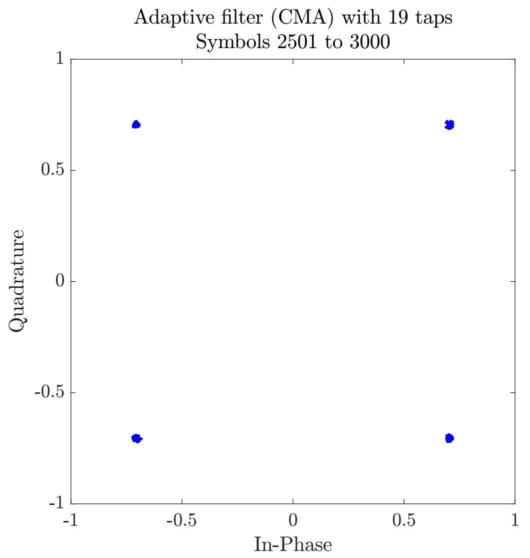

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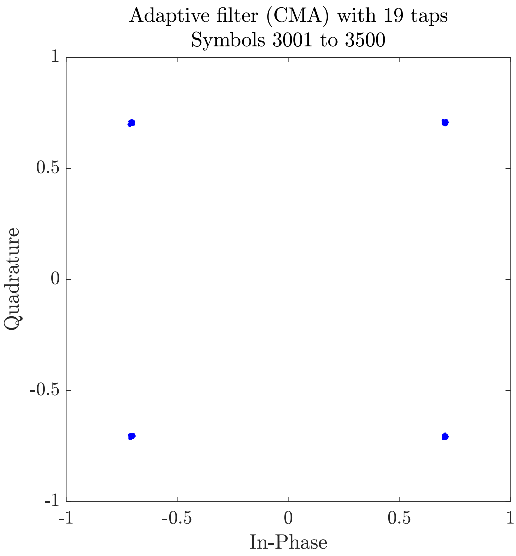

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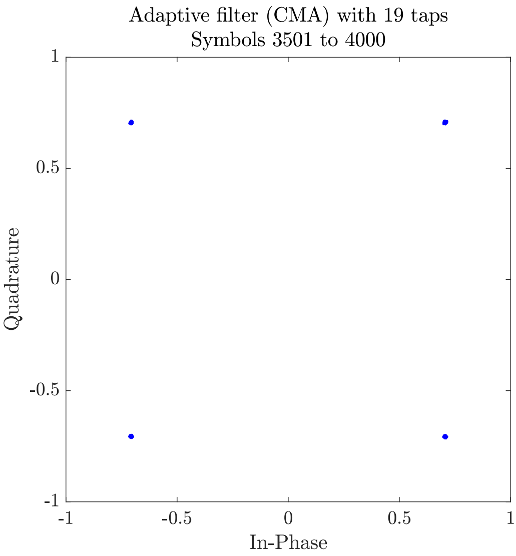

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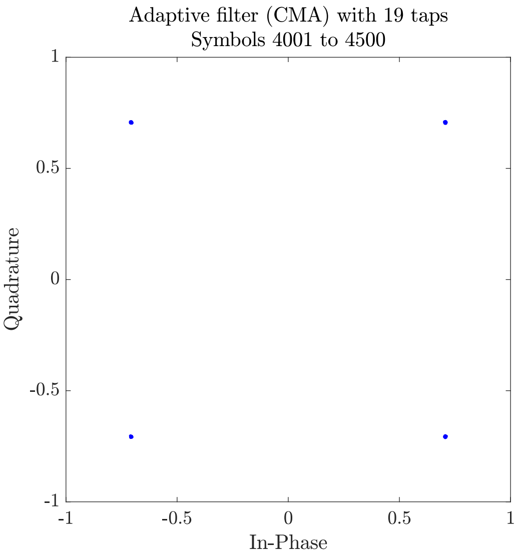

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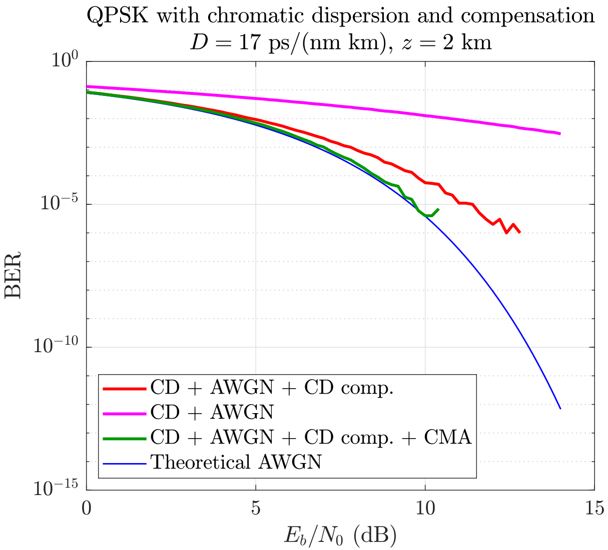
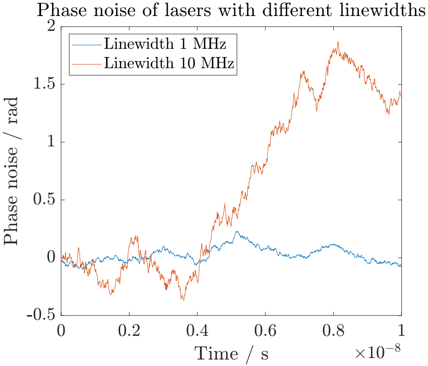


Laser phase noise

- Laser linewidth: deviations from the nominal wavelength
- Instantaneous change in wavelength (frequency) $\rightarrow$ change in phase
- $\phi[k]$ modelled as *one-dimensional Gaussian random walk*

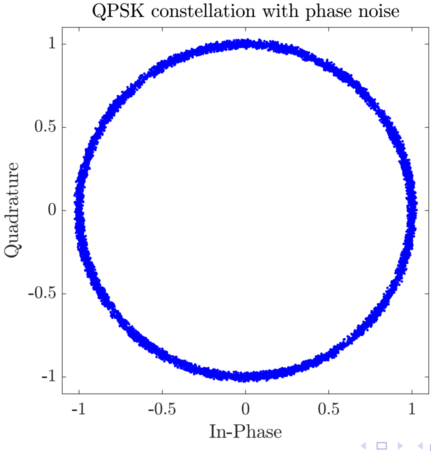
$$\phi[k] = \phi[k-1] + \Delta\phi$$

$$\text{where} \quad \Delta\phi \sim \mathcal{N}(0, 2\pi\Delta\nu T_s)$$



Laser phase noise

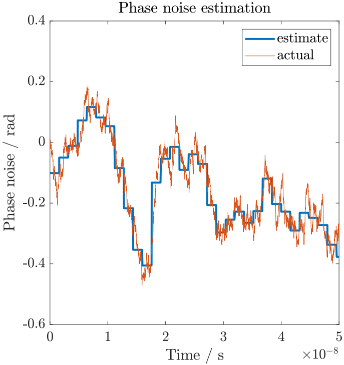
- Rotates symbol constellation
- Problematic, e.g. for QPSK, rotation by $\pi/2$ gives another constellation with all symbols decoded wrongly



Laser phase noise: solutions

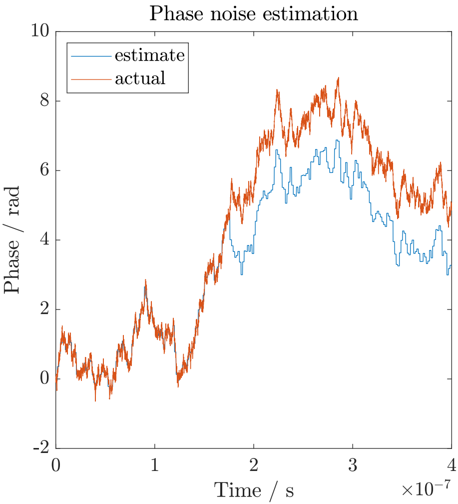
- Differential PSK
- Information encoded as the difference in phase with previous symbol
- Difference in phase noise between consecutive symbols small
- 2 dB penalty at $\text{BER} = 10^{-3}$

- Estimate phase noise by Viterbi-Viterbi algorithm
- Taking average over a small block of samples



Cycle slips

- At large linewidths, Viterbi-Viterbi algorithm can make mistakes
- For QPSK the phase estimate can be off by *pi*/2
- All subsequent symbols will be decoded incorrectly



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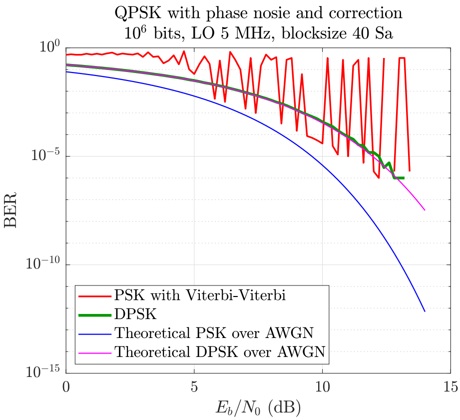

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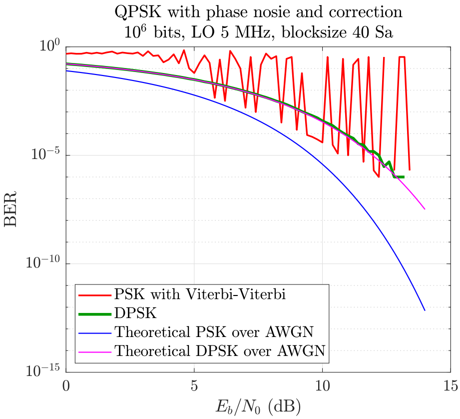

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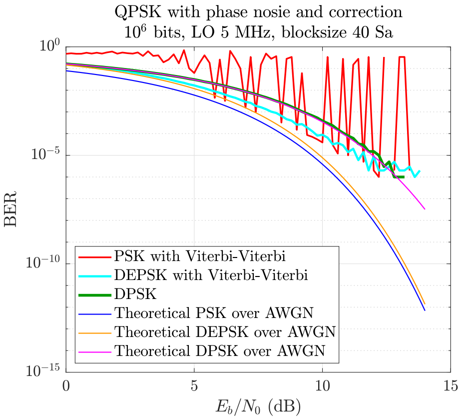

What next?

- Integrating CD and phase noise into a single system
- Adaptive equalizer
  - Decision-directed algorithms
  - Training sequences
- QAM
- Polarization-division multiplexing
  - Polarization mode dispersion
  - Adaptive equalizer
- Non-linear effects

Viterbi-Viterbi algorithm

Assume $\hat{\phi} \approx \phi[1] \approx \phi[2] \approx \cdots \approx \phi[N]$

$$r[k] = \exp\left(\mathrm{j}\phi[k] + \mathrm{j}\frac{\pi}{4} + \mathrm{j}\frac{d[k]\pi}{2}\right) + n[k]$$

$$r[k]^4 = \exp\left(\mathrm{j}4\phi[k] + \mathrm{j}\pi\right) + n'[k]$$

$$\sum_{k=1}^{N} r[k]^4 \approx N\exp\left(\mathrm{j}4\hat{\phi} + \mathrm{j}\pi\right) + n''$$

$$\hat{\phi} \approx \frac{1}{4}\arg\left(-\sum_{k=1}^{N} r[k]^4\right)$$