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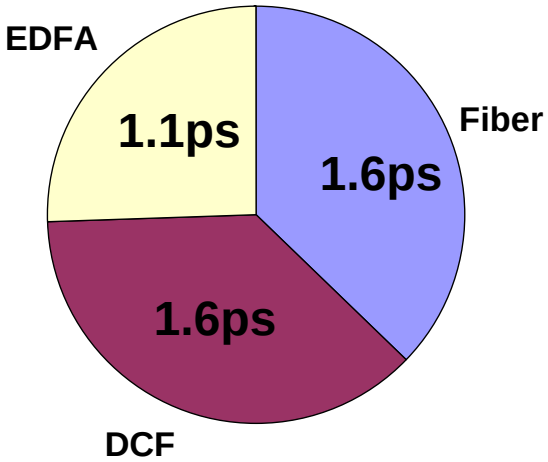
Techno-economic considerations for managing real world installed fiber plant PMD

Observations of the “real world challenge”…

- Around 50% of carriers worldwide have known PMD problems in their networks
- Typically, the early adopters of fiber optics (established IXCs and PTTs) have the biggest PMD problem
  - Older vintage fiber where PMD was not controlled in the manufacturing process
  - Some exceptions have deployed new fiber, e.g. AT&T
  - New carriers such as Level (3) and Qwest deployed new fiber and are in better shape
- Of the high PMD fiber plant, approx. 90% have link PMD of 8ps or less
- The other 10% can have PMD as high as 20ps
- Dynamic changes in PMD statistics less well-characterized than the magnitude of DGD
  - Needs more field study

PMD budget for new fiber systems



$\Rightarrow$ 2.5ps total PMD = 40Gb/s limit
($\sqrt{\Sigma\tau^2}$ addition)

Assumptions:
Route length = 1,600km
Number of spans = 20
Fiber PMD = 0.04ps/√km;
DCF PMD = 0.08ps/√km;
EDFA PMD = 0.25ps

- For DWDM systems deployed with new fiber, DCF and EDFAs make comparable contributions as fiber to the total PMD
- 40Gb/s is a “sweet-spot” for operation on new fiber systems
- 50Gbaud is likely a max rate for new fiber system operation without PMD compensation

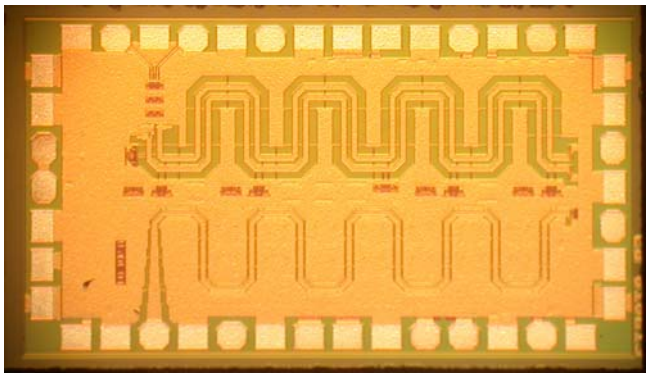
Cost of PMD mitigation

- There will always be a tax payable to enable higher capacity transport on high PMD fiber. Options:
  1. Deploy or lease new fiber
  2. Use electronic or photonic PMD compensators
  3. Deploy more OEO regenerators
  4. Use more advanced modulation formats
  5. Stick with lower speed line rates

- The PMD mitigation solution that works for 40Gb/s will not necessarily work for 100Gb/s
  - PMD mitigation complexity [and cost] increases with bit rate
  - Carriers with high PMD fiber will eventually HAVE TO deploy new fiber, or live with a growing competitive disadvantage as transmission speeds increase
  - Or live with IMUX'ing

40Gb/s PMD compensation technology

Electrical



vs

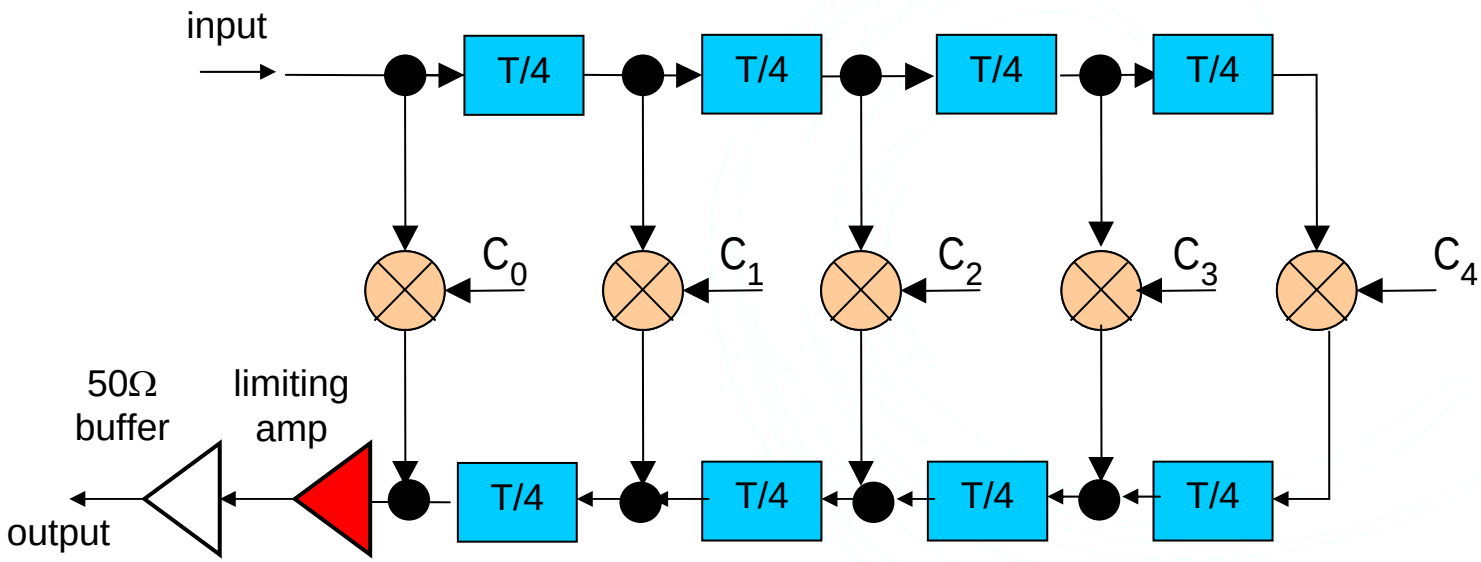
Optical

- SiGe equalizer IC
- Compensates 4ps <DGD>
- Can be integrated with CDR
- Fast, ms tracking speed
- Low cost

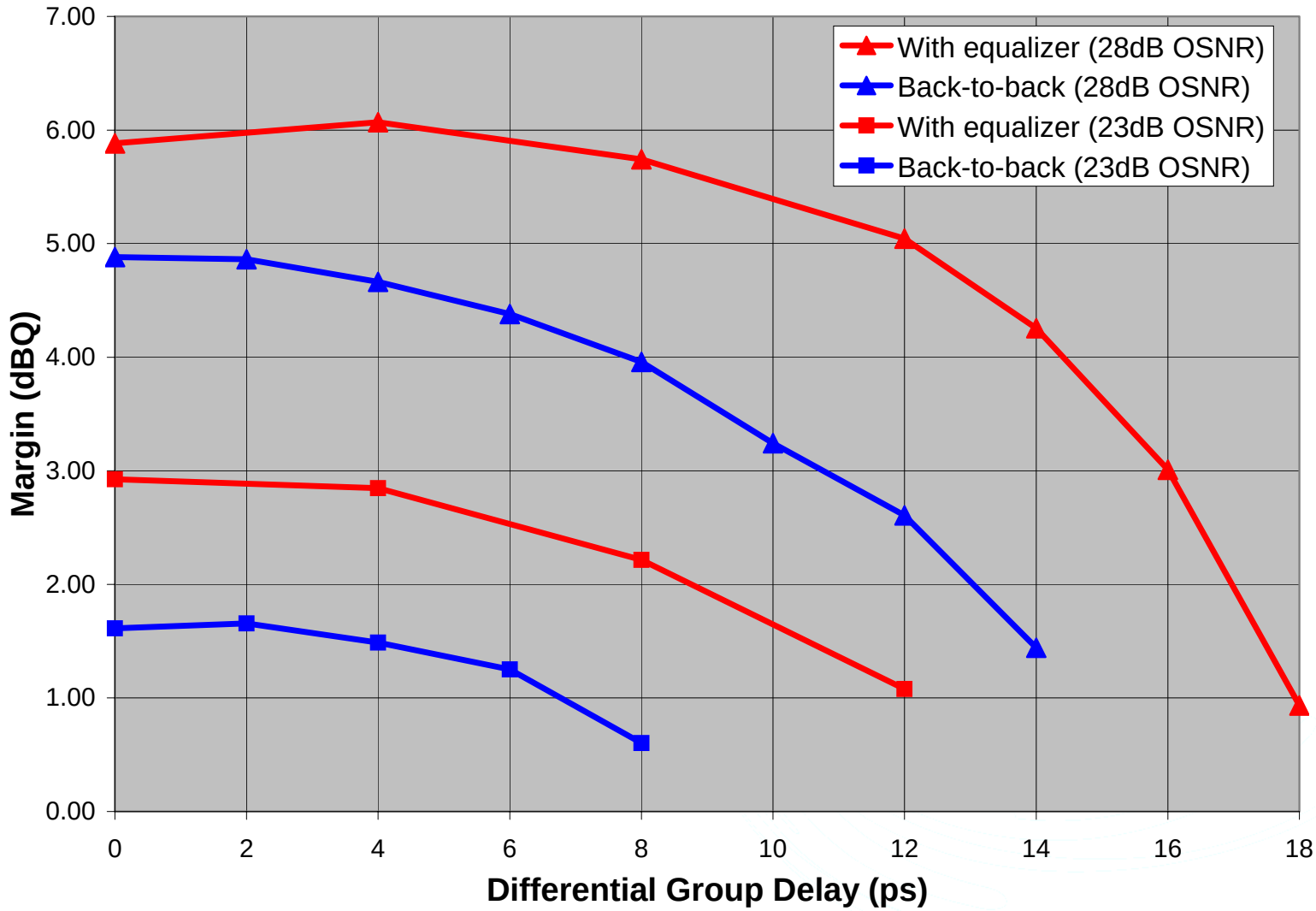
- Uses discrete optical components
- Compensates 8ps <DGD>
- Separate optional module
- Fast, ms tracking speed
- Higher cost

Electronic PMDC architecture

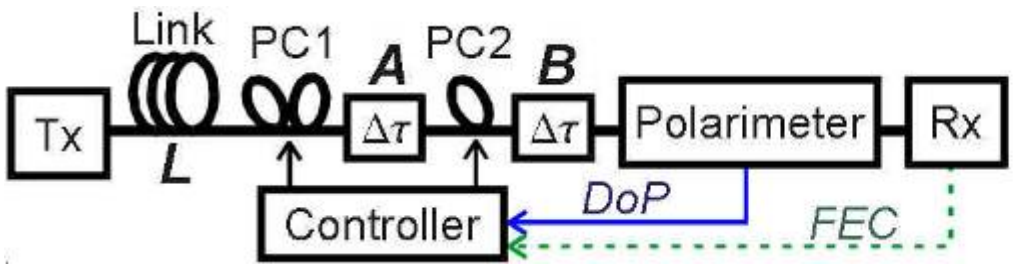
- Finite Impulse Response (FIR) equalizer
- Uses SiGe BiCMOS 200GHz f_t process
- Results presented at OFC 2006:
  - Talk: **Advances in SiGe ICs for 40G Signal Equalization**
    Session title: OTuE - Electronic Impairment Compensation
    Pres. no.: OTuE1

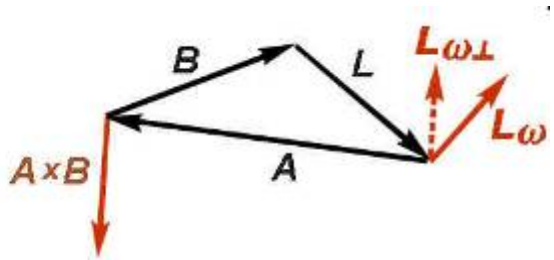


PMD sensitivity with equalizer



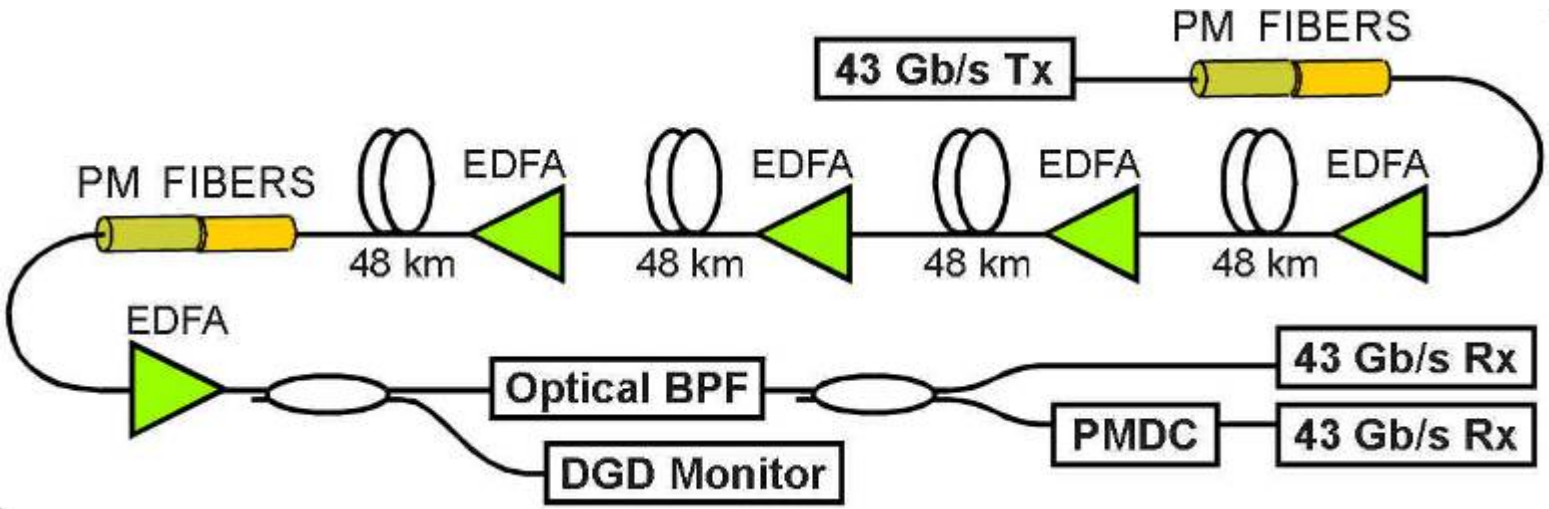
Optical PMD compensator





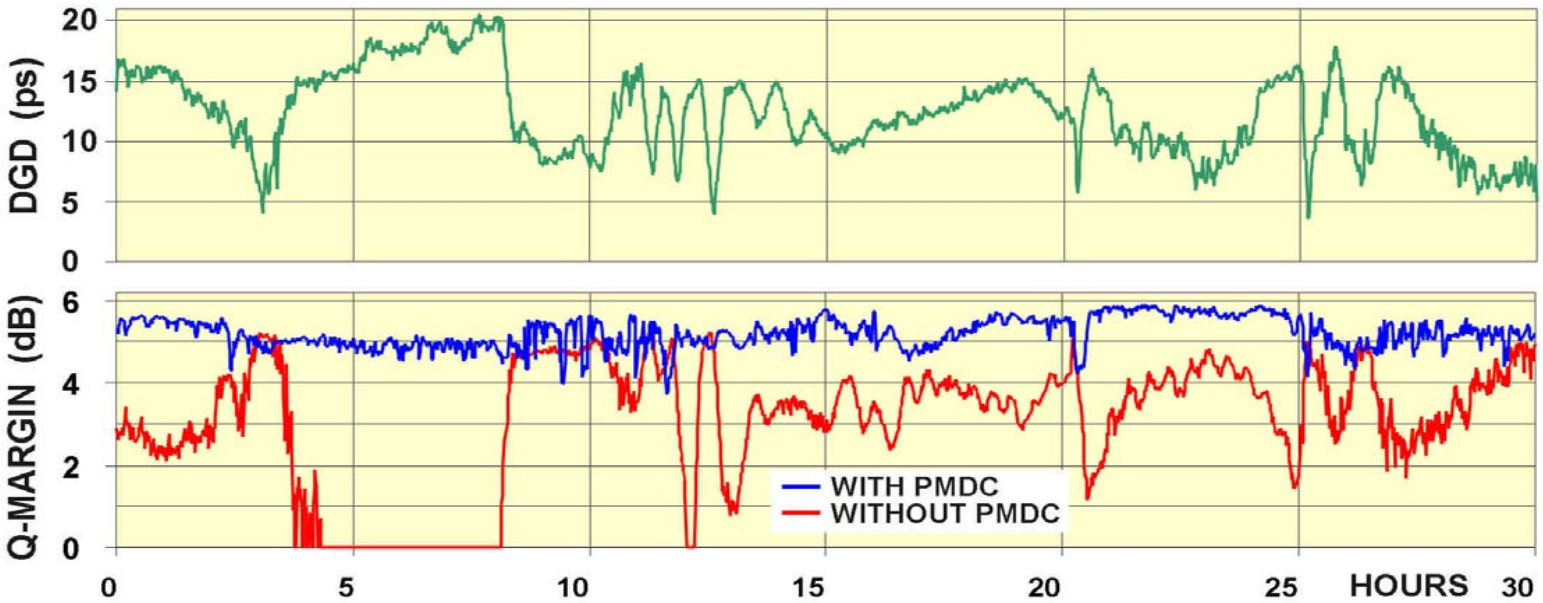
- 2 stages: fixed DGDs with electro-optic PCs
- Signal quality judged by degree of polarization
- Sets A+B = -L for DGD compensation
  - No local minima to trap control loop, in contrast to 1st-order compensator
  - Scanning Tx polarization has little effect
- Some 2nd-order compensation is possible
- 50-us dither cycle (now upgraded to 5 us)

Sprint test bed measurement setup



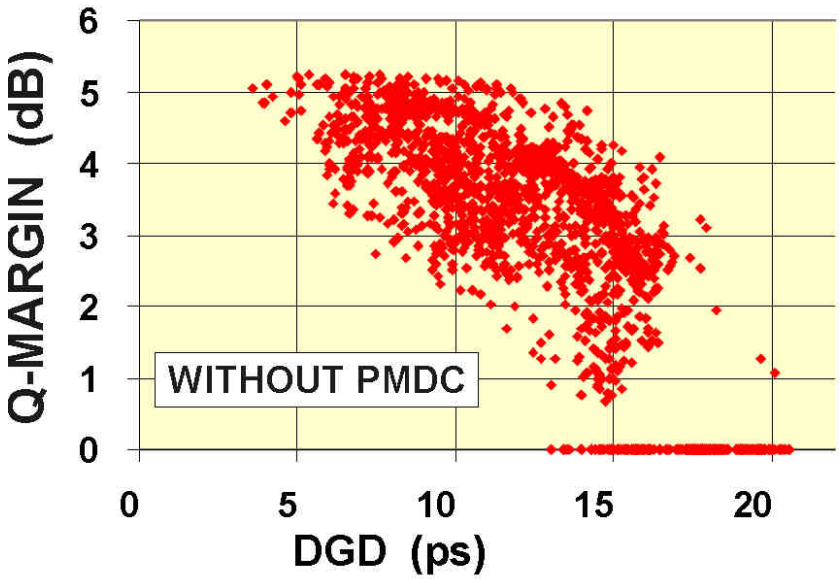
- Signal split to simultaneous measurements:
  - DGD monitor
  - Rx without PMDC
  - Rx with PMDC
- Direct measure of PMDC benefit vs DGD
- Slow polarization changes – scrambling inside DGD monitor only

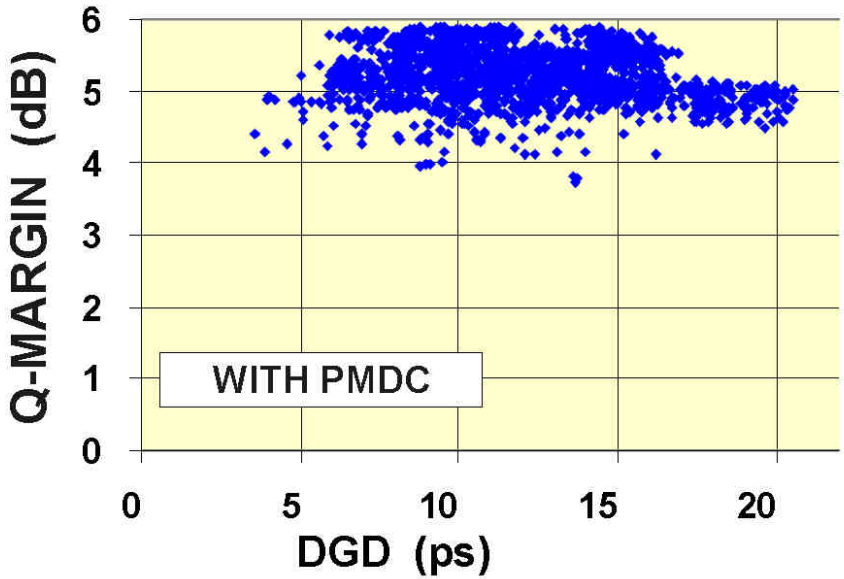
DGD vs Q margin correlation



- DGD varied over 5~20 ps in 30 hours with high PMD
- Without PMDC, Q-margin varied opposite to DGD
  - Good Q-margin for DGD < 8 ps (bit period is 23.3 ps)
  - Q-margin degrades rapidly as DGD increases
- With PMDC, Q-margin remained steady
- Full results will be presented on Thursday (NTuA1)

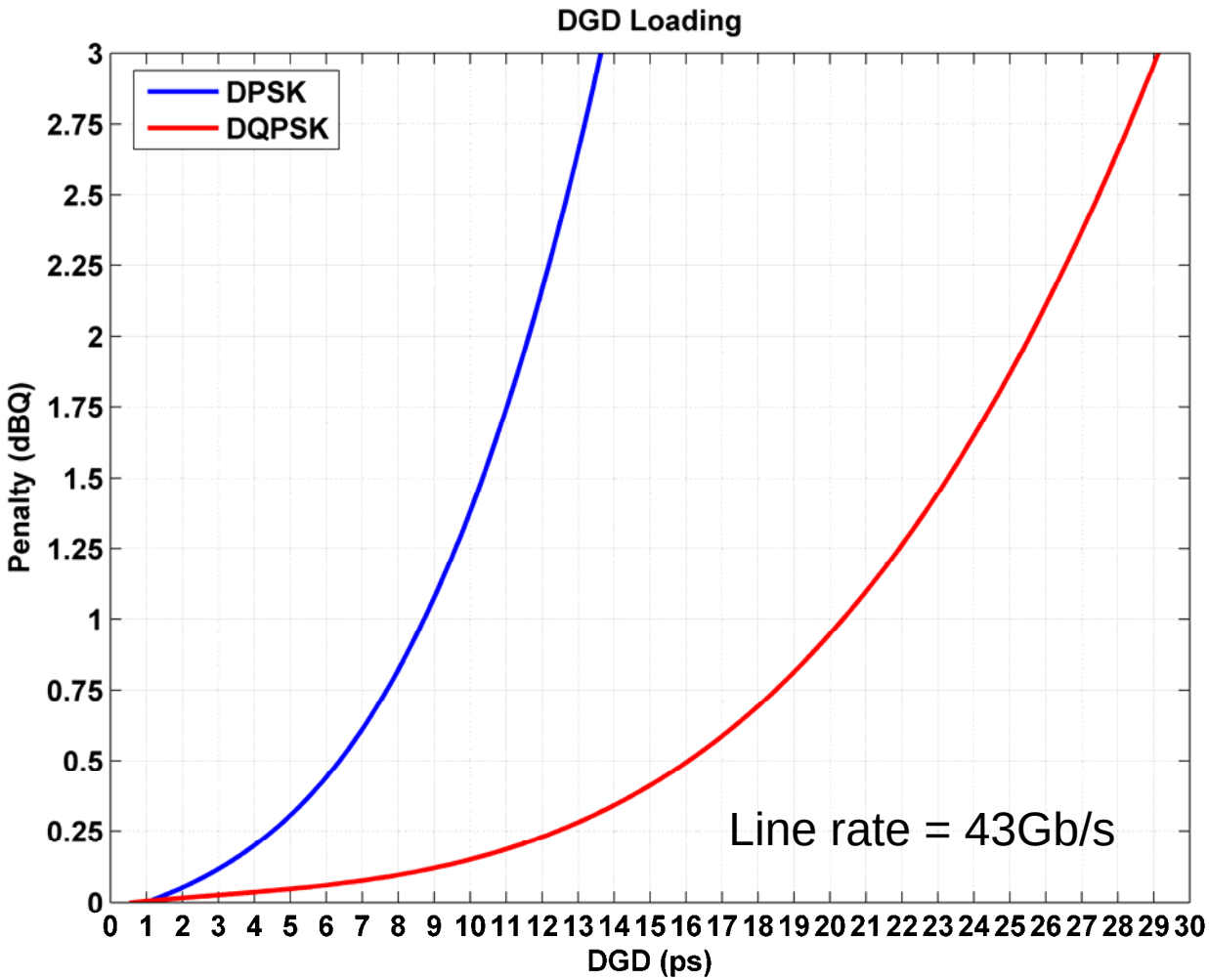
Correlation between DGD and Q





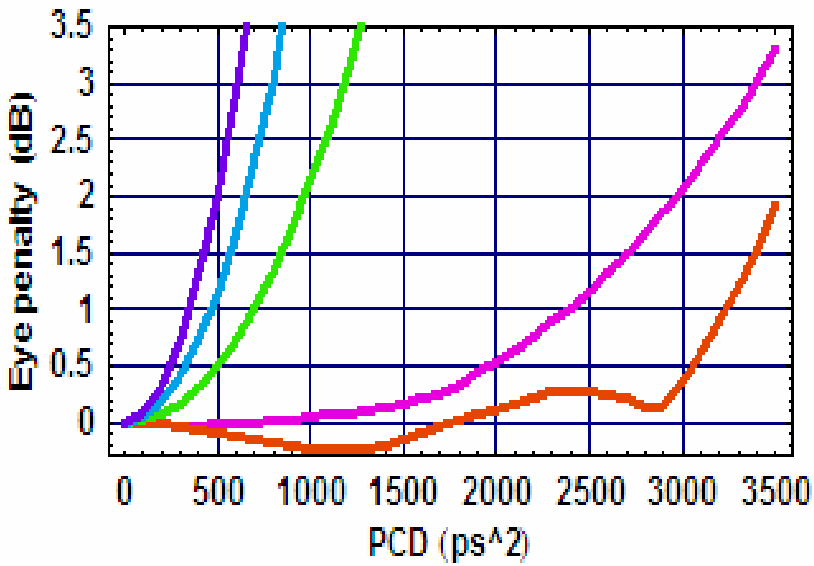
- Results taken over 3 week field soak
- Scatterplots show connection between high DGD and poor Q-margin without PMDC
- PMDC breaks the correlation between DGD and Q
- Without PMDC, framing often lost for DGD > 13 ps
- With PMDC, consistent Q-margin

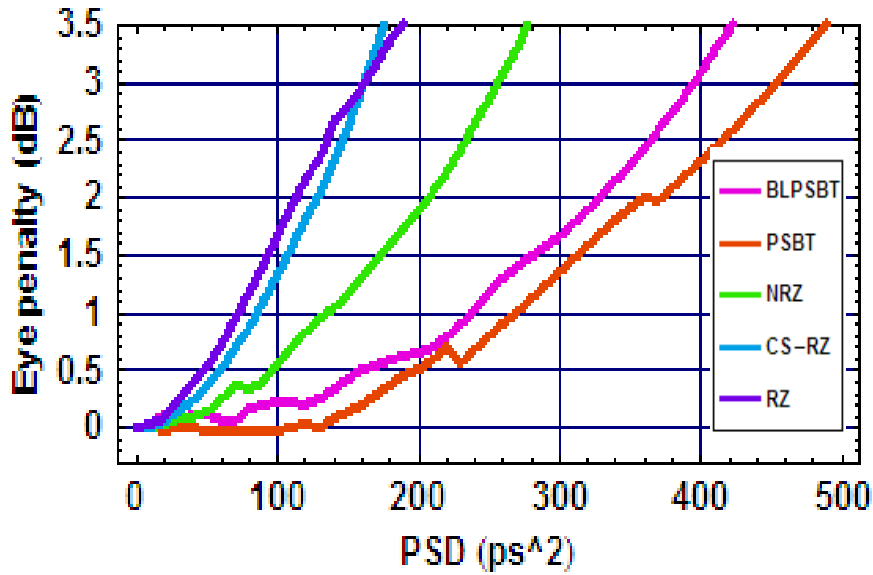
Use more bits per baud…



Impact of 2nd order PMD tolerance

- High order PMD is angular, so using spectrally efficient modulation reduces its impact on eye distortion
- PSBT shows superior tolerance to 2nd order PMD
  - Polarization State Depolarization (PSD)
    - 2x improvement over NRZ; 4x improvement over RZ
  - Polarization Dependent Chromatic Dispersion (PCD)
    - 6x improvement over NRZ; 9x improvement over RZ
- Simplifies PSBT PMDC design to 1st order only

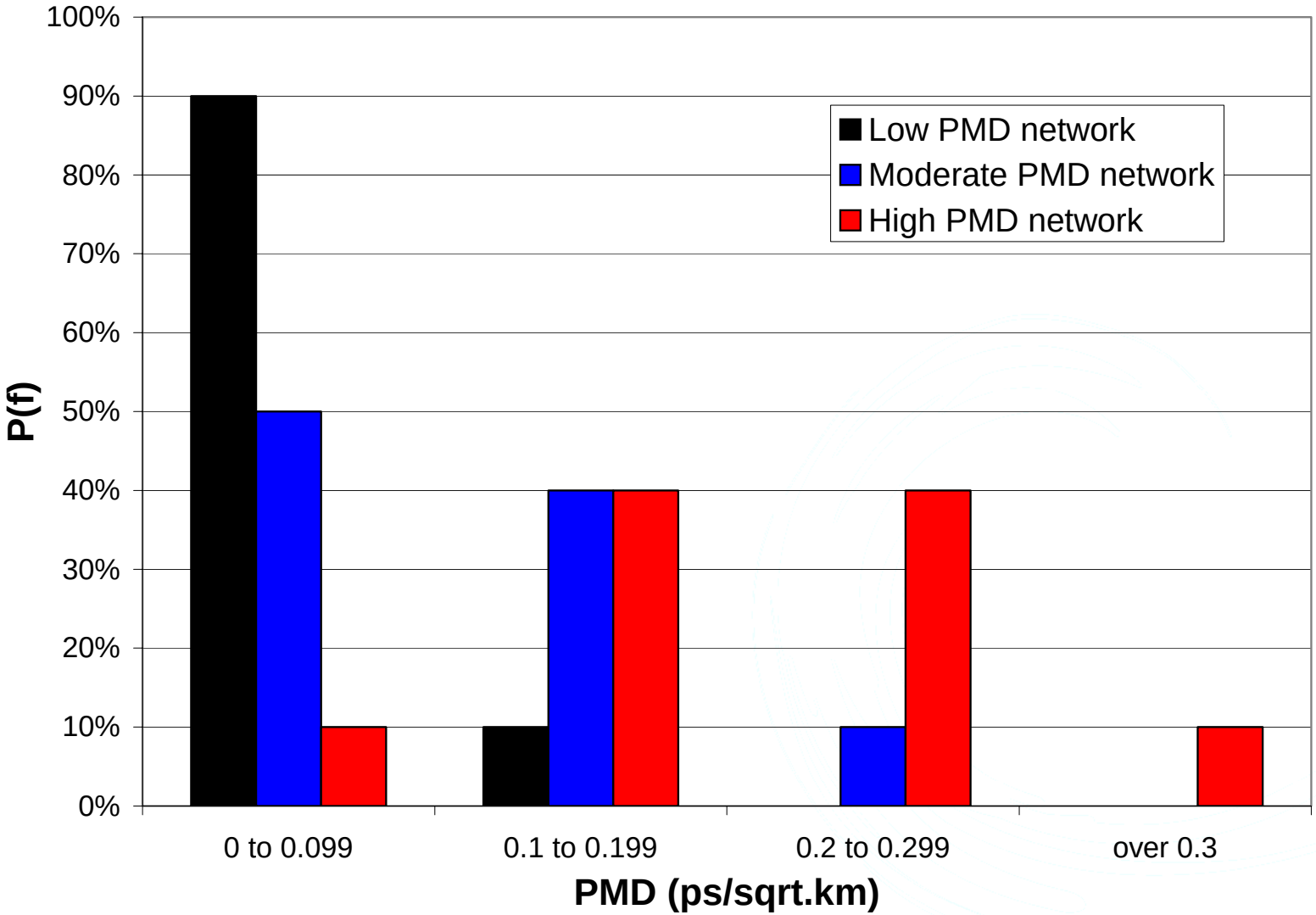




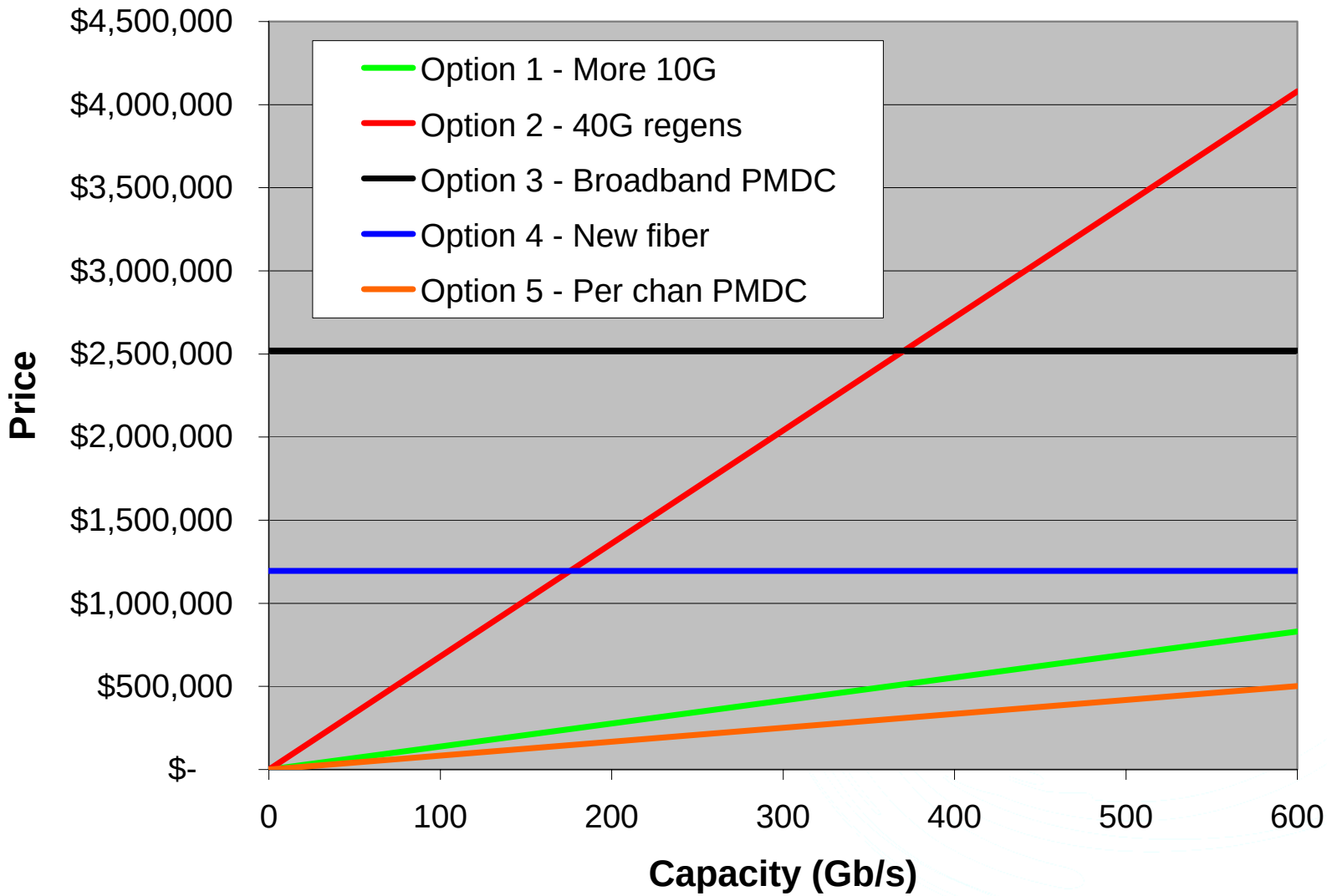
Economic PMD modeling assumptions

- 200 line amplifier sites
- 50 terminal/OADM sites
- Average nodal degree = 2.5
- DWDM capacity approx. 600Gb/s per OMS
- Nominal 10Gb/s ULH reach = 1,920km
- Nominal 40Gb/s reach = 960km
- Price per 10Gb/s transponder = $25,000
- Price per 10Gb/s regenerator = $20,000
- Price per 40Gb/s (4x10G) muxponder = $75,000
- Price per 40Gb/s regenerator = $60,000
- Price per optical line amplifier site = $80,000
- Price per OADM common optics site = $160,000
- Dark [2] fiber cost = $300/fiber.km (no trenching costs)
- Broadband PMDC cost = $200,000/OMS.fiber
- Per channel optical PMDC cost = $15,000

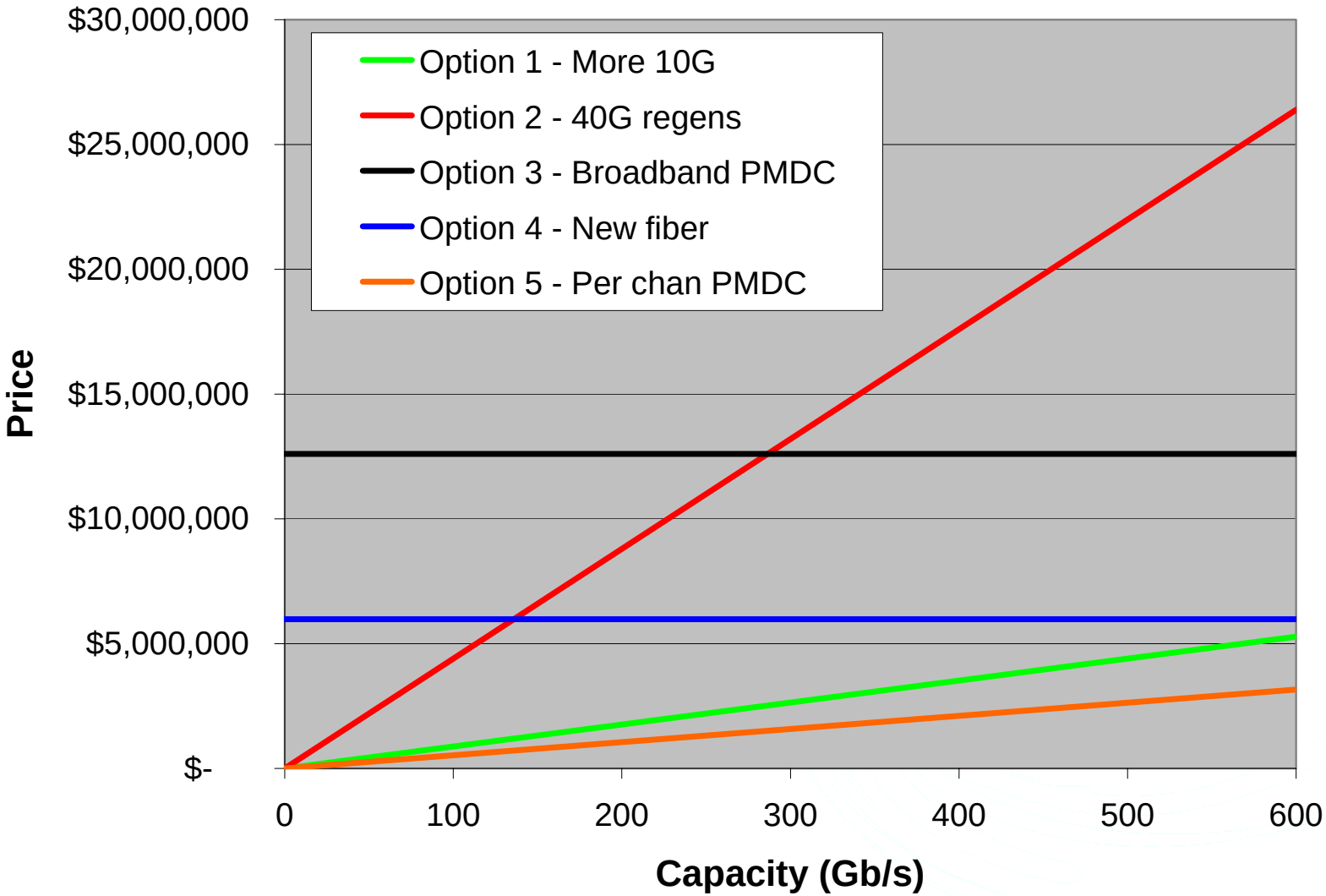
Network PMD distribution assumptions



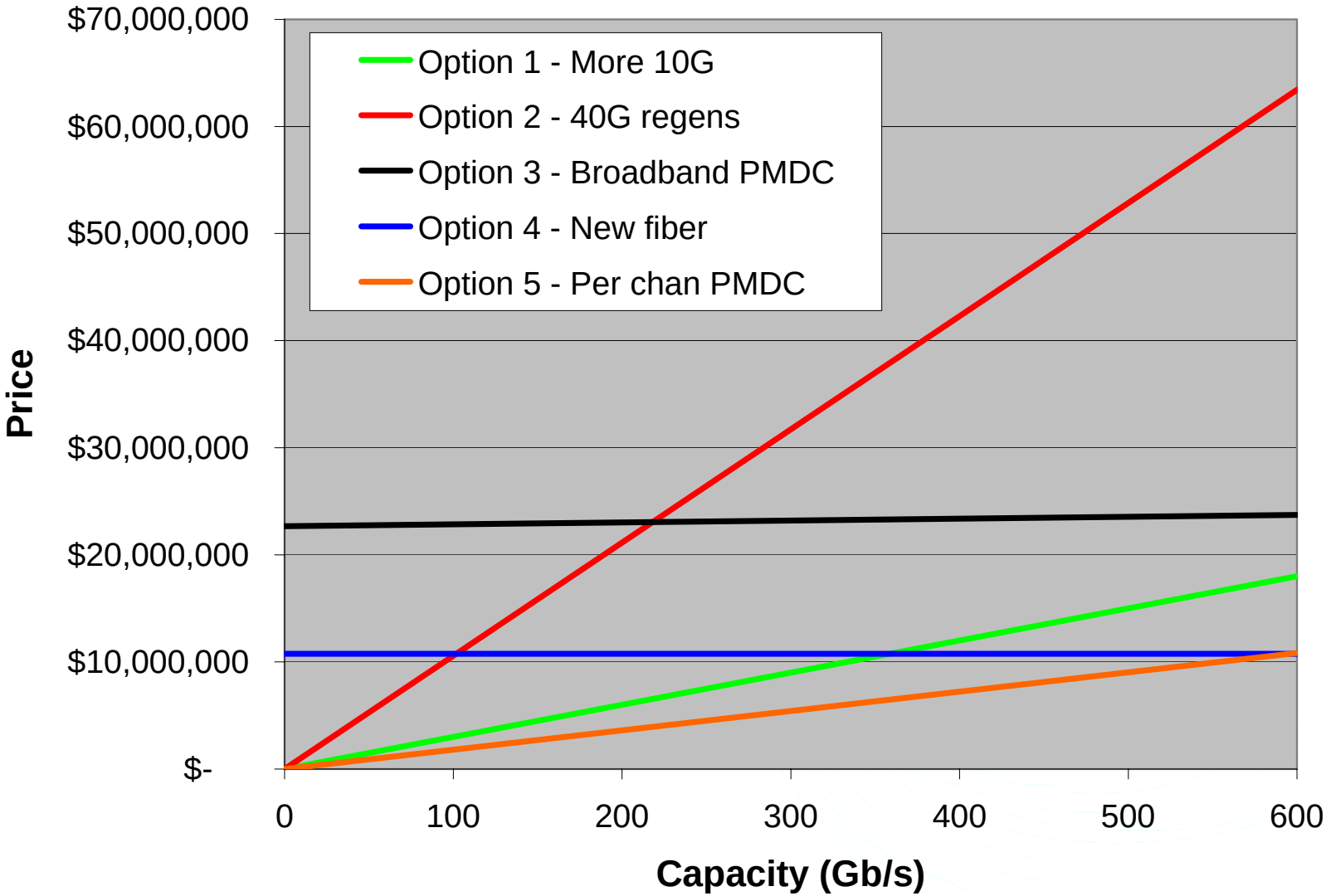
Cost for low PMD network



Cost for moderate PMD network



Cost for high PMD network



Economic PMD study conclusions

- Selectively deploying per channel PMDCs on a per demand/route basis is the most cost-effective solution
- Per channel PMDCs are also PAYG, so lower upfront investment than broadband PMDCs or new fiber
- Additional cost of deploying per channel PMDCs is
  - 0.4% for a low PMD network
  - 2.4% for a moderate PMD network
  - 8.1% for a high PMD network
- Deploying per channel PMDCs enables 40Gb/s retrofits on existing 10Gb/s routes without disrupting traffic
- Using per channel PMDCs with 40Gb/s also allows the network to support OC-768 interfaces from IP routers

Conclusions

- Without PMD mitigation, approx. 50% of carriers will have some 40G route blocking
- PMD can be attacked via modulation scheme choice and/or post compensation
- PMD compensators can be implemented in optical or electronic domain
- PMD compensator technology proven in field trials
  - First network deployments in 2H 2007
- At present, economics favor per channel PMDC
  - Deploy selectively only where needed
  - PAYG cost structure
- Long term, replacing old fiber will give the best payback