Roadmap to Terabit DSLs
(Digital Subscriber Lines to Waveguides)

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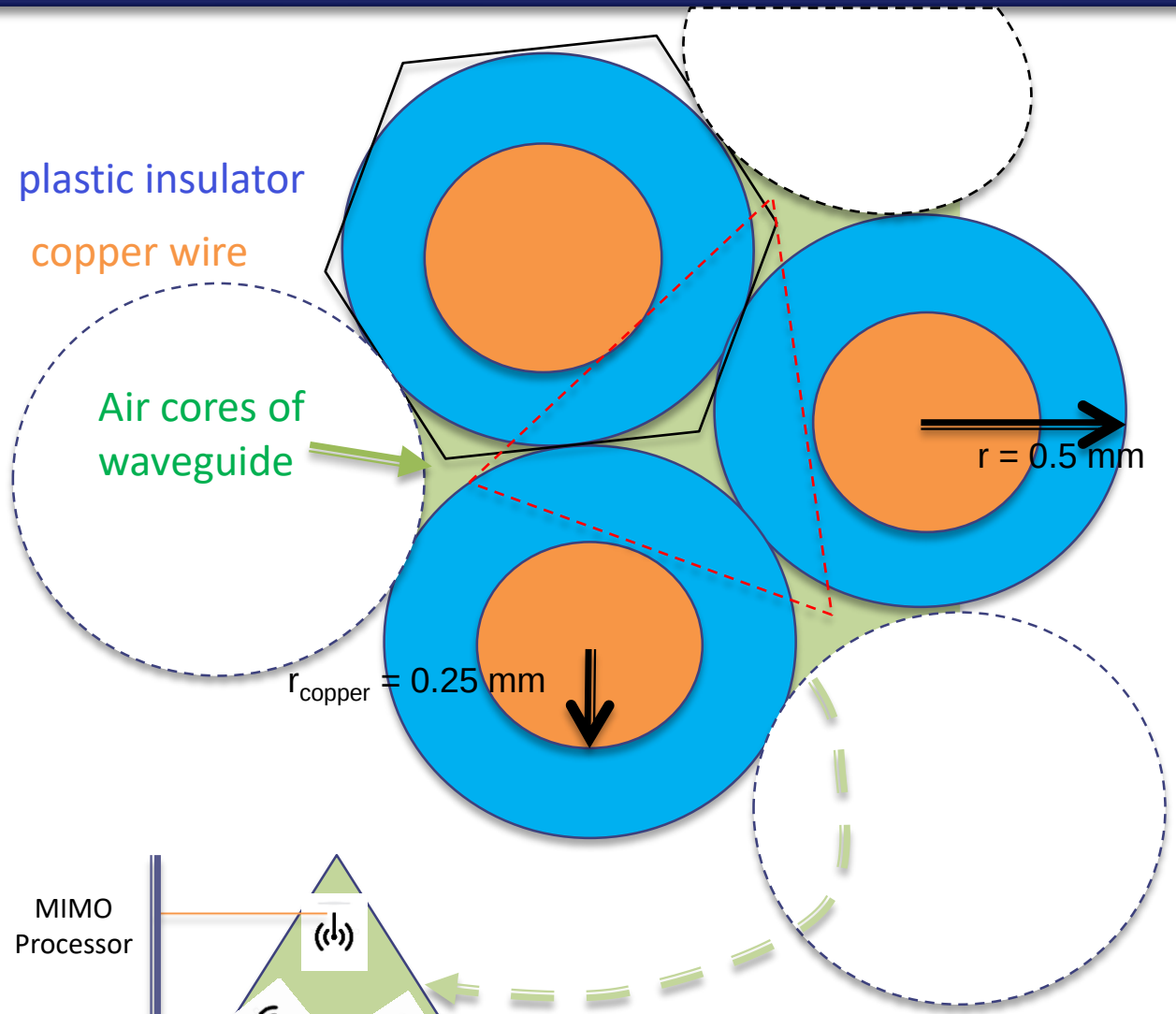
Vectoring (MIMO) across all



Terabit/s – 1 pair, 100 m
100 Gbps – 1 pair, 300m
10 Gbps – 1 pair, 500m

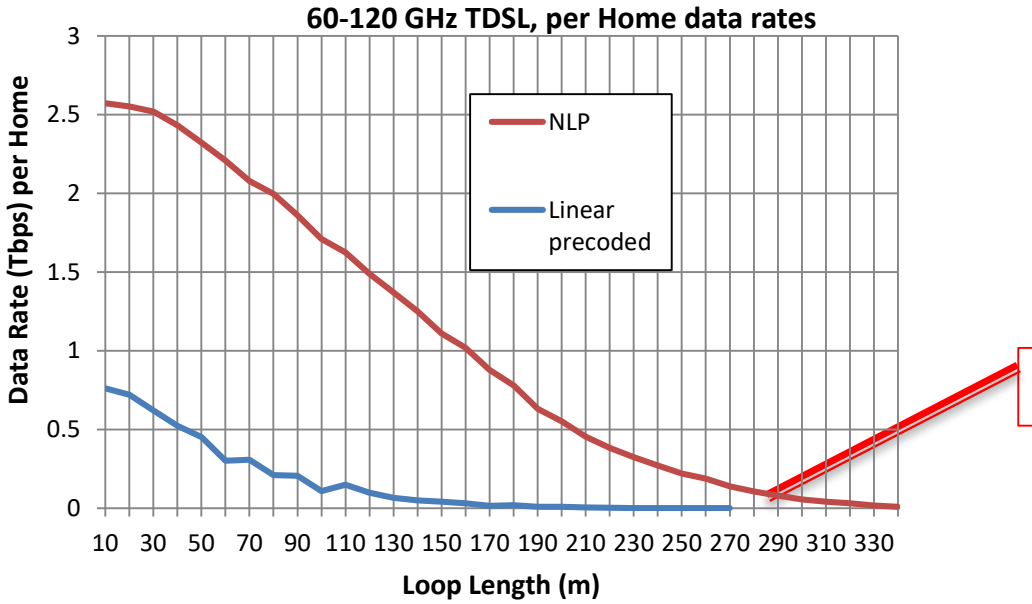
- Applications
  - Access connections (xDSL)
  - 5G “back/front/X” haul
  - Data Center connectivity
- Each application benefits from
  - Absence of infrastructure construction
  - Lower costs (and usually time to do)

ASSIA

“TDSL” feedback from ISPs (Telcos)

- Terabit/s at 100m is exciting, thank you
- What length for 10 Gbps? (500 m)
  - Yes, good , but ……..
- What length for 1 Gbps symmetric? (600m - 700 m)
- Can you do it tomorrow?
  - Well, there are some intermediate steps G.veryfast, G.ultrafast, … , G.tdsl ??
  - Or maybe G.longfast, G.longerfast, … ?

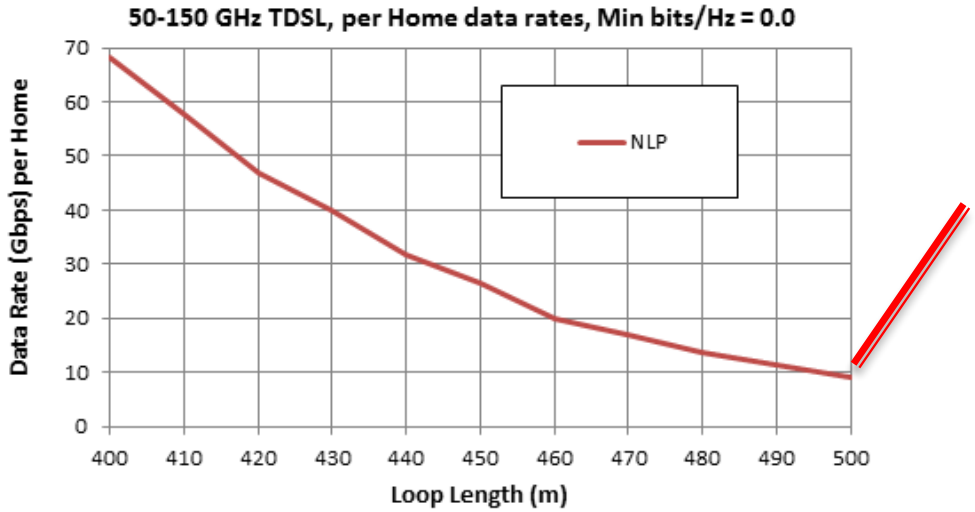
Waveguides: Longer Range, Lower Speed?



100 Gbps > 300m

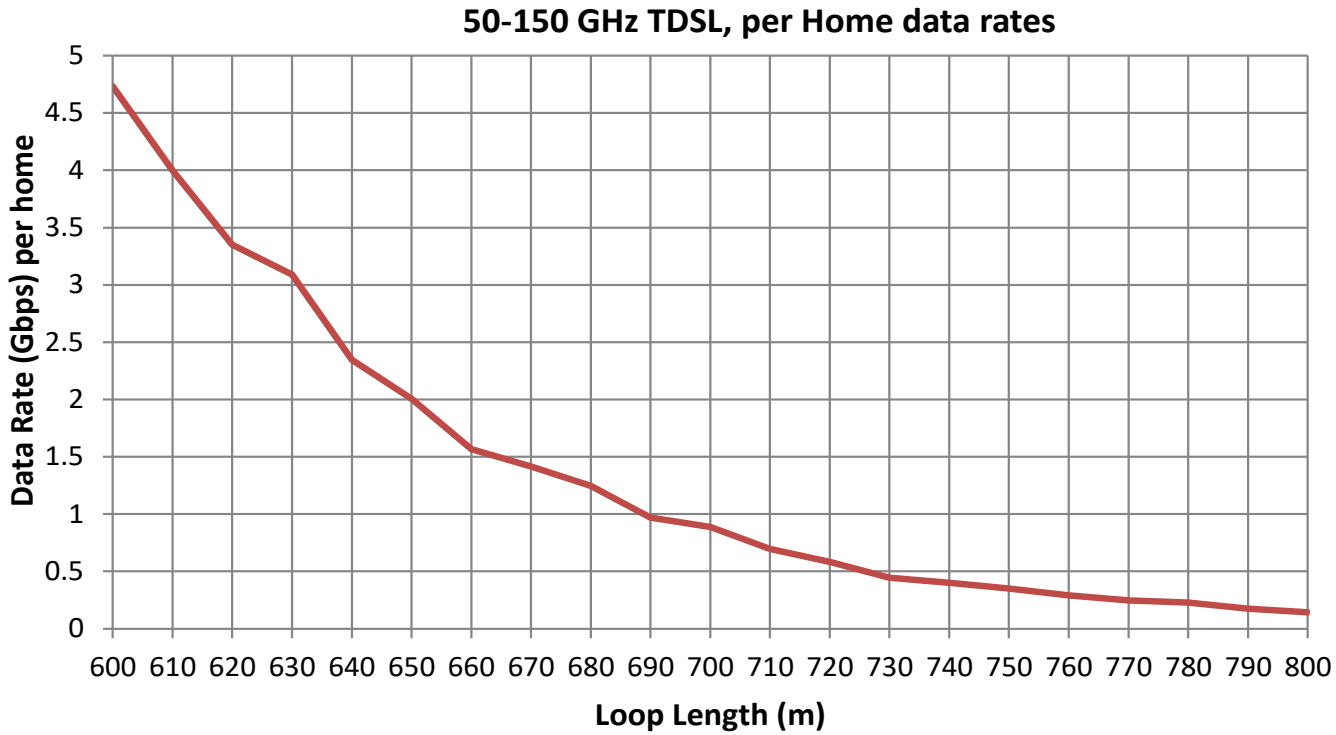
Repeated from last year

Note the Nonlinear Precoder (NLP) gains – this is important



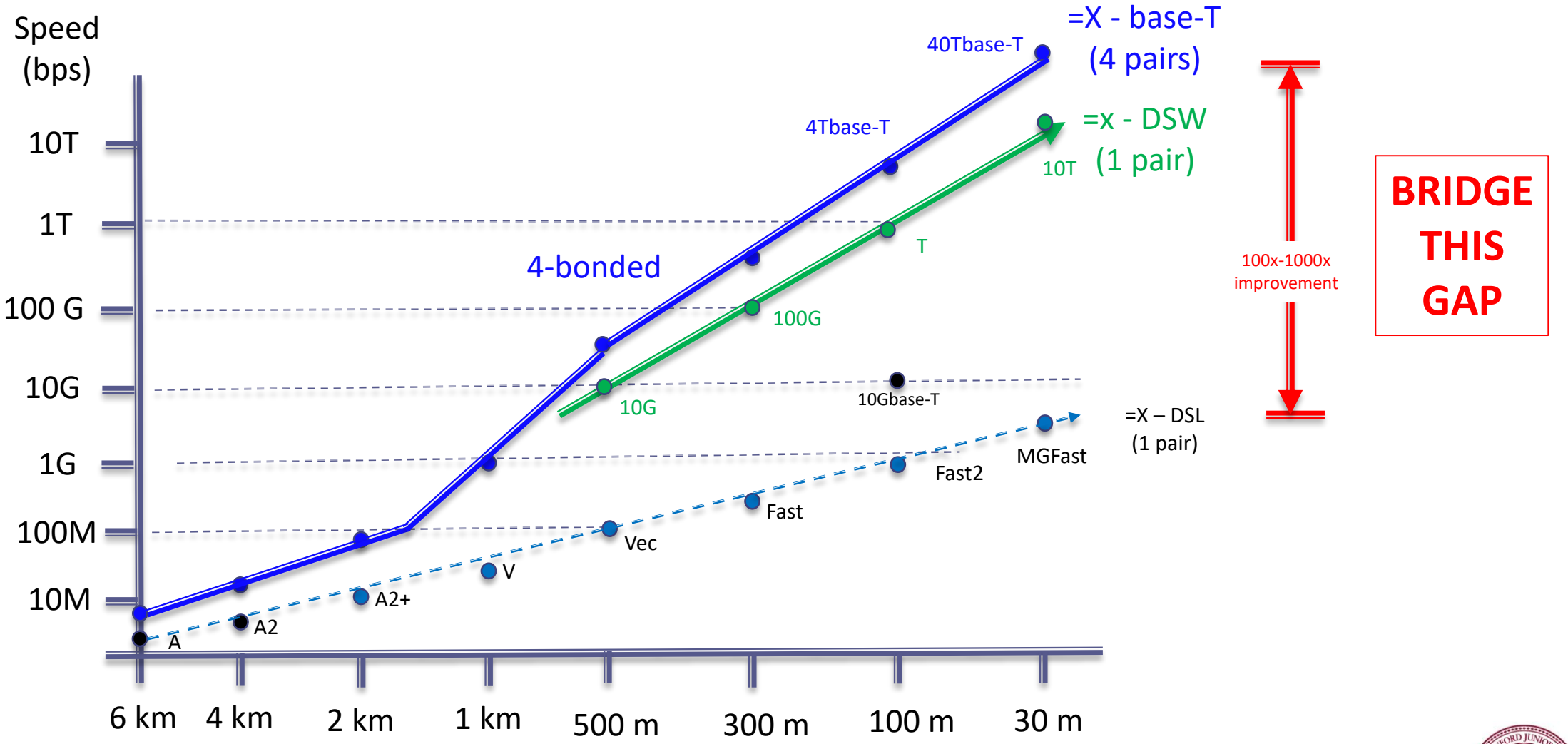
10 Gbps > 500m (~0.5km)

Very long range Waveguide - squeezes low-end of band



1 Gbps at roughly 2100 feet (symmetric) or 640m

Updated slide from 2017 TNO: Waveguide DSL

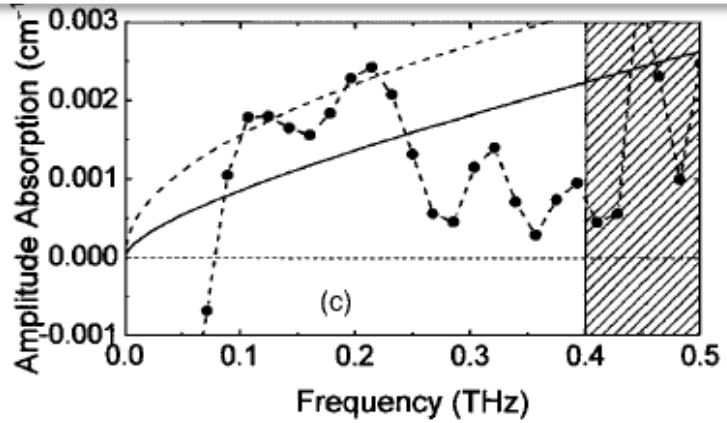


How do we get there?

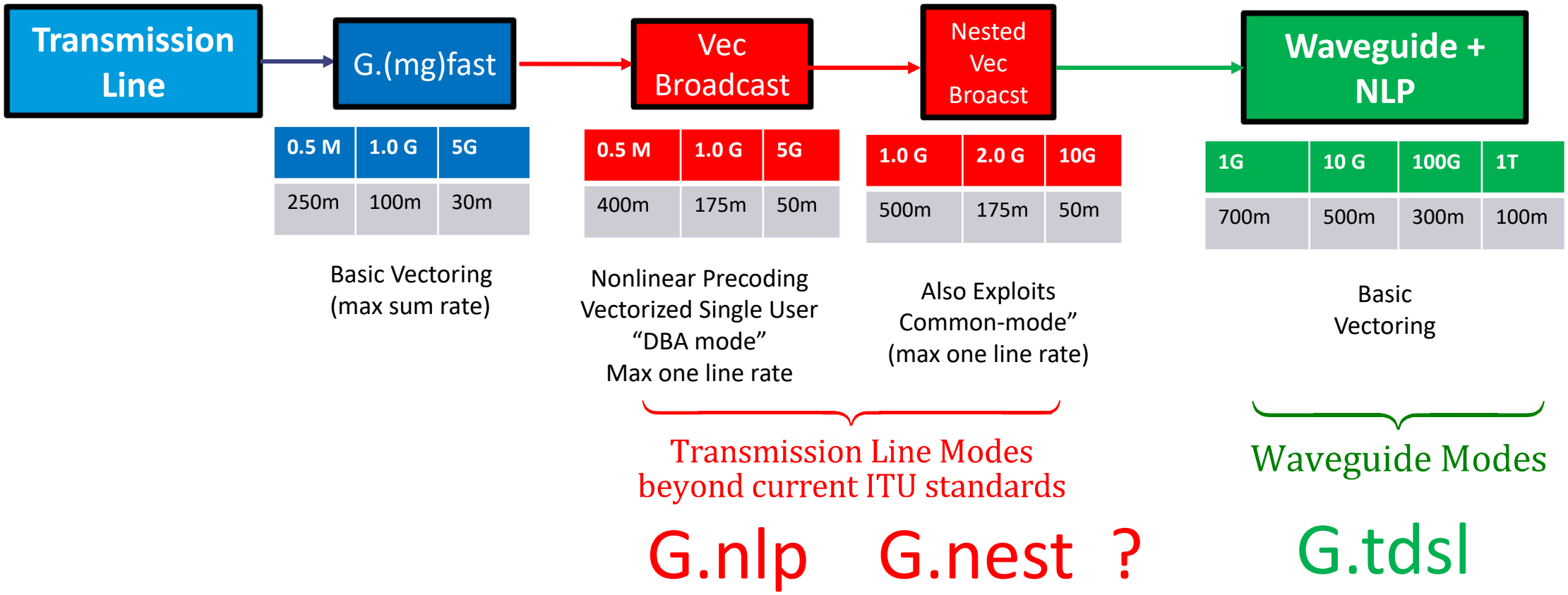
Reliably Fast Broadband & Wi-Fi for the Home

Measurement Programs

- Test lab chosen (Brown University, Prof D. Mittleman)
  - Strong copper/metal waveguide experience (see measurements)
  - MIMO data analysis by ASSIA/Stanford
- Funding sources (US Government) appear in place (expect 1 Sep 2018 start)
- Will start with 1 meter tests on cable of twisted pair
  - Repeated excitation and sensing with photo-detective elements in Terahertz Band
  - Stepper system to move transmit and receive locations
  - Collection of outputs for each and every input
- Expect some results in first year on 1m, 10 m, then expanding to 100m and beyond
  - So kind of reverse order, but this needs to be done from prudent lab practice standpoint



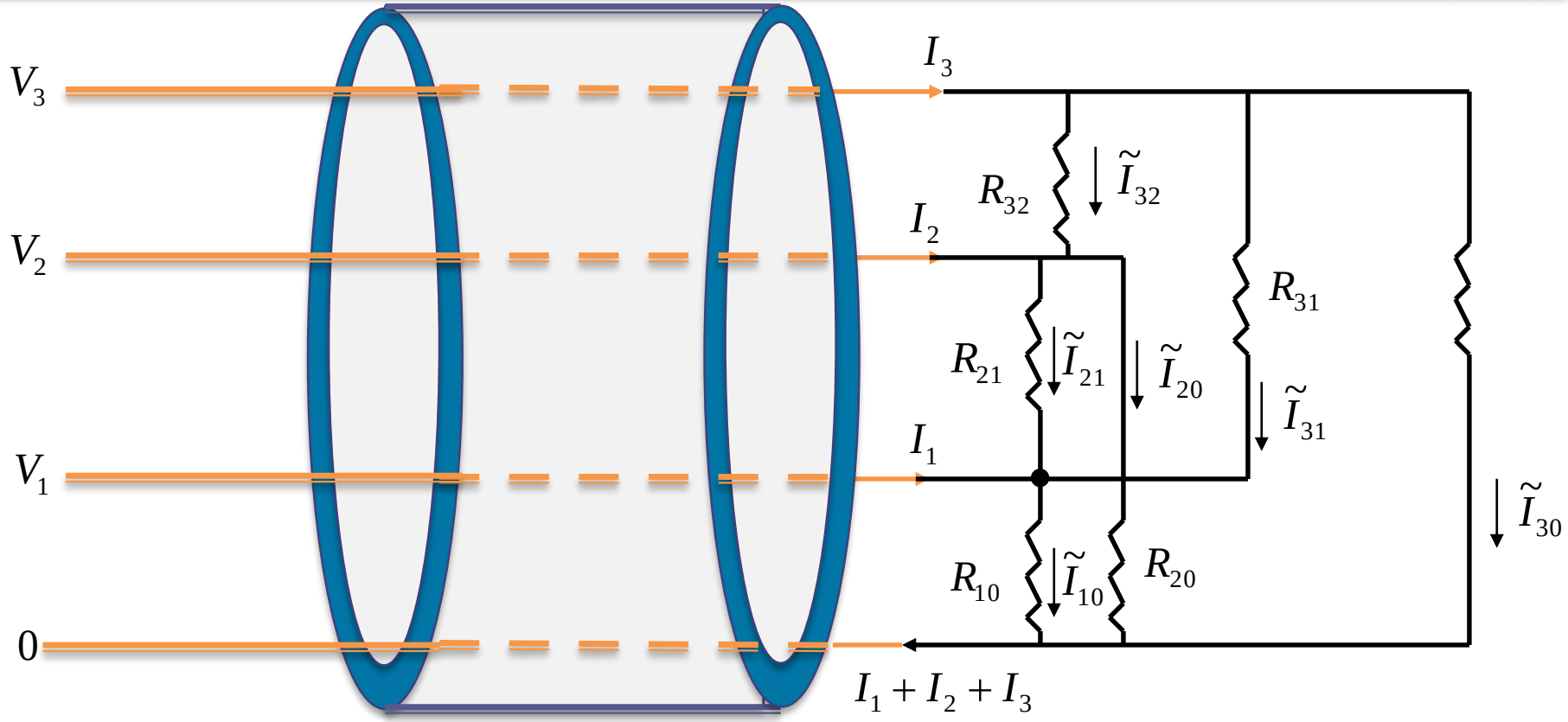
Roadmap to Waveguide: single pair to each home



Note the emphasis here is on LONGER and fast, not necessarily faster (until waveguide)

BONDING with multiple pairs (but "single user" or single stream)

- Xhaul and Data-Center uses will allow bonding of 2 or more pairs
- See for instance NOKIA 10 Gbps demonstrations (2 pair, 3 modes with Phantoms)
  - Also Lee, Cioffi, Jagannathan, Mohseni Sept 2007 IEEE Com Trans
- Residential access may have more than 1 pair
  - Really it does …
  - Also cord cutting increasing
  - More pairs available
- Mentioned here as reminder – multiply data rate by 2N-1 with N lines



In general, N pair → 2N-1 channels

N=101 and R = 50 Mbps (G.vec) → 700m
N=101, and R= 0.5Gbps (G.MGfast) → 100 Gbps – 250 m
N=101, and R= 5Gbps (G.MGfast) → 1 Tbps – 30 m

Cheaper Xhaul
5G sooner?

Rate Regions (Vector Broadcast)

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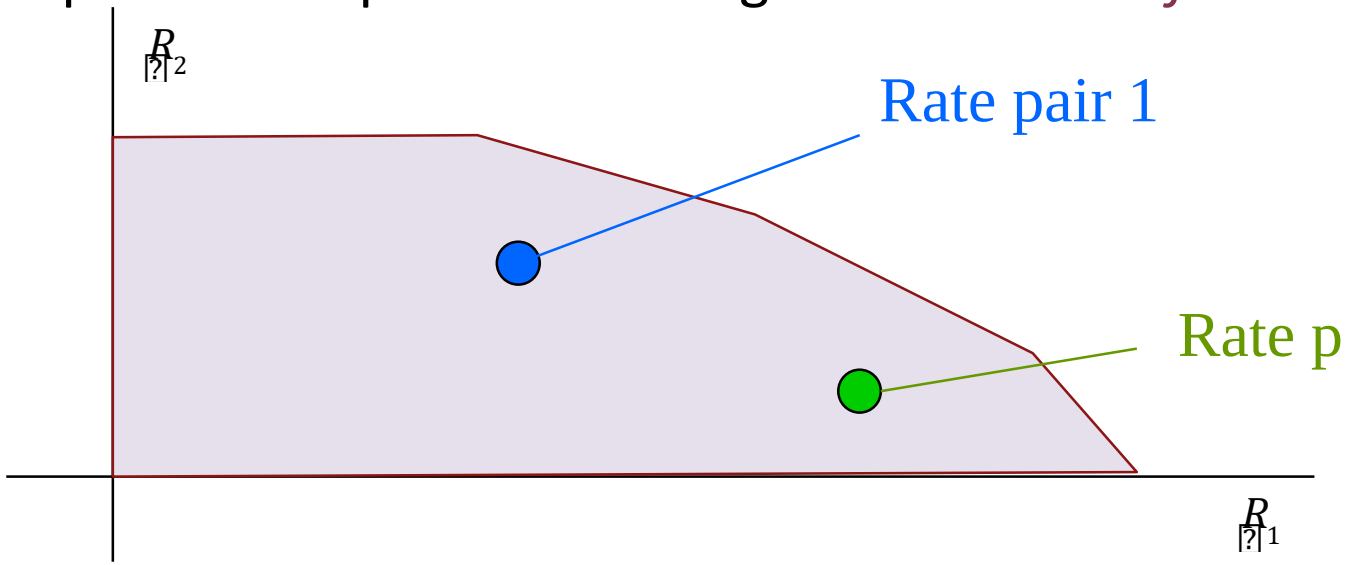
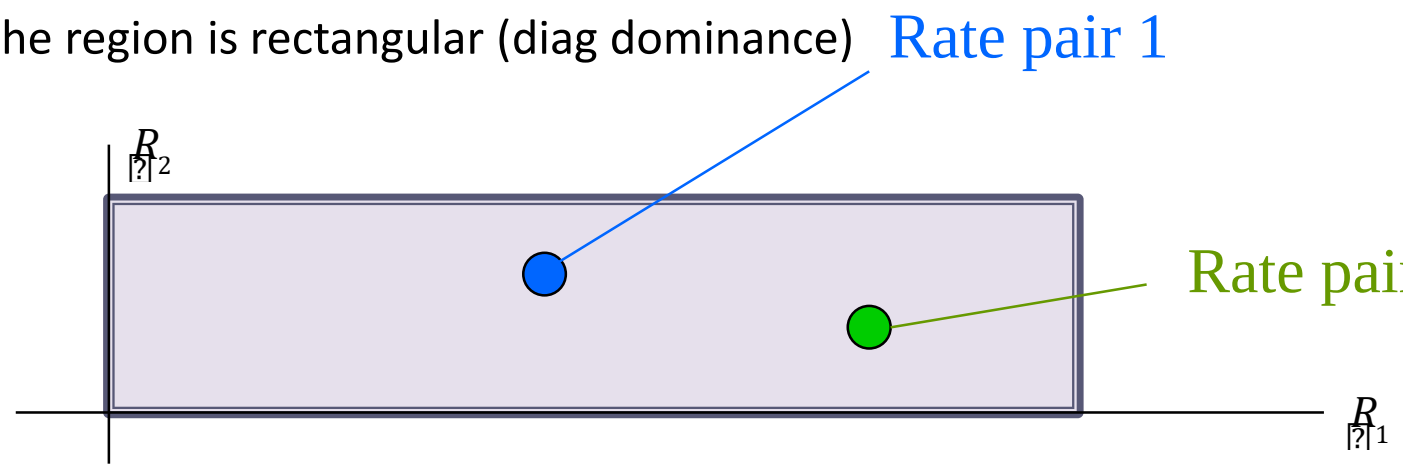
The Rate Region

- The two users' rates often are not independent → **Rate Region**
  - Originally important in spectrum management *without full vectoring*



Returns in Vectoring when Single user is important

- Early G.vector and G.fast, the region is rectangular (diag dominance)



Diagonally Dominant No NLP For max sum rate

Simple Example

- A 2x2 channel (ignore phantoms for now)

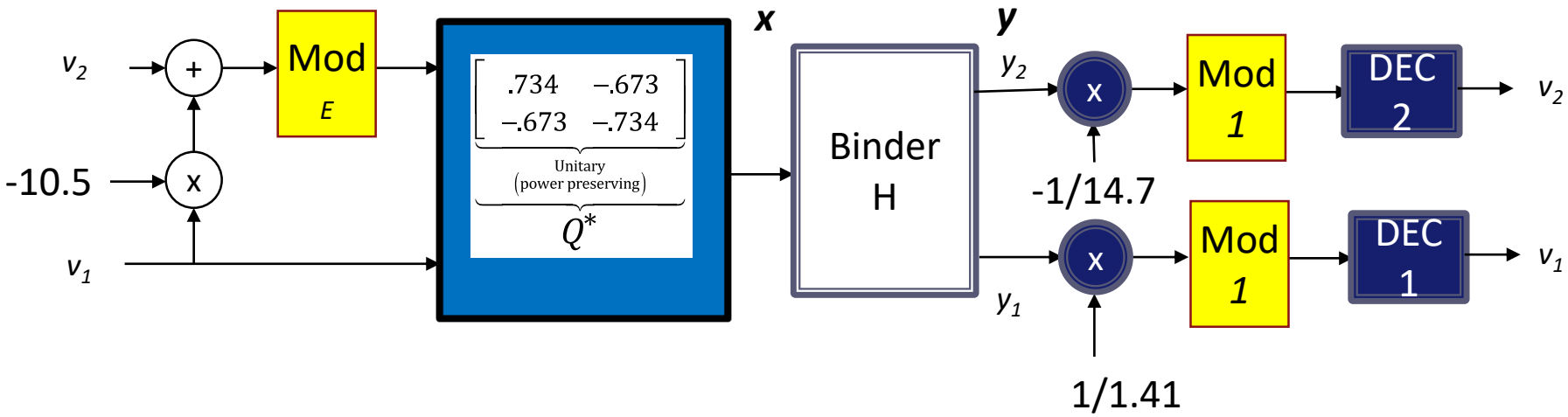
$$H = \begin{bmatrix} 11 & 10 \\ 10 & 11 \end{bmatrix}$$

Let each independent noise be 1

- Has large FEXT (FEXT is actually good)
- Definitely NOT diagonally dominant

$$H = \underbrace{\underbrace{\begin{bmatrix} 1.413 & 0 \\ 0 & -14.87 \end{bmatrix}}_{\text{Diagonalized Channel Gains}} \cdot \underbrace{\begin{bmatrix} 1 & -10.48 \\ 0 & 1 \end{bmatrix}}_{\text{Defines Nonlinear Precoder}}}_{R} \cdot \underbrace{\begin{bmatrix} .734 & -.673 \\ -.673 & -.734 \end{bmatrix}}_{Q^* \left(\text{power preserving}\right)}$$

Simplified System Diagram



Most of data rate here
If $v_1 = 0$

- Special type of "power-bonding" occurs in the channel
  - Inputs are phased/optimized to force most of data rate to user 2
    - Vector signal processing here does not avoid/cancel FEXT, it is used to reinforce a single user
- Classic Vector (non-degraded) broadcast channel in information theory
  - Calculations used zero-forcing here – there is slightly better MMSE version that looks more complicated
- User 2 is 2.6 dB better than traditional vectoring
  - limit is 3 dB better here when H becomes singular, which can be forced

100 pair, 200 wires (with Phantoms)

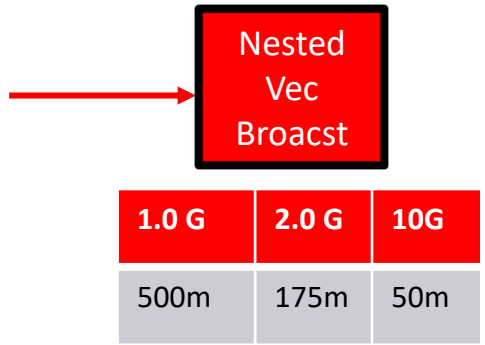
- Limit is 23 dB gain
- All power can be assigned (for given time interval) to any particular user
  - Take that cable-company - the telcos can do it too!
- This would increase 1 Gbps from current 100m in G.fast to 175 m
  - For a single pair to the home
  - CLEARLY, bonding could at least double rate (probably triple) for 2 pair drop
- Requires DBA algorithm used in PON/Cable

0.5 M	1.0 G	5G
400m	175m	50m

Nonlinear Precoding
Vectorized Single User
"DBA mode"

Nested Vectoring (still single pair)

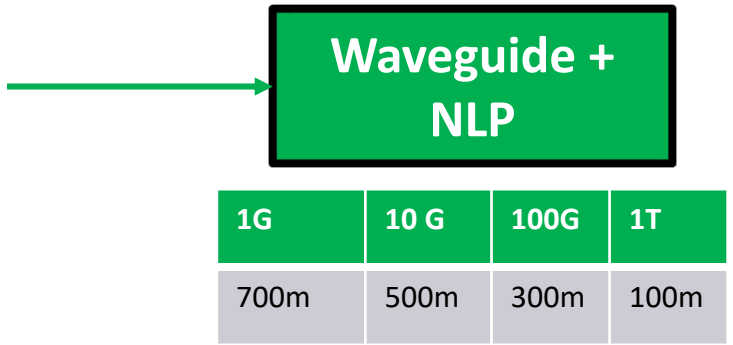
- See Jagannathan, Cioffi, et all – IEEE Trans Com, Feb 2009
  - See also ITU Contribution Q4/15-C12 (17-09-25) NOKIA, Van Bruyssels, Maes
- Vectored systems can use the common mode
  - And crosstalk removed (involves block RQ factorization and SVD in the blocks)
- This would roughly double data rates of Vec Broadcast
  - In terms of range, 1 Gbps 400m to 500m
  - Double the rate for two-pair drop
- No waveguides yet
- Keep in mind that only one line/user gets this speed at any given time
  - That is, this is TDMA beyond simple ping-pong
  - It is the DBA used in GPON and Cable (and LTE … 5G)



Also Exploits Common-mode”

Bridges Gap to Waveguides

- These intermediate Trans-Line steps attend the waveguide measurements
- Terahertz band development of components, equipment, network planning, etc. progresses already
- Note the low end of waveguide is not that much better from high-end of transmission lines with proposed approach



FEXT FORCING

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Moving the vector-matched-filter into the channel or transmitter

- The Vector Matched Filter (VMF) is in the channel?
  - This VMF is (sometimes) essentially the FEXT itself
    - when FEXT is large, it is like the VMF
  - The VMF does not happen if channel is diagonally dominant (FEXT too small)
  - FEXT can be GOOD (if used properly)

- Design FEXT into the transmitter? (again, FEXT can be good)
  - Yes, analog vector matching circuit would enable the time-sharing
  - Think 100 Ohm resister between every possible pair of wires
  - No longer diagonally dominant

- Reminder: True Vector Broadcast Channel has ONLY a sum-across-all-users energy/power constraint
  - This creates kind of a ***spatial*** peak-to-average issue across the different transmitters
  - Linearity/Precision of DAC's and analog driver circuits will need to increase by (10/6) log(N) bits
    - Power driven into wire need not increase w.r.t. today's DSLs (power adds in channel)

- Upstream does not improve by such methods
  - So improvement is downstream only
  - Although the nested vectoring does work upstream by itself to double data rate

FEXT can be intentionally introduced at the OLT/DSLAM

- Vector Matched Filter Circuit (or other filter)
- Instead of high-power amplifier on one wire
  - Introduce imbalance in the driver circuits of each wire
  - Basically resistively couple them together
- This will confuse today's ADSL, VDSL, and Vector/FAST
  - so back-compatible mode necessary
  - Earlier methods are designed to accept a penalty from FEXT (A/V)
  - Or to cancel the FEXT (instead of using it)
- No fundamental physics break-through here
  - We're just aligning the energy to the dominant mode(s) of one user (at a time)
  - Increasing the peak (and actually reducing the sum) at particular time points
  - Can be reassigned at other times to other users

Conclusions

- There are steps that will help
  - Access network planning and cost
  - 5G Xhaul where fiber cannot connect
  - Other applications like data centers
- Focus on length for speed (not higher speed at yet shorter length)
  - In the interim to waveguides
- This could help yet more decades of efficient copper plant returns
  - The waveguide modes will simply continue the opportunity to higher speeds

Thank You

End of Presentation

Essential to Reliably Fast Connectivity

www.assia-inc.com

Back Up - Electronics in the Terahertz Band

NTT and Tokyo Institute reach 100Gbps in 300GHz band

18 June 2018 I Natalie Bannerman