Dynamic Spectrum Management (DSM):

Multi-User Information Theory at work in DSL

Summer Academy at Jacobs University

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Some References

- DSL Advances, Starr et al, Prentice Hall, 2003 – see Chapter 11.
- American DSM Report, Alliance for Telecommunications ATIS-0600007 – Dynamic Spectrum Management , Solutions (ATIS, ANSI accredited), May 2007. (draft on flash, final may be purchased by ATIS – used for course/student educational purposes – DO NOT DISTRIBUTE.
- B. Lee et al, “Binder MIMO Channels,” to appear IEEE transactions on Communications (on flash)
- B. Lee et al, “Gigabit DSL,” to appear, IEEE transactions on Communications (on flash).
- J. Cioffi et all, “The CuPON,” IEEE Communications Magazine, June 2007.
- J. Cioffi, Class notes on DSM: http://www.stanford.edu/class/ee479/ and vectoring: http://www.stanford.edu/class/ee379c/

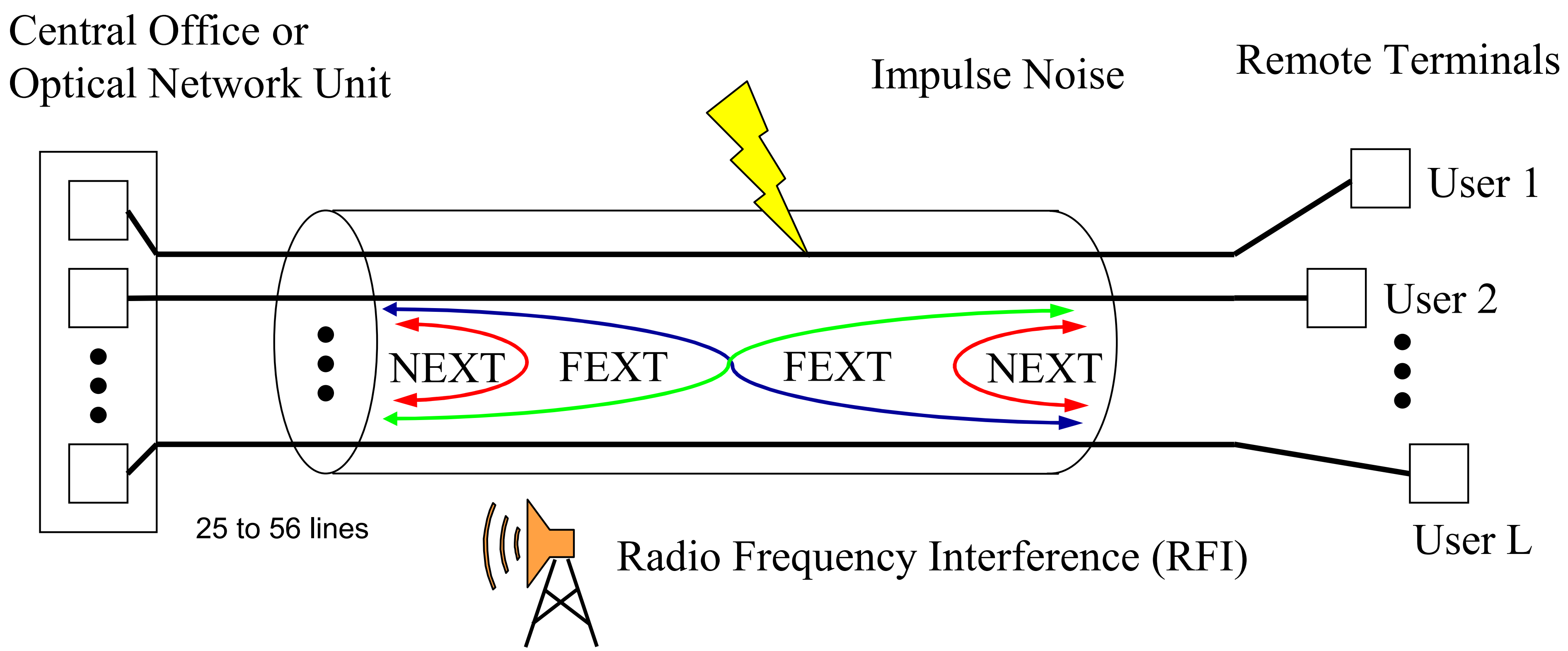
Evolution of JC’s Interest

- Worked on DSL (DMT) 1986-1998
  - single-user transmission optimization
    - Inter-symbol interference very large
    - Noise correlation (non white) also large (crosstalk)
  - Company (Amati -> Texas Instr -> Infineon)
    - Started 1991 to pursue an “optimal” design
    - Sold in 1998 to TI (full time return to Stanford)
- Intrigued by potential application of multi-user to telephone-line binder full of DSLs
  - Initiated new research area in university
    - Pretty mathematical at first
    - Called “friendly DSLs” evolved in name to Dynamic Spectrum Management

Outline

- DSL Multi-user Binder
- DSM Basics
- Impulse Control and Politeness
- Band Preference
- Vectoring

Existing View of DSL Binder



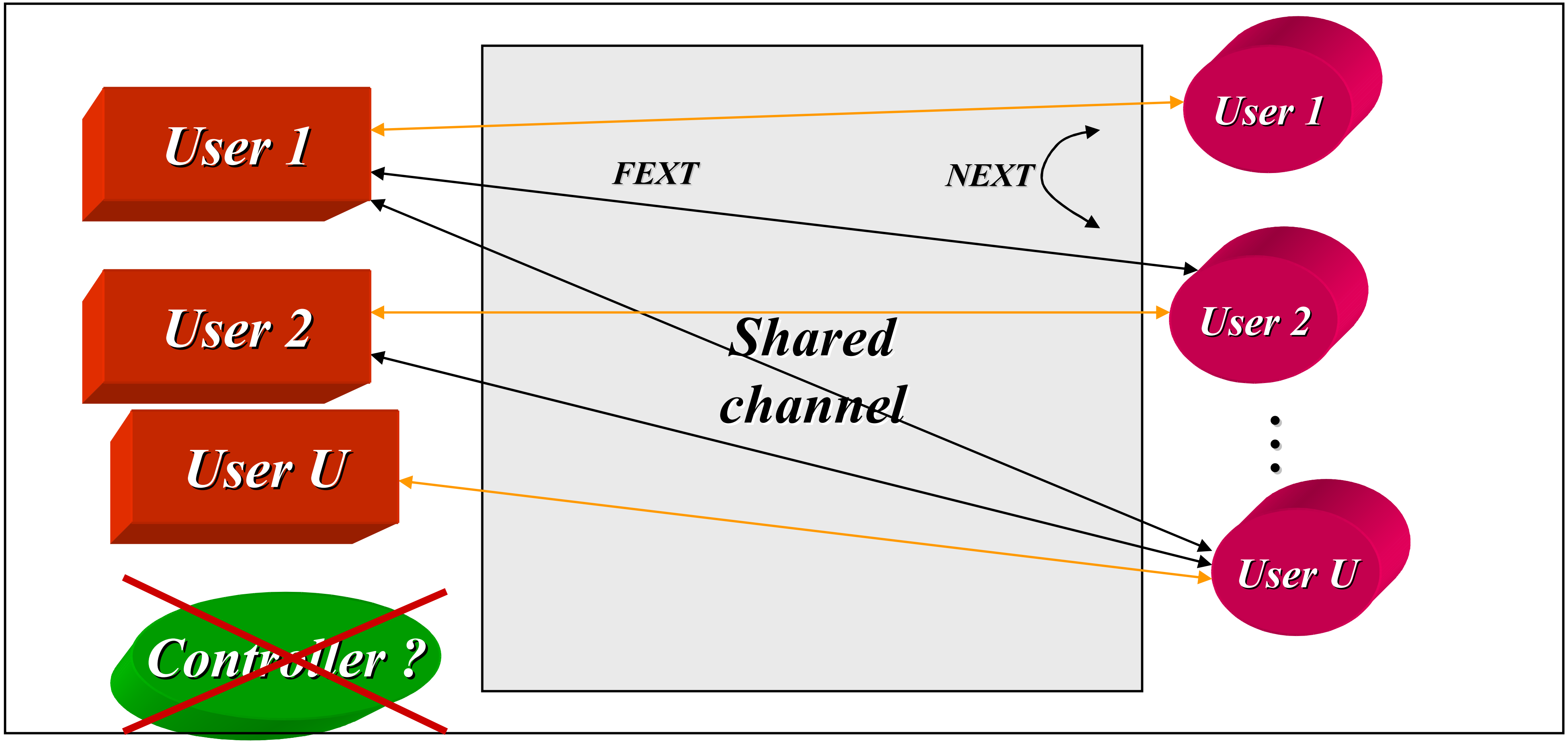
crosstalk is the dominant noise source

MIMO?

channel – yes

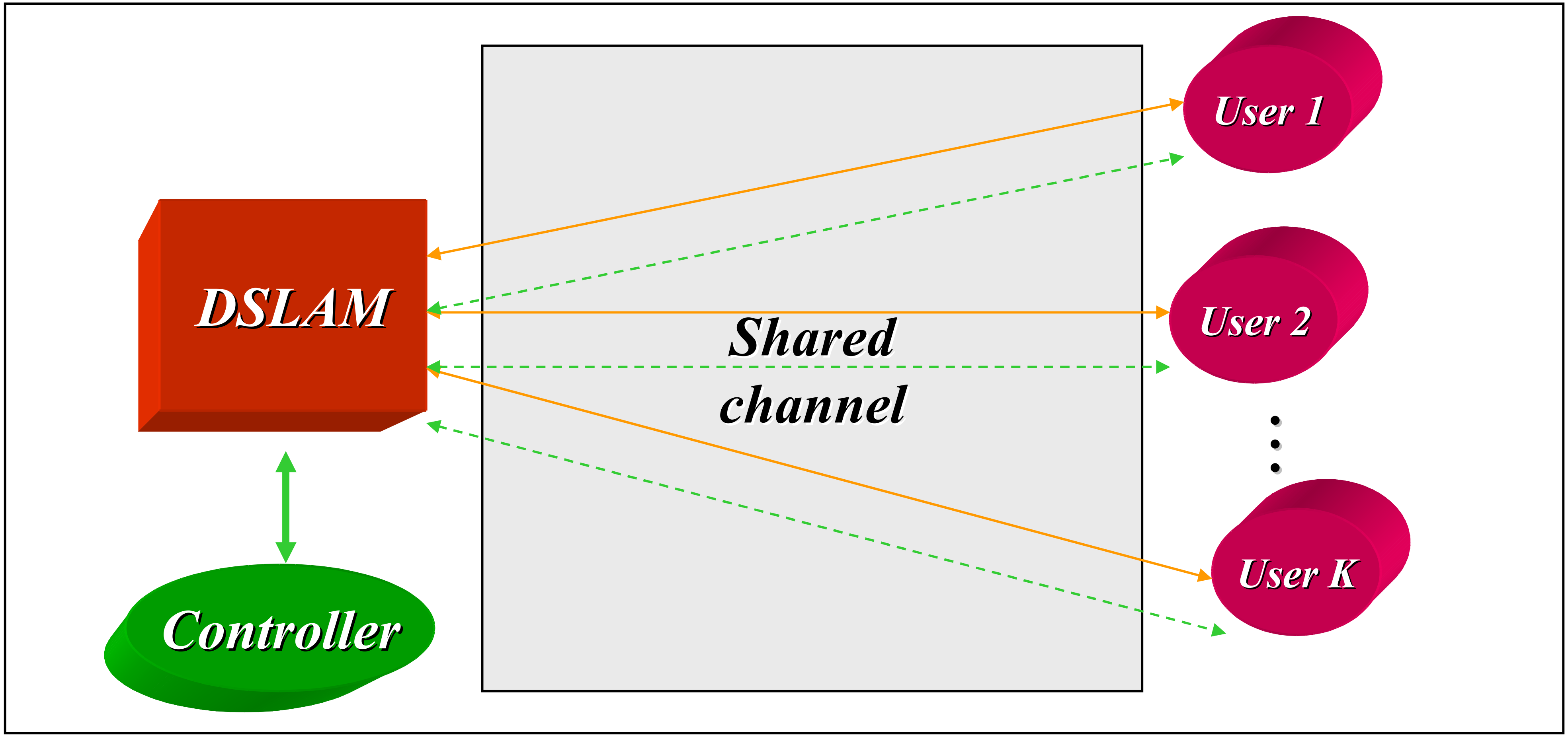
Processing no (MISO or SIMO -> Vector)

Existing DSL



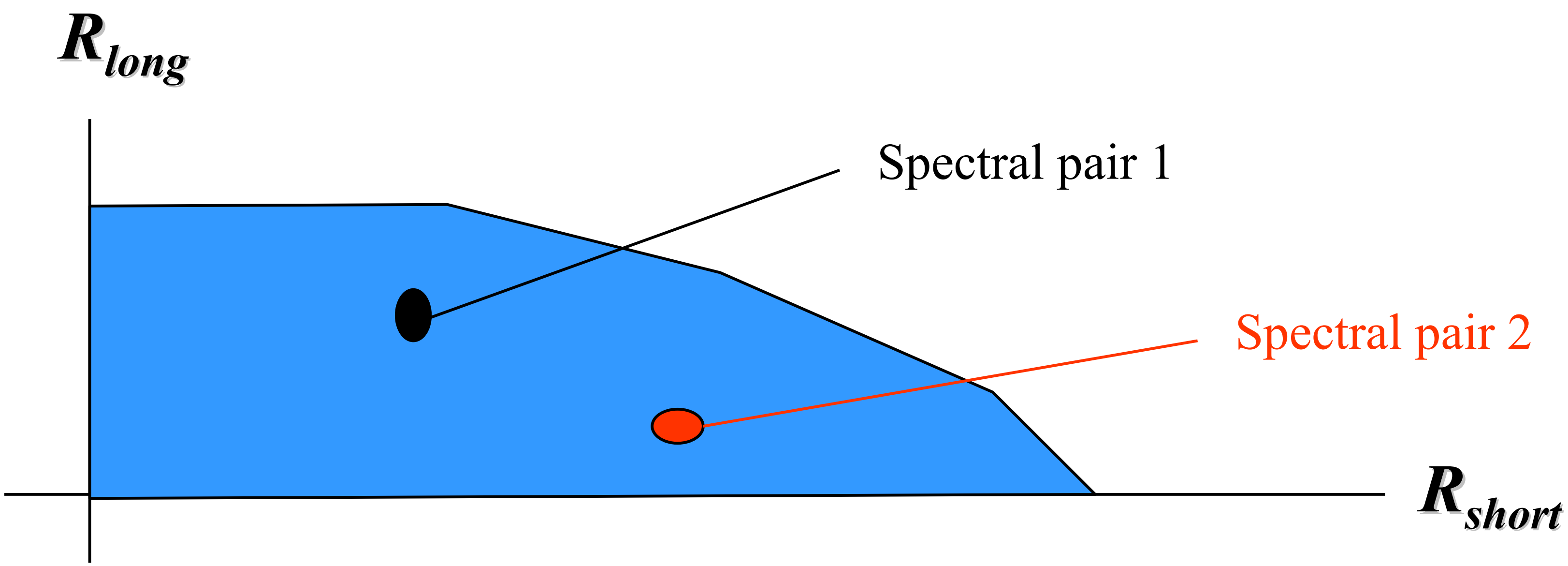
- No coordination
- Often DSL users harming one another

Multiuser View



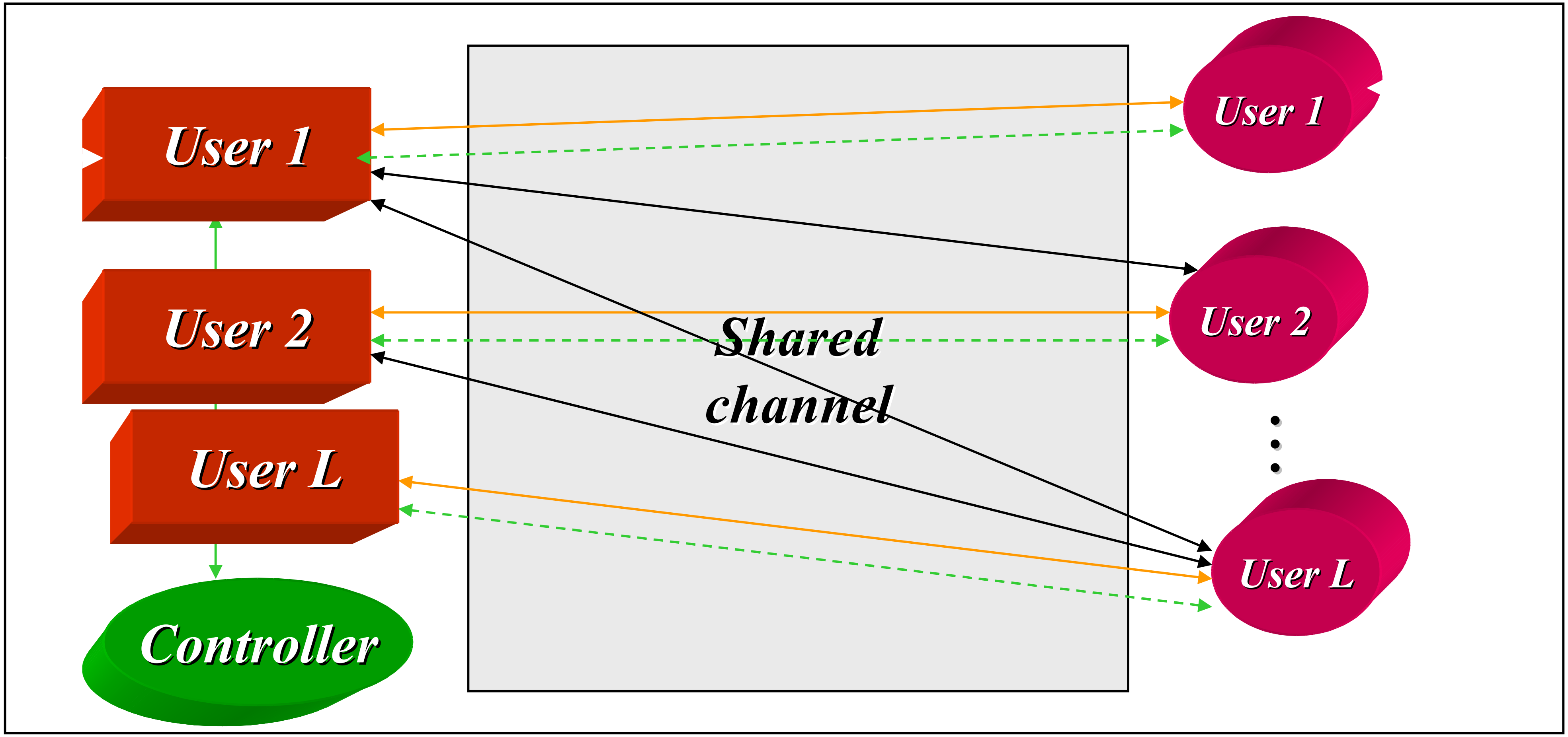
- Goal: Best PHY signals for user sharing of channel
  - Set spectra/signals, optimization via controller

Ultimate Goal: use of Rate Regions



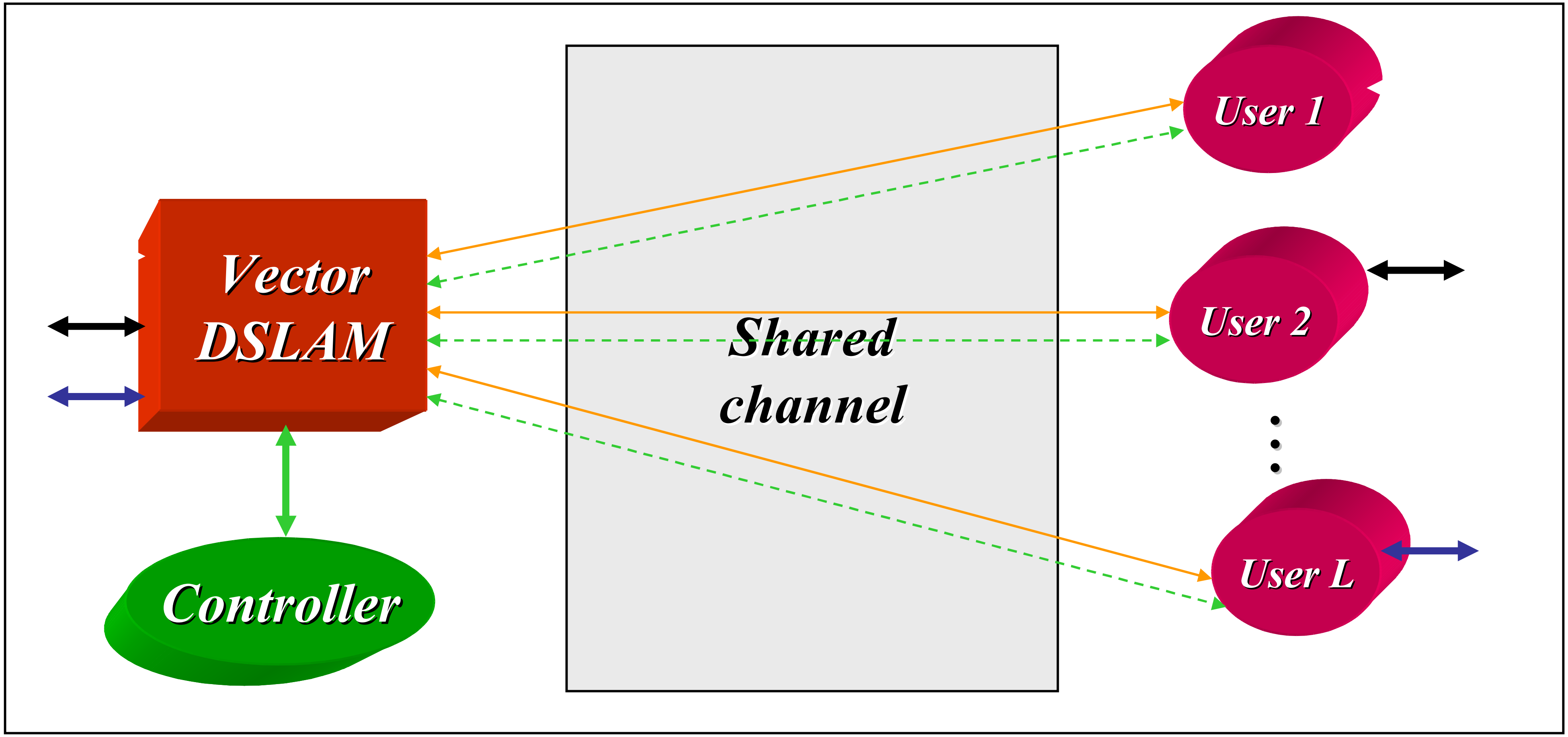
- Plot of all possible rates of users
- Any point in region is possible, but each with different spectra
  - Varies for each channel

Interference Channel



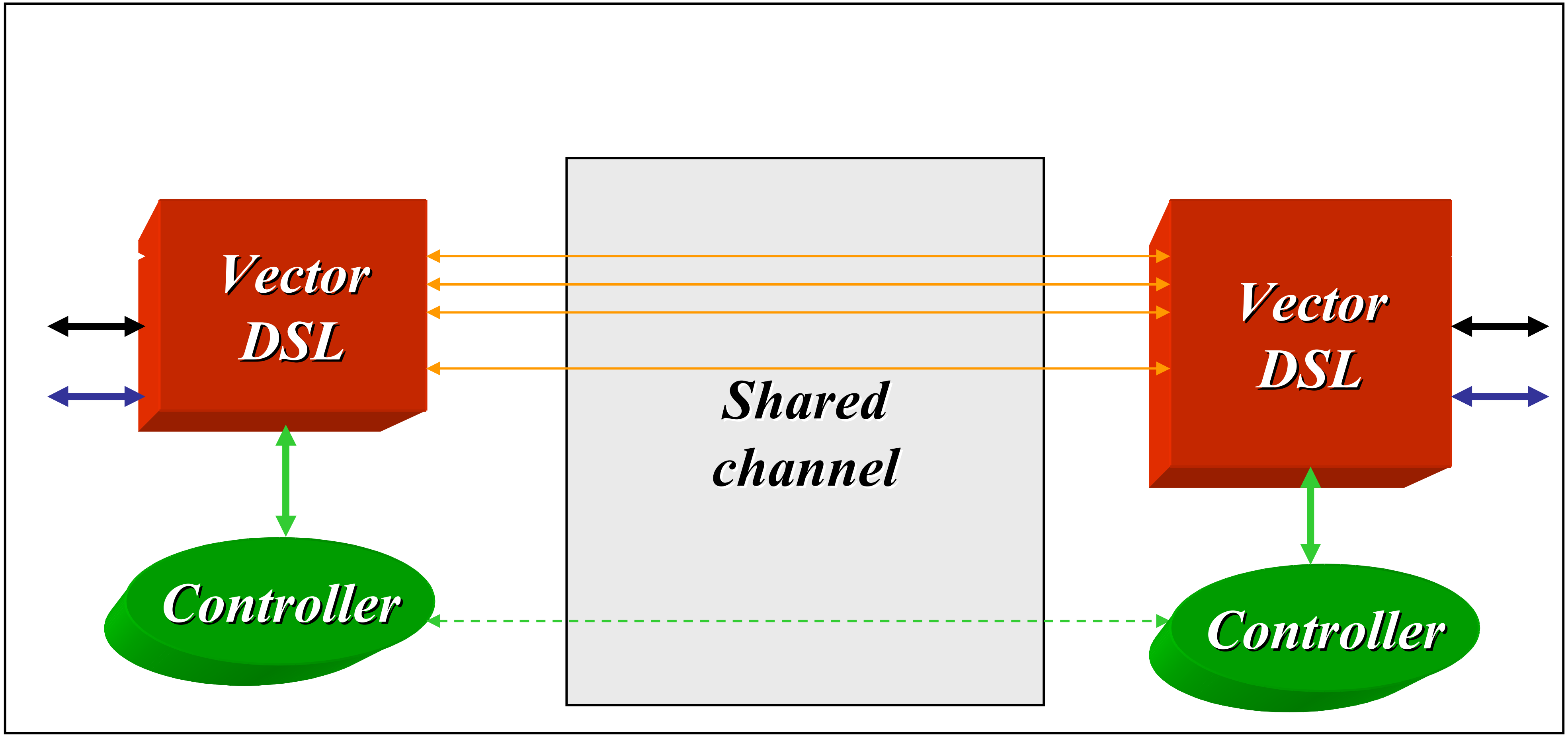
- For DSL "spectral balancing"
  - No successive decoding (distributed interference channel)

Coordinated 1-sided Signals: Vectoring



- Downstream – “Vector Broadcast Channel”
- Upstream – “Vector Multiple Access Channel”
  - Successive detection allowed

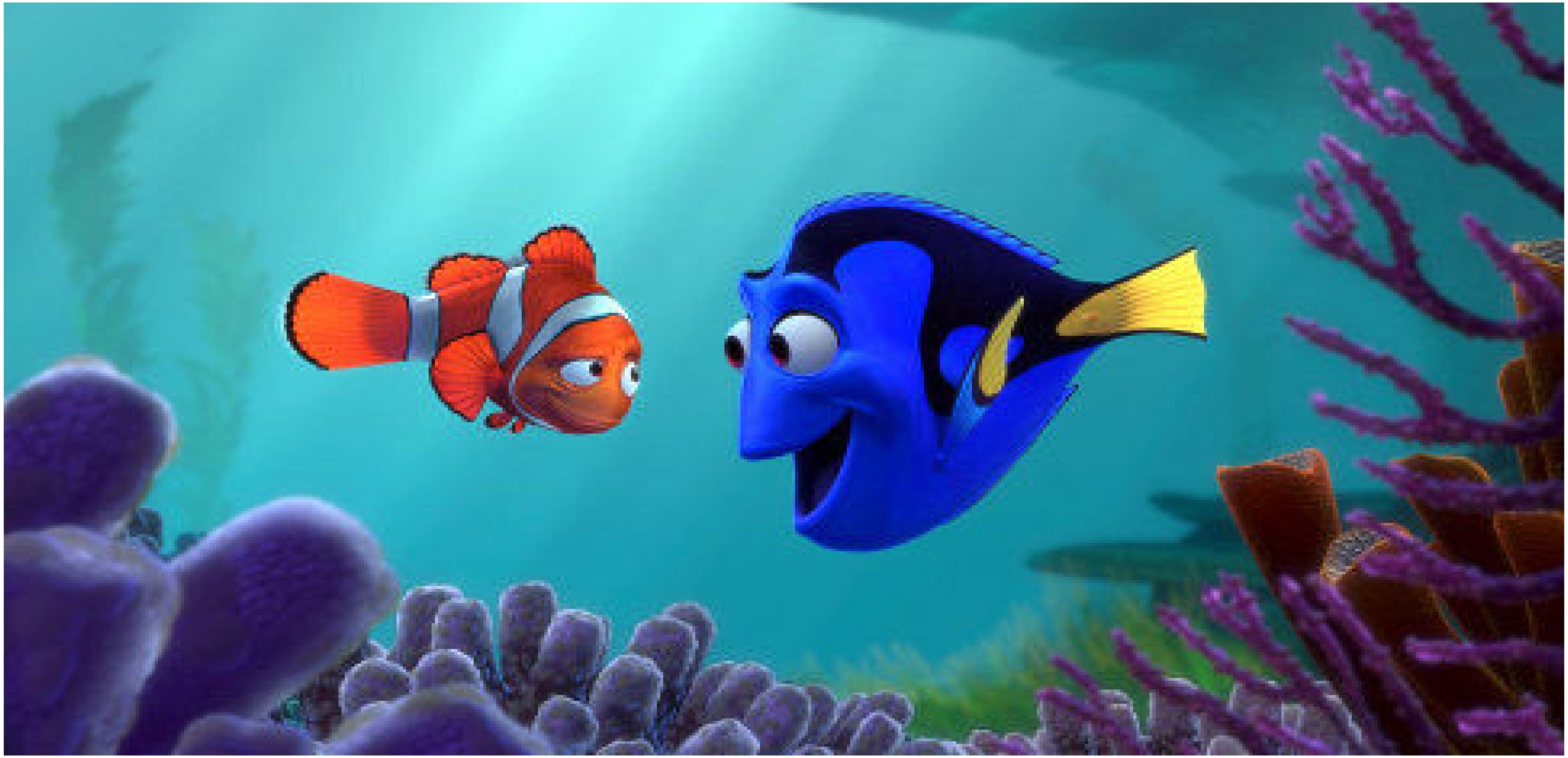
Coordinated 2-sided Signals “MIMO”



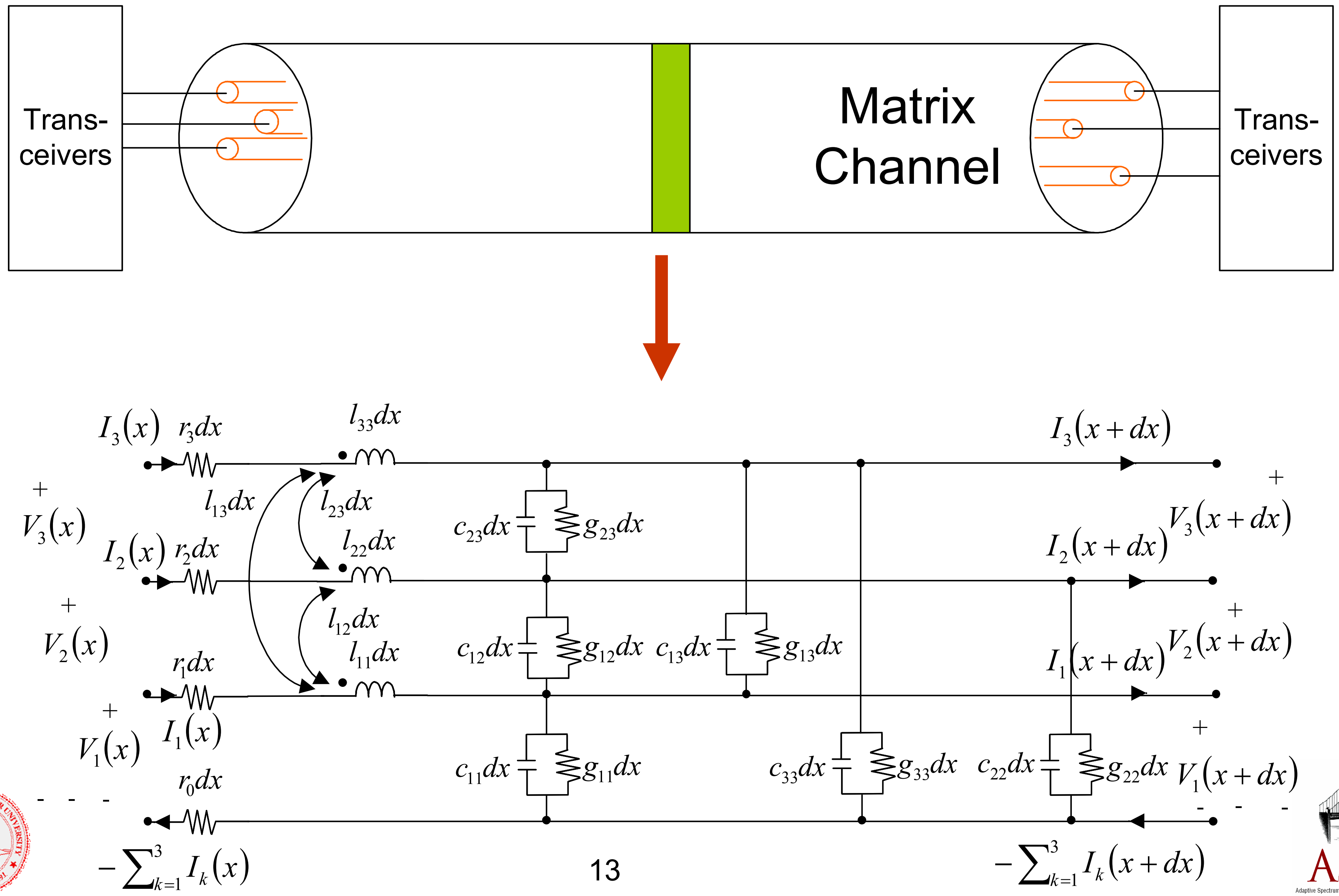
- MIMO (called “bonded” in DSL standards)
  - Often not enough extra telephone lines though …
  - Really just vector single-user hcannel

JC's first Rule: Know the Channel

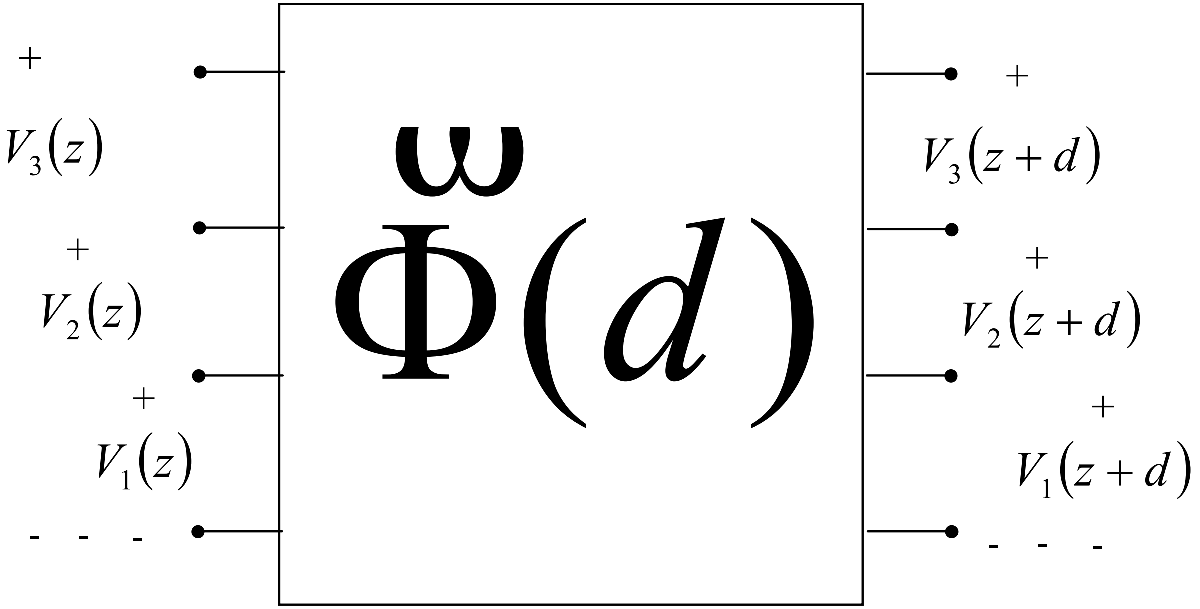
Finding MIMO



Multi-Conductor Transmission-Line Theory



Multi-port Theory for a Segment



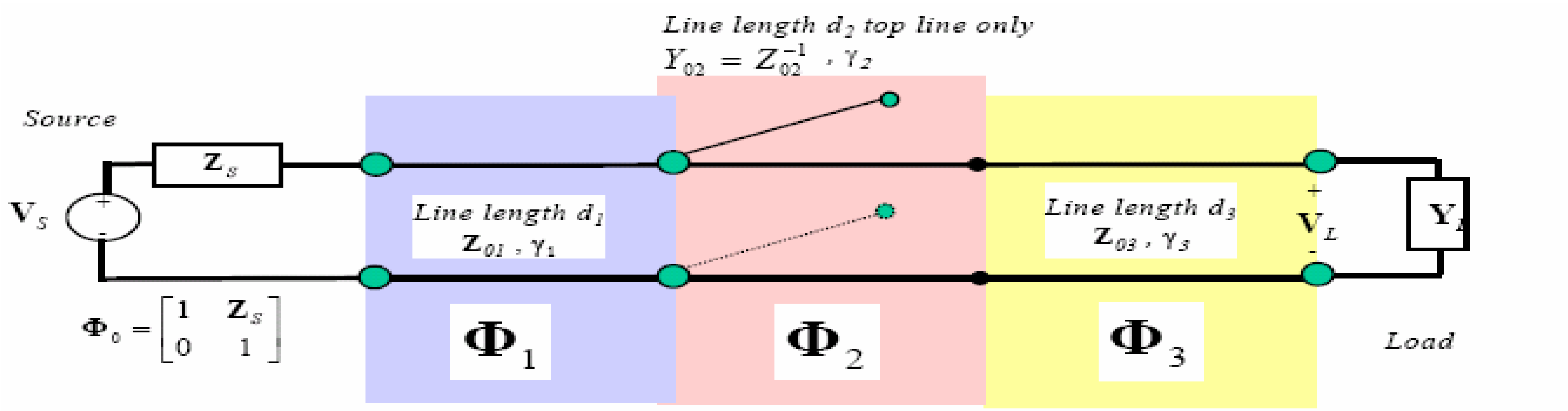
$$\begin{bmatrix} \mathbf{V}(z+d,\omega) \\ \mathbf{I}(z+d,\omega) \end{bmatrix} = \mathbf{\Phi}(z,d,\omega) \begin{bmatrix} \mathbf{V}(z,\omega) \\ \mathbf{I}(z,\omega) \end{bmatrix}$$

$$\mathbf{V}(z) = \begin{bmatrix} V_1(z,\omega) \\ V_2(z,\omega) \\ V_3(z,\omega) \end{bmatrix} \quad \mathbf{I}(z) = \begin{bmatrix} I_1(z,\omega) \\ I_2(z,\omega) \\ I_3(z,\omega) \end{bmatrix}$$

$$\mathbf{\Phi}(z,d,\omega) = \begin{bmatrix} \mathbf{A}(z,d,\omega) & \mathbf{B}(z,d,\omega) \\ \mathbf{C}(z,d,\omega) & \mathbf{D}(z,d,\omega) \end{bmatrix}$$

A,B, C, D is a Matrix

Solution for a Complete System



Complete Systems as cascades of segment

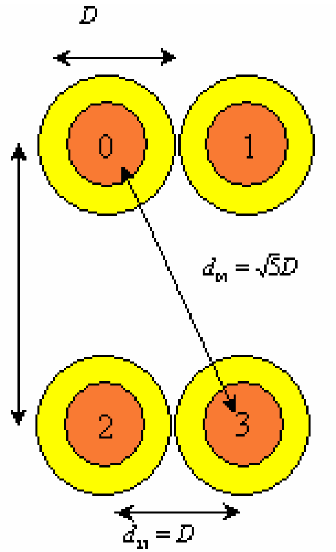
$$\begin{bmatrix} \mathbf{V}(0) \\ \mathbf{I}(0) \end{bmatrix} = \mathbf{\Phi}_1 \cdot \mathbf{\Phi}_2 \cdots \mathbf{\Phi}_N \cdot \begin{bmatrix} \mathbf{V}(d) \\ \mathbf{I}(d) \end{bmatrix} = \mathbf{\Phi} \cdot \begin{bmatrix} \mathbf{V}(d) \\ \mathbf{I}(d) \end{bmatrix} \qquad \mathbf{\Phi} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix}$$

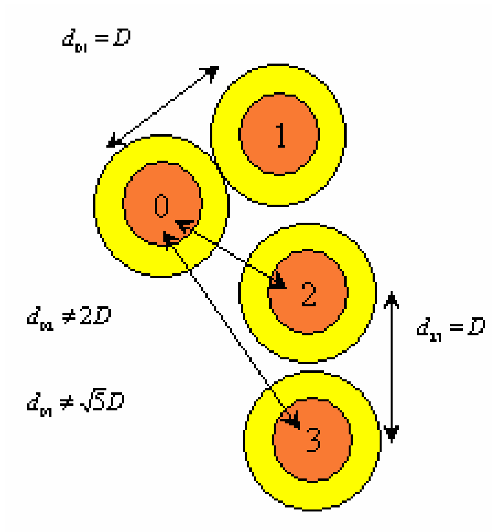
- Common mode channel matrix **H** is completely solved with

$\mathbf{\Phi}$, source and load admittance

$$\mathbf{H} = \left(\mathbf{A} + \mathbf{B} \cdot \mathbf{Y}_L\right)^{-1} \cdot \left(\left(\mathbf{C} + \mathbf{D} \cdot \mathbf{Y}_L\right) \cdot \left(\mathbf{A} + \mathbf{B} \cdot \mathbf{Y}_L\right)^{-1} + \mathbf{Y}_S\right)^{-1} \cdot \mathbf{Y}_S$$

Calculations of **RLCG**





$$\boldsymbol{L} = \begin{bmatrix} l_{11} & l_{12} & l_{13} \\ l_{12} & l_{22} & l_{23} \\ l_{13} & l_{23} & l_{33} \end{bmatrix}$$

$$\mathbf{C} = \mu \cdot \varepsilon \cdot \mathbf{L}^{-1}$$

$$\mathbf{G} = \frac{\sigma}{\varepsilon} \cdot \mathbf{C}$$

$$\boldsymbol{R} = \begin{bmatrix} r_0 + r_1 & r_0 & r_0 \\ r_0 & r_0 + r_2 & r_0 \\ r_0 & r_0 & r_0 + r_3 \end{bmatrix} = r_0 \cdot \begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix}$$

$$l_{ii} = \left(\frac{\mu}{2\pi}\right) \cdot \ln\left(\frac{d_{i0}^2}{w_r^2}\right)$$

$$l_{ij} = \left(\frac{\mu}{2\pi}\right) \cdot \ln\left(\frac{d_{i0} \cdot d_{j0}}{d_{ij} \cdot w_r}\right)$$

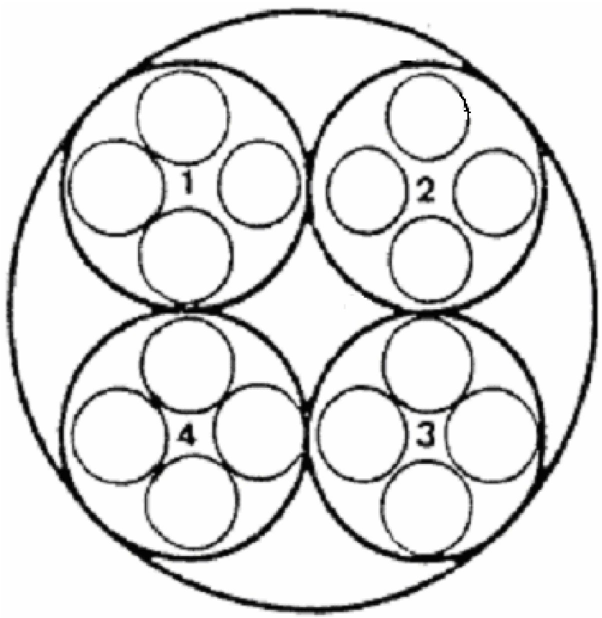
d_{ij} = distance between the center of conductor i and conductor j

w_r = radius of conductor wires

(See C. Paul, J. Faria and other approximations)

Common Cable Types

Quad Cable

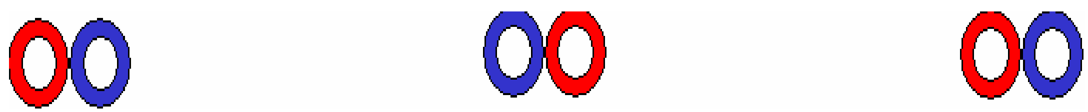


Nice symmetric properties

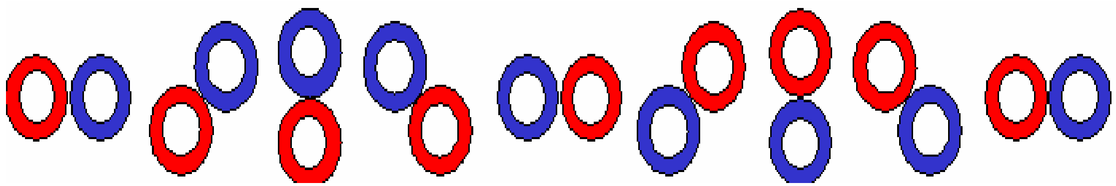
Twisted Pairs

Twisting Modeling Approximations

- *Abrupt Twisting (C. Paul)*

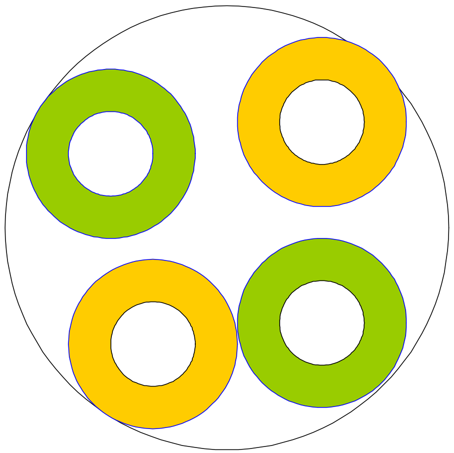


- **Discrete Rotation (C. Paul, J. Fang)**



Multi-pair discrete rotation requires lots of computations

Cable Imperfections Modeling



Non-ideal Quad cables, not forming perfect square

Non-ideal Twisted Pairs

Type 1: Pair center adjustment

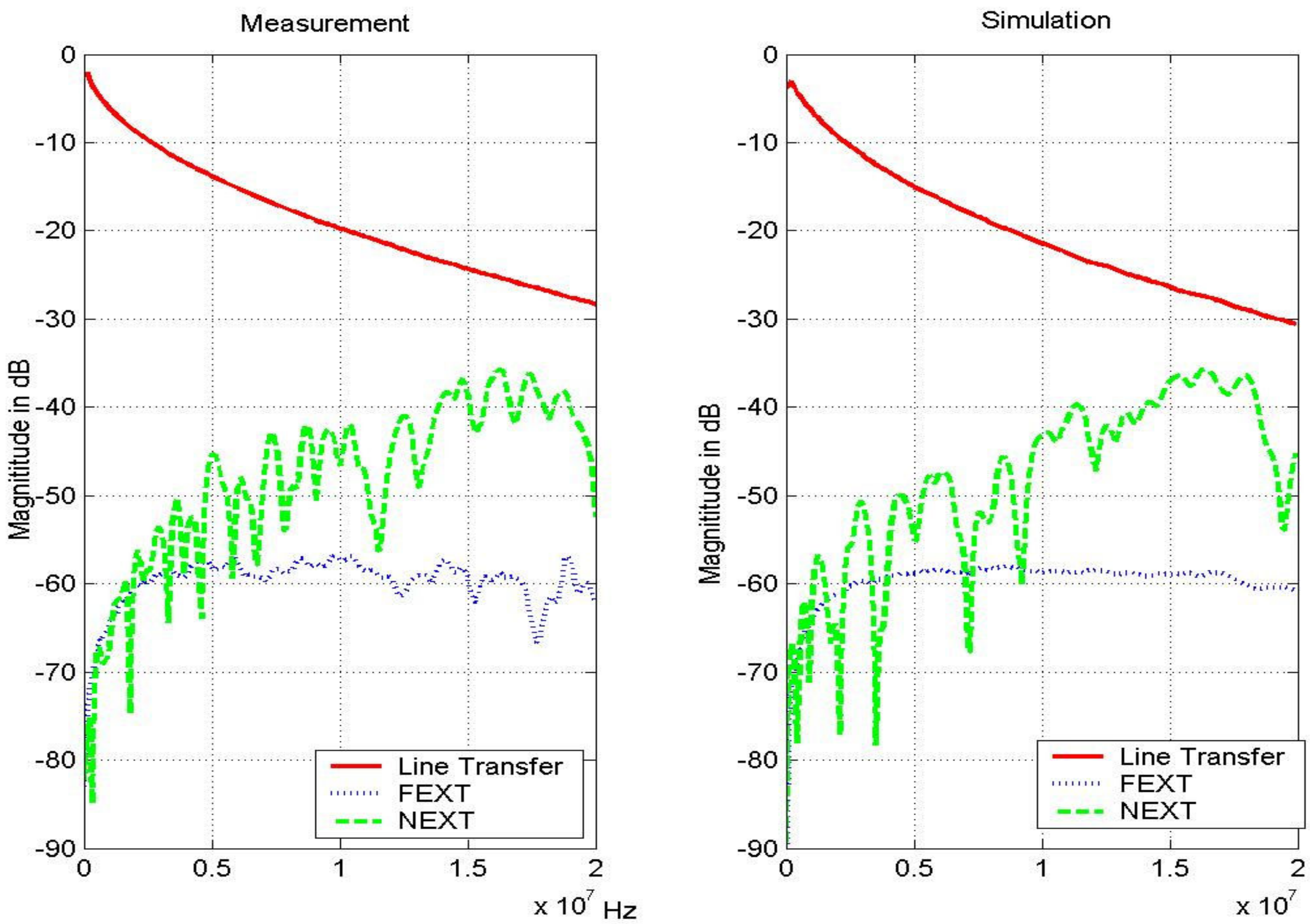
$$pc(i,z) = \overline{pc}(i,z) + \Delta pc(i,z)$$

Type 2: Twist rate adjustment

Ex: $P_{tr}(tr) = 1/2a, tr \in [\overline{tr} - a, \overline{tr} + a]$

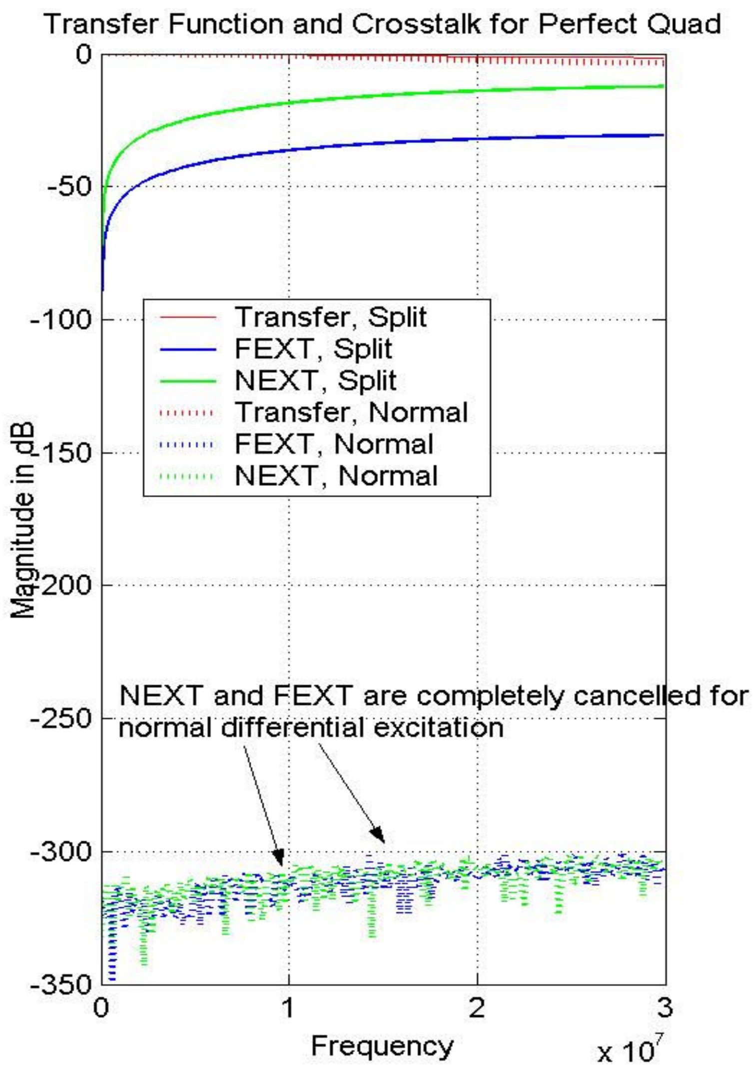
Type 3: Non-twisting cable head and tail

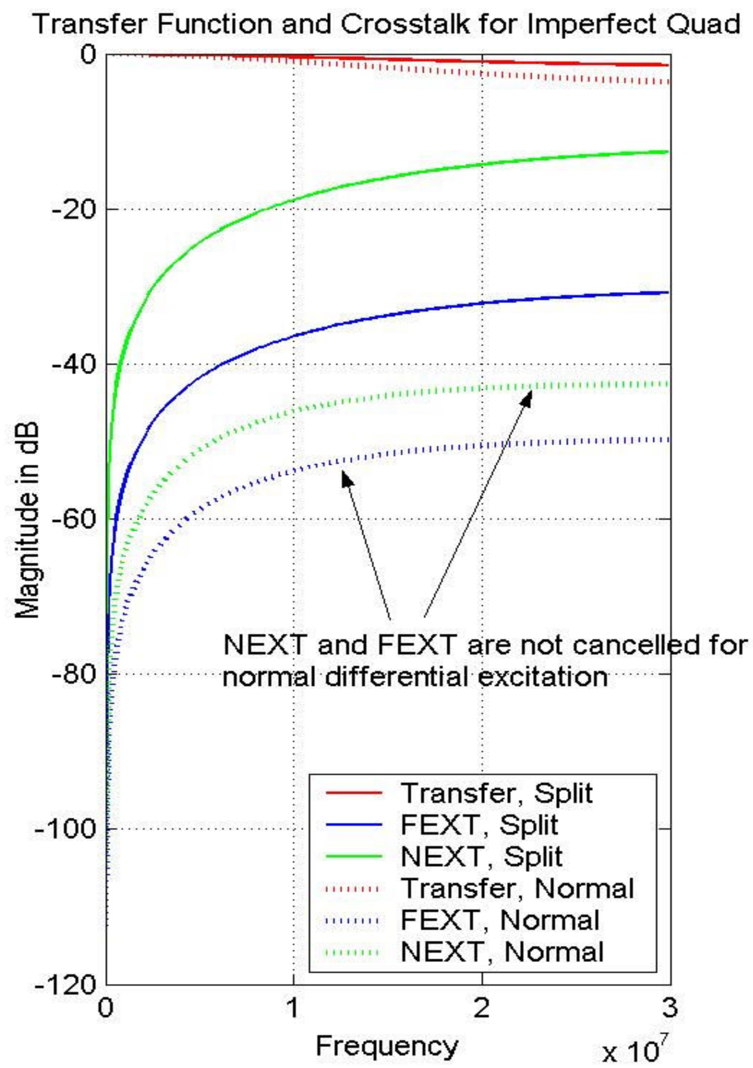
Simulation vs. Measurement



274 Meter, Normal Differential Excitation

Perfect vs. Imperfect Twisting





Some DSLs of interest

DSL Name	Speeds	When
ADSL1 G.992.1 Tones (256/32)	To 8 Mbps down To 800 kbps up	2000
ADSL2+ G.992.5 Tones (512/64)	To 25 Mbps down To 3 Mbps up	2003
VDSL2 G.993.2 Tones (4096/4096)	To 150 Mbps down To 100 mbps up	2006
VDSL3 G.993.3 Effective tones (8192)	100's of Mbps	2008

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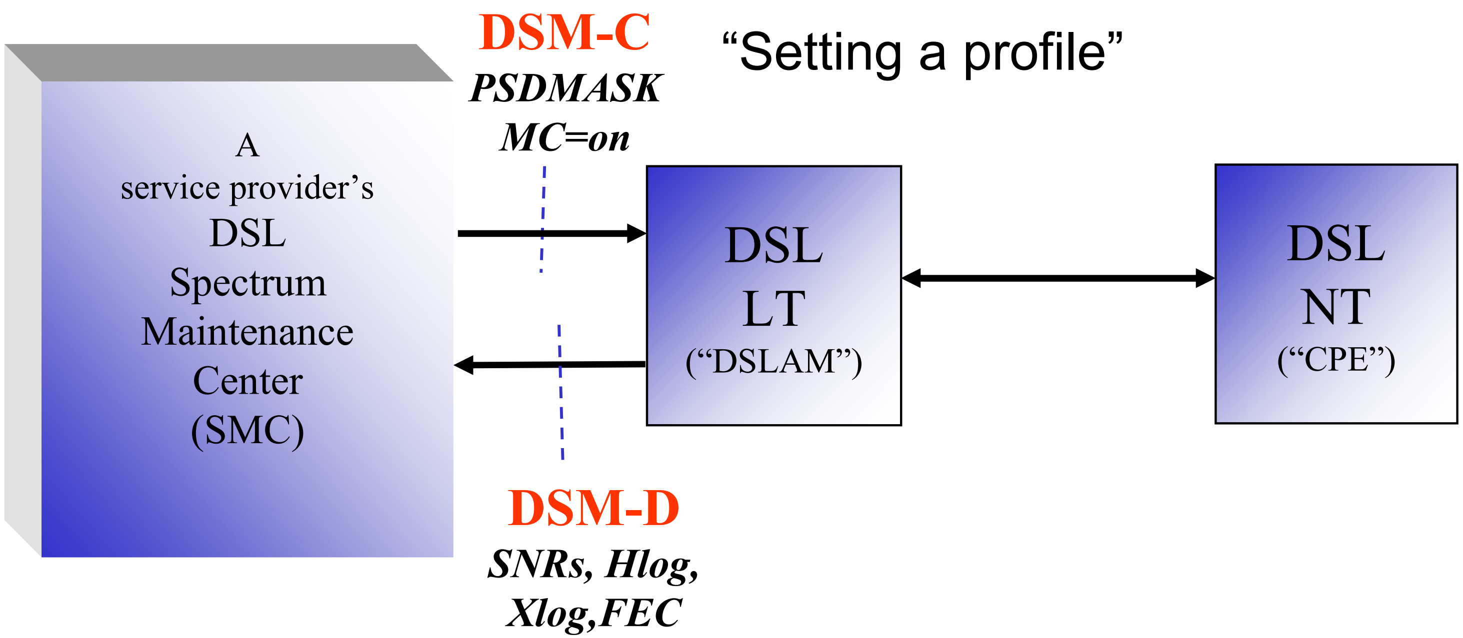
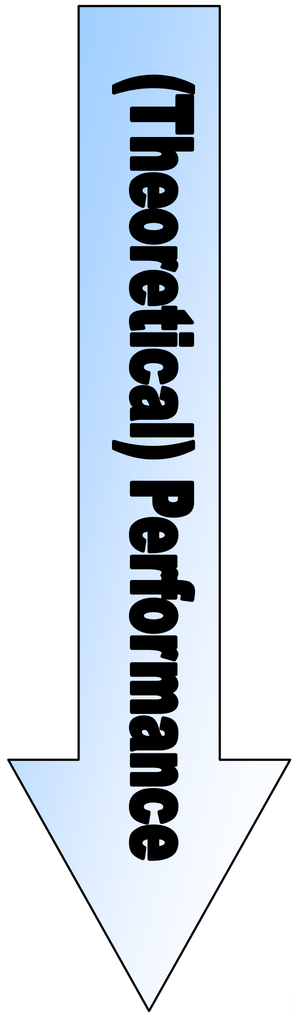
Dynamic Spectrum Managment



- Superset of the terms
  - Dynamic Line Management (DLM)
  - DSL Optimization
- Practiced by a DSL Service Provider (on only their lines)
- Faced enormous opposition in standards (crazy, won't work, …)
- Now a standard: specified (DSM-C / DSM-D some LT/NT support)
  - Superset of G.997.1 (ITU) – see ATIS DSM Report (issued May 2007)
  - Also provides informative examples of use of DSM (what SMC can do)
  - VDSL3 in ITU (G.vector, G.impulse)

DSM Level summary

Table 1 – Dynamic Spectrum Management Levels [From ANSI DSM Report].	
DSM Level	**Description**
0	No DSM
1	Single-line ***Politeness and Impulse Control*** (sometimes called Dynamic Line Management, DLM)
2	Multiple-line ***Spectrum Balancing*** (spectra controls)
3	Multiple-line ***Vectored*** Coordinated LT-side downstream transmission and upstream reception “MIMO” crosstalk cancellation



DSM Level 1 Status

- And I thought crosstalk was largest noise ….
  - Well it is kind of (energy is largest)
  - Impulse noise (when it happens) has larger power
- Line stabilization first (get the burst-error-correction right first) → Level 1 DSM
  - Expanded reach
  - Reduced churn, trouble calls, truck rolls
  - Few $/line-month (typically $100’s of millions annually)
- Lesson for students:
  - Often to get a good idea to work and be accepted, one has to solve several seemingly unrelated problems first
    - Sometimes might be called “Murphy’s Law – anything that can go wrong, will go wrong.”

Bad Impulse Line – Live Customer

(HOME) ShowRF -- Loop Performance Analyzer (DOC)

Line Code Violation and Error Seconds

Downstream Line code violation:

Time	10:30	10:15	10:0	9:45	9:30	9:15	9:0	8:45	8:30	8:15	8:0	7:45	7:30	7:15	7:0	6:45
Value	1000	2939	2790	2648	2746	2712	3298	5379	1884	380	662	728	678	657	696	767
Time	6:30	6:15	6:0	5:45	5:30	5:15	5:0	4:45	4:30	4:15	4:0	3:45	3:30	3:15	3:0	2:45	2:30
Value	737	722	828	845	783	865	867	819	845	1033	1835	3123	4567	3476	2821	458	440

Upstream Line code violation:

Time	10:0	9:45	9:30	9:15	9:0	8:45	8:30	8:15	8:0	7:45	7:30	7:15	7:0	6:45	6:30	6:15
Value	11	0	0	5	8	14	13	18	0	0	0	0	0	0	0	0
Time	6:0	5:45	5:30	5:15	5:0	4:45	4:30	4:15	4:0	3:45	3:30	3:15	3:0	2:45	2:30	2:15	2:0
Value	0	0	0	0	0	0	0	0	2	4	0	0	2	0	0	0	0

Downstream Error Seconds:

Time	10:45	10:30	10:15	10:0	9:45	9:30	9:15	9:0	8:45	8:30	8:15	8:0	7:45	7:30	7:15	7:0
Value	59	867	875	825	807	856	862	785	856	701	218	408	493	496	456	482
Time	6:45	6:30	6:15	6:0	5:45	5:30	5:15	5:0	4:45	4:30	4:15	4:0	3:45	3:30	3:15	3:0	2:45
Value	507	505	514	553	554	530	555	560	551	545	564	789	773	896	884	752	369

Upstream Error Seconds:

Time	10:0	9:45	9:30	9:15	9:0	8:45	8:30	8:15	8:0	7:45	7:30	7:15	7:0	6:45	6:30	6:15
Value	1	0	0	1	3	3	5	9	3	0	0	0	0	0	0	0
Time	6:0	5:45	5:30	5:15	5:0	4:45	4:30	4:15	4:0	3:45	3:30	3:15	3:0	2:45	2:30	2:15	2:0
Value	0	0	0	0	0	0	0	0	2	4	0	0	2	0	0	0	0

Good Line

(HOME) ShowRF -- Loop Performance Analyzer (DOC)

Line Code Violation and Error Seconds

Downstream Line code violation:

Time	3:30	3:15	3:0	2:45	2:30	2:15	2:0	1:45	1:30	1:15	1:0	0:45	0:30	0:15	0:0	23:45
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	23:30	23:15	23:0	22:45	22:30	22:15	22:0	21:45	21:30	21:15	21:0	20:45	20:30	20:15	20:0	19:45	19:30
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Upstream Line code violation:

Time	2:15	2:0	1:45	1:30	1:15	1:0	0:45	0:30	0:15	0:0	23:45	23:30	23:15	23:0	22:45	22:30
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	22:15	22:0	21:45	21:30	21:15	21:0	20:45	20:30	20:15	20:0	19:45	19:30	19:15	19:0	18:45	18:30	18:15
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Downstream Error Seconds:

Time	3:45	3:30	3:15	3:0	2:45	2:30	2:15	2:0	1:45	1:30	1:15	1:0	0:45	0:30	0:15	0:0
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	23:45	23:30	23:15	23:0	22:45	22:30	22:15	22:0	21:45	21:30	21:15	21:0	20:45	20:30	20:15	20:0	19:45
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Upstream Error Seconds:

Time	2:45	2:30	2:15	2:0	1:45	1:30	1:15	1:0	0:45	0:30	0:15	0:0	23:45	23:30	23:15	23:0
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	22:45	22:30	22:15	22:0	21:45	21:30	21:15	21:0	20:45	20:30	20:15	20:0	19:45	19:30	19:15	19:0	18:45
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Impulse Noise – Level 1

- Nonstationary large noise (not other users)
- ~20% of DSLs are “unstable” (likely extra operations cost)
  - Can be as high as 50% for higher speeds and video
  - Causes conservative deployment (range)
  - Increases cost to operate DSL Network (called “opex”)
  - Can forget crosstalk if this dominates – must be handled first
- Simple “burst interleave” helps BUT
  - not nearly enough
  - Some networks have all lines on interleave and still have 20-50% instability
- A more effective solution
  - Increase the ratio parity/codeword, called here R/N
    - In DSM Level 1 controls this is equivalent to “Low delay” with “high burst length”
- Retransmission?
  - Ok but will not address the main issue of intermittent noise that affects all symbols for significant periods
    - May look good in lab, but not in field
  - Low-delay/high-INP is much more desirable

Impulse Remedies

1. Increasing margins (or using “virtual” noises)
   - Very ineffective, large rate loss

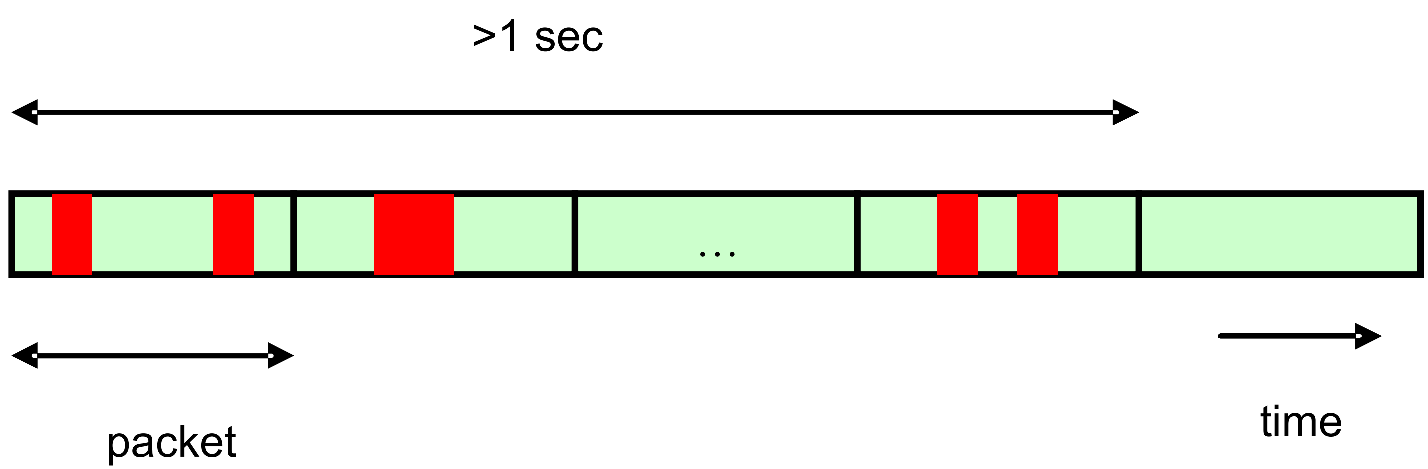
2. “long interleave” not effective (errors still observed)
   - And delay can adversely impact some applications

3. Retransmission (without FEC)
   - Tx buffers overflow (too many packets need to be resent)

4. Tiered Rate Adaption (TRA)

5. Using the FEC better
   - Increase **parity ratio, R/N (parity/codeword)**
     - Or, high burst with low delay

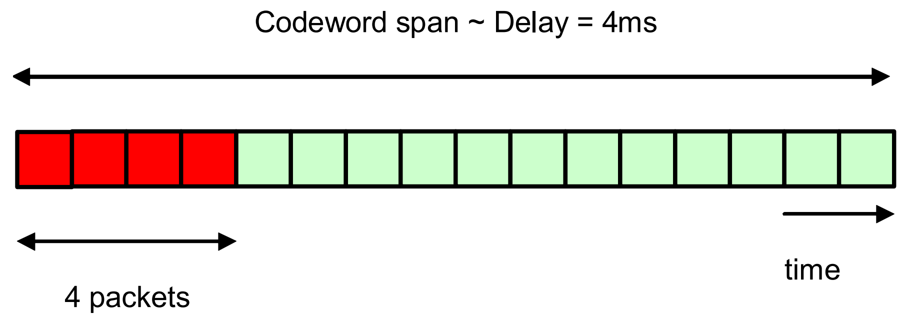
Increasing R/N



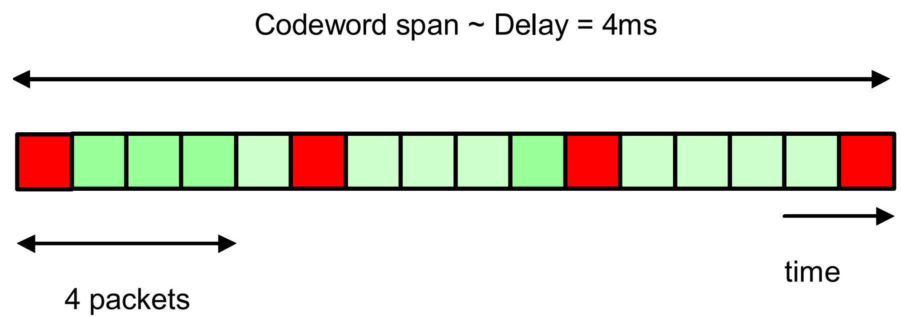
- Bytes corrupted in RS codeword: C %
  - Basically all codewords are “hit”
- R/N ratio required to correct all bytes: 2*C %
  - Without erasure decoding (C% with erasures)

Forcing high R/N with FEC+interleaving

- Choose burst length, Delay to force high R/N
- Example:
  - burst = 4 (250 μs) packets, Delaymax = 4ms
  - 1 in 4 bytes of codeword span in error (25%)
  - Requires R/N = 50% (R=16, N=32)

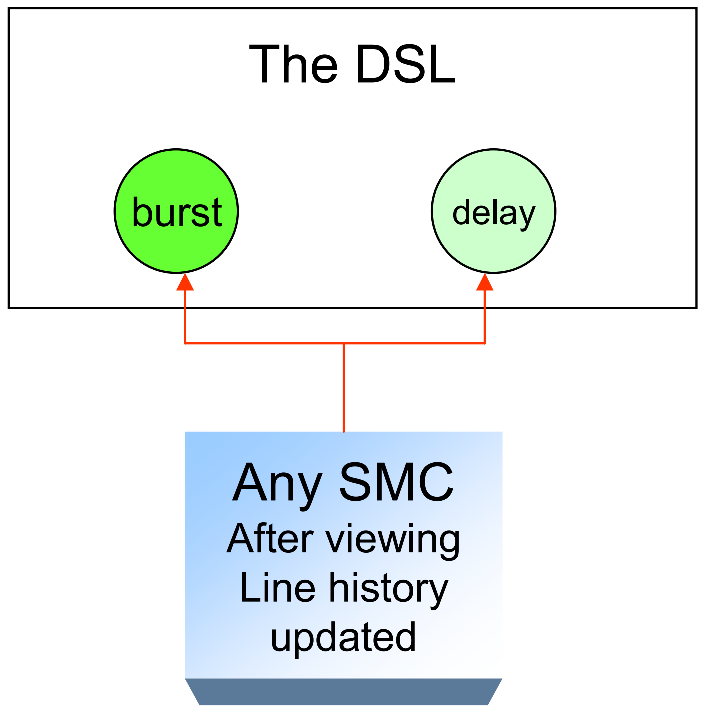


After receiver de-interleaving

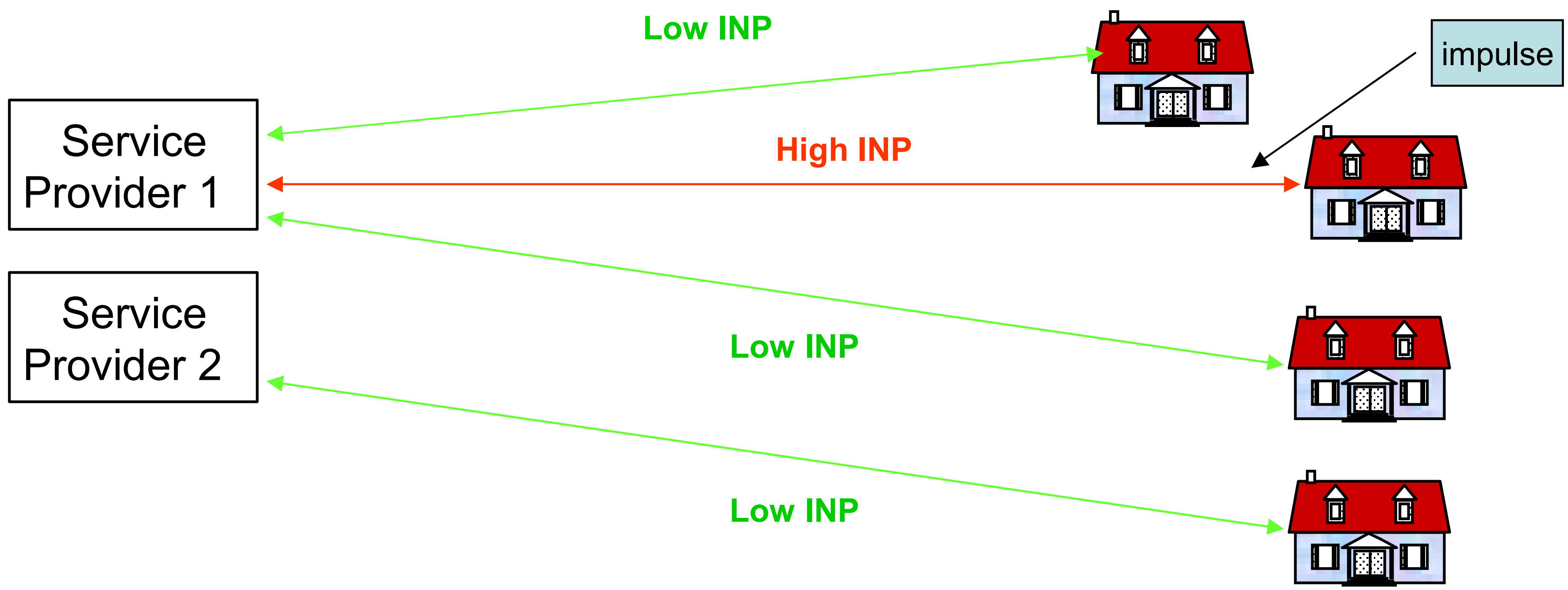


Level 1 DSM: FEC control basics

- Higher R/N drops throughput (real data rate)
- Thus, only do it on line with "CV's"
- Keep boosting R/N
  - Until CV's low enough

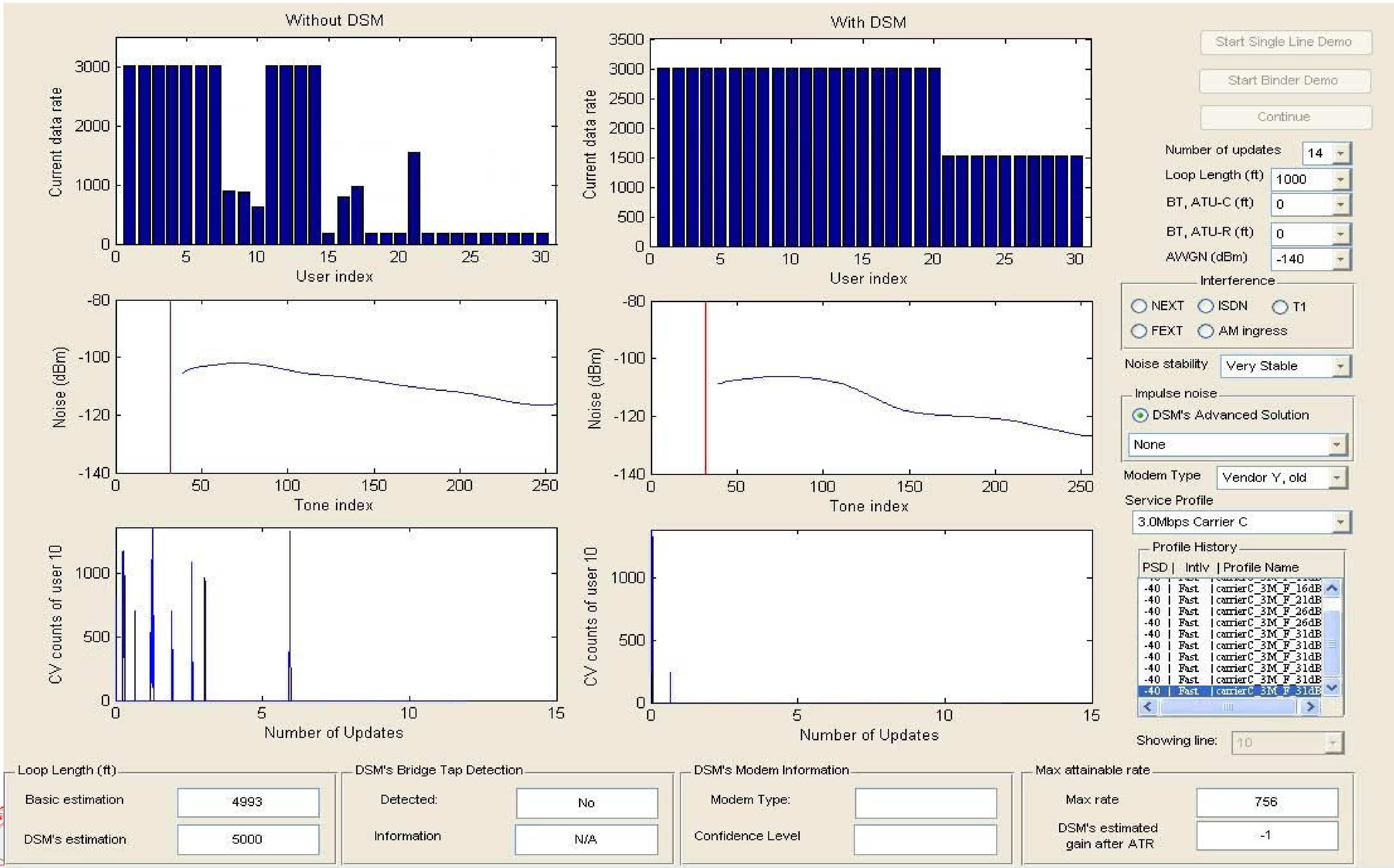


L1: FEC Control Advantages

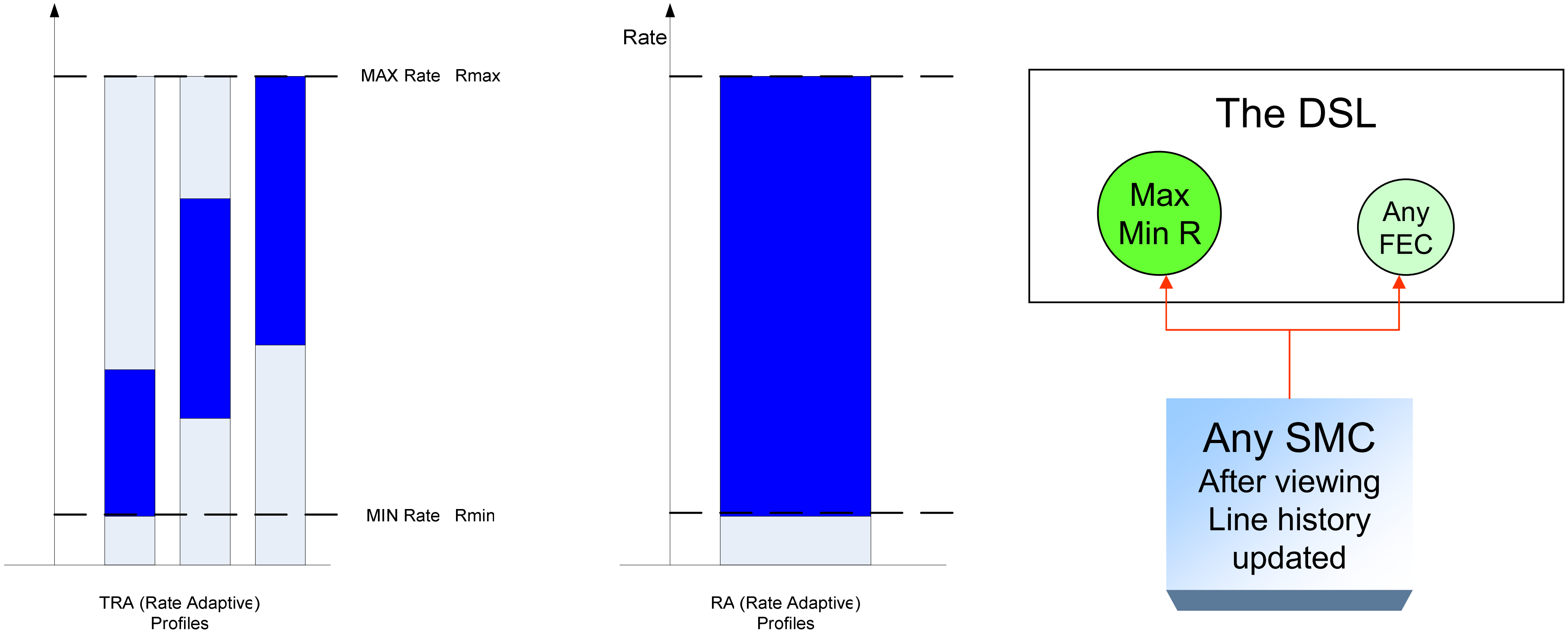


- PSD's become quasi-stationary (thus allows DSM)
- Used only where necessary
  - Largest average footprint increase (know where green/red)
    - Crosstalk also lowered if politeness used on all
- Preferred when possible
  - Some equipment not compliant or blocks the capability (prefer power-blast solution)

Carrier C and DSM: Advanced INP

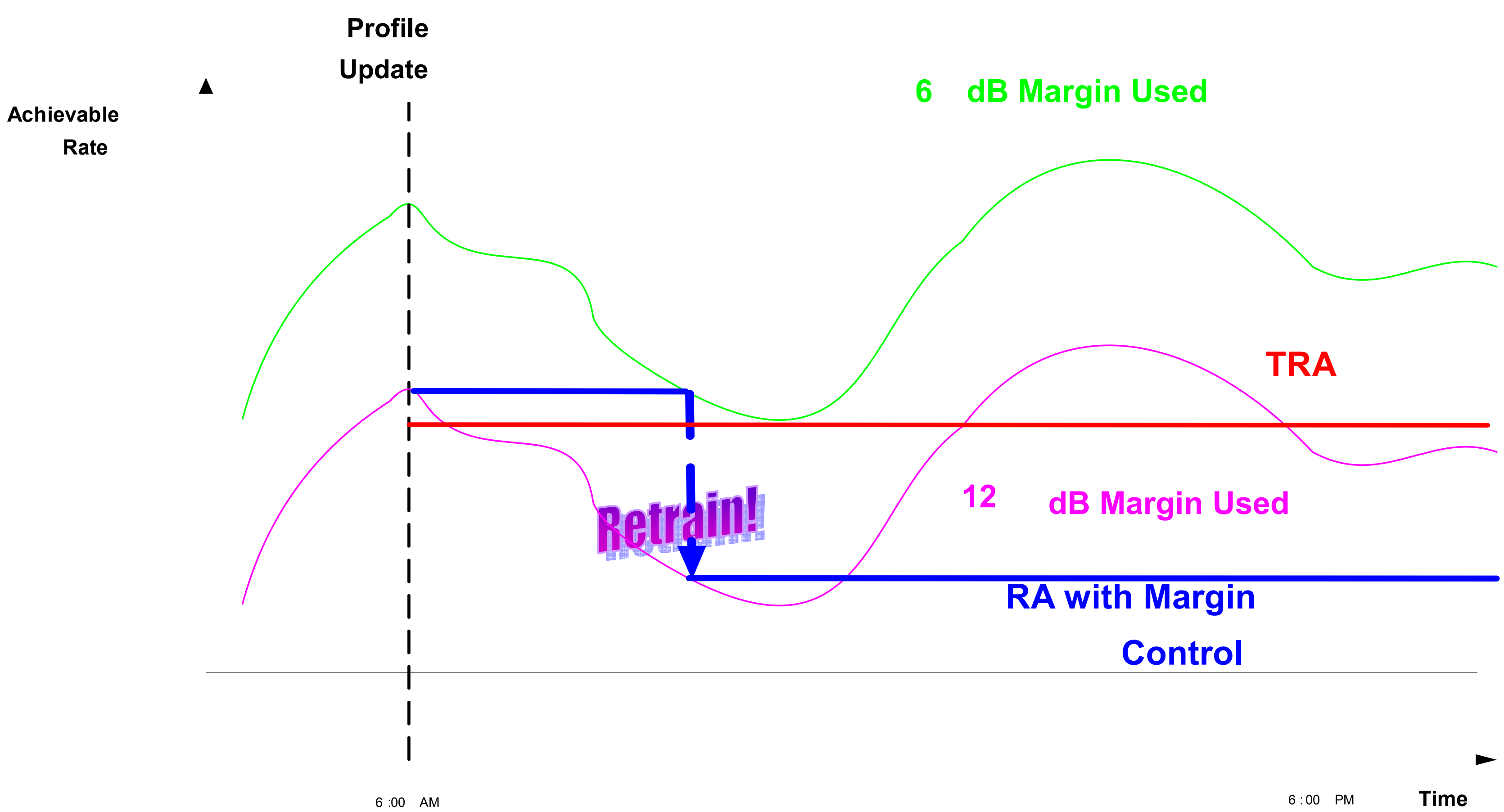


Level 1: Tiered Rate Adaption



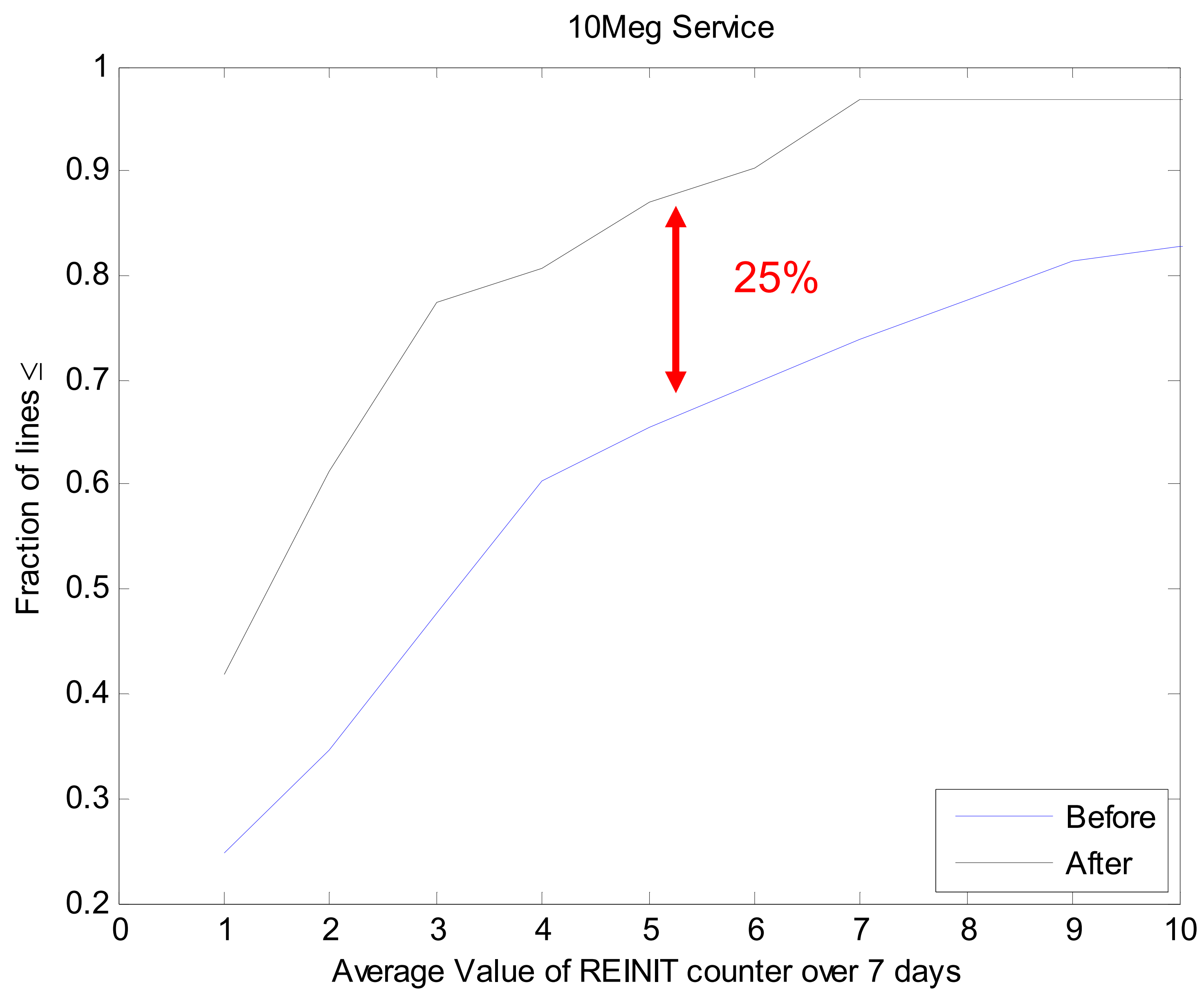
- Adjust range of rates
- Not as good as FEC, but
  - Circumvents blocking vendors

TRA vs. RA with MC

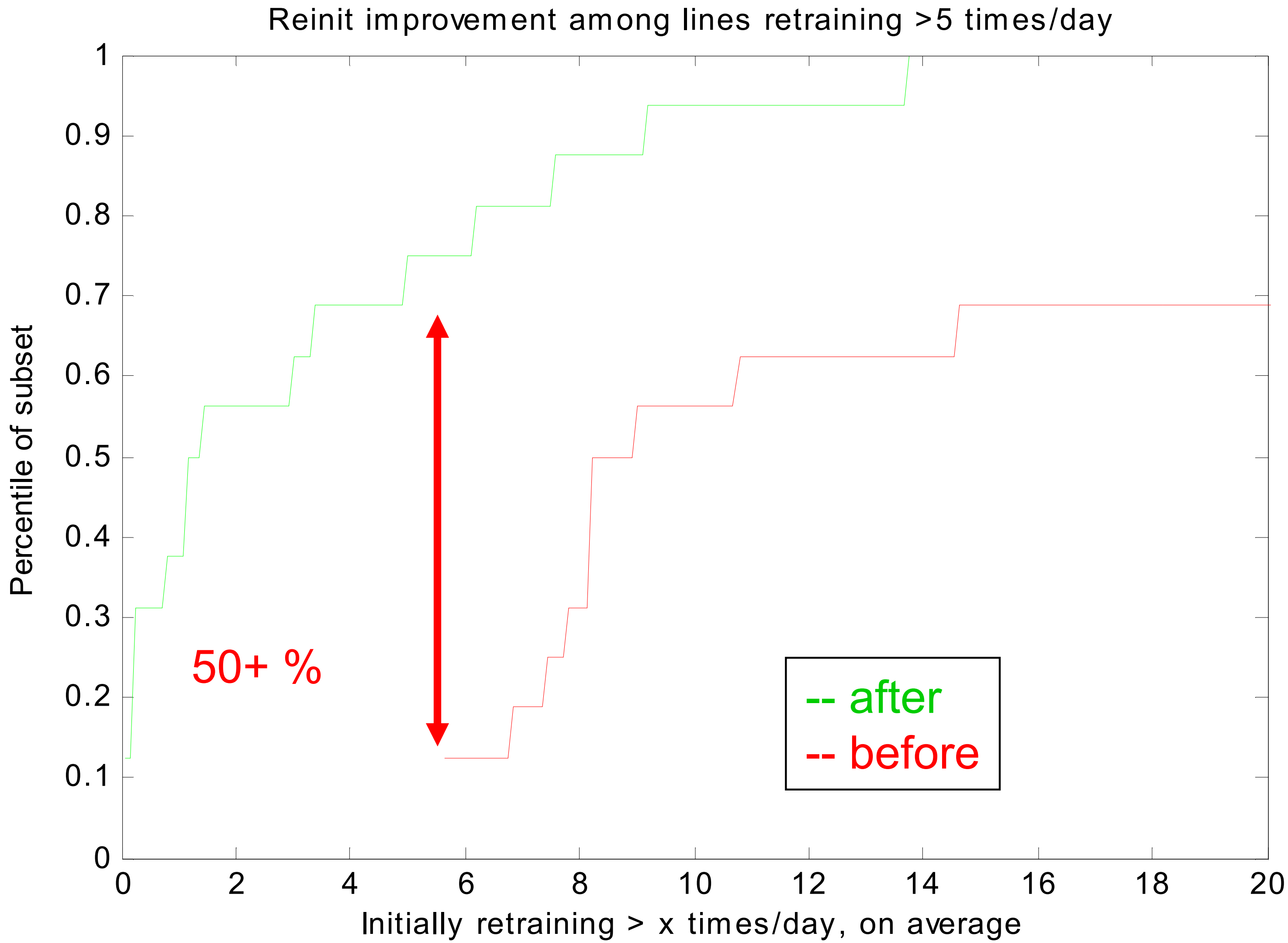


Margin = pretend the noise is “margin dB” higher than measured in case unforseen noise occurs
For give probability of bit error (1e-7 in DSL)

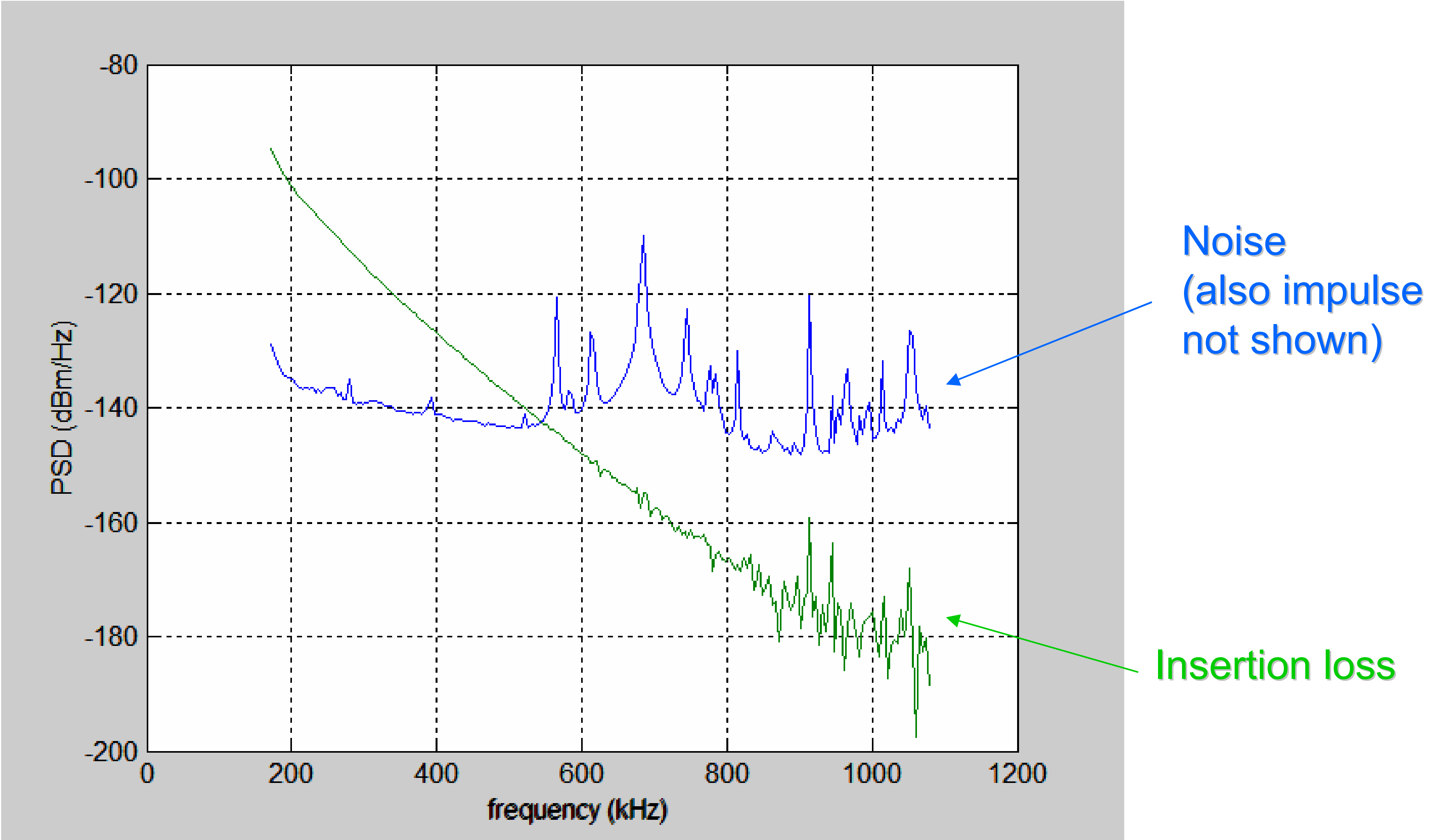
Large “Mature” Service Provider with TRA



Smaller Newer Service Provider with TRA

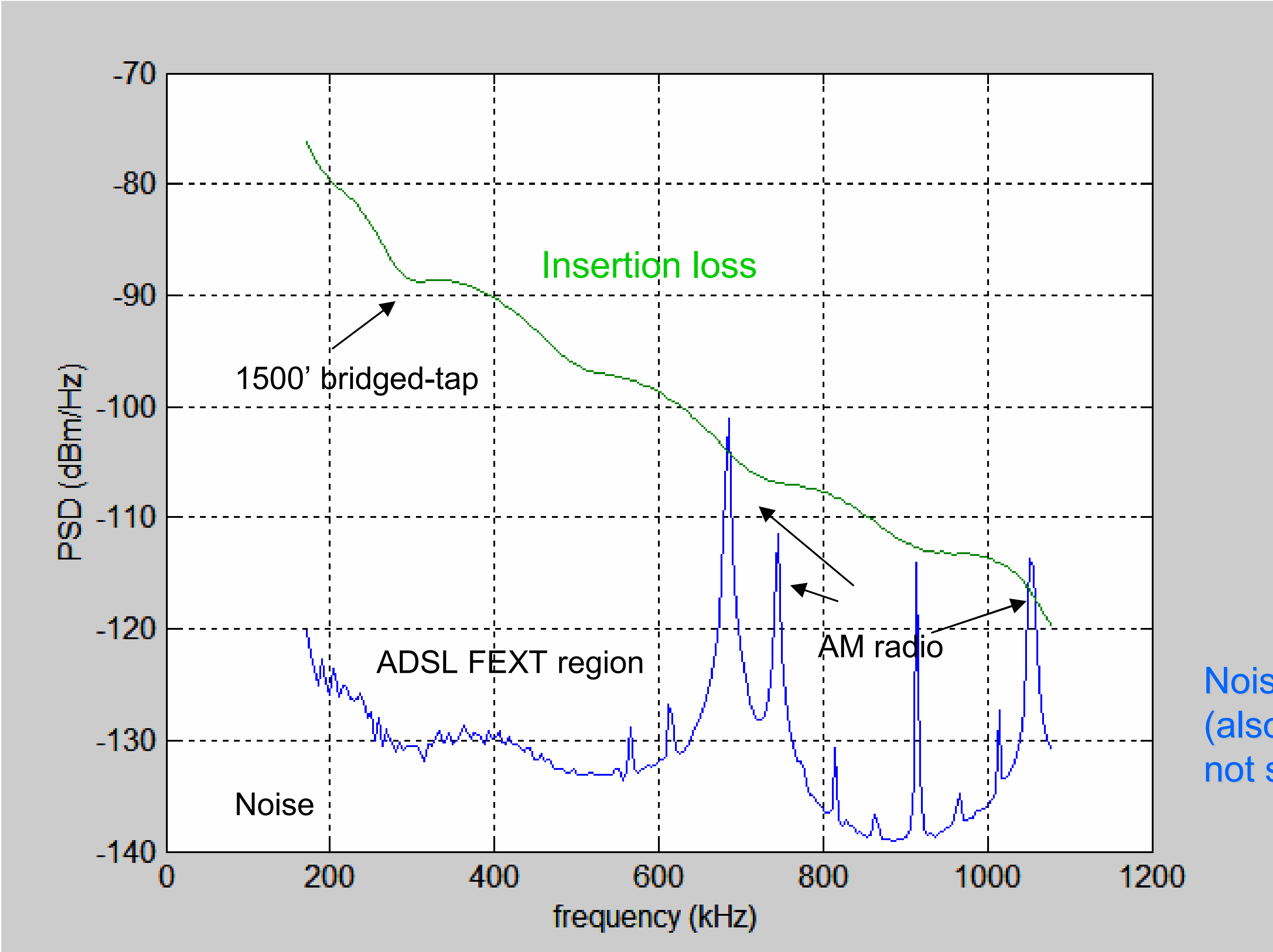


Cioffi DSL Line 1



- 17000’ loop
- Provisioned at 192 kbps, now running 768 kbps with early DSM

Cioffi DSL Line 2



Noise (also impulse not shown)

- 8000' loop (fiber-fed "remote terminal" RT)
- Provisioned at 1536 kbps, now running 6008 kbps with early DSM

Outline

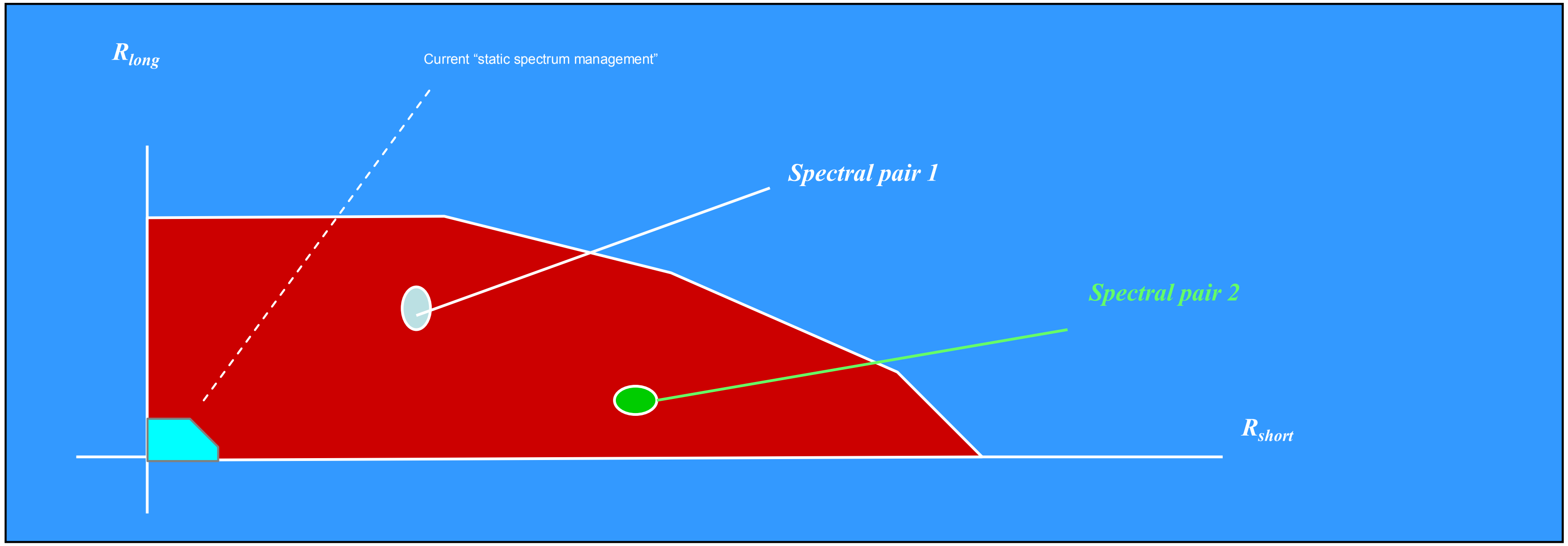
- DSM Basics
- Spectrum Balancing
- Vectoring

Table 1 – Dynamic Spectrum Management Levels [From ANSI DSM Report].

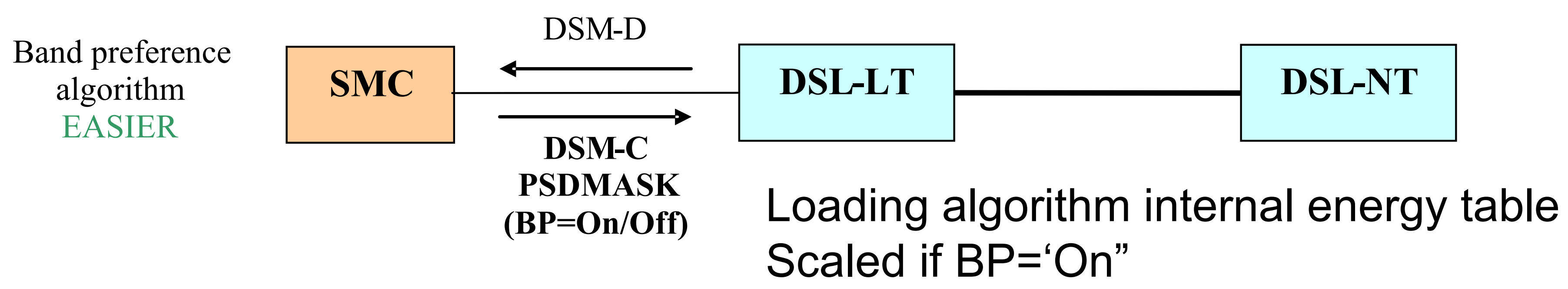
DSM Level	Description
0	No DSM
1	Single-line ***Politeness and Impulse Control***
2	Multiple-line ***Spectrum Balancing*** (spectra controls)
3	Multiple-line ***Vectored*** Coordinated LT-side downstream transmission and upstream reception

Now back to DSM Rate Regions!

- DSM can use the region – any point
  – Consistent with earlier spectrum management standards
  – Static SM leads to smaller region (really a point)

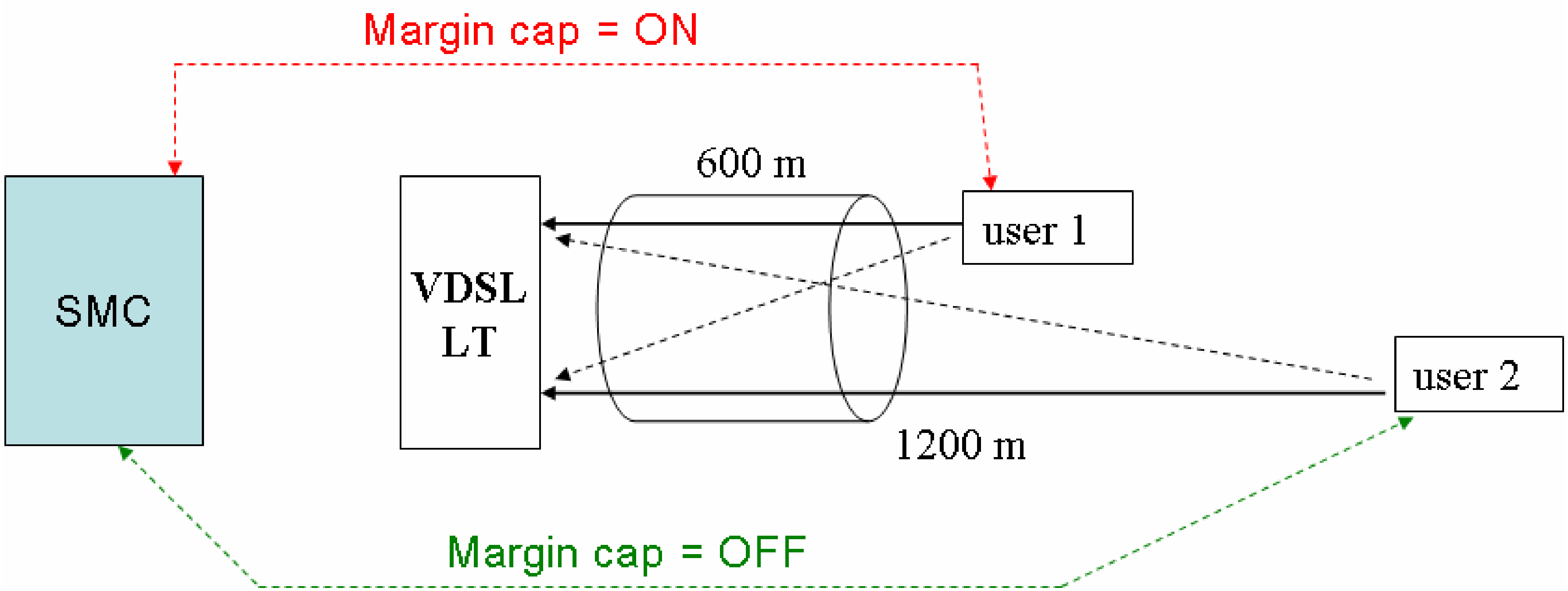


Band Preference/margin-cap



- Two Loading Algorithms:
  - Normal “water-fill” if OFF
  - More polite algorithm if “ON”

Band Preference

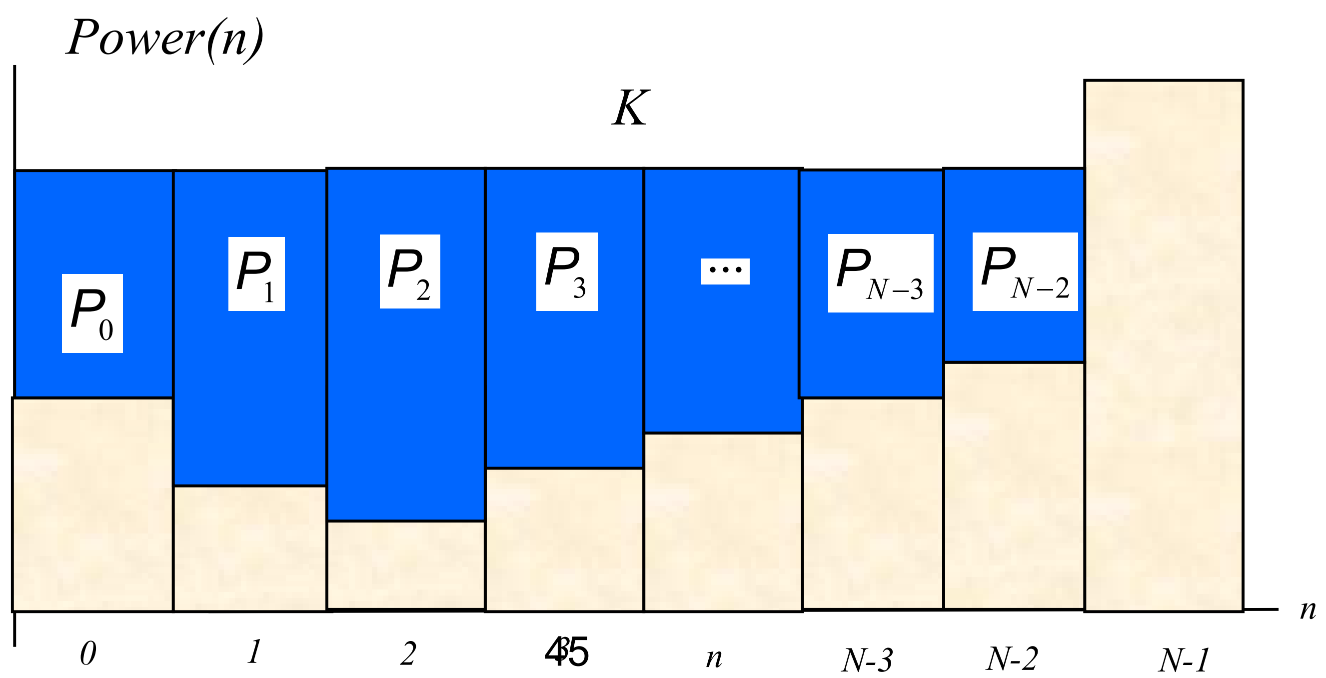


- User 1 = exceptionally polite
- User 2 = normal polite
- In all cases
  - Rest of spectrum management bounds observed

Basic Water Filling (MC off)

- Power on tone n adds to normalized noise to fill to a constant level

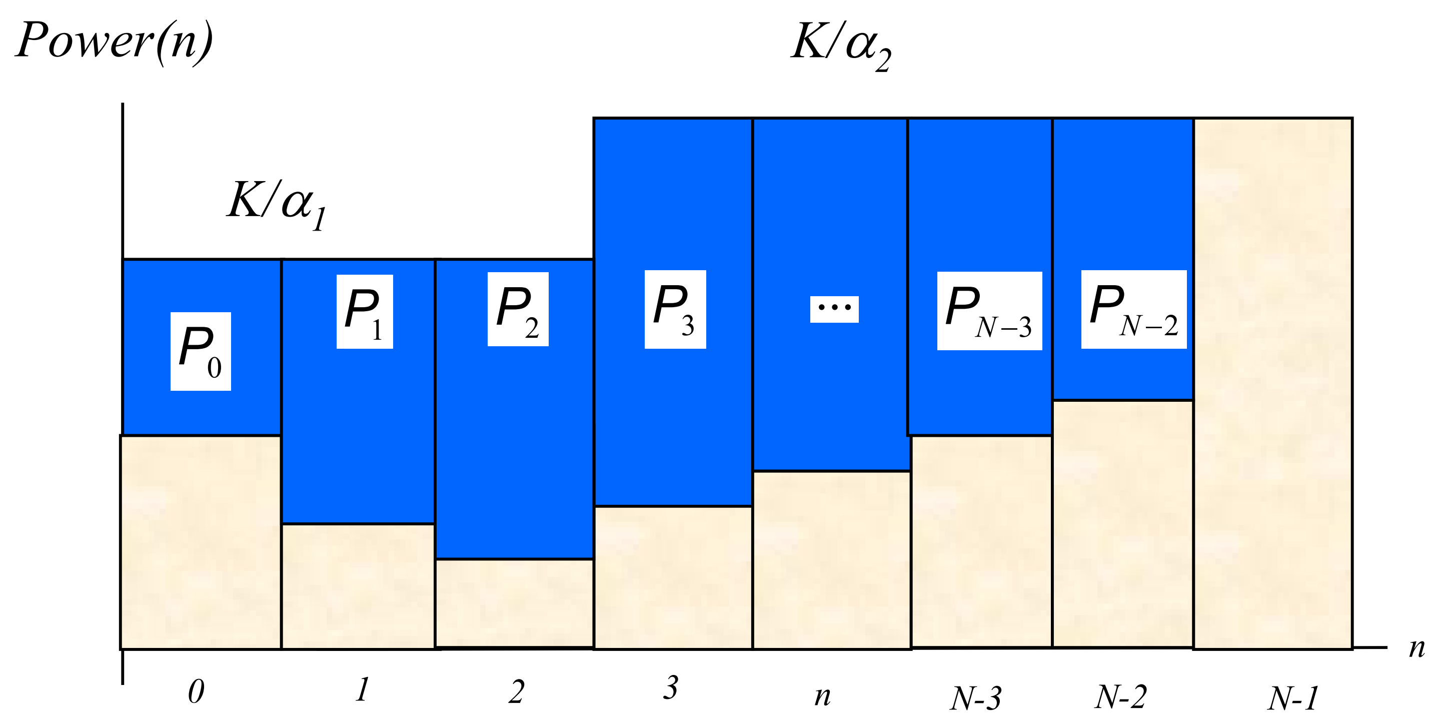
$$Power(n) = K - \frac{Noise(n)}{\Gamma \cdot |Channel(n)|^2}$$



Scaled Water Filling (MC=on)

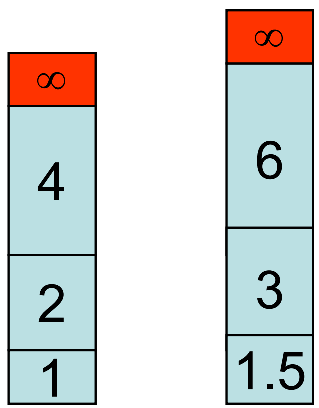
- Victim's bands are reduced if possible

$$Power(n) = \frac{K}{\alpha_m} - \frac{Noise(n)}{\Gamma \cdot |Channel(n)|^2}$$



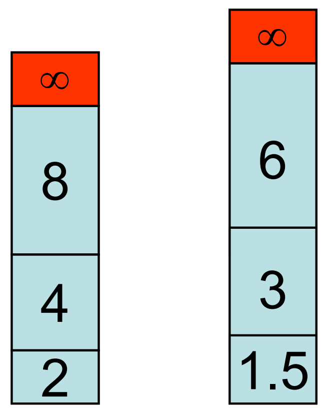
Scaled Water-Filling

- When all α_n equal, then normal water filling
- Normal water-filling maximizes "rate sum over the tones"
- Scaled maximizes weighted rate sum over the tones where weights are $1/\alpha_n$.
- Loading Algorithm is easy with incremental energy tables



Tone n Tone m

BP Off, alpha(n) =1
alpha(m)=1



Tone n Tone m

BP ON, alpha(n)=2
alpha(m) =1

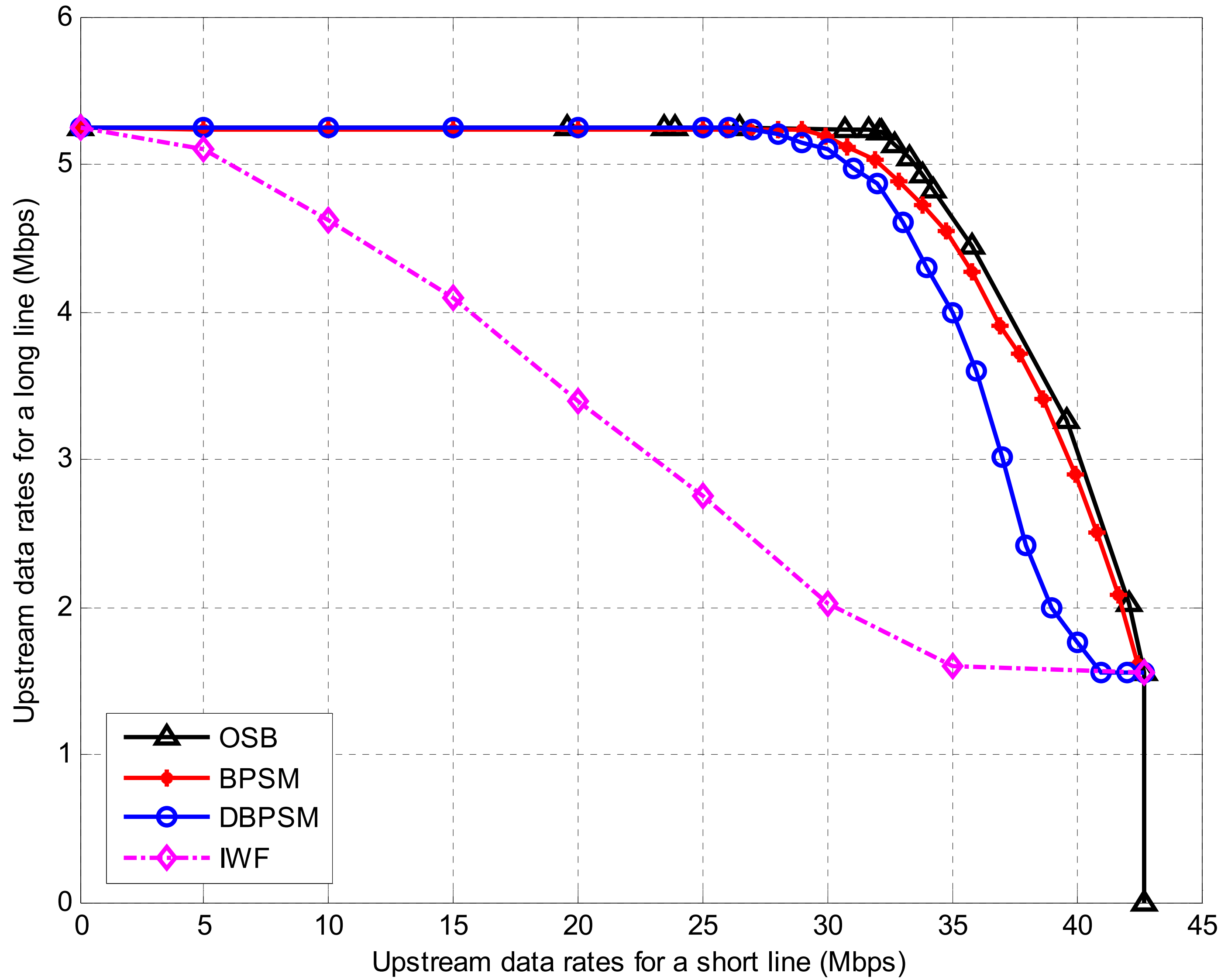
Autonomous α computation

- See 056 Document attached for ex-polite:
  - Runs a normal water fill
  - Incrementally deloads best tones a bit at a time to worst as long as power and PSDMASK constraints obeyed
  - Alpha is then determined from consequent bit distribution
- SMC only turns MC on or off

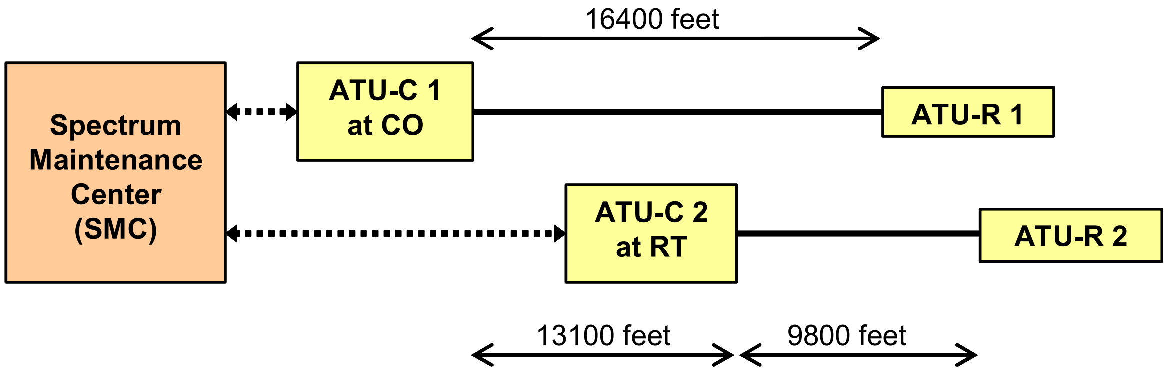
If SMC computes all lines?

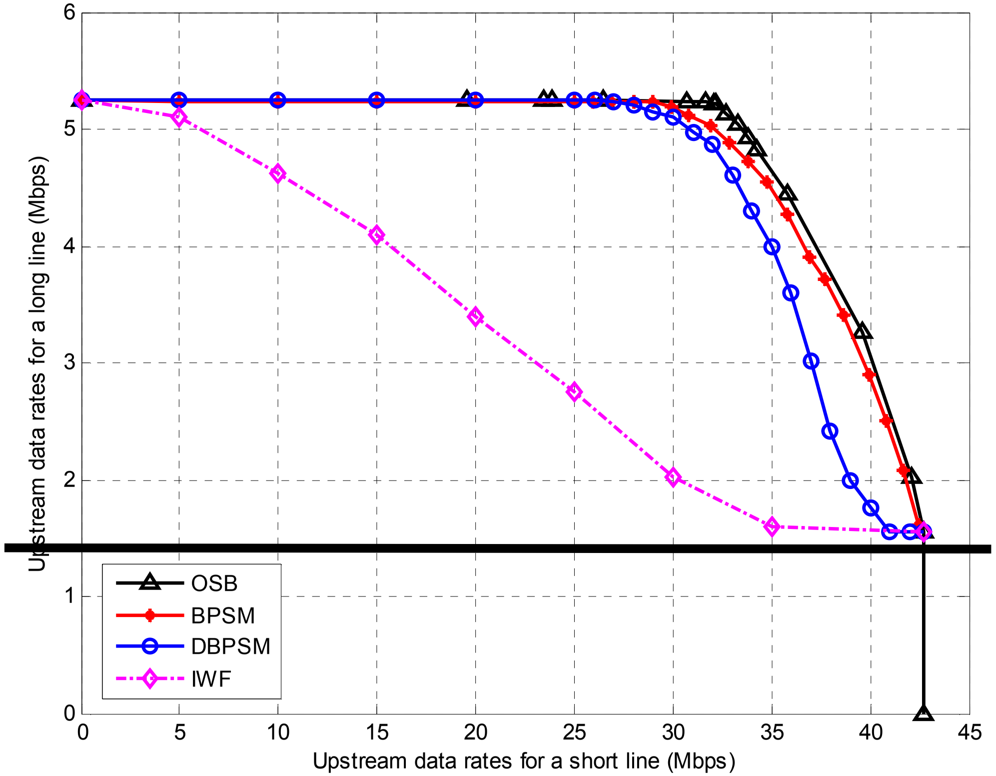
- Can be slightly better
  - But must distribute the α to the DSLs with MC=on (very impractical)
  - An option (need not be done)
    - Use fields not used when MC=on (for instance virtual noise would never be used in the MC=on mode, so could be reused instead to distribute some alphas)

For 1200, 600 VDSL Upstream



ADSL Example – ANSI DSM





DSM
Level 0

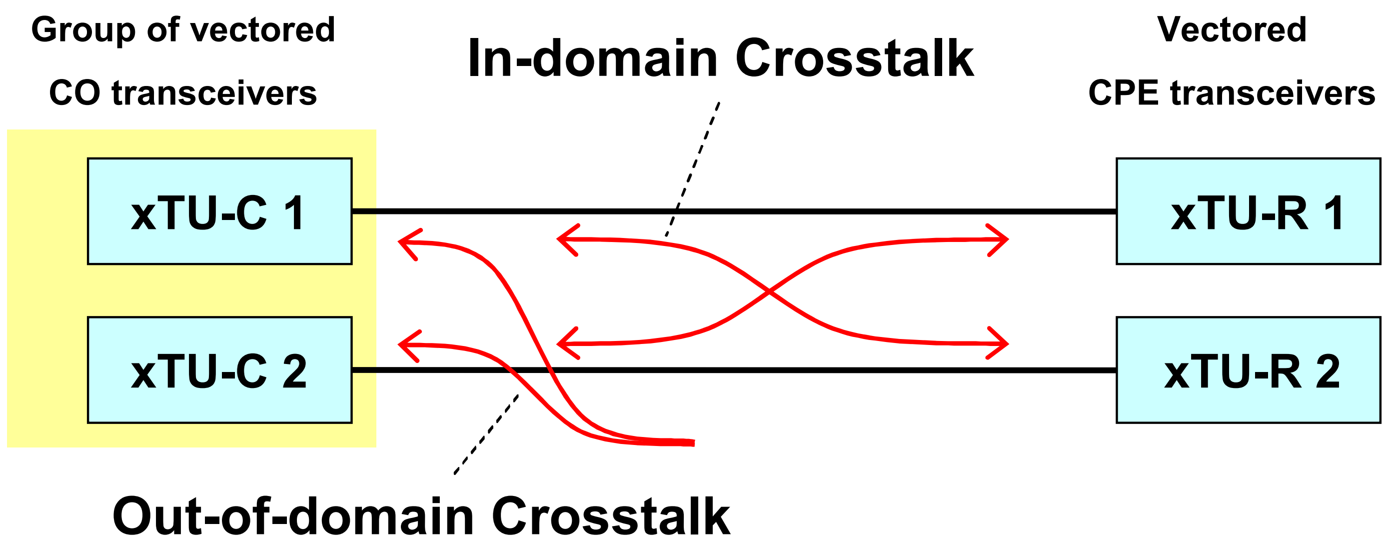
IWF = hold all
Users to 6 dB margin
With water-fil algorithm
On all

Outline

Table 1 – Dynamic Spectrum Management Levels [From ANSI DSM Report].

DSM Level	**Description**
0	No DSM
1	Single-line Politeness and Impulse Control (See 2004 ISSLS Paper “DSM” – Cioffi and Mohseni)
2	Multiple-line Spectrum Balancing (spectra controls)
3	Multiple-line Vectored Coordinated LT-side downstream transmission and upstream reception

Types of Crosstalk

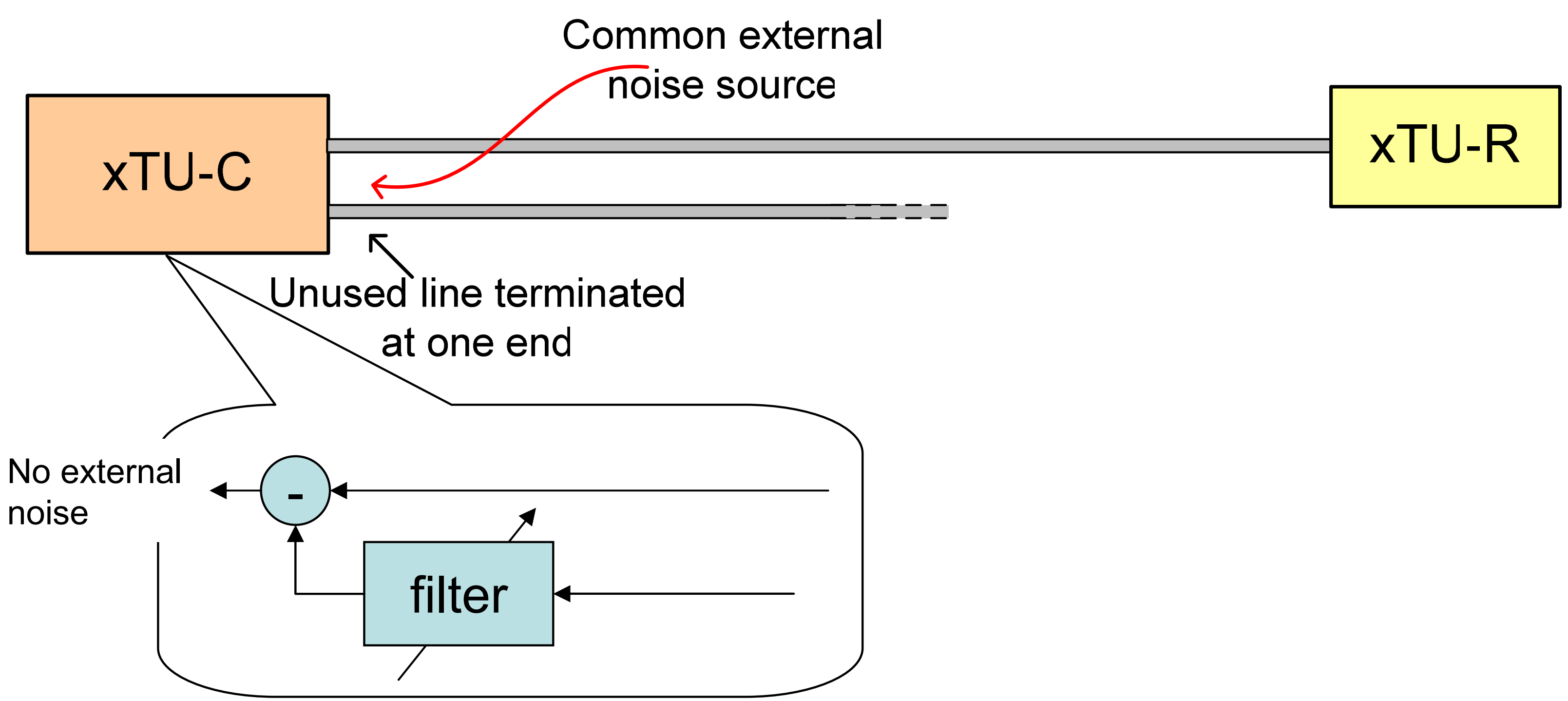


- **In-domain** crosstalk
  - Originates from pair within vectored DSL system.
- **Out-of-domain** crosstalk
  - Originates from source outside vectored DSL system.

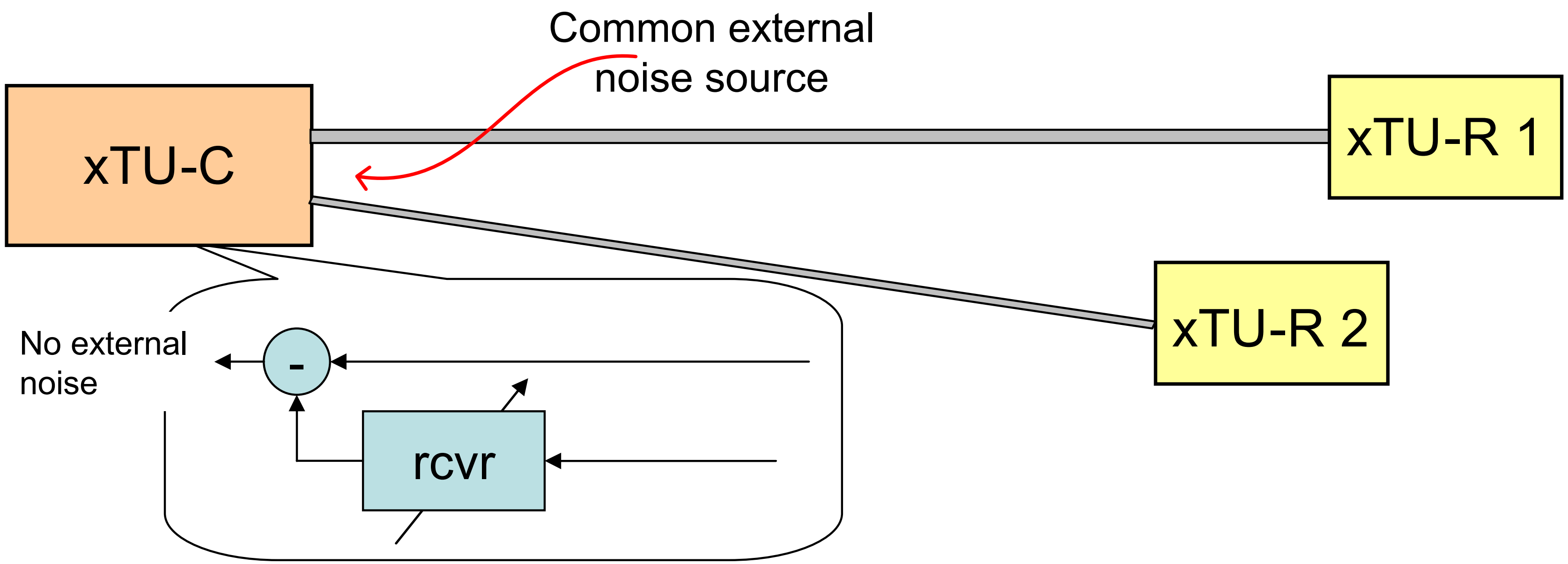
Level 3 DSM Vectoring

- LT Vectoring eliminates most noises
  - In-group FEXT (upstream and downstream)
  - NEXT, RF, BPL, Impulse, out of group upstream xtalk
  - Spatial correlation measures "cancellability"

- Single-customer vectoring

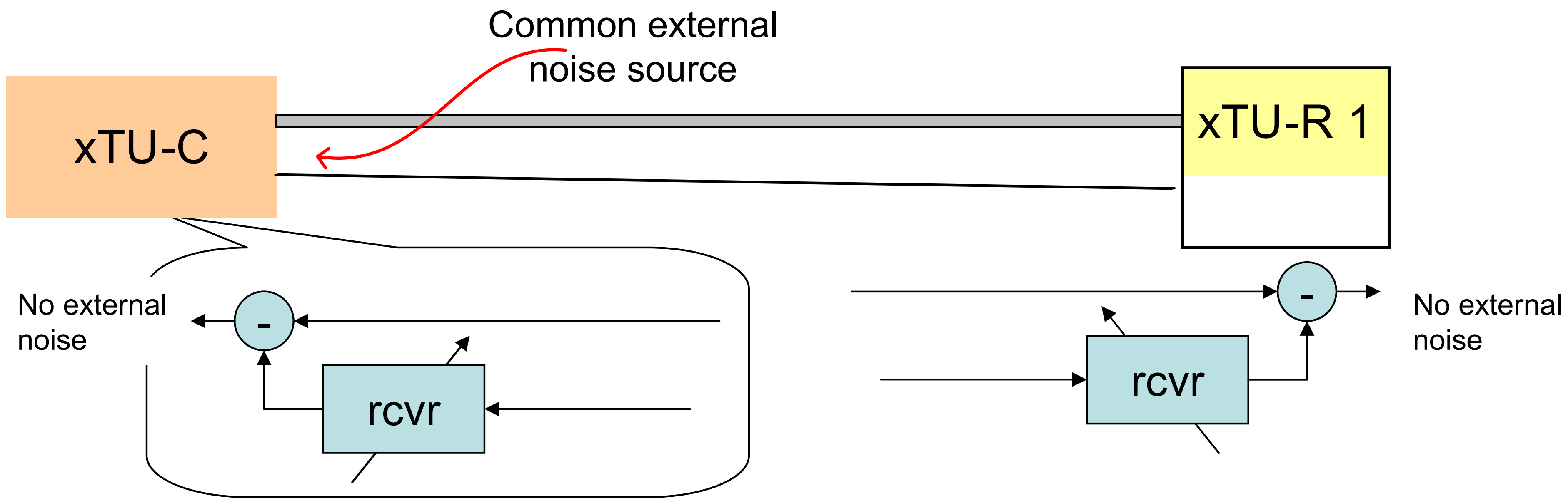


Two-customer vectoring



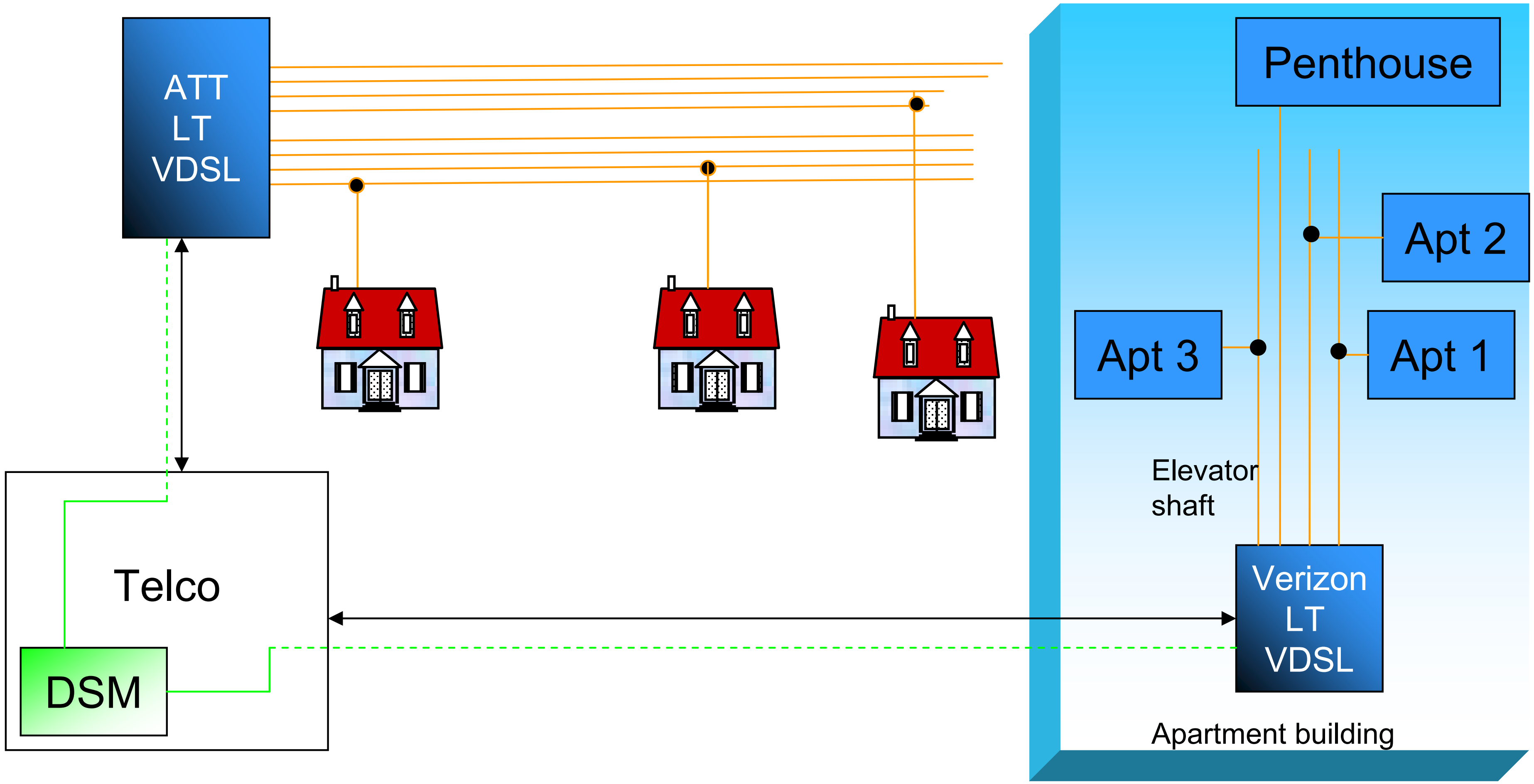
- Not bonding (yet)
  - Concept of order/priority management
- Better on receiver side (more noises cancelled)
- Can remove downstream FEXT among lines in vector group (pre-canceller)
- Noise removal creates rate/range improvement

Bonding and vectoring



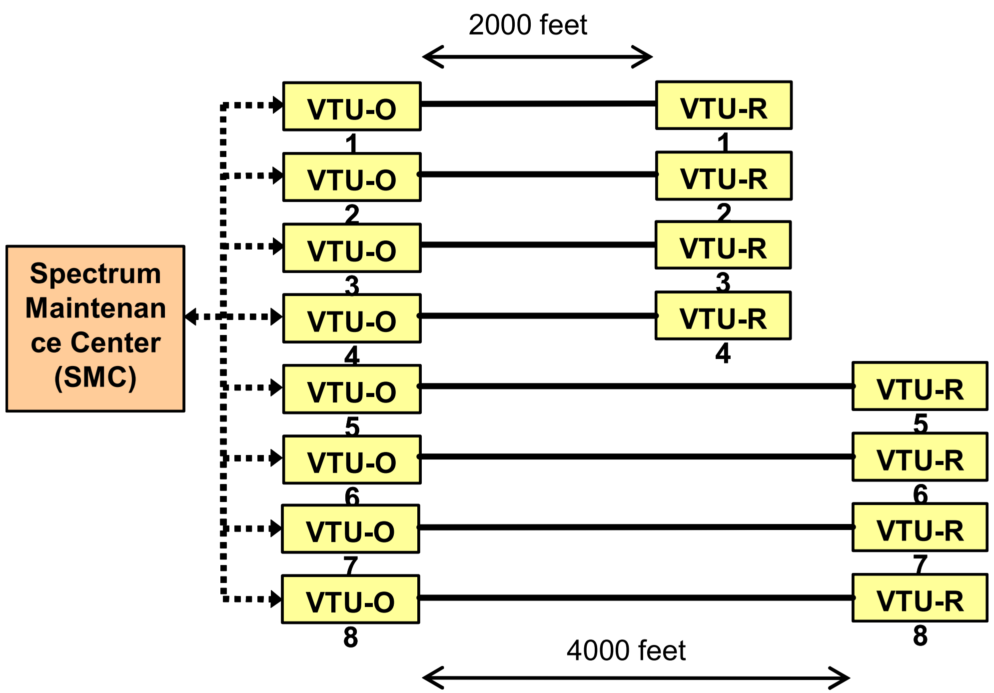
- Receiver vectoring at both ends
  - All noises are cancellable
  - Extra pair can be used or unused (or even common or split-pair modes)
- So data rates for combined vectoring and bonding yet better
  - Achieves 100's of Mbps to 1 Gbps (4 pairs)

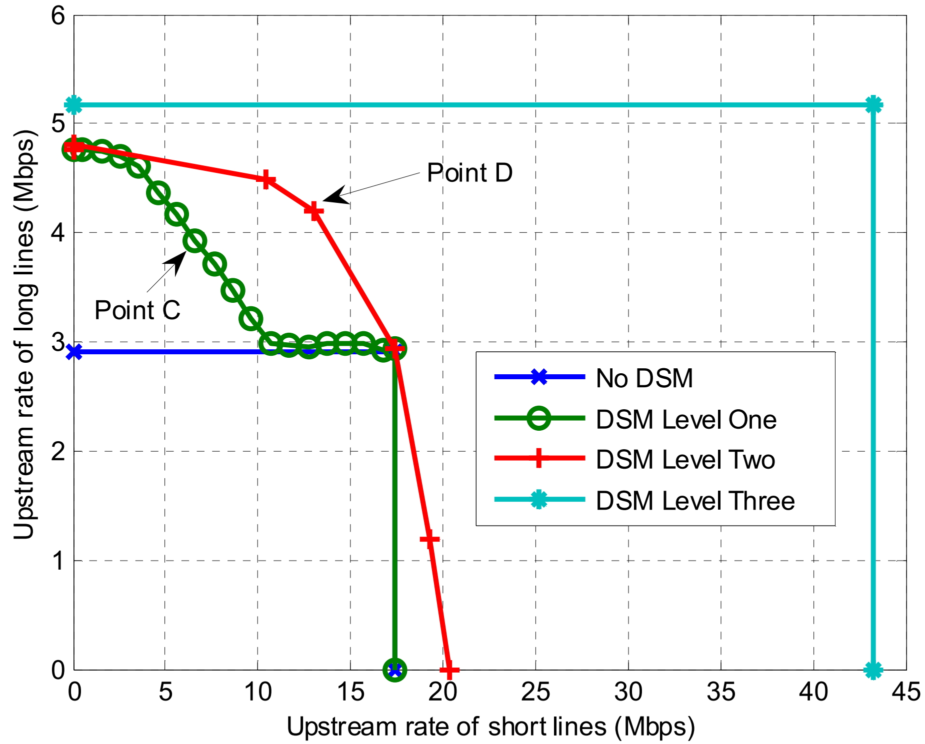
Level 3 – “Vectoring” (VDSL3)
100 Mbps DSLs



- VDSL
  - Already getting 100 Mbps in Japan and Korea (apartment buildings)
- Wide bandwidth (more crosstalk and problems)
  - DSM Level 3 – coordinate the lines of the LT
  - 100 Mbps DSL’s at 1 km range (with Level 3), so anywhere

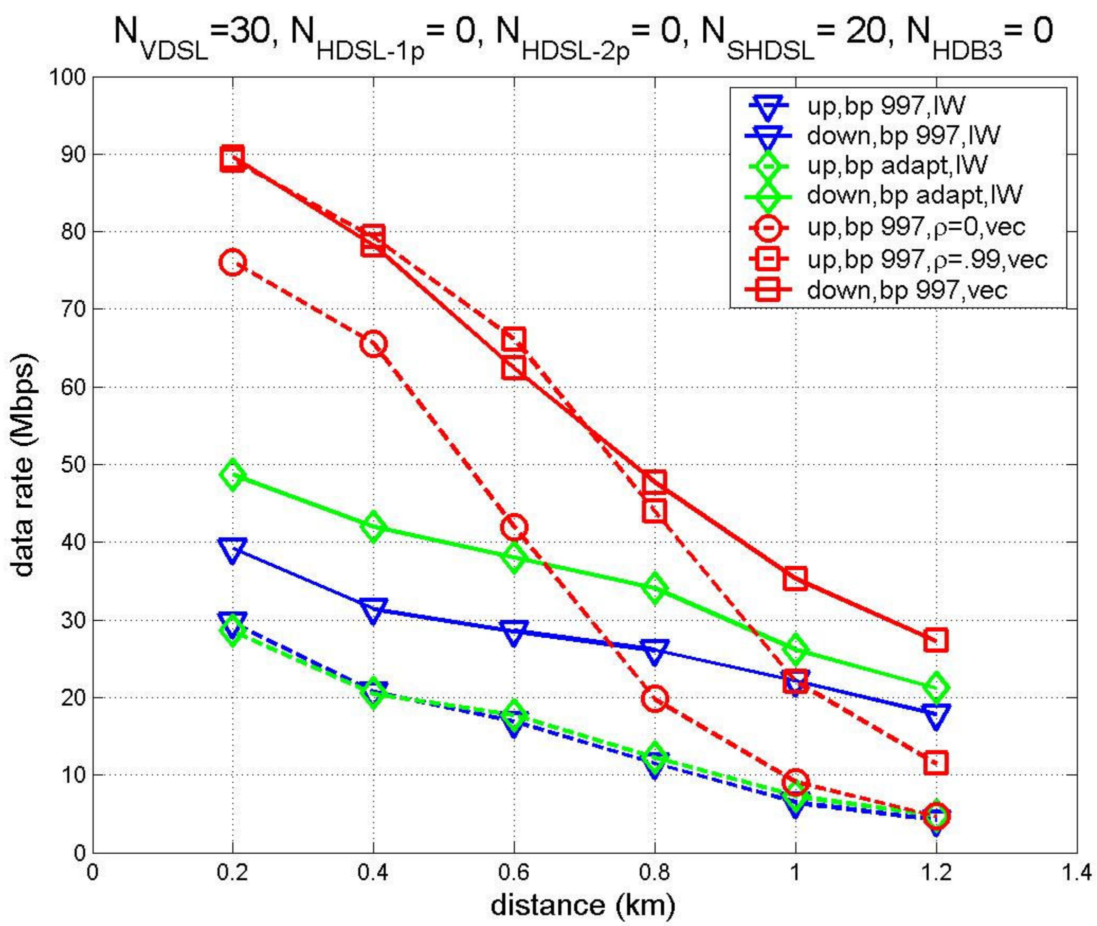
Upstream VDSL3





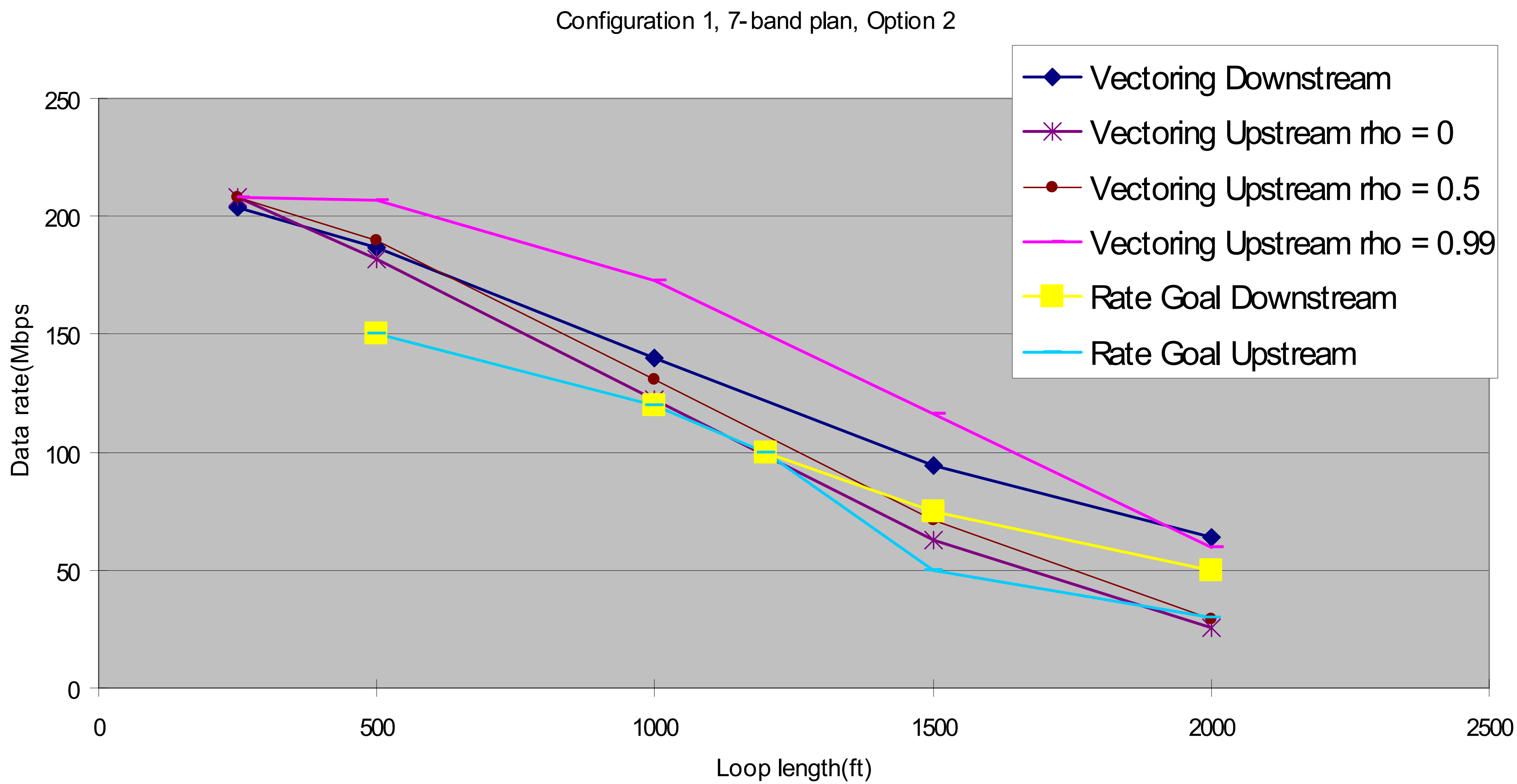
- Essentially successive vector detection used upstream
  – Theoretically can show all crosstalk (in and out of domain) can be eliminated

German Example



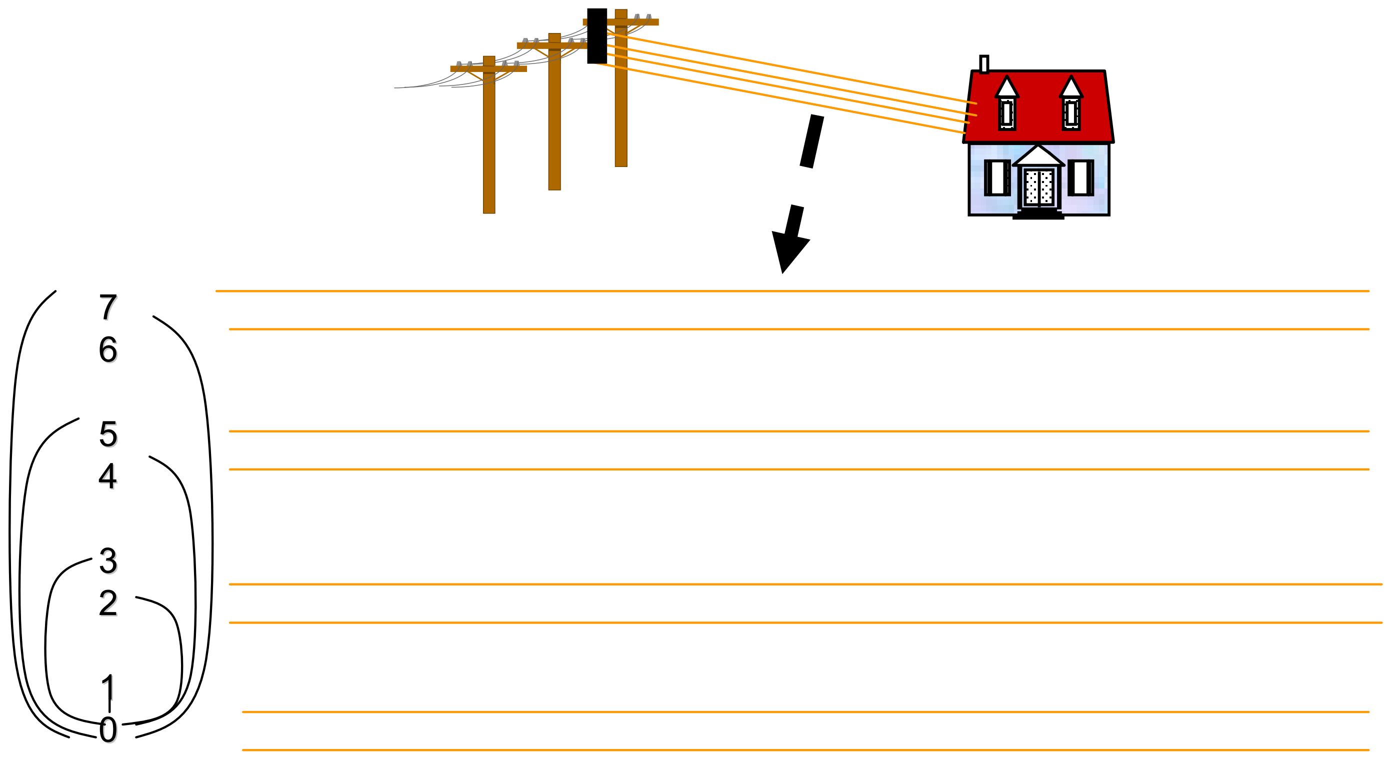
- Fiber-to-Curb/Node (2x data rates) - 997
- To 1 km
  - 500 meters of most interest

FTTC Systems (USA VDSL) – single pair



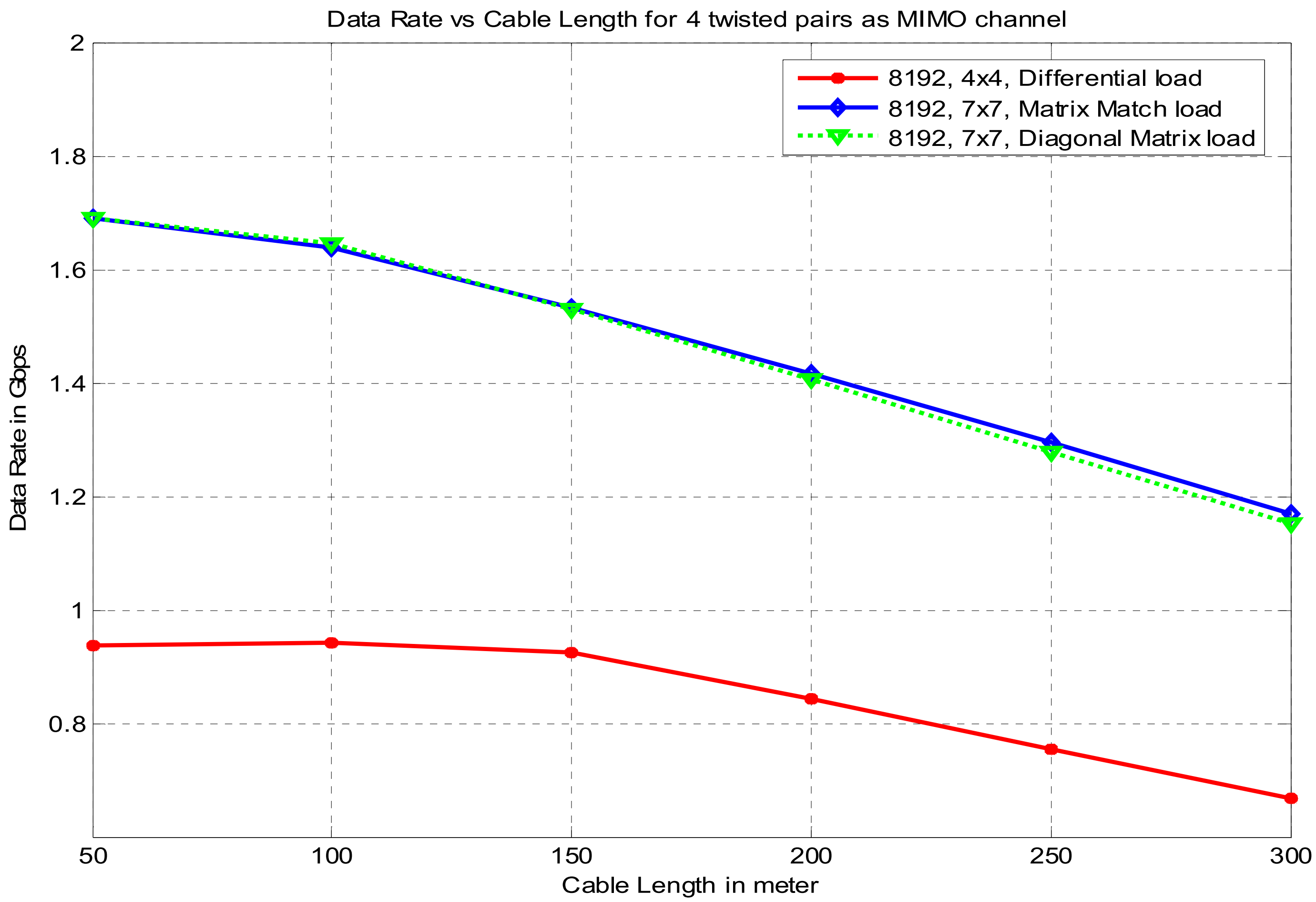
- 100 Mbps symmetric
  - 1000 ft (300 m)

More than one pair? (Gigabit DSL)

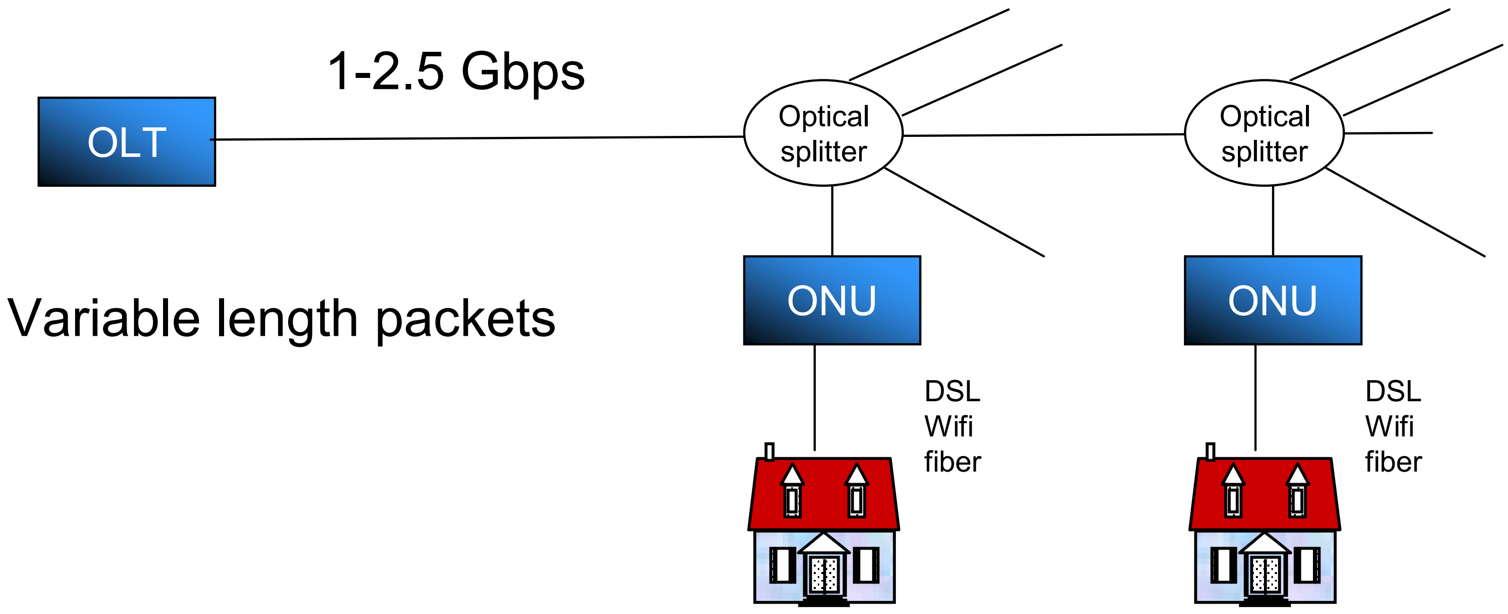


- Uses advanced level 3 DSM
  - Plus bonding of 2-4 pairs
- 1 Gbps DSLs (300 meters, 1000 ft)

4-Pair USA Drop (Gigabit DSL)

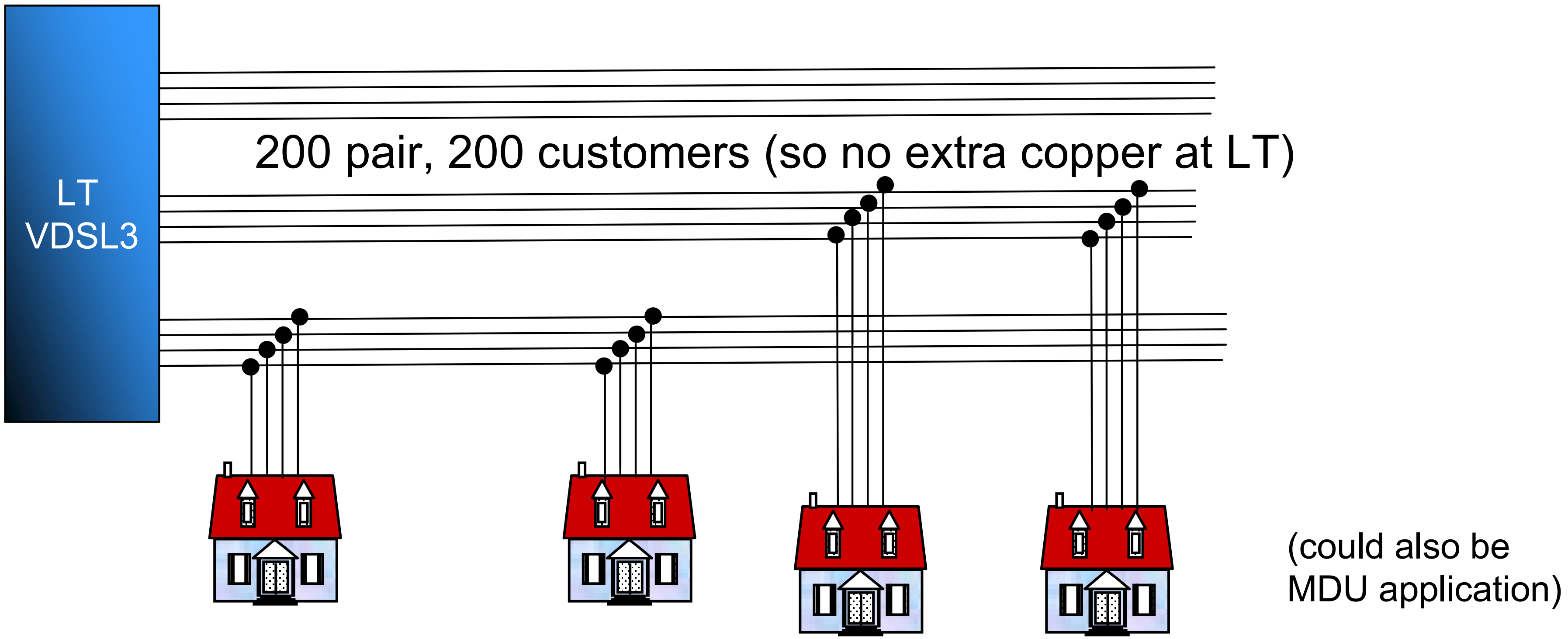


FTTN: G- and E-PONs



- 1-2.5 Gbps each direction (diff wavelengths)
  - Shared (TDM)
  - Upstream (dynamic bandwidth allocation)
- Share up to 128 customers
  - Speed per customer (peak 100 Mbps to 1 Gbps)
  - Average continuous (video) 20-30 Mbps with 32-128 users
- Splitters placed for customer drops
- New 10 Gbps EPON under study in IEEE (handles more users)

Copper PON? (Cu-PON)



- What can the copper do if the fiber is not there yet?
- Some sharing of copper (called a “tap” at “junction box”)
  - Similar to PON sharing, but much easier to make the connection
  - LT DSLAM does the assignment of DSL dimensions
- Peak Customer BW (1 Gbps for 4 wires – could be up to N/4 Gbps)
- Overall BW (50 Gbps each direction)
- 3000 ft, 1 km range (no user less than 200 Mbps)
  - Typically several 100 Mbps

Comparison

	(G and E) PON	Copper (CuPON)
Aggregate data rate	1- 2.5 Gbps	50 Gbps
User continuous data rate	20-30 Mbps	50-250 Mbps
User peak data rate	100M-1Gbps	100Mbps – 10s Gbps
Range	10-20 km	1 km
Power	Battery at ONU (no battery if FTTH)	LT needs to be powered
Splitter	Hard	Easy
Maintenance	Expected to be easy	Needs DSM to be cost effective
Deployment cost	Very high	Much less

Conclusion

- Much Higher Data Rates coming in DSL
- KEY IS DSM
  - Advanced Math/Info-Theory at work
- Steps
  - 3 reasonable steps/levels to get to highest rates
- DSL system
  - As much as 100 Gbps can be shared among 200 users in 1 km range