Vectored Transmission for Digital Subscriber Line Systems

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PhD Oral Defense

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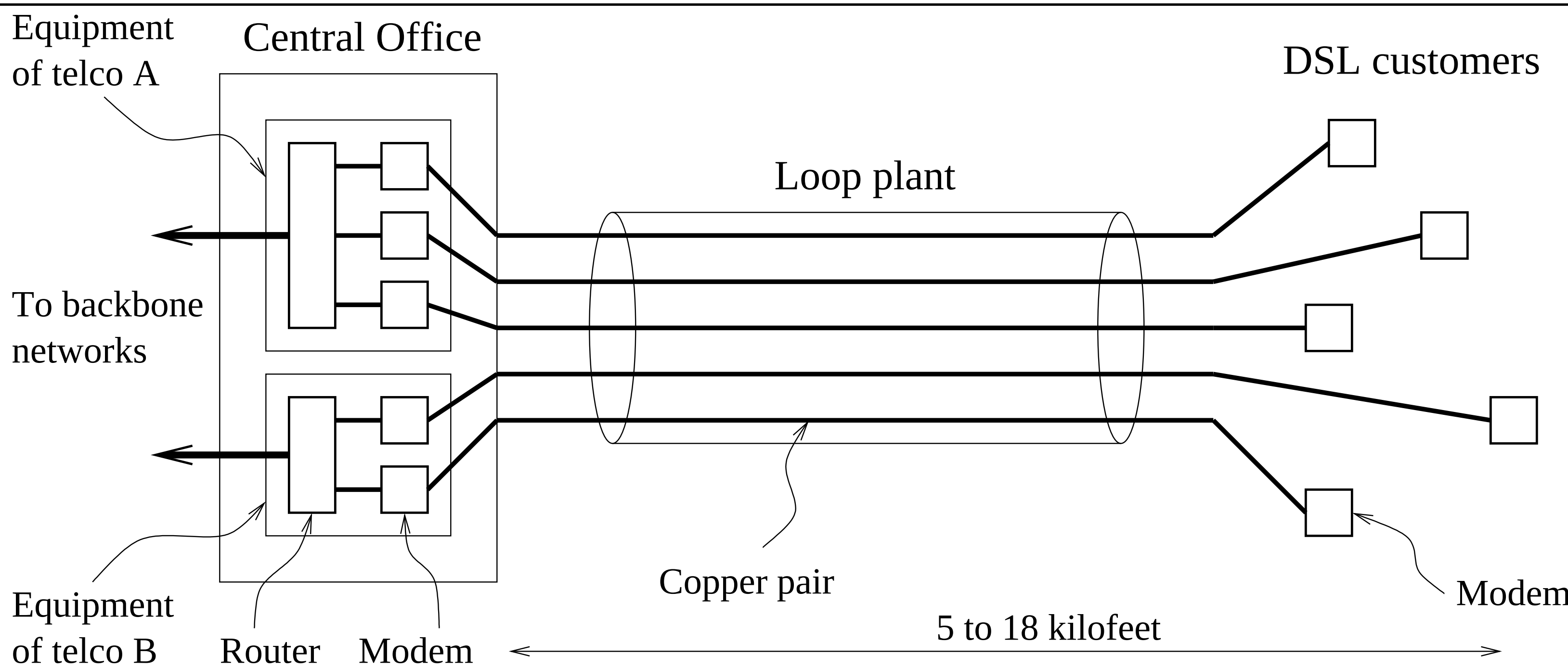
Outline

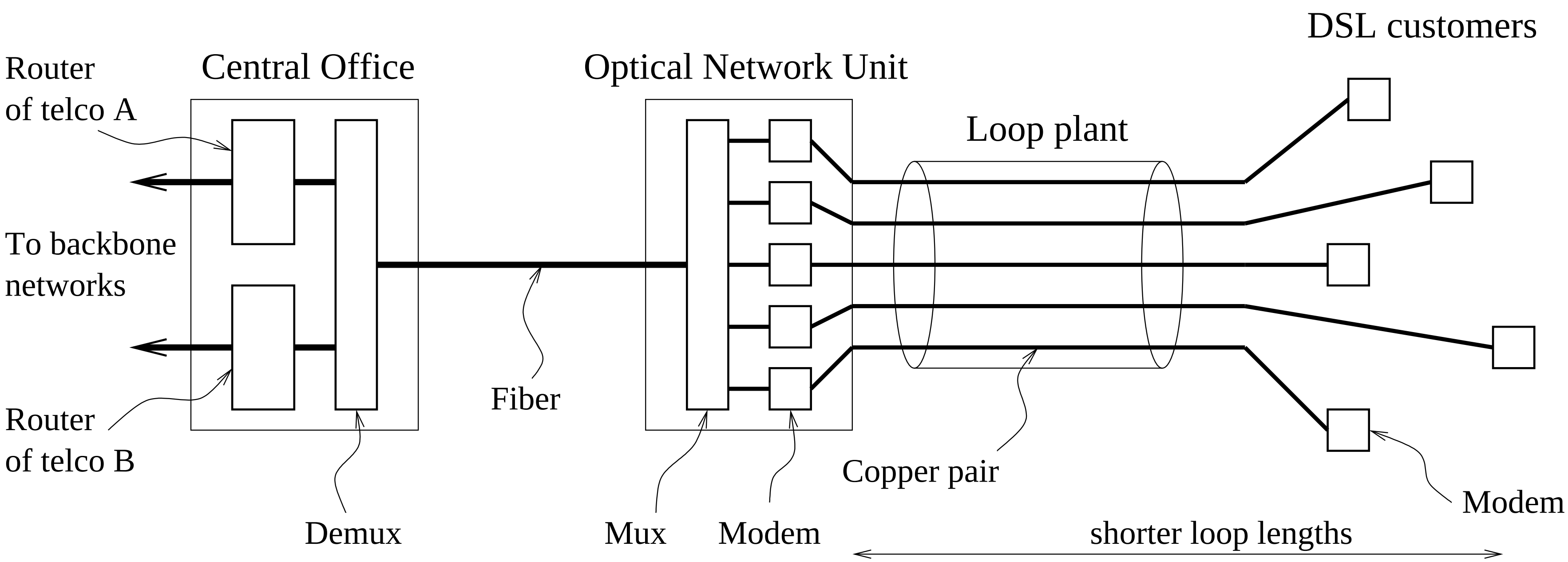
- DSL as a multiuser communication environment.
- Crosstalk mitigation with user coordination.
  - Communication with receiver coordination.
  - Communication with transmitter coordination.
- Transmission optimization and simulation results.

Current DSL Deployment



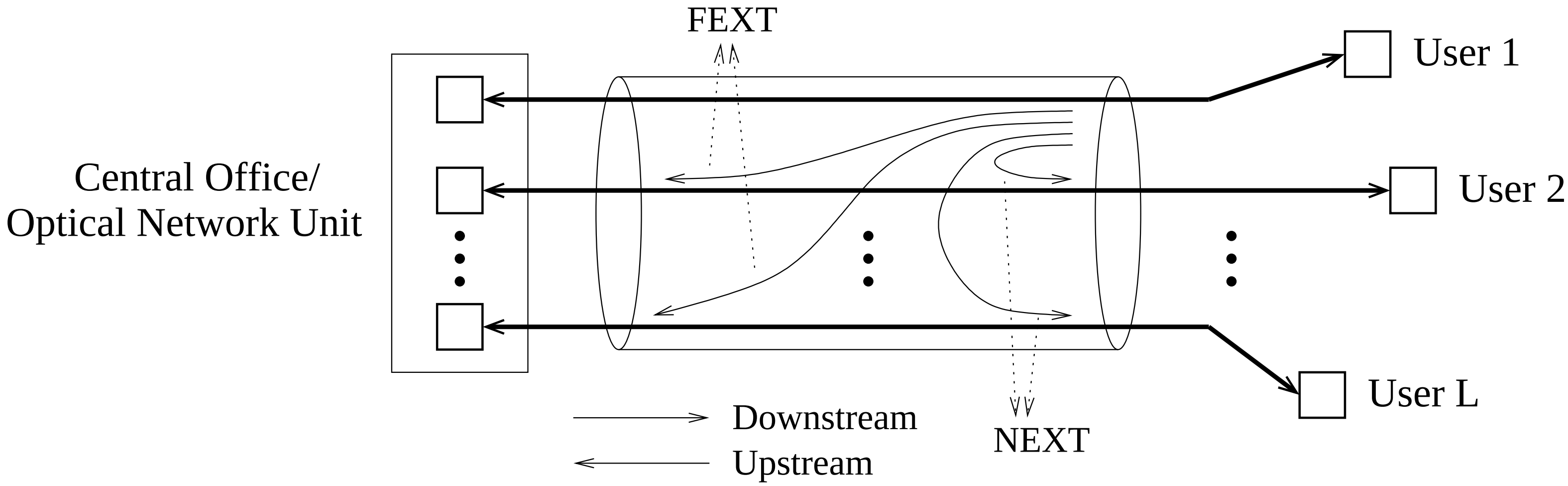
- Systems must obey conservative transmission restrictions to prevent excessive interference (crosstalk) into each other.

DSL Evolution



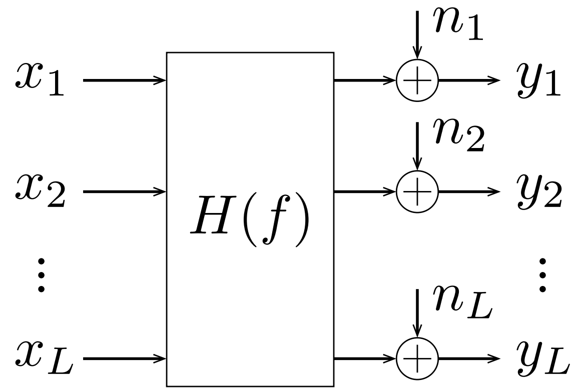
- Cooperation between the modems at the Optical Network Unit provides opportunity for performance improvements.

DSL is a Multiuser Environment



- Near-End-Crosstalk (NEXT) is averted by Frequency Division Duplexing.
- Far-End-Crosstalk (FEXT) is dominant in short loops.
  - Upstream channel is Vector Multiple Access Channel.
  - Downstream channel is Vector Broadcast Channel.

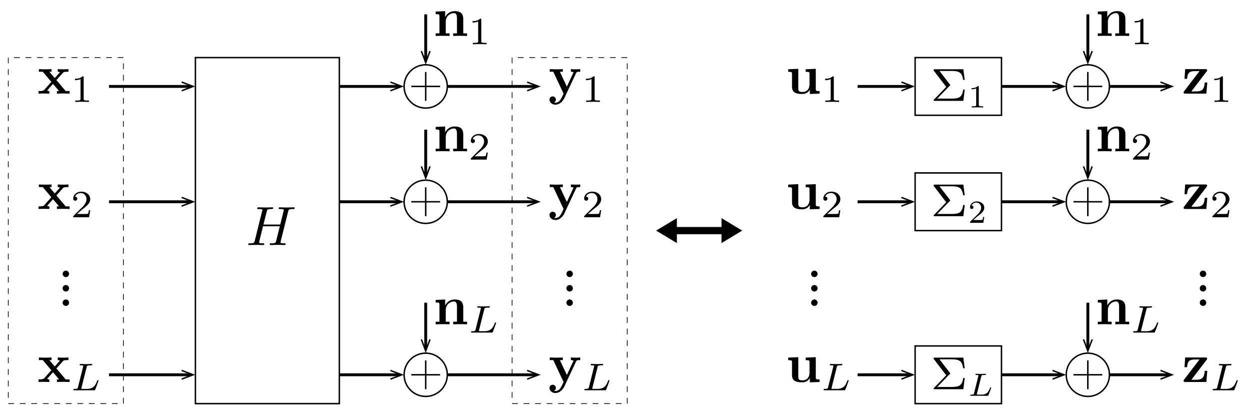
System Representation



- Channel is represented by matrix $H(f) = [H_{ij}(f)]_{j=1,\ldots,L}^{i=1,\ldots,L}$, where $H_{ij}(f)$ is transfer function from input j to output i.

- Noise sources include crosstalk from "alien" DSL systems, radio frequency interference (RFI) and background noise.
  - The noise of each output is assumed additive, gaussian, and colored.

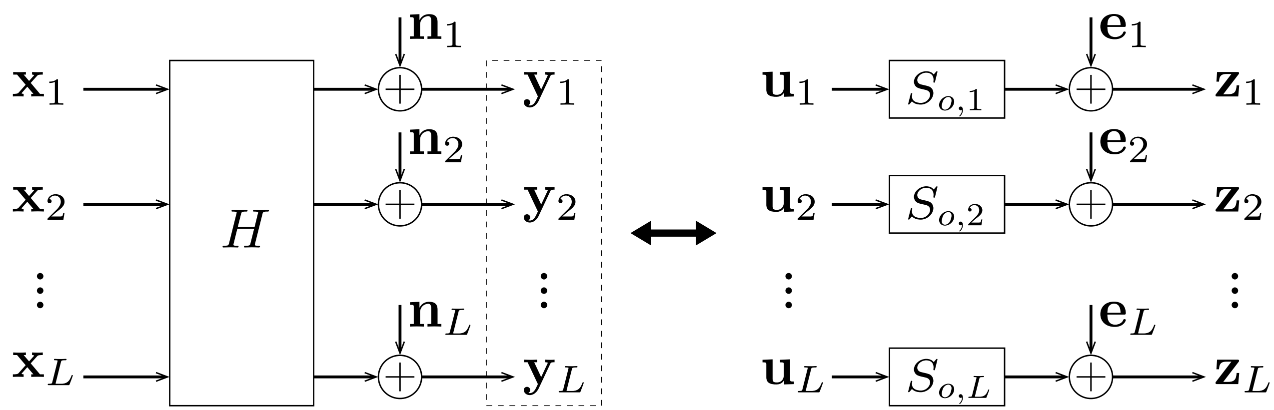
Vector Gaussian Channel



- Capacity can be achieved by:
  - Transmitting in same "direction" with *input singular vectors* of H.
  - Assign energy by water-filling in parallel channels with gains equal to the *singular values* of H.

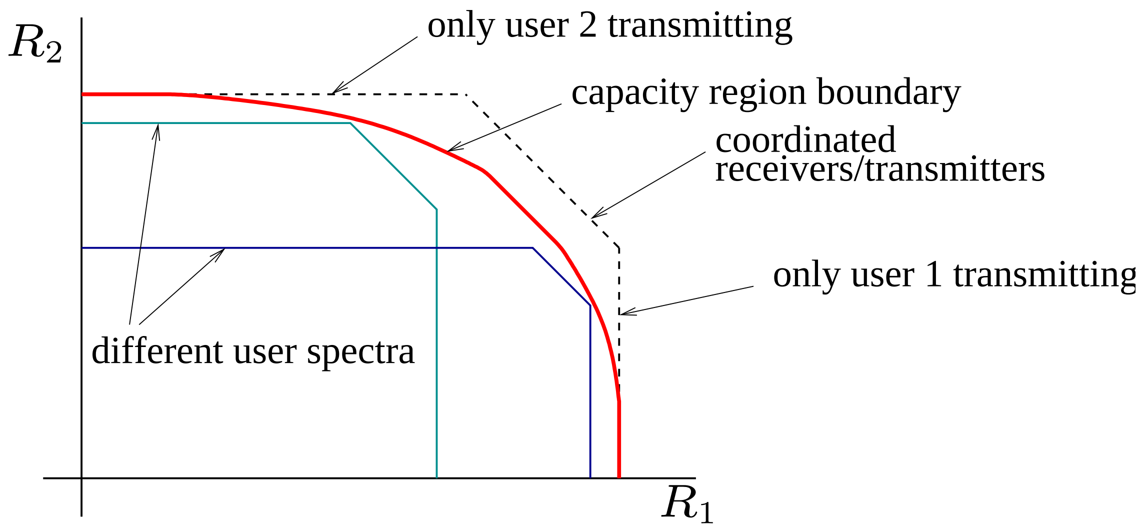
- **Not applicable to DSL** with geographically dispersed users.

Vector Gaussian Multiple Access Channel



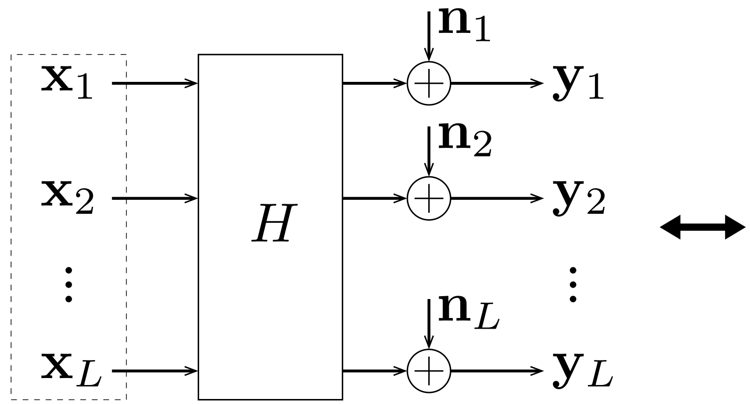
- Capacity can be achieved by *successive decoding*:
  - Prior to decoding the current user, subtract interference from previously decoded users.
- Corresponds to **DSL upstream** communication.

Capacity Region Bounds



- Capacity region is union of pentagons corresponding to user spectra.
- Sum capacity is upper bounded by capacity of vector channel.
- Region is bounded by single user capacities.

Vector Gaussian Broadcast Channel

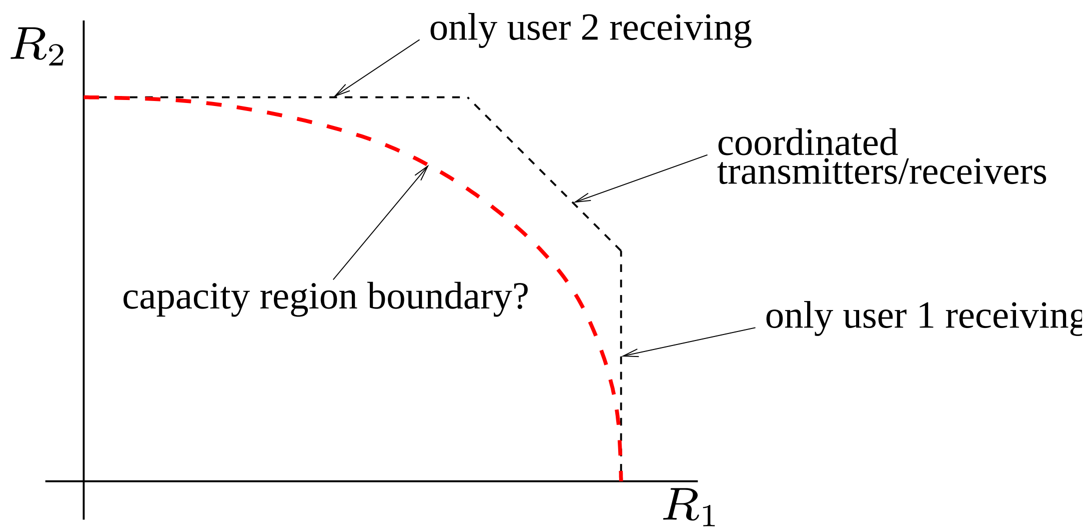


Equivalent decomposition is unknown

- Few information theory results exist for *non-degraded* channel.
  - Results about optimal sum capacity have recently been derived [Caire and Shamai, 2000, Yu and Cioffi, 2001].

- Corresponds to **DSL downstream** communication.

Capacity Region Bounds



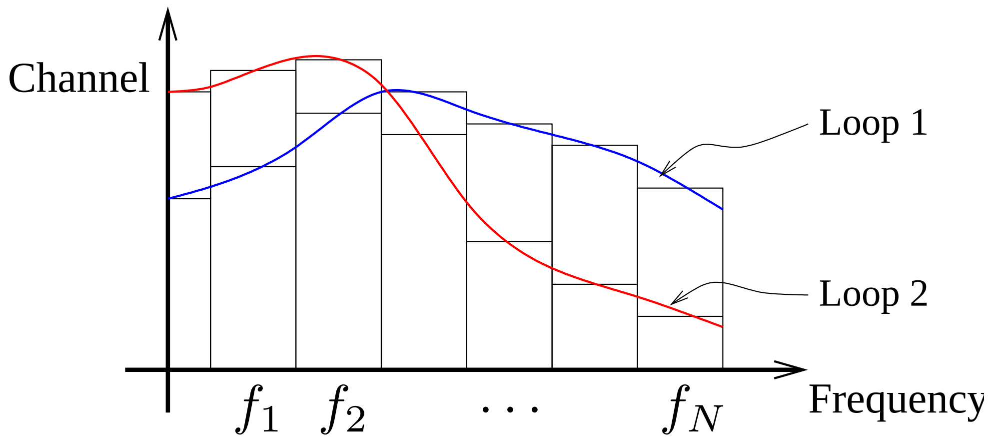
- Capacity region remains unknown.
- Sum capacity is upper bounded by capacity of vector channel.
- Region is bounded by single user capacities.

Outline

- DSL as a multiuser communication environment.
- **Crosstalk mitigation with user coordination.**
  - Communication with receiver coordination.
  - Communication with transmitter coordination.
- Transmission optimization and simulation results.

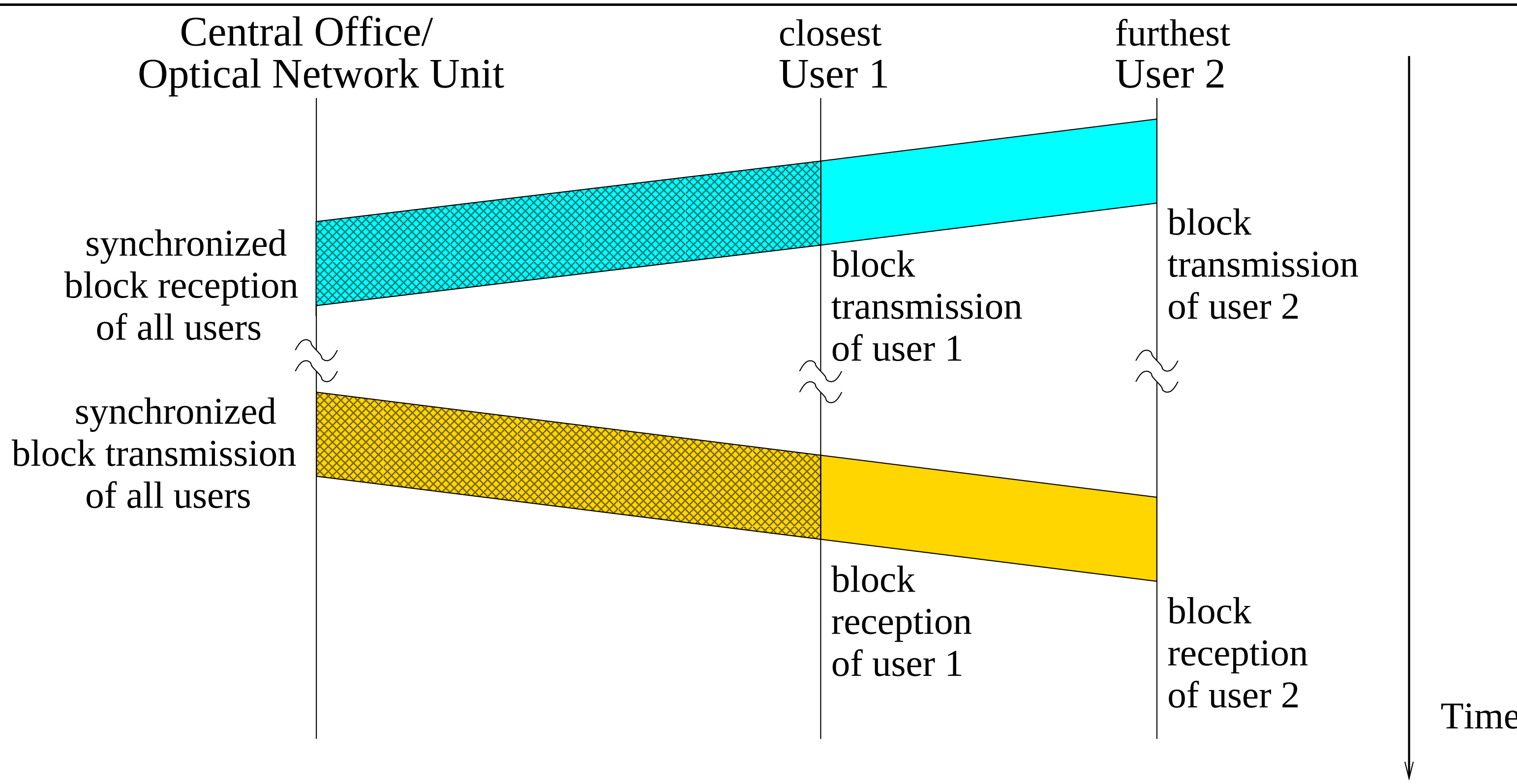
Multicarrier Transmission for the Vector Channel

- Partitioning the bandwidth into many “tones” offers benefits:
  - Processing is performed within each tone.
  - Transmission optimization is simplified.



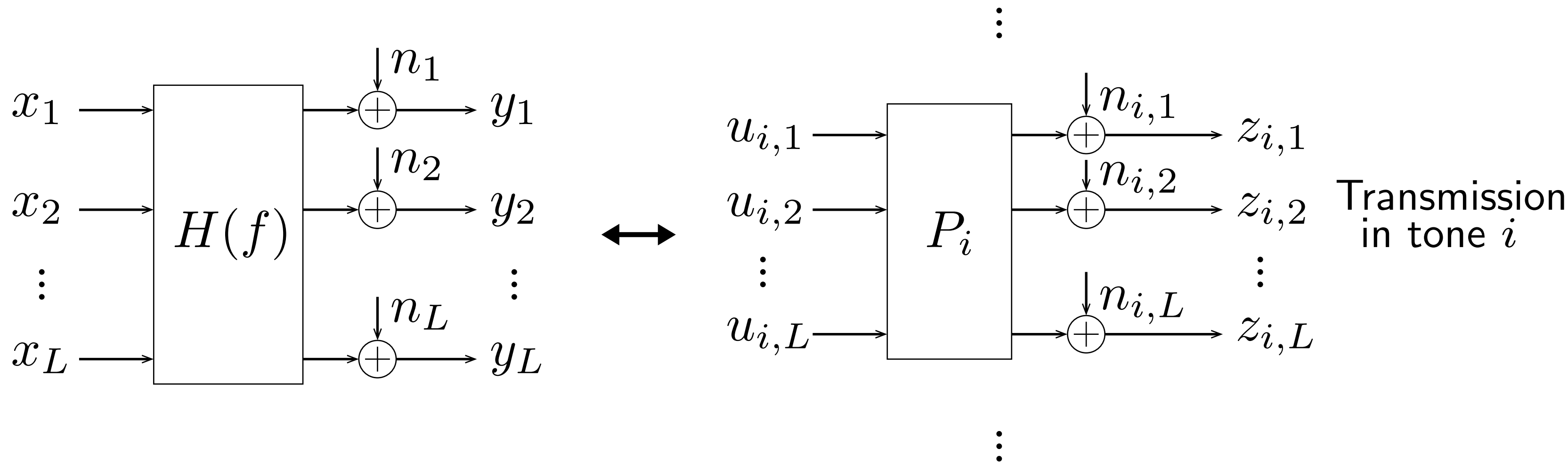
- Discrete Multi-Tone modulation (DMT) can be employed.

User Synchronization



- FFT/IFFT windows of all users are assumed synchronized at "left" side.

Independent Transmission within each Tone



- Transmission within each tone is compactly expressed as:

$$\mathbf{z}_i = P_i \mathbf{u}_i + \mathbf{n}_i \text{ , where } P_i = H(f_i).$$

  - Noise samples are independent, and WLOG, $R_{\mathbf{n}_i\mathbf{n}_i} = I$.

Upstream Vectoring - Channel Triangularization

- **Idea:** Cancel crosstalk within each tone at the *receiver* by successive interference cancellation.

- Decompose channel matrix P_{up} (of specific tone):

$$P_{up} = QR$$

  - Q is unitary matrix (rotation), R is upper triangular matrix.

- Rotate received vector by Q^* to "triangularize" the channel:

$$\tilde{\mathbf{z}} = Q^* \mathbf{z} = R\mathbf{u} + \tilde{\mathbf{n}}$$

Upstream Vectoring - Decision Feedback

- Decode users sequentially, use decision feedback to cancel interference from previously decoded users:

$$\hat{u}_k = \text{decode}\left[\frac{\tilde{z}_k}{r_{kk}} - \sum_{j=k+1}^{L} \frac{r_{kj}}{r_{kk}}\hat{u}_j\right], \quad k = L, L-1, \ldots, 1$$

- Ignoring error propagation, L "parallel" channels are produced:

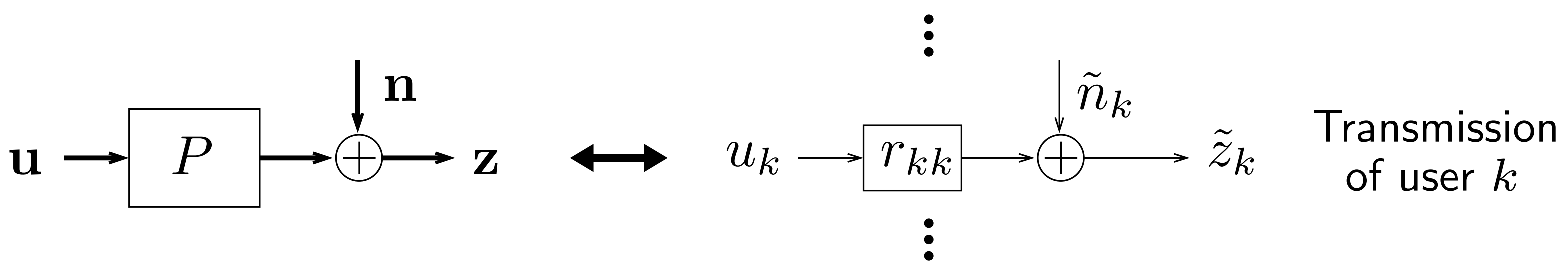
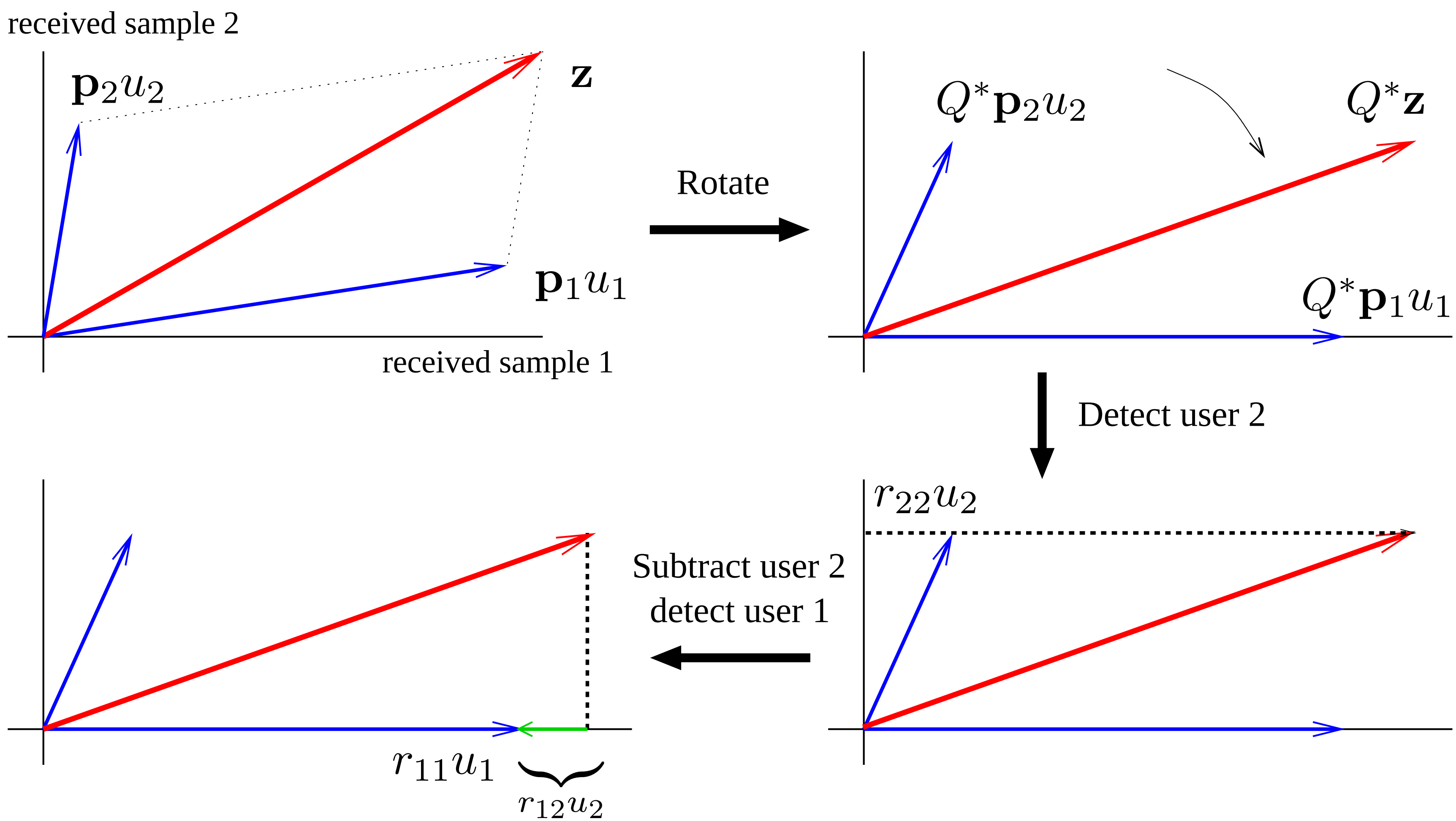
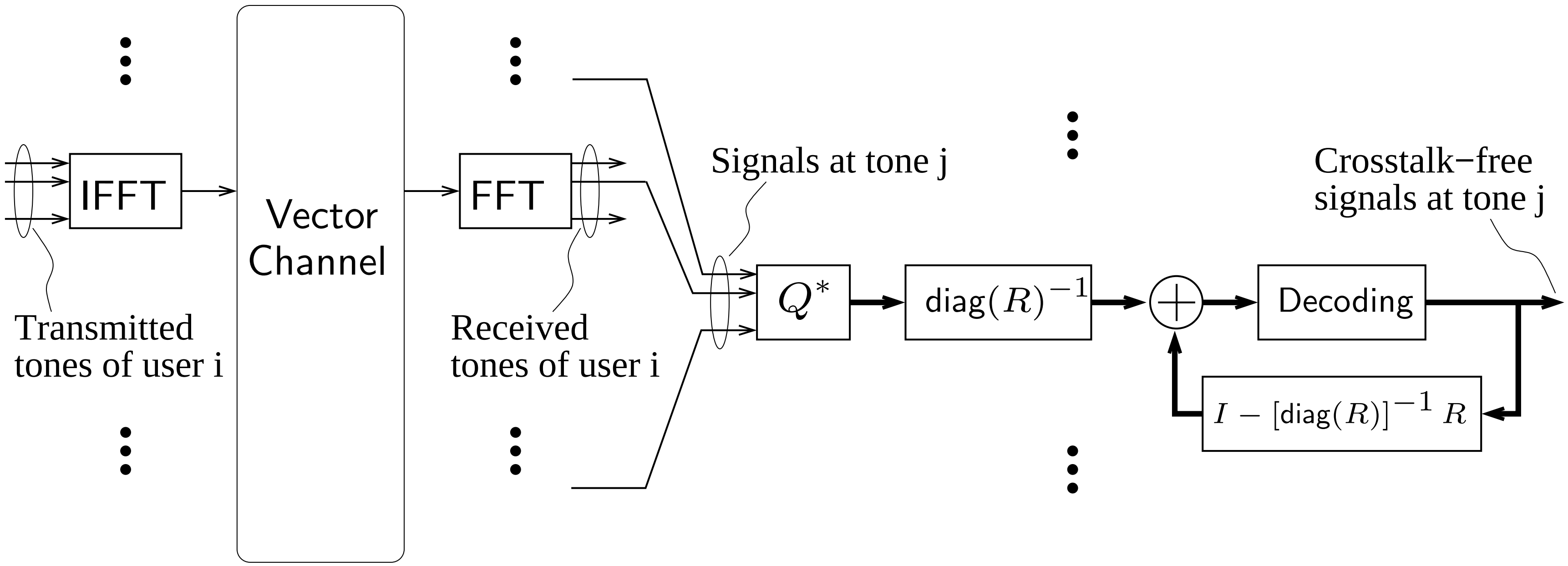


Illustration of Upstream Vectoring



Block Diagram for Upstream



- Canceler blocks remove crosstalk within each tone.

Relation to Other Structures

- QR cancellation is similar to V-BLAST [Foschini et al, 1999].
  - Processing is equivalent.
  - Transmission optimization is not assumed for V-BLAST.
  - DSL channels exhibit less "diversity" than indoor wireless channels.
  - Decoding order has small significance in DSL.

- System is special case of Generalized DFE [Cioffi and Forney, 1996].
  - Employ "zero-forcing" criterion instead of MMSE criterion.
  - Impose condition of no cooperation at the transmitters.
  - Generalized DFE achieves multiple access channel capacity [Varanasi and Guess, 1998].

Downstream Vectoring - Channel Triangularization

- **Idea:** *Precode* signals within each tone at the *transmitter*, so that they are received crosstalk-free.

- Decompose *transposed* channel matrix P_{down} (of specific tone):

$$P_{down}^T = QR$$

  – Q is unitary matrix, R is upper triangular matrix.

- Rotate transmitted vector by Q^{T*} to "triangularize" the channel:

$$\mathbf{u} = Q^{T*}\mathbf{u}' \Rightarrow \mathbf{z} = R^T\mathbf{u}' + \mathbf{n}$$

Downstream Vectoring - Precoding

- Use *precoding* on the triangular channel, combined with modulo operation to prevent energy increase:

$$u'_k = \text{modulo}\left[\tilde{u}_k - \sum_{j=1}^{k-1} \frac{r_{jk}}{r_{kk}} u'_j\right] \ , \ k = 1, 2, \ldots, L$$

- Set of L “parallel” channels is produced:

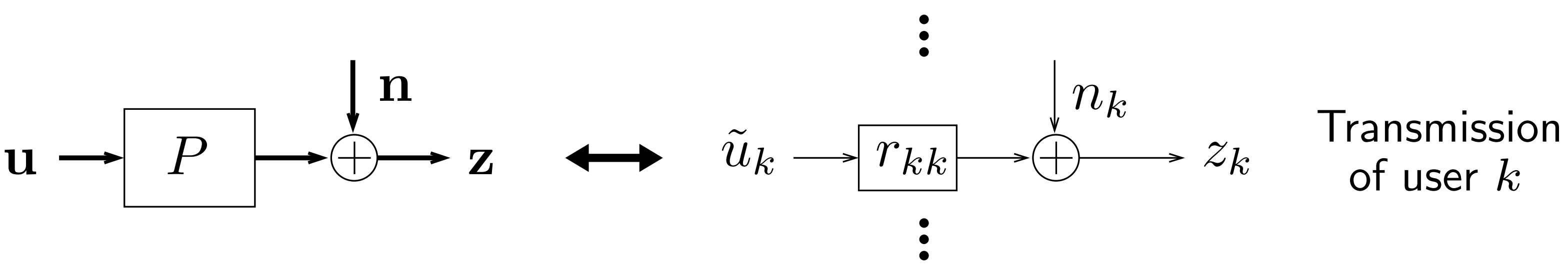


Illustration of Downstream Vectoring

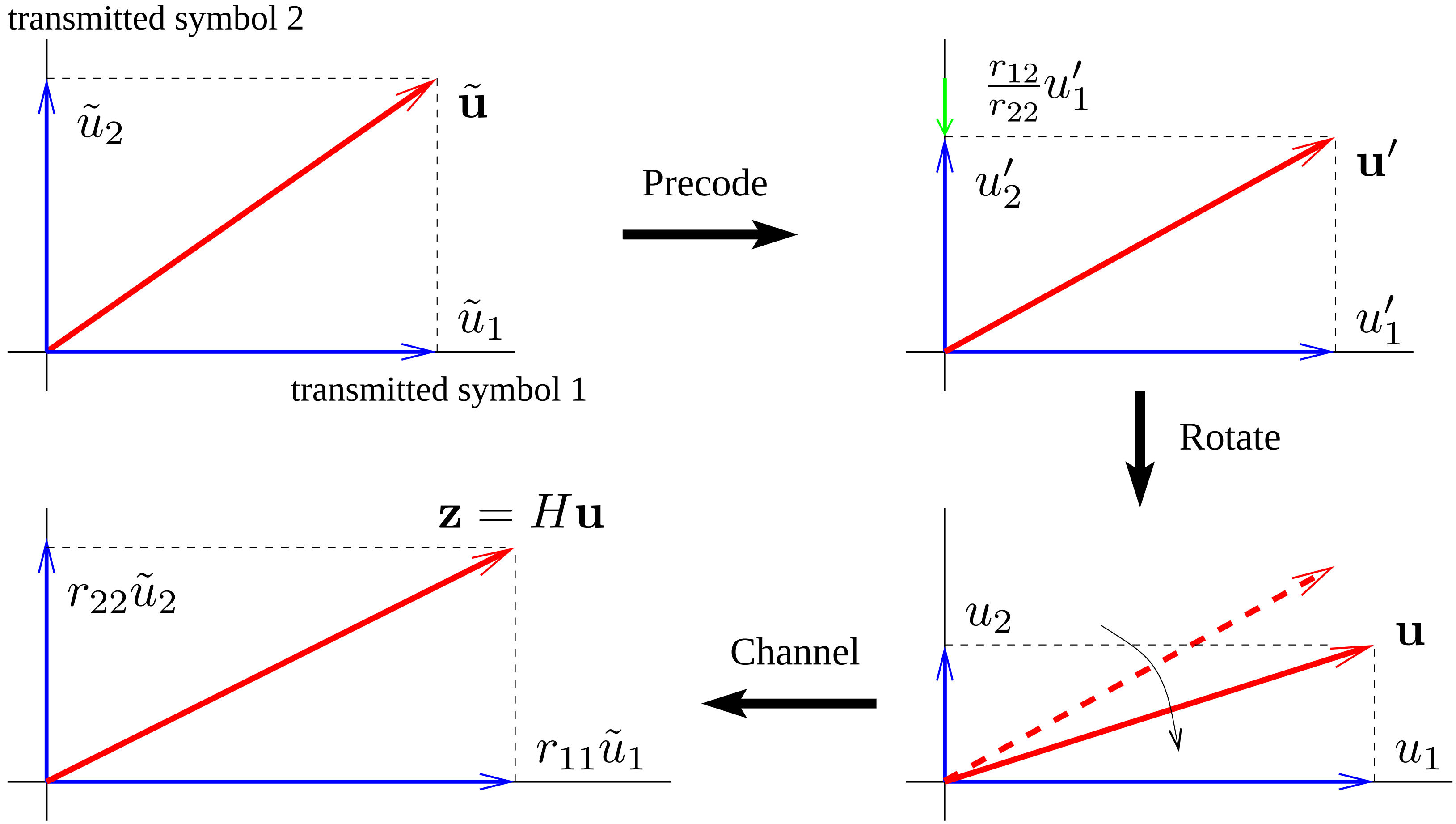
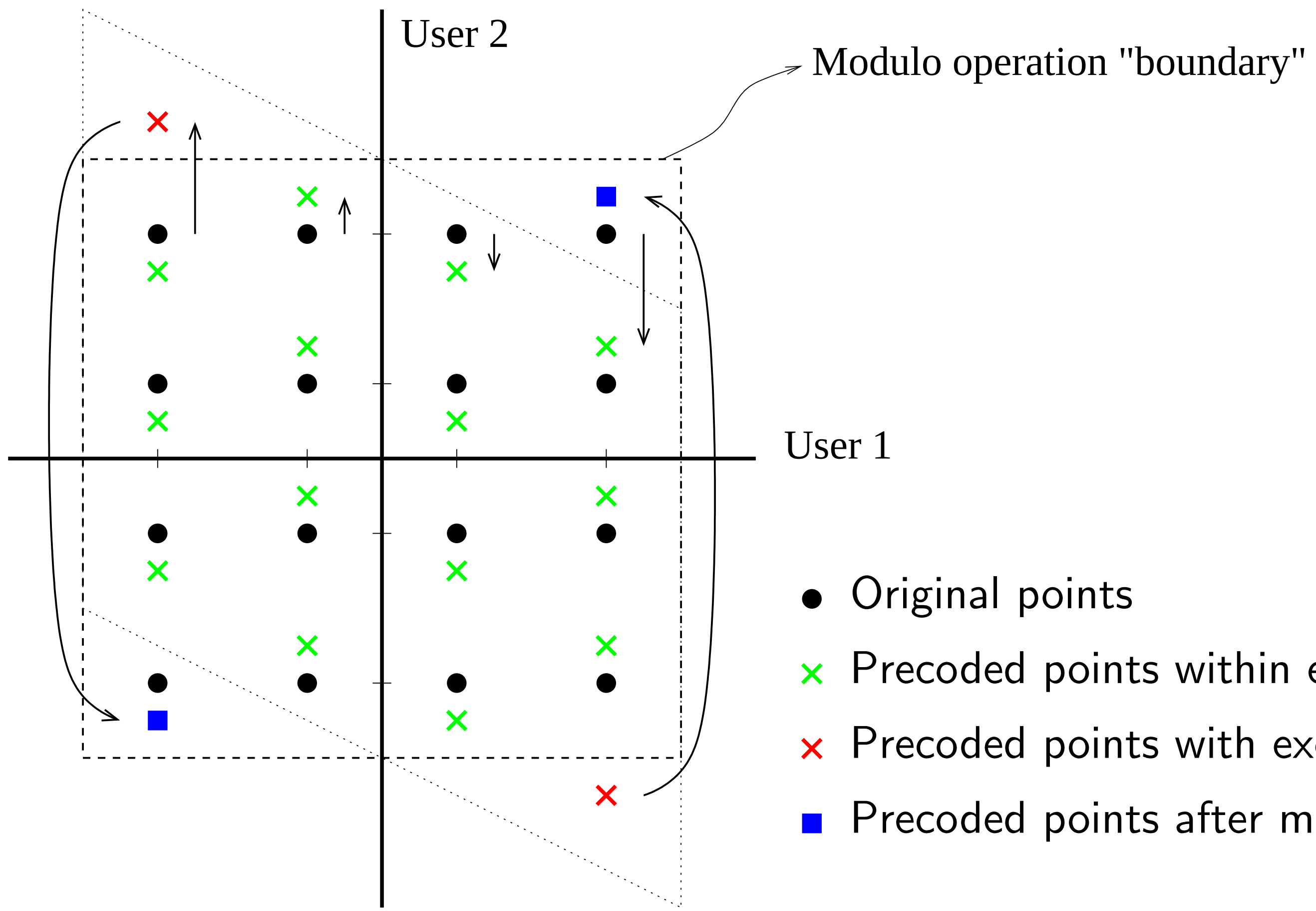
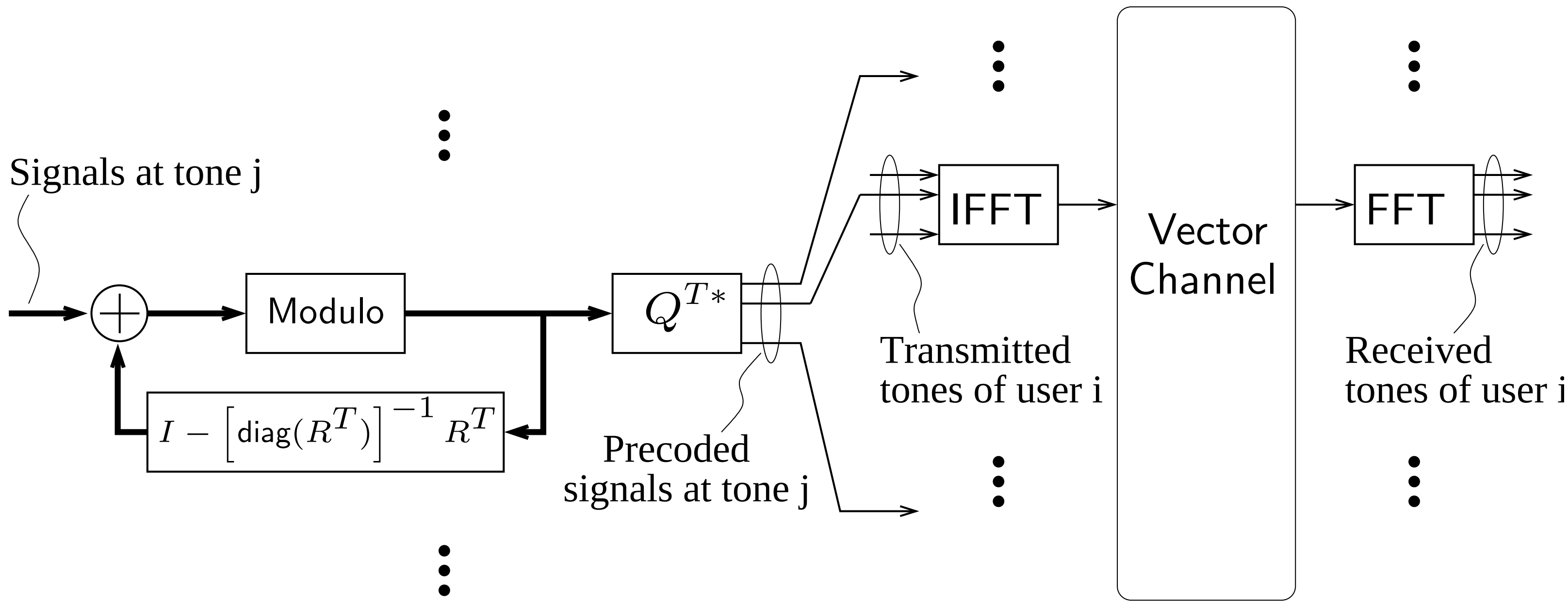


Illustration of Modulo Operation



- Original points
- Precoded points within energy constraints
- Precoded points with excessive energy
- Precoded points after modulo operation

Block Diagram for Downstream



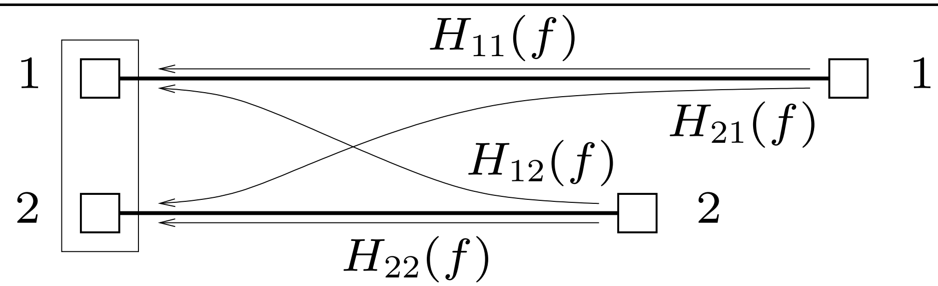
- Precoder blocks pre-distort signals within each tone.

Relation to other Structures

- Approach is similar to “Ranked Known Interference” (RKI) scheme [Caire and Shamai, 2000].
  - QR decomposition used to obtain set of parallel channels.
  - Modulo precoding employed instead of “lattice precoding”.
  - RKI was shown to be asymptotically sum capacity optimal for low and high SNR.

- System can be considered as special case of the Generalized DFE.
  - “Zero-forcing” criterion adopted instead of MMSE criterion.
  - Condition of no cooperation imposed at the receivers.

Channel Matrix for DSL Upstream

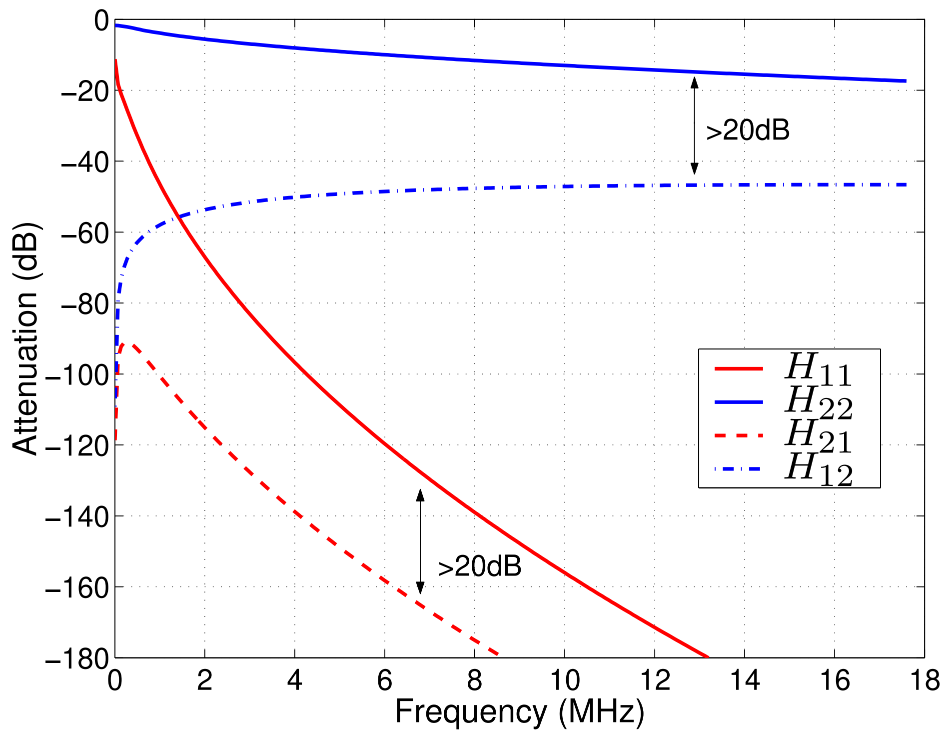


- At any frequency, $H_{11}(f) \gg H_{21}(f)$, $H_{22}(f) \gg H_{12}(f)$.

- In upstream channels, the magnitude of a diagonal element is *always* much larger than the magnitude of any element of the same *column*.

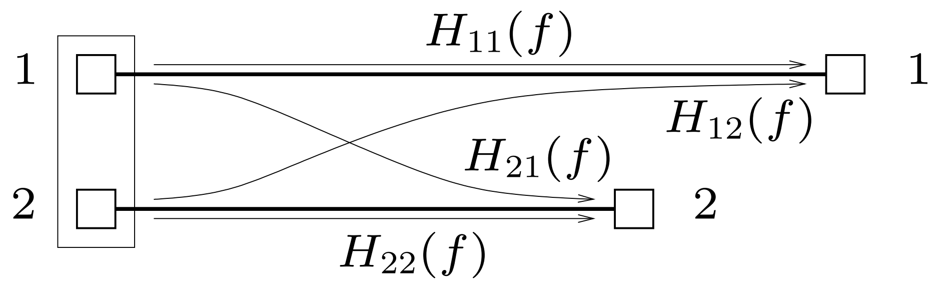
$$H(f) = \left[\begin{array}{c|c|c|c} \mathsf{x} & & & \\ & \mathsf{x} & & \\ & & \cdots & \\ & & & \mathsf{x} \end{array}\right]$$

Upstream Example Channel



- Extreme case, where loop 1 is 6000ft long, and loop 2 is 500ft long.

Channel Matrix for DSL Downstream



- At any frequency, $H_{11}(f) \gg H_{12}(f)$, $H_{22}(f) \gg H_{21}(f)$.

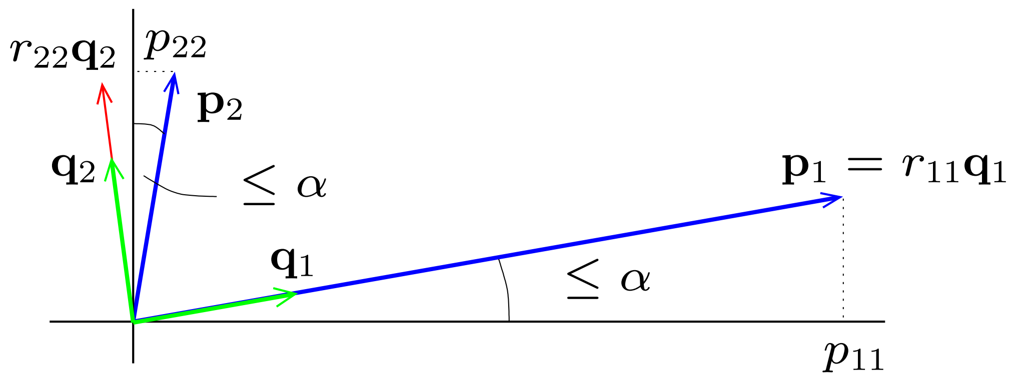
- In downstream channels, the magnitude of a diagonal element is *always* much larger than the magnitude of any element of the same *row*.

$$H(f) = \left[\begin{array}{cccc} \mathsf{x} & & & \\ \hline & \mathsf{x} & & \\ \hline & & \vdots & \\ \hline & & & \mathsf{x} \end{array} \right]$$

QR schemes with DSL channel

- QR schemes form "parallel" channels with gains r_{kk} , $k = 1, \ldots, L$.

- For upstream, R is obtained from QR decomposition of P.



$$\boxed{\alpha \ll 1 \Rightarrow r_{11} \approx p_{11} \ , \ r_{22} \approx p_{22}}$$

QR Bounds

- Generally:

$$|p_{kk}|\left(1-2\alpha^2\right) \le |r_{kk}| \le |p_{kk}|\left[1+(L-1)^2\frac{\alpha^2}{2}\right]\ ,\ k=1,2,\ldots,L$$

- "Angle" α is smaller than -20dB $\Rightarrow$
  - "Parallel" channels have gains approximately equal to the diagonal elements of P.
  - Almost same as zeroing off-diagonal elements of P.

- Re-ordering has minor effect.

Outline

- DSL as a multiuser communication environment.

- Crosstalk mitigation with user coordination.
  - Communication with receiver coordination.
  - Communication with transmitter coordination.

- **Transmission optimization and simulation results.**

Transmission Optimization

- Optimization objective is *maximization of weighted data rate sum*:

$$\max \sum_{k=1}^{L} a_k R_k$$

- Optimization variables.
  - Fixed band plan: Energy allocation, $\mathcal{E}_{i,k}$.
  - Dynamic band plan: $\mathcal{E}_{i,k}$, *and* up/down tone selection, $\mathcal{N}_{up}$, $\mathcal{N}_{down}$.

- Optimization constraints are *energy constraints for each user*:

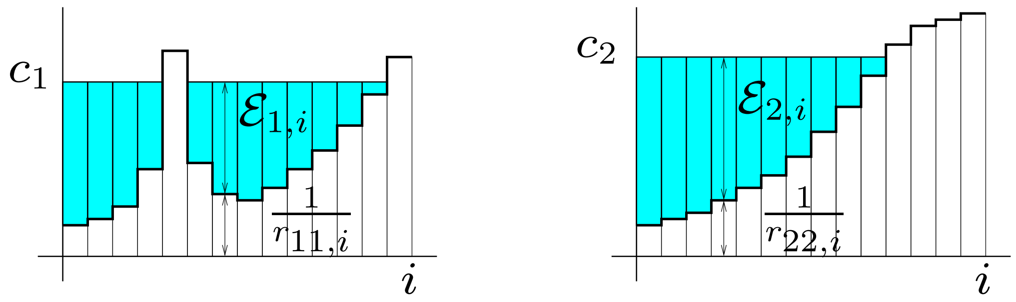
$$\mathcal{E}_k^{\text{total}} = \sum_i \mathcal{E}_{i,k} \leq \mathcal{E}_k^{\text{max}} \ , \ k = 1, \ldots, L$$

Transmission Optimization with Fixed Band Plan

- Given an allocation for upstream/downstream frequencies:
  - QR schemes result in independent channels for each user with independent constraints.
  - The optimization problem is "separable" into L problems:

$$\max R_k \ , \ \text{subject to } \mathcal{E}_k^{\text{total}} \le \mathcal{E}_k^{\text{max}} \ , \ k = 1, \ldots, L$$

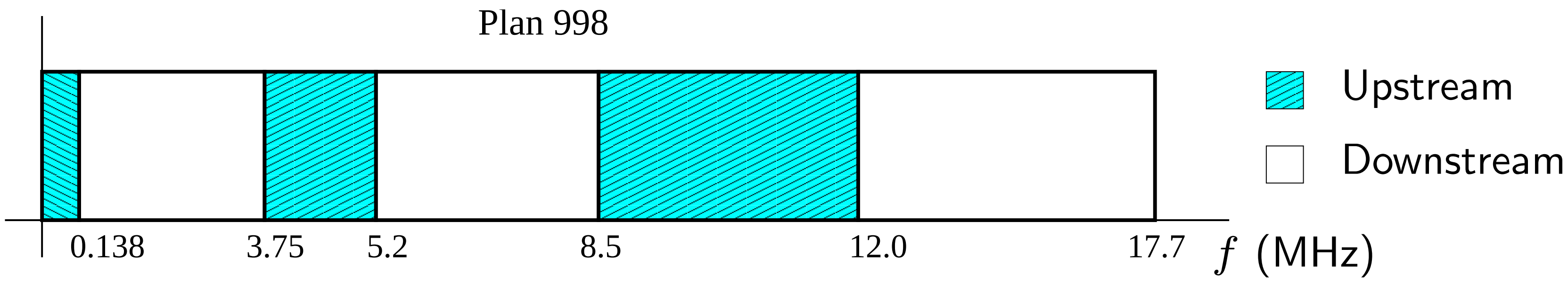
- Solution amounts to L water-fills in channels with gains r_{kk}:



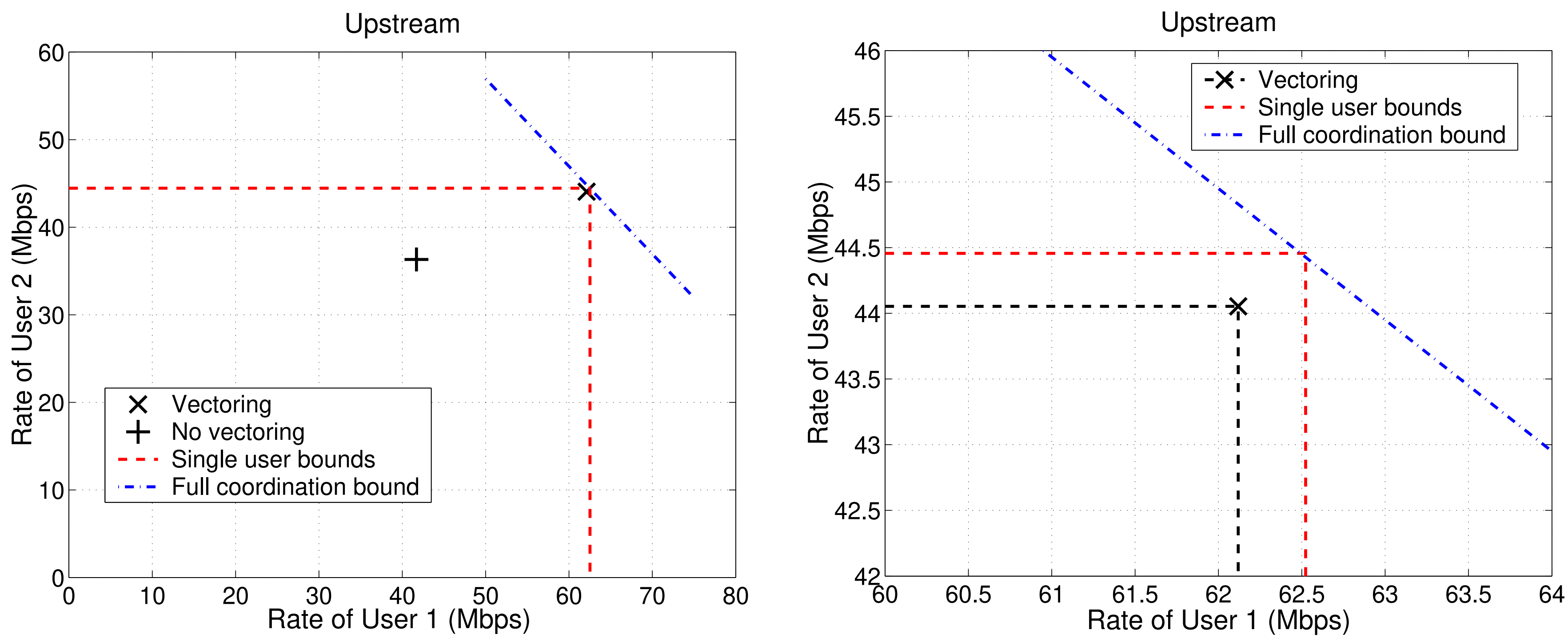
VDSL System

- Very-High-Speed DSL (VDSL) is the next DSL generation.
  - Utilizes frequencies up to 18MHz.
  - Aims for symmetric and asymmetric rates between 5 and 50Mbps.
  - Deployed in loops shorter than 6000ft.

- Frequency band plan is fixed for all users.

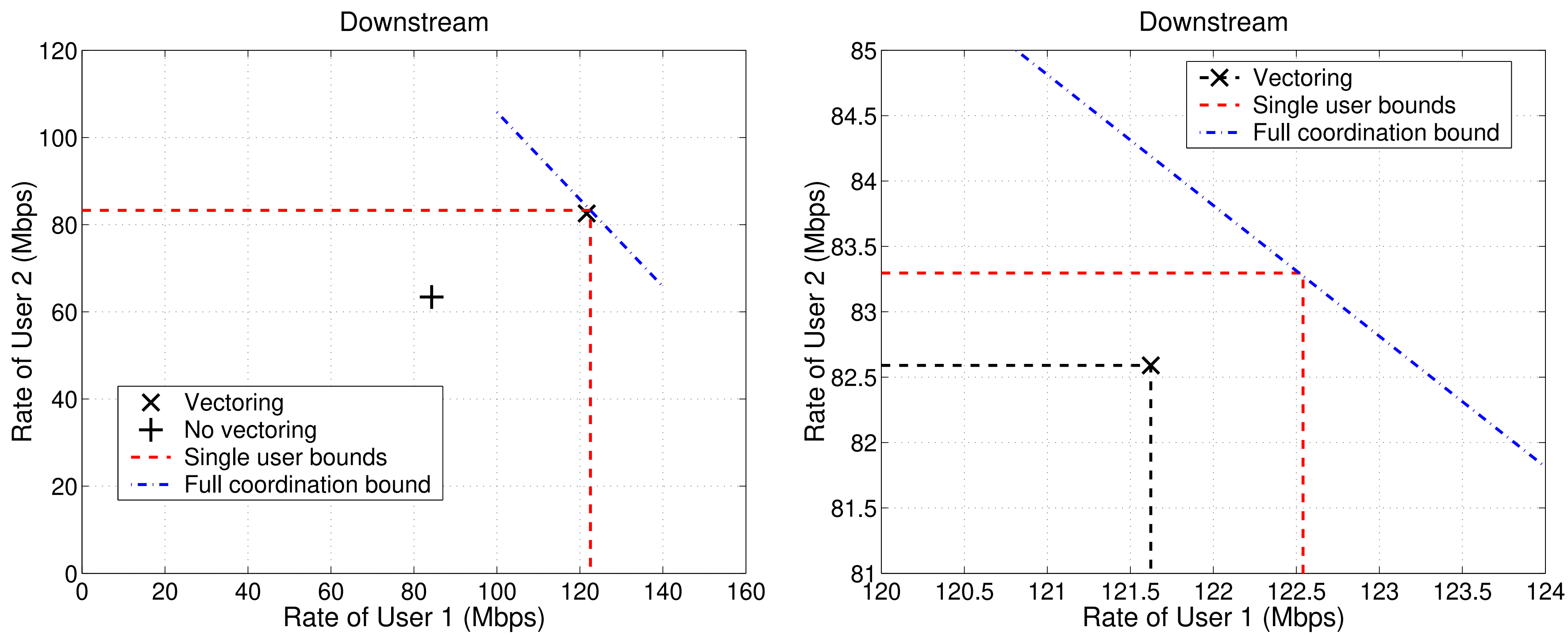


Example Upstream Rate Region



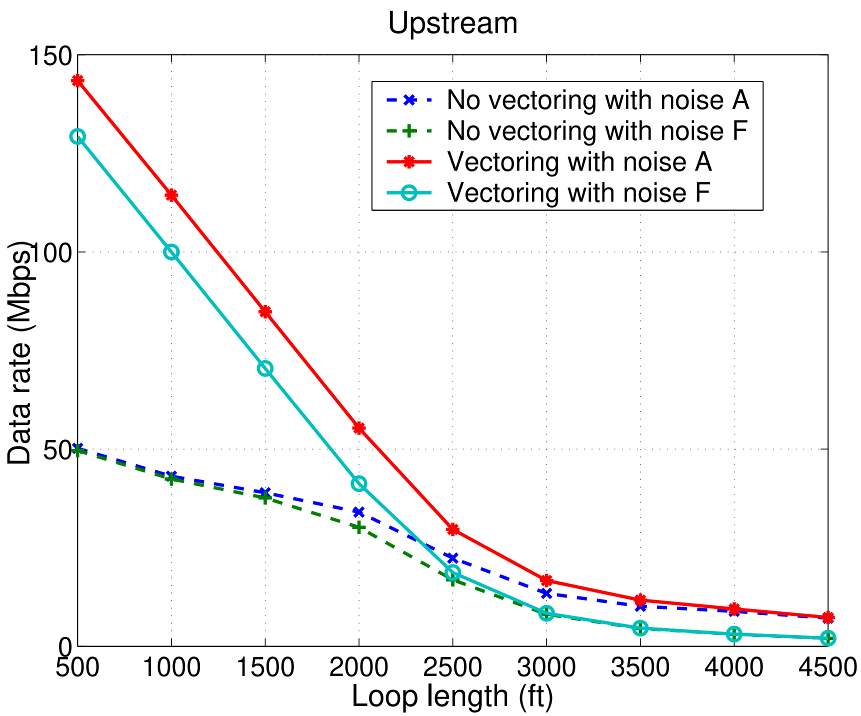
- Loop 1 is 1500ft long, loop 2 is 2000ft long. SNR gap is 12dB.

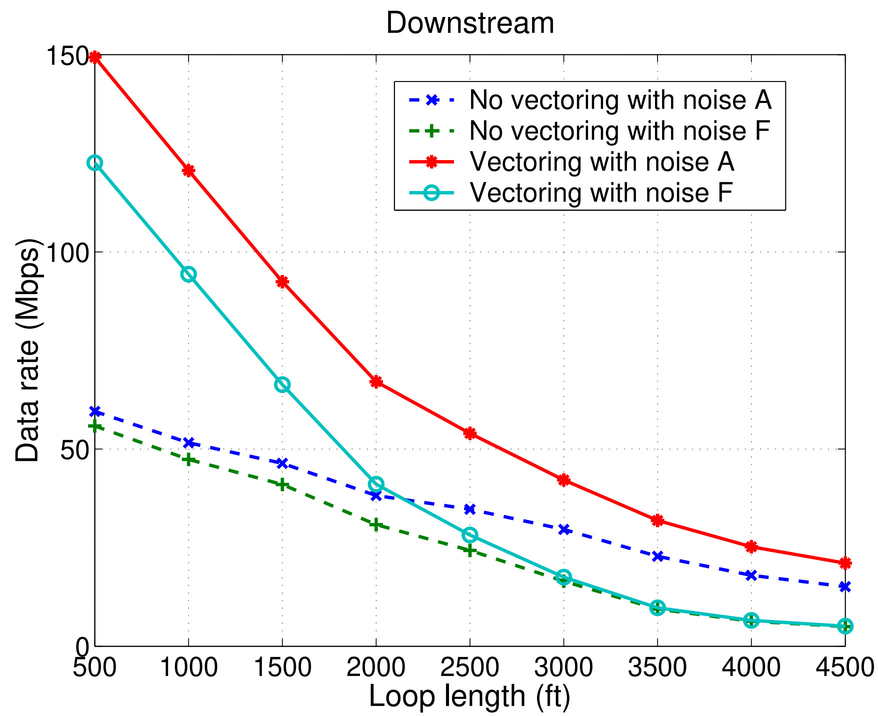
Example Downstream Rate Region



- Vectoring region differs from bounds by less than 1%.

Rate vs Loop Length Plots





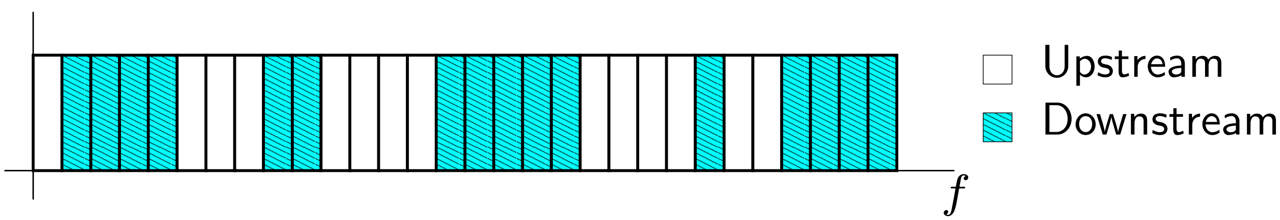
- Rate/reach improvements are very large in short loops.

Transmission Optimization with Dynamic Band Plan

- Band plan adapts to user requirements and transmission environment.
- Optimization objective becomes:

$$\max \sum_{k=1}^{L} (a_{k,up} R_{k,up} + a_{k,down} R_{k,down})$$

- Optimization variables include upstream/downstream tone selection.



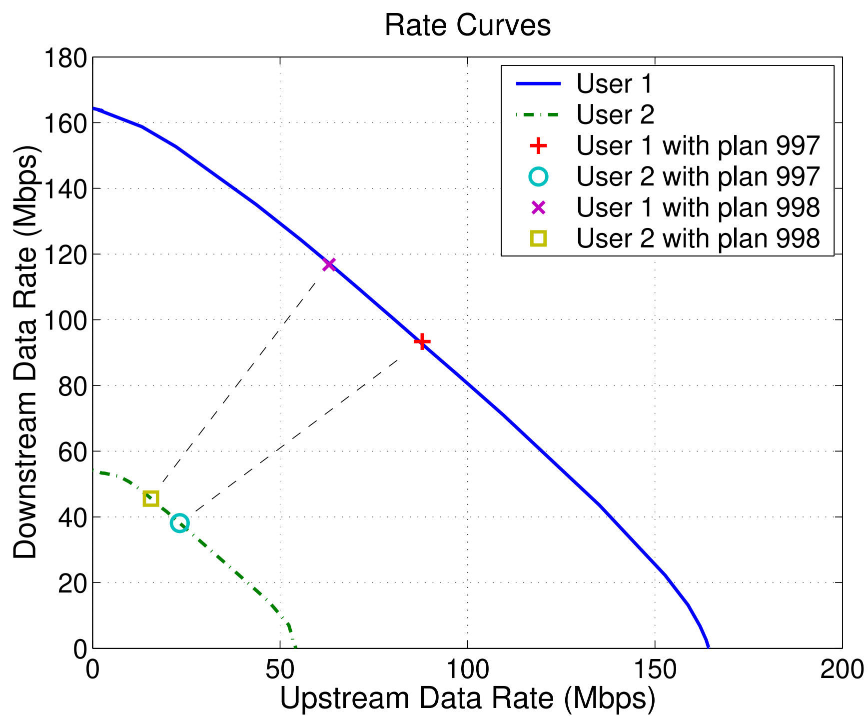
Transmission Optimization with Dynamic Band Plan

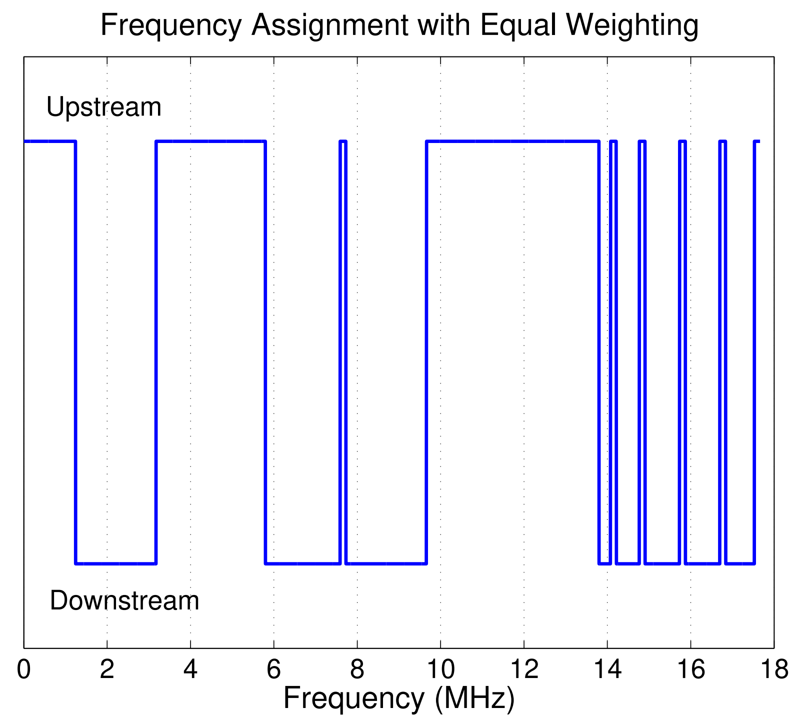
- **Idea:** Form *relaxation* of original problem that allows for easier solution. (Similar approach as "Multiuser OFDM" [Wong et al, 1999].)

- Assume initially that each tone is time-shared between upstream and downstream.
  - Let $t_{i,\mathsf{up}}$ ($t_{i,\mathsf{down}}$) be the fraction of time that tone i is used for upstream (downstream).
  - Resulting optimization problem can be shown to be convex.
  - Compute optimum $t_{i,\mathsf{up}}$, $t_{i,\mathsf{down}}$.

- Round $t_{i,\mathsf{up}}$, $t_{i,\mathsf{down}}$ to determine *near-optimum* frequency band plan.

Simulation Results with Dynamic Band Plan





- Loop 1 is 1500ft long, loop 2 is 3000ft long.

Conclusions

- There is potential for greatly improved performance in DSL systems by utilizing coordination at the Central Office/Optical Network Unit.
- Multicarrier can be employed in the multiuser case to partition the bandwidth.
- Decision feedback at the receivers effectively removes the crosstalk.
- Precoding at the transmitters achieves crosstalk-free reception.
- These techniques achieve performance close to the theoretical optimum.
- Transmission optimization methods allow for dynamic spectrum management strategies.

Acknowledgments

- Advisor:
  - Prof. Cioffi
- Committee members:
  - Prof. Siegman
  - Prof. Goldsmith
  - Prof. Cox
- Group members and Joice DeBolt.
- Friends and family.

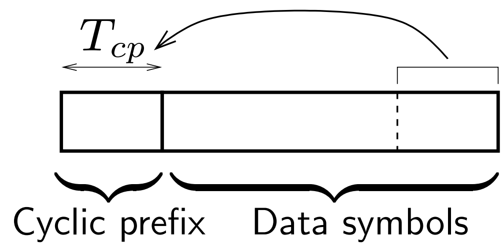
List of Contributions (1)

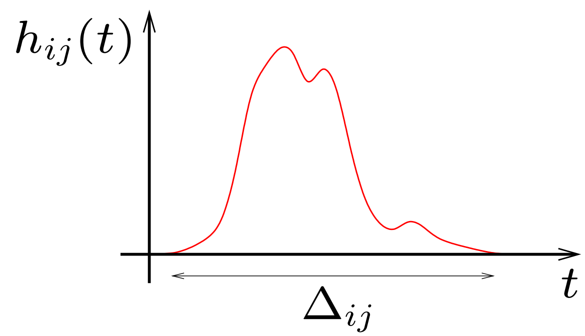
- Vectored transmission for DSL systems.
  - G. Ginis and J.M. Cioffi, "A Multiuser Precoding Scheme achieving Crosstalk Cancellation with Application to DSL Systems," *Proceedings of the 34th Asilomar Conference,* Pacific Grove, CA, pp. 1627-1631, October 2000.
  - G. Ginis and J.M. Cioffi, "Vectored-DMT: A FEXT Canceling Modulation Scheme for Coordinating Users," *Proceedings of ICC 2001,* Vol. 1, Helsinki, Finland, pp. 305-309, June 2001.
  - G. Ginis and J.M. Cioffi, "Vectored Transmission for Digital Subscriber Line Systems", *accepted in JSAC special issue on twisted-pair transmission.*
  - G. Ginis, Y. Bar-Ness and J.M. Cioffi, "Blind Adaptive MIMO Decision Feedback Equalization using Givens Rotations", *submitted to ICC 2002.*
- Bandwidth partitioning with ADC constraints.
  - G. Ginis, K. Khoo, T.D. Au, D. Mijuskovic, D. Messerschmitt and J.M. Cioffi, "Optimum Bandwidth Partitioning with Analog-to-Digital Converter Constraints", *in preparation.*

List of Contributions (2)

- Relation of the Generalized DFE to V-BLAST and MMSE-DFE.
  - G. Ginis and J.M. Cioffi, "On the Relation between V-BLAST and the GDFE," *IEEE Communications Letters,* Vol. 5, Issue 9, pp. 364-366, September 2001.
  - G. Ginis and J.M. Cioffi, "On the Convergence of the Generalized DFE to the MMSE-DFE," *accepted for presentation at Globecom 2001,* San Antonio, TX.
- Program for the analysis of convolutional and trellis codes.
  - "Enhanced dmin program," *http://www.stanford.edu/class/ee379b/software.html* .
- Joint work.
  - W. Yu, G. Ginis and J.M. Cioffi, "An Adaptive Multiuser Power Control Algorithm for VDSL," *accepted in JSAC special issue on twisted-pair transmission*.
  - V. Stojanovic, G. Ginis and M.A. Horowitz, "Transmit Pre-emphasis for High-Speed Time-Division-Multiplexed Serial-Link Transceiver", *submitted to ICC 2002.*
  - A. Agrawal, G. Ginis and J.M. Cioffi, "Channel Diagonalization through Orthogonal Space-Time Coding", *submitted to ICC 2002.*

Cyclic Prefix



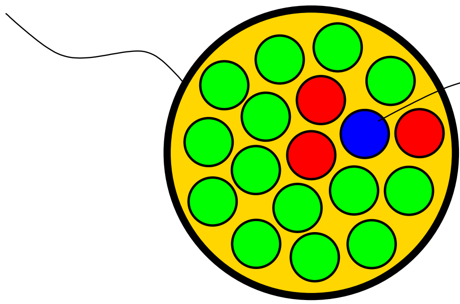


- The cyclic prefix duration must exceed the duration of the matrix channel impulse response, $T_{cp} \geq \max_{i,j} \Delta_{ij}$.

- Under these conditions, transmission within each tone is decoupled.

Complexity Reduction

cable cross-section



Most crosstalk coupling into a specific pair emanates from 3-4 neighboring pairs.

- Channel matrix P is approximately sparse.

- Computational savings arise from expressing rotation matrix Q in terms of "Givens rotations".

- Computational complexity for rotation is reduced from $\mathcal{O}(L^2)$ to $\mathcal{O}(L)$.

Ordering

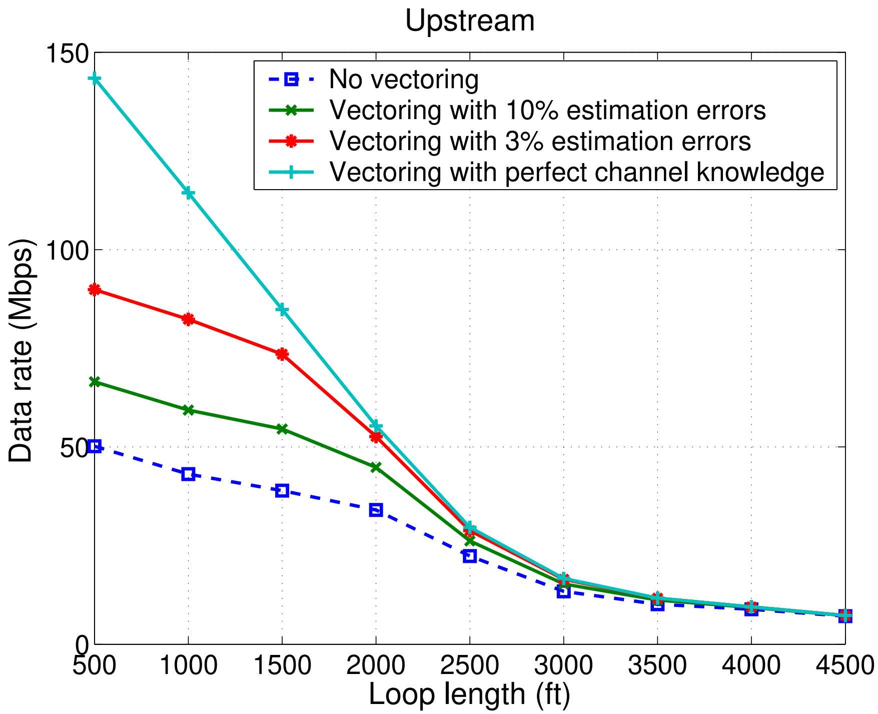
- Re-ordering amounts to exchanging columns and rows of the channel matrix T.

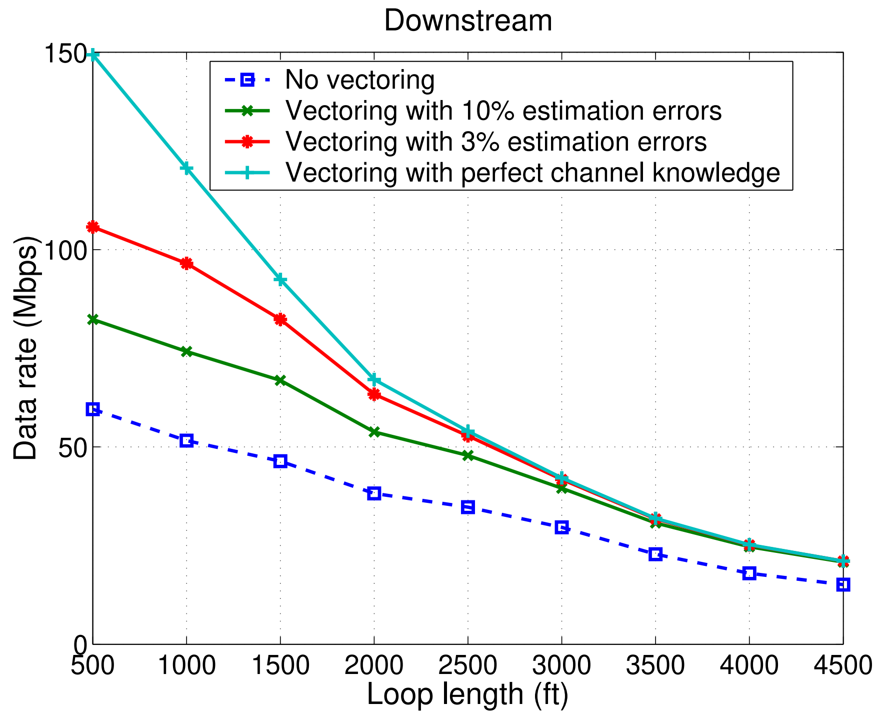
$$\begin{bmatrix} & t_{1i} & t_{1j} & \\ t_{i1} & t_{ii} & t_{ij} & t_{iL} \\ t_{j1} & t_{ji} & t_{jj} & t_{jL} \\ & t_{Li} & t_{Lj} & \end{bmatrix} \xrightarrow{\text{re-order}} \begin{bmatrix} & t_{1j} & t_{1j} & \\ t_{j1} & t_{jj} & t_{ji} & t_{jL} \\ t_{i1} & t_{ij} & t_{ii} & t_{iL} \\ & t_{Lj} & t_{Li} & \end{bmatrix}$$

- In general, such operations affect the gains r_{kk} , $k = 1, 2, \ldots, L$.

- However, for DSL channels, the effect of re-ordering is insignificant.

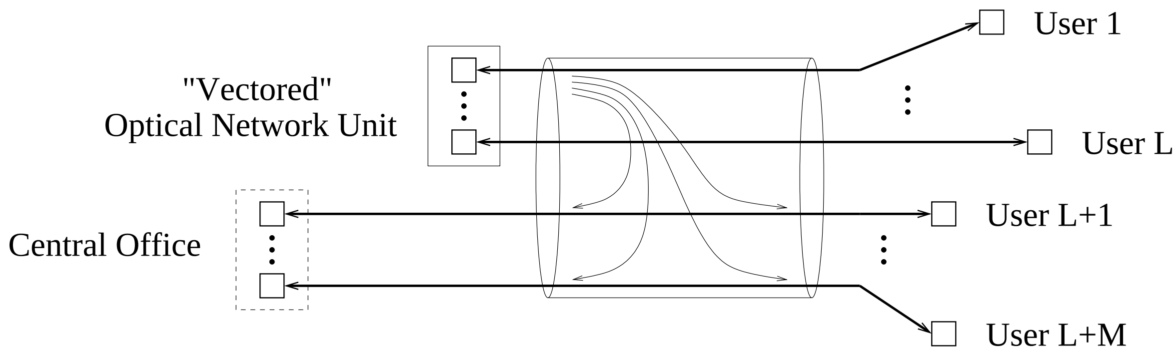
Plots with Crosstalk Coupling Estimation Errors





- Performance degradation due to estimation errors is graceful.

Fixed Band Plan with Power Back-Off



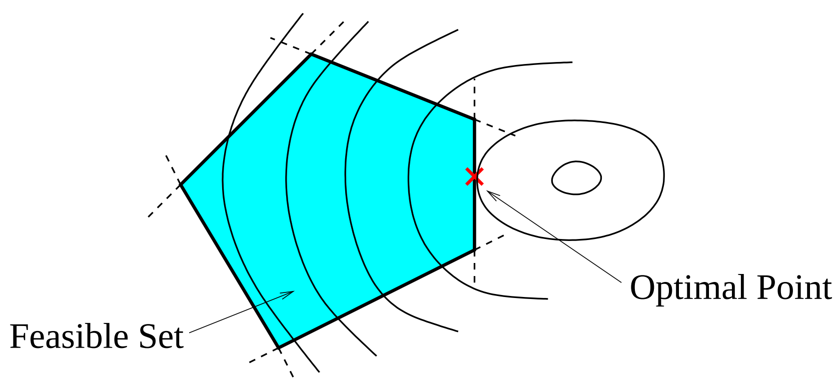
- Induced crosstalk PSD on established services must not exceed that of hypothetical system with same loop length as the affected line.

- Extra constraints for the optimization problem:

$$\sum_{k=1}^{L} c_{km,i} E_{k,i} \leq E_{m,i}^{\mathsf{ref}} \ , \ m = L+1, \ldots, L+M \ , \ \text{for all } i$$

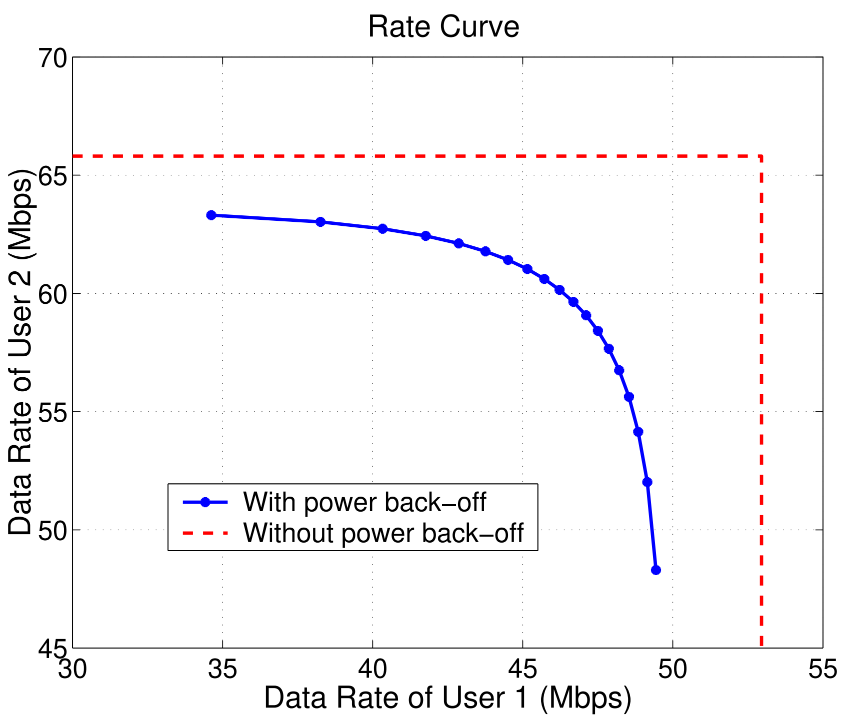
Transmission Optimization with Power Back-Off

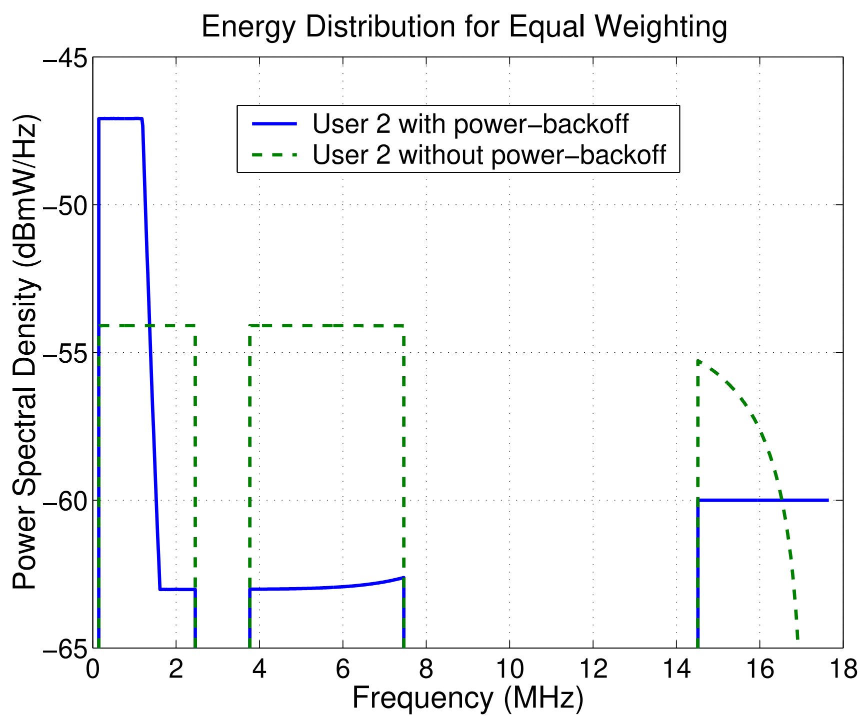
- Objective function $\sum_{k=1}^{L} a_k R_k$ is *concave*.
- Energy constraints and PSD constraints form *convex* sets.



- Resulting problem is *convex*, and numerical solutions are efficiently produced.

Simulation Results with Power Back-Off





- Loop 1 is 2500ft long, loop 2 is 2000ft, affected loop is 3000ft.