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Dynamic Spectrum Management
in Wireline Access Networks

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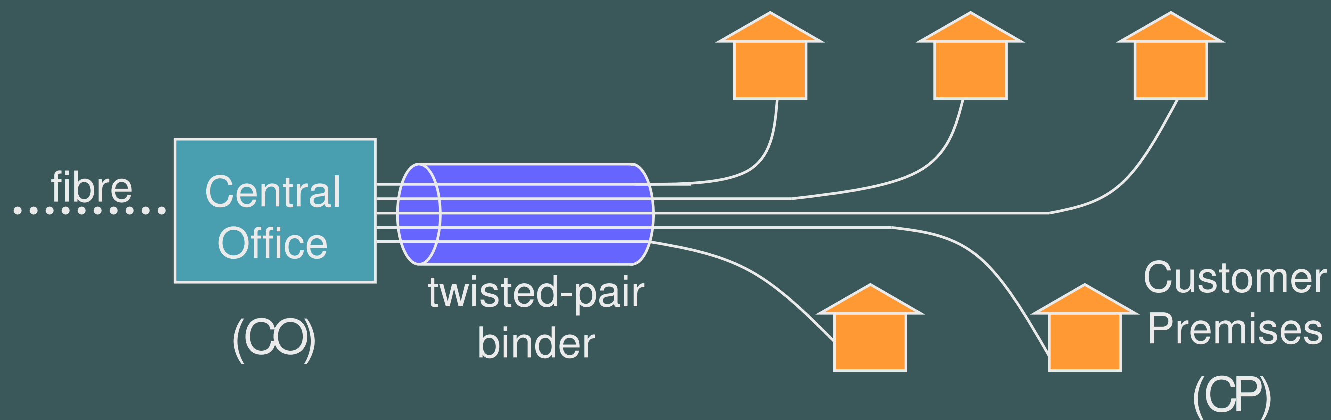
thanks to Raphael Cendrillon (for 40% of the slides), Paschalis Tsiaflakis (40%),
thanks to current/former phd/postdocs & to Alcatel-Bell/Alcatel-Lucent co-workers (1996-2011)

Contents

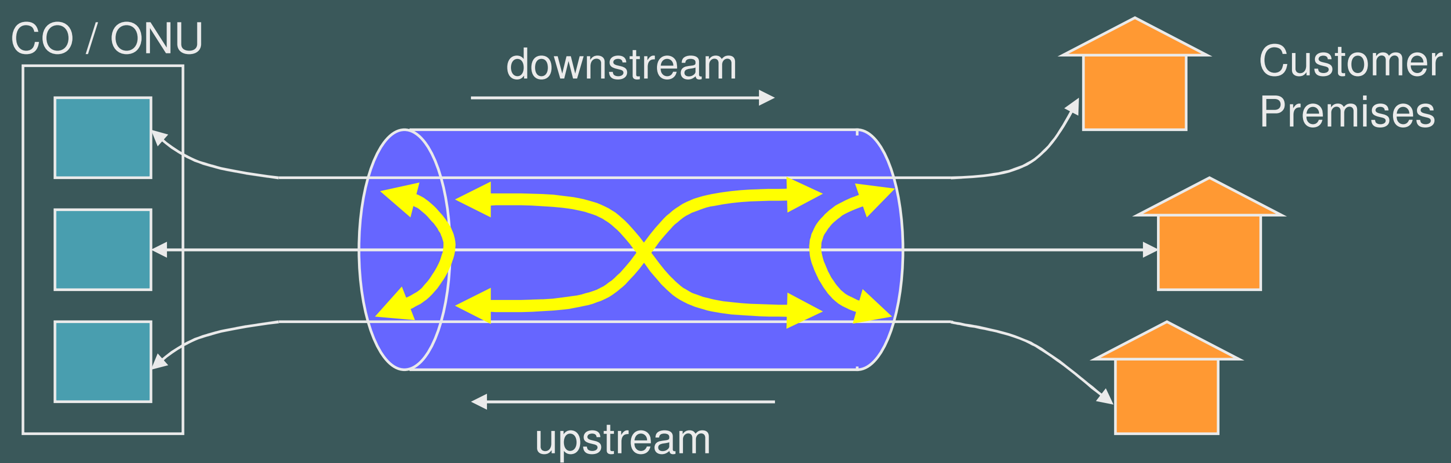
Digital Subscriber Lines - DSL

- Broadband services over existing telephone line
  - ADSL - ADSL2 – ADSL2+ 6... Mbps
  - VDSL – VDSL2 52...Mbps
- 300 million subscribers world-wide, 65% market share
- Stepping stone for Fibre-to-the-Home (2020?)
- Not a shared medium: '<u>single-user system</u>' (although....)



Signal Processing Challenges in DSL

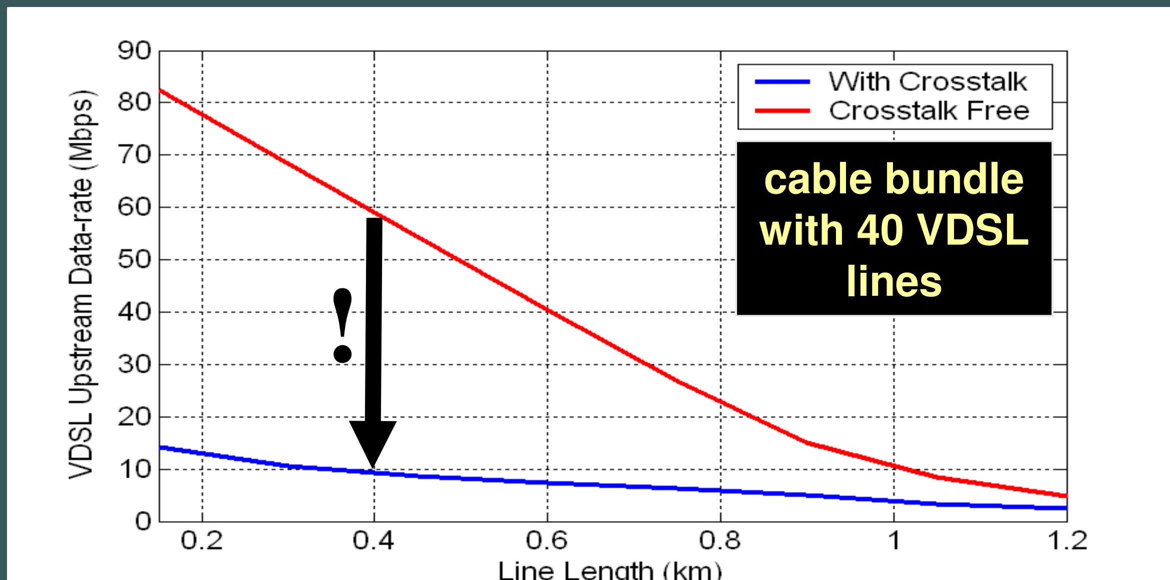
- Telephone network designed for voiceband (< 4 kHz)
- ADSL uses up to 1.1 MHz, VDSL uses up to 30 MHZ
- Problems: channel dispersion-equalization (*), RFI, crosstalk…
- **Crosstalk** : 10-15 dB larger than background noise, hence major source of performance degradation



Van Acker et al, Per tone equalization for DMT-based systems, IEEE Tr.Com 2001
Vanbleu et al, Bit-rate maximizing time-domain equalizer design for DMT, IEEE Tr.Com 2004

Signal Processing Challenges in DSL

- How bad ? Significant loss of data-rate…



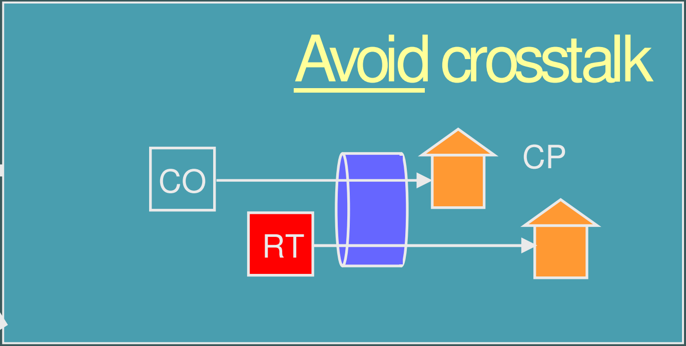
- Multi-user system: calls for

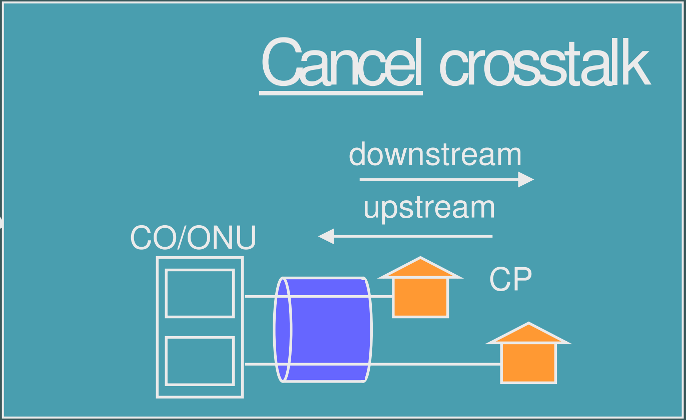
  `Dynamic Spectrum Management' (DSM)

  = multi-user spectrum and/or signal coordination

Contents

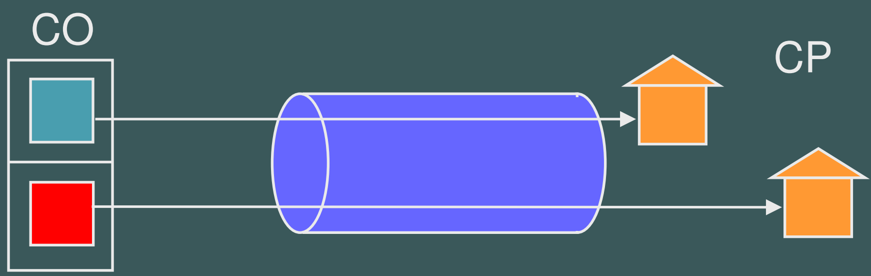
- Wireline Access: DSL
- Signal Processing Challenges
  - Equalization/ Crosstalk
- Spectrum Coordination
  - Optimal Spectrum Balancing (OSB)
- Signal (& Spectrum) Coordination
  - MAC-OSB with MMSE-GDFE
  - MAC with linear zero-forcing cancellation & partial crosstalk cancellation
  - Other/Mixed Scenario's
- Cross-Layer Optimization
  - Dynamic Resource Allocation / Max-Weight Scheduling
- Conclusions



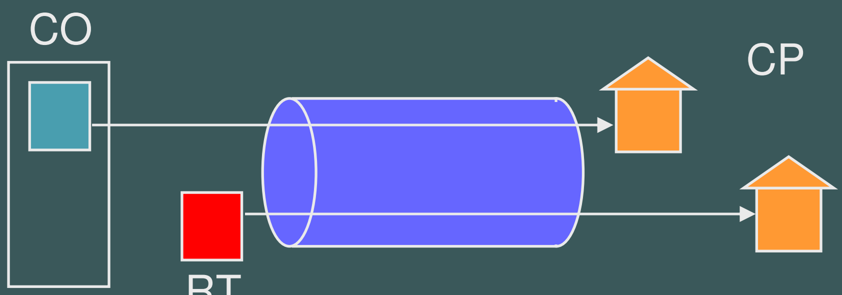


Spectrum Coordination ('DSM-level2')

- Scenario's where coordination of signals not possible, only transmit spectra may be coordinated
  (by 'spectrum management center', based on direct/crosstalk channel knowledge)
- Occurs when (e.g.)
  - Unbundled binder



  - CO modems not co-located



Spectrum Coordination

- Simple example: FDMA
  - Crosstalk avoided by transmitting in non-overlapping frequency bands

  - FDMA quite sub-optimal in practice
- Better solutions possible…

Spectrum Coordination: Data Model

- **DMT / OFDM** : tone k=1..**K**, users n=1..**N**

$$y_k^n = \overbrace{h_k^{n,n}}^{\text{direct channel}} x_k^n + \sum_{m \neq n} \overbrace{h_k^{n,m}}^{\text{Xtalk channel}} x_k^m + n_k^n$$

$$\mathbf{y}_k = \mathbf{H}_k . \mathbf{x}_k + \mathbf{n}_k$$

N

- Bit-rate for user n on tone k (given Tx powers)

'SNR Gap'

$$b_k^n = \log_2 \left(1 + \frac{1}{\Gamma} \frac{|h_k^{n,n}|^2 \, s_k^n}{\sum_{m \neq n} |h_k^{n,m}|^2 \, s_k^m + \sigma_k^n} \right) \qquad (*)$$

- Total bit-rate and total power for user n

$$R^n = f_s \sum_k b_k^n \qquad P^n = \sum_k s_k^n$$

Spectrum Coordination: Data Model

- **Question:**

  What are achievable rates, for given power budget for each user?

  i.e. optimization problem in **K.N variables** (*b*'s or *s*'s) !

- PS: power loadings $s_k^1, s_k^2, \ldots, s_k^N$ can be computed from bit loadings $b_k^1, b_k^2, \ldots, b_k^N$ (or vice-versa) based on (*)
- PS: May assume either integer power loading or integer bit loading

  e.g. $b_k^n \in \{0,1,2,\ldots, b_{\max}\}$
- PS : This is Interference Channel : rate regions generally unknown.

  Here: 'achievable rate regions' for receivers that treat crosstalk interference as noise.

Spectrum Coordination

- Objective function = **Weighted rate-sum**

Non-convex objective function

$$\max_{\mathbf{s}_1\ldots\mathbf{s}_N,\mathbf{b}_1\ldots\mathbf{b}_N} \quad w_1 R_1 + \ldots + w_N R_N$$

$$\text{s.t.} \quad \sum_{\text{tones } k} s_k^n \leq P_n, \forall n \quad \text{(users)}$$

i.e. unlike single-user case (water-filling etc.)

Coupled across tones by total power constraint

- Weights represent priority given to each user.

  Can trace achievable rate region by varying weights
- PS: Can easily add in spectral mask constraints (omitted)

Spectrum Coordination: OSB

- Non-convex optimization problem ☹
- Finding global optimum (e.g. for integer bit loading) by exhaustive search = O(B^(KN)) = computationally intractable (e.g. B=14, K=4096, N=20)
- '**Optimal Spectrum Balancing**' (**OSB**)

  [Cendrillon et al. IEEE Tr Comm. 2006] [Yu et al. Globecom 2004]
  - Based on dual problem formulation (Lagrangian)
  - Provides global optimum of primal problem, i.e. globally optimal spectra ('duality gap=zero' (asymptotically) [Yu et al 2006] [Luo et al 2008])
  - Low-complexity algorithms based on convex relaxations

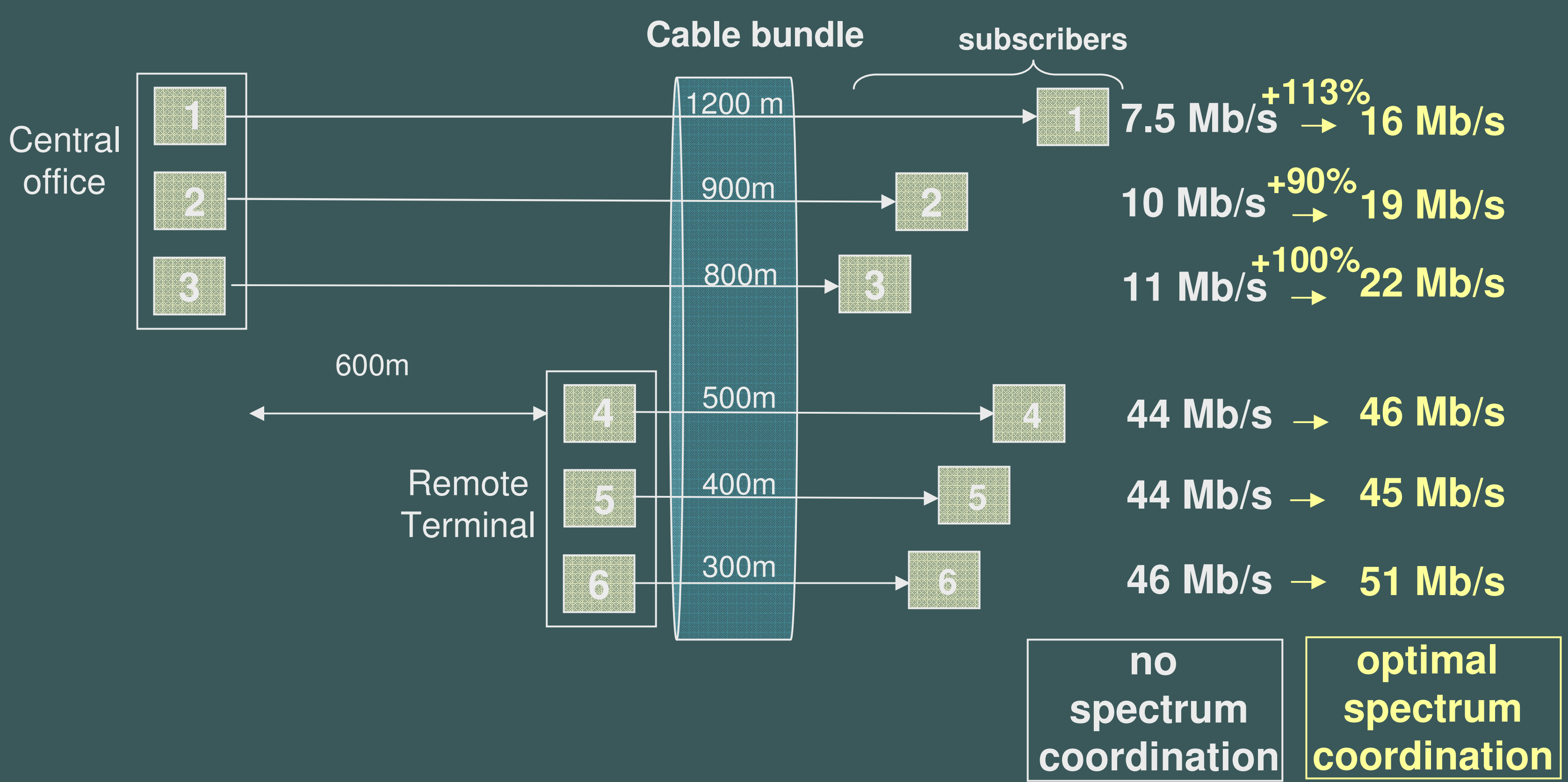
    `Distributed Spectrum Balancing' (DSB) [Yu 2007] [Tsiaflakis et al., 2007]

  - Typical data-rate gains : 100%..150% over state-of-the-art !

Cendrillon et al, Optimal Multiuser Spectrum Balancing for DSLs, IEEE Tr.Com 2006
Tsiaflakis et al, Distributed Spectrum Management Algorithms for Multiuser DSL, IEEE Tr.SP 2008

Spectrum Coordination: example

Downstream VDSL, bandplan 998



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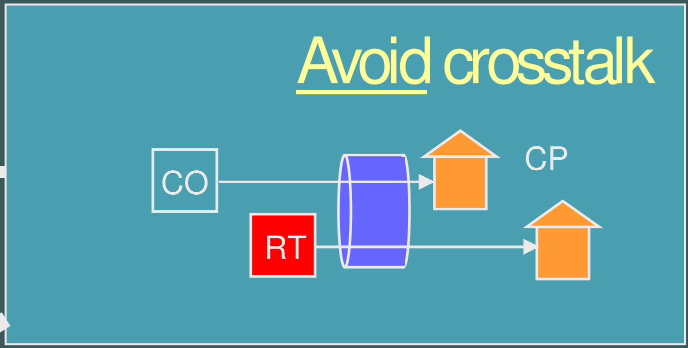
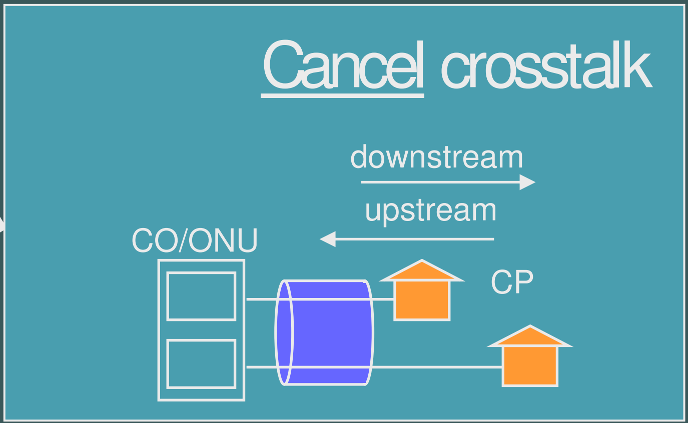
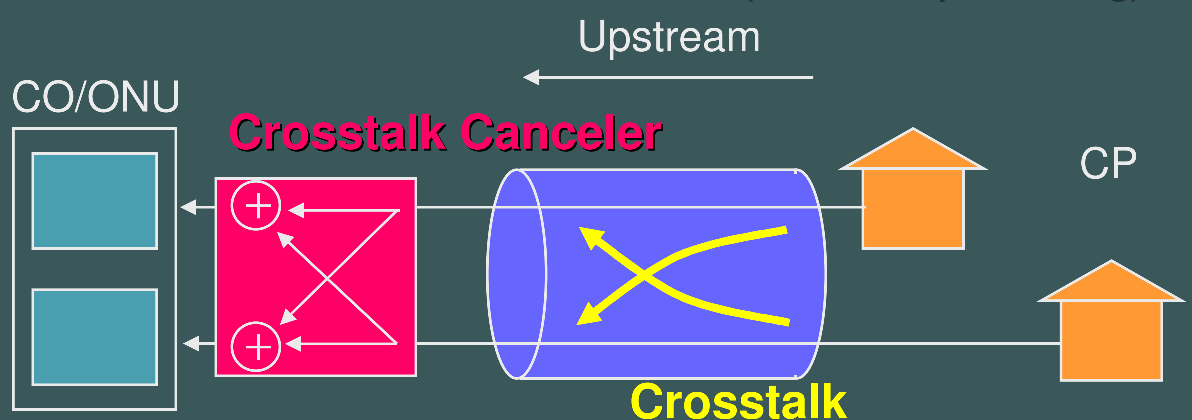




Signal Coordination ('DSM-level2&3')

- So far considered spectra coordination only
- If CO/ONU modems are co-located can also coordinate signals
- Upstream
  - RXs co-located
  - Filter crosstalk after reception (crosstalk cancellation)
- Downstream
  - TXs co-located
  - Prefilter crosstalk before transmission (crosstalk precoding)



Signal Coordination

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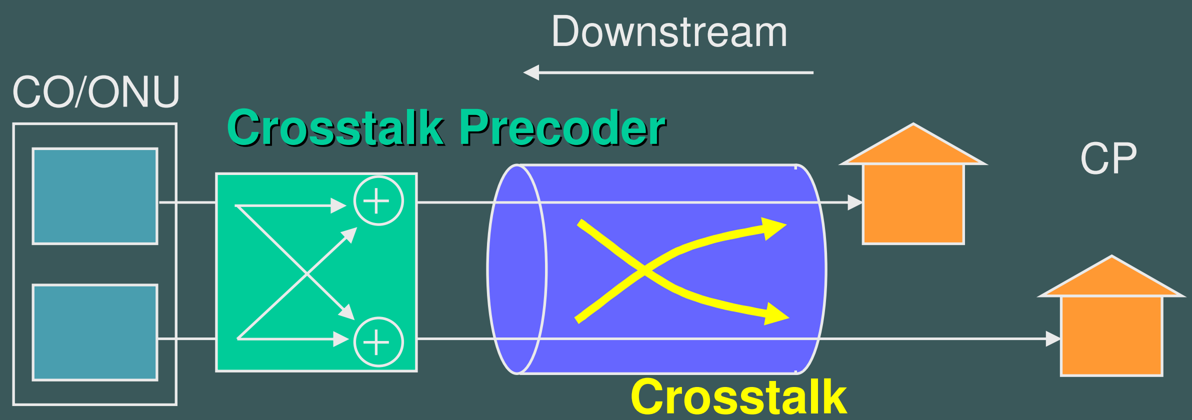


Signal Coordination: Data Model

- DMT (OFDM): tone k=1..K, users n=1..N

$$\mathbf{y}_k = \mathbf{H}_k.\mathbf{x}_k + \mathbf{n}_k$$

↕ N

$$E\{\mathbf{n}_k.\mathbf{n}_k^H\} = I_{N\times N}$$

(non-white noise is pre-whitened)

- Upstream Channel (Rx co-ordination) = MAC ('Multiple Access Channel')
- Downstream Channel (Tx co-ordination) = BC (`Broadcast Channel')

- Will discuss **upstream** (**MAC**) first (other scenario's later)
- MAC capacity (=unweighted rate sum) is

$$\sum_n b_k^n = \log_2(\left| I + \mathbf{H}_k.\mathbf{S}_k.\mathbf{H}_k^H \right|) \qquad \mathbf{S}_k = diag\{s_k^1,\ldots,s_k^N\}$$

Signal Coordination: MAC

- **Questions:**

  What are achievable rates for given power budget per user ?
  Which receiver structures? Performance/complexity trade-off ?

- **3 Parts:**
  - OSB with optimal receiver (=MMSE-GDFE) : **MAC-OSB**
  - OSB with simplest possible receiver (=linear zero-forcing, ZF)
  - OSB with partial (ZF) coordination

Signal Coordination: MAC-OSB

- Objective function is a **weighted** rate sum

$$\max_{\mathbf{s}_1\ldots\mathbf{s}_N,\mathbf{b}_1\ldots\mathbf{b}_N} w_1R_1+\ldots+w_NR_N$$

$$\text{s.t.} \quad \sum_{\text{tones } k} s_k^n \le P_n, \ \forall n \quad \text{(users)}$$

- Optimal Receiver is MMSE-GDFE (*), a.k.a. MMSE-VBLAST [Ginis & Cioffi 2001]
- Weights set detection order (user with smallest weight detected 1st)
- Link between *b*'s and *s*'s (e.g. 2-user case with w1<w2)

Insert 'SNR Gap'

$$b_k^1 = \log_2\left(\left|I+\frac{1}{\Gamma}(I+\mathbf{h}_k^2.s_k^2.\mathbf{h}_k^{2^H})^{-1}.\mathbf{h}_k^1.s_k^1.\mathbf{h}_k^{1^H}\right|\right)$$

$$b_k^2 = \log_2\left(\left|I+\frac{1}{\Gamma}\mathbf{h}_k^2.s_k^2.\mathbf{h}_k^{2^H}\right|\right) \quad (**)$$

(*) Generalized Decision Feedback Equalizer

Signal Coordination: MAC-OSB

- Can now straightforwardly apply dual decomposition procedure (cfr.supra) (with (**) p.19 instead of (*) p.9)
- …Leads to OSB procedure : **MAC-OSB**

  = optimal spectrum management (bit & power loading) under optimal (=MMSE-GDFE) receiver

  [Tsiaflakis et al 2007]
- Low-Complexity algorithms based on convex relaxations:

  MAC-DSB [Tsiaflakis et al 2010]

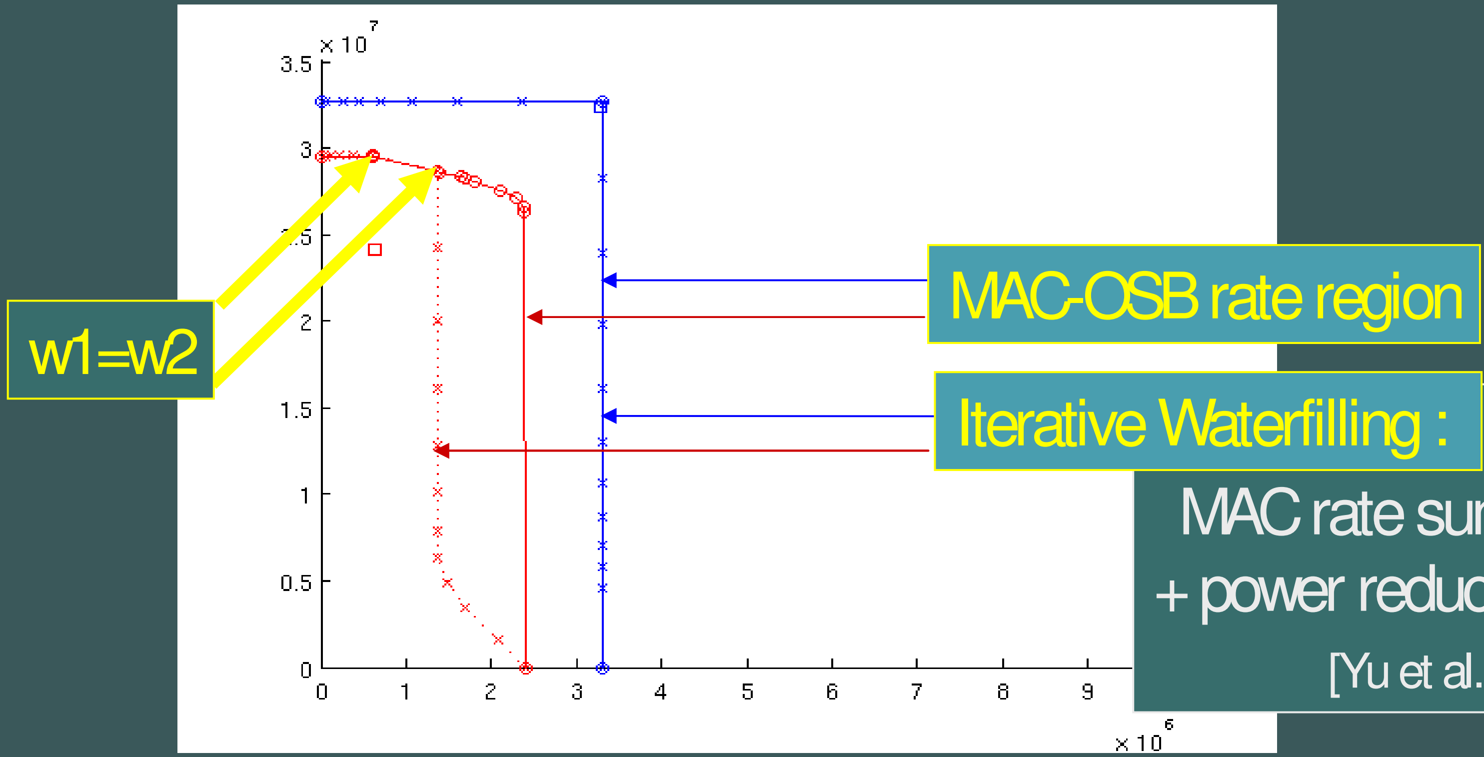
Tsiaflakis et al, Multiple Access Channel OSB for Upstream DSL, IEEE Com Letters 2007
Tsiaflakis et al, An improved MAC-OSB algorithm for upstream DSL, Internal Report 2010

Signal Coordination: MAC-OSB

- Upstream VDSL, FDD 998 Bandplan, 2 users (1200m & 600m)

  blue= additive white noise

  red = additive white noise + alien crosstalk from two 600m-lines



=unweighted MAC rate sum optimization + power reduction for 1 user [Yu et al., IEEE Tr. IT 2004]

Signal Coordination

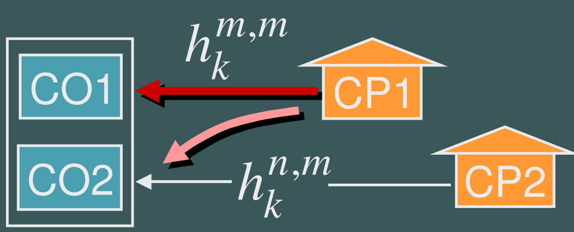
- **Questions:**

  What are achievable rates for given power budget per user ?
  Which receiver structures? Performance/complexity trade-off ?

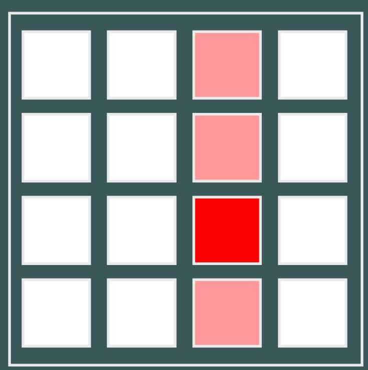
- **3 Parts:**
  - OSB with optimal receiver (=MMSE-GDFE) : **MAC-OSB**
  - OSB with simplest possible receiver (=linear zero-forcing, ZF)
  - OSB with partial (ZF) coordination

Signal Coordination: MAC -ZF

- <u>Upstream Channel Property</u>: Crosstalk must propagate through full length of disturbers line



- Implies **Column-Wise Diagonal Dominance (CWDD)**



$\mathbf{H}_k$

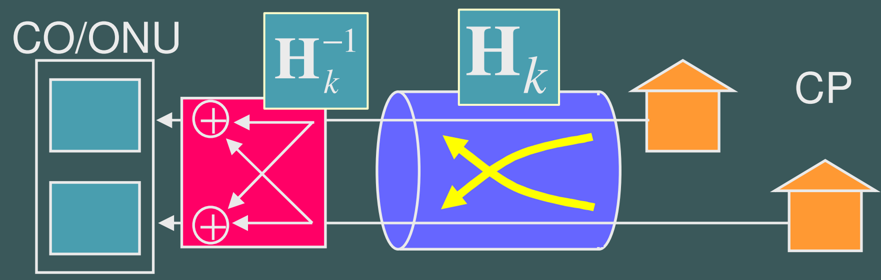
Along a column diagonal element has largest magnitude

$$\left|h_k^{n,m}\right| << \left|h_k^{m,m}\right|, \forall m \neq n$$

PS: Downstream channel -> Row-Wise Diagonal Dominance

Signal Coordination: MAC-ZF

- Assume additive noise is white, hence no pre-whitening (which otherwise destroys CWDD structure ☹)
- Linear ZF canceler removes all crosstalk perfectly



- Use CWDD to <u>bound noise enhancement</u> of ZF canceler

> Linear ZF canceler achieves 92% capacity in 99% of VDSL channels!!

- ZF implies modems operate as if no crosstalk present. Hence OSB reduces to <u>single-user</u> waterfilling !

Cendrillon et al, A Near-Optimal Linear Crosstalk Canceler for Upstream VDSL, IEEE Tr.SP 2006
Cendrillon et al, A Near-Optimal Linear Crosstalk Precoder for Downstream VDSL, IEEE Tr.Com 2007

Signal Coordination: MAC-ZF

- Upstream VDSL, FDD998 Bandplan, 2 users (1200m & 600m)

  blue= additive white noise

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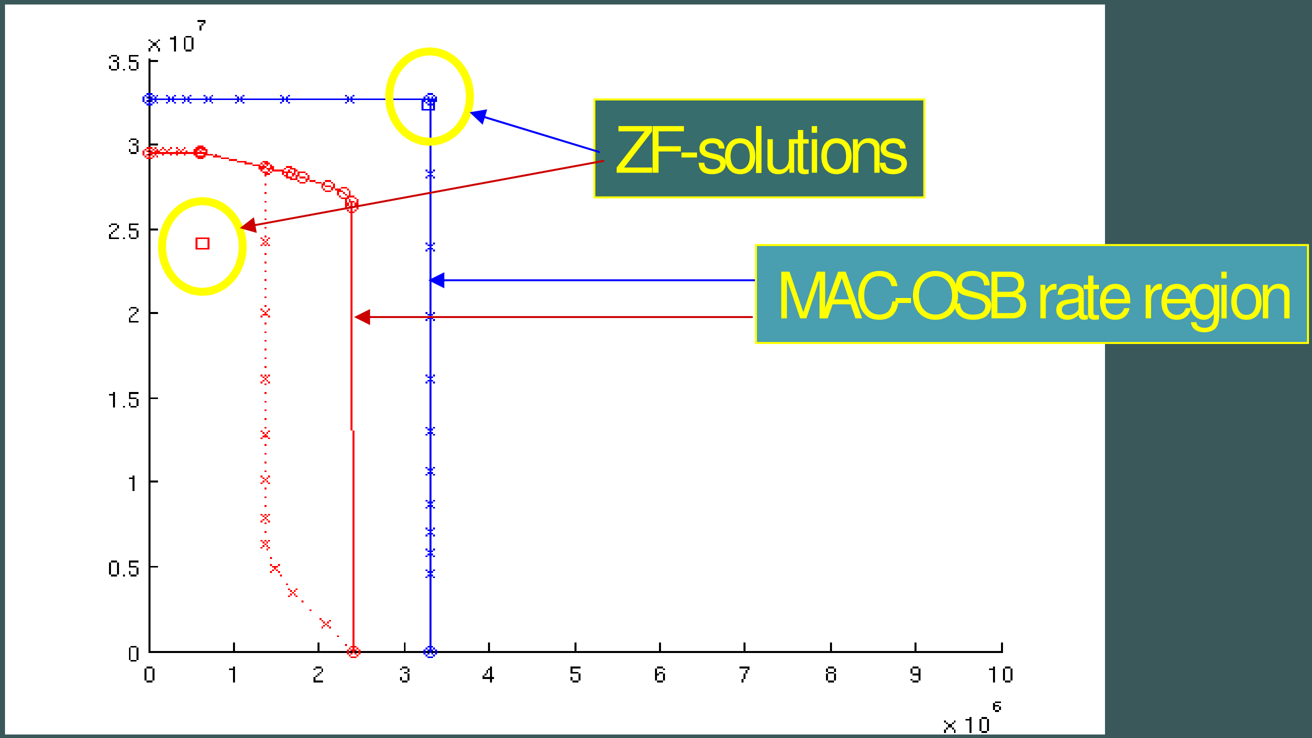


Signal Coordination

- **Questions:**

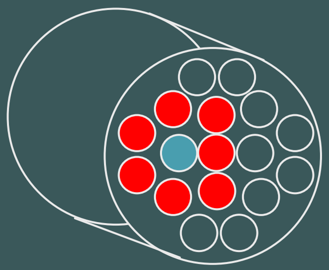
  What are <u>achievable rates</u> for given power budget per user ?
  Which <u>receiver structures</u>? Performance/complexity trade-off ?

- **3 Parts:**
  - OSB with optimal receiver (=MMSE-GDFE) : **MAC-OSB**
  - OSB with simplest possible receiver (=linear zero-forcing, ZF)
  - OSB with partial (ZF) coordination

Signal Coordination: MAC-Partial ZF

- MAC-ZF canceler yields large benefits

  …but still high **run-time complexity** (in large bundles)



- Observation:
  - majority of the crosstalk comes from a few lines
  - worst effects of crosstalk are experienced on a few tones
- Can replace Hk^{-1}'s by a `**sparser**' matrix? (=partial canceler)

> Given a limited amount of run-time complexity (=canceler tap budget) how to distribute across tones such that data rate is maximized?

- Optimal solutions typically achieve 90% of data-rate with 30% run-time complexity

  [Cendrillon et al, JASP 2004] [Cendrillon et al, Signal Processing 2004]

Cendrillon et al, Partial Crosstalk Cancellation for Upstream VDSL, EURASIP JASP 2004
Cendrillon et al, Partial crosstalk precompensation in downstream VDSL, Signal Processing 2004

Signal Coordination: MAC-Partial ZF

- Optimal Resource Allocation (power+canceler taps)

$$\max_{\mathbf{s}_1,\ldots,\mathbf{s}_N,\mathbf{b}_1,\ldots,\mathbf{b}_N} \quad w_1 R_1 + \ldots + w_N R_N$$

$$\text{s.t.} \quad \sum_k s_k^n \le P_n, \ \forall n$$

=Power budget

$$\sum_k \sum_m \sum_n c_k^{n,m} \le C^{tot} \qquad \begin{cases} n,m = 1\ldots N \\ k = 1\ldots K \end{cases}$$

1 (cancelation) or 0 (no cancellation)

=Canceler tap budget

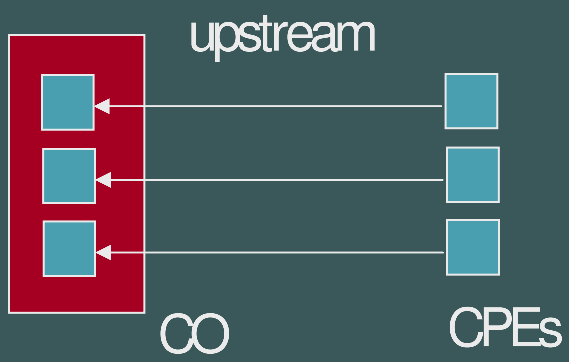
- b's (bit loading) depend on s's (power loading) and c's :

$$b_k^n = \log_2\left(1 + \frac{1}{\Gamma}\frac{|h_k^{n,n}|^2 \ s_k^n}{\sum_{m\neq n}(1-c_k^{n,m})|h_k^{n,m}|^2 \ s_k^m + \sigma_k^n}\right)$$

- Dual decomposition, etc. [Yu et al., Globecom 2003] [Van Gorp et al., 2005]

Vangorp et al, Joint spectrum management and constrained partial crosstalk cancellation in a multi-user xDSL environment, Signal Processing, 2007.

Signal Coordination: MAC



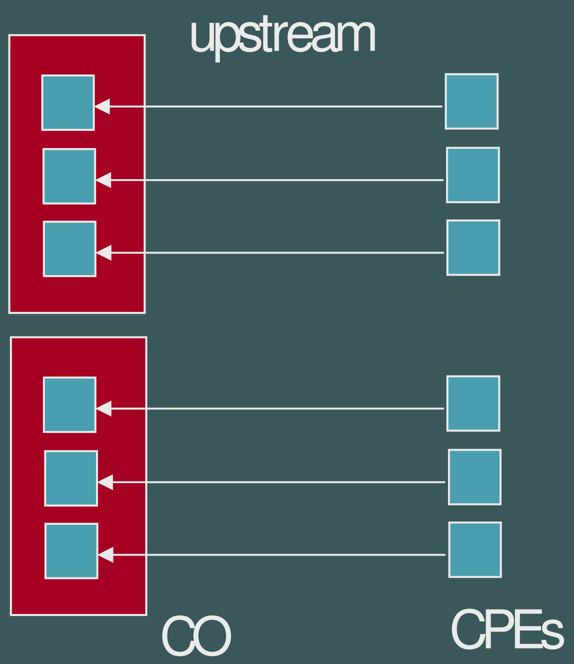
Conclusion (**MAC**):

- Optimal power allocation algorithms for different rx structures
  - Optimal receiver MMSE-GDFE
  - Simplest receiver Linear ZF
  - Other: Linear MMSE (not shown), …
- Optimal Resource Allocation (power+canceler taps) algorithms
  - Partial Linear ZF
  - Other: Partial Linear MMSE, Partial MMSE-GDFE (not shown)

Pandey et al, MMSE-based Partial Crosstalk Cancellation for Upstream VDSL, IEEE ICC 2010

Contents

Signal Coordination



Other/Mixed Scenario's: **IF-MAC**

- Spectrum coordination over all users
- Signal coordination amongst groups of receivers (line cards)

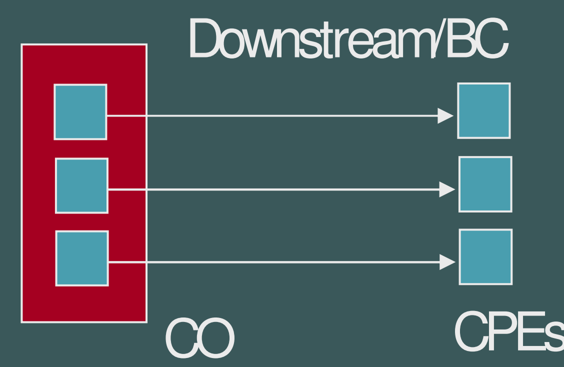
- General scenario with IF and MAC as special cases
- Algorithm for optimal power allocation straightforwardly derived (with OSB and MAC-OSB as special cases)

Forouzan et al, Joint Level 2 and 3 DSM for Upstream DSL, Internal Report 2010

Signal Coordination

Other/Mixed Scenario's: **BC**

- Spectrum coordination over all users
- Signal coordination: Precoding



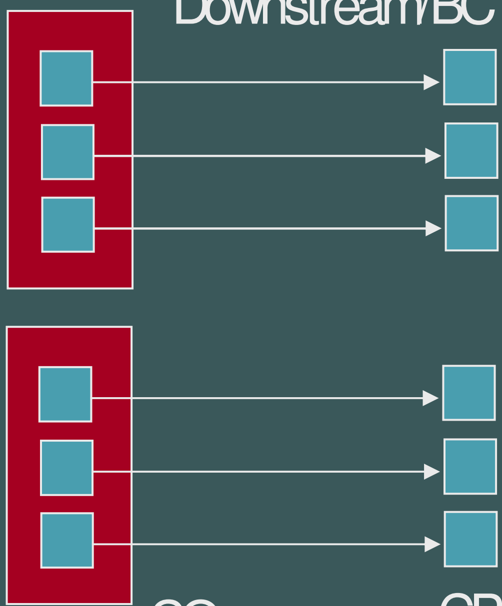
- Per-Tx power budgets instead of per-user power budgets (!)
- Optimal power allocation algorithms based on duality theory [Viswanath & Tse 2003, Yu & Lan 2007]
- BC-OSB [LeNir 2009]

Le Nir et al, Optimal power allocation for downstream xDSL with per-modem total power constraints : Broadcast Channel Optimal Spectrum Balancing:BC-OSB, IEEE Tr.SP 2009

Signal Coordination

Other/Mixed Scenario's: **IF-BC**

- Spectrum coordination over all users
- Signal coordination amongst groups of receivers (line cards)



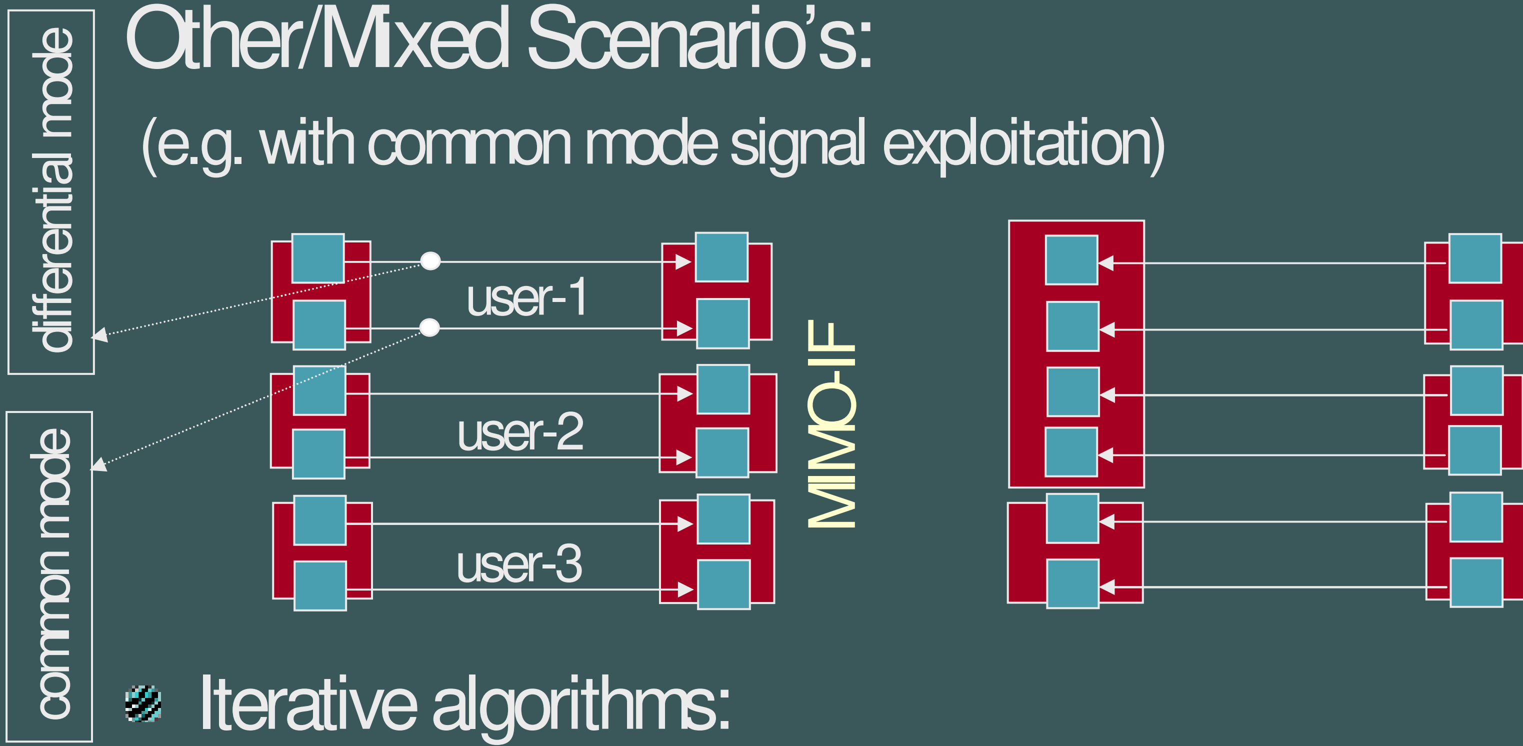
- General scenario with IF and BC as special cases
- Algorithm for optimal power allocation with OSB and BC-OSB as special cases

Forouzan et al, Joint Level 2 and 3 DSM for Downstream DSL, Internal Report 2010

Signal Coordination

Other/Mixed Scenario's:

(e.g. with common mode signal exploitation)



- Iterative algorithms:

  iterate between power allocation, precoder optimization ('BC'), equalizer optimization (`MAC')

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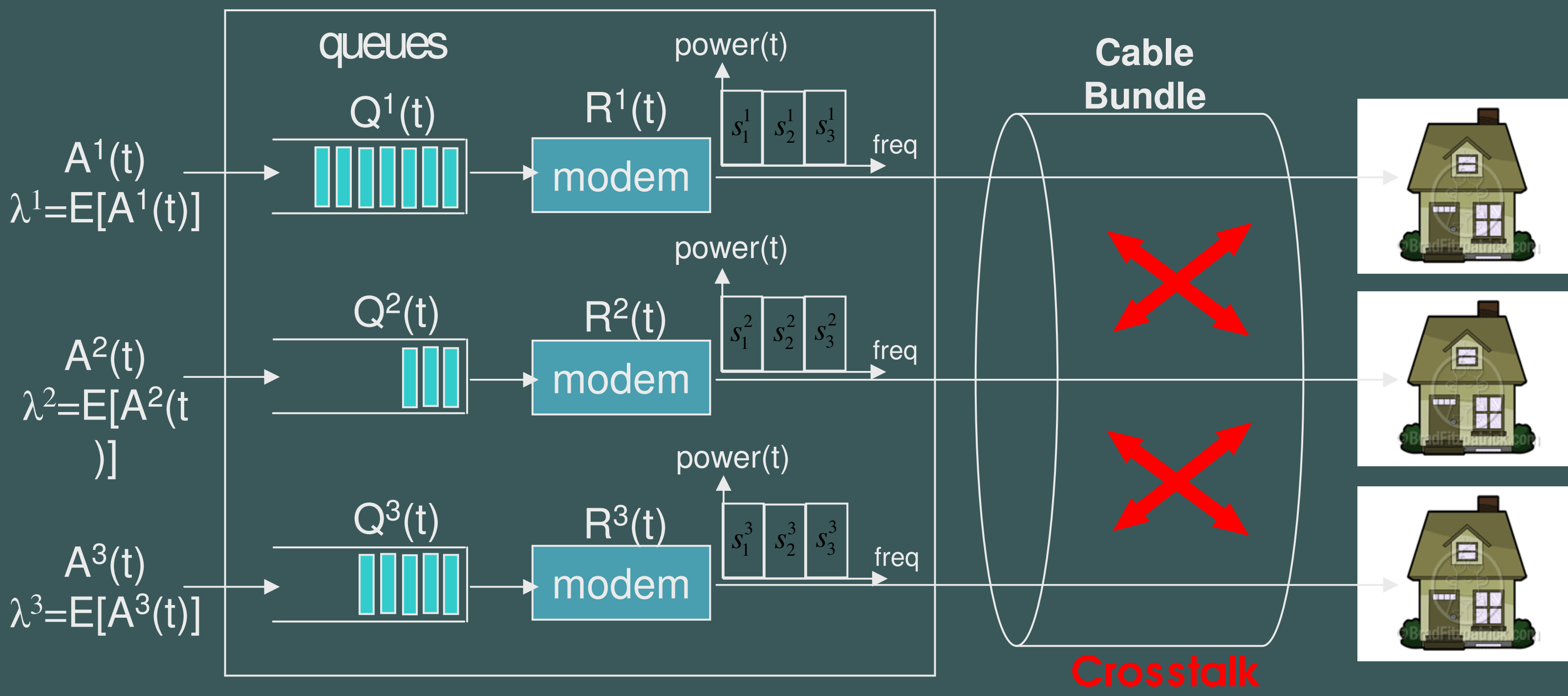
Cross-layer optimization

- DSM discusses so far:
  - Physical layer optimization/resource (power & tap) allocation
  - Weighted rate sum optimization: Weights???
  - Infinite workload assumption for each user
  - Delay not taken into account
    - Many application however are delay-sensitive (video, voice, gaming)
- Upper layer performance metrics may be much more important to improve user QoE
- ➔ Extension to upper-layer system model
  - Joint scheduling and physical layer DSM
  - Consider upper layer performance metrics: Throughput & Delay

Cross-layer optimization: system model



- Time-slotted system: Can modify power/tap allocation at every time slot t
- $Q^n(t)$ = queue length of buffer for modem n at time slot t
- $A^n(t)$ = arrival process of bits for modem n at time slot t with mean λ^n
- Queueing dynamics: $Q^n(t+1)=[Q^n(t)-R^n(t)]^+ + A^n(t+1)$

Cross-layer optimization

- Stability: system is stable, iff

$$\lim_{t\to\infty} \sup \frac{1}{t}\sum_{\tau=0}^{t} \mathrm{E}\left[\sum_{n\in \mathrm{N}} Q^{n}(\tau)\right] < \infty$$

- Throughput region: set of all mean arrival vectors $\lambda=(\lambda^n,\forall n)$ for which there exists a scheduling algorithm stabilizing the system
- Max Weight scheduling:
  - At time slot *t*, it schedules $\mathbf{R}^*(t)$ where

$$\mathbf{R}^*(t) = \arg\max_{\mathbf{R}} \sum_{n\in \mathrm{N}} Q^n(t) R^n$$

  - Achieves throughput optimality

Cross-layer optimization

- Joint scheduling and DSM
  - At time slot *t*, schedule transmit powers/canceler taps where

$$\mathbf{R}^*(t) = \arg\max_{\mathbf{R}} \sum_{n \in \mathrm{N}} Q^n(t) R^n$$

  - Weights w_n = queue lengths $Q^n(t)$
  - Achieves throughput optimality!
  - Requires the use of globally optimal DSM algorithms
- Can we still obtain throughput-optimality with suboptimal DSM algorithms?
  - Yes but delay penalty…

Tsiaflakis et al, Throughput and Delay of DSL DSM with Dynamic Arrivals, IEEE GLOBECOM 2008
Li et al, Dynamic Resource Allocation Based Partial Crosstalk Cancellation…, IEEE GLOBECOM 2010

Conclusions

- DSL Crosstalk = major (signal processing) challenge
- **Spectrum Coordination** **=Power Allocation**
  - Optimal Spectrum Balancing (OSB) provides optimal solution to spectrum coordination problem in 'interference channel' (i.e. no Rx/Tx signal coordination)
  - Complexity under control!
- **Signal Coordination** **=Resource (power+taps) Allocation**
  - MAC-OSB : OSB under optimal receiver (MMSE-GDFE)
  - Zero-Forcing Equalization & Partial (ZF) Coordination for reduced run-time complexity
  - Downstream, Other/Mixed Scenario's, .. = similar
- **Cross-layer Optimization** **=Dynamic Resource Allocation**

Reports: http://www.esat.kuleuven.be/scd/person.php?persid=2