Dynamic Spectrum Management in Wireline Access Networks

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  - MAC with linear zero-forcing cancellation & partial crosstalk cancellation
  - Other/Mixed Scenario’s
- Cross-Layer Optimization
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- Conclusions
Digital Subscriber Lines - DSL

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

![Diagram of DSL setup]

- Central Office (CO)
- twisted-pair binder
- Customer Premises (CP)

(Although...)

300 million subscribers worldwide, 65% market share.
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
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  - 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

\[ y^n_k = h^{n,n}_k x^n_k + \sum_{m \neq n} h^{n,m}_k x^m_k + n^n_k \]

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

\[ b^n_k = \log_2 \left( 1 + \frac{1}{\Gamma} \sum_{m \neq n} \left| h^{n,m}_k \right|^2 s^m_k + \sigma^n_k \right) \]  

- Total bit-rate and total power for user n

\[ R^n = f_s \sum_k b^n_k \quad P^n = \sum_k s^n_k \]
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

\[ b_k^n \in \{0, 1, 2, \ldots, b_{\text{max}}\} \]

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**

  \[
  \max_{s_1 \ldots s_N, b_1 \ldots b_N} \sum_{n} w_i R_i + \ldots + w_N R_N
  \]
  \[
  \text{s.t. } \sum_{k} s_k^n \leq P_n, \forall n \text{ (users)}
  \]

  - **Non-convex** objective function
  - 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)**

- 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
Spectrum Coordination: example

Downstream VDSL, bandplan 998

Central office

Cable bundle

Remote Terminal

 subscribers

7.5 Mb/s $\rightarrow$ 16 Mb/s
10 Mb/s $^{+90\%}$ $\rightarrow$ 19 Mb/s
11 Mb/s $^{+100\%}$ $\rightarrow$ 22 Mb/s
44 Mb/s $\rightarrow$ 46 Mb/s
44 Mb/s $\rightarrow$ 45 Mb/s
46 Mb/s $\rightarrow$ 51 Mb/s

no spectrum coordination

optimal spectrum coordination
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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)  

![Diagram of CO/ONU, Crosstalk Canceler, and CP connections](Diagram.png)
Signal Coordination

- 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: Data Model**

- **DMT (OFDM):** tone \( k = 1 \ldots K \), users \( n = 1 \ldots N \)

\[
y_k = H_k \cdot x_k + n_k
\]

\[
E\{n_k \cdot n_k^H\} = I_{N \times N}
\]

( 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 scenarios later)

**MAC capacity** (= unweighted rate sum) is

\[
\sum_n b_k^n = \log_2 (|I + H_k \cdot S_k \cdot H_k^H|) \quad S_k = \text{diag} \{s_k^1, \ldots, s_k^N\}
\]
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

\[
\max_{s_1 \ldots s_N, b_1 \ldots b_N} w_1 R_1 + \ldots + w_N R_N
\]

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

- Optimal Receiver is **MMSE-GDFE** 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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]
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

MAC-OSB rate region

Iterative Waterfilling:
- $w_1 = w_2$
- 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

- **Upstream Channel Property:** Crosstalk must propagate through full length of disturbers line

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

  Along a column diagonal element has largest magnitude

  \[ |h_{k}^{n,m}| << |h_{k}^{m,m}|, \forall m \neq n \]

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 bound noise enhancement 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 single-user waterfilling!

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*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
  - red = additive white noise + alien crosstalk from two 600m-lines
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-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 $H_k^{-1}$’s by a `**sparser**` matrix? (=partial canceler)

  Given a limited amount of run-time complexity (=canceller 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]
**Signal Coordination: MAC-Partial ZF**

- **Optimal Resource Allocation (power + canceler taps)**

\[
\max_{s_1, \ldots, s_N, b_1, \ldots, b_N} \quad w_1 R_1 + \ldots + w_N R_N
\]
\[
\text{s.t. } \sum_k s_k^n \leq P_n, \forall n
\]

- **Power budget**

\[
\sum_k \sum_m \sum_n c_{k, m}^{n, m} \leq C_{\text{tot}} \quad \left\{ \begin{array}{l}
    n, m = 1 \ldots N \\
    k = 1 \ldots K
\end{array} \right.
\]

- **Canceler tap budget**

\[
b_k^n = \log_2 \left( 1 + \frac{1}{\Gamma} \sum_{m \neq n} \frac{|h_{k, m}^{n, m}|^2 s_k^n}{(1 - c_{k, m}^{n, m})} + \frac{|h_{k, m}^{n, n}|^2 s_k^n}{s_k^m + \sigma_k^n} \right)
\]

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

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

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
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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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ISPLC 2011
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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 \( \lambda^n \)
- Queueing dynamics: \( Q^n(t+1) = (Q^n(t) - R^n(t))^+ + A^n(t+1) \)
Cross-layer optimization

**Stability:** system is stable, iff

\[
\lim_{t \to \infty} \sup_{t} \frac{1}{t} \sum_{\tau=0}^{t} E \left[ \sum_{n \in \mathbb{N}} Q_n^\tau(n) \right] < \infty
\]

**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 \( R^*(t) \) where

\[
R^*(t) = \arg \max_{R} \sum_{n \in \mathbb{N}} Q_n^\tau(t) R^n
\]

- Achieves throughput optimality
Cross-layer optimization

- Joint scheduling and DSM

  - At time slot $t$, schedule transmit powers/canceler taps where
    
    $$ R^* (t) = \arg \max_R \sum_{n \in N} Q^n (t) R^n $$

  - Weights $w_n = \text{queue lengths } Q^n(t)$
  - 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…

Tsiavlis 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**
  - 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**
  - 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

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