Forschungszentrum Telekommunikation Wien
[Telecommunications Research Center Vienna]

On the Road to GreenDSL

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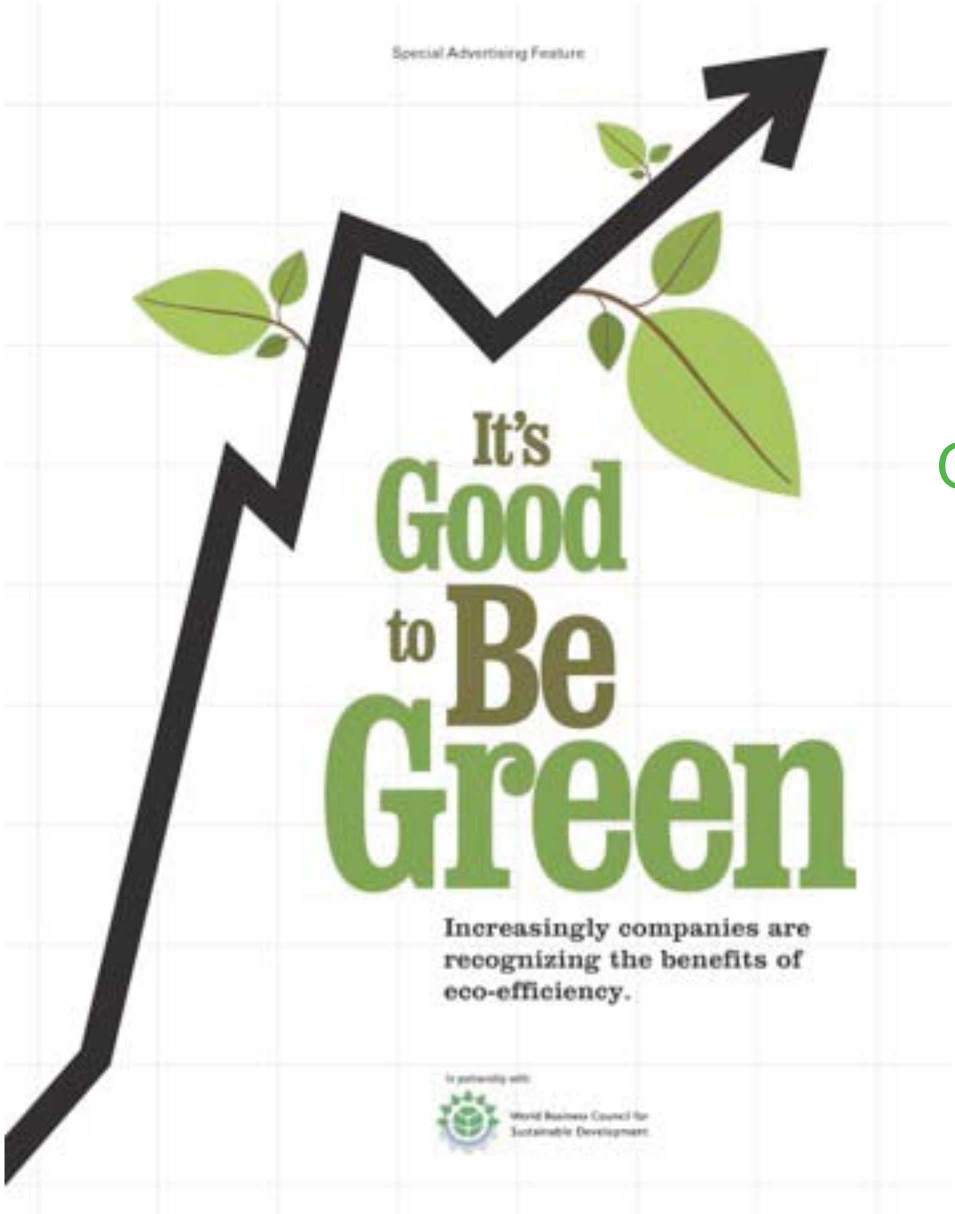
FIT-IT [GreenDSL

Outline

- Why Green DSL?
- DSL basics
- GreenDSL Technologies
  - System Level Optimization (top-down)
  - Communication Algorithms
  - Module Optimization (buttom-up)
- Conclusions and a look on the Road Ahead

WHY GreenDSL?

ftw Creating Communication Technologies



End Users

Feel Good

Government

CO_2 reduction goals
Code of conduct
Research grants

Operators

OPEX
Company Profile
Allow for remote deployment

System Manufacturers

Allow for higher densities
Allow for remote deployment

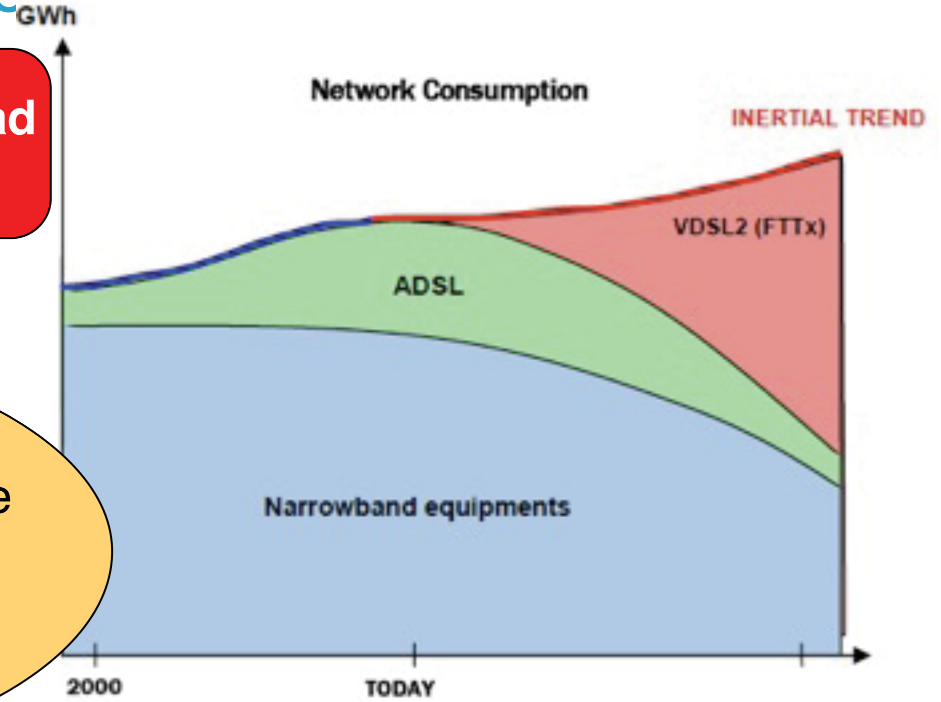
COMET

DSL and Energy

Today, the energy needed by the Telecom Italia's Network is more than 2.000.000.000.000Wh (>2TWh) representing nearly 1% of the total National energy demand, second user only to the National Railways

Trend of Energy Consumption of the Telecommunications Network

…if not modified, the present trend will lead to a boost on the consumption



- Increased OPEX

the cost of energy is constantly increasing (it more than doubled in the last five years), being a sufficient reason itself to **push for strong reduction measures**.

- Strong negative impact on eco sustainability

the requests from EC, Governments and stakeholders on environmental protection and sustainable development **add extra urgency** on such actions

Code of Conduct (CoC) Background

- European Commission
- Directorate-General Joint Research Center
- Institute for the Environment and Sustainability
- Renewable Energies Unit
  - Agreement on stand-by power of electrical equipment (1997)
  - CoC for External Power Supplies and for Digital TV Services (1999)
  - CoC on Efficiency of External Power Supplies (2003)
  - CoC for Digital TV Services (2004)
  - **CoC on Energy Consumption of Broadband Communication Equipment** (2006)
  - CoC on AC Uninterruptible Power Systems (2006)
  - CoC for Data Centres (Draft 2007)
  -

CoC on Energy Consumption of Broadband Communication Equipment

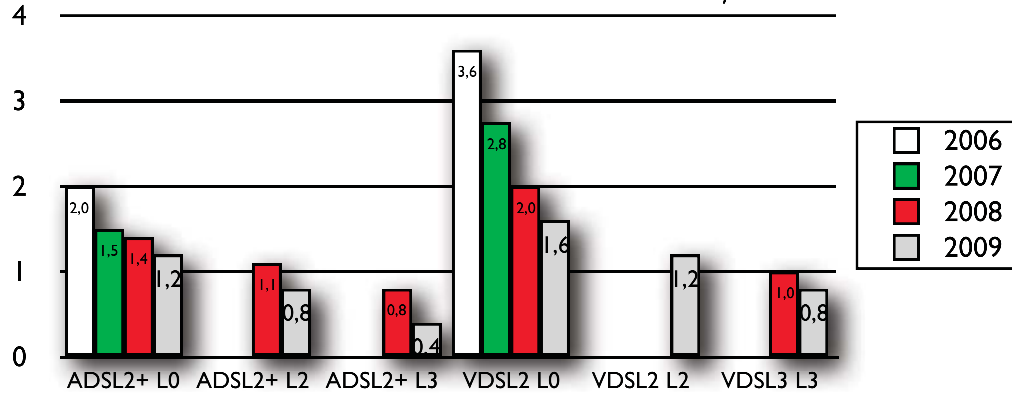
- The CoC is a voluntary base initiative and is aiming "**To target reduced energy consumption of broadband communication equipment without hampering the fast technological developments and the service provided**"
- It was first issued in July 2006, with a second version July 2007, a third November 2008.
- It is aiming to both Network and Customer equipments, requiring power reduction and adoption of power management (Low Power Modes L2/L3) for new systems (ADSL2+/VDSL2)

CoC Power Targets

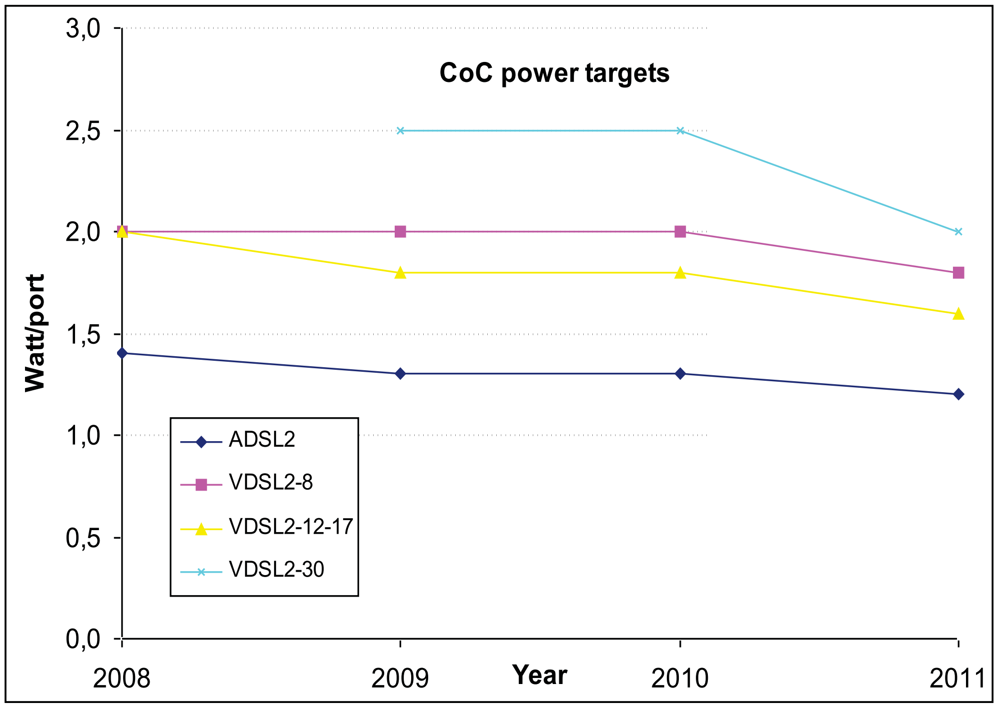
- The power targets are challenging
- In CoC version 2.0 almost too challenging!

CoC BB Equipment power targets for ADSL2+ and VDSL2 [W/port]

At The Network Side, ***CoC version 2.0***



At The Network Side, ***CoC version 3.0***

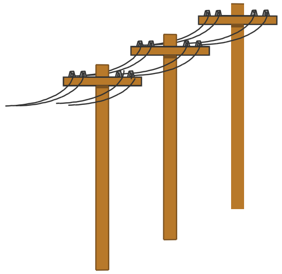


- The CoC version 3.0 targets are "more realistic"
- But still the 2011 goals will imply a complete redesign of xDSL chips and systems
- The development of "power management" mechanisms will need analysis and new proposal
- The potential benefit is huge and can justify the big investments needed to study, develop and to test such systems

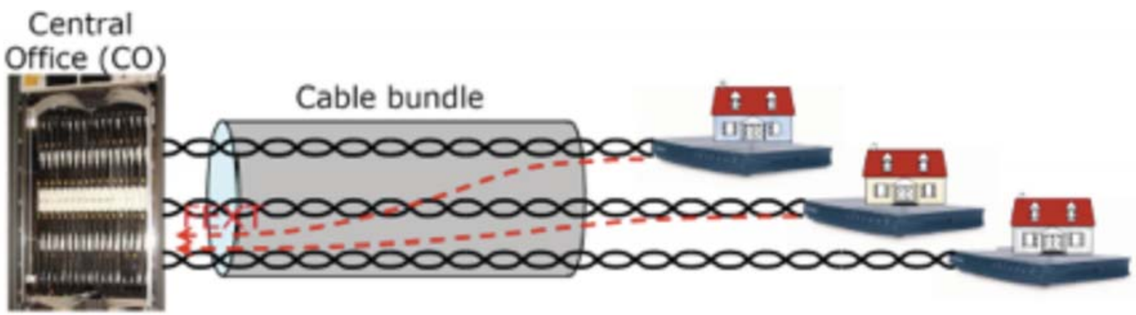
The following companies have signed the Code of Conduct:

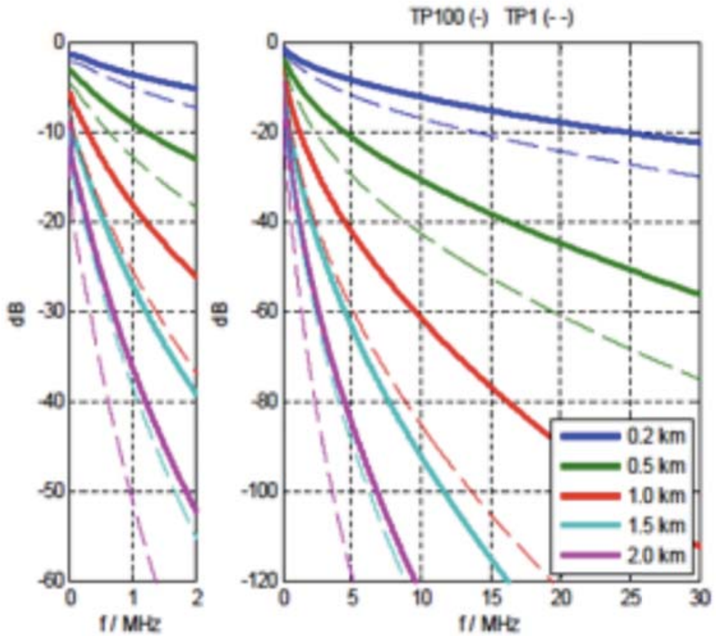
- Deutsche Telekom AG
- HUAWEI Technologies CO., LTD
- Swisscom
- Telecom Italia
- Telia Sonera
- TDC Services
- Thomson
- Alcatel-Lucent

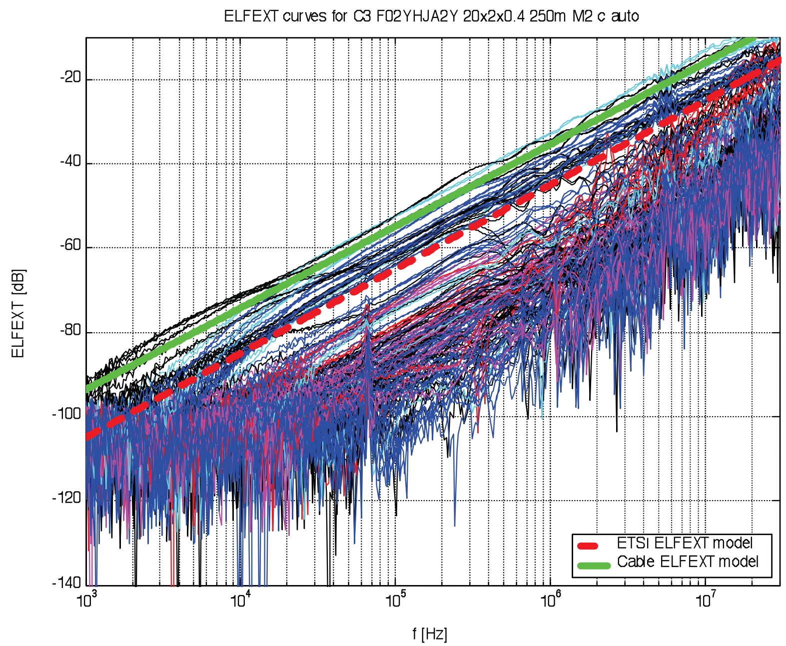
DSL Basics - Channel



- Frequency Selective
- Crosstalk limited
- Large SNR





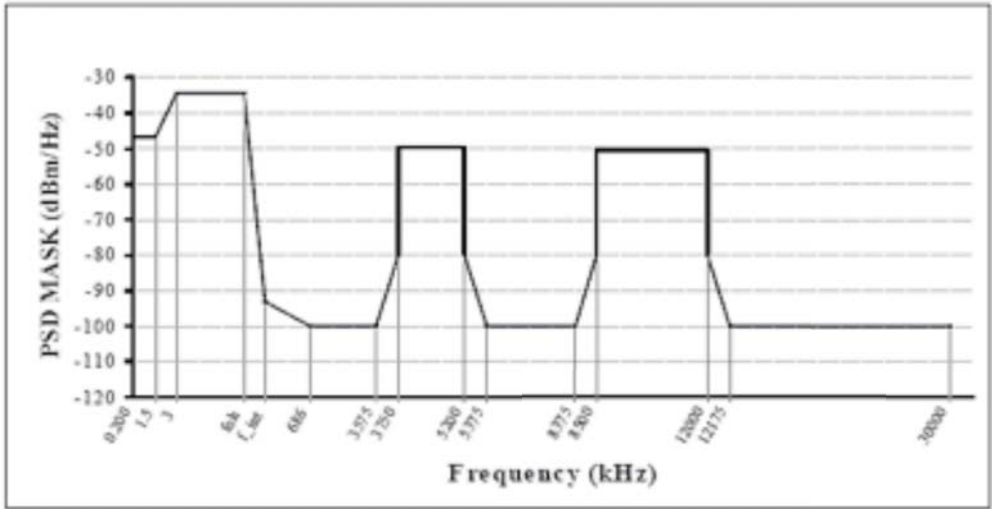


DSL Basics - Spectrum Management

- Avoiding near-end crosstalk (NEXT) by using frequency division multiplex. Thus upstream and downstream uses different frequencies.
- ADSL uses only one (small) upstream band and one (large) downstream band, up to 1.1-2.2 MHz
- VDSL has 2-4 bands in each direction, up to 30 MHz
- To avoid RFI egress can notches be applied to bands with long and medium wave radio amateurs.

- => Complex Spectra

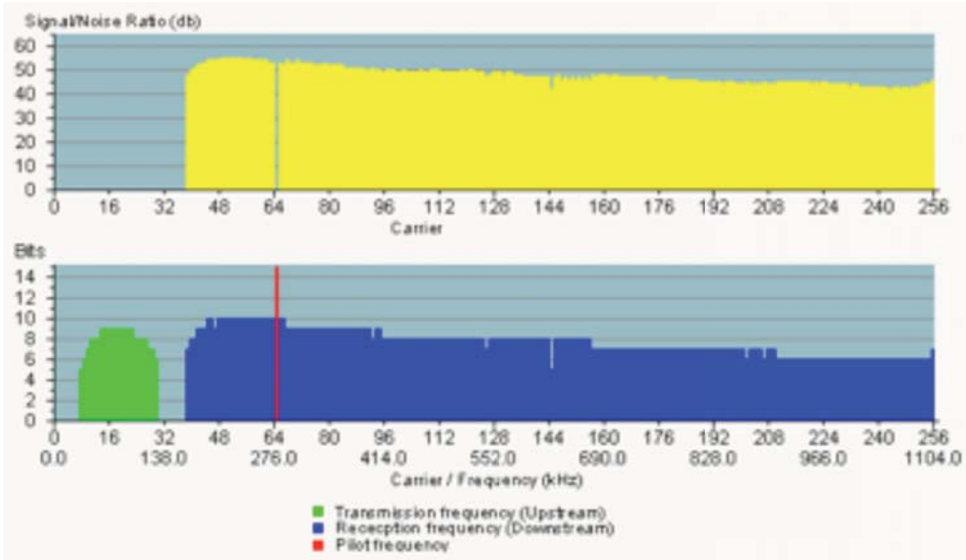
- Various profiles
- Max P of all profiles = 110mW
- Max f of all profiles 30MHz



DSL Basics - Transmission Technology

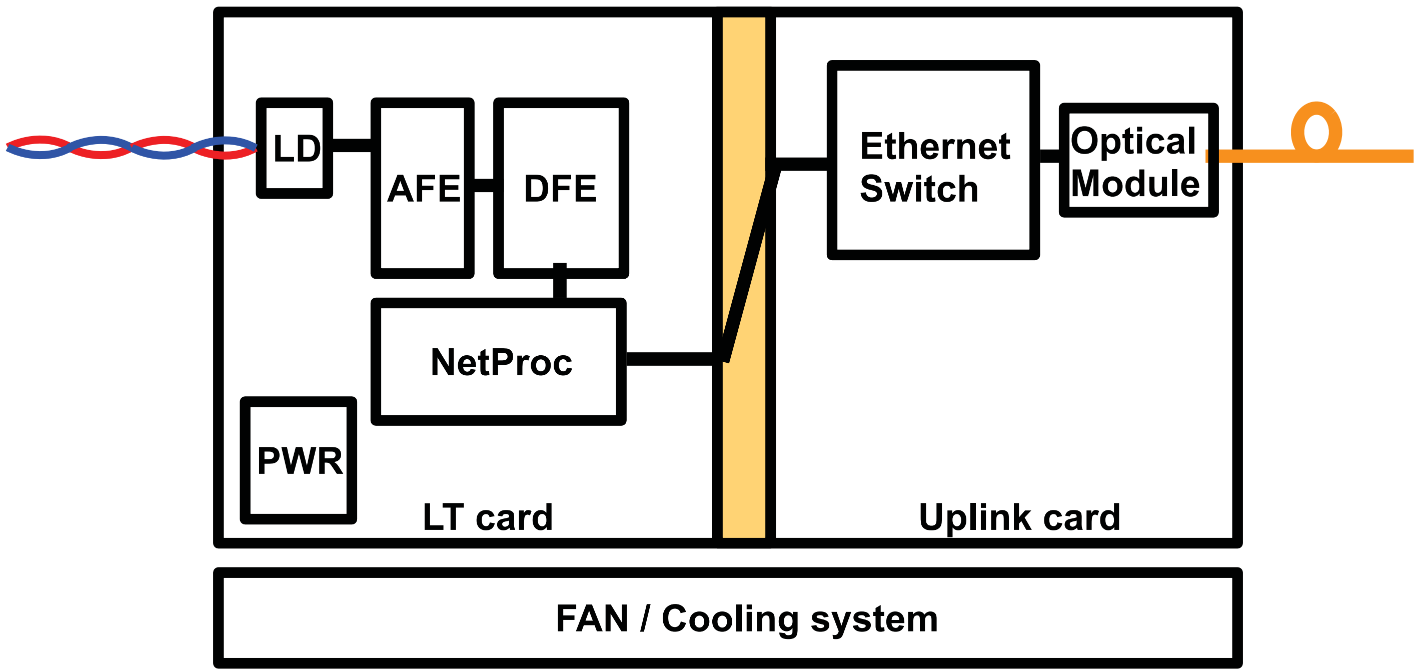
- With complex Spectra the natural choice is a multi-carrier technology (used for ADSL1/2/2+ & VDSL2)
- We call it Discrete Multi-Tone (DMT) ≈ OFDM but
  - in baseband transmission
  - uses bit-loading/waterfilling
- With SNR up to 55-60 dB we can use up to QAM-32768 (15bits)!

- ADSL 32 + 256/512 carriers
- VDSL up to 4096 carriers
  (potentially with the same HW)



DSL System

- Digital Subscriber Line Access multiplexer
- DSLAMs aggregates DSL lines (using ATM or IP) and connects them to a high-speed Internet backbone



Comparing Wireless and Wired Systems

Wireless

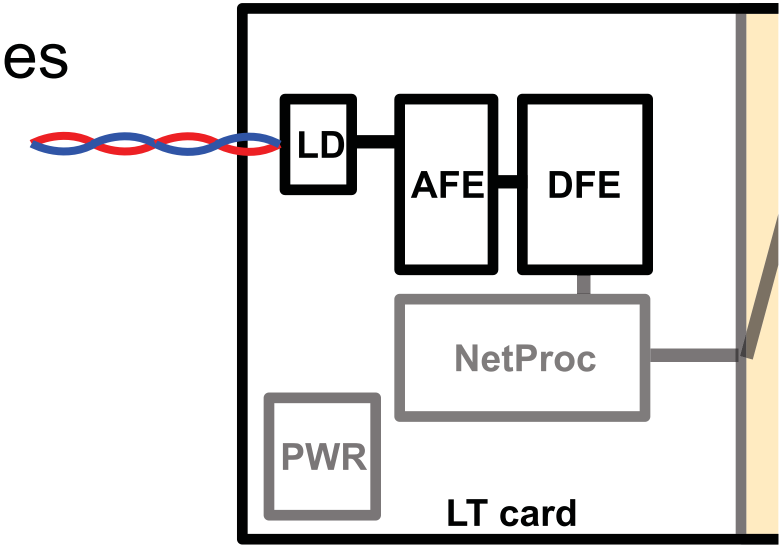
- High output power
- Single profile
- Medium SNR demand
  - Linearity important
  - Some clipping acceptable
  - Focus on out of band noise
- PA largest part of transceiver energy consumption

Wired

- Low output power
- Multiple profiles
- High SNR demand
  - High linearity critical
  - No clipping allowed
  - Focus on in-band noise
  - Need for low-noise component
- PA maybe a 1/3 of transceiver energy consumption

Making DSL Green

- Energy efficient DSL hardware modules
  - Line Driver (LD) / Power Amplifier (PA)
  - Analog Front End (AFE)
  - Digital Front End (DFE)
- Energy efficient (EE) DSL algorithms
  - EE Spectrum Management
  - Vectoring (Multi-user signal processing)
  - Cross-layer optimization
    - Low-power modes
    - Spectrum scheduling over time
    - Rapid PHY/Profile switching (e.g. using VDSL2 profiles with lower power demand)

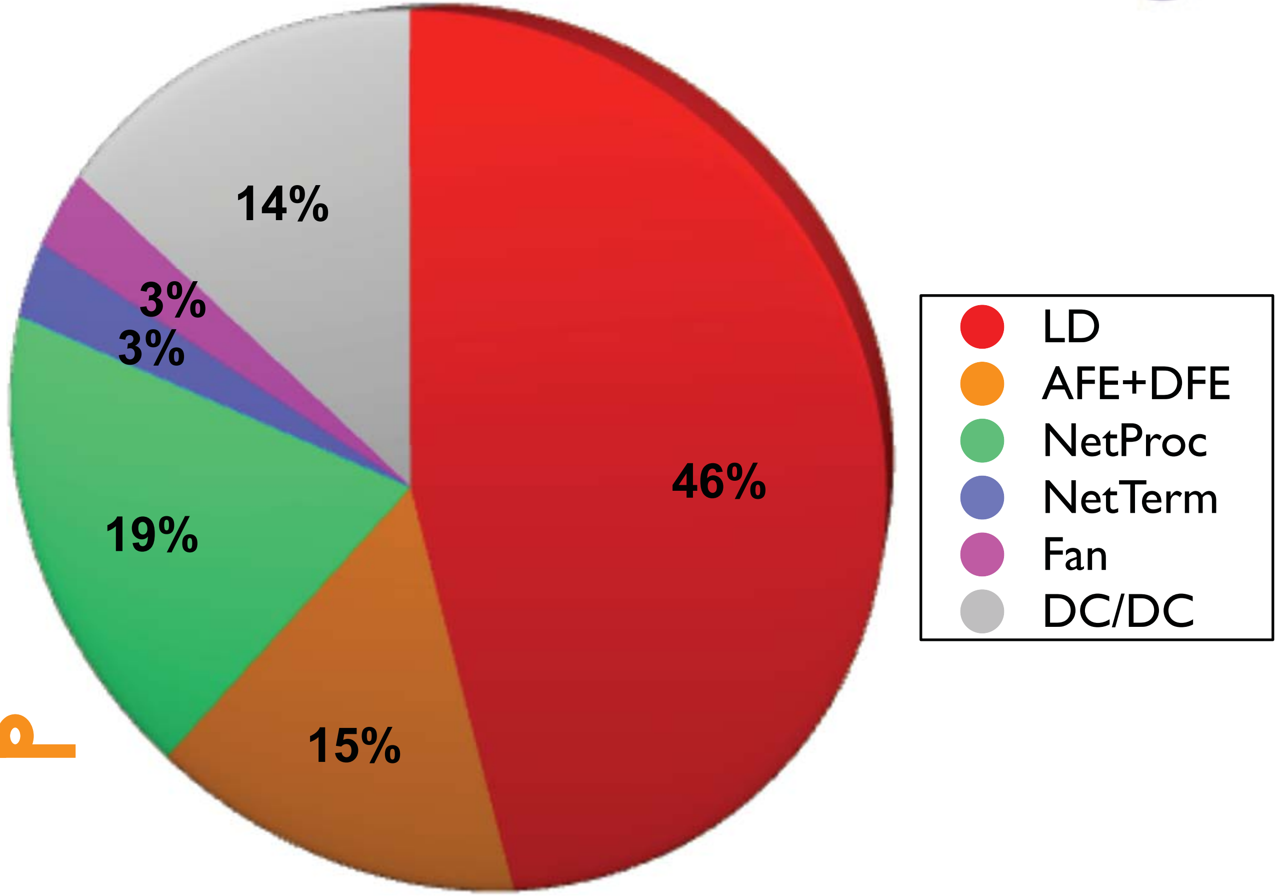


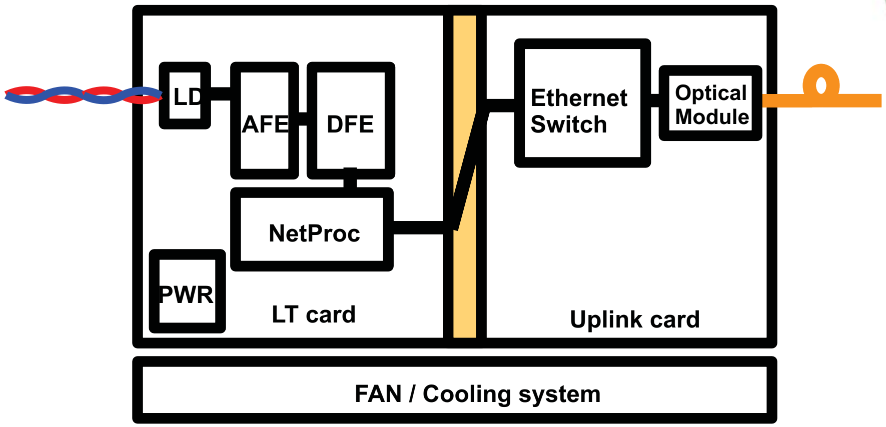
Making DSL Green

- Other system components
  - AC/DC and DC/DC conversion
  - Cooling
- Energy Management
  - Energy Aware Design and Improvement Process
  - Monitoring, Metering, Visualization, Managing
- Energy Aware Applications
  - Get rid of keep-alive traffic
- Network Optimization
  - Remote deployment

Where is the Energy Used?

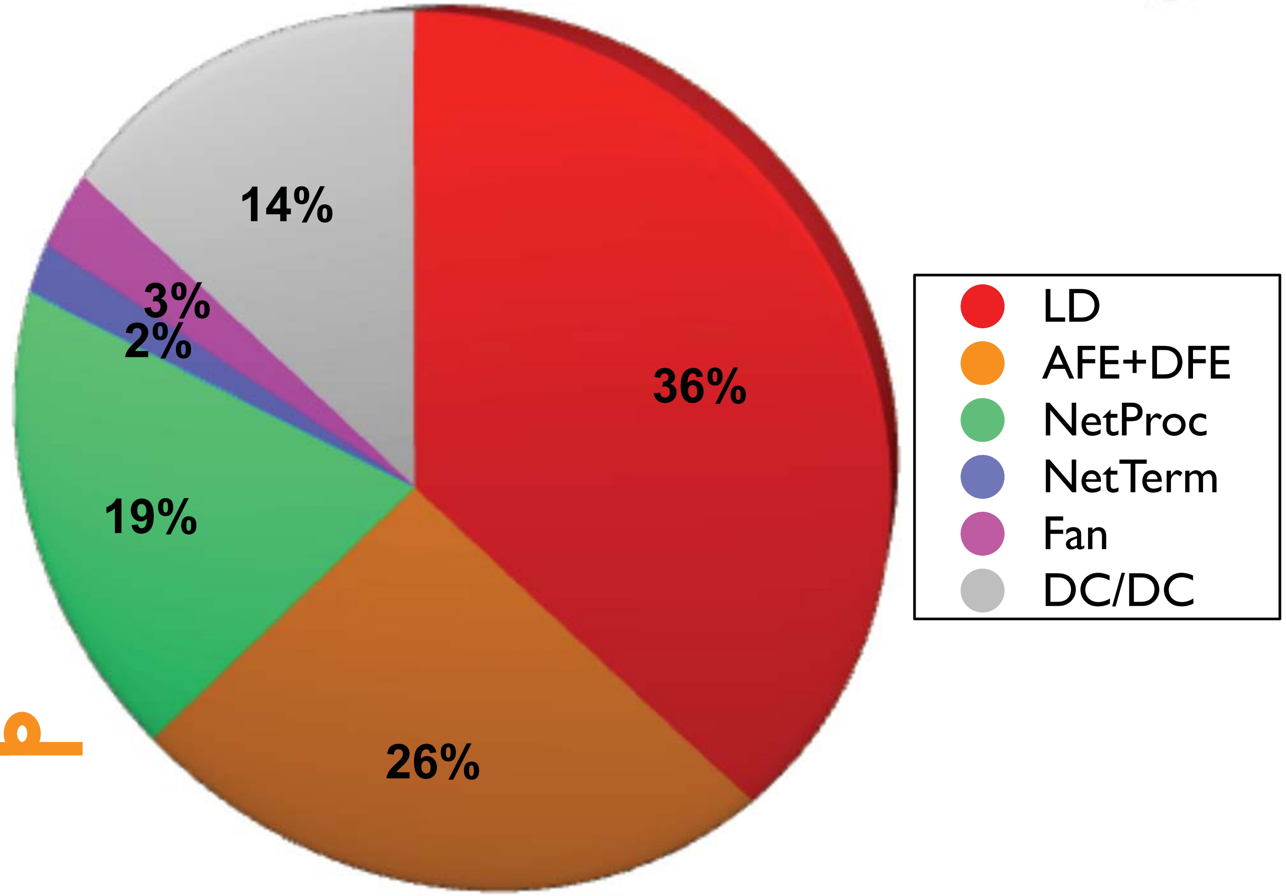
- ADSL2+ IP DSLAM Power Decomposition

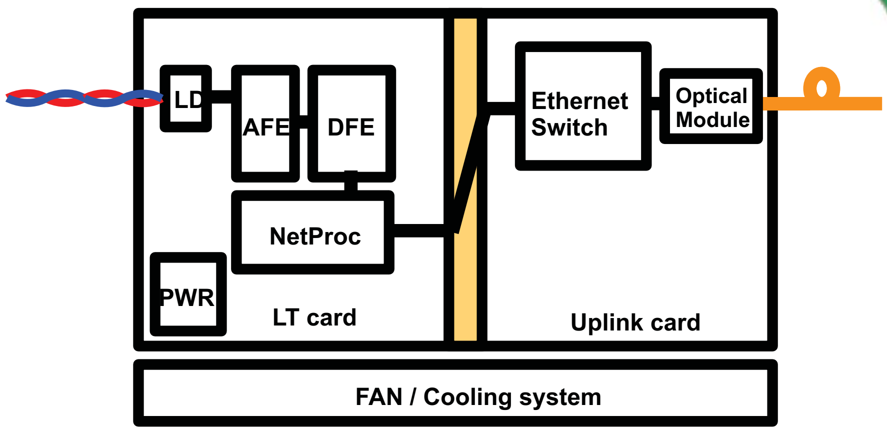




Where is the Energy Used?

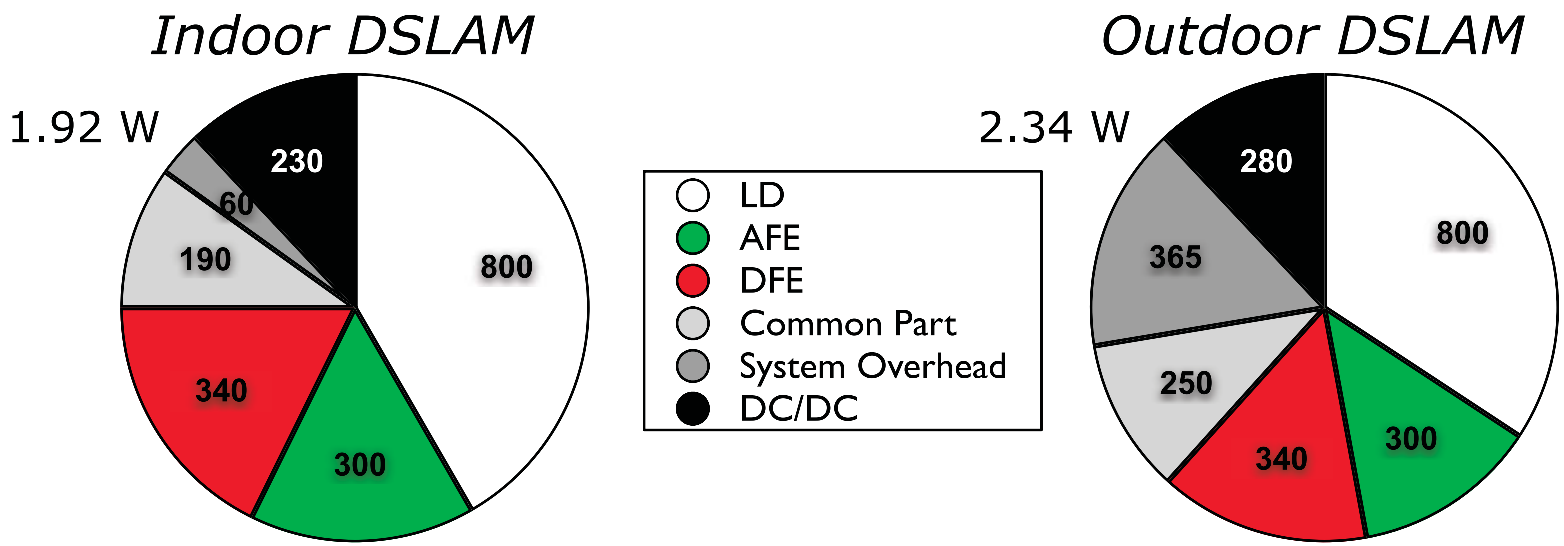
- VDSL2 IP DSLAM Power Decomposition





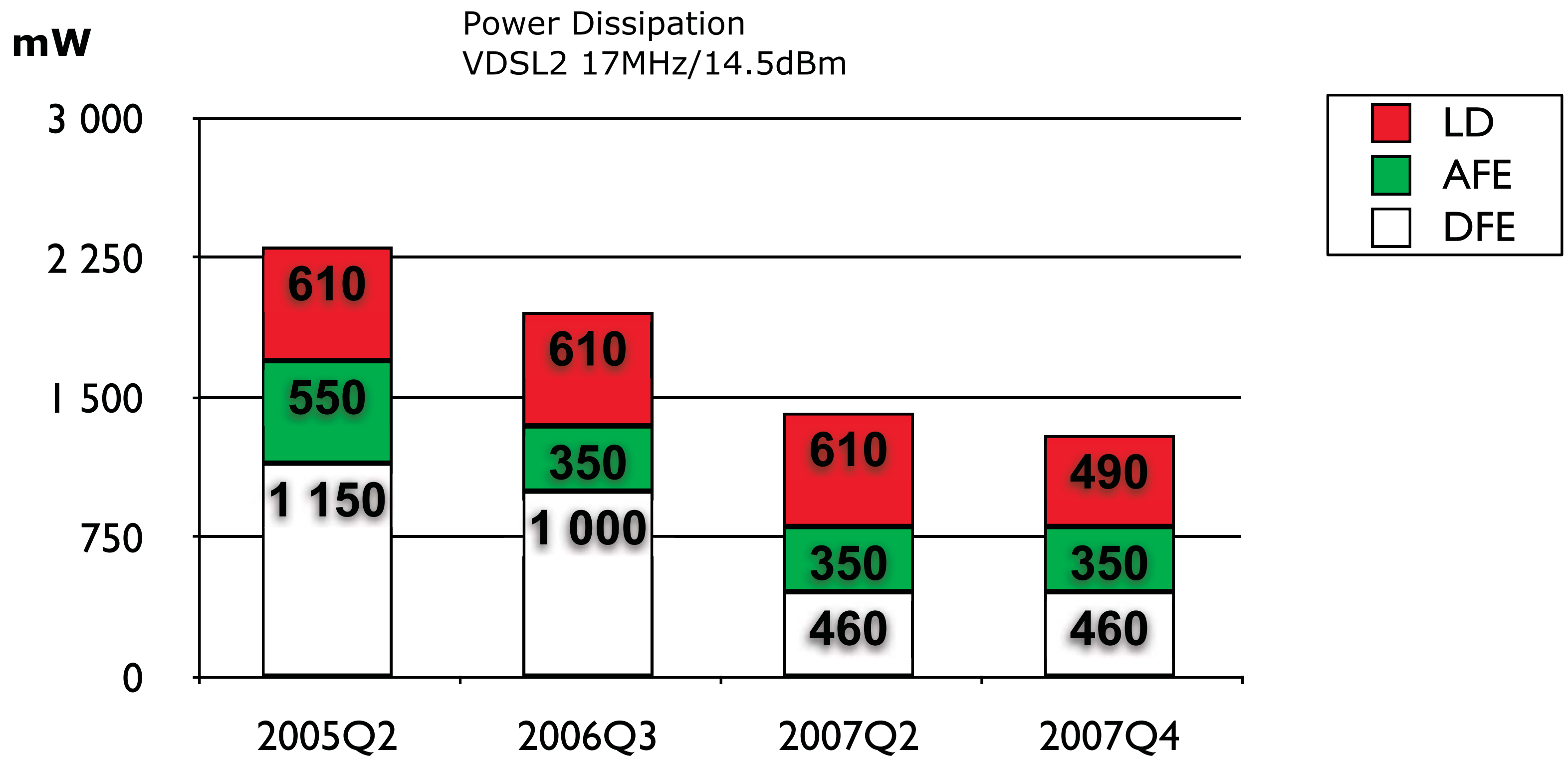
System Level Power Consumption

- Best of 2008 VDSL2 chip set used 1.44 W (the 8b profile, 8.8MHz/20.5dBm, being the worst)
- But the system will have additional losses like: DC/DC conversion losses, controllers and network processors, active splitters, ...



Power Consumption in DSL Modules

- There have already been a lot done to reduce power consumption



What can still to be improved?

Studied in our FIT-IT Project:

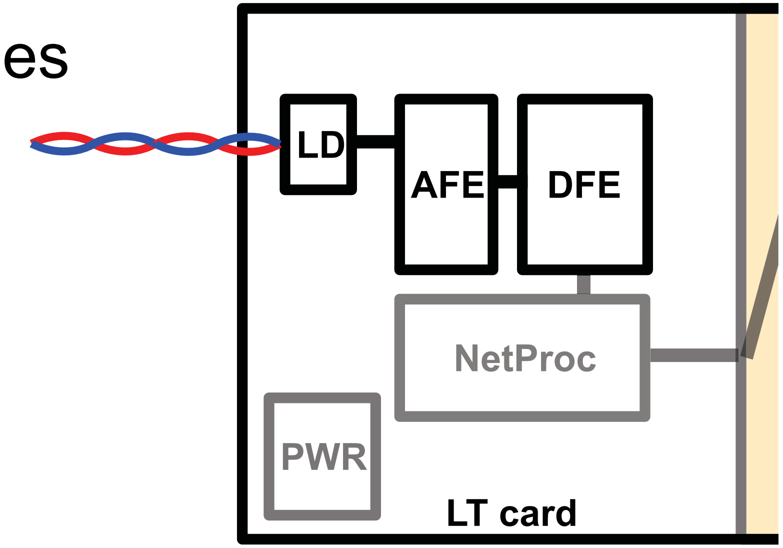
Global Resource and Energy Efficiency for Next-Generation DSL

GreenDSL

- Call: Embedded Systems
- Partners: Lantiq (former Infineon) & FTW
- Volume: 2 Years, 117 PM, 1.26 MEUR
- Start Date: April 2009
- Research Topic
  - Energy-Efficient Cross-layer Design
  - Rate and Power Adaptive Signal Generation
  - Energy-Efficient Building Blocks (e.g. AFE & LD Design)

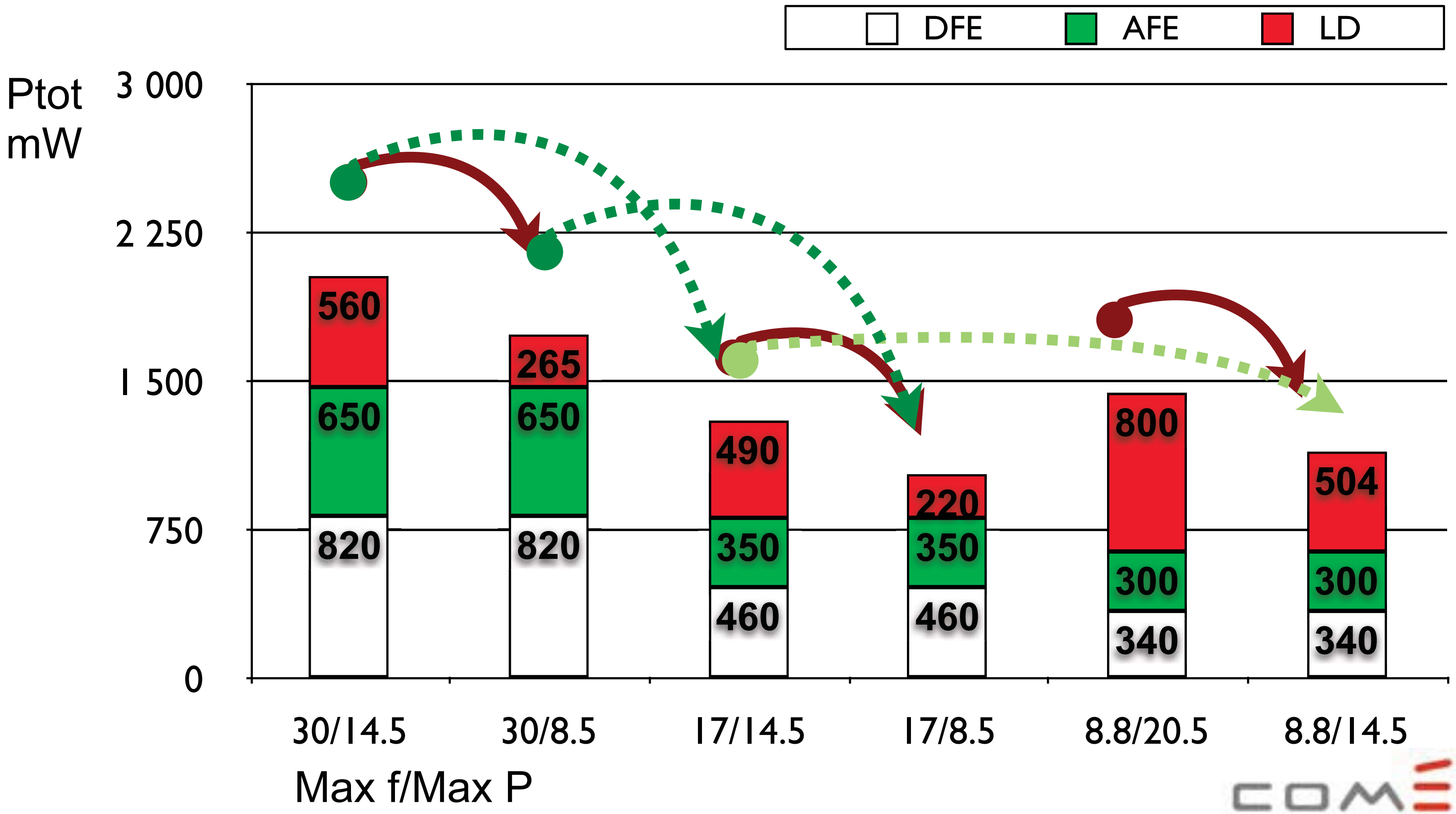
GreenDSL HW

- Energy efficient DSL hardware modules
  - Line Driver (LD) / Power Amplifier (PA)
  - Analog Front End (AFE)
  - Digital Front End (DFE)



Quick Analysis of Influences

- Current VDSL2 Generation



What Influences Chip-level Power Consumption?

- **LD** power consumption depends on
  line output power
- **AFE** power consumption depends on
  sampling rate (thus max frequency used by profile)
- **DFE** power consumption depends on
  FFT size (thus max frequency used by profile)
- **System overhead** power loss depends on
  number of ports per system (cf. indoor vs. outdoor)
- **DC/DC** power loss depends on
  used power (if correctly designed/tuned)

Optimizing for Energy Efficiency

Digital Front-End Processing

- Target: develop digital signal processing architectures that scale in energy depending on utilization
- Issues
  - Multi-core processing
  - Clock-rate vs. sleeping modes
  - Granularity of clock-domains
  - Processing Model (circular processing, event driven, etc)
  - ...
  -

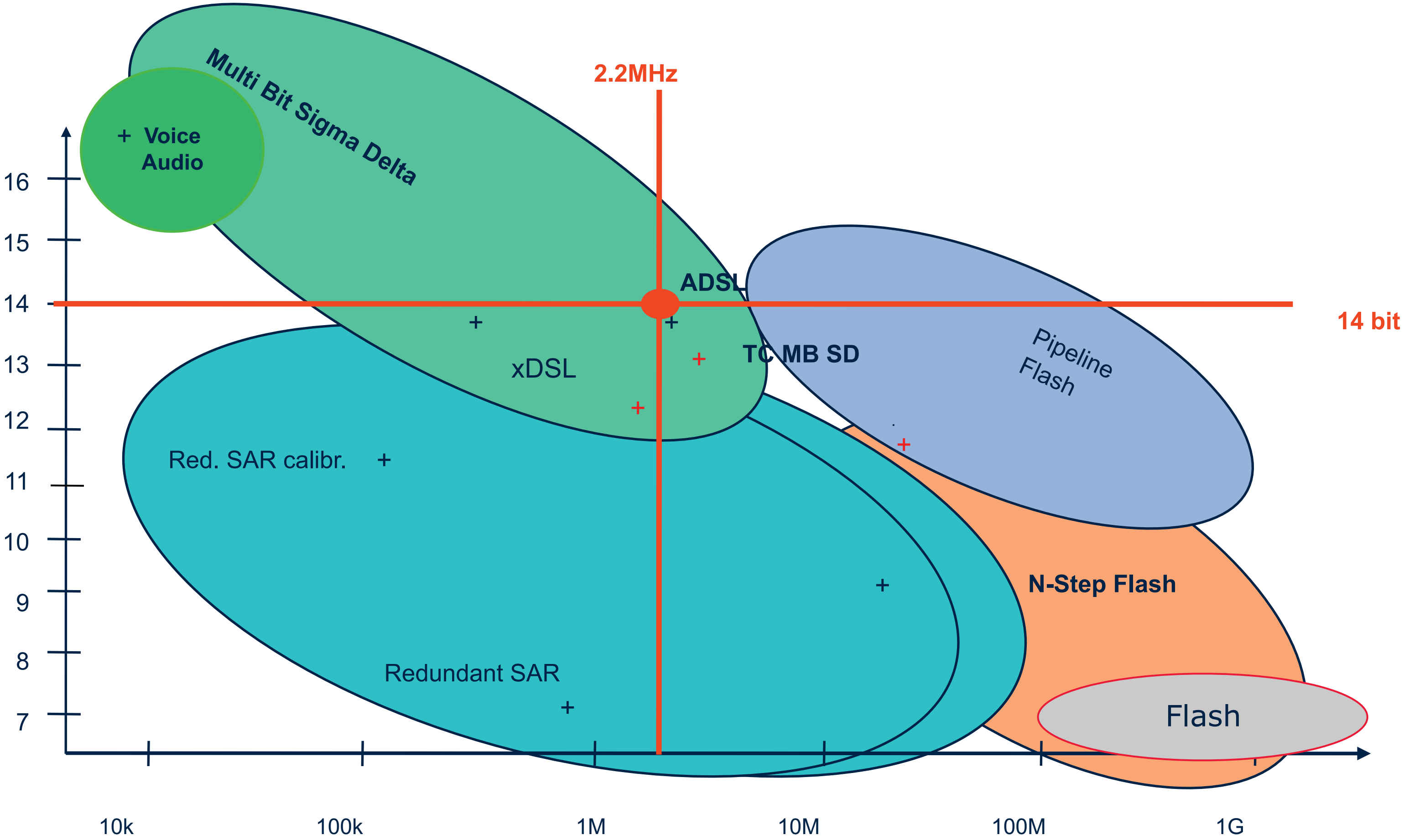
Optimizing for Energy Efficiency

Analog Front-End

- The largest energy consumer in the analog front-end (AFE) is the analog to digital converter (ADC)

AFE - ADC Design Space

- ADSL



ΣΔ Modulator

- Analog level =>
- Pulse intervals

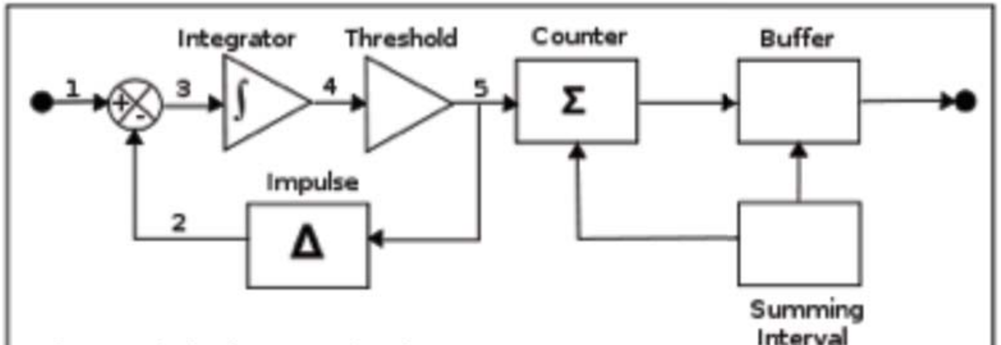
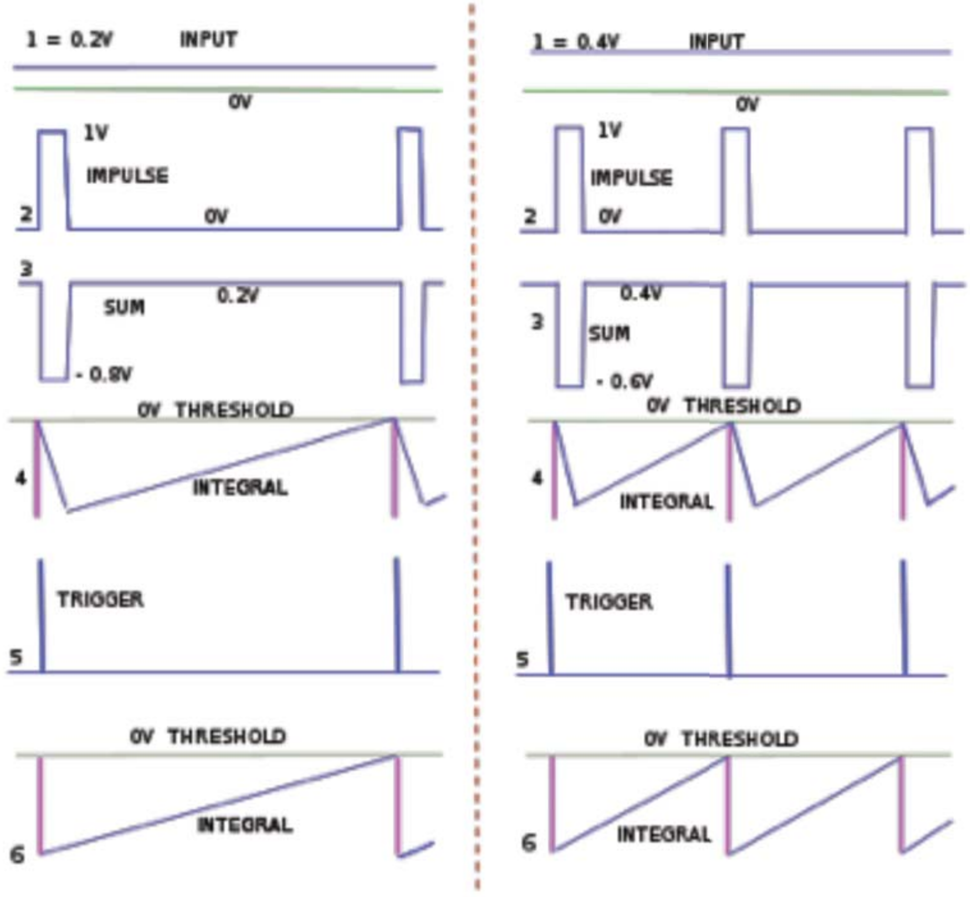
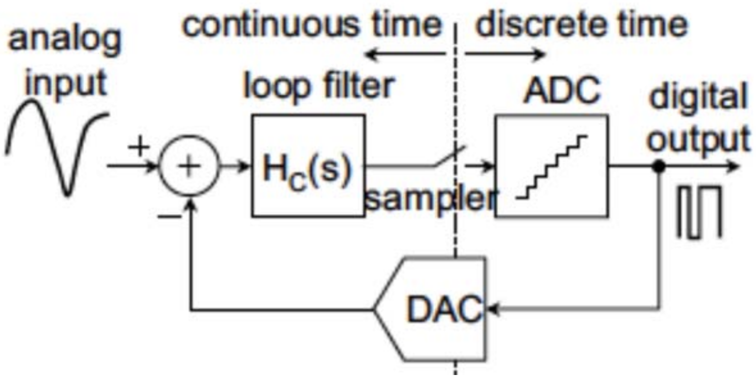


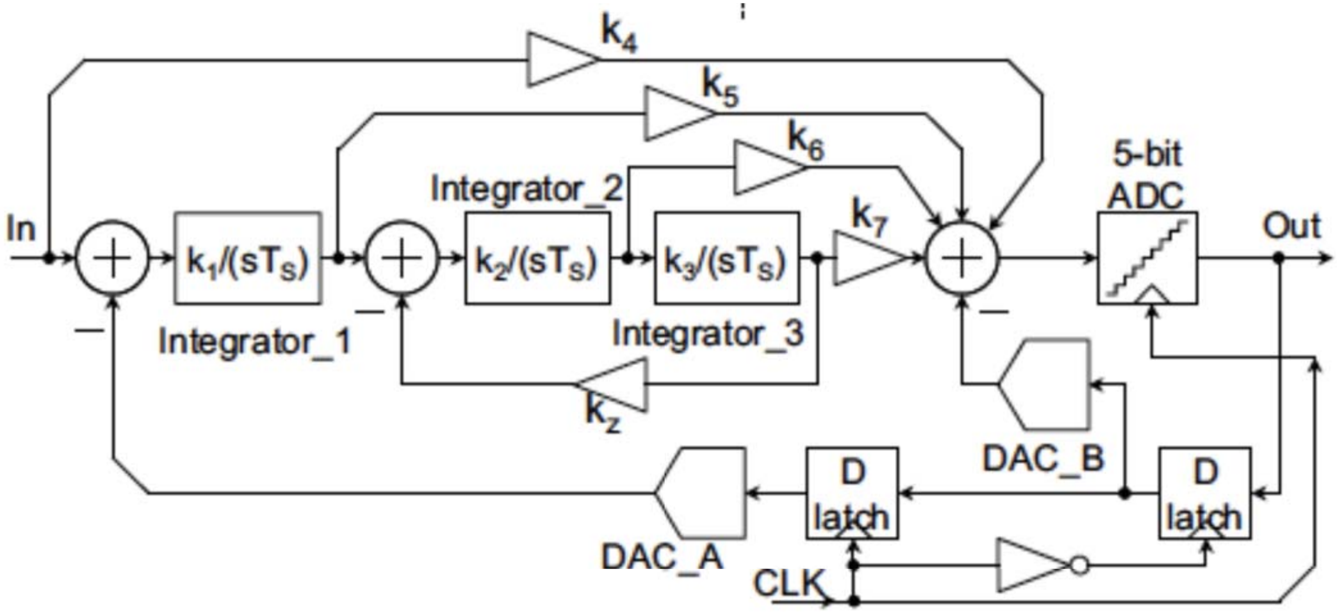
Fig. 1 - Block Diagram Delta Sigma ADC



Typical Waveforms

ADC - Current State-of-the-art for DSL Continuous-Time ΣΔ Modulator

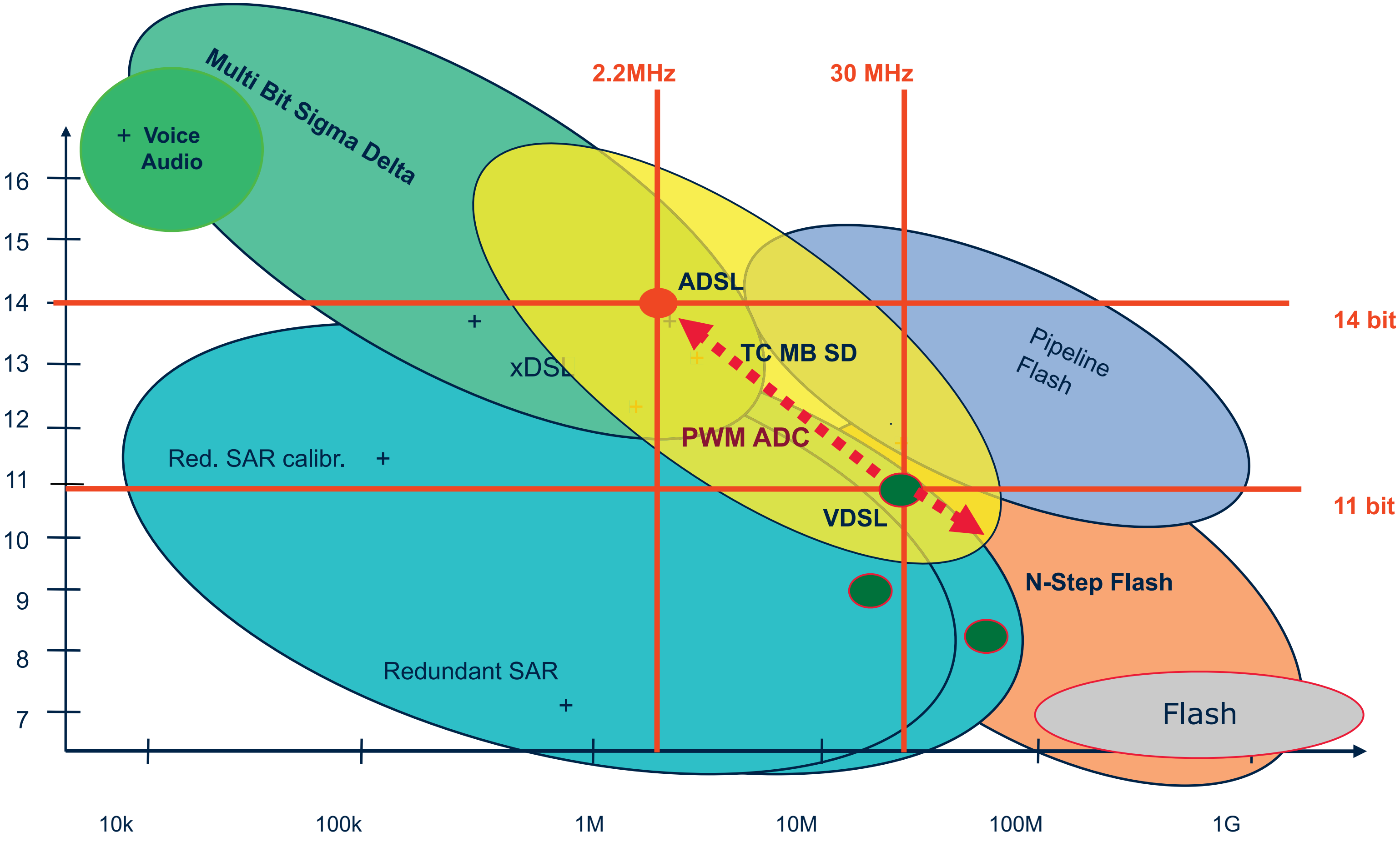




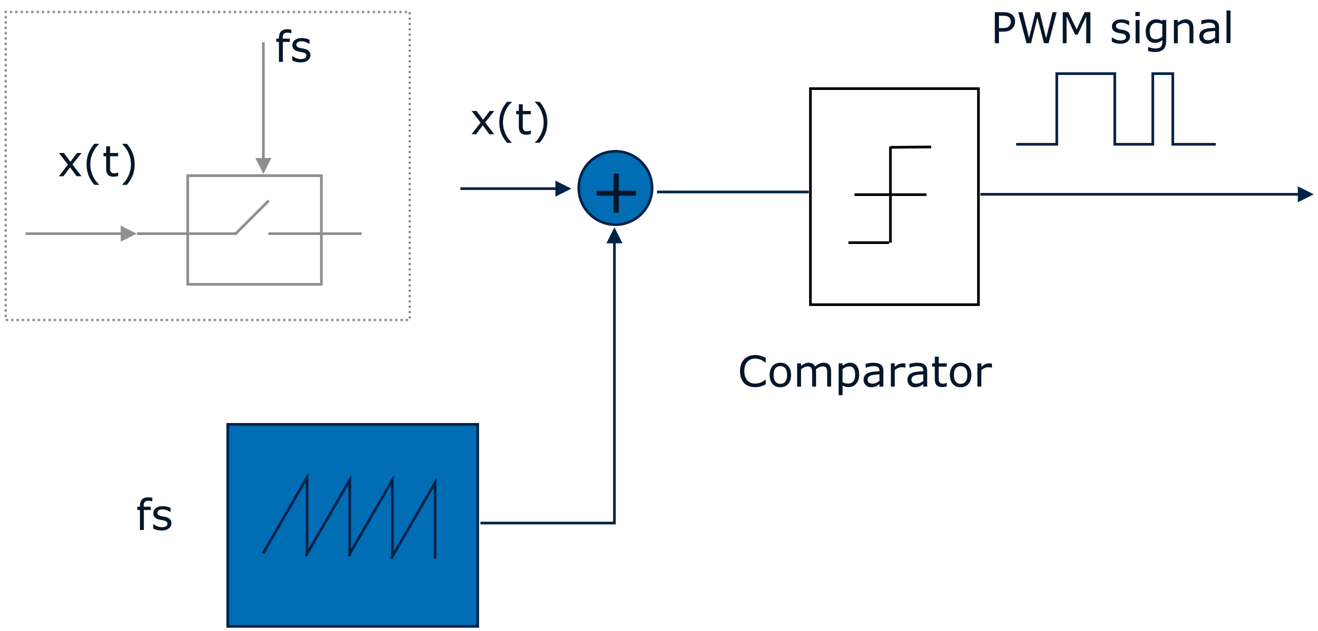
S. Yan and E. Sánchez-Sinencio, "A Continuous-Time ΣΔ Modulator With 88-dB Dynamic Range and 1.1-MHz Signal Bandwidth". *IEEE Journal of Solid-State Circuits*, pp. 75-86, January 2004.

AFE - GreenDSL ADC

- ADSL + *VDSL*



A classical PWM modulator

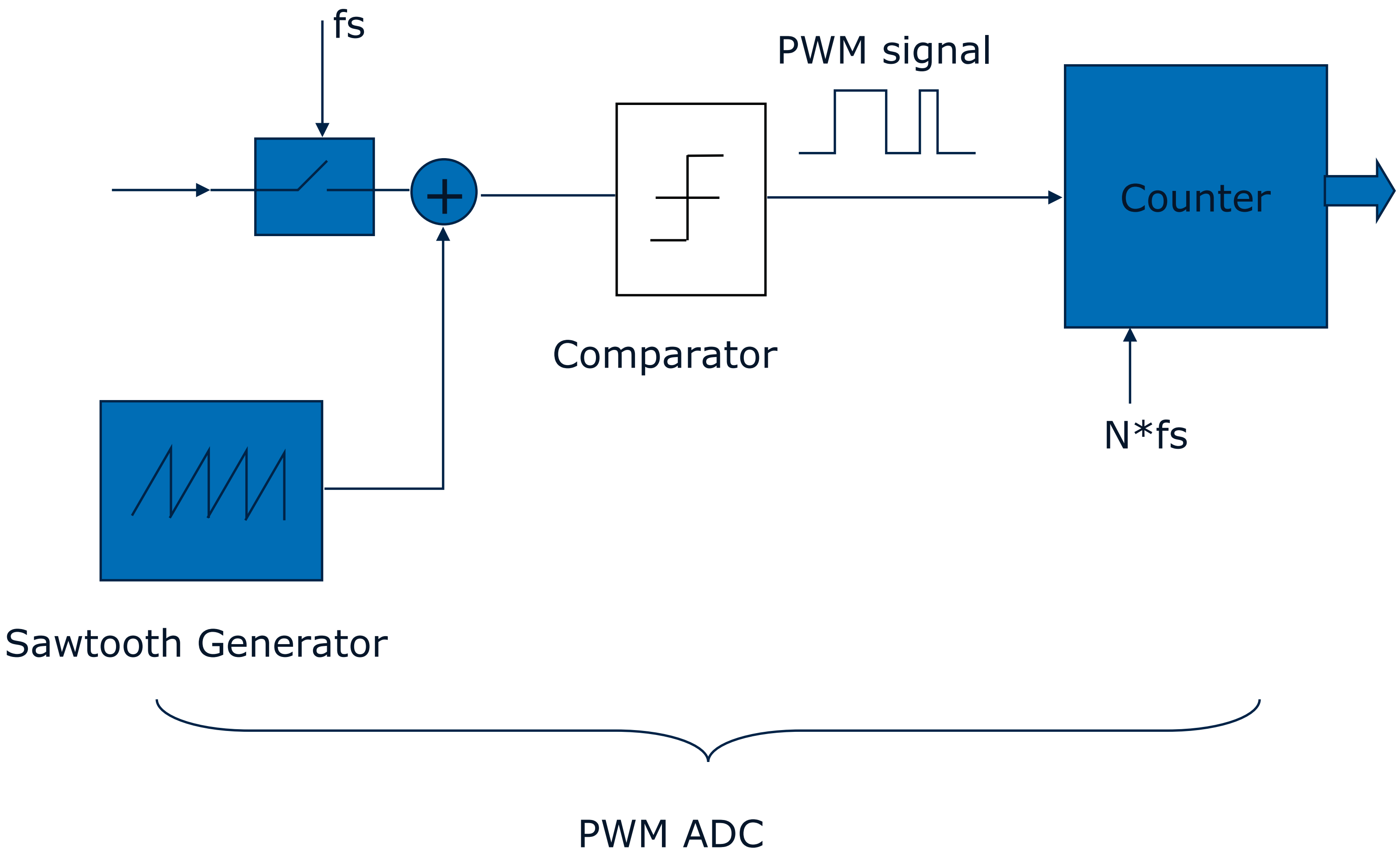


•Continuous time system

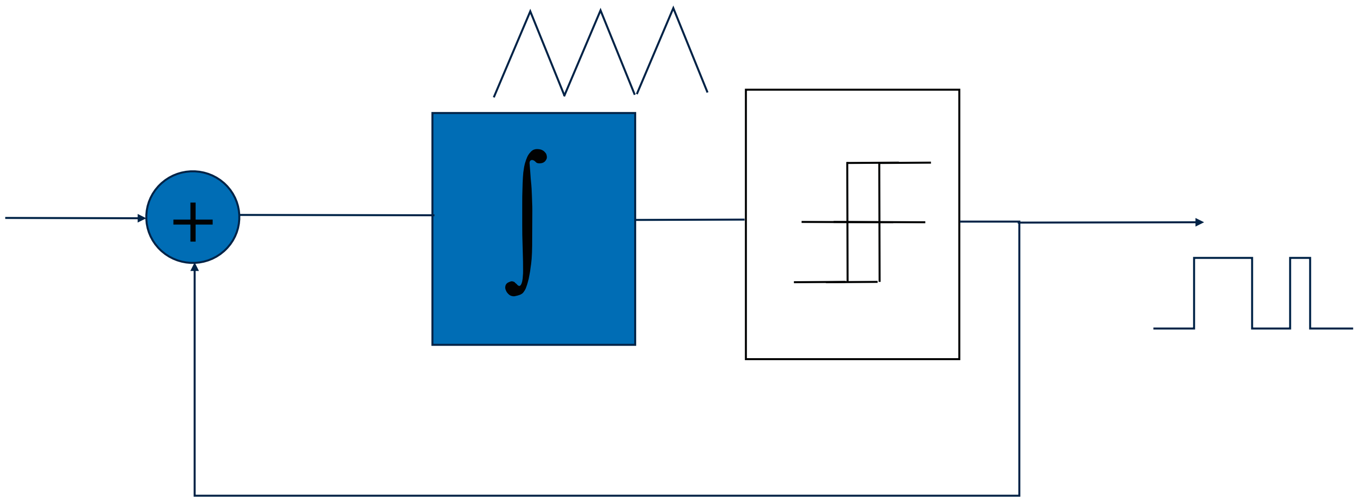
•Requires a linear Sawtooth generator

•Implicit sampling frequency=Sawtooth frequency

ADC with classical PWM modulator

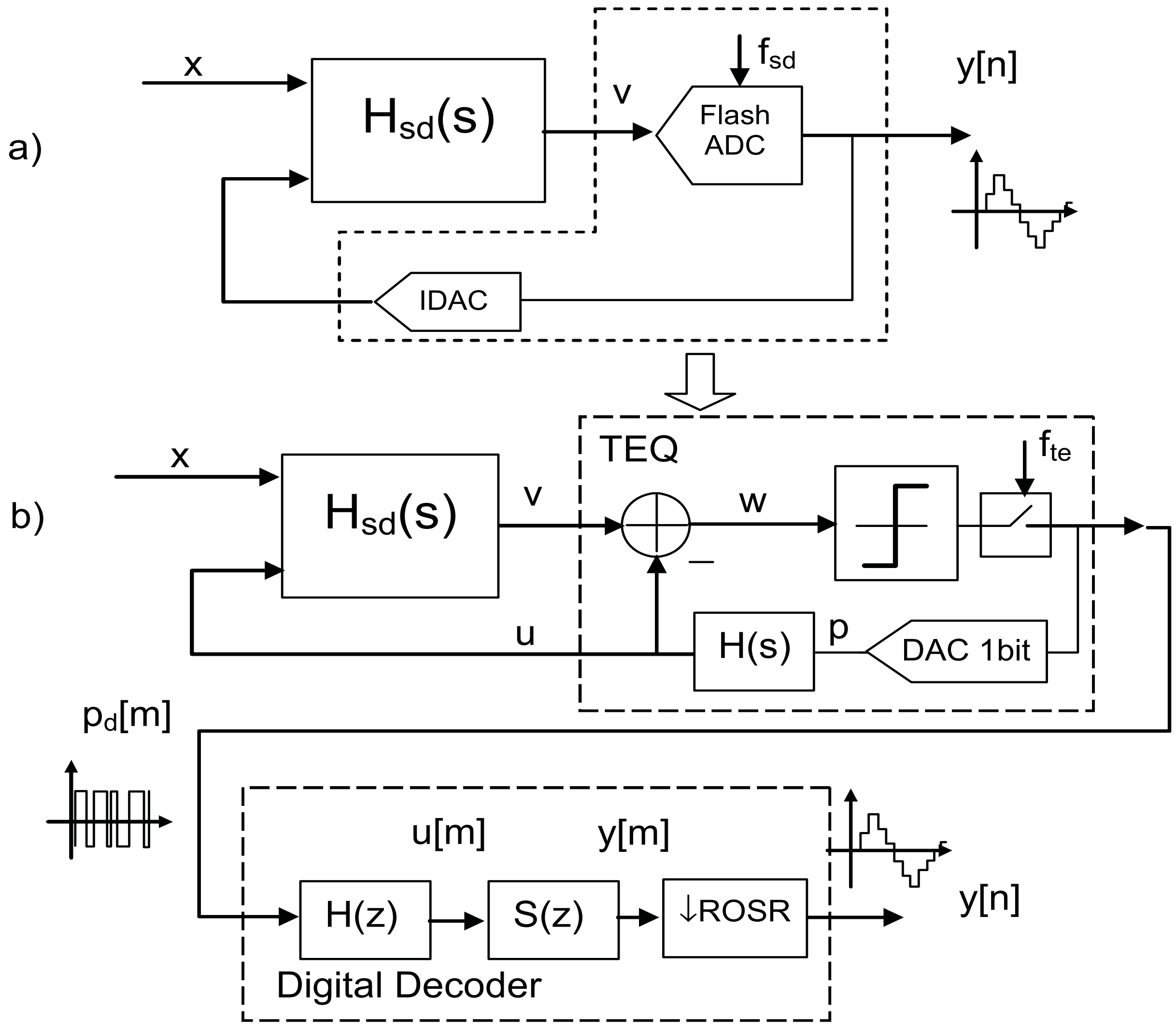


Self oscillating PWM modulator



- Continuous time system
- Limit cycle modulated by the input
- Does not need high linearity Sawtooth waveform
- Can be seen as a non uniform sampler

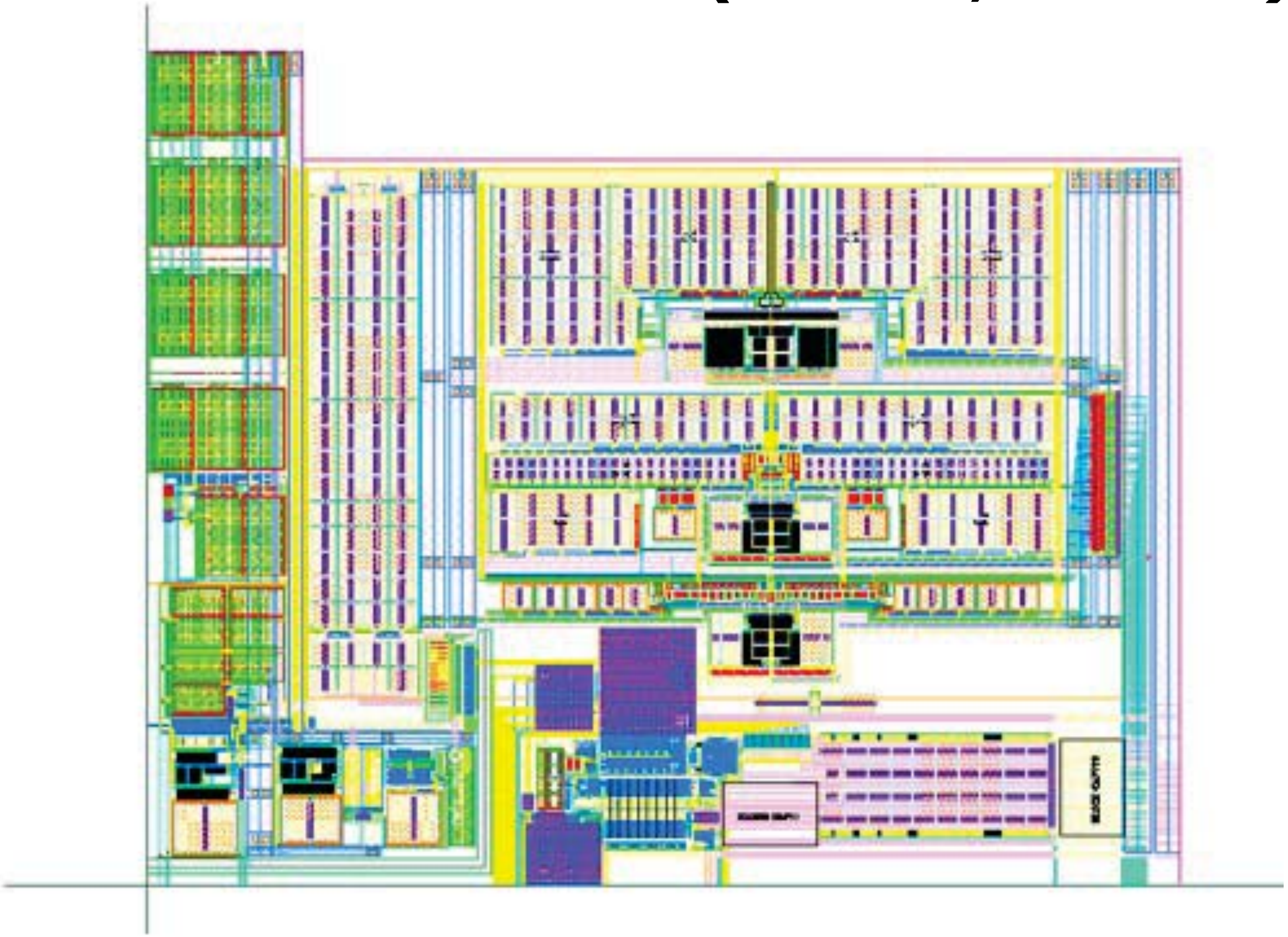
Replacement of the quantizer of a ΣΔM by a Time Encoding Quantizer



Status GreenDSL PWM-ADC (April 2009)

ftw Creating Communication Technologies

- Area incl. REF = **0.2**mm² (**14**% of MASH)
- Power incl. REF = **30**mW (**27**% of MASH)
- FoM = 200fJ / conv. ***(30MHz, 11.5bit)***



COMET

Optimizing for Energy Efficiency

Line Driver/Power Amplifier

- Currently Class-AB is used

GreenDSL Line Driver/Power Amplifier

Switch Mode Amplifier

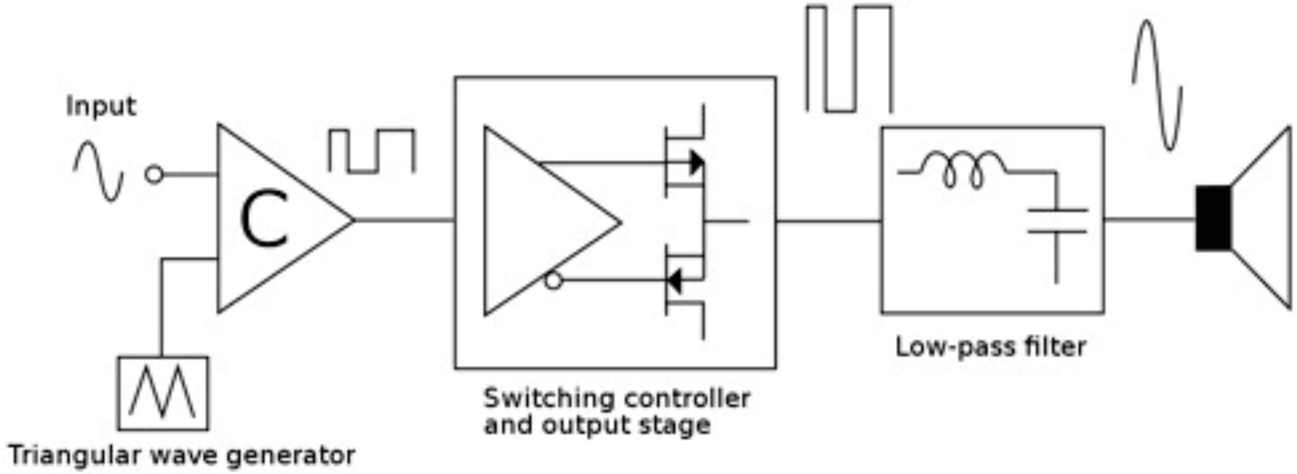
Class D

Switch Rail Amplifier

Class G
Class G single rail
Class H

Class D

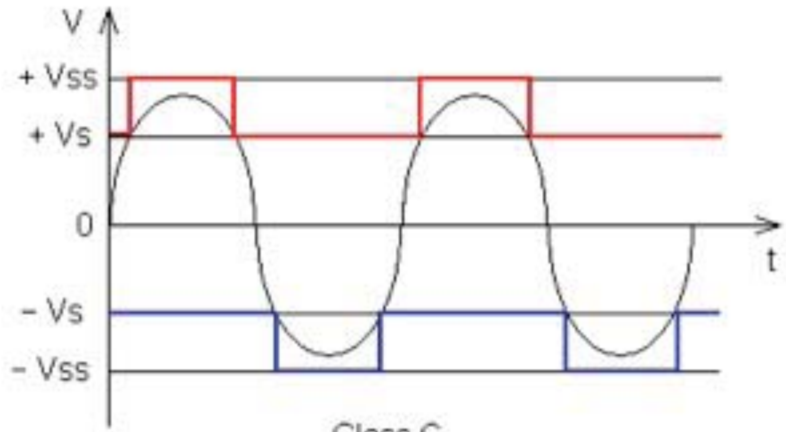
- use PWM modulated signal for switching output stage transistors



- Class-AB P_{diss}= 550 .. 680mW   η=15%
- Class-D P_{diss}= 250 .. 350mW   η=22% .. 38%   (theory 100%)
- higher material compared to Class AB due to required out-of-band filter
- highest efficiency only for Full Power modes

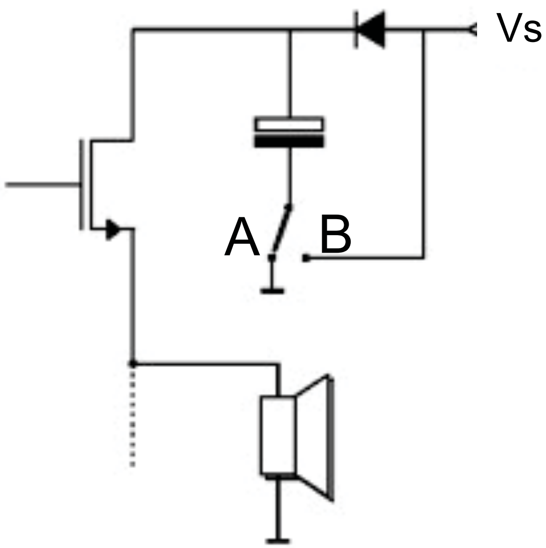
Class G

- Class G: two pairs of external supply voltages for low and high amplitude signals, optimal for high-crest factor signals



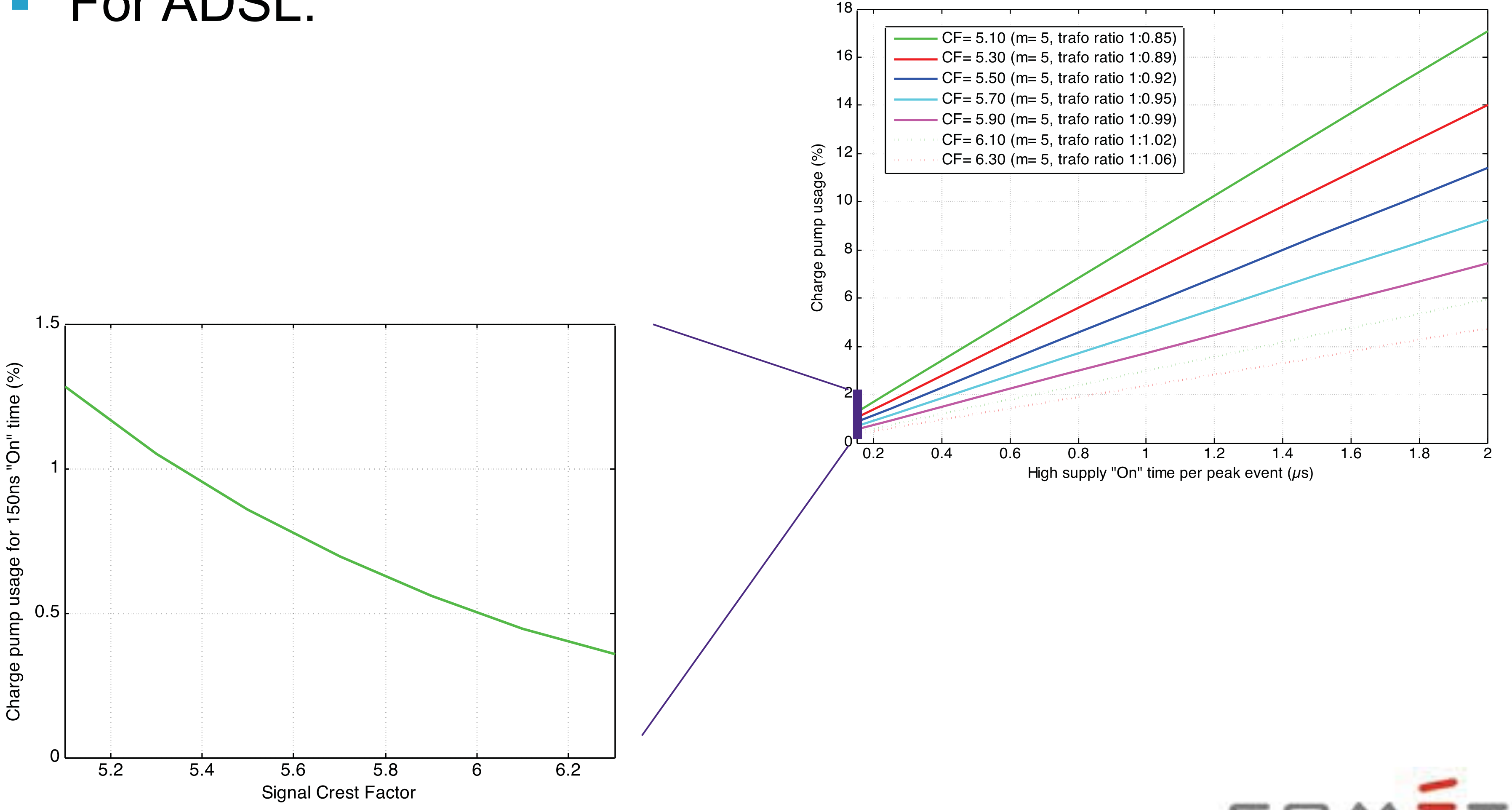
Class G

- Class G *Single rail*: single supply voltage Vs, Vss internally generated using a charge pump



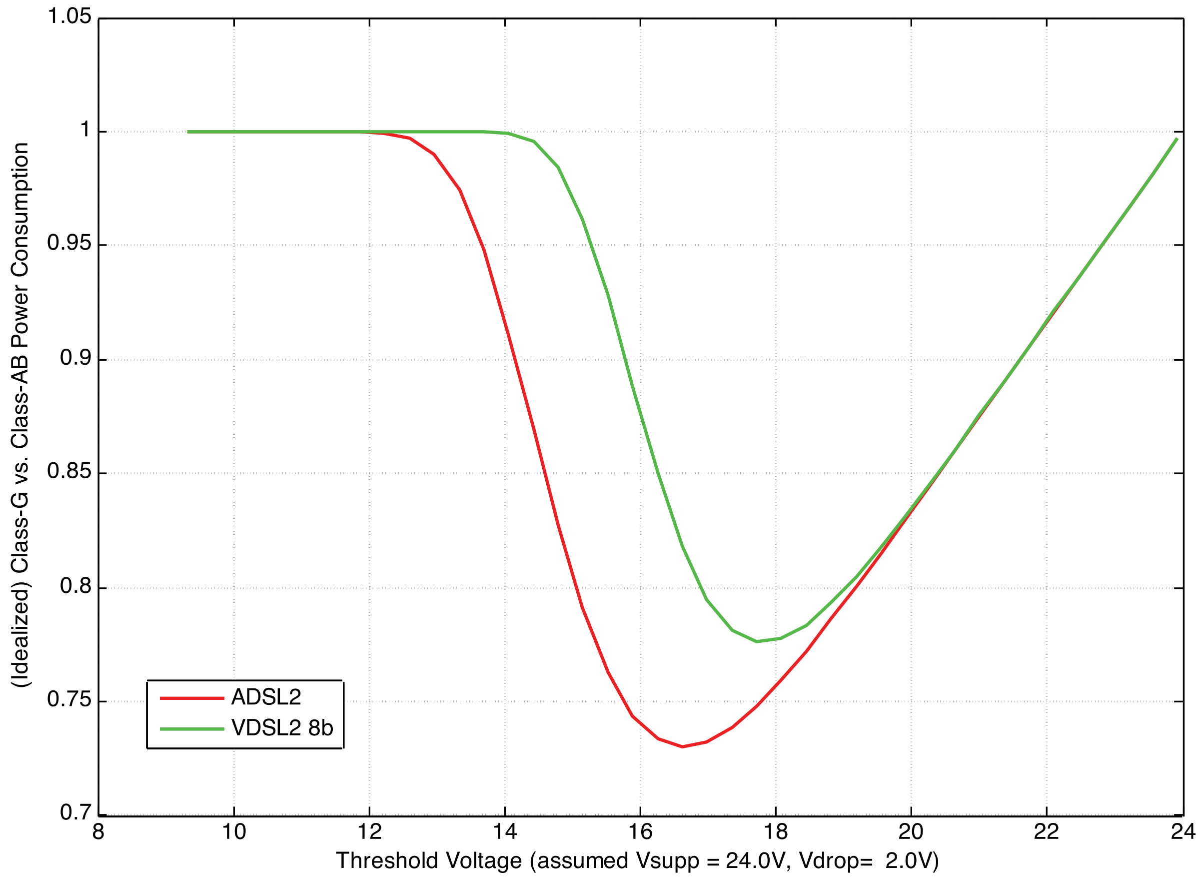
Class G Design

- Charge-pump usage, function of crest factor (CF)
- For ADSL:



Class G Design

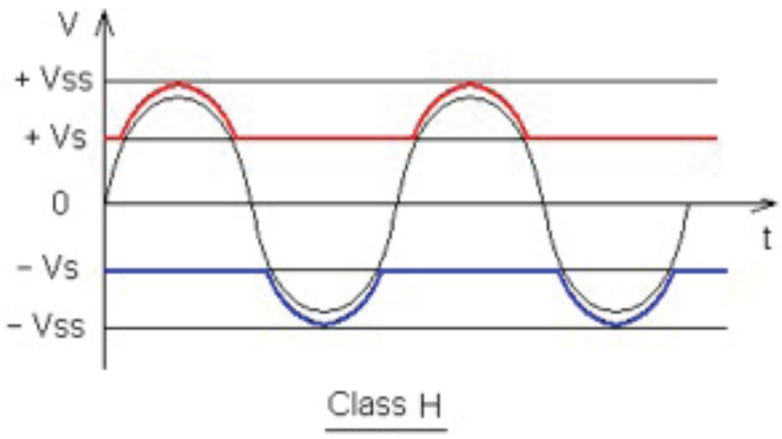
- Class G, with change pump, efficiency for symbol-wise switching between low and high supply

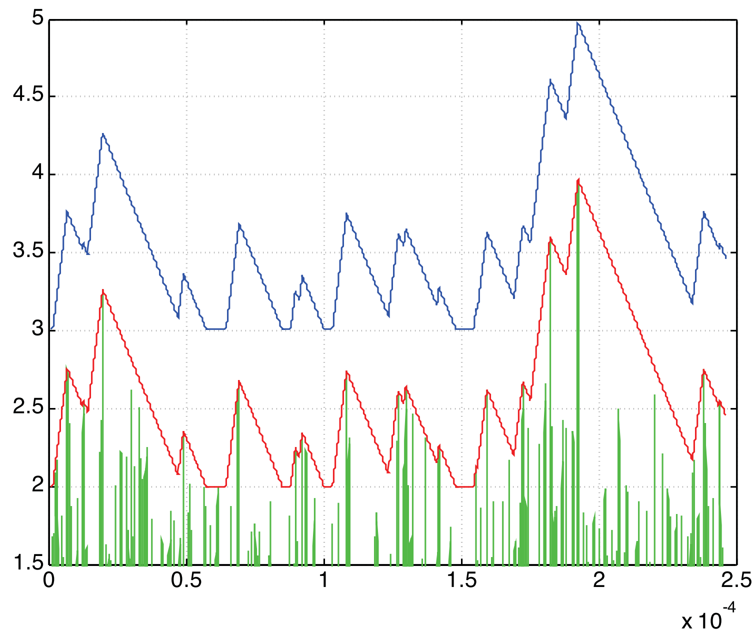


Class H

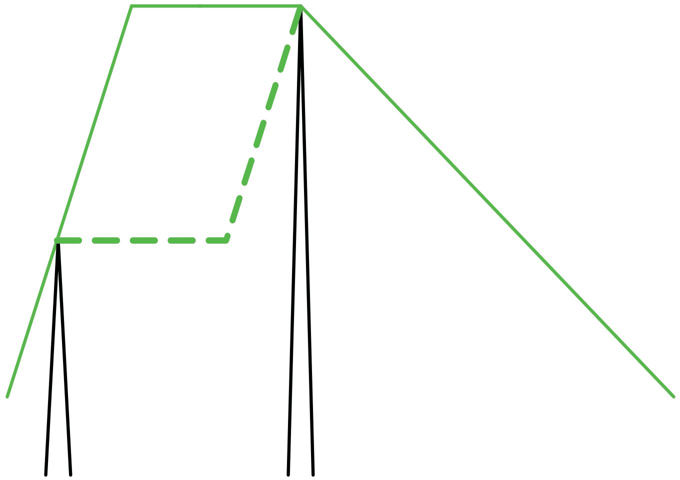
- supply follows the signal envelope above Vs, improved efficiency

- Needs a DC/DC converter (ClassD amplifier?) to generate a supply voltage that follows the signal envelope





- Ongoing investigation: How to generate a good envelope signal?



Class H

- Power reduction by 30 to 40 % compared to conventional designs
  - ADSL 2+, 20dBm: 32 % power reduction
  - 8b, 20dBm: 30 % power reduction
  - 17a, 14dBm: 44 % power reduction
  - 30a, 14dBm: 42 % power reduction
- Power supply follows the signal envelope to provide optimal signal swing for the current signal amplitude at close-to-minimal power dissipation
- Perfect for high-crestfactor signals – no more crestfactor reduction needed
- Envelope information is generated in the DFE

Best GreenDSL Power Amplifier?

ADSL power consumption

Class A/B: 710 mW

Class G: 485 mW

Class H: 410 mW

(Source: Scott Wurcer, ADI):

- Even if Class H has the highest potential efficiency we still believe a Class G with change pump is the best power amplifier architecture for multi mode DSL (ADSL-VDSL2)
  - Very high efficiency
  - Much less complex than a true Class H

GreenDSL Algorithms

- Energy efficient (EE) DSL algorithms
  - EE Spectrum Management
  - Vectoring (Multi-user signal processing)
  - Cross-layer optimization
    - Spectrum scheduling over time
    - Low-power modes
    - Rapid PHY/Profile switching (e.g. using VDSL2 profiles with lower power demand)

Energy Efficient Spectrum Management

- *Idea*: reduce transmit power by balancing the users power spectrum densities (PSDs) to reduce interference/cross talk

Notation:

c, u, n	… Indices of Carriers, Users, Frames
C, U, N	… # Carriers, Users, Frames
$\mathbf{p} \in \mathscr{R}_+^{CUN}$	… Power Densities

Rate on particular frame of user u in carrier c

$$r_c^u(\mathbf{p}_c) = \log_2\left(1 + \frac{H_c^{uu} p_c^u}{\Gamma(\sum_{i \in \mathscr{U} \setminus u} H_c^{ui} p_c^i + N_c^u)}\right)$$

FEXT interference noise

Problem Formulation

Weighted Sum-Power Minimization

$$\underset{\mathbf{p}}{\text{minimize}} \quad \sum_{n,u} w_u \sum_{c} p_c^{u,(n)}$$

Weighted Sum-Power Objective

subject to

$$\frac{1}{N}\sum_{n,c} r_c^u\left(\mathbf{p}_c^{(n)}\right) \geq R_u, \quad \forall u,$$

Target-Rate Constraints

$$\mathbf{p}_c^{(n)} \in \mathcal{Q}_c, \quad \forall c,n,$$

Feasible Bit-Loading Constraints

$$\left(p_c^u p_c^i = 0, \forall i \neq u, \forall u,c,n\right)$$

Orthogonality Constraints

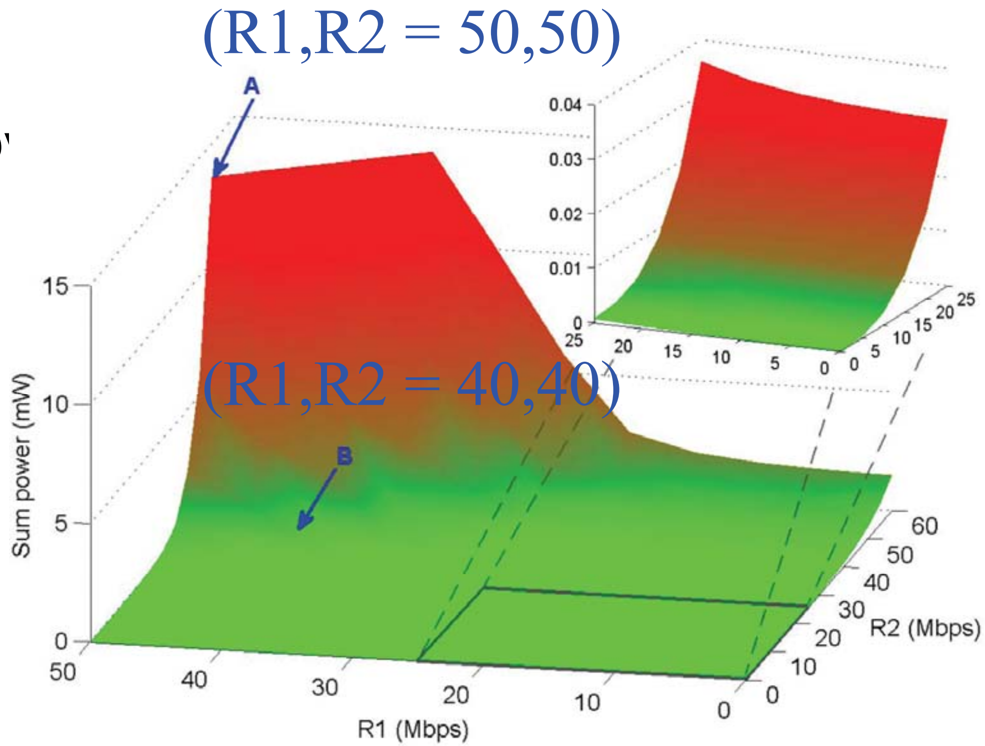
Non-convex problem!

We have a family of energy efficient spectrum balancing algorithms

- A family of algorithms have been developed and explored by us
  - **EESB** – Our own energy efficient spectrum balancing method
  - **EEOSB** – An energy efficient extension to the optimal spectrum balancing algorithm
  - **EEISB** – An energy efficient extension to the iterative spectrum balancing algorithm
  - **EEIWF** – An energy efficient extension to the iterative water-filling algorithm
  - **EEPBO** – Our own energy optimizing user-unique power back-off algorithm
- We have also explored the integration of channel uncertainty for improved robustness

Example of Savings Potential with EESB

- By **reducing the bitrates of users by 20%** (from point A to point B) the consumed total **sum-power for transmission is reduced by as much as 95.9 %** (13.1mW).

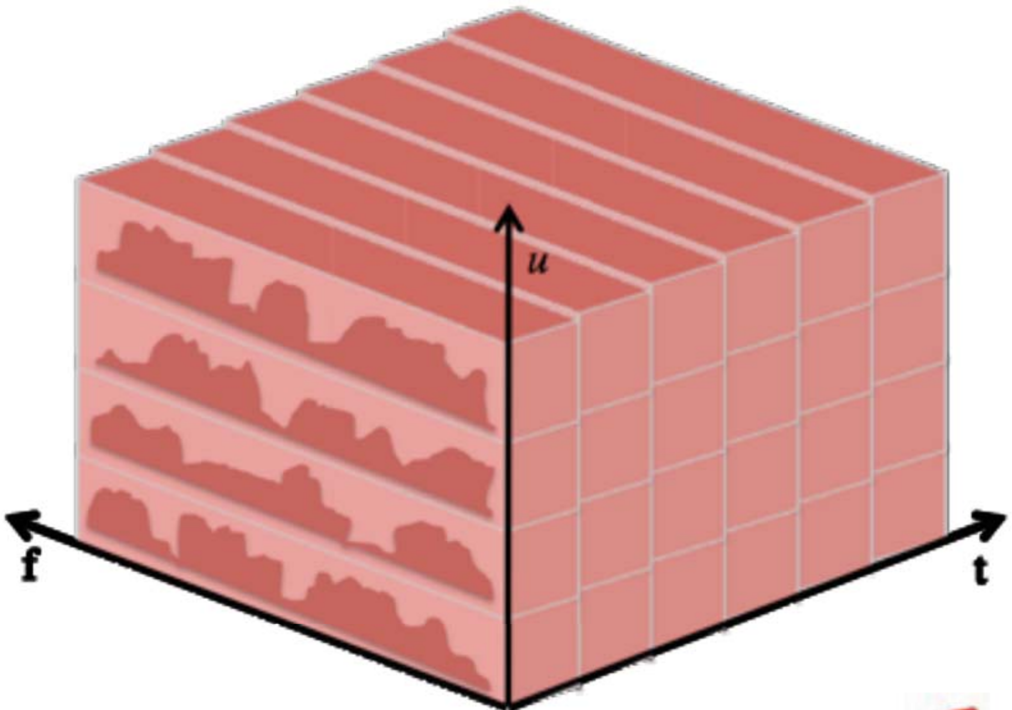


Transmit sum-power for different bitrate in a typical two-user case network scenario with loop lengths of 300 m and 600 m, respectively.

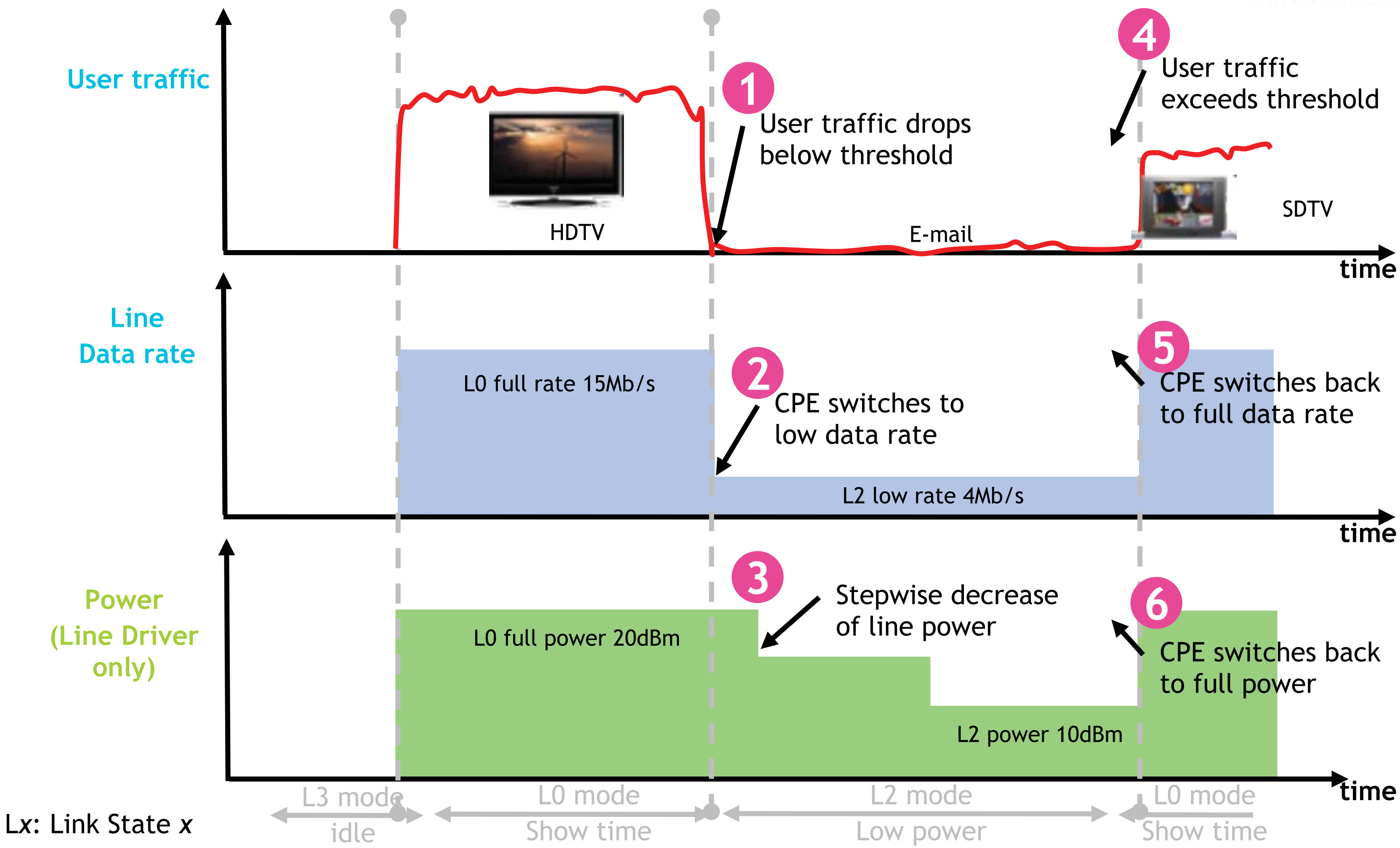
Cross-Layer Design for DSL

- In addition to the earlier spectrum managing methods we now add the time dimension
- An energy efficient scheduler has been developed that uses spectrum balancing in its inner stages.

- Static Spectrum
- Water-filling
- Spectrum Balancing
- Scheduling (single user)
- Multi-user scheduling



L2 Power Mode: switch to lower bitrate and power when user traffic is low

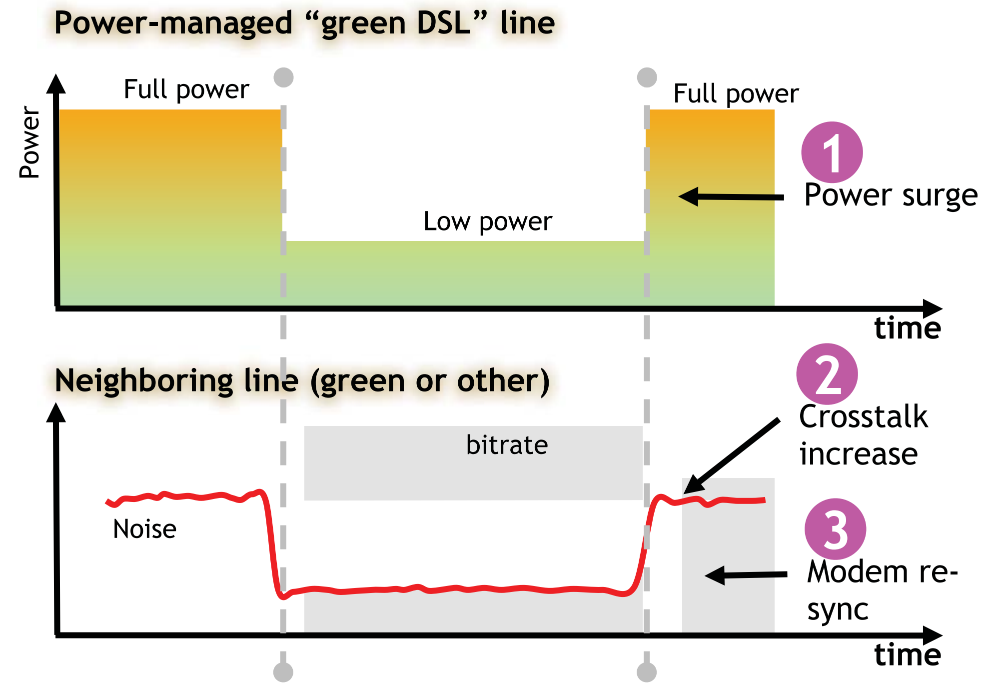


Reduce power per line by up to 25% when low user traffic
Strongly depends on loop length & conditions, and requires L2 compliant

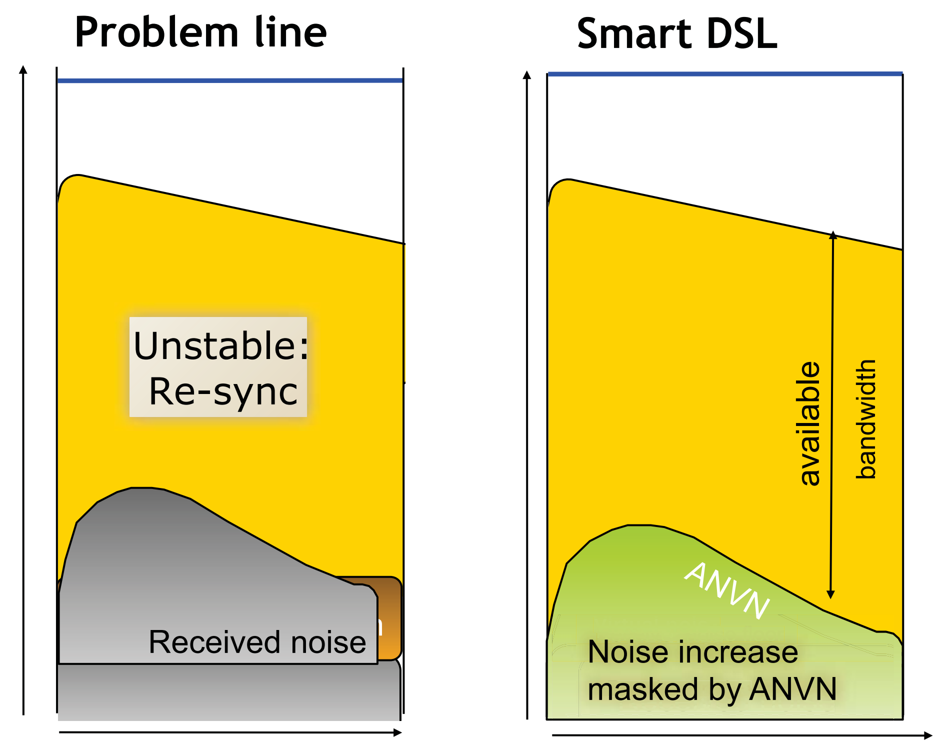
Stabilizing green DSL with Smart DSL (Artificial Noise / Virtual Noise)

Fluctuating power levels result in cross-talk variations and unstable lines

Cross-talk variations can be masked with Virtual/Artificial Noise



Power management leads to crosstalk fluctuation - which can make neighbouring lines unstable



Unstable - Crosstalk exceeds margin

Stable @ high rate frequency-specific NM

Artificial Noise / Virtual Noise protects lines from crosstalk variations caused by power fluctuations in neighbouring lines

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Conclusions

- Energy efficiency is one of the most important global issues today
- We are on the road to half the energy consumption for DSL systems.
  - With today's systems in the field, maybe 25% reduction can be achieved
  - With the next generation hardware and signal processing 50% reduction should be possible

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