TUG

VDSL

Very-high-bit-rate Digital Subscriber Lines

Klaus Doppler

TU Graz

2002

Outline

- VDSL Applications, Goals
- Network Architecture
- CAP
- Achievable Bit-Rates and Limitations
  - Noise
  - Compatibility
- CAP vs. DMT
- Standard development
- Conclusion

VDSL Applications

Application	Downstream	[illegible]
distance learning	384 kbps–1.5 Mbps	[illegible]
telecommuting	1.5 Mbps–3.0 Mbps	[illegible]
multiple digital TV	6.0 Mbps–24.0 Mbps	64 kbps–640 kbps
Internet access	400 kbps–1.5 Mbps	128 kbps–640 kbps
Web hosting	400 kbps–1.5 Mbps	400 kbps–1.5 Mbps
video conferencing	384 kbps–1.5 Mbps	384 kbps–1.5 Mbps
video on demand	6.0 Mbps–18.0 Mbps	64 kbps–128 kbps
interactive video	1.5 Mbps–6.0 Mbps	128 kbps–1.5 Mbps
telemedicine	6.0 Mbps	384 kbps–1.5 Mbps
high-definition TV	16 Mbps	64 kbps

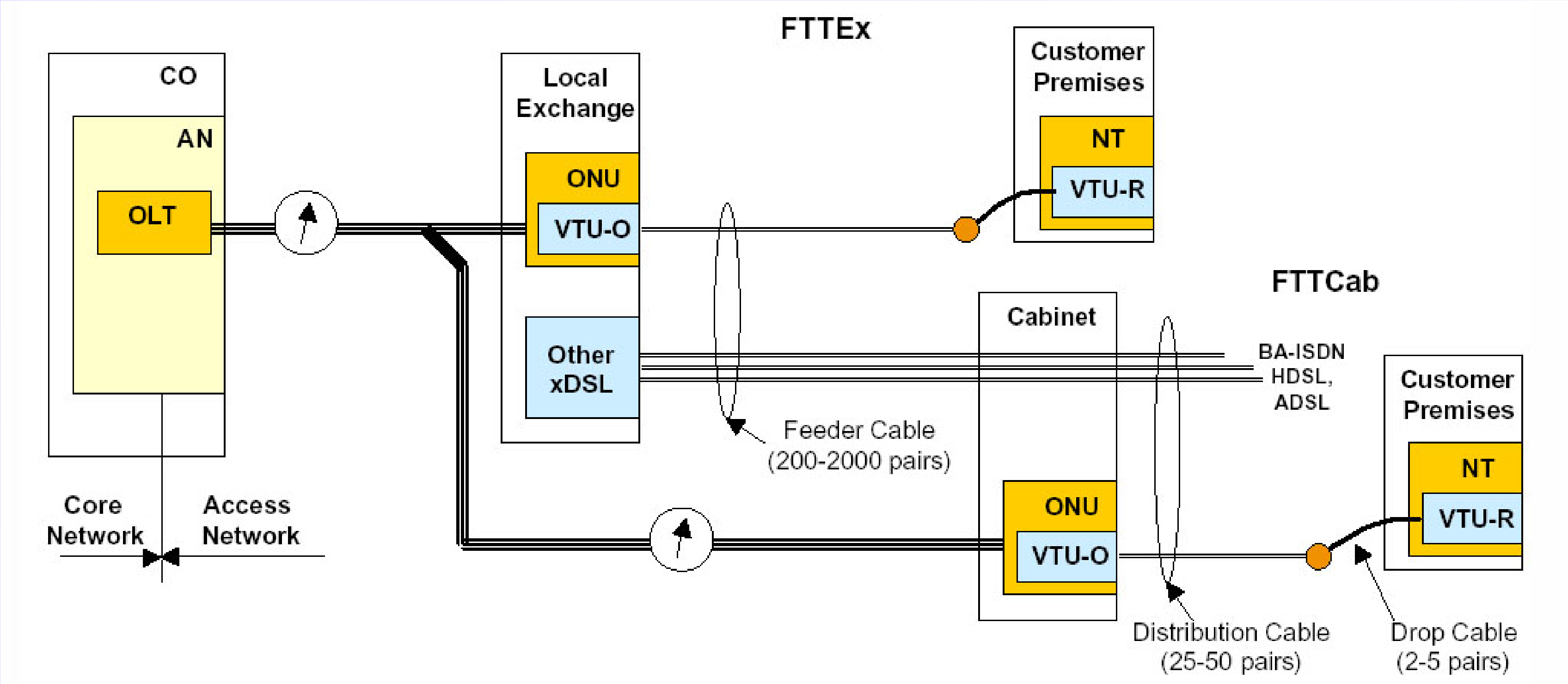
Goals

- Performance Requirements
  - Noise Margin > +6 dB
  - Bit Error ratio of < 1 in 10^7
  - Data rate (Mbps)
    asymmetric 22/3 (NA) 23/4 (Europe)
    symmetric 13/13 (NA) 28/28 (Europe)
  - Latency fast/slow path 1ms/20ms
  - POTS or BA-ISDN life-line over the same pair
  - Power Consumption < 1W at the Cabinet

Outline

- VDSL Applications, Goals
- Network Architecture
- CAP
- Achievable Bit-Rates and Limitations
  - Noise
  - Compatibility
- CAP vs. DMT
- Standard development
- Conclusion

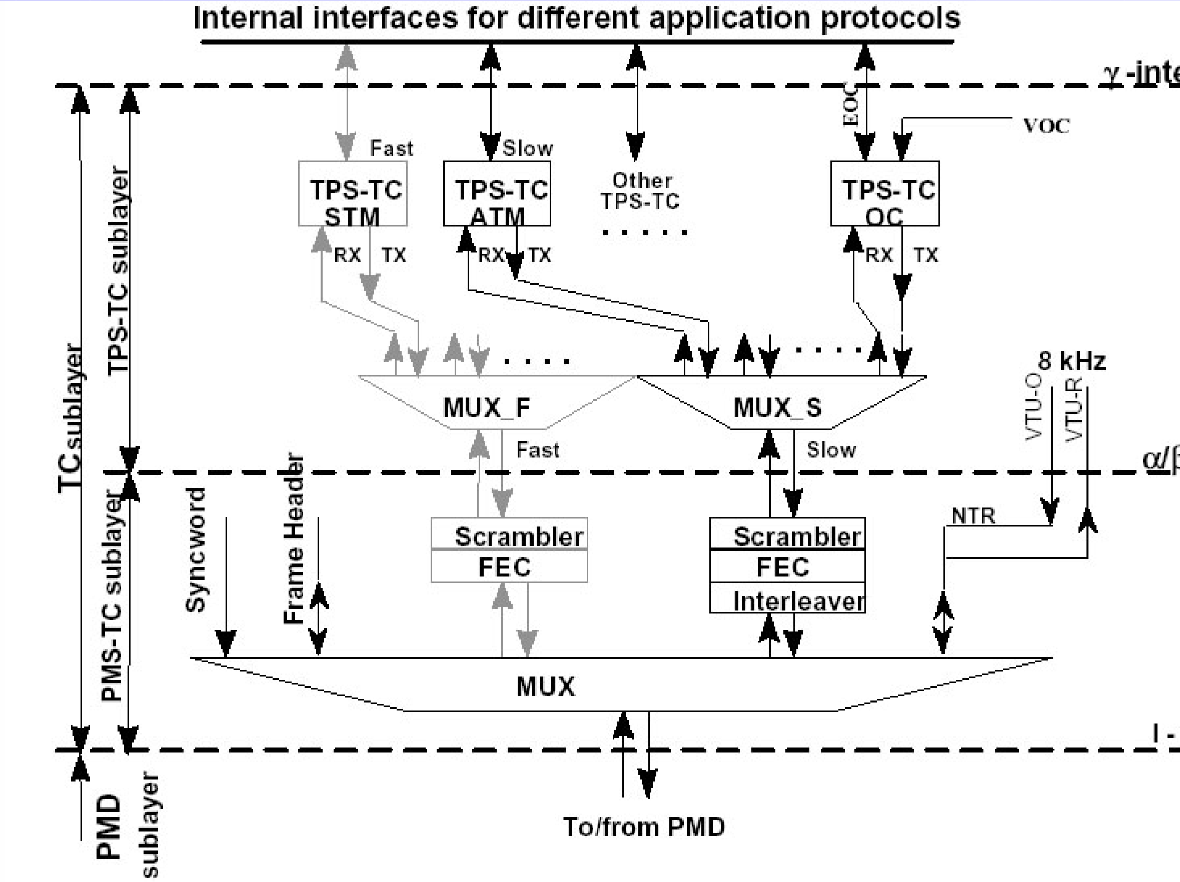
General network architecture



Abreviations:

AN	**Access Network**	**FTTEx**	**Fiber-To-The Exchange**
ONU	**Optical Network Unit**	**CO**	**Central Office**
VTU	**VDSL Transmitting Unit**	**OLT**	**Optical Line Termination**

TC sublayer architecture



Transport protocol specific TC (TPS-TC): independent of the physical medium

Physical medium specific TC (PMS-TC): independent of the user application

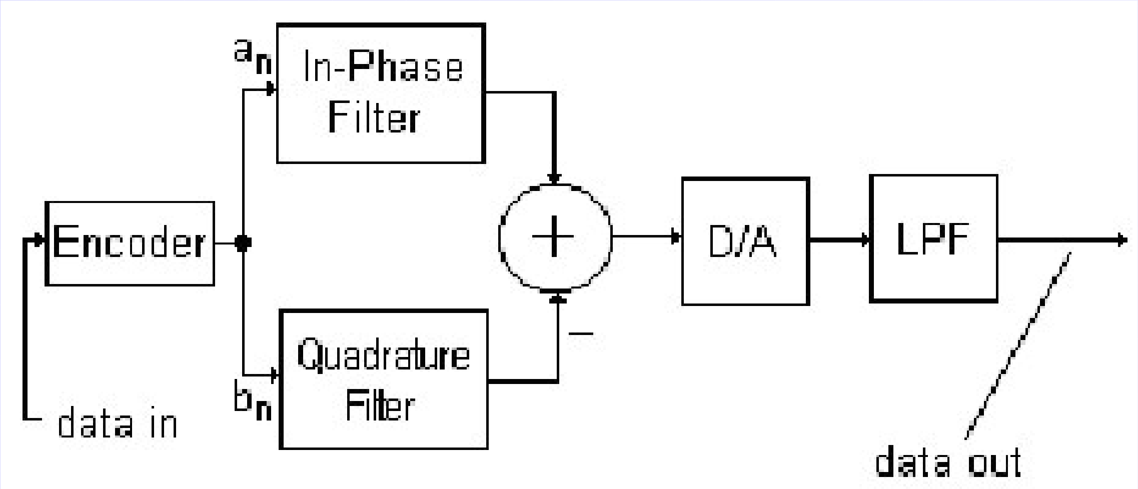
TC Transmission Convergence

Outline

- VDSL Applications, Goals
- Network Architecture
- CAP
- Achievable Bit-Rates and Limitations
  - Noise
  - Compatibility
- CAP vs. DMT
- Standard development
- Conclusion

CAP Transmitter

TUG



256-CAP

$$A_n = a_n + jb_n$$

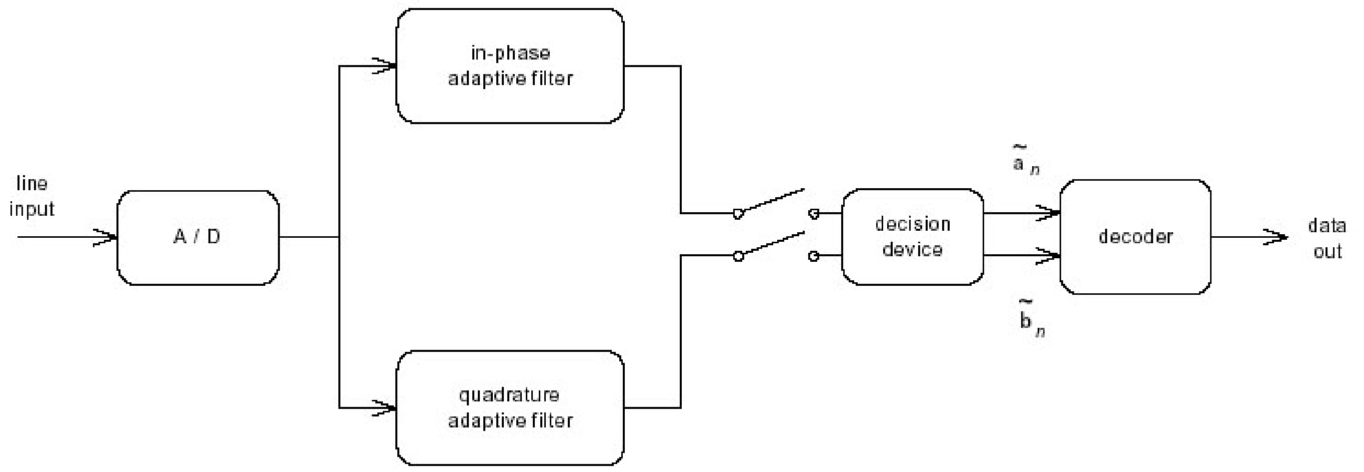
Impulse responses *h(t)* and h‘*(t)* form a Hilbert pair

$$h(t) = g(t)\cos(2\pi f_c t) \qquad h'(t) = g(t)\sin(2\pi f_c t)$$

Transmitted Signal

$$s(t) = \sum_{n=-\infty}^{\infty} [a_n h(t - nT) - b_n h'(t - nT)]$$

CAP Receiver



Conceptual CAP Receiver

- T/I fractionally spaced linear equalizer (FSLE)
- outputs FSLE → symbol rate 1/T → decision device

Recover symbols

- Linear filtering step:

$$h(t) \otimes f(t) = p(t) \rightarrow h'(t) \otimes f(t) = \tilde{p}(t)$$

- Impulse Responses of adaptive filters:

$$e_{II} = -\tilde{e}_{I}$$

- Output of adaptive filters:

$$s_{I} = \sum_{n=-\infty}^{\infty} \left[\left(a_n p(t-nT) \right) - b_n \tilde{p}(t-nT) \right]$$

$$s_{II} = \sum_{n=-\infty}^{\infty} \left[\left(b_n p(t-nT) \right) - a_n \tilde{p}(t-nT) \right]$$

Outline

- VDSL Applications, Goals
- Network Architecture
- CAP
- Achievable Bit-Rates and Limitations
  - Noise
  - Compatibility
- CAP vs. DMT
- Standard development
- Conclusion

How can we achieve such Very-High-Bit-Rates?

TUG

- Channel Capacity:

$$C = \int_{f_1}^{f_2} \log_2\left(1 + \frac{S(f)}{N(f)}\right)$$

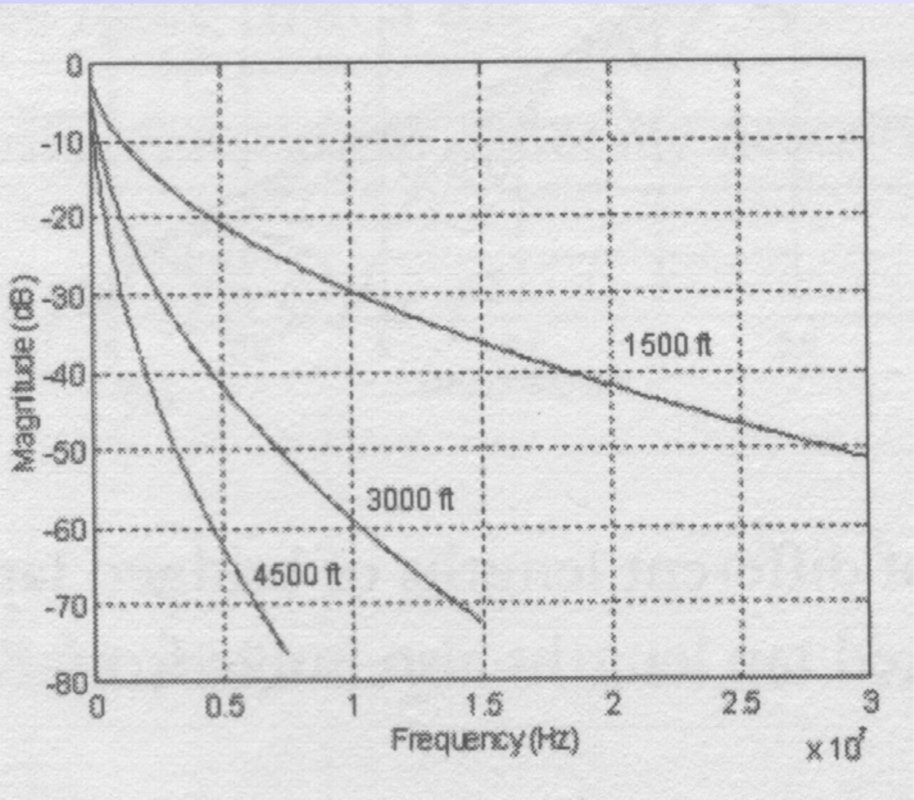
  - Expanding signal bandwidth
  - High signal-to-noise ratio
  - Sophisticated Coding and Modulation

Limiting factors

- Insertion loss
  - Especially for higher frequencies
- Noise
  - Background noise
  - Crosstalk noise
  - Impulse noise
- Compatibility
  - Existing services (e. g. POTS, ISDN, ADSL)
- Radio Frequency Interference
  - Standard amateur and broadcast radio bands
- Economic limitations
  - Power consumption at the Cabinet
  - Cheap and robust solution

Insertion Loss

Insertion Loss of a 24-gauge twisted pair loop



Transfer Function:

$$H(d,f) = e^{-d\gamma(f)} = e^{-d\alpha(f)} e^{-jd\beta(f)}$$

Propagation Loss in dB/m:

$$\mathrm{Lp(f)} = -20 \log\left|H(1,\mathrm{f})\right|$$

$$Lp(f) \approx 8.686(a\sqrt{f} + bf)$$

Noise Model

- Background Noise
  - White noise –140 dBm/Hz
- Crosstalk Noise

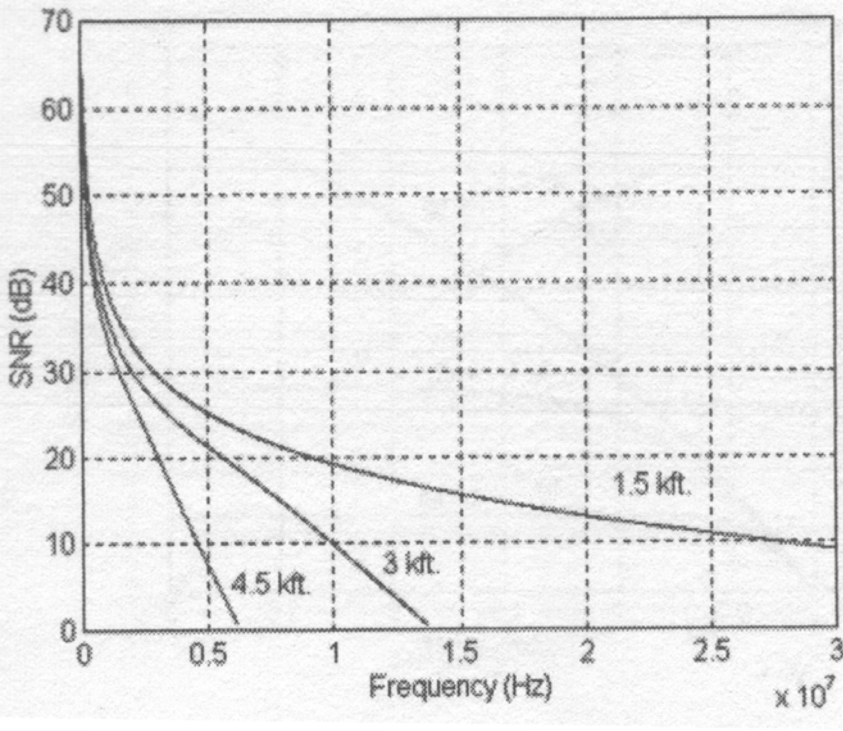
$$\frac{S(f)}{N_F(f)} = \frac{Q(f)|H(f)|^2}{Q(f)FEXT(f)} = \frac{1}{klf^2}$$

S(f) Received signal power density

Q(f) Transmit power spectral density

H(f) Channel transfer function

FEXT(f) power sum transfer function

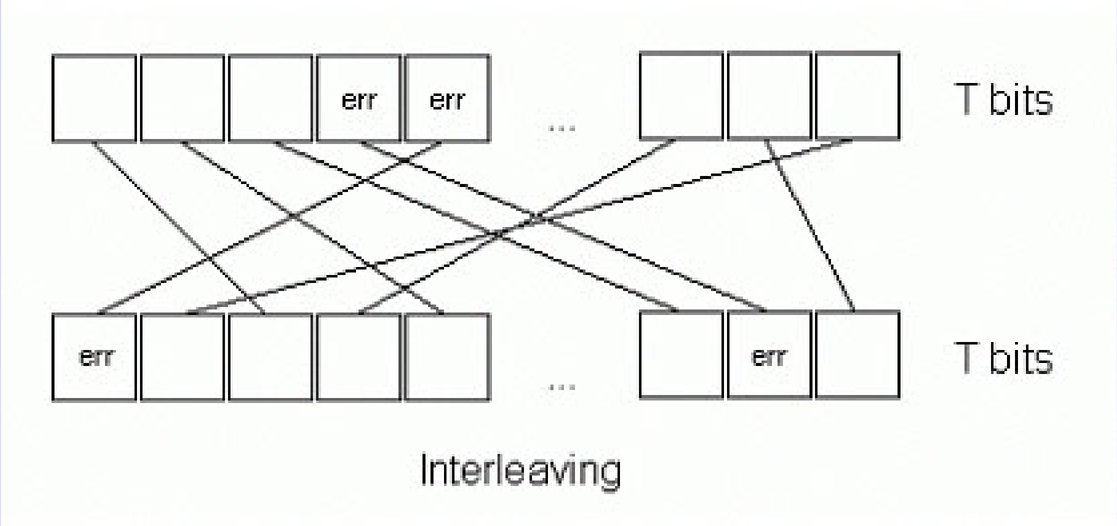


SNR for 24-gauge TP-Loop

Channel Capacity

- Channel Capacity Results:
  - Length of TP loop in m → Mbps
  - 500/1000/1500 → 160/68/25
- 6 dB performance margin
  - 500/1000/1500 → 108/44/18
- Realized transmission throughputs
  - Lower due to allocation of guardbands and not using the whole spectrum
  - Europe 28Mbps/28Mbps

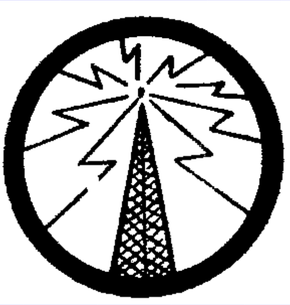
Impulse Noise



- Interleaving
  - Temporal permutation of Bits
  - Errors spread over block
  - Only for slow path

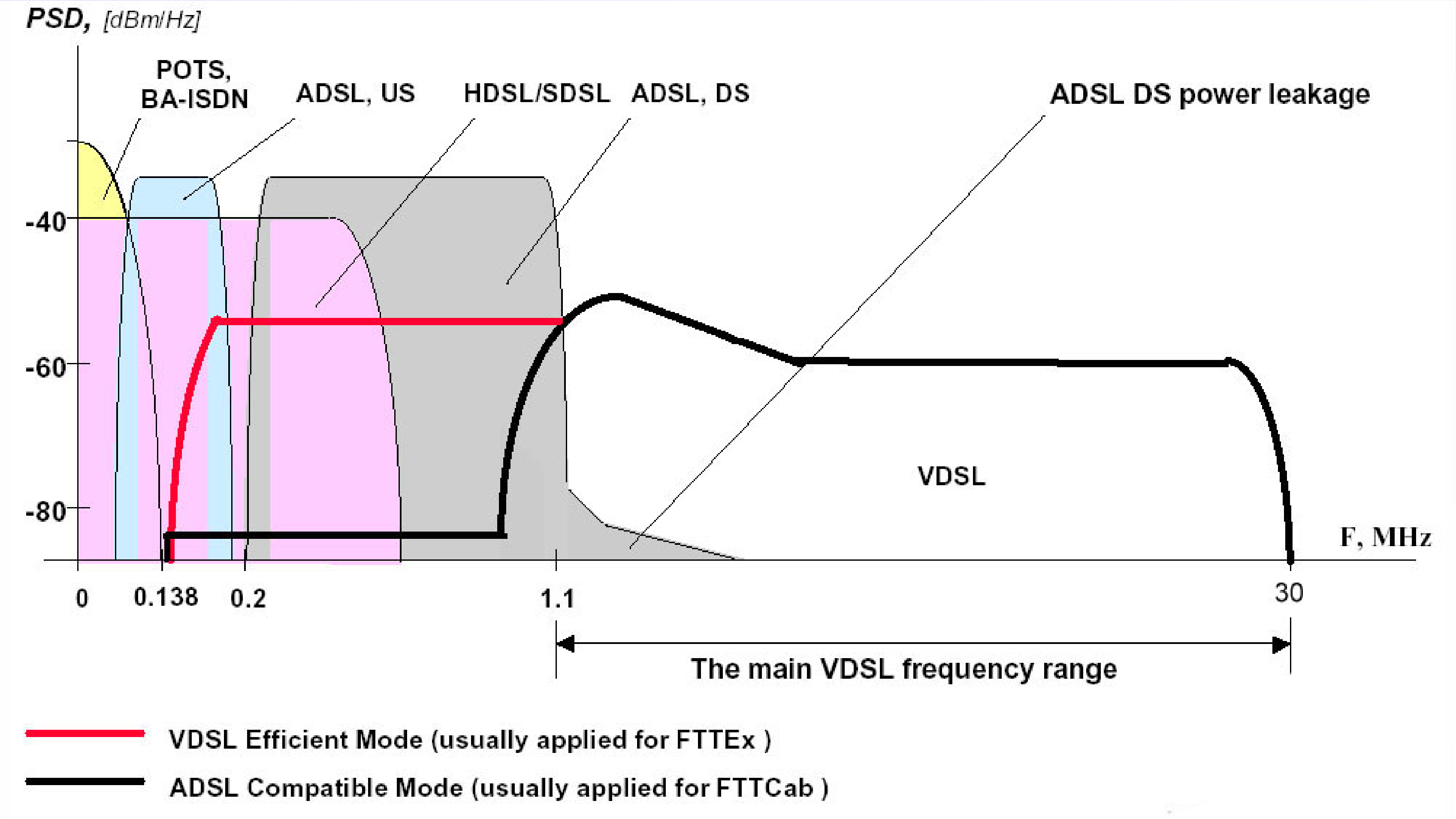
Radio Frequency Interference

- RF Egress
  - Caused by drop cable connection
  - At cusomer premises
  - HAM radio frequencies
    - CAP ⟶ Set notch filters
    - DMT ⟶ switch off subcarrier



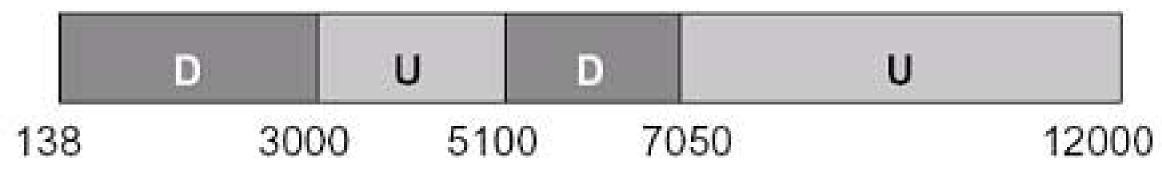
- RF Ingress
  - CAP ⟶ equalizer
  - DMT ⟶ switch off subcarrier

Spectral Compatibility



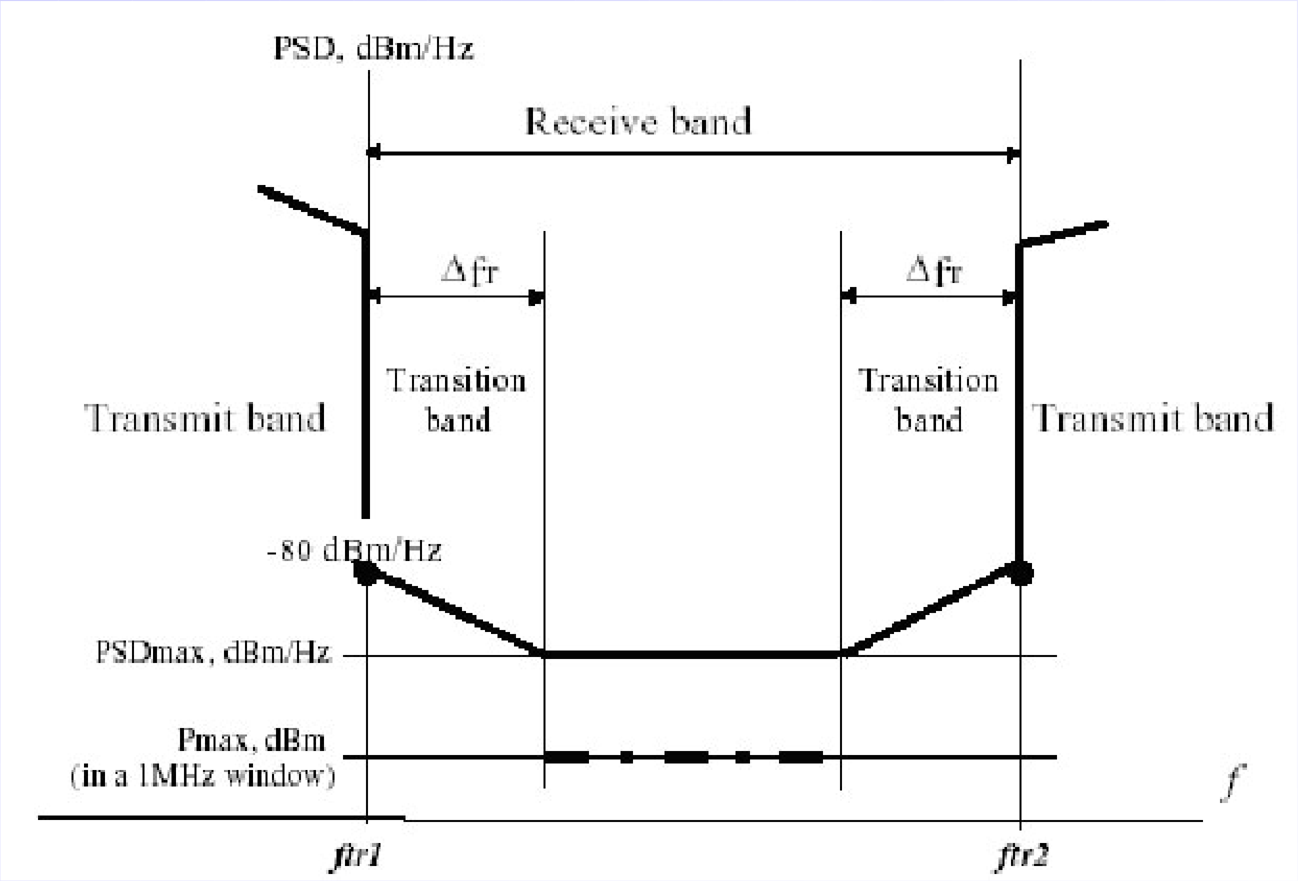
Transmit spectra

- Band allocation Europe



- D ... Downstream transmission
- U ... Upstream transmission

Out-of-Band PSD mask



Outline

- VDSL Applications, Goals
- Network Architecture
- CAP
- Achievable Bit-Rates and Limitations
  - Noise
  - Compatibility
- CAP vs. DMT
- Standard development
- Conclusion

CAP vs DMT I

- DMT – VDSL Alliance
  - Texas Instruments and Alcatel
- CAP - Coalition
  - Lucent, Broadcom, Infineon

CAP vs DMT II

- DMT
  - ☺ No error propagation
  - Subchannels degrade → redistributing data to other subchannels
  - ☹ Relies on signal analysis techniques → reliability in the field?
  - Requires 0.18 micron processes to meet the power constraints
- CAP
  - ☺ 0.25 micron processes to meet the power constraints
  - Relies on well-known and extensively field-proven digital signal processing algorithms
  - ☹ Equalizer can create errors that propagate
  - Equalizers with short, low-complexity filters. do not perform well on difficult channels

Outline

- VDSL Applications, Goals
- Network Architecture
- CAP
- Achievable Bit-Rates and Limitations
  - Channel Capacity
  - Noise
  - Compatibility
- CAP vs. DMT
- Standard development
- Conclusion

VDSL Standard

TUG

- Europe (ETSI TM6)
  - 2 parts: Functional requirements and Transceiver specification
  - SCM, MCM technologies are specified as possible implementations
- North America (ANSI T1E1.4)
  - 3 parts: Functional requirements,
    SCM, MCM Transceiver specification
- International (ITU-T)
  - only Functional requirements

Outline

- VDSL Applications, Goals
- Network Architecture
- CAP
- Achievable Bit-Rates and Limitations
  - Channel Capacity
  - Noise
  - Compatibility
- CAP vs. DMT
- Standard development
- Conclusion

Conclusion

- VDSL is
- ... a well developed technology
- ... at the last stages of standardization
- ... a multiservice architecture
- ... designed to operate in the presence of all kinds of impairments in copper pairs
- ... spectrally compatible with other xDSL
- And will have a great market potential