VDSL PHY (DMT option) for EFM-Cu

Christophe Del-Toso, Denis Mestdagh, Sabina Fanfoni

ST Microelectronics

Contact: christophe.del-toso@st.com

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Scope

- Propose a PHY layer solution based on FDD DMT-VDSL concepts
- The DMT-VDSL PHY specifications relies on ETSI/TM6 and ANSI/T1E1.4 standard documents (DMT part) and ITU-T G.993.1 recommendation
- This solution is scalable, flexible and is compatible/interoperable with existing ADSL, ADSL-Lite and DMT-VDSL systems
- This solution is suitable for both Public and Private Networks deployments
- The PHY specifications fulfill all the objectives of EFM
  - PHY for a single non-loaded voice grade copper pair (0.4 mm) able to provide bitrate >= 10 Mbps in each direction @ distance >= 750 m
  - Respect the spectral compatibility rules as per defined in T1.417

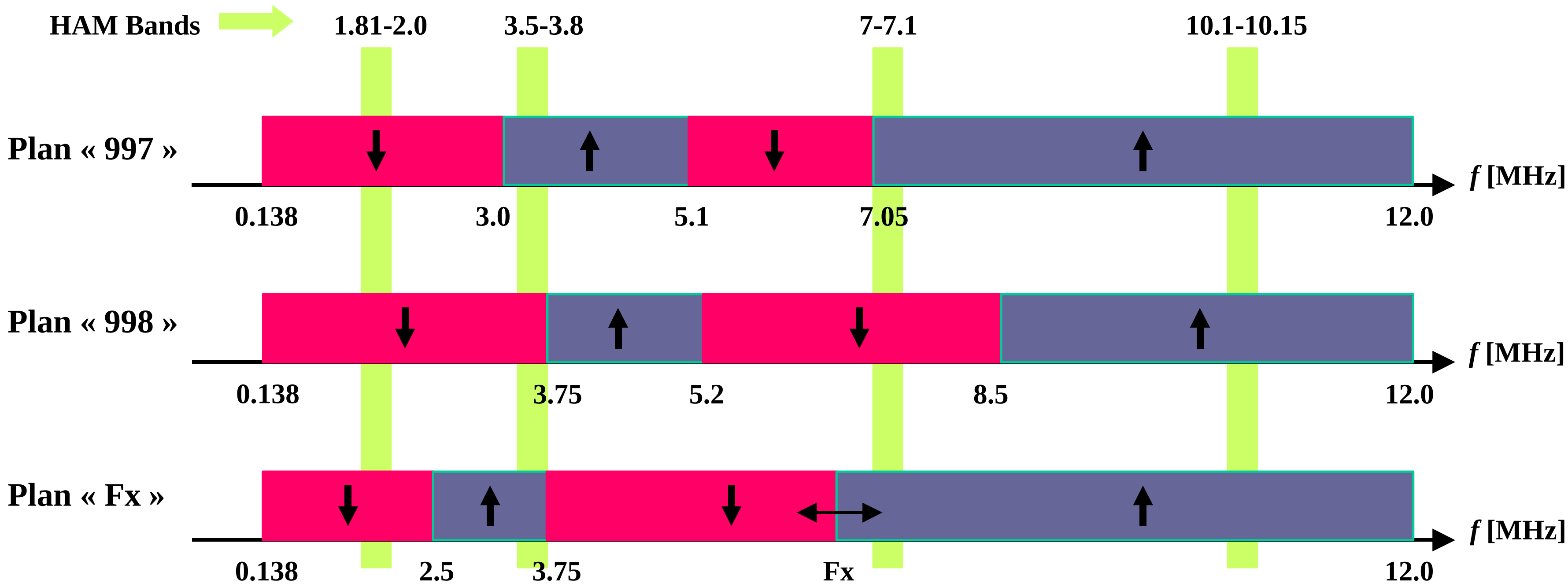
VDSL standardization status

- ETSI TM6
  - **Functional requirements, ref: TS 101270-1 approved**
  - **Spec document approved in Nov.2000, ref. TS 101270-2 contains:**
    - System specification of Multi-Carrier Modulation (MCM) VDSL
    - System specification of Single-Carrier-Modulation (SCM) VDSL

- ANSI T1.E1.4
  - **Draft Trial use standard in comment resolution**
  - **After publication, this document will be valid for a period of 2 years**
    => Trial use standard for a period of two years
  - **Document contains:**
    - Common Functional requirements
    - System specification of Multi-Carrier Modulation (MCM) VDSL
    - System specification of Single-Carrier-Modulation (SCM) VDSL

- ITU-T SG15/Q4
  - **Foundation document G.vdsl.f specifying functional requirements approved in ITU-T plenary meeting in October 2001 (G.993.1)**
    => This document specifies the « Packet Transfer Mode » (PTM-TC) layer and the encapsulation method to handle the transport of generic packets

Frequency plans specified for VDSL



- Plans 998 approved for ANSI T1 (North America, Japan)
- Plans 997, 998 approved for ETSI (Europe)
- Plans 997, 998, Fx accepted in ITU-T
- For all frequency plans, optional ADSL Upstream band [25, 138 kHz] may be used to increase capacity in Upstream

Services requirements specified for VDSL

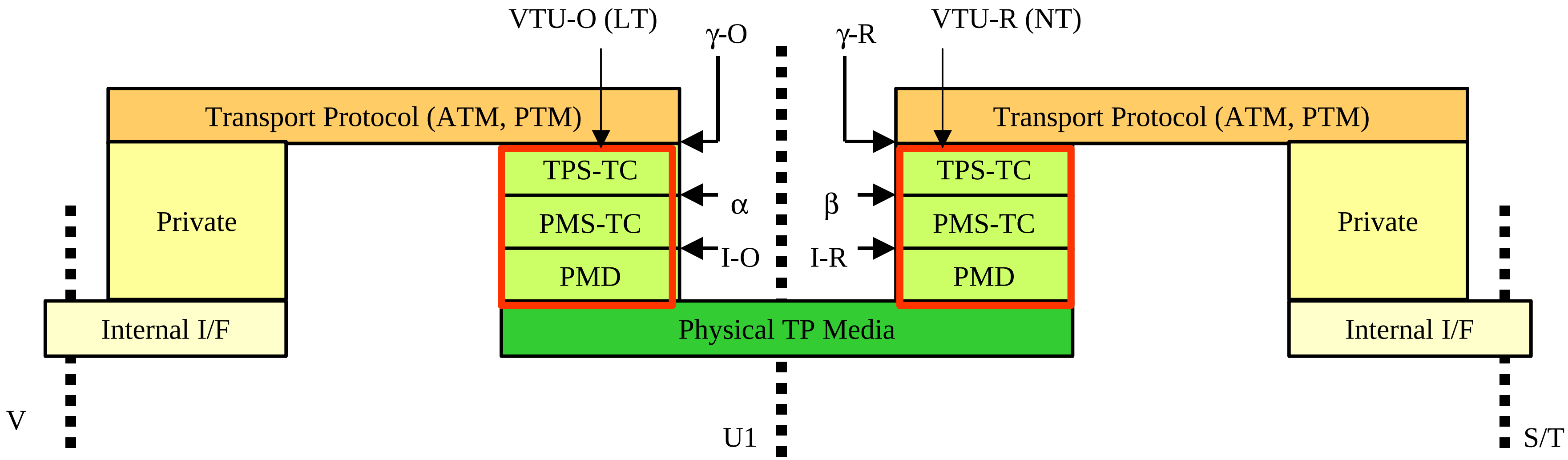
Services specified in ETSI

Service type	Up (Mbps)	Down (Mbps)
A1	2.048	6.4
A2	2.048	8.576
A3	3.072	14.464
A4	4.096	23.168
S1	6.4	6.4
S2	8.576	8.576
S3	14.464	14.464
S4	23.168	23.168
S5	28.288	28.288

Services specified in ANSI

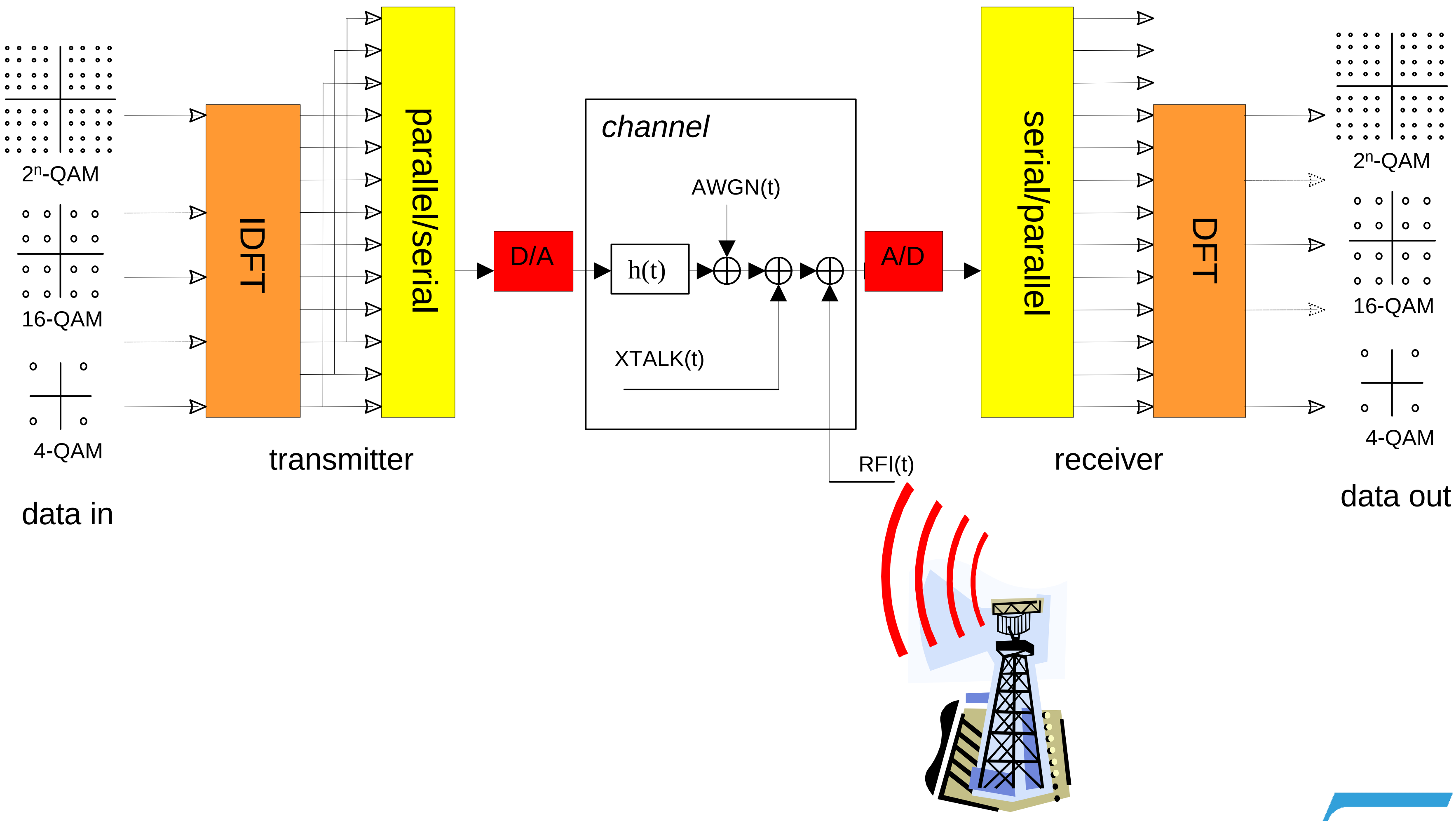
Service type	Up (Mbps)	Down (Mbps)
Asymmetric	3	22
Symmetric	6	6
Symmetric	13	13

VDSL protocol layer model

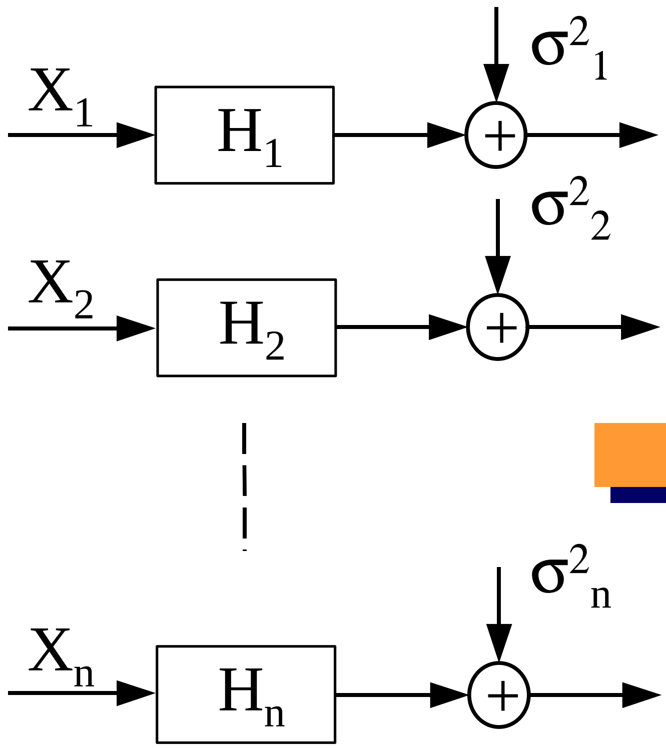


- PMD (Physical Medium Dependent) sub-layer performs DMT functions
- PMS-TC (Physical Medium Specific Transmission Convergence) sub-layer performs VDSL framing and channel coding
- TPS-TC (Transport Protocol Specific Transmission Convergence) sub-layer performs transport protocol specific functions:
    - supports ATM data transport
    - supports packetized data transport (PTM) as defined in G.993.1 Annex H

DMT modulation principles (1)

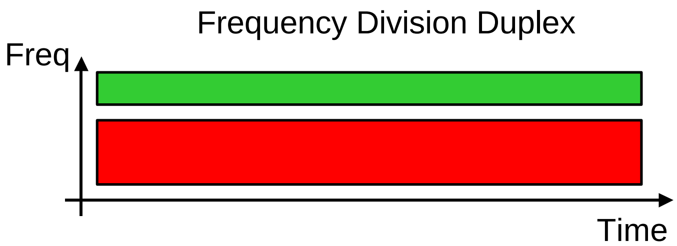


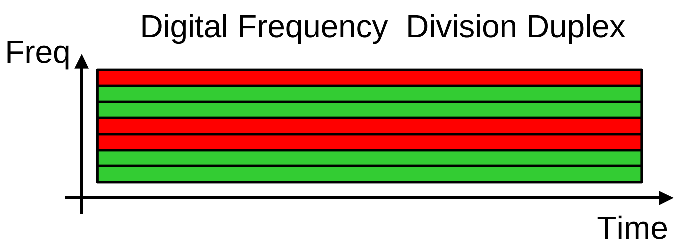
DMT modulation principles (2)

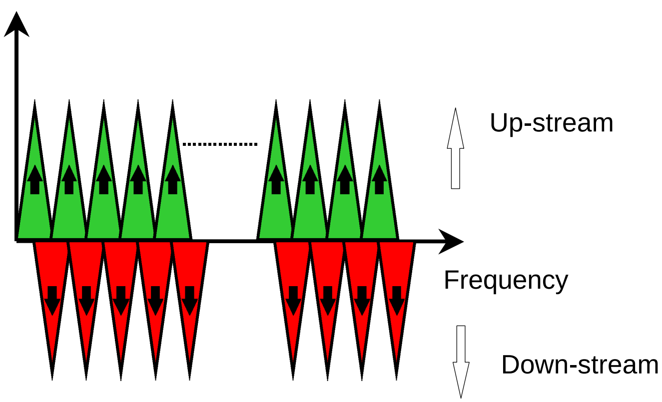


- DMT provide *n* independent, parallel AWGN channels
- Each channel is 4 kHz wide and transmits 1-15 bits constellations
- The SNR determines the number of bits on each channel
- DMT VDSL uses up to 4096 tones (bandwidth up to 12 MHz)

DMT-VDSL duplexing methods

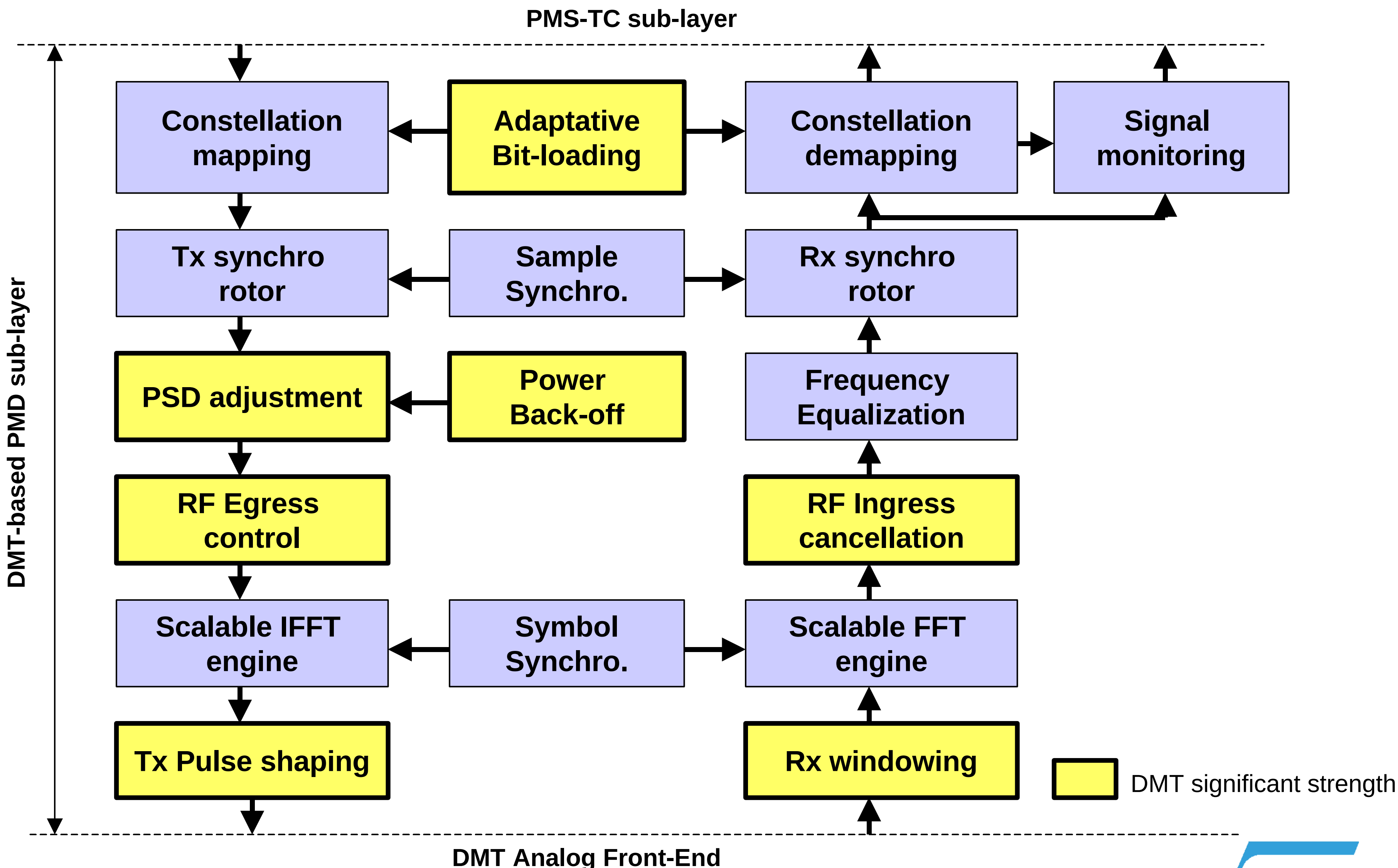






- Useful bandwidth from 138 kHz to 12 MHz is divided into 4096 tones equally spaced by Δf=4.3215 kHz
- Digital Frequency Division Duplexing (DFDD)
  - Flexible allocation of carriers in either US or DS
  - No analog filtering required for band separation
  - DFDD does not require synchronization of all the lines in the same cable bundle
  - 3 plans with 4 bands specified in standards
    - 997,998, Fx
    - 2 Upstream + 2 Downstream bands
  - Can provide both symmetric and asymmetric services
  - Max 11.5 to 14 dBm power sent over the line

DMT-based PMD sub-layer (1)



DMT-based PMD sub-layer (2)

- In the transmit path (Tx)
  - Mapping with constellation from BPSK to 2^{15}-QAM
  - PSD adjustment
    - Fine adjustment to cope with standard PSD masks
    - Accurate Power Back-Off algorithms
  - RF Egress control to limit PSD leakage in HAM bands
  - Scalable IFFT/FFT engine (see next slide)
  - Tx pulse shaping to limit out-of-band energy spreading
  - Adaptative bit-loading algorithm
    - Nb of bits carried out by each sub-carriers is determined as a function of the SNR computed for this sub-carrier
    - Bit-swapping allows system to cope with sudden channel variations by re-allocating bits carried by affected carriers on other carriers which have more SNR margin
- In the Receive path (Rx)
  - Rx windowing to limit RF Ingress leakage
  - Efficient RF ingress cancellation algorithm performed in the digital frequency domain

DMT-based PMD sub-layer (3)

- FFT engine supports all FFT/IFFT lengths from 256 to 4096 points
- Each FFT/IFFT size corresponds to a certain bandwidth and consequently to a certain achievable bitrate/loop reach
- System bandwidth can be scaled as a function of the loop length and the targeted service

FFT length	Bandwidth (MHz)	Ex of targeted aggregate bitrate (Mbps)	Max asymmetric services Us/Ds (Mbps)	Ex of targeted reach on 26 AWG cable (kft)
256	1.1	1.5	0.3 /1.2	10
512	2.2	12	5/7	6
1024	4.4	25	5/20	4
2048	8.8	40	10/30	3
4096	12 (17.6 max)	70	25/45	2

Conditions: 26 AWG, 998 frequency plan, -140 dBm/Hz thermal noise + 20 VDSL self-FEXT, extended US bans up to 500 kHz, 6 dB margin, 5.5 dB coding, 14 bits/s/Hz max

Bit-loading in DMT VDSL PHY (1)

$$BitRate = eff \cdot \Delta f \cdot \sum_i \log_2\left(1 + \frac{SNR_i}{\Gamma}\right)$$

$$SNR_i = \frac{Ei\left|Hi\right|^2}{s_i^{\,2}}, \quad eff \cdot \Delta f = 4k$$

SNR_i is the SNR computed on each sub-carrier i

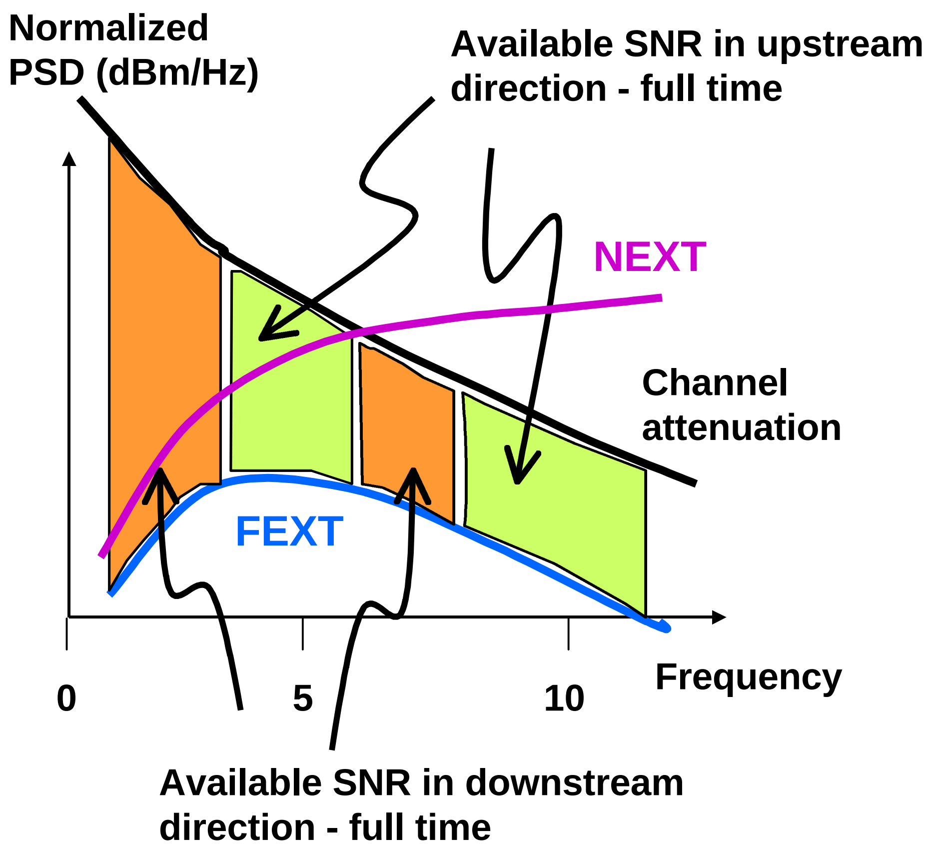
Γ is determined as a function of:

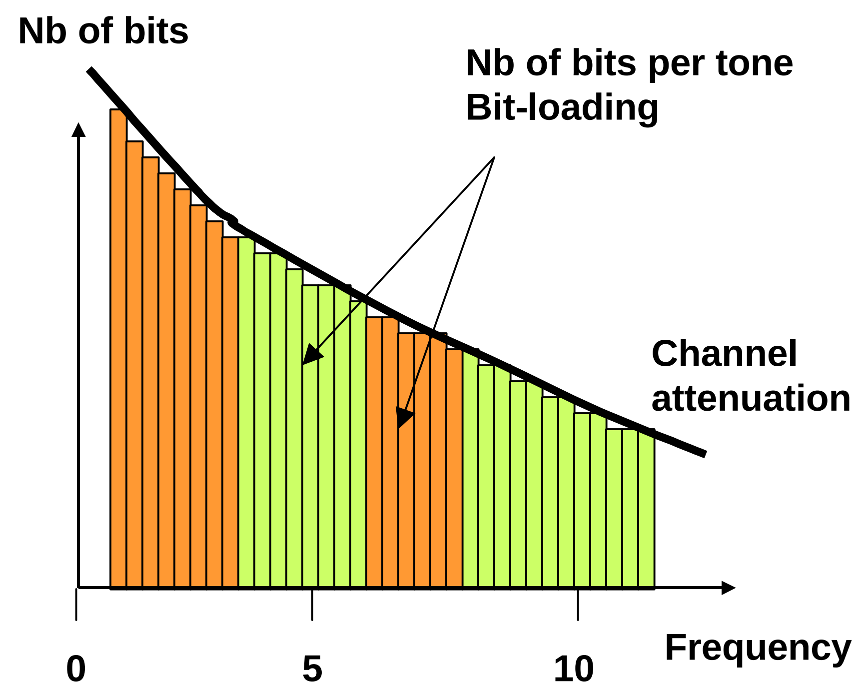
- Bit error rate (BER), typically 10^{-7}, appr 10 dB (Shannon gap)
- System margin, typically 6 dB
- Coding gain: 3.5 dB
- Constellation (b=1 up to 15 bits) appr 3 dB per bit

This would lead to a SNR_i of : 12.5 + 3*b_i dB

Bit-loading in DMT VDSL PHY (2)

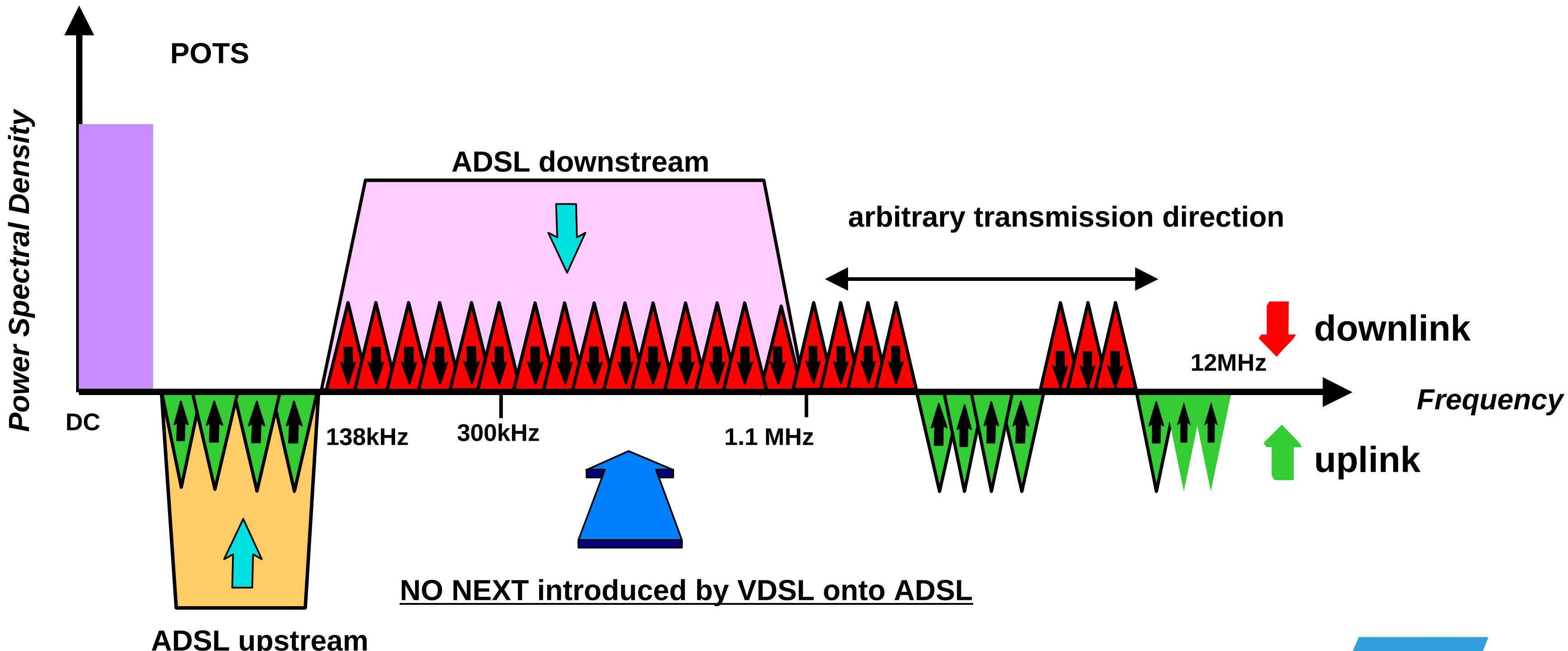
DMT-VDSL PHY layer maximizes the nb of modulated bit per carrier according to the SNR computed in real-time on each carrier





DMT-based PMD sub-layer (5)

- DMT-VDSL PHY is by nature spectrally compatible and backward interoperable with existing ADSL and ADSL-lite systems
  - **It is a DMT-based system like ADSL and supports 256-FFT size**
  - **The tone spacing (Δf= 4.3125 kHz) is the same as for ADSL**
  - **It can fit the ADSL frequency plan and PSD masks**



PMS-TC sub-layer

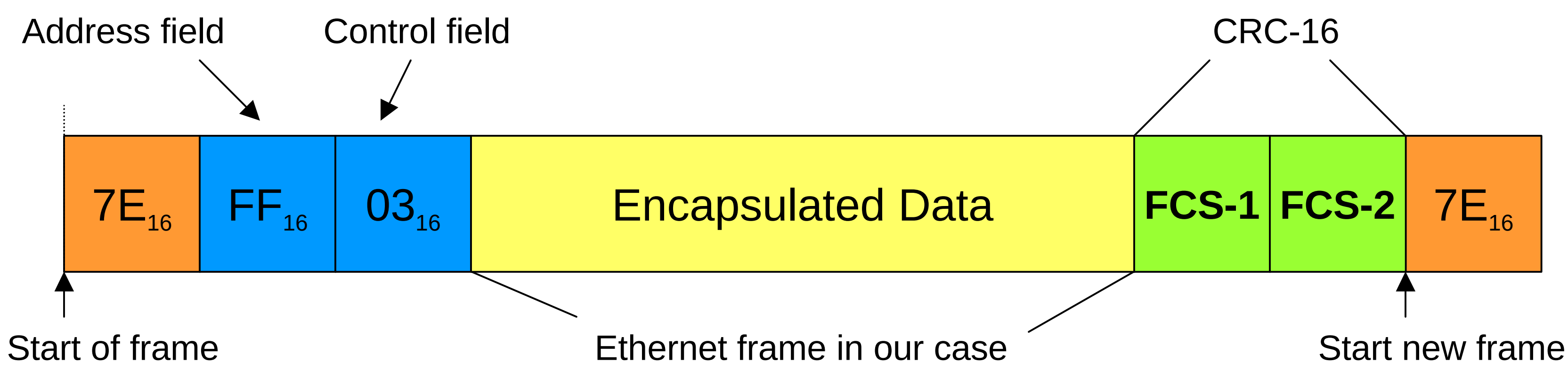
- VDSL framing as per defined in ESTI/TM6 and ANSI/T1E1.4 standard documents
  - VDSL framer aims at mapping an integer number of payload bytes per DMT frame
  - Includes EOC, VOC bytes in each DMT frame

- Forward Error Correction code
  - Scrambler
  - Reed-Solomon
  - Convolutinal interleaver
  - Target BER = 10^{-7}

PTM-TC sub-layer (1)

- PTM-TC sub-layer is compliant to ITU-T recommendation G.993.1 approved in October 2001

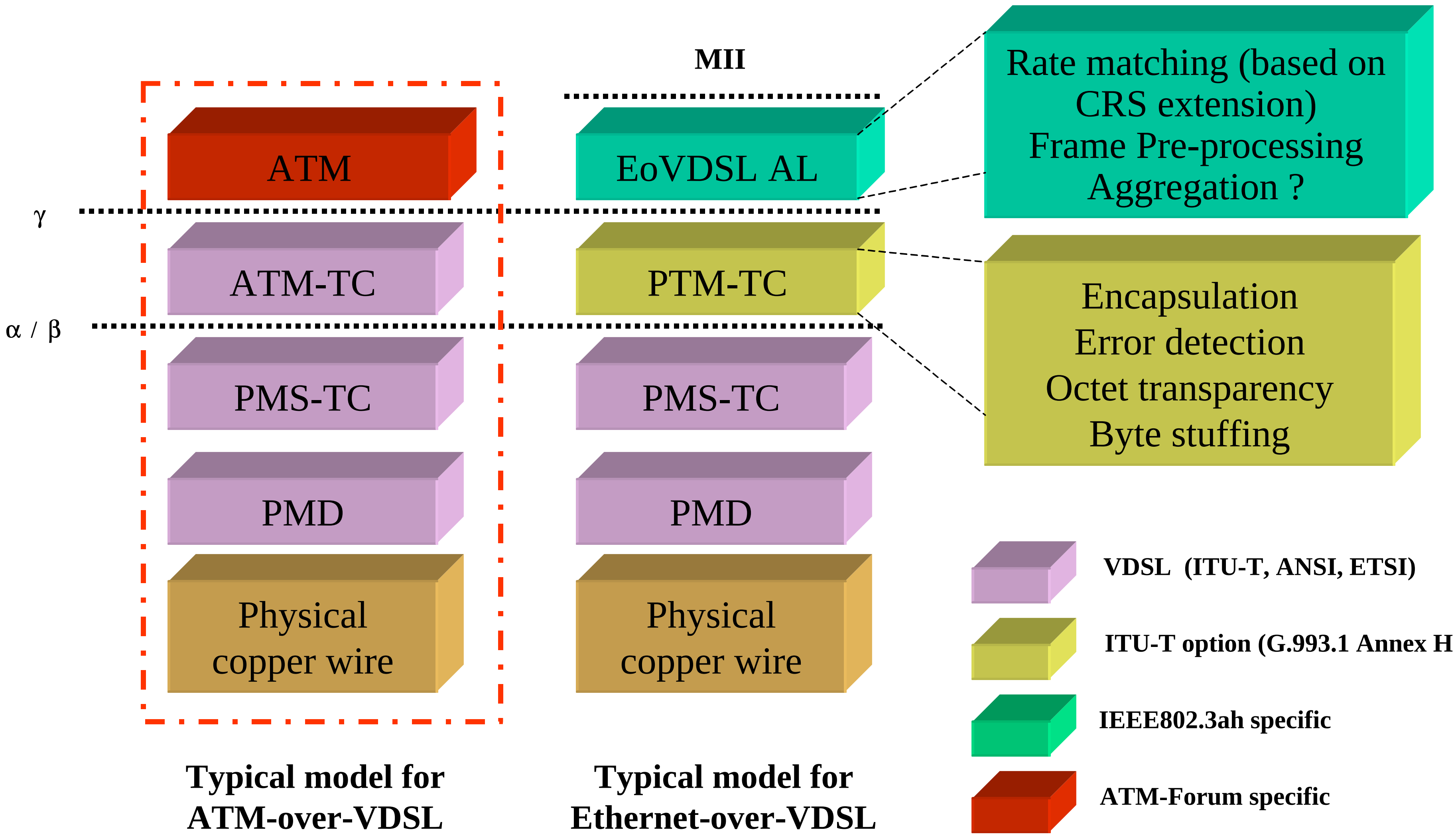
- Encapsulation is based on a HDLC-like frame
  - Use Start/End Flag sequence (7E)h to delineate frames
  - Address and Control fields set at their default values
  - Variable-length (octed-based) data field
  - 2-byte Frame Check Sequence (FCS) as defined in ISO/IEC 3309



PTM-TC sub-layer (2)

- PTM-TC functionalities:
  - Octet transparency
    - Octet substitution is used whenever (7E)h or (7D)h sequences are contained in the data field:
      - (7E)h is replaced by the 2-byte sequence (7D)h – (5E)h
      - (7D)h is replaced by the 2-byte sequence (7D)h – (5D)h
  - Data rate decoupling
    - To fill time gaps between two consecutive packets, VDSL link is stuffed with idle byte (7E)h
  - Frame delineation
    - Frame Start/End is detected by detecting (7E)h flag
    - Frame with 2 or more consecutive (7E)h flags constitute an empty frame that shall be discarded
  - Packet error monitoring
    - Detection of invalid and errored frames

Complete Ethernet-over-VDSL protocol model

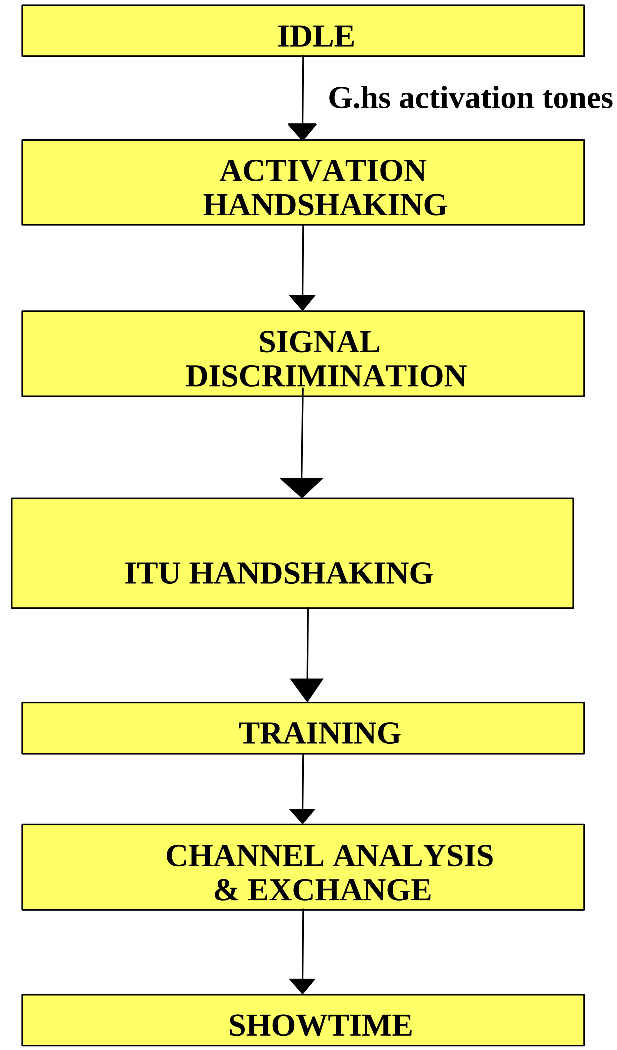


DMT-VDSL line set-up and monitoring

- Line activation and communication link set-up
  - Protocol for activation by VTU-O and VTU-R
  - ITU-T G.hs protocol (G.994.1) to determine common mode of communication
- Set-up and initialisation
  - Line parameters computation (loop length, channel response, SNR)
  - PSD adjustment (Power Back Off algorithm)
  - Frequency-domain equalizer training
  - Symbol and sample synchronisation
  - Bit-loading computation
  - Parameters exchange through « Specific Operation Channel » messages (SOC)
- Show-time
  - FEQ and synchronisation monitoring
  - Bit-loading adaptation through « bit-swapping »

Activation & initialization overview

- Activation of VTU-O/VTU-R
  - G.hs (exchange of FFT size, CE)
  - Decide the use of optional ADSL upstream band
  - Activation thanks to 3 G.hs tones
- Initialization of VTU-O /VTU-R:
  - Common mode of operation
  - Synchronization (symbol & sample)
  - Exchange of frequency band plans
  - Exchange of PSD masks
  - Channel response computation at both ends
  - Frequency-domain equalizer settings
  - Calculation of bit-loading tables at both ends
  - Exchange of parameters at both ends (RS and interleaver parameters, EOC/VOC capacity, bit-loading tables)



Measurement results obtained with a DMT-VDSL prototype platform

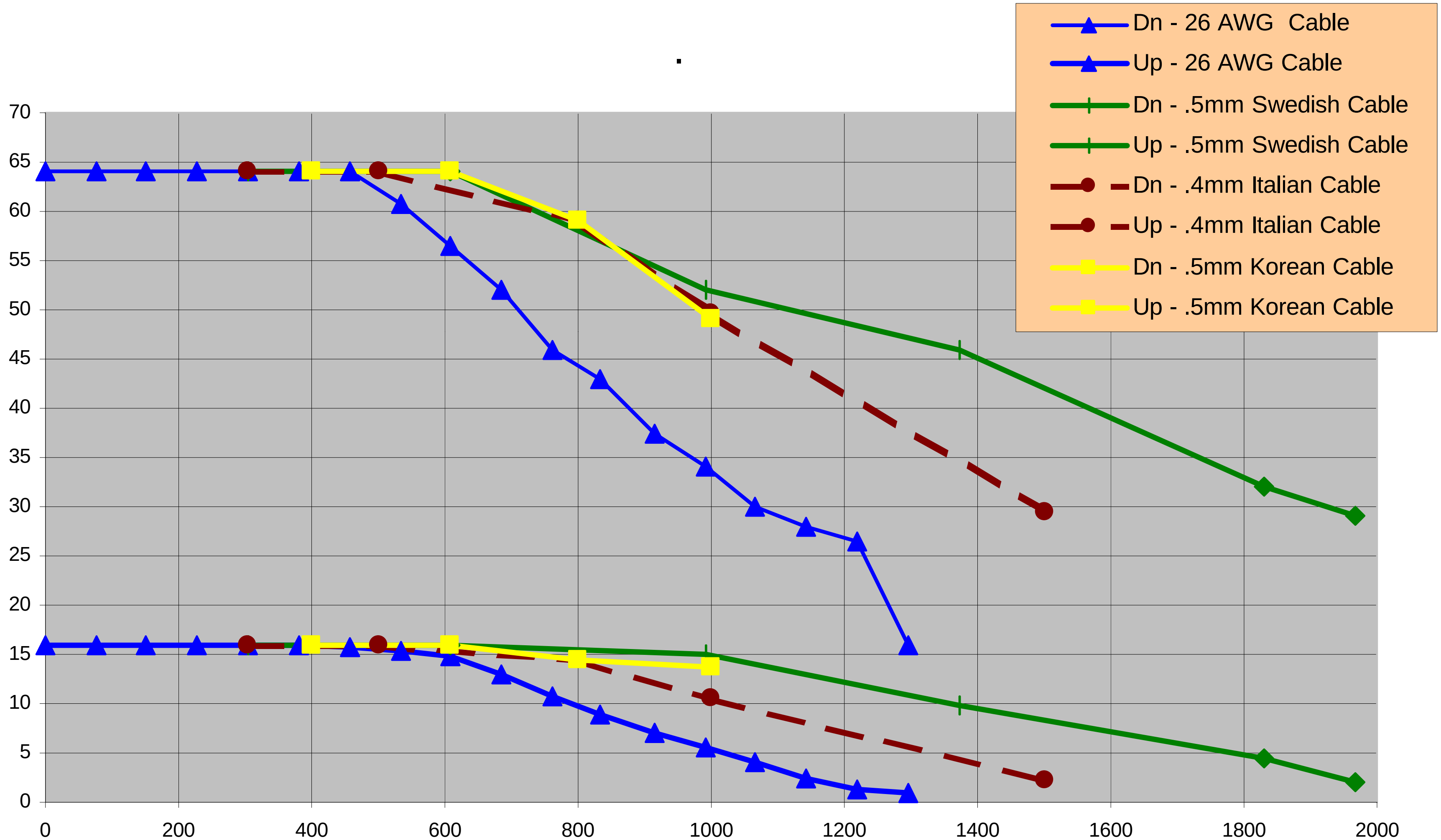
- Point-to-point DMT-VDSL application using two DMT-VDSL prototype modems

- Each VDSL-DMT platform supports:
  - ATM data transport through UTOPIA I/F
  - Native Ethernet data transport:
    - Supports PTM-TC features as defined in ITU-T G.993.1
    - EoVDSL Adaptation Layer supporting rate matching method based on the CRS extension (cf A. Marris's baseline proposal)

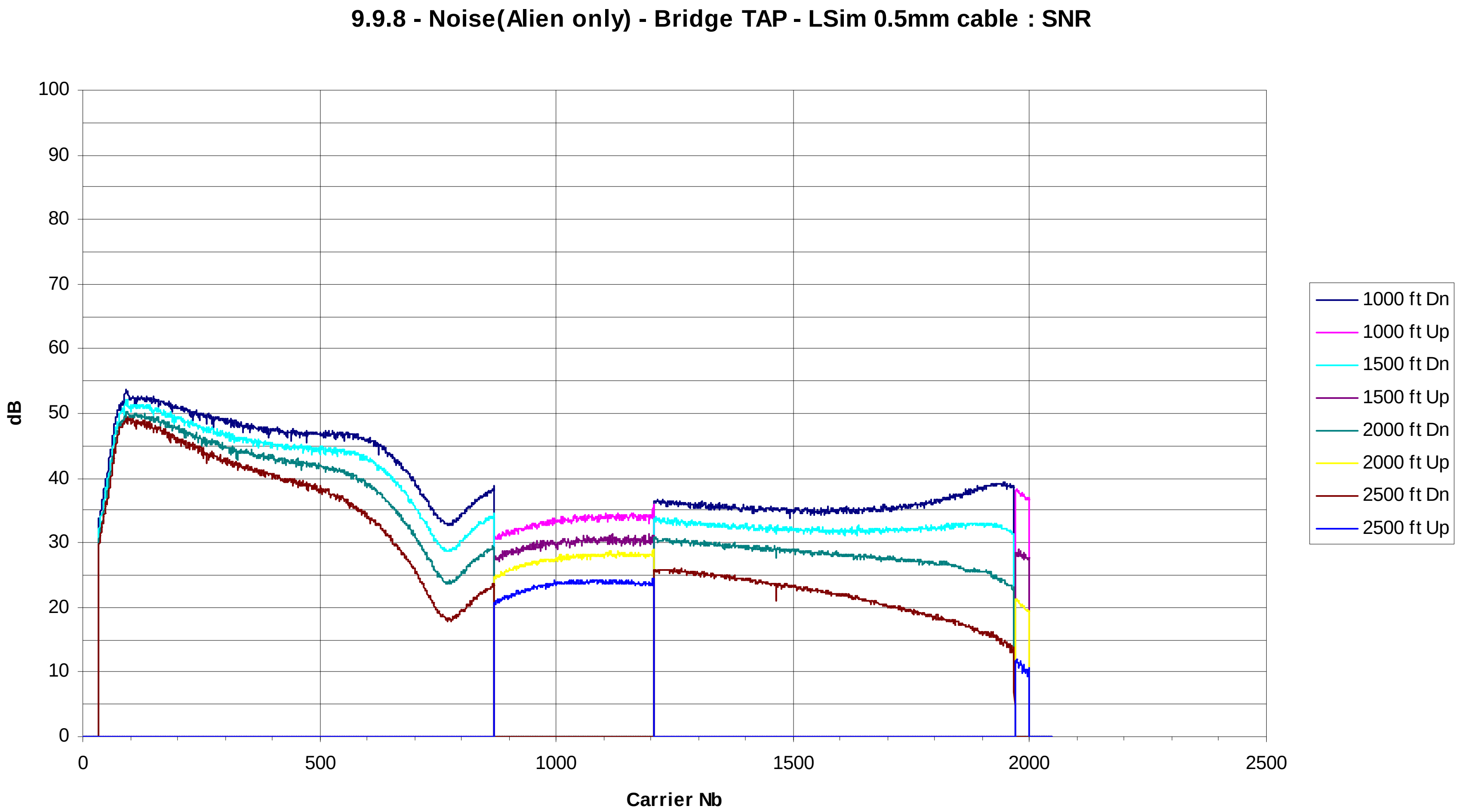
Tests conditions

- VDSL-DMT platform configuration
  - 2048 tones equally spaced by Δf = 4.3125 kHz
  - Maximum useful bandwidth = 8.832 MHz
  - Max. nb of bits per tone = 11 bits (i.e., 2048-QAM constellation)
  - Coding gain: 3 dB
  - System margin: 6 dB
  - Flat PSD mask with –60 dBm/Hz PSD on each tone
  - Maximum Power sent over the line < 11 dBm
- Frequency plan selected for the tests
  - 998 limited at 8.832 MHz due to prototype limitation
- Types of cable tested
  - 0.4 mm telephone cable, Type 278, untwisted, worse than 26 AWG
  - 26 AWG, 24 AWG, 0.5 mm European
  - Different lengths: from 1 kft to 5 kft
- Background noise at –140 dBm/Hz
- No Self, no Alien crosstlaks considered

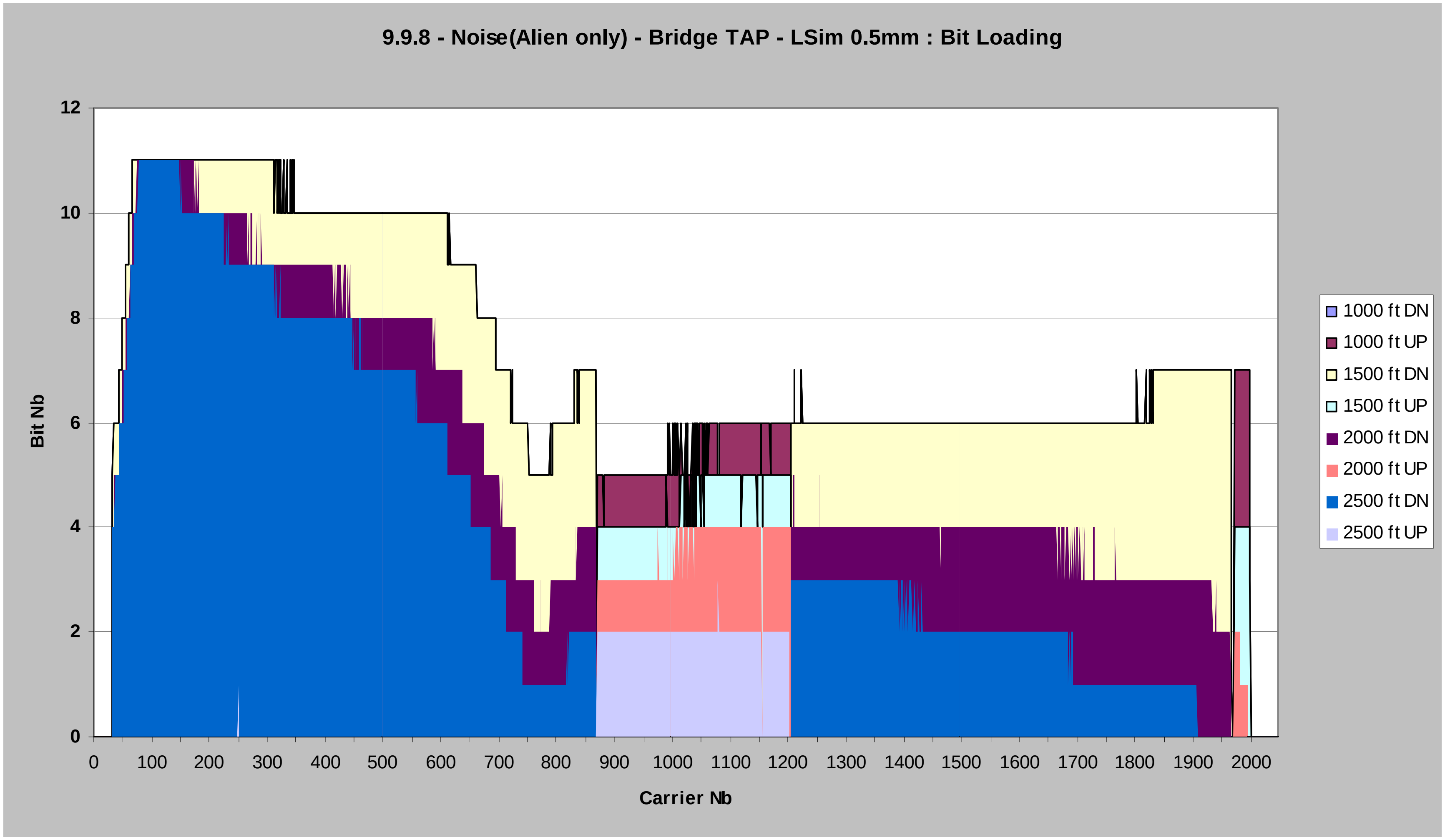
Examples of loop-reach obtained with the DMT-VDSL platform (Physical bitrates)



Example of SNR measurement vs the carrier index for different loop length

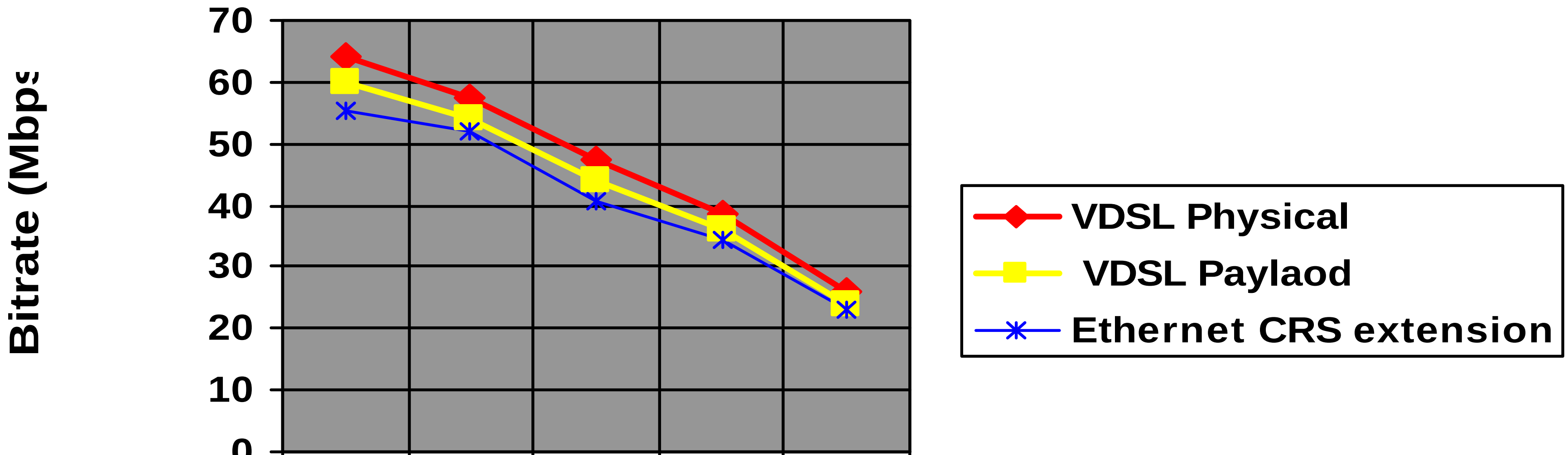


Example of bit-loading computation for different loop length



Examples of EoVDSL loop-reach obtained with the DMT-VDSL platform (1)

Downstream bitrate with 998 frequency plan



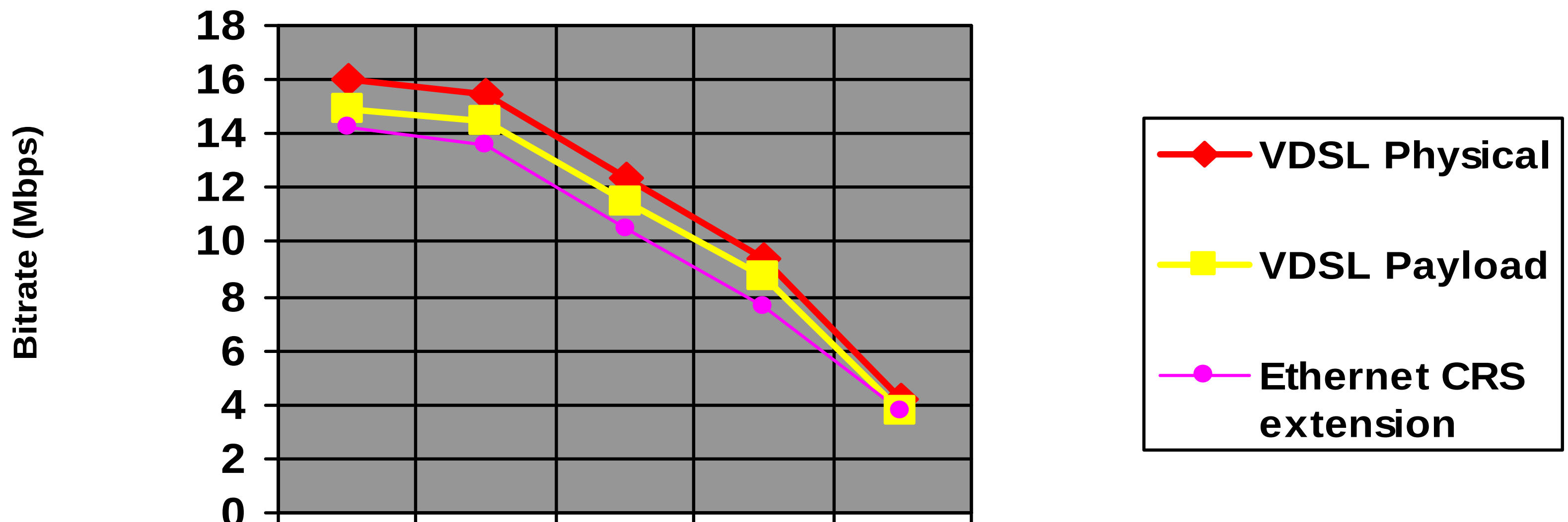
	1 kft	2 kft	2,5 kft	3 kft	4,2 kft
VDSL Physical	64	57,6	47,2	38,6	25,8
VDSL Paylaod	59,9	53,9	44,1	36,1	24,1
Ethernet CRS extension	55,3	51,9	40,6	34,4	22,9

line length (kft)

Obtained on 0.4 mm telephone cable, Type 278,untwisted, worse than 26 AWG

Examples of EoVDSL loop-reach obtained with the DMT-VDSL platform (2)

Upstream bitrate with 998 frequency plan



	1 kft	2 kft	2,5 kft	3 kft	4,2 kft
VDSL Physical	16	15,5	12,4	9,4	4,2
VDSL Payload	14,9	14,5	11,5	8,7	3,8
Ethernet CRS extension	14,3	13,6	10,5	7,6	3,7

line length (kft)

Obtained on 0.4 mm telephone cable, Type 278,untwisted, worse than 26 AWG

Conclusion

- A DMT-VDSL PHY that fullfills the EFMCu requirements has been presented. This PHY is:
  - Compliant to ETSI/TM6, ANSI/T1E1.4 and ITU-T G.993.1 standard documents
  - Supports all standard frequency plans (998, 997, Fx)
  - Allows full duplex through digital FDD
  - Is robust against RFI, bridged-taps, impulsive noise
  - Does not need analog filters to separate US/DS bands
  - Allows flexible frequency allocation by software
  - Ensures spectral compatibility with other DSL services when deployed in Public Networks
  - Is natively backward interoperable with ADSL Annexes A and B
- The DMT-VDSL PHY specifications relies on the DMT technology already proven with ADSL
- The DMT-VDSL technology is supported by an Alliance of more than 40 companies, five of which have recently expressed their intention to deliver DMT-VDSL interoperable products by end of 2002.