Capacity Calculations

Unbiased methodology to determine the rate vs. range EFM can achieve

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What this presentation is about

- Capacity calculations are a technology-independent method of services simulation
- This method is used by all worldwide experts including ITU/ETSI/ANSI, operators and academic groups
- Formalization and modeling of the assumptions allows an open discussion and verification of results

What this presentation will show

- What is NEXT (collision) and FEXT
- What are capacity calculations
- What are the assumptions used
- How noise and interference influence the results

What is channel capacity

- Channel capacity is an integral of the signal to noise ratio over the available bandwidth

$$C = \int_{f_{min}}^{f_{max}} \log_2\left(1 + \frac{S(f)}{N(f)}\right) df$$

  - **C is the limit of the achievable bit rate**

- A loss factor (L) that sums the influence of:
  - **Transmission efficiency @10^{-7} BER**
  - **Coding gain and noise margin**

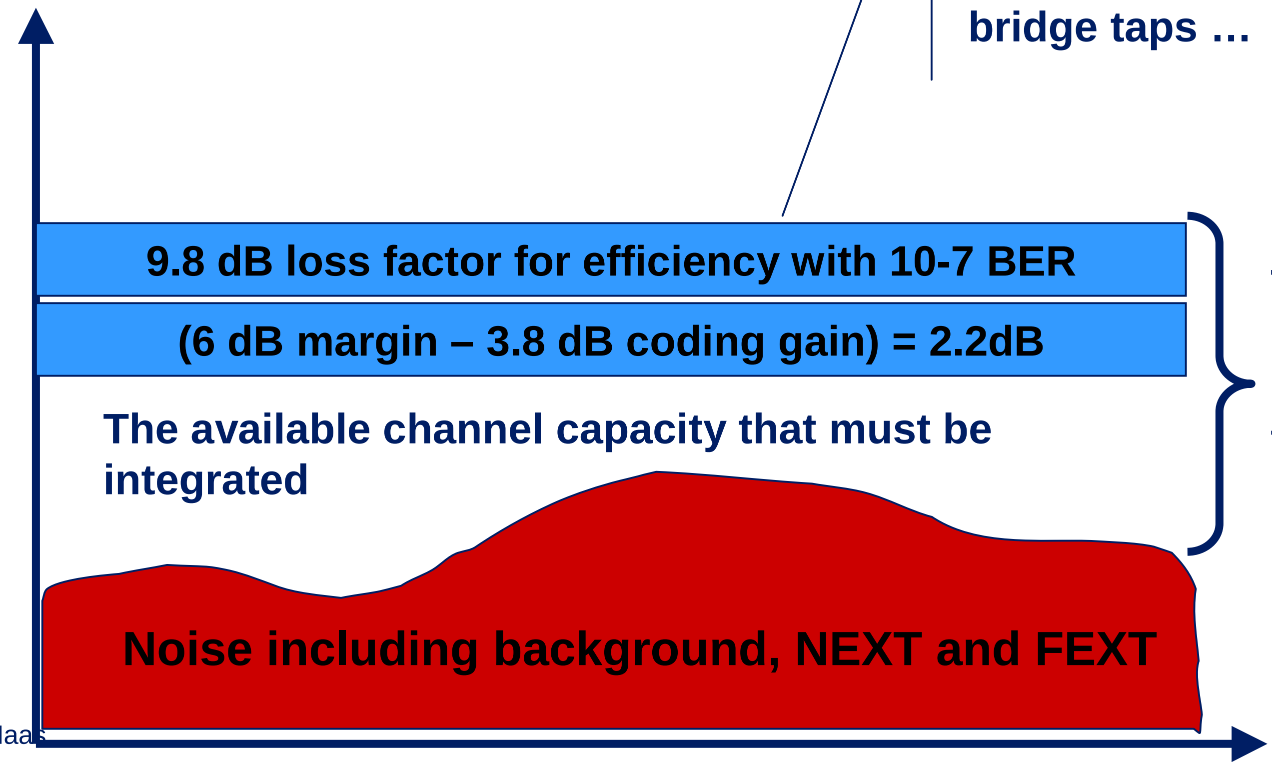
- The achievable bit rate for any system is:

$$B_{[bitrate]} = \int_{f_{min}}^{f_{max}} \log_2\left(1 + \frac{S(f)}{L \cdot N(f)}\right) df$$

Channel capacity in graphical terms

-From standards bodies

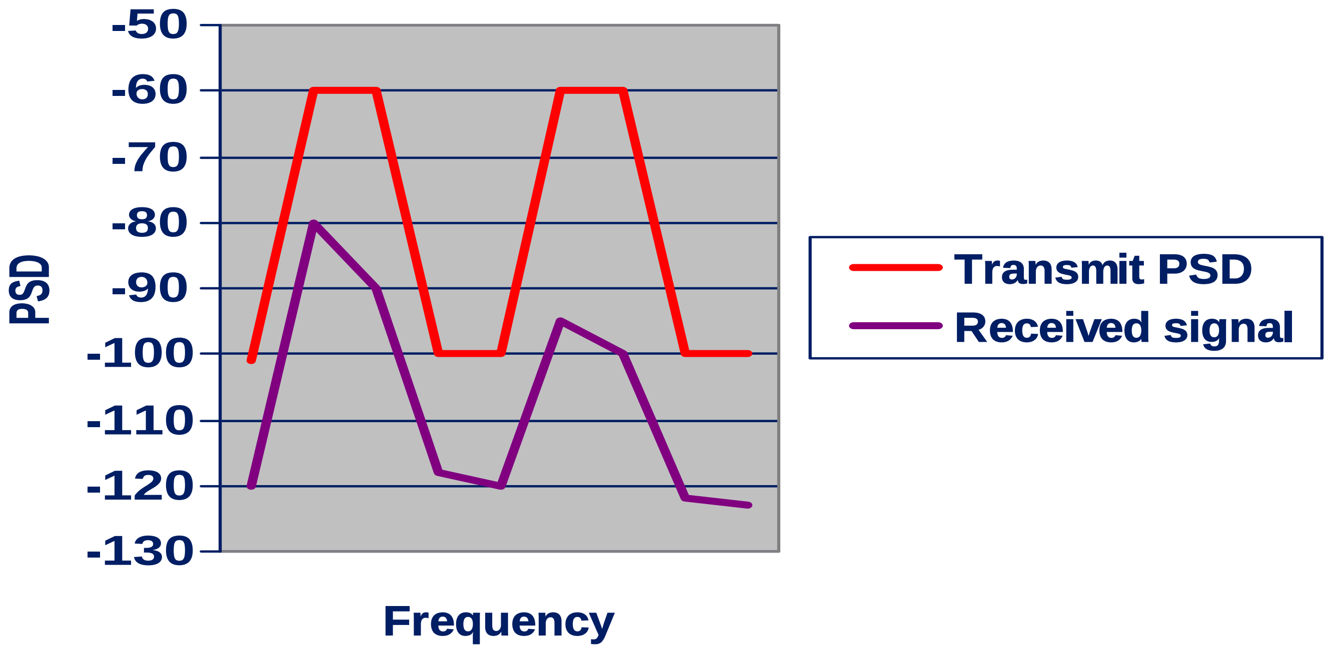
The received signal depends on the PSD of the transmitted signal and the channel characteristics (attenuation, bridge taps …



The maximal channel capacity for the received signal

The received signal [S]

- The received signal is a function of:
  - **The transmitted signal (limited by PSD masks)**
  - **The channel attenuation**



The loss factor (L)

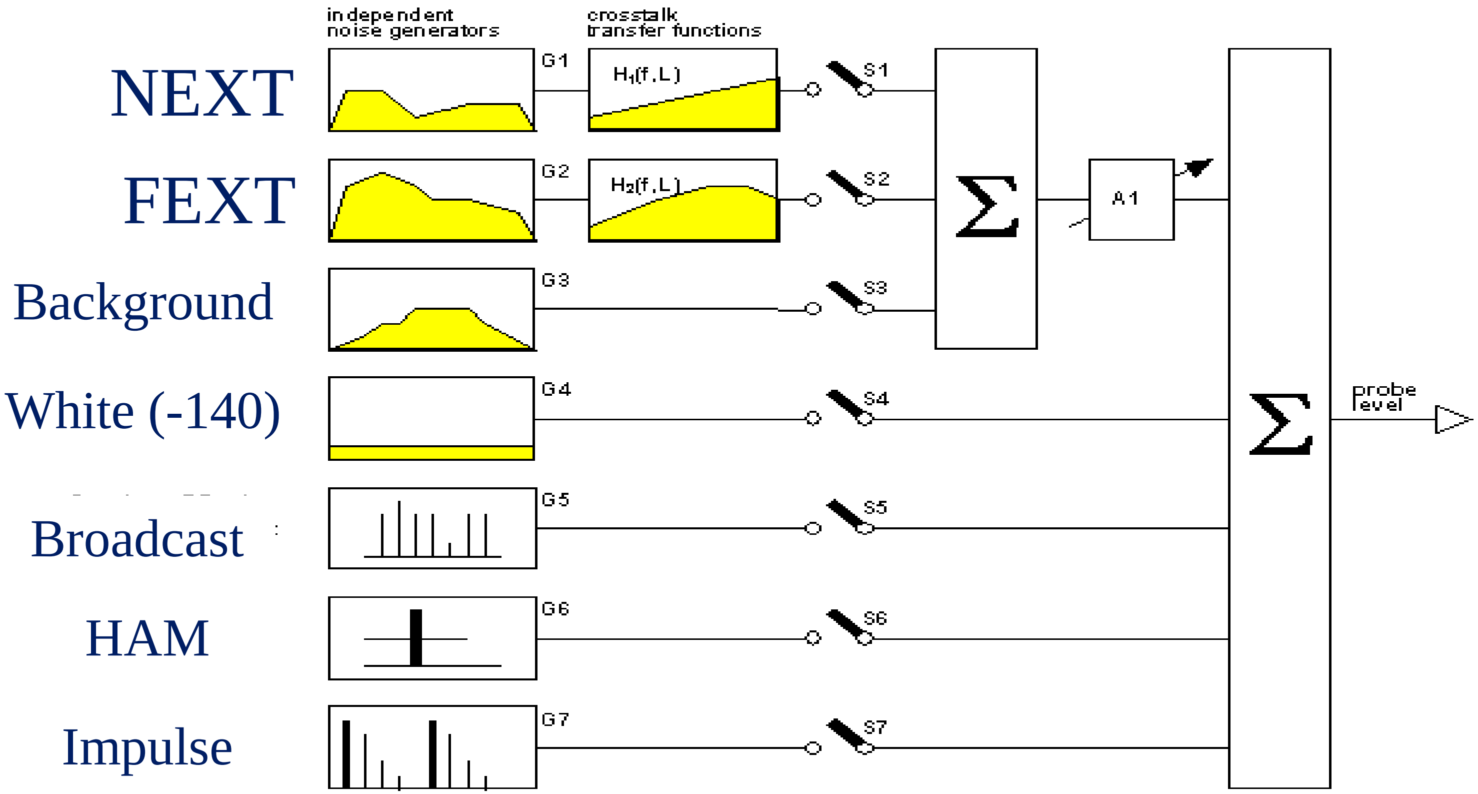
- The VDSL industry (all technologies)used:
  - –9.8 dB efficiency for BER of 10-7
  - –6 dB margin
  - +3.8 dB coding gain (Reed Solomon)

= 12.0 dB gap from theoretical capacity

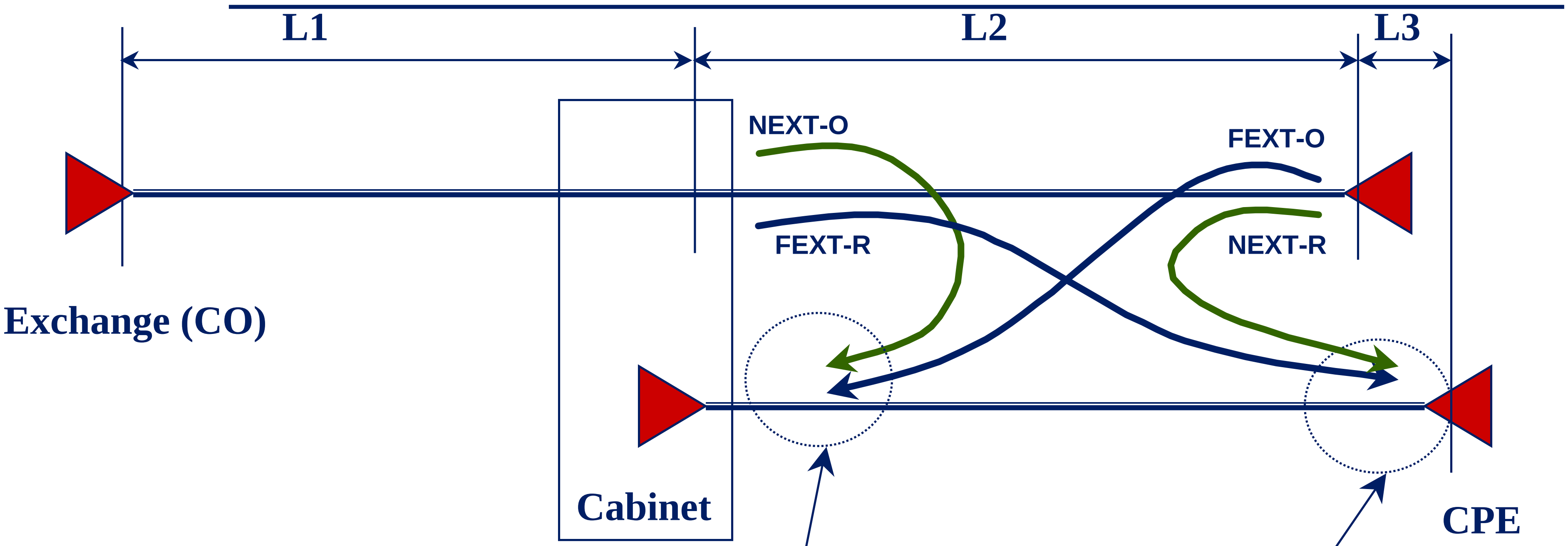
- May be improved in the long term as advances in coding become feasible in low cost silicon
- Differences in cables and variances in the local loops created the 6 dB margin

The Noise in the capacity calculations

- The FSAN noise model is used to summarize the noise at both ends of the loop.



FEXT and NEXT occur in cable bundles



<u>VTU-O (LT) scenario</u>
NEXT-O: DS (from CO) attenuated by **L1** km;
FEXT-O: US (from CPE) attenuated by **L2** km

<u>VTU-R (NT) scenario</u>
NEXT-R: US (from CPE) attenuated by **L3** km;
FEXT-R: DS (from CO) attenuated by **(L1+L2+L3)** km

NEXT can be avoided by duplexing

- Self–NEXT can be avoided if
  - – **the adjacent transmitter is turned off while the link is receiving (synchronized TDD)**
    - **TI has a presentation that was scheduled for Copenhagen that presented this**
  - – **or if different bands are used (FDD)**

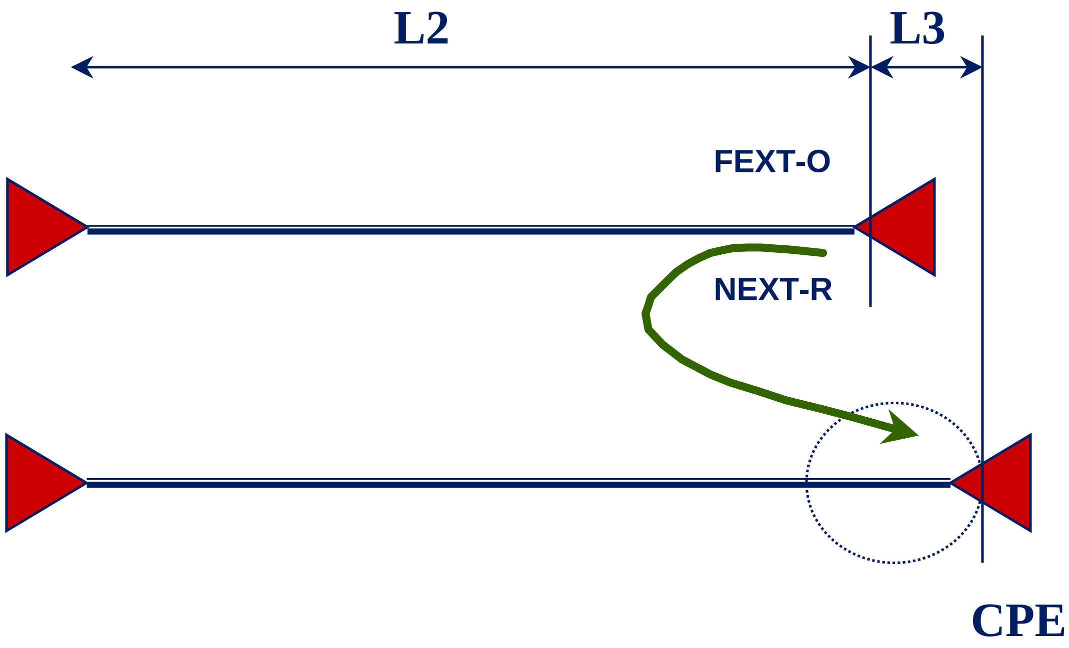
$$PSD_{NEXT} = PSD_{disturber} \cdot K_{next} \cdot (N/49)^{0.6} \cdot f^{1.5}$$

NEXT example from a non-synchronized TDD system

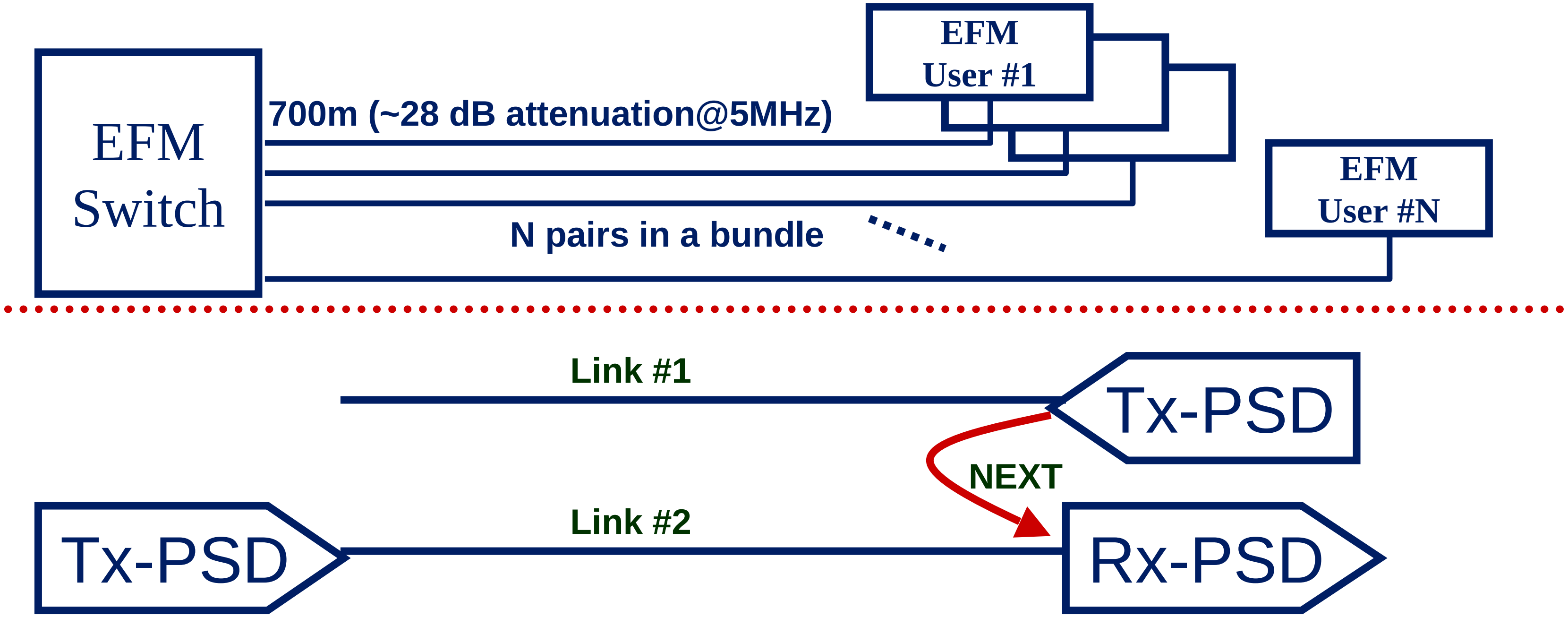
- No duplexing used (is a burst system)
- At 3000 ft / 5 MHz the first disturber injects noise which is only attenuated by 40dB

$$(1/49)^{0.6} K_{next} \cdot f^{1.5} \approx 5.9 \cdot 10^{-2} = -40dB$$

- The self-NEXT noise can be as strong as the real signal!!!

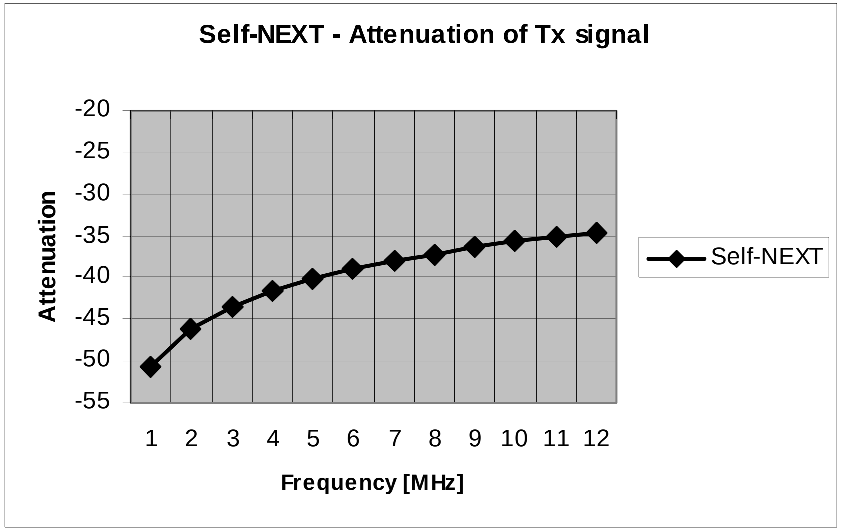


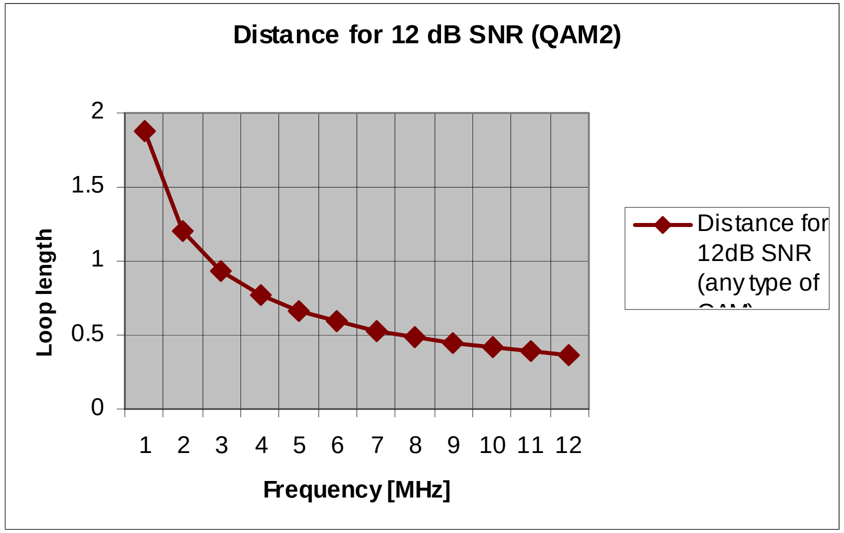
Every new user creates Self-NEXT and lowers the bit rate of the existing users (example)



- The received signal is attenuated by about 28 dB for a 700m 26 gauge cable (5MHz signal)
- The NEXT is attenuated by about 40 dB
- A "collision" occurs to all packets whenever an upstream burst takes place (not enough SNR)

A non-synchronized TDD system is NEXT limited in distance





- The self-NEXT level of a non-synchronized TDD system (relative to transmitted signal) can be found with the NEXT formula.
- The distance [km] at which the received signal is hidden by the self-NEXT is found for every frequency.
- The channel attenuation used is for 26 gauge cable (0.4mm).

Self-FEXT is in-band noise and can not be filtered

- The FEXT is a function of the disturber's signal (PSD), the number of disturbers, the length of coupling and the frequency
  - **Transmitting a stronger signal increases the self FEXT!**
  - **The higher the frequency, the stronger the FEXT**

$$PSD_{FEXT} = PSD_{disturber} \cdot K_{fext} \cdot |H(f)|^2 \cdot (N/49)^{0.6} \cdot d \cdot f^2$$

- At 3000 ft / 5 MHz the first disturber comes within –32 dB of first user

$$\mathbf{(1/49)^{0.6} K_{fext} \cdot d \cdot f^2 = 5.8 \cdot 10^{-2} = -32 dB}$$

- Every additional link reduces the SNR:
  - 1 new user = -32 dB
  - 2 new users = -30.2 dB
  - 4 new users = -28.4dB
  - 10 new users = -26 dB
  - 20 new users = -24.2 dB
  - 49 new users = -21.9 dB
  - Note: A loss of 3dB equals a loss of 1bit/sym

VDSL uses FDD and assumes 20 users in all calculations

- To avoid self-NEXT, VDSL uses FDD
  - **Clear boundaries between US and DS**
  - **Different types of users and services can co-exist in the same bundle**
  - **Synchronization is not needed (as in TDD)**
- Self-FEXT is considered for 20 users in a bundle
  - **Bandwidth is guaranteed to the users**
  - **There are no surprises and loss of bandwidth when a new user is connected to the service**

How do we use the capacity calculations

We decide on the available bandwidth, the PSD mask, the channel and the noise that will be used.

Achievable BIT RATE is determined with the capacity calculations. This rate is for a given distance

The duplexing method is modeled and creates another loss

Now we know what we really get

An example of channel capacity in Mbps

- The frequency range from 1.1-12MHz (from the cabinet or basement) can provide:
  - **over a 26AWG cable (no bridge tap)**
  - **Noise model A (ADSL exists in the bundle)**
  - **-60 dBm/Hz PSD**
  - **-140 dBm/Hz background noise**
  - **12 dB loss to Shannon capacity limit**

Mbps of achievable capacity

	100m	500m	1000m	1500m	2000m	3000m
1 pair **(No FEXT)**	209	115	29	6.5	0.7	0.002
24 FEXT	72	48	21	6.1	0.7	0.002

A band allocation is chosen

- An FDD band allocation was chosen so that it supports a mix of services
- Plan 998 is asymmetric oriented
- It is a compromise between the needs of different services and service providers

Duplexing losses

- Now we subtract the duplexing losses:
  - For FDD we subtract capacity of the guard/transition band
  - For synchronized TDD we subtract the bit rate that corresponds to the guard time
- Burst technology duplexing losses from “collisions”
  - Burst technology creates non-synchronized noise that can be translated to self-FEXT and self-NEXT. These interferences are actually collisions.
  - The more the burst service per bundle, the higher the probability of self-FEXT and self-NEXT collisions

Summary and Recommendations

- FDD is the only “standard” duplexing method that guarantees service. Non-synchronized TDD suffers from self-NEXT and self-FEXT collisions
- Models used in capacity calculations provide a common method to understand the physical limits of the cable plant
  - **Any topology or service model can be used**
- Capacity based calculations accepted globally as the way to determine what VDSL can achieve (rate vs. range) and should be accepted by IEEE as well
  - **VDSL standardization used this tool extensively and successfully, regardless of technology**