# Transmission properties of pair cables

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# Overview

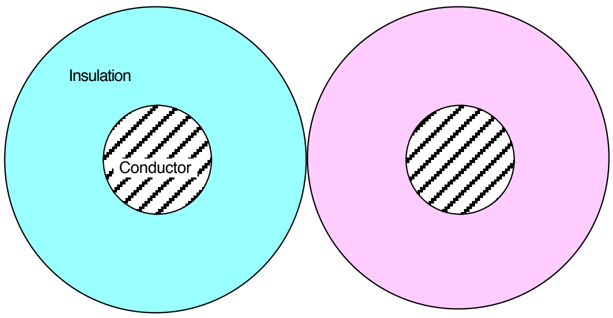
- Part I: Physical design of a pair cable
- Part II: Electrical properties of a single pair
- Part III: Interference between pairs, crosstalk
- Part IV: Estimates of channel capacity of pair cables. How to exploit the existing cable plant in an optimum way

# Part I
# Basic design of pair cables

- A single twisted pair
- Binder groups
- The cross-stranding principle
- Building binder groups and cables of different sizes
- A complete cable

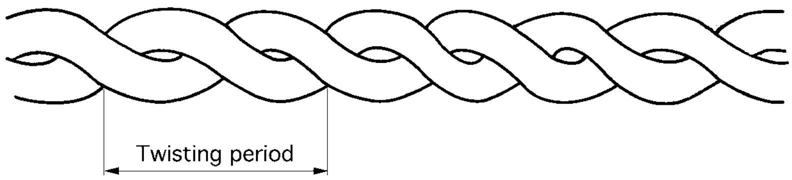


# Cross section of a single pair




Most common conductor diameters: 0.4 mm, 0.6 mm
(0.5 mm, 0.9 mm)

# A twisted pair

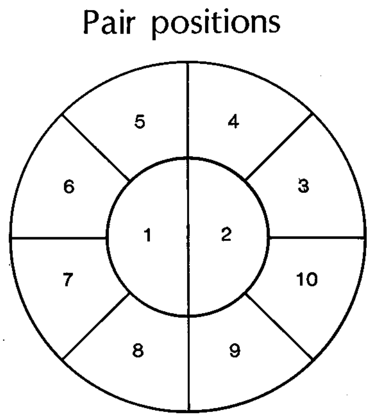





# Typical pair cables of the Norwegian access network

- 0.4 and 0.6 mm conductor diameter
- Polyethylene insulation (expanded)
- Twisting periods in the interval 50 - 150 mm
- 10 pair cross-stranded binder groups
- 10 - 2000 pairs in a cable

# Pair positions in a 10 pair binder group




**Cross-stranding [13]:**
The positions of all the pairs are alternated randomly along the cable. Interference is thus randomised, and all pairs will be almost uniform

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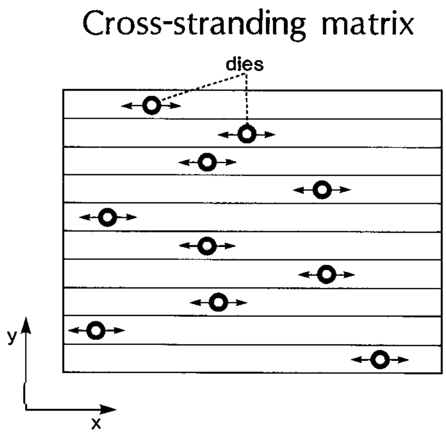
# Cross-stranding




**Cross-stranding technique:**
Each pair runs through a die in the cross-stranding matrix.
The positions of the dies are set by a random generator

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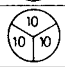
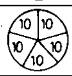
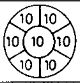
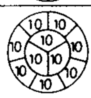
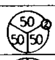
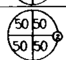
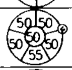
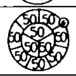
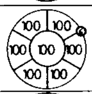
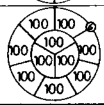
# Design of binder groups up to 100 pairs

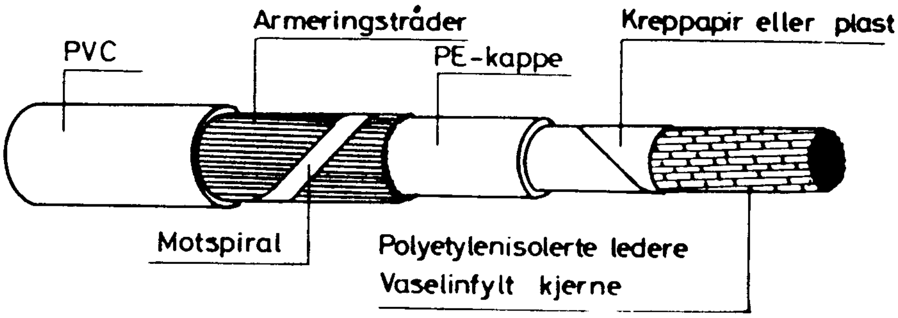
| Partall | Grunn-grupper | Kabalsnitt | Merknad |
|---|---|---|---|
| 10 | 1 |  | Grunngruppe |
| 20 | 2 |  | |
| 30 | 3 |  | |
| 50 | 5 |  | Hovedgruppe 50 pars |
| 70 | 1+6 |  | |
| 100 | 3+7 |  | Hovedgruppe 100 pars |



# Design of binder groups up to 1000 pairs

| Partall | Grupper | Kabelsnitt | Reservepar |
|---|---|---|---|
| 150 | 3 |  | 2 |
| 200 | 4 |  | 2 |
| 300 | 1+5 |  | 4 |
| 500 | 3+7 |  | 6 |
| 700 | 1+6 |  | 6 |
| 1000 | 3+7 |  | 6 |

# Typical cable design ("Kombikabel")



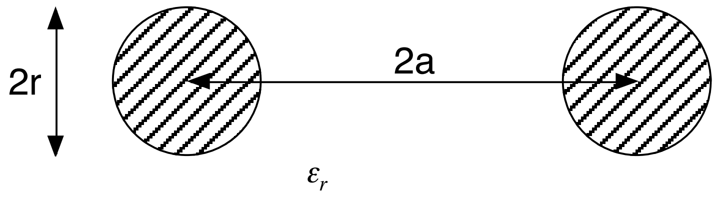

This cable may be used as:
1) overhead cable
2) buried cable
3) in water (fresh water)



# Part II
# Properties of a single pair

- Equivalent model of a single pair
- Capacitance
- Inductance
- Skin effect
- Resistance
- Per unit length model of a pair
- The telegraph equation - solution
- Propagation constant
- Characteristic impedance
- Reflection coefficient, terminations

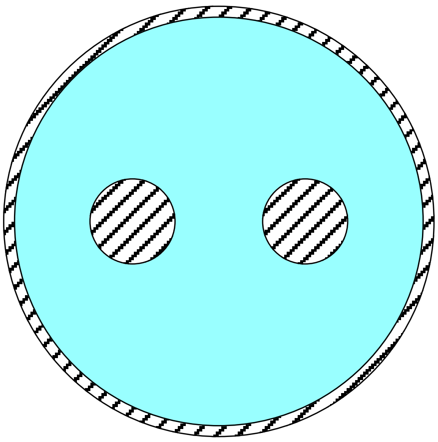
# A single pair in uniform insulation




A coarse estimate of the primary parameters R, L, C, G may be found assuming a >> r, uniform insulation, and no surrounding conductors



# Model of a single pair in a cable



The electrical influence of the surrounding pairs in the cable may be modelled as an equivalent shield. This model will give accurate estimates of R, L, C and G [12]

## Capacitance of a single pair

The capacitance per unit length of a single pair is given by:

$$C = \frac{\pi \varepsilon_0 \varepsilon_r}{\ln \frac{2a}{r}}$$

The capacitance of cables in the access network is 45 nF/km



## Inductance of a single pair

The inductance per unit length of a single pair is given by:

$$L = \frac{\mu_0}{\pi} \ln \frac{2a}{r}$$

# Skin effect

At high frequencies the current will flow in the outer part of the conductors, and the skin depth is given by [12]:

$$\delta = \frac{1}{\sqrt{\pi f \mu_r \mu_0 \sigma}}$$

$\sigma$ is the conductance of the conductors

For copper the skin depth is given by:

$$\delta = \frac{2,11}{\sqrt{F_{\text{kHz}}}} \quad \text{mm}$$

$\delta$ = 2.11 mm at 1 kHz

$\delta$ = 0.067 mm at 1 MHz



# Resistance of a conductor

The resistance per unit length of a conductor is for r << a given by:

$$R_C = \begin{cases} \dfrac{1}{\sigma \pi r^2} & \text{for} \quad \delta >> r \quad \text{(low frequencies)} \\ \dfrac{1}{2\sigma \pi r \delta} & \text{for} \quad \delta << r \quad \text{(high frequencies)} \end{cases}$$

# Resistance of a pair

The resistance per unit length of a pair will be the sum of the resitances of the two conductors and is given by:

$$R = 2 \cdot R_C = \begin{cases} \dfrac{2}{\sigma \pi r^2} & \text{for} \quad \delta >> r \quad \text{(low frequencies)} \\ \dfrac{1}{\sigma \pi r \delta} & \text{for} \quad \delta << r \quad \text{(high frequencies)} \end{cases}$$



# Conductance of a pair

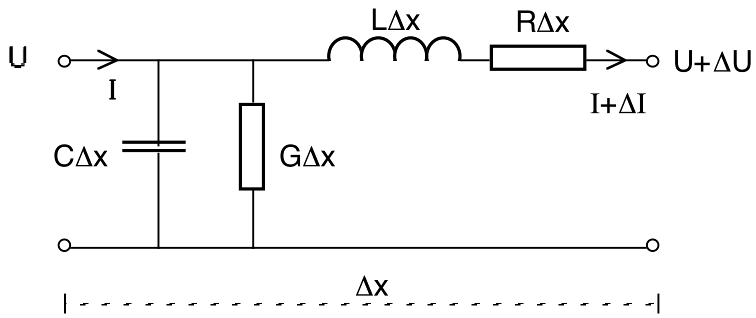
The conductance per unit length of a pair is given by:

$$G = \delta_l \cdot \omega C$$

$\delta_l$ is the dielectric loss factor

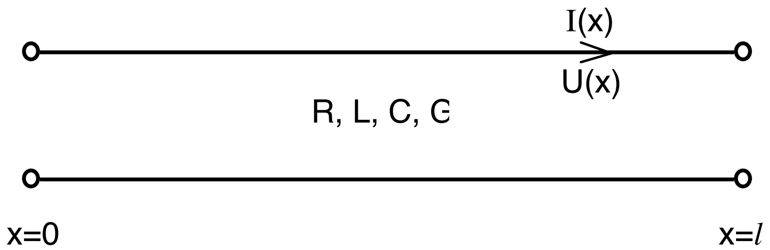
A typical value of the loss factor is $\delta_l = 0.0003$. This means that the conductance is usually negligible for pair cables.

# Per unit length model of a pair






# Model of a pair of length *l*



# The telegraph equation

From the circuit diagram:

$$\frac{d}{dx}U(x) = -(R + j\omega L)I(x) = -Z \cdot I(x)$$

$$\frac{d}{dx}I(x) = -(G + j\omega C)U(x) = -Y \cdot U(x)$$

Combining the equations:

$$\frac{d^2}{dx}U(x) = Z \cdot Y \cdot U(x)$$



# Solution of the telegraph equation

$$U(x) = c_1 \cdot e^{\gamma \cdot x} + c_2 \cdot e^{-\gamma \cdot x}$$

$$I(x) = -\frac{c_1}{Z_0} \cdot e^{\gamma \cdot x} + \frac{c_2}{Z_0} \cdot e^{-\gamma \cdot x}$$

$c_1$ and $c_2$ are constants
$\gamma$ is propagation constant
$Z_0$ is characteristic impedance

# Propagation constant

$$\gamma = \sqrt{Z \cdot Y} = \sqrt{(R + j\omega L) \cdot (G + j\omega C)} =$$

$$\sqrt{(R + j\omega L) \cdot j\omega C}$$

$$\gamma = \alpha + j\beta$$

$\alpha$ is the attenuation constant in Neper/km
$\beta$ is the phase constant in rad/km

Neper to dB:

$$\alpha_{dB} = \frac{20}{\ln(10)}\alpha = 8.69\alpha$$



# Characteristic impedance

$$Z_0 = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}} = \sqrt{\frac{(R + j\omega L)}{j\omega C}}$$

At high frequencies $R << j\omega L$ :

$$Z_0 = \sqrt{\frac{L}{C}}$$

The characteristic impedance is approximately 120 ohms at high frequencies for pair cables in the access network

# Attenuation constant

At high frequencies ($f > 100$ kHz) $R << \omega L$.
By series expansion of $\gamma$ :

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} = \frac{R}{2}\sqrt{\frac{C}{L}} = k_1 \cdot \sqrt{f}$$

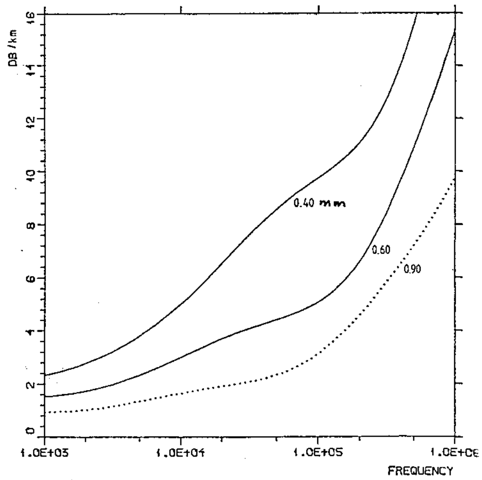
At low frequencies ($f < 10$ kHz) $R >> \omega L$. Hence:

$$\gamma = \sqrt{j\omega C \cdot R} = (1 + j)\sqrt{\frac{\omega \cdot R \cdot C}{2}}$$

$$\alpha = \beta = \sqrt{\frac{\omega \cdot R \cdot C}{2}} = k_2 \sqrt{f}$$



# Attenuation constant of pair cables



# Phase constant

At high frequencies ($f > 100$ kHz):

$$\beta = \omega\sqrt{L \cdot C} = k_3 \cdot f$$

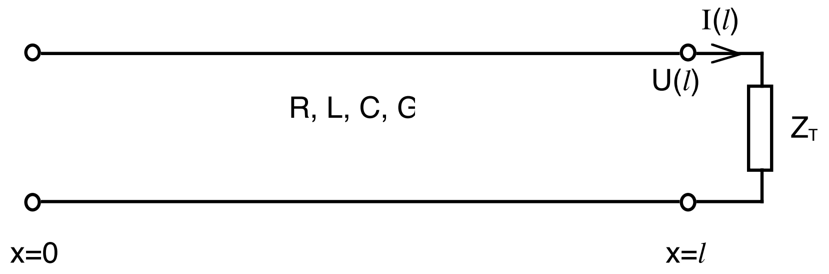
Phase velocity:

$$v = \frac{\Delta x}{\Delta t} = \frac{\text{wavelength}}{\text{cycle}} = \frac{2\pi/\beta}{2\pi/\omega} = \frac{\omega}{\beta} = \frac{1}{\sqrt{L \cdot C}} = \frac{c}{\sqrt{\varepsilon_r}}$$

Phase velocity is 200 000 km/s for pair cables at high frequencies ($\varepsilon_r = 2.3$ for polyethylene)



# Termination of a pair



# Reflection coefficient

$$U(x) = V_+ \cdot e^{\gamma\cdot(\ell-x)} + V_- \cdot e^{-\gamma\cdot(\ell-x)}$$

$$I(x) = \frac{V_+}{Z_0} \cdot e^{\gamma\cdot(\ell-x)} - \frac{V_-}{Z_0} \cdot e^{-\gamma\cdot(\ell-x)}$$

$$Z_T = \frac{U(\ell)}{I(\ell)} = Z_0 \frac{V_+ + V_-}{V_+ - V_-}$$

Solution of telegraph equation including termination imp. $Z_T$
$V_+$ is voltage of wave in positive direction at $x=l$
$V_-$ is voltage of reflected wave in at $x=l$

Reflection coefficient:

$$\rho = \frac{V_-}{V_+} = Z_0 \frac{Z_T - Z_0}{Z_T + Z_0}$$

No reflections ($\rho = 0$) for $Z_T = Z_0$ . Ideal terminations are assumed in later crosstalk calculations



# Part III
# Crosstalk in pair cables

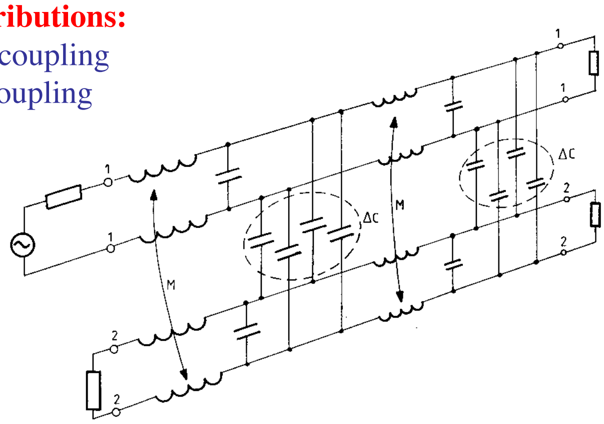
- Basic coupling mechanisms
- Crosstalk coupling per unit length
- Near end crosstalk, NEXT
- Far end crosstalk, FEXT
- Statistical crosstalk coupling
- Average NEXT and FEXT
- Crosstalk power sum - crosstalk from many pairs
- Statistical distributions of crosstalk

# Crosstalk mechanisms

**Main contributions:**

Capacitive coupling

Inductive coupling

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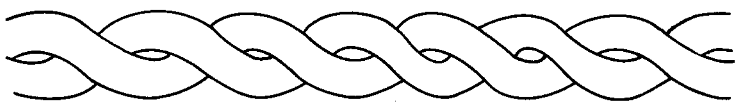
# Ideal and real twisting of a pair

Ideal twisting



Actual twisting of a real pair

The crosstalk level observed in real cables
is caused mainly by deviations from ideal twisting

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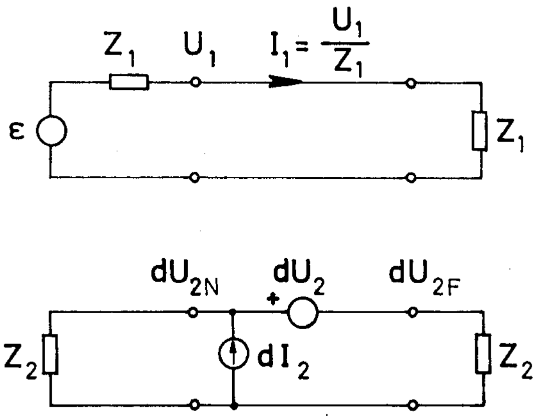
# Crosstalk coupling per unit length

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# Crosstalk coupling per unit length

Normalised NEXT coupling coefficient [11]:

$$\kappa_{\mathrm{N}i,j}(x) = \frac{1}{j\beta_0} \cdot \frac{dU_{2\mathrm{N}}}{U_1 \cdot dx} = \frac{1}{2} \cdot \left( \frac{C_{i,j}(x)}{C} + \frac{L_{i,j}(x)}{L} \right)$$

Normalised FEXT coupling coefficient [11]:

$$\kappa_{\mathrm{F}i,j}(x) = \frac{1}{j\beta_0} \cdot \frac{dU_{2\mathrm{F}}}{U_1 \cdot dx} = \frac{1}{2} \cdot \left( \frac{C_{i,j}(x)}{C} - \frac{L_{i,j}(x)}{L} \right)$$

$C_{i,j}(x)$ is the mutual capacitance per unit length between pair $i$ and $j$
$L_{i,j}(x)$ is the mutual inductance per unit length between pair $i$ and $j$
$\beta_0$ is the lossless phase constant, $\beta_0 = \omega\sqrt{L \cdot C}$

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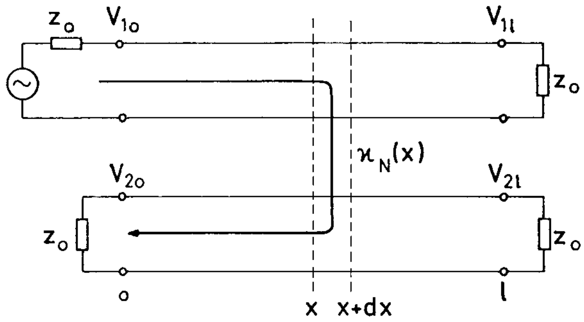
# Near end crosstalk, NEXT





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# Near end crosstalk, NEXT

Assuming weak coupling, the near end voltage transfer function is given by [11]:

$$H_{NE}(f) = \frac{V_{20}}{V_{10}} = j\beta_0 \int_0^{\ell} \kappa_N(x) e^{-2\alpha x - 2j\beta x} dx$$


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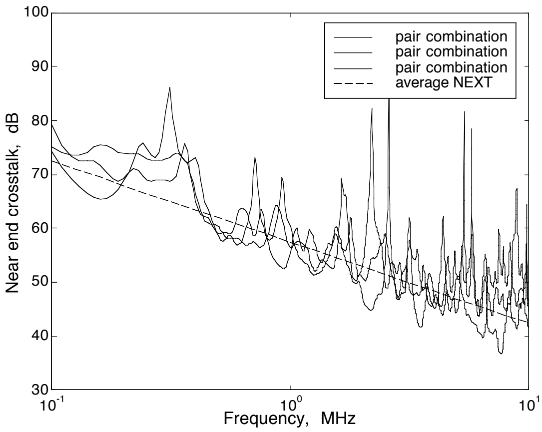
# NEXT between two pairs






# Stochastic model of crosstalk couplings

Crosstalk coupling factors are white Gaussian stocastic processes:

NEXT autocorrelation function [6]:

$$R_N(\tau) = E\left[\kappa_N(x)\cdot\kappa_N(x+\tau)\right] = k_N \cdot \delta(\tau)$$

FEXT autocorrelation function [6]:

$$R_F(\tau) = E\left[\kappa_F(x)\cdot\kappa_F(x+\tau)\right] = k_F \cdot \delta(\tau)$$

$k_N$ and $k_F$ are constants

# Average NEXT

Average NEXT power transfer function between two pairs [6]:

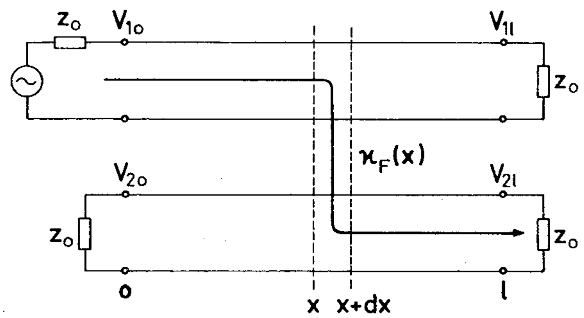
$$p(f) = E\left[\left|H_{NE}(f)\right|^2\right] = E\left[\left|\frac{V_{20}}{V_{10}}\right|^2\right] =$$

$$\beta_0^2 k_N \int_0^{\ell} e^{-4\alpha x} dx = \frac{\beta_0^2 \cdot k_N}{4\alpha}\left(1 - e^{-4\ell}\right) \approx \frac{\beta_0^2 \cdot k_N}{4\alpha} = k_{N2} \cdot f^{1.5}$$

NEXT increases 15 dB/decade with frequency



# Far end crosstalk, FEXT



# Far end crosstalk, FEXT

Assuming weak coupling, the far end voltage transfer function is given by [11]:

$$H_{FE}(f) = \frac{V_{2\ell}}{V_{1\ell}} = j\beta_0 \int_0^{\ell} \kappa_F(x)\, dx$$



# Average FEXT

Average FEXT power transfer function between two pairs [6]:

$$q(f) = E\left[\left|H_{FE}(f)\right|^2\right] = E\left[\left|\frac{V_{2\ell}}{V_{1\ell}}\right|^2\right] =$$

$$\beta_0^2 \int_0^{\ell} k_F\, dx = k_F \cdot \beta_0^2 \cdot \ell = k_{F2} \cdot f^2 \cdot \ell$$

FEXT increases 20 dB/decade with frequency
FEXT increases 10 dB/decade with cable length

# Crosstalk from *N* different pairs crosstalk power sum

- Only crosstalk between identical systems is considered (self NEXT and self FEXT)
- Crosstalk from different pairs add on a power basis
- Effective crosstalk is given by the sum of crosstalk power transfer functions, which is denoted **crosstalk power sum**



# Crosstalk from N different pairs crosstalk power sum

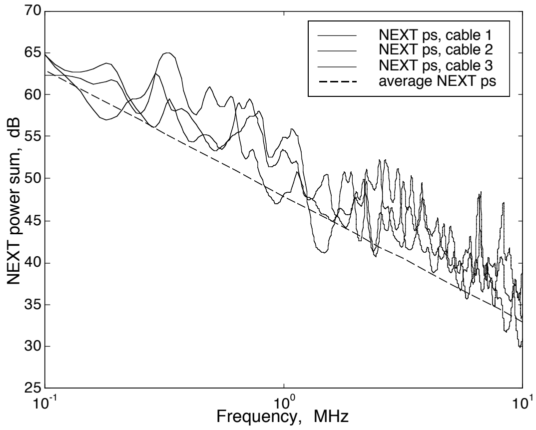
NEXT crosstalk power sum for pair no *i*:

$$\left|H_{NE\,ps}(f)\right|^2 = \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[ \left|H_{NE\;i,j}(f)\right|^2 \right]$$

FEXT crosstalk power sum for pair no *i*:

$$\left|H_{FE\,ps}(f)\right|^2 = \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[ \left|H_{FE\;i,j}(f)\right|^2 \right]$$

# NEXT power sum





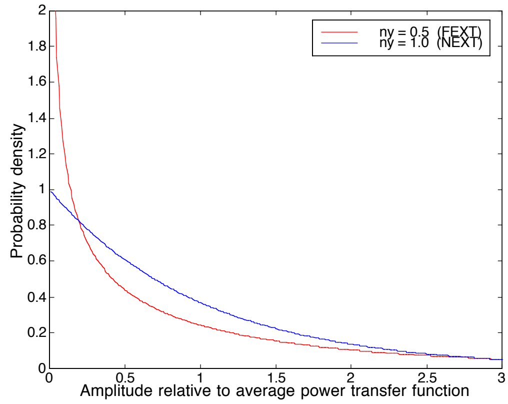

# Probability distributions of crosstalk

Crosstalk power transfer function for a single pair combination at a given frequency is gamma-distributed with probability density [6]:

$$p_z(z) = \frac{1}{\Gamma(\nu)} \cdot \left(\frac{\nu}{a}\right)^{\nu} \cdot z^{\nu-1} \cdot e^{-\frac{\nu z}{a}}$$

$\nu = 1.0$ for NEXT
$\nu = 0.5$ for FEXT
$a$ is average crosstalk power

# Probability density of NEXT and FEXT for a single pair combination






# Probability of crosstalk for an arbitrary pair combination

Different pair combinations will have different levels of crosstalk coupling (different $k_N$ and $k_F$).

It can be shown that:

The crosstalk power transfer function for a random pair combination is approximately gamma-distributed

The number of degrees of freedom, $\nu$ must be found empirically. $\nu < 1.0$ for NEXT and $\nu < 0.5$ for FEXT

# Probability of crosstalk power sum

Crosstalk from different pairs add on a power basis. Hence, crosstalk power sum is approximately gamma-distributed with probability distribution:

$$p_{ps}(z) = \frac{1}{\Gamma(\nu_{ps})} \cdot \left( \frac{\nu_{ps}}{a_{ps}} \right)^{\nu_{ps}} \cdot z^{\nu_{ps}-1} \cdot e^{-\frac{\nu_{ps} z}{a_{ps}}}$$

$a_{ps}=Na$, where a is the average crosstalk of one pair combination
$\nu_{ps}=N\nu$, where $\nu$ is the number of degrees of freedom for a random pair combination
$N$ is the number of disturbing pairs

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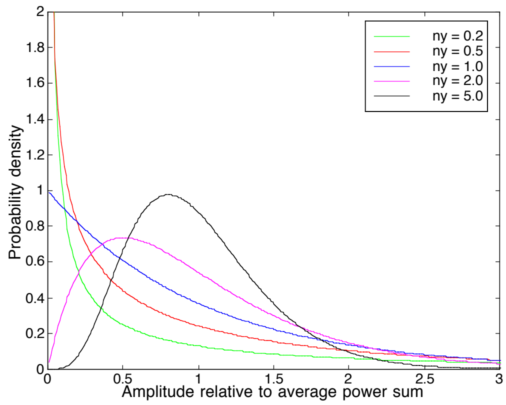
# Probability density of crosstalk power sum

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# Worst case crosstalk

Crosstalk dimesioning is usually based upon the 99% point of NEXT and FEXT power sum, which is given by (1% of the pairs will have crosstalk that exceeds this limit):

$$p_{ps99}(f) = N \cdot E\left[k_{\mathrm{N2}}\right] \cdot f^{1.5} \cdot c_{99}(v_{ps}) \quad \text{for} \quad \text{NEXT}$$

$$q_{ps99}(f) = N \cdot E\left[k_{\mathrm{F2}}\right] \cdot f^{2} \cdot \ell \cdot c_{99}(v_{ps}) \quad \text{for} \quad \text{FEXT}$$

$c_{99}(v_{ps})$ is the ratio between the 99% point and the average power sum in the gamma distribution

The expectations $E[k_{\mathrm{N2}}]$ and $E[k_{\mathrm{F2}}]$ are taken over all pair combinations



# Empirical worst case NEXT model

International model of 99% point of NEXT power sum based upon 50 pair binder groups:

$$p_{ps\,99}(F) = 10^{-4} \cdot \left(\frac{N}{49}\right)^{0.6} \cdot F^{1.5}$$

$N$ is the number of disturbing pairs in the cable
$F$ is the frequency in MHz

This model fits well with 100% filled Nowegian cables with 10 pair binder groups

# Empirical worst case FEXT model

International model of 99% point of FEXT power sum based upon 50 pair binder groups:

$$q_{ps\,99}(F) = 3 \cdot 10^{-4} \cdot \left(\frac{N}{49}\right)^{0.6} \cdot F^2 \cdot L$$

*N* is the number of disturbing pairs in the cable
*F* is the frequency in MHz
*L* is the cable length in km

This model fits well with 100% filled Nowegian cables with 10 pair binder groups



# Part IV
# Channel capacity estimates [1,2,8]

- Shannon's channel capacity formula
- Signal and noise models
- Realistic estimates of channel capacity
- Channel capacity per bandwidth unit
- One-way transmission
- Two-way transmission
- Crosstalk between different types of systems, alien NEXT, alien FEXT

# Shannon's theoretical channel capacity

Maximum theoretical channel capacity
in the frequency band [*fl*,*fh*]:

$$C_{Sh} = \int_{fl}^{fh} \log_2\left(1 + \frac{S(f)}{N(f)}\right) df \quad \text{bit/s}$$

*S*(*f*): signal power density
*N*(*f*): noise power density



# Capacity per bandwidth unit

A realistic estimate of bandwidth efficiency [2]:

$$\eta(f) = \frac{\Delta C}{\Delta f} = k_{eff} \cdot \log_2\left(1 + \lambda \cdot \frac{S(f)}{N(f)}\right) \quad \text{bit/s/Hz}$$

*S*(*f*): signal power density
*N*(*f*): noise power density
$\lambda \leq 1$: factor for margin (safety margin + margin for mod.meth.)
$k_{eff} \leq 1$: factor for overhead (sync bits, RS-code, cyclic prefix)

# Signal transmission

- Attenuation proportional to $\sqrt{f}$ due to skin effect ($f$ > 100 kHz)
- Signal transfer function:

$$H(f) = 10^{-\frac{\alpha_{dB}\ell}{20}} = \exp\left(-k\ell\sqrt{f}\right)$$

$\alpha_{dB}$: attenuation constant in dB



# Signal and noise models

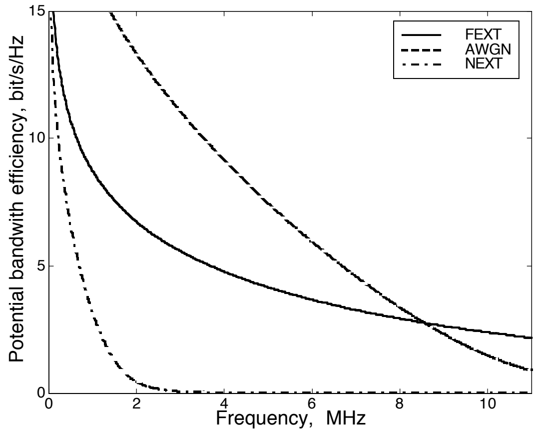
- Signal:

$$S(F) = e^{-2\alpha L}$$

- Noise models:

$$N(F) = \begin{cases} N_{NEXT} = 10^{-4} \cdot F^{1.5} & NEXT \\ N_{FEXT} = 3 \cdot 10^{-4} \cdot F^2 \cdot L \cdot e^{-2\alpha L} & FEXT \\ N_{AWGN} = 10^{-8} & AWGN \end{cases}$$

# Channel capacity vs. frequency

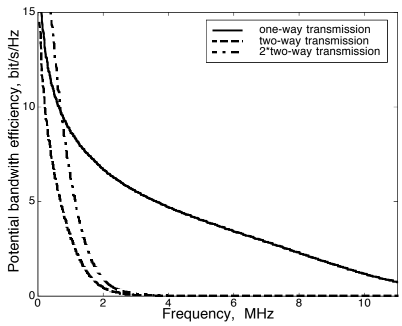



L=1 km

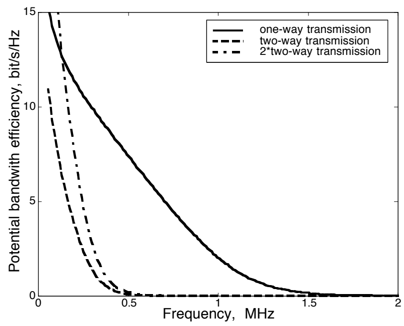


# Channel capacity vs frequency II

L=1 km




L=3 km



# Total channel capacity

One-way transmission:

$$R_{one-way} = k_{eff} \int_{fl}^{fh} \log_2 \left( 1 + \lambda \cdot \frac{S(F)}{N_{FEXT} + N_{AWGN}} \right) df$$

Two-way transmission:

$$R_{two-way} = k_{eff} \int_{fl}^{fh} \log_2 \left( 1 + \lambda \cdot \frac{S(F)}{N_{NEXT} + N_{FEXT} + N_{AWGN}} \right) df$$

The channel capacity is somewhat greater than this expression for two-way transmission due to uncorrelated NEXT in different frequency bands [9,10]



# Assumptions for estimation of bitrates

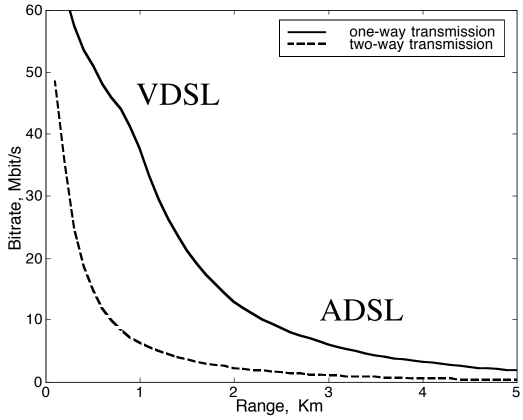
- For one-way transmission, the total bitrate found in the calculations must be divided by downstream and upstream transmission
- Identical systems in all pairs of the cable (only self NEXT and self FEXT)
- All pairs are used, the cable is 100% filled
- Net bitrate is 90% of total bitrate ($k_{eff}$=0.90)
- Frequency band: $f \geq$ 100 kHz, upper limit 11 MHz

# Assumptions II

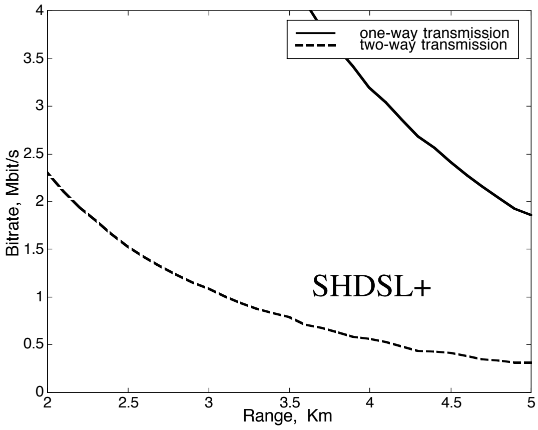
- Multicarrier modulation [7]
- Adaptive modulation in each sub-band
- M-TCM modulation in each sub-band
  $4 \leq M \leq 16384$, 1 - 13 bit/s/Hz
- Distance to Shannon ($\lambda$): 9 dB
  (6 dB margin + 3 dB for modulation)
- White noise: 80 dB below output signal
- Cable: 0.4 mm, 22.5 dB/km at 1 MHz



# Potential range for .4 mm cable



# Potential range for .4 mm cable II



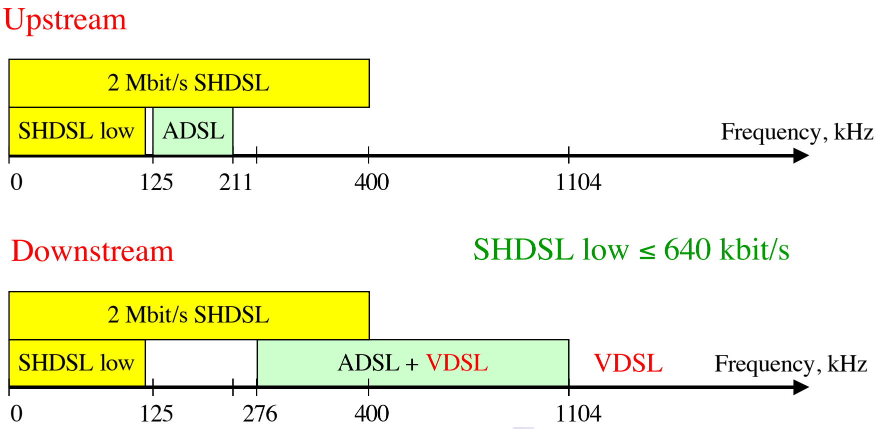

SHDSL+ means a multicarrier system using approximately the same frequency band as SHDSL



# Digital Subscriber Line systems, xDSL

- ADSL; Asymmetric Digital Subscriber Lines [5]
  - Asymmetric data rates, 256 kbit/s - 8 Mbit/s downstream, range up to 4 - 5 km
- SHDSL; Symmetric High-speed Digital Subscriber Lines [3]
  - Symmetric data rates, 192 kbit/s - 2.3 Mbit/s, range up to 6 - 7 km
- VDSL; Very high-speed Digital Subscriber Lines
  - Asymmetric or symmetric data rates (still under standardisation), up to 52 Mbit/s downstream, range typically ≤ 1 km [4]

# Frequency allocations in the access network






# Conclusions

- Frequency planning in pair cables is very important
- New systems should be introduced with great care in order to preserve the potential transmission capacity of the cable
- Full rate SHDSL systems overlaps with ADSL

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