Transmission media for Telecommunication

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1 INTRODUCTION

The course "Transmission media for Telecommunication" introduces students to a wide range of knowledge for transmitting various types of information. Seen from the historical point of view, media for information transmission are closely connected with the invention of the telegraph (Samuel Morse, 1832) using one wire line with earth as the backhauling conductor. Intensive development of telegraph began subsequently; Europe was linked with America in 1858. The invention of telephone (Alexander Graham Bell, 1876) initiated the development of telephone lines. The following invention of wireless transmission (Guglielmo Marconi, 1901) led to a stormy development of this type of transmission. The discovery of short waves (1926) enabled first of all intercontinental transmissions (1927 - England - USA). Further research and development returned focus on opening new horizons in quality as well as reliability of transmissions.

The first coaxial cable connecting Europe and America (1956), known as TAT-7, enabled transmission of 36 analogue telephone channels. The next step are satellites (1961). Everybody has the impression that the most perspective connection has entered the scene.... The last coaxial cable (TAT-10) was installed in 1983. The transmitting capacity is 4200 telephone channels, the repeating step is 9km. A new phenomenon has recently appeared: the optical fibre. An extreme broad bandwidth enables the transmission of a large information capacity; the high bit rates are coupled with excellent reliability, immunity from disturbances and tapping, including very light weight. The first optical transatlantic submarine cable TAT-8 was introduced in 1988.

The very last to have been installed was TAT 12-13, equipped with optical amplifiers using ring topology, enables a bit rate of 2.5 Gbit/s, that is 38000 digital telephone channels. The subsequent upgrade came with wave multiplexing (WDM). The transmission capacity may be enlarged 4x, 8x, 40x and, expressed in telephone channels maybe one million calls could be reached. The transfer to fibre optics is comparable with the change of simple walking to flying by plane. Although the technical features of fibre optics seem to be infinite, we are obliged to integrate its costs into the balance sheet.

We try to reach extreme bit rates in closing the metallic last mile - using a precise technology for the so-called structured cabling systems as well as utilising new types of sophisticated xDSL modulations. xDSL systems can exploit the existing access networks: sort of treasure trove due to the extreme costs of laying cables.

As mentioned before, transmission media are the linkage agent between two points, cities, states and continents. These connections require international cooperation in technical standardisation, design, maintenance, billing, etc. Therefore the International Telecommunication Union (Telegraph originally) was already founded in 1865 (May 17th is celebrated as the World Day of Telecommunication). ITU is seated in Geneva, Switzerland. ITU has been a technical organisation of the United Nations since 1947: it is obliged to keep and broaden international cooperation in upgrading all types of telecommunication services, supporting the deployment of technical means as well as their exploitation. ITU is involved in the allocation of frequency bandwidths, in the prevention of disturbances of all wireless services, in tariffing, supporting investments, and the deployment and upgrading of telecommunication equipment in the developing countries. Two commissions are currently active: ITU-T (telecommunication) and ITU-R (radiocommunication).

Their outputs are published in Recommendations, the so-called 'colour' books. These
Recommendations are mandatory, being authorised by the Council of Government Deputies of individual member states (once in 5 years, with almost all states of the world participating). Well-known are the former abbreviations CCITT, CCIR (for the French: Comité Consultatif International Télégraphique et Téléphonique, Radionique). The course introduces individual transmission media as follows.

The theoretical knowledge is amended with laboratory exercises; they focus on gaining practical skills in installing optical fibres (welding, quality and fault measurements, simulation of systems). The text is printed without language editing.
2 INCLUSION OF THE COURSE IN THE STUDY PROGRAMME

2.1 Introduction to the course

The course is registered as optional in summer semester of 2nd year of Bc studies. It offers a basis for the majority of courses given such as communication technologies, data communication, network architecture in the same year as well as for courses taught in next years of studies.

2.2 Entry test

This will be specified after consultations with lecturers in courses already completed by the student.
3 ANALYSIS OF LINE - BASIC RELATIONS OF HOMOGENOUS LINE

From the transmission point of view, electrical properties of line are characterised by primary parameters: resistance $R[\Omega/km]$, inductance $L[H/km]$, capacitance $C[F/km]$ and conductance $G[S/km]$. These parameters are independent of voltage as well as transmitted current; they are dependent on the composition of line, used materials and, last but not least, on the frequency of transmitted signal. If a two-conductor homogeneous line is considered, the equivalent scheme of a part of blue-line can be drawn up - Fig. 3.1.

\begin{align*}
  \frac{-dU_x}{dx} &= (R + j\omega L)I_x, \quad (3.1) \\
  \frac{-dI_x}{dx} &= (G + j\omega C)U_x. \quad (3.2)
\end{align*}

To solve the equations we differentiate equation (3.1) with respect to $x$

\begin{equation}
  \frac{-d^2U_x}{dx^2} = \frac{dI_x}{dx} (R + j\omega L). \quad (3.3)
\end{equation}

After substituting in equation (3.2) we obtain

\begin{equation}
  \frac{-d^2U_x}{dx} = -U_x[(R + j\omega L)(G + j\omega C)]. \quad (3.4)
\end{equation}

Writing

\begin{equation}
  (R + j\omega L)(G + j\omega C) = \gamma^2, \quad (3.5)
\end{equation}
we can rewrite this equation in the following form
\[
\frac{d^2U}{dx^2} - \gamma^2 U_x = 0. \quad \frac{d^2U}{dx^2}.
\] (3.6)

The solution of this linear homogeneous differential equation of second order is the following:
\[
U_x = A_1 e^{\gamma x} + A_2 e^{-\gamma x}. \quad (3.7)
\]

The value of \(I_x\) is calculated from (3.1)
\[
I_x = -\frac{1}{R + j\omega L} \frac{dU_x}{dx}. \quad (3.8)
\]

For \(dU_x/dx\) we substitute from equation (3.7), which must first be differentiated with respect to \(x\)
\[
\frac{dU_x}{dx} = \gamma A_1 e^{\gamma x} - \gamma A_2 e^{-\gamma x},
\]
and
\[
I_x = \frac{\gamma}{R + j\omega L} (-A_1 e^{\gamma x} + A_2 e^{-\gamma x}) = \sqrt{\frac{G + j\omega C}{R + j\omega L}} (-A_1 e^{\gamma x} + A_2 e^{-\gamma x}). \quad (3.9)
\]

The term in round brackets is dimensioned in voltage (see 3.7) and therefore the term
\[
\sqrt{\frac{G + j\omega C}{R + j\omega L}} = \sqrt{\frac{Z}{Y}}. \quad (3.10)
\]
is dimensioned as admittance.

Its reciprocal value will be impedance and is called the characteristic impedance \(Z_c\). It is given by primary parameters \(R, L, C\) and \(G\) for a specific line; for a defined frequency \(\omega\) it holds:
\[
Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \sqrt{\frac{Z}{Y}}. \quad (3.11)
\]

Equation (3.9) will now be expressed as
\[
I_x = \frac{1}{Z_c} (-A_1 e^{\gamma x} + A_2 e^{-\gamma x}). \quad (3.12)
\]
Integration constants \(A_1, A_2\) are determined from the relations at the end of line for \(x = 1; U_x = U_2; I_x = I_2\),
therefore
\[
U_2 = A_1 e^{\gamma l} + A_2 e^{-\gamma l}, \quad (3.13)
\]
and
\[
Z_c I_2 = -A_1 e^{\gamma l} + A_2 e^{-\gamma l}. \quad (3.14)
\]
Subtracting (3.14) from (3.13) will yield

\[ A_1 = \frac{1}{2}(U_2 - Z_c I_2)e^{-\gamma l}, \quad (3.15) \]

and by adding-up (3.14) and (3.13) we obtain

\[ A_2 = \frac{1}{2}(U_2 + Z_c I_2)e^{\gamma l}. \quad (3.16) \]

### 3.1 Infinite homogenous line

This type represents the most frequent type of line. For this case it holds \( l = \infty \) and thus

\[ A_{1\infty} = 0 \]

Then for (3.7) and (3.12) the following equations are valid:

\[ U_{x\infty} = A_2 e^{-\gamma l}, \quad (3.17) \]
\[ I_{x\infty} = \frac{1}{Z_c} A_2 e^{-\gamma l}. \quad (3.18) \]

The integration constant \( A_2 \) is determined from the known by relations at the beginning of the line, where \( x = 0 \)

\[ U_{1\infty} = A_2, \quad (3.19) \]
\[ Z_c I_{1\infty} = A_2, \quad (3.20) \]

Substituting (3.19) into (3.17) and (3.20) into (3.18) gives

\[ U_{x\infty} = U_{1\infty} e^{-\gamma x}, \quad (3.21) \]
\[ I_{x\infty} = I_{1\infty} e^{-\gamma x}. \quad (3.22) \]

For this and the preceding equations it holds

\[ \gamma = \sqrt{(R + j\omega L)(G + j\omega C)}, \]

which is a complex magnitude, which may be expressed in the form

\[ \gamma = \alpha + j\beta. \quad (3.23) \]

Denoting the vector voltage at the beginning of infinite line as

\[ U_{1\infty} = |U_{1\infty}|e^{j\phi l}, \]
and expressing (3.23) as
\[ e^{-\gamma x} = e^{-\alpha x} e^{-j\beta x}, \quad (3.24) \]
then substituting into (3.21) will give.
\[ U_{x\infty} = |U_{1\infty}| e^{-\alpha x} e^{j\varphi_{1\infty} - \beta x}. \quad (3.25) \]

Similarly for the current it holds
\[ I_{x\infty} = |I_{1\infty}| e^{-\alpha x} e^{j\varphi_{1\infty} - \beta x}. \quad (3.26) \]

The left part of equation (3.25) represents the amplitude of voltage in \( x \), which is declining exponentially according to
\[ |U_{x\infty}| = |U_{1\infty}| e^{-\alpha x}. \quad (3.27) \]

Parameter \( \alpha \) is called the **specific loss**, usually given in dB/km and it changes with the type of line. The value \( \alpha \cdot l = a \) is the loss in dB (related to the length \( l \)).

The second part of equation (3.25) expresses the value of phase in place \( x \), thus
\[ e^{j\varphi_{x\infty}} = e^{j(\varphi_{1\infty} - \beta x)}. \quad (3.28) \]

It follows from this term that with increasing \( x \) the phase of voltage vector is delayed by \( \beta x \), where \( \beta \) is the **specific phase shift** (which related to length is equal to \( \beta \cdot l = b \)), \( b \) is the **phase shift** (for both events is \( l \) in km).

The line constant \( \gamma \) (3.25) is the **specific propagation coefficient**. Related to the length \( \gamma \cdot l = g \) it is called the **propagation coefficient**. Then it also holds
\[ g = \gamma \cdot l = a + jb. \quad (3.29) \]

\[ \lambda \cdot \beta = 2\pi. \]

This helical surface fully represents the voltage vector pattern. It is evident that the voltage vector decreases with the distance by geometrical series, the phase delay by arithmetic series.

Let us observe once more equations (3.7) and (3.12). We can see that they are composed of two components; the first one, so-called gradual component, which decreases with the distance
\[ U_{xp} = A_2 e^{-\gamma x}, \quad (3.30) \]
\[ I_{xp} = \frac{1}{Z_c} A_2 e^{-\gamma x}, \quad (3.31) \]
and the reflected component
\[ U_{xr} = A_1 e^{\gamma x}, \quad (3.32) \]
\[ I_{xr} = -\frac{1}{Z_c} A_1 e^{\gamma x}, \quad (3.33) \]
which increases with the distance (decreasing from the termination to the beginning of line).

The value of voltage (current) at any point \( x \) is given by vector summation of these components. The resulting magnitude and phase are given by the magnitude and the phase of reflected wave.

Let us divide equation (3.17) by (3.18); we will obtain impedance at point \( x \) (\( Z_{x\infty} \))

\[
Z_{x\infty} = \frac{U_{x\infty}}{I_{x\infty}} = Z_c
\] (3.34)

It is evident from this equation that at a distance \( x \) from the beginning of infinite line, the impedance \( Z_{1\infty} \) measured to the termination of line is equal to the characteristic impedance \( Z_c \). This characteristic impedance is independent of \( x \) (contrary to the DC resistance!) - it is a certain value for a specific type of line and a specific frequency. Let us divide equation (3.19) by (3.20) to obtain the input impedance of infinite line

\[
Z_{1\infty} = \frac{U_{1\infty}}{I_{1\infty}} = Z_c
\] (3.35)

The conclusion emerging from this equation implies that the input impedance \( Z_{1\infty} \) of infinite line is equal to the characteristic impedance \( Z_c \). The characteristic impedance can be measured directly as the input impedance of infinite line (or line correctly terminated, adapted to impedance - see below), or calculated using the primary parameters \( R, L, C \) and \( G \) according to equation (3.11). Finally, it should be noted that the quantities \( Z_c \) and \( \gamma \) are collectively referred to as secondary parameters of line.
### 3.2 Voltage vs. current relations at the beginning and termination of line

We often come across the necessity to determine voltage \( U_1 \) and current \( I_1 \) at the beginning of a homogeneous line characterized by secondary parameters \( Z_c, \gamma \) and longitude \( l \), while voltage \( U_2 \) and current \( I_2 \) at the line termination are known. To do so it is necessary to determine the relations

\[
U_1 = f(U_2, I_2), \quad I_1 = f_x(U_2, I_2).
\]

With \( x = 0 \) we determine voltage and current at the beginning of line, using equations \( (3.7) \) and \( (3.12) \)

\[
U_1 = A_1 + A_2, \quad (3.36)
\]

and

\[
I_1 = \frac{1}{Z_c}(-A_1 + A_2). \quad (3.37)
\]

Substituting into \( A_1 \) and \( A_2 \) from (2.15) and (2.16) we obtain

\[
U_1 = \frac{U_2 - Z_c I_2}{2} e^{-\gamma l} + \frac{U_2 + Z_c I_2}{2} e^{\gamma l} = U_2 \frac{e^{\gamma l} + e^{-\gamma l}}{2} + Z_c I_2 \frac{e^{\gamma l} + e^{-\gamma l}}{2},
\]

or

\[
U_1 = U_2 \cosh \gamma l + Z_c I_2 \sinh \gamma l. \quad (3.38)
\]

Likewise for

\[
I_1 = \frac{1}{Z_c} \left[ - \frac{U_2 - Z_c I_2}{2} e^{-\gamma l} + \frac{U_2 + Z_c I_2}{2} e^{\gamma l} \right] = \frac{1}{Z_c} U_2 \frac{e^{\gamma l} - e^{-\gamma l}}{2} + I_2 \frac{e^{\gamma l} + e^{-\gamma l}}{2},
\]

or

\[
I_1 = \frac{U_2}{Z_c} \sinh \gamma l + I_2 \cosh \gamma l. \quad (3.39)
\]

The equations can also be written in the form

\[
U_1 = A_{11} U_2 + A_{12} I_2, \quad (3.40)
\]

\[
I_1 = A_{21} U_2 + A_{11} I_2, \quad (3.41)
\]

where

\[
A_{11} = \cosh \gamma l \quad A_{12} = \sinh \gamma l \quad A_{21} = \frac{1}{Z_c} \sinh \gamma l
\]
3.3 Phase and group velocities of propagation

We will explain these concepts using the mutual relations between phase constant $\beta$, wave length $\lambda$ and velocity of propagation $v$.

For the phase constant $\beta$ (constant of wave length), the following relation emerges from equation (3.28) and from Fig. 3.2

$$\beta \cdot \lambda = 2\pi.$$  

Let us lay down

$$\lambda = \frac{2\pi}{\beta}.$$  

In connection with velocity

$$v_f = \frac{\lambda}{T} = \lambda \cdot f = \frac{2\pi}{\beta} \cdot \frac{\omega}{2\pi} = \frac{\omega}{\beta},$$

we obtain the final expression for phase velocity of propagation.

It is necessary to realise that all calculations were done for one frequency, but in reality complete frequency bands are transmitted. Therefore the frequency dependence of secondary parameters needs to be examined.

For example, in case the phase velocity is constant across the whole band, we have the most ideal situation that is necessary for transmitting. Then $\beta$ is directly proportional to $\omega$ and the following equation is valid:

$$\beta = k\omega.$$  

(3.43)

This case is shown in Fig. 3.3.

In most cases, however, the relation $\beta = \varphi(f)$ is a curve (see Fig. 3.4). In that case equation (3.42) is expressed by differentials.

$$v_s = \frac{d\omega}{d\beta}.$$  

(3.44)

This term expresses the so-called group velocity of propagation, i.e. the velocity at which a 'group' of two very close frequencies propagates.

Fig. 3.4 gives two possible cases of the effect of the frequency relation

$$\beta = \varphi(\omega)$$

There is a concave curve in Fig. 3.4 (left), when $d\omega/d\beta = v_s = tg\psi$, velocity decreases with frequency. On the other hand, in the same Fig. 3.4 (right), velocity increases with frequency. Phase distortion appears in both cases.

The velocity of propagation approximates the velocity of light; for air lines it is roughly 280 000 km/s; while for coiled lines it is significantly lower, ca. 16000 km/s (depending on the type of coiled line). We can see that the velocity of propagation differs and so does the wavelength. Distances of lines should therefore be related to wavelengths and not to metrical longitudes.
3.4 Delay of signal

The delay of signal is used in practice for the evaluation of propagation velocity. Starting from the known relation for velocity, the signal delay is:

\[ t_f = \frac{l}{v_f} \]
From equation (3.42) we substitute for $v_f$ and obtain

$$t_f = \ell \cdot \frac{\beta}{\omega} = \frac{b}{\omega},$$

(3.45)

where, as we know, $b$ is the phase shift related to the integral line. Analogous relation is valid for the group delay using differentials

$$t_s = \frac{db}{d\omega}.$$  

(3.46)

If we consider that according to equation (3.46) $b = \beta l$, then the curve of group delay is nothing but the differentiation of phase characteristics. Performing such treatment in Fig. 3.4 makes it evident that group delay will be greater in low frequencies than in HF. In practice there are different frequency groups of the band transmitted and for various lines of different lengths (e.g. 2500 km) maximal admissible times of group delay (in ms) are defined.

### 3.5 Input impedance of homogenous line terminated variably

In general, the input impedance of line $Z_1$ depends on the terminating impedance $Z_2$. It is not equal to the characteristic impedance $Z_c$ as with the infinite homogeneous line. The relation for $Z_1$ will be expressed from equations (3.40) and (3.41)

$$Z_1 = \frac{U_1}{I_1} = \frac{A_{11}U_2 + A_{12}I_2}{A_{21}U_2 + A_{11}I_2}.  

(3.47)$$

Let us divide the numerator and the denominator by $I_2$ and substitute $Z_2$ for $U_2/I_2$. We obtain

$$Z_1 = \frac{A_{11}Z_2 + A_{12}}{A_{21}Z_2 + A_{11}} = \frac{\cosh \gamma l Z_2 + Z_c \sinh \gamma l}{\frac{1}{Z_c} \sinh \gamma l Z_2 + Z_c \cosh \gamma l},$$

and by rewriting

$$Z_1 = Z_c \frac{Z_2 \cosh \gamma l + Z_c \sinh \gamma l}{Z_2 \sinh \gamma l + Z_c \cosh \gamma l}.$$  

(3.48)

Using this equation we will be able to analyse other possible cases.

**Impact of infinite line termination**

As mentioned before $Z_{1\infty} = Z_c$ in accordance with the derived equation (3.35). The same result should be reached by analysing relation (3.48). The hyperbolic sine and cosine of complex argument $\gamma l = (\alpha + j\beta)l$ change in dependence on $a$ according to Fig. 3.4. From a certain value $a$ we can consider

$$\cosh \gamma l = \sinh \gamma l = \cosh a = \sinh a.$$  

(3.49)
Then for the input impedance it holds

\[ Z_{1\infty} = Z_c \frac{(Z_2 + Z_c) \cosh \alpha l}{(Z_2 + Z_c) \cosh \alpha l} = Z_c. \tag{3.50} \]

It is evident that the input impedance \( Z_{1\infty} \) is equal to the characteristic impedance \( Z_c \), irrespective of the termination \( Z_2 \). This is also valid for short-line \( (Z_2 = 0) \) as well as the open line \( (Z_2 = \infty) \).

**Input impedance of finite line, terminated by impedance \( Z_2 = Z_c \)**

Substituting induction \( Z_2 = Z_c \) into equation (3.48), we obtain

\[ Z_1 = Z_c \frac{Z_c (\cosh \gamma l + \sinh \gamma l)}{Z_c (\cosh \gamma l + \sinh \gamma l)} = Z_c. \tag{3.51} \]

When the line terminates by characteristic impedance, irrespective of the length of line, the input impedance is equal to the characteristic one. This configuration of line is of the same behaviour as the infinite line; the only difference is, in fact, that the voltage and current at the end of line have finite values. No reflections are inflicted at the end (so-called correct termination).

**Input impedance of open line**

We assume \( I_{2p} = 0 \) and \( Z_{2p} = \infty \). By substituting it into equations (3.38) and (3.41) we obtain

\[ Z_{1p} = \frac{A_{11}}{A_{21}} = \frac{\cosh \gamma l}{Z_c \sinh \gamma l} = Z_c \coth \gamma l. \tag{3.52} \]

It is evident that the input impedance of open line \( Z_{1p} \) will be related to the frequency dependence \( Z_c \) as well as to the frequency dependence of \( \coth \gamma \). As will be seen later, it will be undulant about the \( Z_c \) curve just by the value of frequency dependence \( \coth \gamma \) will decrease with increasing frequency. This situation is demonstrated in Fig. 3.5, where hyperbolic functions are shown as function of \( a \); also shown are curves of phase angle (full lines). With increasing \( a \) it holds:

\[ \coth \gamma l = \coth \alpha = \tgh \alpha = 1. \tag{3.53} \]

We can deduce from phase angle curves that the character of open line may be capacitive as well as inductive or purely real, resistive. The curve of \( Z_{1p} \) is in principle a consequence of the reflections of voltage and current waves at the terminating point of line, which are added to the basic waves.
Input impedance of short-line

For this case it holds: \( Z_{2k} = 0, U_{2k} = 0 \). We use again equations (3.38) and (3.41).

\[
Z_{1k} = \frac{A_{12}}{A_{11}} = \frac{U_{1k}}{I_{1k}} = Z_c \tanh \gamma l. \tag{3.54}
\]

The frequency curve \( Z_{1k} \) will depend on

\[
tanh \gamma = \tanh(\alpha + j\beta) l = T e^{j\varphi T}
\]

The situation is analogous to open line; it is demonstrated in Fig. 3.5 (dot and dash).

We obtain important information, mainly from the point of view of measuring possibilities, if we multiply (3.52) by (3.54) we obtain:

\[
Z_{1p}Z_{1k} = Z_c^2 \cosh \gamma l \tanh \gamma l,
\]

and subsequently

\[
Z_c = \sqrt{Z_{1p}Z_{1k}}. \tag{3.55}
\]

The characteristic impedance \( Z_c \) is equal to the geometric mean of the input impedance of open line \( Z_{1p} \) and the input impedance of short-line \( Z_{1k} \).

This derived equation (3.55) is very suitable for the calculation of \( Z_c \) for lines without the possibility of a correct termination as well as for very short lines.

Dividing equations (3.52) by (3.54) we can determine equations for the calculation of \( Z_c \) and \( \gamma \), if we know \( Z_{1p} \) and \( Z_{1k} \), and also equations for gaining the primary parameters \( R, L, G \) and \( C \). The ratio

\[
\frac{Z_{1k}}{Z_{1p}} = \frac{Z_c \tanh \gamma l}{Z_c \frac{1}{\tanh \gamma l}} = \tanh^2 \gamma l, \tag{3.56}
\]

and therefore

\[
tanh \gamma l = \sqrt{\frac{Z_{1k}}{Z_{1p}}}. \]

From (3.5) and (3.11) it holds

\[
\gamma Z_c = R + j\omega L \frac{\gamma}{Z_c} = G + j\omega C \tag{3.57}
\]

Input impedance of line terminated by common impedance \( Z_2 \neq Z_c \)

We can express the input impedance using (3.48), whose numerator and denominator are divided by \( Z_c \cosh \gamma l \) and we obtain:

\[
Z_1 = \frac{Z_2 \cosh \gamma l + Z_c \sinh \gamma l}{Z_c \sinh \gamma l + Z_c \cosh \gamma l} = Z_c \frac{\frac{Z_2}{Z_c} + \tanh \gamma l}{\frac{1}{Z_c} + \frac{Z_2}{Z_c} \tanh \gamma l}. \tag{3.58}
\]
Figure 3.5: Functions of $tgh\gamma l$ and $cotgh\gamma l$ in dependence on $a$.

The ratio $P = \frac{Z_2}{Z_c} = \left|P\right|e^{i\varphi}$ can be put equal to a hyperbolic tangent of complex
magnitude \( \psi \), so that \( P = \text{tgh} \psi \) and then relation (2.58) will be changed to:

\[
Z_1 = Z_c \frac{\text{tg} \psi + \text{tgh} \gamma l}{1 + \text{tgh} \psi \text{tgh} \gamma l} = Z_c \text{tgh}(\gamma l + \psi).
\]

Comparing equation (3.59) with equation (3.54) for input shortcut impedance, we can judge that these equations are analogous, differing only in the magnitude of complex argument. Reflected voltage and current waves therefore arise at the line termination. These waves cause frequency curve undulation of input impedance. Reflections do not arise at the terminations only, but also in real lines at different points along the line and cause irregular undulation of the input impedance characteristic on non-homogeneities. Refractions will be the greater, the greater the line non-homogenity and the closer it is to the line beginning. Reflections have an unfavourable effect on the stability of circuits, crosstalk and double contours (so called spirits), especially in video transmissions.

### 3.6 Lines practically infinite

As will be shown below, an infinite line need not be infinitely long \( l = \infty \); the character of infinite line, in other words a situation when no reflected voltage and current waves arise, appears from a certain value of attenuation or loss. Let us define the length (expressed in Np or dB) at which the line will be infinite. Let us start from the knowledge about the infinite line, whose input impedance is \( Z_c \) for any termination, including open or shortcut line, (worst cases). Then it holds:

\[
Z_{1p} = Z_{1k} = Z_c
\]

As to (3.52) and (3.54) it holds

\[
Z_{1p} = Z_c \text{coth} \gamma l,
\]

\[
Z_{1k} = Z_c \text{tgh} \gamma l,
\]

then we have the sought case of infinite line, when

\[
\text{cotgh} \gamma l = \text{tgh} \gamma l = 1,
\]

This case occurs, as demonstrated in Fig. 2.5. Expressed numerically it is read from tables

\[
a = \alpha l = 3.0 \text{ Np}.
\]

(With \( a = 3.0 \text{ Np} \text{ tgh} = 0.995; \text{cotgh}a = 1.005 \)).

We can regard a line whose loss is 3,0 Np or larger as practically infinite.
3.7 Electrically short lines

This chapter is devoted to electrically short lines. Only the primary constants $R$, $L$, $C$, $G$ show up in these lines and therefore the open line will behave as capacitance, the shortcut line as inductance. In contrast to electrically long or infinite lines, where the primary constants do not show up separately (they are not measurable directly), but only cumulatively as the secondary parameters $Z_c\alpha\gamma$. For the input impedance of open line it follows from (3.52)

$$Z_{1p} = Z_c \coth \gamma l,$$

If $\gamma l$ becomes so small that

$$\cotgh l = \frac{1}{\gamma l},$$

then $Z_{1p}$ will be changed:

$$Z_{1p} = Z_c \frac{1}{\gamma l} = \frac{\sqrt{(R + j\omega L)}(G + j\omega C)}{(G + j\omega C)} = \frac{1}{(G + j\omega C)} l.$$  \hspace{1cm} (3.60)

As is clear from (3.60), an electrically short open line behaves as a capacitor with losses and its capacitance and leakage are proportional to the length of line $l$. This knowledge is used for fault location of interrupted wires. Analogously, for a line of finite length and input impedance of shortcut line it holds

$$Z_{1k} = Z_c \tgh \gamma l.$$

If $l$ becomes again so small that

$$\tgh \gamma l = 1,$$

$Z_{1k}$ will be changed to:

$$Z_{1k} = Z_c \gamma l = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \sqrt{(R + j\omega L)(G + j\omega C)} l = (R + j\omega L) l.$$  \hspace{1cm} (3.61)

Electrically short shortcut line behaves as inductance with losses, proportional to the length of line $l$.

The table of $\tgh x$ informs us that

$$\tgh \gamma l = \tgh \alpha l = \alpha l,$$

for

$$\tgh \alpha l \leq 0.15 N_p.$$

Conclusion: Lengths of lines cannot be related to km (in accordance with our deliberations above), but it is necessary to relate them to the values of loss. In view of the width of utilised frequency band, one line can exhibit the attributes of an electrically short line, electrically long line, and also electrically infinite line. The division of frequency areas where the line behaves absolutely differently is in Fig. 3.6.
3.8 Frequency dependence of primary and secondary parameters of various types of line

The real frequency dependence of primary and secondary parameters of the line will be shown in this chapter. It is necessary to be aware of the connection with relations for primary parameters when analysing these parameters.

Open air lines

The dependence of $R$, $L$, $C$ and $G$ on frequency is demonstrated in Fig. 3.7. It is evident that deviations will be dependent on wire diameters, material, etc. Leakage changes significantly with weather; the $G$ curve will be extremely increasing during ice accretion, while it will be gradual in dry weather.

The dependence of average loss and phase shift is shown in Fig. 3.8. The value of attenuation is $\alpha \cdot \ell$. It is important from the viewpoint of suitability of line for telephone current transmission.

If $\alpha \ell = 1$ the transmission is excellent,
$\alpha \ell = 2$ the transmission is good,
$\alpha \ell = 3$ the transmission is sufficient,
$\alpha \ell = 4$ transmission is adequate.

For $\alpha \ell \leq 4.8$ communication could be considered possible.

Specific loss $\alpha$ can be determined from the equation for $\gamma$. It holds

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$
Figure 3.7: Frequency dependence of primary parameters of open air lines.

For

\[ |\gamma| = \sqrt{\alpha^2 + \beta^2} = \sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)}, \]

and

\[ \alpha^2 + \beta^2 = \sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)}. \]  

(3.62)
Let there be
\[ \gamma^2 = (\alpha + j\beta)^2 = \alpha^2 + 2j\alpha\beta - \beta^2 = RG + j\omega RC + j\omega LG - \omega^2 LC, \]
from which the real component
\[ \alpha^2 - \beta^2 = RG - \omega^2 LC. \] (3.63)

By adding up we obtain equations (3.62) and (3.63)
\[ \alpha = \frac{1}{2}\sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2) + (RG - \omega^2 LC)}. \] (3.64)

Similarly, by subtracting the equations
\[ \beta = \frac{1}{2}\sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2) - (RG - \omega^2 LC)}. \] (3.65)

The relation for \( \alpha \) can be simplified for practical applications on the assumption of wires of larger diameter and for open air lines at low frequencies, when we can consider
\[ G \ll \omega C \quad \text{and} \quad R \ll \omega L. \] (3.66)

The following holds:
\[ \gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} =, \]
\[ = \sqrt{j\omega L\left(\frac{R}{j\omega L} + 1\right)j\omega C\left(\frac{G}{j\omega C} + 1\right)} =, \]
\[ = \sqrt{-\omega^2 LC\left(\frac{R}{j\omega L} + 1\right)\left(\frac{G}{j\omega C} + 1\right)} =, \]
\[ = j\omega\sqrt{LC}\sqrt{(1 + \frac{R}{j\omega L})(1 + \frac{G}{j\omega C})} =, \]
\[ = j\omega\sqrt{LC}\sqrt{1 - \frac{RG}{\omega^2 LC} + \frac{1}{j\omega\left(\frac{R}{L} + \frac{G}{C}\right)}}. \]

We can neglect the second term under square root, expand the rest of equation into a Taylor series and neglect its superior terms; then
\[ \gamma = j\omega\sqrt{LC}[1 - j\frac{1}{2\omega}\left(\frac{R}{L} + \frac{G}{C}\right)], \]
and by rewriting
\[ \gamma = j\omega\sqrt{LC} + \left[\sqrt{\frac{LC}{2}}\left(\frac{R}{L} + \frac{G}{C}\right)\right]. \]
By comparing the Re and Im components we obtain for

\[ \alpha = R \sqrt{C} + G \sqrt{L} = \alpha_R + \alpha_G, \quad (3.67) \]

and

\[ \beta = \omega \sqrt{LC}. \quad (3.68) \]

The influence of leakage in dry weather is small; then we can neglect the second term in (3.67). The influence of leakage on attenuation is evident from Fig. 3.9.

![Figure 3.9: Attenuation of open air line (bronz ⊙ 3 mm).](image)

In the case of line for LF, we can consider

\[ \omega L \ll R \quad \text{and} \quad G \ll \omega C. \quad (3.69) \]

Equations (3.64) and (3.65) will be transformed into another form

\[ \alpha = \sqrt{0 + \frac{1}{2} R^2 \omega^2 C^2} = \frac{\omega RC}{2}, \quad (3.70) \]

and

\[ \beta = \sqrt{\frac{\omega RC}{2}}. \quad (3.71) \]
Significant dependence on temperature must be taken into consideration; therefore automatic regulation is introduced in long-haul lines. The characteristic impedance of open air lines is determined from the well-known form

\[ Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}} , \]

from which it is evident that the impedance depends on primary parameters. In the case of LF lines, under condition (2.69), it holds

\[ Z_{cnf} = \sqrt{\frac{R}{j\omega C}} = \sqrt{\frac{R}{2\omega C}} - j\sqrt{\frac{R}{2\omega C}} , \]  

and it is evident that the impedance consists of both the Re and the Im components. Compared with \( R, G \), the values \( \omega L \) and \( \omega C \) are negligible by condition (3.66), therefore

\[ Z_{cnf} = \sqrt{\frac{L}{C}} . \]  

The characteristic curve is shown in Fig. 3.10. For comparison, the curve of cable line is also shown. As the last, consider \( f = 0 \); then these forms will change to

\[ \alpha = \sqrt{RG}, \beta = 0 , \]
Figure 3.11: Frequency dependence $\alpha$, $\beta$ and $Z_c$ for several types of coil-loaded lines.
Transmission media for Telecommunication

Cable lines

If we keep to the original division of cable lines, let us pay attention to LF lines without coil-loading. Capacitance $C$ and inductance $L$ are independent of frequency. We can consider resistance $R$ and leakage $G$ also constant in this frequency band; but they are significantly dependent on temperature. Attenuation $\alpha$ will be calculated according to the relation:

$$\alpha = \sqrt{\frac{\omega RC}{2}}$$

The corresponding curve is shown in Fig. 3.11. Similarly, the specific shift

$$\beta = \sqrt{\frac{\omega RC}{2}}.$$ (3.77)

We can consider only resistance in the numerator and the term with capacitance in the denominator. (see also open air lines LF) and so we obtain a simplified form

$$Z_{cn, f} = \sqrt{\frac{R}{j\omega C}} = \sqrt{\frac{R}{2\pi f_c}} e^{-45^\circ}.$$ (3.78)

The curve is shown in Fig. 3.10. Impedance decreases with increasing frequency. For frequencies of the order of 100 kHz, the imaginary component approaches zero and the real component will be stabilised around 100 $\Omega$. The impedance of most ordinary cables used in local or access networks of diameter 0.8 mm is about 600 $\Omega$ at a frequency of 800 Hz. This value was chosen as the terminating impedance for all LF transmission equipment. In view of the impedance decreasing with frequency there is at the beginning of the telephone band a mismatch of plus 400 $\Omega$ (at 300 Hz) and at the upper end of the band (3400 Hz) the reverse case of ca. minus 300 $\Omega$. But these mismatches do not impair the quality of transmission in access networks. Coil-loaded lines decrease attenuation in LF transmission, as we already know. This is obtained by inserting Pupin’s coils into the cable and thus the inductance of cable line is increased. An equivalent scheme of line cannot be considered in simplified form as in lines without coil-loading. It is necessary to consider all primary magnitudes. Coil-loaded line is composed of a series of $\pi$-piles, of low-pass character. The limiting frequency is given by the expression $\omega_0$ in equation (3.78):

$$\omega_0 L_s = \frac{1}{\omega_0 C_s},$$ (3.79)

where $L_s$ is inductance corresponding to one coil-loaded section

$$L_s = L_s + L_p = (L + \frac{L_p}{s})s,$$ (3.80)
where $L$ is the specific inductance of line [H/km], $L_p$ is the inductance of Pupin’s coils [H], $s$ the so called coil-loading step [m] (called also pupinising step).

Capacitance $C_s$ is given by

$$C_s = C_s^s / 4.$$  
(3.81)

Substituting into (2.79)

$$\omega_0(L + \frac{L_p}{s})s = \frac{1}{\omega_0 C_s^s},$$  
(3.82)

and transforming

$$\omega_0 = \frac{2}{s \sqrt{C(L + \frac{L_p}{s})}},$$  
(3.83)

$$f_0 = \frac{1}{\pi s \sqrt{C(L + \frac{L_p}{s})}}.$$  
(3.84)

Attenuation and impedance rise to extreme values at this frequency. Therefore, the effectively transmitted band is limited by $0.75 f_0$.

Specific attenuation is calculated according to the relation

$$\alpha = \left[ \frac{R + R_p}{2} \sqrt{\frac{C_s}{L_s + L_p}} + \frac{G}{2} \sqrt{\frac{L_s + L_p}{C_s} \frac{1}{\sqrt{1 - (\frac{\omega}{\omega_0})^2}}} \right],$$  
(3.85)

and characteristic impedance

$$Z_c = \sqrt{\frac{L_{pk}}{C_s} \frac{1}{\sqrt{1 - (\frac{\omega}{\omega_0})^2}}},$$  
(3.86)

where

$$L_{pk} = \frac{1}{f_0^2 \pi^2 s C},$$  
(3.87)

is the inductance of coil-loaded pair.

The transmission properties of coil-loaded lines are synoptically shown in Fig. 3.11. It is evident from the above Figures that due to coil-loading

- attenuation decreases, the more intensively, the heavier the coil-loading (i.e. the greater the inductance),
- attenuation is in a major part of the band almost independent of frequency,
- increasing inductance causes significant narrowing of frequency band.

It is evident from the relation for specific phase shift $\beta$ that

- it significantly increases with increasing inductance and it is closely tied with the decrease in phase as well as group velocities.

It is evident from impedance characteristics that due to coil-loading

- $R_c Z_c$ increases with heavier coil-loading (disadvantage),
Table 3.1: Types of coil-loaded lines and their properties.

<table>
<thead>
<tr>
<th>Inductance</th>
<th>Impedance at 800 Hz</th>
<th>Specific attenuation $10^{-3}$ dB/km</th>
<th>Limiting frequency kHz</th>
<th>Bandwidth kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pup. coils at 800 Hz</td>
<td>mH</td>
<td>W</td>
<td>800 Hz</td>
<td>3.4 kHz</td>
</tr>
<tr>
<td>K 177</td>
<td>1590</td>
<td>188</td>
<td>-</td>
<td>2.9</td>
</tr>
<tr>
<td>F 63</td>
<td>740</td>
<td>198</td>
<td>300</td>
<td>3.6</td>
</tr>
<tr>
<td>K 88</td>
<td>1120</td>
<td>236</td>
<td>274</td>
<td>4.1</td>
</tr>
<tr>
<td>F 36</td>
<td>560</td>
<td>233</td>
<td>246</td>
<td>5</td>
</tr>
<tr>
<td>K 70</td>
<td>990</td>
<td>277</td>
<td>290</td>
<td>4.5</td>
</tr>
<tr>
<td>F 30</td>
<td>520</td>
<td>246</td>
<td>266</td>
<td>5.5</td>
</tr>
</tbody>
</table>

- attenuation increases (significantly) in the range close to the limiting frequency (significant disadvantage),
- the imaginary component is approaching zero (advantage),
- at the limiting frequency there is also an increase in the phase (disadvantage).

Overall we can say that the main effect of coil-loading is in the decrease of attenuation in the frequency range of telephone voice band (according to UIT 300-3400 Hz), which was of extraordinary importance on the eve of telephony, since the decrease in attenuation resulted in increased range of telephone link. Also in this area, properties were obtained that are usually obtained only at higher frequencies (over 30 kHz), i.e. characteristic impedance is approximately real and constant, phase shift is linear and also phase and group velocities of propagation are roughly constant. On the other hand, the narrowing of band, increasing $R_eZ_c$ and decreasing $v_f$ and $v_s$ are of disadvantage (in some cases so called decoil-loading is performed, i.e. eliminating the inductance units in order to introduce HF analogue or digital multiplexes).

Currently the importance of coil-loading is decreasing due to the fact that it is a significant bar in broadband services. It survives
- in short trunk (former node) cables,
- in LF analogue radio transmissions.

The use of LF coil-loaded cable lines was till the appearance of broadband services the simplest, cheapest and low cost solution, above all for short distances. Let us conclude with some typical parameters of coil-loading used in CZ. The length of coiling step 1830 m, inductance of coiling unit 88/36 mH, wire diameter 0.9 Cu.

Note: The very last concept of high quality of Hi-Fi audio transmissions was developed in the seventies of last century with inductance of coiling units 3.2 mH, and coiling step halved to 915 m, which enables transmission up to 15 000 Hz.

Symmetrical HF cables

The basic information about these cables was mentioned before. The relation for attenuation $\alpha$ has been also introduced, the characteristics of which is shown in Fig. 3.12 independence on frequency. Specific attenuation increases quasilinearly in this type of cable, while for cables with 0.9 mm Cu diameter the function is curved. The growth of $\alpha$ is caused by parameters $R$ and $G$, while $C$ and $L$ are quasi-independent of $f$. Dependence
\[ \beta = \varphi(f) \] for the same type of cable is shown in Fig. 3.13. This dependence is linear and for the calculation the following relation is used:

\[ \beta = \omega \sqrt{CL}. \] (3.88)

For this case both \( v_f \) and \( v_s \) are constant.

\( \Re Z_c = \psi(f) \) and \( \Im Z_c = \xi(f) \) are plotted in Fig. 3.14. As evident from this Figure, \( \Re Z_c \) is quasi-constant approximately from 30 kHz (being insulated by paper-air ca. 150 \( \Omega \), by styroflex-air ca. 170 \( \Omega \) while \( \Im Z \) is slightly capacitive). It follows from the above figures that the transmission parameters of HF cables are very advantageous in the range of carrier frequencies (\( \alpha, Z_c \)).

Coaxial cables

The basic equations for the calculation of primary parameters have been introduced in chapter 2.3. We can demonstrate their frequency dependence in Fig. 3.15. We can consider the corresponding secondary parameters in a simplified form for HF cables, for coaxial cables from \( f \geq 60 \text{ kHz} \), then

\[ R \ll \omega L \quad \text{a} \quad G \ll \omega C, \]

then

\[ \alpha = \frac{R}{2} \sqrt{\frac{C}{L}} + \frac{G}{2} \sqrt{\frac{L}{C}}. \] (3.89)
Figure 3.13: Dependence of specific shift $\beta$ on frequency.

(the second component is negligible)

$$\beta = \omega \sqrt{CL},$$  \hspace{1cm} (3.90)

and

$$Z_c = \frac{L}{C}.$$  \hspace{1cm} (3.91)

The curves of $\alpha$ and $\beta$ are given in Fig. 3.16. The dependence $Z_c = \varphi(f)$ is plotted in Fig. 3.17. As can be seen, the waveforms of both $\beta$ and $Z_c$ are advantageous from the point of view of transmission. The linear dependence of specific phase shift $\beta$ corresponds to constants $v_f$ and $v_o$ (excluding the beginning of range). For $v_f$ it holds

$$v_f = \frac{\omega}{\alpha} = \frac{1}{\sqrt{LC}}.$$  \hspace{1cm} (3.92)

It could be proved that in HF range the phase velocity is constant and that it is equal to the quotient of light velocity and square root of dielectric constant $\varepsilon_r$. 
3.9 Homogenous line at high frequencies

Let us recapitulate some questions concerning extremely broad bands in conclusion of the second chapter. As stated in chapter 2.10, we obtain for this frequency range forms for

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

and

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

can be simplified fulfilling conditions $R \ll \omega L$ and $G \ll \omega C$. Then we obtain

$$Z_c \doteq \sqrt{\frac{L}{C}},$$

$$\gamma \doteq j\omega \sqrt{CL} \doteq j\beta,$$  \hspace{1cm} (3.93)

and

$$\beta \doteq \omega \sqrt{CL}, \ \alpha \doteq 0.$$  \hspace{1cm} (3.94)
Figure 3.15: Frequency dependence of coaxial cable primary parameters is real ($Z_c = 75 \Omega$).

As evident from relation (3.94), these considerations are solved simplified for HF lossless line. From the form for $Z_c$, it is clear that at HF the homogeneous line has characteristic impedance constant and, moreover, real (see the curve in Fig. 3.17).

HF open air line

A frequent case in telecommunication practice, i.e. HF in links on an extra high voltage line will be described. HF equipment is connected to the EHV line through coupling capacitors CC. An example of two-layer network is shown in Fig. 3.18. Choke coils T1 prevent HF currents from entering the EHV equipment. There are taps coupled to transformers TS. These taps can be regarded in HF as sections of open line. With defined, so-called critical lengths of these taps, HF shortcuts occur and it is necessary to forestall this in the design.

A similar case occurs in HF distribution of modulation for wired radio. Branches are installed at these points (communities) to receivers of audio modulation (see Fig. 3.19). They also represent taps of possibly critical lengths, which we will try to investigate. In these cases we start from $n$ known circumstances at the far end of line, when $Z_{2p} = \infty$, $I_{2p} = 0$ and $U_{2p}$ is of certain amplitude. We use equations (3.62) and (3.12), where integration constants $A_1$ and $A_2$ will be defined according to (3.15) and (3.16), respectively. By substitution we obtain:

$$U_y = \cosh \gamma y U_2 + Z_c \sinh \gamma y I_2,$$

(3.95)
Figure 3.16: Frequency dependence $\alpha$ and $\beta$ of coaxial cable - 1,2/4,4 (small), 2,6/9,4 (medium).

Figure 3.17: Frequency dependence $Z_c = \varphi(f)$ for small and medium coaxial pairs.
Figure 3.18: Circumstances in extra-high voltage in HF current transmission.

It is apparent that $y$ is the distance from the far end, $U_y$ and $I_y$ are voltage and current at point $y$, distanced $y$[km] from the far end of line. (Note: this is an analogy to equations (3.38) and (3.39)).

Figure 3.19: Conditions for modulation of wire radio transmission.

Let us now study voltage and current circumstances along an HF open line:

a) **Voltage circumstances:** We substitute $I_{2p} = 0$ for $I_2$ in equation (3.95) and we obtain (using 3.93)

$$U_{yp} = U_{2p} \cosh \gamma y = U_{2p} \cosh j \beta y.$$  \hspace{1cm} (3.97)

It is valid:
\[ \cosh j\beta y = \cos \beta y, \text{ kde } \beta = \frac{2\pi}{\lambda}, \]
and

\( U_{2p} \) may be written in the following form:

\[ U_{2p} = |U_{2p}|e^{j\omega t}, \]

then

\[ U_{yp} = (|U_{2p}|\cos \frac{2\pi y}{\lambda})e^{j\omega t} = |U_{yp}|e^{j\omega t}. \]  \( (3.98) \)

Part of the term in brackets is the absolute magnitude and the rest of the term represents the phase. It is evident that the absolute magnitude depends on the distance from the far end \( y \) and changes with the cosine function. There will be points along the line where \( \frac{2\pi y}{\lambda} = 0 \), therefore voltage \( U_{yp} \) will be permanently zero, and also points where \( \cos \frac{2\pi y}{\lambda} \) reaches its maximum and minimum \((1,-1)\). As evident from \((3.98)\), the phase will be independent of \( y \). We can state that in an HF open line standing waves occur, expressed by equation \((3.98)\). Investigating the limit relations for \( y = 0 \) we get \( \cos \frac{2\pi y}{\lambda} = 1 \), for \( y = \frac{\lambda}{4} \) we get \( \cos \frac{2\pi y}{\lambda} = \cos \frac{\pi}{2} = 0 \), for \( y = \frac{\lambda}{2} \) we get \( \cos \frac{2\pi y}{\lambda} = \cos \pi = -1 \), etc.

b) We will substitute current relations into equation \((3.96)\) for \( I_2 = I_{2p} = 0 \) and obtain:

\[ I_{yp} = \frac{1}{Z_c} \sinh \gamma y U_{2p}. \]  \( (3.99) \)

Substituting

\[ \sinh \gamma y = \sinh j\beta y = j\sin \beta y = \sin (\sin \beta y)e^{j\frac{\beta y}{2}} = (\sin \frac{2\pi y}{\lambda})e^{j\frac{\beta y}{2}}, \]

and

\[ U_{2p} = |U_{2p}|e^{j\omega t}, \]

we obtain

\[ I_{yp} = \left( \frac{|U_{2p}|}{Z_c} \sin \frac{2\pi y}{\lambda} \right) e^{j(\omega t + \frac{\beta y}{2})} = |I_{yp}|e^{j(\omega t + \frac{\beta y}{2})}. \]  \( (3.100) \)

The term represents the standing wave of current, where the first part means again the variable of absolute magnitude, depending on \( y \) as per function sine. The second part represents the phase, which is rotated by \( \frac{\beta y}{2} \), see Fig. \(3.20\). It is evident from this Figure that maximum and minimum, \( U_{yp} \) and \( I_{yp} \), alternate. This is displayed in Fig. \(3.20\).

c) Voltage and current at the near end of line: We obtain the corresponding terms by substituting variable length \( l \) for \( y \) in \((3.95)\) and \((3.96)\). In the case of a long line:

\[ l = \frac{\lambda}{4} + k\lambda, \]

or
\[ l = \frac{3}{4} \lambda + k\lambda \quad \text{where} \quad k = 0, 1, 2, \ldots, \]

there will be

\[ U_{1p} = 0, I_{1p} = \pm \frac{U_{2p}}{Z_c} e^{j(\omega t + \frac{\pi}{2})}, \]

\text{d) input impedance of open line} will be determined from equation (3.52)

\[ Z_{1p} = Z_c \coth \gamma_1 = Z_c \frac{\cosh \gamma_1}{\sinh \gamma_1}, \]

and according to

\[ \cosh \gamma l = \cosh j \beta l = \cos \beta l = \cos \frac{2\pi}{\lambda} l, \sinh \gamma l = \sinh \beta l = \sin \beta l = \sin \frac{2\pi}{\lambda} l, \]

therefore

\[ Z_{1p} = -j Z_c \coth \frac{2\pi}{\lambda} l. \quad (3.101) \]

\textbf{Figure 3.20:} Dependence of } Z_{1p} \text{ for various lengths of open HF line.}
It follows from this term that input impedance of HF open line is purely imaginary (capacitive or inductive), even if characteristic impedance $Z_c$ is purely real. Expressing numerically the term $\frac{2\pi}{\lambda}$ for different $l$ and by multiplying it by $Z_c$ it is possible to gain the diagram in Fig. 3.21. It is evident that for $2 = 0$ to $2 = \frac{\lambda}{2}$ $Z_{1p}$ is capacitive. For the case $2 = \frac{\lambda}{4}$ an HF shortcut occurs, and the line is acting as a serial oscillating circuit. For $2 = \frac{\lambda}{4}$ to $l = \frac{\lambda}{2}$ $Z_{1p}$ is inductive. Finally for $2 = \frac{\lambda}{2}$ the behaviour of the line is equal to parallel coupling of LC. In the case of line length $\lambda/4$ dangerous HF shortcuts occur, as stated in the beginning of this subchapter. The four-wave line is utilisable in practice as a feeder of aerials in the role of band pass (suppressor of harmonics, see Fig. 3.22).

**Figure 3.21:** Standing wave of voltage and current of open HF line.

**HF short line**

By an analogous procedure to that for open line the following forms can be derived:

$$U_{yk} = (|I_{2k}|Z_c\sin \frac{2\pi}{\lambda} e^{j(\omega t + \frac{\pi}{2})}), \quad (3.102)$$

and

$$I_{yk} = (|I_{2k}|\cos \frac{2\pi}{\lambda} e^{j\omega t}). \quad (3.103)$$

The results are standing waves of voltages and currents, the plane of voltage and current vectors is again rotated by $\pi/2$. Input impedance $Z_{1k}$ is calculated acc. to (3.54)

$$Z_{1k} = Z_c tgh \gamma 2 = jZ_c tgh \frac{\gamma}{2}. \quad (3.104)$$
The curve of $Z_{1k}$ depending on $2$ is a dual case to that given above for the open line. For the case $2 = \frac{\lambda}{4}$ an important situation arises, when the characteristic of line reaches the infinite magnitude of impedance. It is possible to utilise this property in practice as a band stop of aerial feeders (see Fig. 3.22). The band stop can shortcut all harmonics and represents impedance for transmitted frequency.

![Figure 3.22: Four-wave band pass.](image1)

Another possible application follows from the assumption that we will provide the $\lambda/4$ taps bilaterally and continuously, and thus obtain the principle of waveguide, see Fig. 3.23 and Fig. 3.24. In the second chapter we went over the conclusions of the theory of homogeneous lines, which is important for the construction of cables and lines.

![Figure 3.23: Quarter-wave band stop.](image2)

![Figure 3.24: Waveguide principle.](image3)
3.10 Exercises

A) Voltage measured at the beginning of line (near end) was $U_1 = 60\, \text{V}$, impedance $Z_1 = 600\, \Omega$. The current measured at the far end was $I_2 = 10\, \text{mA}$. Calculate the attenuation in $N_P$ and dB.

B) The values of primary parameters of line are given: $R = 42.2\, \Omega/km$, $L = 8.96\, \text{mH/km}$, $C = 6.32\, \mu\text{F/km}$, $G = 0.7 \times 10^{-6}\, \text{S/km}$. Calculate $Z_c$ and $\gamma_0$ at a frequency $f = 800\, \text{Hz}$. 
4 TYPES OF METALLIC LINES AND CABLES

4.1 Open air lines

Open air lines utilise poles, consoles and insulators. They were exploited very intensively during last century, first of all due to their excellent transmitting features. They formed the backbone of trunk links. Difficult assembling in cities and dependence on weather conditions (hoar frost) led to their decline. The first cables in metropolitan networks were laid around the year 1900, the first long-hauled cable, the section Praha-Kolín-Jihlava-Brno-Wien/Bratislava in 1925. Poles fixed on concrete masts are now used for suspended (catenary) cables in access networks, metallic as well as fibre optics.

4.2 Cable lines

Cable lines were subdivided in accordance with standards (ČSN 34 7831 and ČSN 34 7851) into ”Telecommunication local cables” with wires of 0.4; 0.6 and 0.8 mm in diameter, and ”Telecommunication long-hauled cables” with wires of 0.9 and 1.3 mm in diameter. Another subdivision is from the point of view of the frequencies used: LF and HF cables, for data transmission, structured cables lines, etc. Further division is possible according to the type of laying such as free laid, tracked (into ready-built ducts), suspended, submarine cables, etc.

In view of the current technical and technological developments, the above features get intermingled. For example, long hauled cables and node cables are changing to access networks, etc.

Telecommunication cables are formed by a cable core and a protective coating. The cable core is a system of units screwed in concentric positions of opposite directions or screwed in groups - with inlets, fillers and circumference insulation. The basic construction elements are pairs, i.e. two wire conductors twisted together by a certain length of twist. Wires (even pairs) are twisted further into quads to give quad cables.

We recognise cross quads, where all four wires are twisted together. Wires are denoted a-b, c-d in such a way that the opposite ones serve as the basic circuit (trunk) see Fig. 4.1b. They are denoted as the X quad. DM (Dieselhorst - Martin) quads are composed in such a way that both pairs are firts twisted individually with different twist lengths $l_1$ and $l_2$ and finally in the second step the two pairs are twisted by the third length of twist $l_3$ in opposite direction, see Fig. 4.1a.

![Figure 4.1: Construction of a) DM quad, b) cross quad.](image-url)
**Protective coating** protects the cable core against mechanical damage, humidity, disturbances by very high voltages, electrical traction systems, etc. Protective coating is composed of several layers in accordance with the type and designation of cable.

We can give the following case as an example of the construction when the cable core is covered by insulating paper layers with upper coating of stamped lead. These cables with naked lead coating are used as tracked cables laid in ducts. Protection against other dangers (corrosion, electromagnetic induction, mechanical damage or fire) is provided by other special coating layers, such as armouring.

Laid cables are designed for direct laying into soil, they are armoured with steel belts and with other protective coating. The following example of another protection over lead coating can be the so-called pad:

- bitumen
- impregnated paper
- bitumen
- jute
- bitumen
- armour - steel belts - wound
- bitumen
- jute (twines of polypropylene)
- bitumen
- paintwork - lime milk

Protection of cable core may be also provided by other means, for example replacing lead for coating by aluminium. Such a coating is suitable for the protection against induced voltages. Polythene and polyvinylchloride (PVC) sandwiched with aluminium for upper coating is used for a corrosive environment. Cables for river crossing are equipped with wired armour against strong tension. So-called all-plastic cables are also used.

**Conductors**

The most utilised as well as best material for cable conductors (wires, coaxial pairs) is pure electrolytic copper. The diameters of these wires range from 0.32 to 0.8 mm for local cables, from 0.9 up to 1.4 mm for long-hauled symmetric cables. The choice of wire diameter depends on the length of link, attenuation and features of transmitted signal. In view of the permanent shortage of copper worldwide, there were efforts seeking to spare it by decreasing the diameters used (to 0.32 mm - 0.5 mm). There were also attempts to replace copper with aluminium with varying success, above all during WW II in Germany as well as in the former CS till 1965. The required diameter of aluminium wire is calculated by:

\[
\sqrt{\frac{\rho_{Al}}{\rho_{Cu}}} = \frac{0.0299}{0.0175} = 1.3
\]

This replacement leads to larger diameters of cables and material consumption is increasing. Aluminium is worse from the point of view of mechanical strength. Use is made of alloys such as VUK 33E (alloy of Al, Fe, Mg, and Si). These alloys are better as to the before mentioned strength, have better electrical parameters and better homogeneity of wire. In spite of the above properties it is necessary to provide additional compensations.
Insulation of wires

Paper-air insulation. Wires of local cables are twined by one or two layers of paper band. For long-hauled cables it is necessary to increase the share of air layer by twisted cord (generally known as kordel) under the paper bands. This technology enables decreasing the functional capacitance and, due to this fact, the attenuation is better. This technology is utilisable up to 250 kHz.

Figure 4.2: Wrapping of wire with cord.

Styroflex-air insulation is used first of all for HF up to 560 kHz because of their better properties.

Insulation by high-pressure polythene is provided for local cables (all-plastic cables), where wires are insulated by a continuous layer of high-pressure polythene, sized 0.2 to 0.4 mm. The advantage of this technology is that humidity penetrates into the cable very slowly.

Cable profiles

The cable core itself is twisted on twisting machines. Each upper layer has 5 to 10 units more (pairs or quads). There are tables, where the numbers of units have been calculated for various types of cables, e.g. 1, 6, 12, 18, 24. The series of DM cables with 0.9 mm wires (number of quads in individual layers) is: 5, 8, 12, 19, 27, 37, 48, 61, 90.

An example of cable profile LF 27x4x0,9 DM - (DCKQYSE) is shown in Fig. 4.3.

Figure 4.3: Profile of cable.
Construction units in the cable core need not be the same, as in the LF cable, where several shielded pairs for audio can be placed in its centre. **Audio pair RP** is composed of two twisted wires, twined by one to two paper bands and a metal plated paper band (shielding), which decreases the penetration of disturbing voltages into these pairs.

**Example:** 3x1.3 RP + 61x4x 0.9 DM is the profile of 3 shielded audio pairs Ø1,3 and 61 quads DM Ø0.9.

Local cables are only seldom of combined profile; the number of units may be very large. Typical series are: 5, 10, 15, 20, 30, 40, 50, 60, 70, 100, 150, 200, 300, 400, 500, 600, 800, 1000, 1200, 1800, 2000 (in pairs). Twisting in concentric positions is provided only for a low number of pairs; the profile with larger numbers (over 100 pairs) is composed of groups of units (pairs or quads) twisted in advance.

Each group is twisted separately; several groups prepared in this way are again stranded to form the final cable core. Individual groups are transformed by final twisting from radial profile into half- or quarter-radial or segment profile as shown in Fig. 4.4. The advantage is a more economical production and easier transfer of individual groups from one into another cable by branch splicing (cabling of exchange area).

**Figure 4.4:** Composition of elements into cable profile.

**Cable coats and their protection**

Older cables for both trunk and local networks were coated exclusively by lead. Lead as a classical material has suitable features, such as flexibility, strength, resistance against corrosion due to water, etc. Trying to replace lead (shortage, expenses), the applicability of aluminium, plastics as well as steel for above mentioned purposes was investigated.

Aluminium coated cables are more suitable from the point of view of low specific weight and a better reduction factor. On the other hand, they have disadvantages, in particular low mechanical flexibility, difficult splicing and soldering bring other hard-to-solve problems.

**All-plastic cables**, mainly using HDPE and PVC, exhibit good forming ability, sufficient stability as well as corrosion resistance. With long-term action of humidity certain infiltration of water vapour into the cable core cannot be prevented. This construction was upgraded by covering the cable core with aluminium foils formed into a longitudinally seamed tube and then by pressing a final coat of polythene (so-called layered coats). Currently, numerous new, modern sophisticated production methods are used, such as filling the cable core with lubricants. These lubricants improve the protection against longitudinal infiltration of humidity.
**Fundamentals of cable production.** The processes of cable production are subdivided into main operations, auxiliary operations and supervision. An auxiliary operation is, for example, the preparation of copper wire (staining, calibrating), insulating paper, preparation of Pb and Al composition (melting), and preparation of armouring (cutting and impregnation of paper, winding and impregnation of polythene tape, impregnation of jute, polypropylene strands, asphalt glazing).

The main operations consist of:

- drawing of copper wires,
- annealing of copper wires (upgrade of flexibility)
- insulating of copper wires,
- completing of wires into units,
- completing of cable cores,
- drying of cable cores,
- coating of cable cores,
- armouring,
- final quality supervision.

Permanent particular supervisions are provided between individual production phases.

The cable is produced in manufacturing lengths of 200 to 500 m, is wound onto a transporting drum and the beginning and the end are marked. Individual manufacturing lengths are composed into a cable track.

**Marking of cables**

According to cable marking we can recognise the material of wires, insulation type of wires, core and coat, type of coat protection, nominal number of units, type of composition as well as diameter of wires or coaxial tubes. The basis of letter marking is the sign for the type of cable. We can come across these types of telecommunication cables:

- TK - telecommunication cable local,
- DK - telecommunication cable long-distance,
- RK - audio transmission cable,
- NK - signalling cable,
- SK - telecommunication cable indoor.

The basic symbol TK is used for local telecommunication cables (for older marking 'telephone cable'). We insert other symbols after the letter T, which denote the material of wires:

- C - copper
- A - aluminium
- J - alloy of aluminium (VUK 33E)

The next letter gives the type of wire insulation:

- Y - polyvinylchloride (PVC)
- E - polythene (PE)
- G - rubber
- B - balloon polythene insulation

In the case of absence of this letter, paper-air insulation is used. The symbol for coating material is inserted after the letter K:

- O - lead
- Q - doped lead (for tracked cables for ducts)
- A - aluminium
Y - PVC - polyvinylchloride
E - PE - polythene

The letter F means shielding foil for some cables, particularly indoor cables. In all-plastic telecommunication cables, where this shielding is obvious, this sign is absent.

Next letters define the type of coat protection:
V - jute covering, Y - passive anticorrosive protection of PVC (formerly type OK3), B - anticorrosive tape protection of PVC (formerly type OK2), P - armour of steel bands, D - armour of steel wires, R - reinforced armour of steel wires including pad (river cable type), Z - armour of aluminium wires.

After the letter marking there is an entry denoting the number of units, type of design (P for paired wires, XN for quad wires) and diameter of wires in mm.

**Example of cable marking**: TCEKEZE 50 P 0.5 - telecommunication cable local (TK) with copper wires (C) and polythene insulation of wires (E)(inserted between T and K), coated by polythene (E), armoured by aluminium wires (Z) and protective cover of polythene (E). 50 pairs (50 P) of wires of 0.5 mm nominal diameter.

**Marking of wires, pairs and quads**
Different colours are used to distinguish individual wires in units in the following:
- wire a dense printing of blue traverse stripe
- wire b scarce printing of blue traverse stripe
- wire d dense printing of red traverse stripe
- wire d scarce printing of red traverse stripe

Single units (pairs, quads) are distinguished from one another by the colour of marking thread. Red thread marks the so-called counting unit and neighbouring green theared the directive unit. The numbering of units starts from the counting unit in the direction of directive unit. The other units are marked by blue thread (odd units) and white (even units).

**Node (long-distance) cables** use a different way of distinguishing units in cable core. The whole quad is coloured in the same colour and single wires differ by the number of coloured stripes (1 to 4). Neighbouring units differ by the colour of stripes: red and blue are alternating.
Marking

- wire a continuous printing of one traverse strip
- wire b continuous printing of two traverse stripes
- wire c continuous printing of three traverse stripes
- wire d continuous printing of two traverse stripes

**Accessories of telecommunications cables** - Accessories are used for splicing, branching and termination of cables.

We include here: Cable splices used to splice cables of manufacturing lengths. Branching splices and cable heads for termination of cables in buildings or cabinets.

Cable laying of open laid cables is done by laying one or more cables into a dug-out cable groove. Cables are laid manually or by special cable layers. The depth of groove can be from 0.5 to 1 m (urban and outer urban area). The cable should be covered by protective bricks or concrete tables and by coloured signal strip (orange for telecommunications, blue for railway, red for power supply). This is useful in sudden digging works performed by other subjects or also in targeted searching for one laid cable. The track given in the design should be as short as possible, avoiding water streams, railways and main roads. In the case of extreme need for telecommunication services and expected demand for increased capacity, ducts are built, above all close to exchanges. Originally concrete blocks with tubes inside were replaced by the construction of plastic tubes. Both are settled side by side and in layers. Plastic tubes are free from problems with the alkaline character of humid concrete, which can have corrosive impacts. Splicing is provided by special mechanical splices using splicing machines. (3M, Belden, AMP Picabond etc.).

### 4.3 Electrical properties of metallic lines

**A. Open-air line**

The basic quantities influencing decisively the transmission by open-air lines are active resistance, insulating resistance, inductance and capacitance. Using these primary parameters it is possible to derive further characteristic properties of line such as its specific attenuation, phase shift, impedance, etc.

DC resistance of the wires used is denoted \( R_o \). The value of resistance is increased in the transmission of alternating current to \( R_f \), where

\[
R_f = R_o (0.5d \sqrt{\frac{f \mu_r}{\sigma}} + 0.2)[\Omega/km],
\]

(4.1)

where \( d \) is the diameter of conductor [mm], \( f \) is the frequency [kHz], \( \sigma \) is the specific resistance (Table), \( \mu_r \) is the relative permeability (Cu and Al =1, Fe=140).

The increase of resistance to \( \sqrt{f} \) is parabolic. The equation is valid from critical frequency \( f_k \), where

\[
f_k = \frac{4\sigma}{\mu_r d^2}.
\]

(4.2)
Up to this frequency the resistance is increasing with the square of frequency up to the value \( R_f = 1.25R_0 \).

**Inductance** \( L \) of open-air lines is given by the spatial arrangement of their line conductors.

\[
L = 0.4\left(\ln\frac{2a}{d} + 0.25\right)[\text{mH/km}],
\]

where

- \( a \) is the distance of wire axes [cm] and \( d \) is the diameter of conductors [cm].

The factor 0.25 is negligible at higher frequencies.

**Capacitance** \( C \) is calculated from the relation

\[
C = \frac{29\varepsilon_r}{ln\frac{2a}{d}}[\text{nF/km}],
\]

where \( \varepsilon_r \) is 1, when there is hoar frost it is 1.6.

**Conductance** \( G \) is

\[
G = G_o + v.f[\mu\text{S/km}],
\]

where \( G_o \) is the insulation conductance for DC, it is usually 0.1 S/km in dry weather and 0.5 S/km, in rainy weather. \( v \) is the conductance factor - 0.25 in rain and 0.75 in hoar frost, \( v \) 0.05 S/km in dry weather, \( f \) is the frequency [kHz].

From the theory of homogenous telecommunication line we can derive for specific attenuation

\[
\alpha = \frac{R_f}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}}[\text{Np/km}],
\]

where all values are specific and related to 1 km of line. The relation is valid first of all for higher frequencies. For LF transmissions and for conductors with diameter \( d < 2\text{mm} \) the conductance component is negligible and by condition \( \omega L \ll R \) it approximately holds:

\[
\alpha \approx \frac{\sqrt{R\omega C}}{2}[\text{Np/km}].
\]

For **specific phase shift** it is valid

\[
\beta = \omega \sqrt{LC}.
\]

For \( \omega L \ll R \) and low frequencies

\[
\beta = \sqrt{\frac{\omega RC}{2}}[\text{rad/km}].
\]

Characteristic impedance for high frequencies is

\[
Z_c = \sqrt{\frac{L}{C}}[\Omega],
\]
and for low frequencies

\[ Z_c = \sqrt{\frac{L}{\omega C}}[\Omega]. \tag{4.10} \]

B. Electrical properties of cable lines

**Resistance** of symmetric cable circuit is

\[ R = R_o k_f = R_o (k_s k_b k_o)[\Omega/\text{km}], \tag{4.11} \]

where \( R_o \) is the loop resistance, measured by DC [\( \Omega/\text{km} \)]

\( k_s \) is the factor of surface increase by surface effect,

\( k_b \) is the factor of resistance increase by proximity effect,

\( k_o \) is the factor of resistance increase by surrounding conductors (shielding, coating, etc.).

The factor \( k_s \) is calculated from the change of critical frequency (for a wire diameter of 0.5 mm, \( f_k = 280 \text{kHz} \); for 1.3 mm \( f_k = 42 \text{kHz} \)).

For supercritical frequency

\[ k_s = 0.12d\sqrt{f} + 0.25, \]

where

\( d \) is the diameter of wire [mm],

\( f \) is the frequency [kHz].

For frequencies lower than the critical one it is valid

\[ k_s = 1.25\left(\frac{f}{f_k}\right)^2. \]

The proximity factor of conductors \( k_b \) is usually 1.2 to 1.3 and the neighbouring conductors effect 1.20 to 1.10 depending on unit placement close to the coat or in the centre of cable profile. The resulting effective resistance determines the attenuation of cable circuit.

**Specific capacitance** of cable pairs is

\[ C = \frac{28\varepsilon_r}{\ln p^2}a\frac{\text{nF}}{\text{km}}, \tag{4.12} \]

where \( \varepsilon_r \) is the relative dielectric constant of cables insulated with paper-air. It is usually 1.5 to 1.8, with styroflex-air insulation 1.3,

\( p \) is the type of unit factor, for DM quads it is 0.65, for quads X it is 0.75, for \( p \) pairs it is 0.94,

\( a \) is the distance from wires [mm],

\( d \) is the diameter of wire [mm].

Capacitance is almost independent of frequency and is the result of several partial capacitances between wires. Compared with open-air lines this capacitance is 5 -7 times larger.
Inductance $L$ is given by the relation

$$L = 0.4 \ln \frac{2a}{d} + 0.25 \text{[mH/km]}.$$  \hspace{1cm} (4.13)

Inductance of cables is relatively smaller in comparison with air lines. This fact influences negatively the value of attenuation, as will be explained below (coil-loaded cables, artificial enlargement of $L$).

Conductance $G$ is composed of two components. The conductance at DC voltage between $G_o$, which us usually in long-distance cables 0.1 nS/km (corresponds to an insulating resistance of $10^5$ MΩ/km), 0.2 nS/km ($5 \times 10^4$ MΩ/km) for local cables insulated by paper-air; for all plastic cables it is usually larger. The second component of conductance at AC is indicated in relation to the conductance of operational capacitance, thus

$$G_f = k_g \omega C_p.$$  \hspace{1cm} (4.14)

The conductance factor $k_g$ for low frequencies is $0.55 \times 10^{-3}$, the influence of AC in comparison with conductance is small. For high frequencies the magnitude of AC leakage factor increases to $1.2 \times 10^{-3}$ for 10 kHz and up to $7 \times 10^{-3}$ for 100 kHz. Using polythene or styroflex insulation, the $k_g$ factor decreases by up to two orders.

Specific attenuation is calculated by the formula

$$\alpha = \sqrt{\frac{R \omega C}{2}} \text{[Np/km].}$$  \hspace{1cm} (4.15)

Because of enlarged capacitance of cable lines the attenuation increases parabolically in dependence on the frequency of audio telephone range (300-3400 Hz) in lines without coil-loading. This distortion of attenuation is to be respected in the design.

Impedance is determined from the equation

$$Z = \sqrt{\frac{R}{j \omega C}} \text{[Ω].}$$  \hspace{1cm} (4.16)

### 4.4 Coil-loaded cables

Coil-loaded cables based on the principle of so-called *pupinisation* (inventor M. I. Pupin) utilise artificial enlargement of cable line inductance. The decrease of line attenuation in a limited frequency range is enabled as well as the decrease of attenuation characteristics distortion. Inductance coils are inserted into the cable at regular distances, see Fig. 4.5. The distance of coils is the so-called coil-loading step $s$. The starting section, i.e. the first section from the amplifying station to the first coil-loading cabinet is always:

$$l_{\text{nab.}} = \frac{s}{2}.$$

Reasons: There are interconnected starting sections in amplifying station = s, better curve of $Z_c = \psi(f)$
Figure 4.5: Principle of coil-loaded line.

(Note: Coil-loading is one of the methods for artificial enlargement of line inductance. It is the most exploited method. In addition to this one, other methods are known, but they are seldom used. For example, the so-called krarupising (Krarup - a Danish physicist). It uses the principle of taping the copper wire with soft iron wire (complicated manufacturing). Another method is the so-called bimetallic wire and wire with magneto dielectrics.)

Let us confirm the decrease of attenuation due to coil-loading by the following consideration: For attenuation it is valid:

\[ \alpha = \frac{R}{2} \sqrt{\frac{C}{L}} + \frac{G}{2} \sqrt{\frac{L}{C}} = \alpha_R + \alpha_G, \tag{4.17} \]

where

- \( \alpha_R \) is the component of specific attenuation, derived from \( R \),
- \( \alpha_G \) is the component of specific attenuation, derived from \( G \).

Let us adapt relation (4.17) to

\[ \alpha = \sqrt{\frac{R^2 C}{4L}} + \sqrt{\frac{G^2 L}{4C}}. \]

We factor out from the first term

\[ x = \sqrt{\frac{RC}{GL}}, \]

and from the second one

\[ x^{-1} = \sqrt{\frac{GL}{RC}}. \]

We obtain

\[ \alpha = \sqrt{\frac{RC \sqrt{RG}}{2}} + \sqrt{\frac{GL \sqrt{RG}}{2}}. \tag{4.18} \]

Denoting \( \sqrt{RG} = \alpha_o \), we modify (4.18) to:

\[ \alpha = \frac{\alpha_o}{2} x + \frac{\alpha_o}{2} x^{-1} = \alpha_R + \alpha_G. \tag{4.19} \]
We can plot this term in the graph $\alpha = f(x)$ - see Fig. 4.6. It is evident from this Figure that $\alpha$ has a distinct minimum and it is reached when $x = 1$, when it holds

$$\frac{R}{L} = \frac{G}{C},$$

as is also clear from the term

$$\frac{d\alpha}{dx} = 0.$$

![Figure 4.6: Dependence of specific loss for coiled line on $x$.](image)

For practical usage the term (4.19) can be adapted to the form

$$\frac{\alpha}{\alpha_o} = \frac{x}{2} + \frac{1}{2x}. \quad (4.20)$$

Plotting $\frac{\alpha}{\alpha_o} = f(x)$ we obtain a "V" curve, as in Fig. 4.6 (for $x = 1$ the minimum is $\frac{\alpha}{\alpha_o} = 1$). For $x = 1$ it holds $\alpha_R = \alpha_G$ and the attenuation of cable is of the least value

$$\alpha_{min} = \alpha_R + \alpha_G = \alpha_o = \sqrt{RG}.$$

It can be found from the dependence $\frac{\alpha}{\alpha_o} = f(x)$ that coil-loading is meaningful for $x \gg 1$. Decreased attenuation is obtained by reducing

$$x = \sqrt{\frac{RC}{GL}}.$$

It is evident, that $x$ can be diminished by

- **reducing** $R$, i.e. enlarging the wire diameter (impossible)
• **reducing** \( C \), i.e. increasing the distance of conductors (impossible)
• **increasing** \( G \), (impossible!)
• **increasing** \( L \), the only real possibility

The suitability of coil-loading can be assessed from the primary parameters \( R, L, G, \) and \( C \) by calculating \( x \), and if \( x \gg 1 \) then also \( \frac{\alpha}{\alpha_o} \gg 1 \) and by coil-loading \( \alpha \) becomes smaller, that means coil-loading is suitable.

The optimal value of inductance is again derived from considerations and equals

\[
L_{opt} = \frac{RC}{G}. \tag{4.21}
\]

Inductance is introduced into cable lines by coil-loading sections (s) and is denoted, for example, H- 88 - 36, where H means a section length of 1830 m (2000 yards), B means a section length of 915 m (1000 y), 88 inductance of side in mH, 36 inductance of phantom coil (see below) in mH.

Note: Denoting: 1700 - 30 - 12, is a denotation of German origin, where 1700 is the length of coil-loading section in m, 30 and 12 are values in mH for the pair and phantom circuits.

The values of coil inductance are different and they influence the curve of \( \alpha = \varphi(f) \).

As evident from the earlier description, (see also Fig. 4.15), the upper frequency band is limited by introducing inductances into lines - in principle a low pass filter is formed (disadvantage).

The limiting frequency of equivalent filters is calculated

\[
f_m = \frac{318}{\sqrt{L_pC_s}} \text{[kHz]}, \tag{4.22}\]

where

\( L_p \) is the inductance of coil [mH],
\( C \) is the specific capacitance of circuit [nF/km],
\( s \) is the length of coil-loading section [km].

**Impedance** is given by the relation

\[
Z_c = \sqrt{\frac{L_p}{C_s}} \text{ [\Omega]}.
\]

The **Phantom circuit** is created to increase the exploitation of line. The fact is made use of that along two pairs of one quad, a third LF connection can be realised. (Fig. 3.7). The principle consists in the division of the currents of the compound circuit (another term for the phantom circuit) into a, b wires of pair I. and c, d wires of pair II.

As mentioned above, these circuits are also coil-loaded.

In view of the fact that the capacitance \( C_F \) of the phantom circuits of DM, quads is 1.6 times \( C_K \) (for \( XNC_F = 3C_K \) large capacitance, it is not suitable for compound circuits) and resistance \( R \) is halved, then for the same attenuation demand in both types of circuit the following condition holds:

\[
L_{PF} = 0.4L_{PK}
\]
Superphantom circuits have worse transmission properties. If they are used, then only for teletype subscriber lines. As evident from Figure 4.7, the superphantom circuit is realised by two quads.

Practical execution of coil-loading

Coils were originally manufactured of tin, later torroid magnetic and sendust cores were used, and during the last decades ferrite cores are used (H22, H26 - potties with
### 4.5 Symmetrical HF cables and cables for digital transmission

They were used as telephone carrier transmissions and utilised the suitable properties of $\alpha, \beta$ and $Z_c$ in the higher range of frequencies (up to 10 kHz). Only cross quads insulated by paper-air were used (12 to 252 kHz - 60 channels) and quads insulated by styroflex-air (12 to 552 kHz - 120 channels). Currently manufactured cables have profiles 1, 4, 7 and 12 quads with dia 0.9 and 1.3 mm. For each direction of transmission independent cables were used (directions A - B, B - A). For the transmission of digital systems of 1st order (PCM) exploiting 32 channels/pair the current cables are utilised. For digital systems of higher orders the cable $4 \times (7 \ P \ 0.8) + 2 \ P \ 0.8$ can be used. It is composed of Cu 0.8 mm wires (insulated with foamed polythene) and twisted into pairs. Seven pairs (different twists) are made into a group, which is shielded by Al foil. The cable core is composed of 4 groups with double shielding and perimeter insulation of polyester foil. The cable is equipped with continuous polythene coat possibly with mechanical protection. The cable is available for bit rates of up to 34 Mbit/s, that means it enables transmission of digital systems of 3rd order for 480 telephone channels.

### 4.6 Coaxial cables

It is not possible to use symmetrical cables for the transmission of broader frequency bands (problem of balancing the couplings). Therefore coaxial cables are used, where there is no mutual influencing of parallel pairs. The conductors of one pair are arranged in concentric form. They form a coaxial tube with central conductor (Fig. 4.8).

The electro-magnetic field produced remains only inside the tube, and the current passes at high frequencies only through the surface of inner conductor and the surface of tube. The shielding effect of outer conductor is insufficient at lower frequencies ($n.10^4$Hz). Therefore it is equipped with special shielding for this frequency range, composed of two coppered steel bands wound over the outer tube. The outer cylindrical conductor is in this way, also reinforced. The outer conductor is usually of wound copper sheet (about 0.20 mm), which surrounds the polythene insulating bobbins (distant 20 - 25 mm from one another) fixed on the inner conductor. Mutual insulation of conductors may be also provided by full foamed layer of polythene (marked $\alpha$) or by balloon insulation, created of polythene tube, squeezed at regular small distances to the inner conductor. This type is used with small coaxial tubes, typically 1.1/4.4 mm. The outer tube may be spliced in its seam by serration, milling or it is simply edged (the newest design). Peripheral insulation is wound of paper or polyester band and is numbered in accordance with the position of tube inside the cable. The tubes are composed into a cable profile irrespective of the direction of transmission and are combined with symmetrical quad, or audio (radio) pairs and other pairs. (It is necessary to install some circuits for operational communication, signalling, remote measurements, etc.)
The resistance of the two conductors is not the same and therefore it is valid:

\[ R = 83.5 \sqrt{f \left(\frac{1}{d} + \frac{1}{D}\right)} \, [\Omega/\text{km}], \quad (4.24) \]

where \( d \) and \( D \) are the diameter of inner conductor and the inner diameter of the tube [mm], \( f \) is the frequency [MHz].

Specific capacitance is

\[ C = \frac{56 \varepsilon_r}{\ln \frac{D}{d}} \, \text{nF/km}, \quad (4.25) \]

and \( \varepsilon_r \) is usually 1.15 - 15.

Specific inductance is

\[ L = 0.2 \ln \frac{D}{d}. \quad (4.26) \]

Capacitance is

\[ G = k_s \omega C, \quad (4.27) \]

where \( k_s \) may be \( 0.5 \cdot 10^{-4} = 0.005\% \).

For the calculation of \( \alpha, \beta \) and \( Z_c \) the same relations hold as for symmetric cables. The curve of attenuation is parabolic, given by increasing effective resistance.

The manufacture of coaxial cable for telecommunication was stabilised, with two common types, so-called medium and small coaxial pairs, being manufactured.

The medium coaxial pair has the inner copper conductor of diameter \( d = 2.6 \) mm, balloon insulation (older type bobbin - KMB - 4, first coaxial cable in CZ network with 4 medium tubes and 5 cross quads 0.9 Cu) and the outer conductor of copper band with undulated edge, wound with longitudinal seam into a tube of nominal inside diameter 9.4 mm. The pairs are marked 2.6/9.4. The ratio of inner conductor and outer tube is not
random; for copper and dielectrics $\varepsilon_r = 1.2$ and $\mu_r = 1$ and it is determined from the relation for attenuation, when it is valid

$$\alpha = 0.024 \frac{D}{D} \sqrt{f(D + 1)} \frac{1}{\ln \pi}.$$  \hspace{1cm} (4.28)

It is evident from this relation that for a definite $\frac{D}{d} = x$, $\alpha$ will be minimal.

Let the first derivative be zero

$$\frac{d\alpha}{dx} = 0,$$

then we obtain

$$x = \frac{D}{d} = 3.6,$$  \hspace{1cm} (4.29)

This is the ratio of tube diameters, minimising the specific attenuation.

It enables telecommunication transmissions in the frequency range from 300 kHz to 60 MHz, impedance 75 $\Omega$ and specific attenuation 3.6 dB/km at $f = 1$ MHz and temperature 10$^\circ$C. A possible variant of a medium six tube coaxial cable is shown in Fig. 4.9, combined with 4 audio pairs of 1.3 mm wire diameter and styroflex - air insulation, 6 cross quads insulated by polythene, and 4 supervision wires of 0.9 mm in diameter. Schematic marking: $6x2.6/9.4 + 6xN0.9 + 4RP1.3$

![Diagram](image)

**Figure 4.9:** Composition of coaxial cable core.

**Small coaxial pair**

It was developed as a complement to the frequency gap that arose between HF symmetric quads and medium coaxial pairs designed for backbone transmissions over extreme distances with large numbers of channels (1920, 2700 up to 3600 and exceptionally 10 800 channels).

It does not differ in principle from the above described medium coaxial pair. A significant difference is in tube ratio, which for copper is 1.2/4.4 mm. It is provided with balloon
Transmission media for Telecommunication

insulation and has the following parameters: impedance 75 Ω at f = 1 MHz, specific attenuation 5.22 dB/km at f = 1 MHz and temperature 10°C. It enables transmission of up to 12 MHz for telephone as well as TV video signal. It was crucial to the development of CZ trunk telecommunication network in the seventies and eighties of last century.

The composition of cable core varies, the most frequently used in CZ is the type MCBKQY 6x1.2/4.4 + 5XN0.7 + 6RP1.3 + 6X0.6 + 2P0.9

**Micro-coaxial pair**

Its usage for digital systems of second and third order as well as for data transmissions is possible. The diameter of inner conductor varies from 0.6 to 0.8 mm, outer tube 2.2 - 2.8 mm. The insulation is usually foamed polythene or balloon insulation. Impedance 65 - 75 Ω.

## 4.7 Special cables

**Audio (radio) cables**

The radio pair of 1.3 - 1.4 mm in diameter is shielded with metal plated paper or aluminium foil (aluminium foil provided with a layer of thermoplastic mass) and is entwined with 0.3 mm copper wire.

These pairs are placed variably into cable cores, as mentioned before, or as individual cables.

Example: 37 RP 1.3

It is designed for audio transmission:

- 50 - 10000 Hz type A,
- 50 - 6400 Hz type B,
- 30 - 15000 Hz type Q.

Coil-loading is also used (3.2 mH with 1830 m step, which for special cables was later halved to 915 m). The halved coiling step enables upgrading to 17 000 Hz. These special cables are used for transmissions of modulating signal between radio studios and to transmitters.

**Self-contained cables (catenary)**

Cables with polythene insulation are suitable to be constructed as self-contained and as clear from their name, they are provided with a carrying cord. They perform a unit and are designed to be suspended from mast tracks, see Fig. 4.10 (utilising with advantage the existing old tracks).

Older types of self-contained cables were hung on steel cable by suspensions (Fig. 4.11)
Submarine cables

The most important requirement for submarine cables consists in operational reliability together with extreme resistance of outer coating to humidity, and mechanical resistance.

Telecommunication waveguides

Telecommunication waveguides are lumped into a group of new perspective lines. They are manufactured as tubes, most frequently of radial or rectangular cross-section, using high-quality conductive materials. Transmission of electromagnetic energy is based on the same principle as in the atmosphere, but with a strictly defined direction and frequency. The frequency limitation depends on critical wavelength \( \lambda = \frac{c}{f} \) and is dependent on the construction of waveguides. A radial metallic waveguide is demonstrated in Fig. 4.12. The steel tube is metal-plated and then lacquered. Protective coating covers its surface.

A spiral waveguide is demonstrated in Fig. 4.13. This waveguide is formed by copper convolutions coated with a dielectric, followed by shielding and coating in the upper
layers. There is also a design using convolution in a metallic tube. An advantage of spiral waveguides is that they filter parasitic waves generated at non-homogeneous points of the wave link.

Results of experimental operation have been confirmed by the realisation of tracks of about 10 to 30 km in length, attenuation 2 dB/km, designed for 100 000 up to 200 000 telephone channels.

**Telecommunication superconductors**

They are based on the knowledge that at temperatures converging to absolute zero (−273°C) the value of resistance decreases, which decreases attenuation to one quarter of that of classical conductors. It is possible to transmit signals over extreme distances without amplifiers. They are constructed similar to coaxial cables (one or more tubes; material: tantalum, lead), covered with an outer layer of nitrogen or helium to maintain the low temperatures of conductors. However, they require being equipped with special cleaning facilities placed alongside the track every 10 to 20 km, which are extremely expensive.
4.8 Structured cabling systems

Structured cabling systems enable easy installation in buildings for networks such as LAN for data and voice networking. A special construction of twisted pair was developed together with very precise manufacture as a response to the demand for permanent upgrade of bit rates. Manufacturing these innovated copper pairs is an advanced manufacturing process guaranteeing equal distance of conductors; tensile forces are supervised during production and special care focuses on twisting and insulating the conductors. Thanks to these manufacturing processes minimal capacitance unbalances, minimal differences of conductor attenuation, minimal values of near-as well as far-end crosstalks (NEXT and FEXT) are guaranteed. There are also minimal differences in impedance and return loss.

As to the availability of operable frequencies, these systems are sorted into the following categories:

- 1.2 for voice services operation,
- 3 for data, 10 Mbit/s (ISDN),
- 4 for data, 16 Mbit/s (Token Ring Ethernet),
- 5 for data, 100 -300 Mbit/s (ATM, Ethernet),
- 6 for data 1 Gbit/s (6+/ 10 Gbit/s) (ATM, Ethernet).

Example: Cable BELDEN 1584A, number of pairs: 4, $Z_c \sim 100 \Omega$, $\phi$ 0.51mm, $C=49.2$ pF/km

<table>
<thead>
<tr>
<th>$f$ [MHz]</th>
<th>max $\alpha$ [dB/100m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3.67</td>
</tr>
<tr>
<td>10</td>
<td>5.77</td>
</tr>
<tr>
<td>16</td>
<td>7.38</td>
</tr>
<tr>
<td>31</td>
<td>10.39</td>
</tr>
<tr>
<td>100</td>
<td>19.52</td>
</tr>
</tbody>
</table>

**Specification of cables**

The demands on four-pair cables of 100 $\Omega$ impedance used in networks are specified in several standards. Wiring of outlets of physical link, usage of individual pairs, colour coding of pairs, transmission characteristics, testing parameters, testing methods and principles of cabling construction for a four-pair of category 3, 4, 5 and 6 of unshielded twisted pair (UTP) and technical equipment needed for cabling is described in the EIA/TIA-568 standard. The cabling of twisted pair covers a number of cable types of nominal impedance 100 $\Omega$. Beside the above-mentioned four-pair twisted pair cable there are also more capacitive cables containing 25 or more pairs, either of shielded or unshielded construction. Both basic constructions are available in all categories. Unshielded cable of category 3 is standard telephone cable. Connectors used in networks are of the same type as those we can come across in modern telephone systems. There is the RJ-45 connector with 8 outlets or the Telco connector with 50 outlets. For cabling administration, standard interconnecting panels (patch panels) can be used; addition of new access points, changes in the connection of access points, cancellation of no-longer needed access points can be done as easily as in ordinary structured telephone or data cabling. Closer specifications for cables of categories 4 and 5 may support operation over
greater distances; for example, cables of category 5 support distances of up to 150 m. Cabling passing through interconnecting boards to terminating nodes may be terminated in wall sockets equipped with RJ-45 connectors or the cables can terminate by these connectors.

An example of RJ-45 connector wiring is in Fig. 4.14.

![RJ-45 Connector](image)

**Figure 4.14**: Outlet assignment of 5-UTP cabling.

**Testing of UTP cables**, parameters and their acceptable range for operation of 100VG-AnyLAN network. These are the same parameters as those required in the 10 Base-T networks. In the case of 100VG-AnyLAN networks, the option of testing all four pairs for testing frequencies of up to 15 MHz is required.

The testing frequency is used to verify the cables for a network. Attenuation describes the magnitude of signal loss due to the signal passing through the conductor. The longer the cable, the greater the attenuation. In the case of very high attenuation, the receiver need not be able to decode the data received.

Characteristic crosstalk between pairs (pair-to-pair crosstalk) results from a signal in one pair being influenced by other neighbouring pairs.

Multiple Disturber Near-End Crosstalk, MDNEXT, gives the measure to which the signal in one pair is influenced by signals of all remaining pairs of cable, measured at the end of cable using disturbing source of signal in four paired cables.

**Cables with a shielded twisted pair**

Standards for STP (Shielded Twisted-Pair) cable of 150 Ω impedance offer a solid base for networks. Standards EIA/TIA 568, TSB 36 and 40 as well as the newly proposed
standard 568 (presented via SB 2840) specify the wiring of connector outlets, colour coding, characteristics of signal propagation, strategy of cabling, and also describe the attached technical equipment.

**Section of cabling system**

Each structured cabling is sectioned into the following parts:

- The CAMPUS section represents the interconnection of buildings,
- the RISER section forms the backbone distribution frame,
- the horizontal section is formed by fixed distributions frames for individual offices,
- the operational section interconnects the horizontal section and the terminal equipment.

The situation is illustrated in Fig. 4.15

![Diagram of cabling system](image)

**Figure 4.15**: Scheme of cabling system.
The CAMPUS section is realised mainly by optical cable due to the larger distances between facilities and also their galvanic separation. Another argument in favour of optical cable is also the link throughput related to data stream.

The RISER section (backbone line in a building) uses also optical cable as the transmitting medium. The main reason is the link throughput, in some cases also the galvanic separation of individual sections of network. The backbone is realised also by metallic cables. Multi-pair cables (e.g. 25 pairs) are used for categories 3 and 4.

The horizontal section is almost without exception formed by star distribution of four-pair metallic cables. The centre of the star is the point of interconnection to the backbone distribution frame. Optical cables are seldom used in the horizontal section.

The operational section contains connecting cables. These are metallic four-pair cables using the RJ45 connectors (so-called Patch Cord) or optical interconnecting cables. The type of connector of these cables is given by the active equipment used (mainly ST or SC connectors). The operational section serves to interconnect the horizontal section link and the terminal equipment. For example, a socket is interconnected with the computer on one side of the link, while on the opposite side the link in the data distribution frame is interconnected from the Patch Panel to the active element.

An example of system design (see Fig. 4.16):

![Scheme of cabling system](image)

**Figure 4.16:** Scheme of cabling system: CR - campus distribution cabinet, RR - backbone distribution cabinet, HR - horizontal distribution cabinet, Z - sockets.

Advantages of these systems can be seen in the transmission quality and bit rates, easy installation and maintenance, reduction of mistakes during installation and interconnecting.

### 4.9 xDSL Transmissions

The quality, great potentials and advantages of optical fibres have been mentioned several times before. (They will be dealt with individually in chapter 6). Their introduction in the transport (long distance) networks has doubtless been a success. Their introduction
in access (local) networks has not been so successful. There are systems that enable these transmissions but up to now the cost of all experiments is very high. Already in the preceding subchapter the possibility was mentioned how, with the support of special technology of 'twisted pairs', to upgrade the quality of transmission. The effort has focused on exploiting the existing telephone lines, which are wide-spread worldwide. The term "buried treasure" seems to be justified in this connection. The first success has been the deployment of ISDN (Integrated Services Digital Network), so-called integrated digital services, enabling the transmission of telephone calls, data (Internet) and fax services. The transmission of broadband services (TV, video), known as B-ISDN (Broadband-ISDN) is also possible. Other developments offer even more advantageous solutions based on new advanced modulation principles (CAP/QAM, DMT) that enable permanent access, new broadband services, parallel operation of POTS/ISDN and data, using common subscriber lines. These systems bear the generic names xDSL (ADSL, SDSL, VDSL, etc.). Fig. 4.17 demonstrates the roadmap to higher bit rates.

![Figure 4.17: Trends in bit-rate upgrade.](image)

The most extensive transmission uses the ISDN technology (above of all in Europe), and just now ADSL (originally in the USA, since 1998). Currently it is exploding also in CZ. This technology seems to be the most perspective today and depending on the type of local loop enables coverage of up to 6 km. Parallel operation of data as well as POTS/ISDN services is possible. The highest bit rate is as much as 8 Mbit/s (downstream) for a local loop length of 3 km, copper Ø 0.6 mm, and 640 kbit/s for back-haul channel (upstream). Access to services is without dialling (always on). This is an ideal means of accessing the Internet and other broadband services. The VDSL technology, enabling much higher bit rates (up to 52 Mbit/s (downstream) and up to 6.4 kbit/s (upstream)), however, enables transmission to only 300 m, Ø 0.6mm copper. These transmissions are suitable for business users, universities, etc. (Compared with optical transmission). More detailed information about modulation principles and techniques is offered in the course "Theory of Communication" and about network elements, modems, etc., in the course "Architecture of Networks".
4.10 Exercises

A) Demonstrate the relation between the values of inserted coils for a single pair and a compound circuit (phantom).
B) Determine the conditions for reflection of open and short-circuit lines.
5 SHORTCOMINGS OF TELECOMMUNICATION CABLES AND CABLE NON-HOMOGENEITIES

5.1 Non-homogeneities of cables

Telecommunication cables cannot be manufactured absolutely perfect (maybe theoretically yes, but seen from the economic viewpoint such manufacture would be unrealisable). Therefore it is necessary to search for a compromise between perfection and costs.

The reasons of shortcomings are as follows:

- In copper wire production. It is not possible to produce a wire of precisely nominal diameter. (Wires are drawn through drawing dies. These dies get gradually worn off and the diameter of wire is slightly enlarged).
- Analogously it is not possible to produce insulations of absolutely identical quality and thickness.
- It is not possible to obtain precisely identical windings and pressures when twisting pairs, quads and all cable cores to have identical electric properties for all cable lengths.

It is necessary to allow a certain tolerance in electrical properties of cables, as mentioned above. These shortcomings fall into two types:

1) non-homogeneities of primary parameters \( R, L, C, G \) and,
2) asymmetries of particular capacitances, leakages, resistances and inductive couplings (only for symmetric cables).

5.2 Non-homogeneities of primary parameters

Due to the imperfection of manufacture (wires, insulators, etc.) quads of individual production lengths slightly differ in the values of effective resistances \( R\ell \), inductivities \( L\ell \), operational capacitance \( C\ell \), leakages \( G\ell \) (critical in long-distance quad cables is first of all \( C\ell \)). Differences in the primary parameters of individual cable lengths, in joining in cable joints give rise to slight reflections, partial reflections of electromagnetic waves, which are transmitted to the beginning of line and further as multiple reflections also to the end of line. Partial voltages at the beginning of line are proportional to partial reflected waves. Their geometrical sum gives voltage \( U_{1r} \) (reflected) and particular currents, whose geometrical sum gives current \( I_{1r} \). This resulting reflected voltage \( U_{1r} \) is geometrically added to the original voltage \( U_1 \), which is finally changed into \( U_1^* \).

\[
U_1^* = U_1 + U_{1r}. \]

The change of input impedance is equal to changes of \( U_1^* \) and \( I_1^* \) at the beginning of line (instead of original \( Z_1 = Z_c \))

\[
Z^* = \frac{U_1^*}{I_1^*}. \]

The frequency characteristic of input impedance of line (without reflections) \( Z_1 = Z_c = \varphi(f) \) is flat, the frequency characteristic of input impedance of line, irregularly undulated
by partial reflections $Z^i = \varphi(f)$. Undulation of impedance characteristic reduces the possibility of line imitation by balancer (used in line termination), which decreases the balance return loss $a_{nv}$. Aggravation of imitation at the receiving side, in other words the decreased attenuation of missadaptation $a_{np}$ leads to impaired stability, echoes or so-called indirect far-end crosstalks FEXT. In TV transmissions these shortcomings defocus the picture and in the case of a more suitably delayed significant reflection, they will show up by another equidistant weak picture. It is important for the frequency characteristic of input (output) impedances of line to be as flat as possible. This is obtained by careful manufacture and, above all, by high-quality assembling of cable, as will be mentioned below.

Measures for minimising the non-homogeneities of line:

- In the manufacture: it is necessary to focus on the input check of supplied materials and provide consistent supervising operations during manufacture.
- After the completion of all manufactured cable lengths for one section and after finishing all final measurements, the so-called allocation of cable lengths will be proposed, i.e. the plan of placing individual cable lengths along the track.

The goal of allocation is to place, side by side, cable lengths with minimal deviation of wave impedance for a certain $f=\text{const.}$, and to place the best lengths at either end of the whole section, in other words, lengths with minimal deviation from nominal value. As an example we will show the method of allocation for coaxial cables. The manufactured lengths for one repeater will be divided into five groups from the point of view of characteristic impedance $Z_c$ [Ω] of every manufactured length: group I 74.35 - 74.65 (mean value 74.50), group II 74.66 - 74.90 (mean value 74.78), group III 74.91 - 75.15 (mean value 75.03), group IV 75.16 - 75.40 (mean value 75.28), and group V 75.41 - 75.65 (mean value 75.53).

Individual lengths are laid in such a way that to both ends of the amplifying (repeater) section the best lengths of group III will be placed. Further composition is done such that neighbouring lengths are always from the neighbouring impedance group. In this way the differences in impedance between neighbouring lengths will be minimised.

Not the impedance $Z_c$ [Ω] but the operational capacitance $C$ which influences $Z_c$ is measured in symmetric cables. Allocation is derived from the mean value of operational capacitance deviation (composition of lengths along tracks).

Assembling: Operational capacitance is improved by joining minimum deviations of neighbouring quads. In other words, a quad with positive deviation ($+\Delta C$) is joined with a quad with roughly the same negative deviation ($-\Delta C$) so that for two lengths there will be

$$C^i + \Delta C + C^i - \Delta C = 2C^i.$$

These asymmetries can be found only in symmetric cables, i.e. in paired cables or in quads (they need not be mechanically symmetric). By contrast, the coaxial pair is of perfect mechanical symmetry and yet electrically asymmetric.
5.3 Asymmetry of partial capacitances and leakages

Asymmetries of partial capacitances and leakages, so-called lateral asymmetry, can be explained on a schematic illustration of a quad (Fig. 5.1) which is composed of pair 1 (conductors a, b) and pair 2 (conductors c, d), with appropriate partial capacitances $C'_{ad}, C'_{ac}, C'_{bc}, C'_{bd}, C'_{ab}, C'_{cd}$ and earth capacitances $C'_{ao}, C'_{bo}, C'_{co}, C'_{do}$.

Partial capacitance is the capacitance between two conductive objects (conductors, metal plates, armatures, conductor and earth, etc.), which is given by the geometrical configuration of conductive objects (such as shape, position, distance) and the dielectrics between them. It is possible to measure partial capacitances; they do not show up independently. We will transform the four-arm star of earth capacitances $C'_{ao}, C'_{bo}, C'_{co}, C'_{do}$ into an equivalent complete polygon, which is shown in Fig. 5.2. These capacitances are marked with two dashes in this figure and they are added in parallel to the partial capacitances between conductors. Effective partial capacitances thus appear, i.e. effective partial capacitances between two conductors $C'_{ab}, C'_{cd}, C'_{ac}, C'_{ad}, C'_{bc}, C'_{bd}$ as shown in Fig. 5.3. Since in the following deliberations we will be concerned with crosstalk circumstances of an individual quad, we may leave out $C'_{ab}, C'_{cd}$, as crosstalks are not influenced by the effective partial capacitances inside the first and the second pairs.

Part of the current penetrates from the 1st into the 2nd pair, leading to crosstalk between the pairs. The asymmetry of effective partial capacitances of one quad (in the range of an electrically short element) causes therefore crosstalk between the circuits of this quad. The unbalanced bridge of partial capacitances causes the crosstalk. Crosstalk is minimised
**Figure 5.2:** Partial capacitances transformed from star of four earth capacitances into a full polygon.

**Figure 5.3:** Network of effective partial capacitances inside cable quad.

**Figure 5.4:** Capacitive bridge of effective partial capacitances of quad.
such that the bridge is balanced by additional capacitance $k_1$ (on the basis of measurement) as is evident from Fig. 5.4 for example. Additional capacitance is called capacitive asymmetry and it balances the bridge of effective partial capacitances.

To simplify the calculation of crosstalk we often use coupling according to Fig. 5.5.

\[ k'_{1} \]

(compensation for Fig. 5.5 without capacitor $k_1$), in which two conductors are coupled by capacitor $k'_{1}$, which is called fictitious capacitive coupling, and the remaining two conductors are connected directly. The value $k'_{1}$ is dimensioned such that current will flow through telephone receiver, as in the case of Fig. 5.4. As will be further evident, there is a simple relation between $k'_{1}$ and $k_1$: \[ k'_{1} = k_1 / 4 \]. The equivalent coupling given in Fig. 5.5 is used when solving theoretical considerations of crosstalk.

As to the asymmetry of partial leakages, which are due to losses in the dielectric, there is no critical situation as in cases of partial capacitance asymmetry. Partial leakages are illustrated as parallel coupling of $g_{ac}, g_{ad}, g_{bc}, g_{bd}$ to partial capacitances. We thus obtain a complex admittance (Fig. 5.4) \[ g_{ac} + j\omega C_{ac} \] etc.

To conclude this chapter, let us explain the term of operational capacitance. For simplification, let us denote effective partial capacitances $C_{ac}, C_{ad}, C_{bc}, C_{bd}$ as \( x \) and capacitance $C_{ab}$ as \( y \). Then the resulting operational capacitance of length \( l \) will be:

\[ CI = y + \Sigma x \]

This situation is shown in Fig. 5.6. Two capacitances \( x \) are always in series (\( \frac{x}{2} \)) and these capacitances are parallel to \( y \). Operational capacitance is the effective partial capacitance between two wires, forming one circuit (pair, phantom) with \( l = 1 \text{ km} \) sometimes. It is not possible to speak about "asymmetry $C$" as it is sometimes incorrectly used because it is one capacitance connected between two conductors (circuit) and thus it is no asymmetry.
5.4 Magnetic asymmetries

There are so-called longitudinal asymmetries, which have both real components (resistance asymmetries) and imaginary components (asymmetries of inductance couplings). Inductance couplings arise in electrically short sections between individual quad wires (partial mutual inductances), which can be thought of as transformer couplings $m_{ac}, m_{ad}, m_{bc}, m_{bd}$ - see Fig. 5.7.

![Figure 5.6: Capacitive asymmetry $k_1$ and functional capacitance $C.l$ of manufactured length.]

We also obtain unbalanced bridge due to the differing inductance couplings, with crosstalk as the resulting effect. Since we are again interested in asymmetries between the 1st and the 2nd pairs, we can provide a compensation of connection in our theoretical considerations about crosstalk and consider only fictitious inductance coupling between pairs, denoted $m'_1$ (see Fig. 5.7b). The above couplings between individual conductors have also real components, caused by losses due to currents inside the conductors and coating, which in asymmetric configuration can also cause crosstalk.

So-called resistance asymmetries of individual pairs $R_a - R_b$ and $R_c - R_d$ cause unbalancing the differential bridges of pairs 1, 2 (as illustrated in Fig. 5.8) and, consequently, the appearance of crosstalk between the 1st or the 2nd pair and the phantom. Similarly, the inductances of individual conductors $L_a - L_b$ and $L_c - L_d$ (see Fig. 5.7) can cause crosstalk between the 1st and the 2nd pairs.

In conclusion we can say that crosstalk in symmetric quaded cables is due to asymmetries of partial capacitances, leakages, inductances and resistance couplings.

5.5 Corrective measures against asymmetry

The respective measures are taken both during manufacturing and during assembling.

Measures during manufacturing the cable

I. Technological measures:

As mentioned before, the best measure to minimise asymmetries is precision manufacture. To guarantee identical resistance of all four conductors in one quad the respective wires must be cut from the same coil of wire. Identical diameter is thus obtained for the
whole length of wire. The preparation of insulating materials must proceed in a similar way. From time to time, $k_1 - k_3$ are checked in the quad itself.

II. **Cable design**

Capacitance asymmetries are more significant in comparison with magnetic ones in the low frequencies (up to 15 kHz). The DM (Dieselhorst - Martin) quad gives better results as to capacitance asymmetries than the cross quad. The DM quad has a higher operational capacitance $C$ than the cross quad (38.5 nF/km vs. 34.0 nF/km) and all the quad conductors get perfectly interchanged and thus a practically identical mean value of the distance between individual wires is obtained, together with roughly identical partial capacitances between conductors.

Magnetic asymmetries are more important in the region of higher frequencies (carrier systems) in comparison with capacitance asymmetries and therefore the cross quad is to be preferred here. What matters here is the inductance coupling between individual wires (i.e. the face of loops formed by two neighbouring conductors). Equity of these loop faces is reachable much easier by cross quad in compare with DM quad.

**Measures during assembly:** Assembling of cables has the following steps: I. Symmetrizing. This is a process in which capacitance asymmetries by joining electrically short sections of cable are reduced. Symmetrizing is done by:

1. Choosing the quads and crossing,
2. Additional capacitors.
Symmetrizing is called in English cable-fitter argot doping. This process is only possible with acoustic frequencies; several manufacturing lengths may be symmetrized up to a section of 2 km. It is not possible to symmetrize using higher frequencies, because manufacturing lengths are (in view of the few quads inside the cable) longer in comparison with LF cables, e.g. 460 m (in contrary to 230 m in LF cables) and they are not electrically short.

II. Direct minimising of crosstalk
If by joining a greater number of manufacturing lengths sections are reached that are no longer electrically short or if at higher frequencies the manufacturing lengths themselves are not electrically short, symmetrizing is not possible, and the next stage sets in, namely direct crosstalk balancing. This operation is not oriented to causes of crosstalk itself, but to the resulting effect of asymmetries, the crosstalk itself. This method changes either the crosstalk itself or the effective admittance couplings at a defined point of line: in the case of FEXT at the end, while NEXT should be compensated at the point of bad coupling. Crosstalk is decreased by crossing pairs and quads in suitably placed joints. This process of crosstalk minimising by joining longer sections of cable is called poling.

III. Final balancing of crosstalk via compensation connections
The above mentioned measures are usually not sufficient to obtain the required crosstalk attenuation, particularly in cables used by the carrier system. Thus there is yet another
step, the third step of assembling, i.e. fine balancing via compensating (balancing) by compensation wiring - most frequently at the end of amplifying section. As can be seen, the measures and methods for homogeneity upgrade or, in other words, minimising the crosstalk is very complicated.

5.6 Non-homogeneities of lines

The previous chapter focused on shortcomings of telecommunication cables, mainly from the viewpoint of manufacturing length ($l = 230$ m). Let us extend the currently studied problematic to the case of joining individual lengths as well as to connecting the terminal equipment. It is evident that to maintain homogeneity (of the amplifying section, for example) equipment impedance and characteristic impedance of line should be correctly adapted in a broad frequency band. It is practically unrealisable to reach the ideal state. Despite this fact we try to accommodate the situation by minimising the impedance non-homogeneities. Shortcomings in this case result in that part of the voltage and current waves reflected from impedance non-homogeneities along the line because of non-adaptation of equipment and line impedances is after return to the beginning of line reflected again back to the far end. Another reflection occurs there due to non-adaption. We will examine reflections in greater detail as well as measures for ensuring homogeneity.

Theory of the origin of single and multiple reflections in homogeneous line and their impact.

Characteristic impedance $Z_c$ of a homogeneous line at a defined frequency is not constant along the whole distance but differs from the mean value $Z_c$ due to partial non-homogeneities by deviation $Z(x)$. Deviations $Z(x)$ in manufacturing lengths are due to the primary parameters of line, caused by deviations of wire diameters, mutual wire distance, non-homogeneity of wires, deformations of elements during manufacturing and cable laying. Other deviations $Z(x)$ may arise when splicing individual manufacturing lengths, in which the mutually followed values $Z_c$ vary. Every impedance non-homogeneity causes the reflection of a part of voltage and current waves propagating along the line. If the reflected wave returning to the beginning of line meets a point with impedance non-homogeneity, a part of the wave is again reflected back, i.e. in the direction of the primary progress of main wave to the end of line. The principle of reflections, demonstrated in Fig. 5.9, is repeated on all impedance non-homogeneities. The sum of all just once reflected voltage and current waves causes a change in the input impedance of line and therefore a change also in the power of useful signal, which is transmitted into the line. The change of input impedance is frequency-dependent, hence the undulation of frequency characteristics as well as residual attenuation. The sum of all twice reflected voltage and current waves will cause troubles in the far end of line. The impact of three and more times repeated reflections can be neglected, because these reflected voltage and current waves are severely attenuated by now. From the above it is clear that every impedance non-homogeneity disturbs transmitted signal and causes a decrease in the signal/noise ratio. The above mentioned mean value of $Z_c$ and deviations $Z(x)$ may be illustrated for a defined frequency as in Fig. 5.10.
Figure 5.9: Scheme of voltage and current waves reflected from impedance non-homogeneities.

Figure 5.10: Undulated characteristic impedance about its mean value.

Characteristic impedance $Z_c$ at distance $x$ from the beginning of line is

$$Z_c = Z_c + Z(x). \quad (5.1)$$

Function $Z(x)$ will be called function of undulation because it characterises the undulation of $Z_c$ about its mean value.

Let at point $x$ in the length element of line $dx$ be a jump of impedance $Z_1(x) - Z_2(x + dx) = \Delta Z(x)$, then the reflection factor at this point is

$$p = \frac{\Delta Z(x)}{Z_1(x) + Z_2(x + dx)}. \quad (5.2)$$

Since impedance deviation $Z(x)$ is in comparison with the mean value of impedance
$Z_c$ very small, and so is also the difference of impedances $Z_1(x) - Z_2(x + dx) = \Delta Z(x)$, we are able to define the reflection factor as follows

$$p \doteq \frac{\Delta Z(x)}{2Z_c}. \quad (5.3)$$

Then for a voltage reflected from the non-homogeneity at point $x$ of the line, which at the line beginning shows up as disturbing voltage $U_{1b}$ we can write:

$$U_{1b} = U_{10} \frac{\Delta Z(x)}{2Z_c} e^{-2\gamma x}, \quad (5.4)$$

where $\gamma = \alpha + j\beta$ is the specific propagation constant.

Introducing a factor of disturbing voltage caused by reflection at the near end $P_n(\omega)$ (ratio of disturbing reflected voltage $U_{1b}$ at the beginning of line to effective voltage $U_{10}$ at the beginning of line), relation (5-4) can be rewritten for a single point of reflection

$$P_n(\omega) = \frac{U_{1b}}{U_{10}} = \frac{\Delta Z(x)}{2Z_c} e^{-2\gamma x} \quad (5.5)$$

In the case of equally distributed non-homogeneities along the line the resulting factor of disturbing voltage caused by reflection at the near end of complete line will be

$$P_n(\omega) = \frac{1}{2Z_c} \int_0^l e^{-2\gamma x} dZ(x) = \frac{1}{2Z_c} \int_0^l (Z(x))' e^{-2\gamma x} dx, \quad (5.6)$$

where $(Z(x))'$ is a derivative of undulation function $Z(x)$ with respect to $x$.

It is evident that a decrease in disturbing voltages caused by reflection can only be reached by decreasing the non-homogeneities along the cable line.
5.7 Exercises

A) Cable \( \odot \)1.3mm Cu has \( C_k = 38.5 \mu \text{F/km} \). Determine operational capacitance for a manufacturing length of 230 m.
6 WIRELESS TRANSMISSIONS

6.1 Radio transmissions

We take this concept to mean telecommunication supported by radio waves. Fixed terrestrial service utilising radio links and fixed satellite service are the most important for telecommunication purposes. Both types of systems are operated in microwave bands and are exploited for the transmission of telephone calls, data, TV and audio signals. Other applications of radio communication transmission are radio broadcasting in bands of ultra-short, short, medium and long waves, terrestrial TV broadcasting and satellite broadcasting. First long-distance transmissions used cable links, then radio transmission overtook cable transmissions (shortwave and satellite broadcasting); optical transmissions reversed the situation back again. Mobile radio communication is currently gaining supremacy. It can be said that cable and radio (wireless) transmissions now complement each other. Radio links may be used as hot reserve in the case of cable fault (and vice versa). Radio links are used above of all in the mountains due to their quick installation, and when building networks for mobile operators. They were extraordinarily important during the launching of digital overlay network in CZ. The schematic of radio link system is given in Fig. 6.1.

Between the signal source (SS) and the modulator (M) is the signal processing block in basic band (BBB). ZZS depends on the transmission type: analogue vs. digital. Coming next are the transmitter block (TB) and the aerial system. The band from 1 to 10 GHz is used in radio links and fixed satellite service. Parabolic aerial systems are utilised for transmitting as well as for receiving. This system is composed of primary emitter and rotary parabolic reflector. Spherical wave impinges on the surface of parabolic reflector to be reflected. This wave is transformed from spherical into plane wave, which is emitted from the mouth of parabolic reflector. Similarly, the receiving side is composed of receiver (R), detector (D), signal processing circuits (SPC) and consument (C). Radio link points are built on suitable hills distant 30 to 70 km securing direct line of sight as links of point-to-point type or, for longer sections, so-called "radio relay" stations are built (composed of a receiver and a transmitter, with a change of carrier frequency). Systems of this type are exploited for data transmissions, for connecting distant localities to LAN networks, etc. Naturally, the whole problematic is much more complex; to obtain good transmission, radio wave propagation, noise, bandwidth and other parameters have to be considered.
6.2 Satellite transmissions

The most important for telecommunication are satellites on a geostationary trajectory linked with fixed terrestrial stations. Satellites are stationed at a height of 38 600 km and observed from the earth surface they seem to be stationary. Intelsat is an example. They are exploited for telephone calls, data transmissions, TV, etc. The intersputnik system of former Soviet origin covers the Nordic, Indian and Atlantic areas utilising a system of three satellites orbiting on an extreme eclipse trajectory around earth poles.

6.3 Mobile transmissions

These systems have developed explosively in recent years. They are being permanently upgraded as regards both services offered and comfort of subscriber terminals. (video and TV transmissions). The principle lies in the cell structure, where the transceiver dispatches subscribers demands. The transceiver is linked by a radio link, optical fibre or cable to a higher network layer up to the control switch. The switch interconnects subscribers of the same operator (O2, T-Mobile and Vodafone in CZ) or provides mutual interconnection with the network of another operator or with the fixed line (O2) or abroad (more detailed in the courses Radio and mobile communications, Subscriber terminals). These systems have developed explosively in recent years. They are being permanently upgraded as regards both services offered and comfort of subscriber terminals. (video and TV transmissions). The principle lies in the cell structure, where the transceiver dispatches subscribers demands. The transceiver is linked by a radio link, optical fibre or cable to a higher network layer up to the control switch. The switch interconnects subscribers of the same operator (O2, T-Mobile and Vodafone in CZ) or provides mutual interconnection with the network of another operator or with the fixed line (O2) or abroad (more detailed in the courses Radio and mobile communications, Subscriber terminals).

6.4 Optical transmissions

Open-air optical transmissions utilise the laser link and atmosphere as the transmission medium. These are links with line of sight visibility, easy to realise and do not require official permission for operation as in the case of radio links. They are duplex links exploiting the optical carrier frequency, the power of which is concentrated into a narrow beam. Mostly digital intensity modulation is used. Using new principles (multi-channel transmission-higher costs) a reliability of close to 0.999 is achieved. These systems are produced by prestigious manufacturers. Transmissions at bit rates of 155 Mbit/s bridging distances of up to several km are used most frequently. Application can be found in LAN and MAN networks. Another method of optical cable-less transmission can be realised by IRLED emitters to "cover" room space for wireless connection of PC, headphones, interpreter equipment, etc. Radiation in these cases propagates by diffusion and reflection.
7 OPTICAL FIBRES AND CABLES

7.1 Basic principles of transmission

Transmission of information through optical fibre is made possible by light ray. The peculiarities of information transmission by light result from differences between electrical and optical light signals. Signal carriers are crucially different. These carriers are live electrons in galvanic couplings while in optical couplings they are neutral photons, which do not influence one another. During transmission there are no magnetic and electric fields, which often lead to various parasitic couplings. The optical link is immune to outer interference signal and hard to tap. There is no back influencing from output to input. The linkage is absolutely unidirectional. Full galvanic separation of input and output is also advantageous. The optical link is basically formed by modulated ray source, optical environment and receiver of rays. The input and output signals of optical link are electric, and so the transmitting as well as receiving parts contain in addition to optoelectronic elements and optical systems also electronic circuits for input and output signal processing. The basic connection of one possible variant of optical link is in Fig. 7.1.

The light source is usually a laser or luminiscent diode. The light ray is modulated in an optical modulator or, in the case of semiconductor source, directly by changing the excitation current. The task of the transmitting and the receiving parts of an optical system is to transmit optical signals with as low losses as possible from transmitter to the optical environment and then at the receiver end to a photodetector. The receiver then transforms the light signal back into an electric signal, with the receiver securing optimal processing with respect to signal-to-noise ratio. Signal processing circuits transform the signal into a suitable form for transmission. These are circuits for multiplexing, and at the receiver and circuits for demultiplexing.

![Basic scheme of optical link](image)

Figure 7.1: Basic scheme of optical link.
The range of optical radiation extends between 100nm and 1mm, and is divided into
7 subranges:
- three ultraviolet (100 nm–280 nm; 280 nm–315 nm; 315 nm–380 nm) subranges,
- followed by the visible light subrange (380 nm–780 nm),
- three infrared (780 nm–1.4 \( \mu \)m, 1.4 \( \mu \)m–3 \( \mu \)m, 3 \( \mu \)m–1 mm) subranges.

As a limit for optical communication exploitability the wavelength around 10 \( \mu \)m may
be considered. Powerful lasers and detectors are available for this infrared range. A substantially narrower range of 0.4 to 1.7 \( \mu \)m is of primary importance for optical transmission of information. Minimum attenuation of materials used for the manufacture of light waveguides corresponds with this range, whereas in the range of ultraviolet rays their attenuation rises. No effective photodetectors are available for the range close to X-rays and it is difficult to excite radiation with such a high energy of light quanta. On the other hand it is crucial to upgrade the low immunity of receivers against disturbing signals in the infrared range. Receivers should be protected against disturbing signals radiated by warmed objects. The parameters of optical signal are changed when passing through an optical environment. This is accompanied by attenuation as well as changes of the shape of transmitted pulses or their time position. The range can be extended by the implementation of repeaters, which are either of the amplifying or the regenerating type. Repeaters of the first type amplify across the optical band by laser amplifiers. Addition of noise by every amplifier and consequent degradation of link quality with increasing length of line is a disadvantage. Regenerating repeaters, which provide a complete renewal of the signal to original quality, enable on the basis of PCM creating links, whose quality is independent of the length of track. The invisible light ray is the carrier of information in optical transmission. Changes in its amplitude, frequency, phase, polarisation, and duration may display the transmitted information either each of them independently or in a suitable combination. It is necessary to consider the random character of photon radiation in optical transmission and in the link design. Its impact is the generation of noise, which is directly part of optical signal. The principle of fibre optics transmission consists in the total reflection on the dividing line of two optical environments with differing refraction indices. They are formed by a cylindrical dielectric core with refraction index \( n_1 \) which is surrounded by dielectric cladding with refraction index \( n_2 \) (Fig. 7.2). It holds \( n_1 > n_2 \).

For rays entering the core at a smaller angle than \( \Theta \), where \( \cos \Theta = n_2/n_1 \), there is total reflection on the core/cladding dividing line.

Lasers (LD) and light-emitting diodes (LED) serve as light sources in optical links. LEDs are non-coherent sources and may be used only for links with lower requirements on bandwidth and range. The most suitable and advantageous sources for telecommunication purposes of all light sources are semiconductor lasers. Most advantageous photodetectors for links with fibre light waveguides are semiconductor photodiodes (PIN) or avalanche photodiode (AFD). The level of useful signal and noise magnitude on photodetector output are the basic parameters defining the choice of photodetector.
7.2 Types of optical fibres

As to the technology and type of transmission, lightguides can be divided into single-mode and multi-mode with constant index of refraction of core and cladding, or step-index, and gradient (multi-mode) with varying index of refraction.

*Single-mode lightguides*

These lightguides have an extremely small diameter of core and for a defined numerical aperture and wavelength of light enable the transmission of only a single, i.e. basic mode of electromagnetic wave \( V < 2,405; HE_{11} \). These lightguides reach lower values of attenuation, but the extremely small diameter of core makes it difficult to couple light into fibre. (Fig. 7.3). These lightguides have a lower dispersion, i.e. they have a larger transmission bandwidth. Their excitation is secured by a light source with low spectral line (lasers). They are currently the most widely used fibres in long distance transmitting applications.

*Multi-mode lightguides*

Enlarging the core diameter (the condition \( V > 2,405 \) is valid), the number of modes that can propagate through the fibre increases. In currently used light guides with core diameters of 50 to 100 μm, thousands of modes are propagating on the wavelength 0.85 m (see Fig. 7.4). The mode dispersion appearing in this type of lightguide limits the bandwidth to a value of ca. 50 MHz/km. Application is in short-distance transmissions.
Gradient (multi-mode) lightguides

These types of lightguide, exploiting the change in refraction index $n = n(x)$ inside the core cross-section in transverse direction, mostly with quadratic parabola curve, according to the relation:

$$n = n_0(1 - \alpha^2 x^2),$$

enable a significant reduction of mode dispersion (see Fig. 7.5).

The maximum value of refraction index is in the fibre axis, and in the direction out of the axis it decreases in accordance with the above described law. With the same core diameter and the same difference $\Delta n$ of refraction indices, half the number of modes are transmitted. This is very suitable for the quality of transmitted signal, when these lightguides reach bandwidths of over 1 GHz-km, the core diameter varies approximately from 50 to 100 $\mu$m, with $NA$ of roughly 0.2. They are used for transmissions over medium distances, preferably for multiplexed transmissions.

Examples of characteristic parameters of optical fibres by Lucent Technologies:
Single-mode fibre with accommodated refraction index profile (Matched Clad, MC)

**General characteristic**

Single-mode optical fibre with accommodated refraction index profile is composed of germanium doped core and coated with pure silicon glass. The schematic of refraction index profile is shown in Fig. 7.6. Fibre is designed for all applications where low attenuation and broad bandwidth for higher bit rates are required. The fibre can be used on both wavelengths used, i.e. 1310 and 1550 nm. The other advantages are as follows:

- extremely low attenuation for both wavelengths,
- excellent geometrical parameters enable reaching extremely low inserted attenuations of welded splices as well as connectors,
- doubled primary coating D-LUX 100 ensures excellent mechanical and climatic immunity D-LUX,
- if the fibre is placed in a Lucent Technologies cable, the manufacturer guarantees excellent parameters of fibre as well as cable as regards polarisation dispersion. The guarantee of this parameter is important especially for analogue applications (cable TV).

![Image of fibre](image)

**Figure 7.6**: Refraction index of SM fibre.

**Geometrical parameters**

**Fibre**

- Diameter of core: 8.3 μm (nominal value)
- Diameter of coating: 125 ± 1 μm
- Excentricity of core: < 1%
- Excentricity of core-coating: ≤ 0.8 μm

**Primary protection**

- Diameter of primary protection: 245 ± 10 μm
- Excentricity of primary protection - coating: < 12 μm

**Transmitting parameters**:

- Mode of field diameter (MFD): 9.3 ± 0.5 μm (1310 nm)
  10.5 ± 1.0 μm (1550 nm)
Limit wavelength ($\lambda_{cut-off}$): 1150 - 1350 nm (for a fibre length of 2 m)
Limit wavelength in cable: $\leq$ 1260 nm
Attenuation (client specifies max. value of range): 0.35 - 0.40 dB/km for 1310 nm
0.21 - 0.30 dB/km for 1550 nm
Spectral change of attenuation: $\leq$0.1 dB/km in the range 1285-1330 nm
$\leq$ 0.05 dB/km in the range 1525-1575 nm
Longitudinal homogeneity of attenuation: no point discontinuities $> 0.1$ dB
Attenuation in wavelength of absorption maximum of OH ions ($1383\pm3\mu m$) $\leq$2 dB/km

**Chromatic dispersion**
Wavelength of zero chromatic dispersion $\lambda_0$: 1300 - 1322 nm (typically 1312 nm)
Dispersion between 1200 and 1600 nm can be calculated according to the relation
$$D(\lambda) = 0.25.S_0.\lambda.(1 - (\lambda/\lambda_0)^4)$$
Maximum dispersion for 1550 nm: 18 ps/km.nm
Max. slope of dispersion characteristics on the wavelength of zero chromatic
dispersion:
$$S_o \leq S: 0.092 ps/nm^2.km$$ (typically 0.088 ps/nm^2.km)
Losses due to macro-bending:
Less than 0.5 dB on one winding of 32 mm in diameter, for $\lambda = 1550$ nm
Less than 0.05 for dB = 1310 nm and less than 0.1 dB for $\lambda = 1550$ nm on 100 windings
of 75 mm in diameter.
Polarisation mode dispersion: 0.5 ps/$\sqrt{km}$ for 1310 nm (Lucent Technologies cable).

**Mechanical parameters:**
Tensile strength (Proof Test): 0.7 GPa
Tightening force of primary coating: < 8.9 N , $\geq$ 1.3 N

**Climatic immunity**
Temperature dependence of attenuation: $\leq$0.05 dB/km within the range from -60°C
to +85°C
Static fatigue: Value of static fatigue coefficient is $> 20$ using the D-LUX 100$^R$
protection.
Preservation of colour marking:
Colour marked fibres in D-LUX 100$^R$ primary protection do not exhibit any changes
in colour after the following tests of aging:
- 30 days at 95°C and 95% relative air humidity. - 20 days in dry heat 125 °C

**Other characteristics**
Relative difference of refraction index: $\Delta_1 = 0.33\%$
Effective group refraction index: 1310 nm 1.466
1550 nm 1.467
Numerical aperture: 0.12
Rayleigh’s coefficient of backscattering: 1310 nm -49.6 dB
1550 nm -52.1 dB
Curving of fibre: curving radius $\geq$ 2 m
**Single-mode fibre with depressed profile of refraction index (Depressed Clad, DC)**

*General characteristics*

Single-mode fibre with depressed profile of refraction index is composed of germanium doped core, outer coating, core, inner coating and coated by pure silicon glass. The schematic of refraction index profile is shown in Fig. 7.7. The fibre is designed for all applications where low attenuation and broad bandwidth for higher bit rates are required. The fibre can be used on both wavelengths, i.e. 1310 and 1550 nm. The other advantages are as follows:

- Extremely low attenuation for both wavelengths.
- Excellent geometrical parameters enable reaching extremely low inserted attenuations of welded splices as well as connectors.
- Doubled primary coating D-LUX 100 ensure excellent mechanical and climatic immunity.
- if the fibre is placed in a Lucent Technologies cable, the manufacturer guarantees excellent parameters of fibre as well as cable as regards polarisation dispersion. The guarantee of this parameter is important especially for analogue applications.(Cable TV).
- Depressed profile of refraction index ensures excellent immunity of attenuation against all micro and macro-bending, also when changing the wavelength to 1550 nm.

![Figure 7.7: Profile of refraction index for DC.](image)

*Geometrical parameters*

**Fibre**
- Diameter of core: 8.3 μm (nominal value)
- Diameter of coating: 125 ± 1 μm
- Excentricity of core: < 1%
- Excentricity of core-coating: ≤ 0.8 μm

*Primary protection*
- Diameter of primary protection: 245 ± 10 μm
Excentricity of primary protection - coating: < 12μm

*Transmitting parameters:*
Mode field diameter (MFD): 8.8± 0.5 μm (1310 nm)
9.7± 0.6 μm (1550 nm)
Limit wavelength (λ_{cutoff}): 1170 - 1310 nm (for a fibre length of 2 m)
Limit wavelength in cable (22m): ≤1260 nm
Attenuation (client specifies max. value of range): 0.35 - 0.40 dB/km for 1310 nm
0.21 - 0.30 dB/km for 1550 nm
Spectral change of attenuation: ≤ 0.1 dB/km in the range 1285-1330 nm
≤0.05 dB/km in the range 1525-1575 nm
Longitudinal homogeneity of attenuation: no point discontinuities > 0.1 dB
Attenuation on the wavelength of absorption maximum of OH ions (1383±3μ):
≤2 dB/km

*Chromatic dispersion*
Wavelength of zero chromatic dispersion (λ₀): 1310±10 nm (typically 1310 nm)
Dispersion between 1200 and 1600 nm can be to calculated according to the relation:
\[ D(\lambda) = 0.25.S₀.\lambda.(1 - (\lambda/\lambda₀)^4) \]
Maximum dispersion for 1550 nm: 18 ps/km.nm
Max. slope of dispersion characteristics on the wavelength of zero chromatic
dispersion (S₀):
0.092 ps/nm².km (typically 0.088 ps/nm².km)
Losses due to macro-bending:
Less than 0.5 dB on one winding of 32 mm in diameter, for λ = 1550 nm
Less than 0.05 dB for 1310 nm and less than 0.1 dB for λ = 1550 nm on 100 windings
of 75 mm in diameter.
Polarisation mode dispersion: 0.5 ps/√km for 1310 nm (Lucent Technologies cable).
Two-layer primary protection Lucent Technologies D-LUX\textsuperscript{R}100

When choosing a suitable optical cable it is important from the user point of view, to what extent the attenuation of fibres can increase due to the various mechanical or climatic effects. Increased attenuation is often caused by microbends on optical fibres. Two-layer primary coating Lucent Technologies D-LUX\textsuperscript{R}100 prevents the appearance of microbendings and upgrades the quality of Lucent Technologies optical fibres and cables also from other points of view. Primary coating D-LUX\textsuperscript{R}100 is composed of two acryllat layers of approximately the same thickness applied to the fibre in such a way that the overall fibre diameter with primary coating is 245 ± 10 \( \mu \text{m} \). The inner layer exhibits a lower Young’s elasticity modulus and creates something like a pad protecting the fibre against outer influences and prevents the appearance of microbendings. Outer layer with a higher Young’s elasticity modulus protects the fibre against the influence of outer factors.

Advantages of two-layer primary coating Lucent Technologies D-LUX\textsuperscript{R}100:

1. Minimising of micro-bendings. The soft inner layer of primary coating provides for the fibre relatively loose embedding and eliminates thus the action of outer forces leading to the appearance of microbendings. This feature is very important for the behaviour of fibre at low temperatures.
2. Upgraded immunity against the effects of outer forces.
3. Easy removal of primary coating off the fibre (for welding or connecting).
4. Excellent stability and long lifetime of fibres.

The two-layer primary coating Lucent Technologies D-LUX\textsuperscript{R}100 is designed such that it is maximally immune against degradations due to both hydrolysis and oxidation. Fibres with such a primary coating exhibit excellent stability of parameters and long lifetime in both humid and dry environments. All these features provide the following advantages:

- Colour marking does not change during the whole lifetime.
- Fibres do not adhere to one another.
- The cohesion of primary coating does not change during the whole lifetime and the strength needed for its removal does not significantly change either.
- Excellent immunity of fibres against static fatigue.

The two-layer primary coating Lucent Technologies D-LUX\textsuperscript{R}100 is used in all fibre types of Lucent Technologies.

7.3 Theory of optical transmission, loss and dispersion

Transmission through optical fibre in the case of multi-mode light guides is provided by hundreds to thousands of modes, in contrast to single-mode light waveguides, which enable only single-mode propagation of electromagnetic waves of type \( HE_{11} \). For single-mode transmission the condition should be fulfilled that the core diameter should in this case be of similar order as the wavelength of the radiation used. The core diameter is in this case substantially smaller than in the multi-mode light waveguide.

The transmission properties of optical light guides can be investigated using two methods. In the case of much larger core diameter than the wavelength of transmitted light energy, laws of geometric optics can be used with advantage. This condition is not fulfilled
for single-mode light guides. The other method of solution is derived from wave equations that were derived from Maxwell’s equations.

Compared with considerations valid in hollow metallic waveguides, the theoretical investigation of dielectric lightguides is much more difficult, which is due to the limiting condition on the core-coating interface. In view of these facts, solutions are based on the simplifying assumptions that lightguide is composed of a core and a cladding, which extends to infinity.

Specific attenuation and dispersion are defined as basic transmission parameters of lightguide. Both these parameters are a function of the wavelength of light propagating through the lightguide. They are dependent on the material used, its purity and the geometric and physical parameters of the lightguide.

The lightguides manufactured from silicon glass and doted to reach the required refraction index properties of core and coating, release light of wavelength from 0.5 up to 1.6 \( \mu m \) (see Fig. 7.8).

![Figure 7.8: Loss characteristics of optical waveguide.](image)

This so-called permeability window is from the side of shorter wavelengths by ultraviolet absorption associated with a change in the energy level of electrons in glass fibre. Increase of attenuation on the side of longer wavelengths is caused by absorption of infrared radiation, due to mechanical vibrations of molecules of glass. The window is limited from below by Rayleigh’s back-scattering, which decreases with the fourth power of \( \lambda \). In lightguides the lower margin of the window is undulated due to the influence of contaminations, which absorb light on certain wavelengths. This increase of specific attenuation is pronounced on wavelengths of 0.95; 1.24; and 1.39 \( \mu m \); it is caused by OH radicals, which stem from the remainders of water molecules contained in the core of lightguide. The quantity of water increases the attenuation of glass fibres and decreases mechanical
strength. Fig. 7.8 gives regions that are suitable for transmission from the viewpoint of minimal specific attenuation. They are wavelengths of 0.8 to 0.9 $\mu$m, and also around 1.3 $\mu$m (region of zero dispersion) and on the wavelength 1.55 $\mu$m.

These narrow regions are referred to as the 1st, 2nd and 3rd windows. In Fig. 7.8 are marked out newly exploited windows (bands) 4 and 5. The wavelength 1.625 $\mu$m is used for supervising and control systems.

All these parameters influence the transmission of signal through the lightguide. Because of attenuation, the amplitude of individual signal components is reduced and the signal distorted. The most important impact on distortion is due to dispersion. It may be divided into:

- Materials dispersion. This is the dependence of group delay on wavelength, $n = n(\lambda)$.
- Mode dispersion. This is the dependence of group delay of core waves (individual modes) on wavelength.
- Dispersion of group delay. In this case, core waves of different orders, i.e. different modes, have different group delays.

The dispersion characteristic is demonstrated in Fig. 7.9, where the currently most widely used fibres are marked.

![Figure 7.9: Curve of chromatic dispersion.](image)

Fibres as per Recommendation ITU-T G.652 have zero value coefficients of chromatic dispersion in the 1310 nm wavelength region and roughly 18 ps/km.nm for 1550 nm. Fibre as per Recommendation G.653 with shifted chromatic dispersion (DSF) is suitable for very high bit-rate systems, but not for WDM operation. Very suitable seems to be Recommendation ITU-T G.655 with non-zero chromatic dispersion (NZDF), where there is a low value of chromatic dispersion but the impact of four-wave mixing is suppressed. This fibre supports the implementation of DWDM as well as very high bit rate transmission systems. If the proposed track does not meet attenuation requirements, the repeater or a new element, optical amplifier, must be connected. The optical amplifier does not require the O-E-O conversion used in repeaters.

**Optical amplifiers (EDFA)**

The principle of optical amplifier is based on stimulated emission. This energy is supplied by a laser source through coupler to the doped fibre (EDFA - Erbium Doped
Fibre Amplifier. Stimulating radiation excites atoms of active materials, so that a photon of transmitted signal may trigger stimulated emission. Advantages of optical amplifiers:

- They are independent of bit rate,
- They amplify all types of modulation,
- They amplify all channels of WDM.

Application of optical amplifiers:

- Link amplifier,
- Preampifier,
- Power amplifier.

These new trends find important application in the realization of long-distance tracks.

### 7.4 Optical cables

The core itself and the coating must be protected against mechanical stress by a several millimeter thick protective layer, so-called primary protection and then by a plastic layer several tenths of mm thick - the secondary protection. Fibres prepared in this way will be coiled into a lightguide cable. So-called loose secondary protection is used in addition to the above design. Loose secondary protection of fibres consists of a plastic tubule, in which either one or more fibres are placed. The inside space of the tubule can be filled with gel.

It is necessary to consider these main factors:

- Optical: the number of fibres in cable, attenuation on a certain wavelength, dispersion of transmitted pulses, numerical aperture of fibre.
- Mechanical: tensile strength, immunity against transverse compression, bending properties, resistance to abrasion, vibrations and influence of environment.
- Constructional: material and dimensions of core, coating and protection layers, reinforcement materials and their dimensions. Examples of various profiles of optical cables are given below. Classical construction, when the fibres are twisted in a layer (layers) around the tensile element Fig. [7.10].
- Grooved construction where fibres alone or in secondary protection are placed in grooves (Fig. [7.11]).
- Ribbon construction where individual ribbons of 4, 6 or 12 fibres are placed on one another (Fig. [7.12]) and then cabled. Groups of ribbons are composed to give a higher number of fibres. Application mainly in access networks. Welding machines able to splice 12-fibre ribbons are today available.
- Also other different cable constructions are known. For example, the tensile elements are on the and the other fibres in the centre.

Examples and basic optical cable characteristics: (company Lucent Technologies)
Figure 7.10: Various designs of optical fibre cables a, b, c.

Figure 7.11: Grooved construction of cable.

Figure 7.12: RIBBON cable, banded.
OPTION1
Full dielectric, dry optical cable.

Application
Optical cable OPTION1 (Outside Plant to Indoor Optical Network) is full-dielectric universal (outdoor as well as indoor application) optical cable with dry core inside. The design of OPTION1 cable is similar to other outdoor cables, and provides the required tension and mechanical features for outdoor application. The dry construction of cable core enables the protection of cable by non-combustible coating without halogens (LSZH - Low Smoke Zero Halogen). Therefore this cable is suitable for indoor applications, Fig. 7.13.

Description of cable
The design of OPTION1 cable is based on the well known construction of Loose Tube. Optical fibres are protected by a tubule of loose secondary protection, whose the diameter is several times larger than the diameter of fibres. The tubules are filled with a special gel, which prevents water from penetrating to fibres, and also provides of relative mechanical independence of fibre from cable. Protective tubules are easy to identify thanks to colour marking.

The tubules are wound around the central tensile element. In contrast to common cable of the type of Loose Tube, the core is not filled with gel: but anti-humidity protection is ensured by dry bands impregnated with a material called SAP (Super Absorbent Polymer). The absence of gel inside the cable simplifies the preparation of cable before jointing.

The required tension resistance is provided by hosiery yarn (aramid) placed under the cable coating, which is made of LSZH material. Optical cable OPTION1 meets all the requirements for outdoor as well as indoor cables. Optical cable OPTION1 is very suitable for tracks where the cable passes from outdoors into indoor rooms. Installation costs are thus significantly reduced, since the junction of two types of cables is avoided.

Features
• Optical cable for indoor/outdoor applications with a capacity of up to 144 fibres.
• Full dielectric construction.
• LSZH coating immune to UV rays.
• Absorption SAP bands barring infiltration of water along the cable are inside.
• No change of cable type is necessary when passing from indoor into outdoor environment.
• The technique of reverse oscillation, ROL, used for tubule twining in cable manufacturing enables easy access to fibres and simple jointing.
• Ripping cord simplifies the removal of individual layers of coating.
• Cable can be used in a temperature range of 40° to 70°C.
• Optical cable OPTION1 meets all requirements for outdoor as well indoor cables.
• Dry composition of cable core makes installation and maintenance effective.
• Low weight of cable enables further reduction of installation costs. (blowing-in, pulling-in, transportation, ...).
• The manufacturer holds quality certificates ISO 9001 and Bellcore CSQP.

Notation of cables for ordering
AT - \( S_1, S_2, S_F, S_3, S_4, S_5, S_6 \) - Number of fibres up to 144
$S_1$ - Operational wavelength
1 = only 1310 nm,
2 = equal attenuation on both 1310 and 1550 nm
3 = attenuation on 1550 nm is 0.1 dB/km less than on 1310 nm
6 = 1550 nm (True Wave™ fibre)
R = transmission on 850 and 1300 nm (multi-mode fibre)

$S_2$ - Maximal attenuation to 1310 nm
Conventional single-mode fibre
B = 0.35 dB/km
4 = 0.40 dB/km
Dispersion shifted fibre (TrueWave™ fibre)
2 = 0.25 dB/km (1550 nm only)
3 = 0.30 dB/km (1550 nm only)
Multi-mode fibre
S = 3.5/1.0 dB/km 160/500 MHz.km (min. transmission band)
U = 3.4/1.0 dB/km (850/1300) 200/500 MHz.km (min. transmission band)

$S_F$ - Type of fibre
0 = Lucent DC (Depressed Clad) M = Lucent MC (Matched Clad)
D = Lucent DS (Dispersion Shifted SMF)
9 = 62.5/125 μm Multi-mode
T = TrueWave™ fibre

$S_3$ - Dielectric central element
1 = D-P

$S_4$ - Tensile strength
2 = 2700 N

Ss - Solution of fibre protection
O = OPTION! Loose Tube

$S_6$ - Number of fibres per one tubule
2 = 2 fibres
4 = 4 fibres
6 = 6 fibres
8 = 8 fibres
N = 10 fibres
T = 12 fibres

Notes:
P = Non-inflammable coating
D = Dielectric tensile element
POWERGUIDE TM
Full-dielectric self-contained optical cable (Fig. 7.14)

Application: Optical cable PowerGuide (TM) is full-dielectric self-contained optical cable suitable for distances of up to 100 m between masts and braces. Thanks to its construction, which secures high immunity against weather influences, and because of easy installation with minimised costs, optical cable PowerGuide (TM) is an advantageous choice for suspended optical tracks.

Description:
The fully tested and highly reliable Loose Tube protection, known from the construction of out-door cables is utilised. Optical fibres are protected by a tubule of secondary protection with a diameter several times larger than that of the fibre. The tubule can thus contain several fibres. The tubules are filled with a special gel against water infiltration into fibres. Relative mechanical independence of fibre and cable is ensured. The tubules are wound around the central dielectric tensile element. Protective tubules are easy to identify thanks to the colour marking. The required tensile strength is provided by hosiery (aramid) yarn placed under the cable coating; using this cable the auxiliary carrying elements known from the construction of other cables are eliminated. Optical cable OPTION1 meets all requirements for outdoor and indoor cables. Optical cable OPTION1 is very suitable for such tracks where the cable crosses the outdoors/indoors interface. Installation costs are therefore reduced significantly because the change between two types of cable is avoided. The small diameter, smooth radial form and integrated tensile elements secure high immunity against weather influences such as wind or ice, reduce cable sagging and loading of masts.

Features:
- Easy installation.
- Each cable is manufactured customised for individual applications.
- Distance between masts up to 100 m.
- Tested technology of Loose Tube protection.
- Cable is prepared from up to 144 fibres.
- The technique of reversed oscillation (ROL) used for tubule twisting in the manufacture of cables enables easy access to fibres and simple jointing.
- Tensile elements are manufactured of dielectric aramid (kevlar) hosiery yarn.
- Ripping cord simplifies the removal of individual layers of coating.
- The manufacturer holds the ISO 9001 quality certificate.
Installation:

Optical cables **PowerGuide TM** can be hung on masts of power supply distribution network without the effect of electromagnetic field on transmitted signal. It is not necessary to interrupt power supply during the process of hanging the cable. Installation can be done quickly and without complications also in dense urban areas.

- Low installation cost.
- Easy installation.
- It is not necessary to interrupt power supply.
- Quick and simple installation in densely populated areas.

Optical cable of the Mini-LXE type

**General characteristics:**

Cables of the Mini-LXE type are a light-weight and simple-construction version of cables **LXE** (**Lightguide Express Entry**). Their core is formed by a single central polythene tubule of outer diameter 3.9 mm. The tubule is gel filled and can contain up to 3 bundles of 6 fibres each, i.e. a maximum of 18 fibres. Each fibre bundle is held together and identified by a coloured identification thread. Individual fibres are also of different colours (Fig. 7.15).

Mechanical protection of the cable is provided by armour (corrugated waveguide) of chromium-plated steel and two steel tensile elements. This combination ensures a tensile strength of 1800 N, which is sufficient for most installation methods. The outer coating of cable is made of **Middle Dense Polythene (MDPE)**.

*Cable Mini-LXE represents an economical and space saving solution for all optical networks, not requiring a high number of fibres. Its applications can be found above all in access and Cable TV networks.*

Cable Mini-LXE is fully compatible with other accessories supplied by Lucent Technologies (splices, cabinets, distribution frames,...) and enables complex end-to-end solution of optical networks.
Recapitulation of the basic features of cable Mini-LXE type:

- Optimized cable construction for a maximum of 18 fibres.
- Colour marking of fibres and fibre bundles (6 fibres in one bundle).
- Core of the Light-pack type (single central tubule with fibres), coating of the LXE type (steel armour + two steel tensile elements).
- Small diameter and low weight at a tensile strength of 1800 N - simple and very quick access to fibres.
- Available with fibres of the DC (Depressed Clad) or MC (Matched Clad) types.
- Primary protection of D-LUX 100 fibres affords excellent mechanical and climatic robustness as regards fibres and the cable itself.
**Indoor optical cable of the ACCUMAX type**

Indoor optical cable of the ACCUMAX type can be used in practically all indoor applications due to its excellent mechanical properties not requiring a higher number of fibres. It is applicable for cable room - exchange connection. This cable is jointed there to the outdoor cable in the optical main distribution frame or connected directly to transmission facilities. It is very suitable for the **FTTD** (Fiber to the Desk) application, (Fig. 7.16).

Cables of the ACCUMAX type contain single-mode optical fibres protected by double primary coating D-LUX $\phi$ 100 and a close secondary protection of outer diameter 0.9 mm. The fibres can be of the **DC** (Depressed Clad) or **MC** (Matched Clad) types. Identification of fibres is ensured by the colour of close secondary coating. The maximum number of optical fibres in cable ACCUMAX is 72. Optical fibres are surrounded by kevlar (aramid) fibres, which provide tensile and mechanical strength. The outer coating of polyvinylchloride is yellow.

**Parameters:**
- Type of fibre: Lucent Technologies SM DC or SM MC
- Primary coating: D-LUX $\phi$ 100 $\pm$ 10 $\mu$m
- Diameter of close secondary protection: 0.9 mm
- Attenuation of fibre: 1310 nm $\leq$ 0.4 dB/km
  - 1550 nm $\leq$ 0.3 dB/km
- Chromatic dispersion: 1310 nm $\leq$ 2.8 ps/km.nm
  - 1550 nm $\leq$ 18 ps/km.nm
- Limiting wavelength: $\leq$1230 nm
- Operational temperature: $-20^\circ$C $\div$ $+70^\circ$C

**Installation of optical fibres and cables**

The currently most widely used method of optical fibre splicing is **Splicing**
- technology of electric arc welding employs single-purpose semi-automatic or micro-computer-controlled automatic welding machines. Strength tests and attenuation measurement usually follow the splice completion. It is necessary to break the splice in the case of any fault and repeat the whole process: remove coatings, crank the fibre, clean splice tails and fasten them into welder aligner. For more details see the course-book Transmission media - laboratory exercises. Connectors are used in facilities where cables are terminated. Connectors require a sophisticated manufacturing process due to the required precision. Optical tracks are built by:
  - laying a buried cable,
  - laying a cable into polythene tube,
  - when the most frequent method is "blowing" the cable into polythene tube. Roughly 2 to 6 km of optical cable length can be blown.

Machines for classical mechanical pulling should be equipped with a device for controlling the pulling force or automatic stopping in case the tensile strength is exceeded (damage to optical fibres).

A very recent novelty is the "grooving" method. Developed by Siemens, the **MCS** - (Micro Cabling Systems) method enables optical cables to be laid economically, without trenches.
The first method (MCS-Road) enables cable laying into a road-way or pavement into a groove only 6 to 10 cm below surface. Excavations and cable laying in depths of 60-80 cm can thus be avoided. A specially developed cable is provided with a copper tube.

The second method (MCS-Drain) exploits drainpipes for laying the cables. Both conceptions are mutually compatible. Advantages: Quick progress of cable laying, dramatic reduction of excavation costs, minimal impact on transport and environment.

Optical joints and distribution frames belong to cable accessories.

![Indoor optical cable](image)

**Figure 7.16**: Indoor optical cable.

Examples:

1. **Optical joint (armature) type 2500 LG**
   Type 2500LG optical joint is an individual optical joint for universal application. Its cover is made of reinforced thermoplastic, which provides very good mechanical, climatic and chemical protection. In the basic version the joint is equipped with three cassettes for the storage of welded or mechanic splices of optical fibres. The joint equipped with these cassettes can store 24 splices. Optionally, one additional cassette D-182563 can be placed inside. Using this additional cassette it is possible to place there 3 type UC-54 cassettes. These cassettes enable extending the joint capacity to 54 welded splices, using mechanical sandwich protection of these splices. All components needed for assembling two cables (⌀10 ÷ 21.6 mm) are in the basic joint package. The only consumption material which is to be ordered separately is the filling mass, so-called Encapsulant, which the joint bottom is filled to prevent water from penetrating into the joint (Fig. 7.17).

   **Basic features and parameters:**
   - Universal usage (SC).
   - Capacity: 24 splices of optical fibres, with extension cassettes 30 or 54 splices.
   - Optional possibility of mechanical splices.
   - Optional possibility of welded splices with thermo contractible weld protection.
   - Welded splices protected by sandwich weld protection.

2. **Optical distribution frames**
   Optical distribution frames of the LGX series are designed for the termination or interconnection of optical cables inside buildings. Distribution frames together with their accessories form a modular easily extendable construction set. They can be placed in 19", 21" (ETSI) or 23" rack or fixed directly on the wall. The cornerstone of the LGX series is individual racks. As to their function these racks are divided into:
**Figure 7.17**: Optical splice.

- Termination rack designed for direct termination of fibres in connectors.
- Free laid racks for splices-serve the laying of welded fibre splices and their reserves either in pigtail welding or in direct welding of fibres from different cables.
- Laying racks for connecting modules (storage) - serve the laying of the surplus length of connecting optical modules.
- Combined (combination) racks - serve the combination of laying and terminating racks (Fig. 7.18).

They enable the welding of pigtails and their termination on connector boards. The capacity of a single rack may be 24, 72 or 144 fibres. Their width is 43.2 cm (17") and depth 27.9 cm (11"). The height varies acc. to the type from 12.7 cm (5") to 53.4 cm (21"). Some distribution frames are installed in the transmission media laboratory.

**Figure 7.18**: Optical distribution frames.
7.5 Practical usage of optical fibres for high bit-rate transmission

Many years’ practice of experienced telecommunication specialists has led to the opinion that the capacity and quality of long-distance (transport) networks are unlimited. This opinion was supported by the dramatic development of optical networks. Increasing numbers of operators, new ring topology (security and reliability upgrade) support this opinion. The existing transmission capacity was considered over-dimensioned. The reality of last two years is just the opposite. The quick exhaustion of capacity is given by the stormy development of computer networks and their enlargement into worldwide dimensions. The growth of data transmission rises approximately 35% a year in comparison with telephone operations (8%). Another upgrade is connected with the installation of subscriber data loops, which may result in overloaded access networks. Even if multimode fibres are sufficient for numerous applications, the change to single-mode fibres will be necessary in many cases. Concluding this introduction, we may say that transmission using single-mode fibres is not unlimited and in some cases they are fully loaded. What should be done?

Methods of upgrading transmission capacity

There are three possibilities:

• fibre multiplex, or enlargement of the number of fibres in a given track (reserve tubes); for extremely long tracks (submarine cables), difficult to realise,

• increasing the bitrate of modulation is the most widely used method of solving this problem. It was possible to upgrade (in SDH - Synchronous Digital Hierarchy, e.g.) the bitrate 155 Mbit/s (STM - 1), through 622 Mbit/s (STM - 4) up to the currently most utilised bitrate 2.5 Gbit/s (STM - 16). In transmissions of over 2.5 Gbit/s the chromatic and polarisation mode dispersion of optical track becomes the limiting parameter for conventional single-mode fibres in addition to attenuation. By upgrading the bitrate from 2.5G to 10 Gbit/s the maximum range of track will be reduced to the value 0.063 ℓ. Problems appearing with chromatic dispersion may be compensated using a source with extremely small spectral halved bandwidth or using some special techniques (insertion of a compensating fibre or the Bragg grid).

• A very perspective method has been introduced in the form of WDM (Wavelength Division Multiplexing) utilising parallel transmission of more wavelengths through a single optical fibre. Thus, for example, transmission at a bit rate of 2.5 Gbit/s using four wavelengths enables increasing the transmission capacity to 10 bit/s. This idea is not completely new, but only thanks to the newly developed technologies these means of transmission have recently been introduced into service. It can be expected that this technology will become an important asset not only from the optical transmission point of view. We will be involved in this perspective method in the following.
Realisation of wave multiplexes

One of the simplest solutions offered by manufacturers is WDM exploiting two wavelengths, e.g., 850 nm and 1300 for multi-mode fibres or 1310 and 1550 nm for single-mode fibres. The system enables either a full duplex using a single fibre only or doubling the capacity. But this is not a perspective solution seen from a long-term point of view. This method uses only so-called "attenuation windows".

A much more promising solution lies in the exploitation of highly selective radiation sources, four wavelengths may be transmitted in the third "window" (minimum of attenuation). An example of a multi-wavelength multiplex is shown in Fig. 7.19.

![Figure 7.19: Scheme of optical link with wave division multiplex.](image)

This way was prepared by new technological findings, which enabled the realisation of spectral spacings of individual channels of less than 1 nm. It concerned the invention of lasers with so-called DFB (Distributed Feed-Back) or laser with the Bragg grid. These lasers are the source of an extremely pure radiation spectrum characterized by extraordinary narrow spectral line. Lasers offering a spectral half-line in the order of 5 MHz, i.e., 0.00004 nm for 1550 nm, are available today. They have excellent dynamic properties together with the possibility of precise wavelength adjustment.

Increasing the number of wavelengths has cleared the way for practical application of so-called DWDM - Dense Wavelength Division Multiplexing. This progress has accelerated also the standardization work in the International Telecommunication Union (ITU). Recommendation G.692 defines standards for these transmissions. The wavelength of krypton spectral line of frequency 193.1 THz was chosen as the basic spectral channel. Other spectral channels spaced 100 GHz from each other were derived from this frequency. Systems with dense 50 GHz spacing are commercially available and a narrower spacing of 25 GHz is expected to be available soon. Spectral channels and their spacing were defined in the frequency scale and for their conversion to wavelengths the following relation can be used:

\[
\Delta \lambda = \lambda \Delta f / f = \lambda^2 \Delta f / c
\]

where \( c \) is the light velocity in vacuum \((2.99792458 \times 10^8 \text{ m/s})\). Then for a wavelength of 1550 nm channel spacing \( \Delta f = 100 \text{ GHz} \) equals a wavelength spacing of approximately \( \Delta \lambda = 0.8 \text{ nm} \).
Exploitable technologies: multiplexers and de-multiplexers

As can be seen from Fig. [7.19], for wavelength merging the multiplexer is used, and on the output the de-multiplexer. Wave multiplexer, which multiplexes several wavelengths into a single optical fibre, can be simply implemented as fibre splitter with several inputs and a single common output. For a greater number of channels multi-spectral sources with tuneable wavelength are used.

The implementation of de-multiplexer is more complicated, since the dispersion element has to be used, e.g. diffraction grid, prism or optical filter.

Optical filters are used for a lower number of wavelengths; this is advantageous also as regards the cost. Diffraction methods are unavoidable for a higher number of wavelengths. Insertion loss varies between - 35 and - 50 dB. A solution of spectral de-multiplexer based on integrated optics with a phase series of waveguides (AWG - Array Waveguide Grating) is very promising.
Two-wave multiplex

The above mentioned simple wave multiplex for full duplex purposes, or for the doubling of transmission capacity is shown in Fig. 7.20.

![Wave multiplex (Coupler)](image)

830 nm demux/1310 nm mux

830 nm mux/1310 nm demux

Figure 7.20: Wave multiplex (Coupler).

Four-wave multiplex

Frequently demanded multiplex for a rapid increase in network capacity, at a relatively low cost. It is based on the principle of cascaded interference filters with 8 mm spacing (see Fig. 7.21).

![WDM JDS FITEL (1533/1541/1549/1557 nm)](image)

Figure 7.21: WDM JDS FITEL (1533/1541/1549/1557 nm).
**Dense Wavelength Division Multiplexers DWDM**

Lucent Technologies, Alcatel, Nortel, NEC, etc. are the most prestigious manufacturers of DWDM. DWDM providing 16, 20, 40, 60 up to 100 spectral channels are currently offered. Let us give as an example the Wave Star OLS 806 multiplexer of Lucent Technologies. It exploits 16 wavelengths, by-passing an attenuation of 33 dB, which is equal to a distance of 120 km without amplifying. (True Wave - non zero dispersion fibre is supposed). It is possible to use this device for composing ring topologies, as evident from Fig. 7.21.

![Figure 7.21: OLS 806 in "ring application".](image)

**Influences on quality of WDM transmission**

To ensure quality transmission it is necessary to meet appropriate limits, which are verified by measurement. They are as follows:

- Central wavelength, which is obliged to meet the appropriate standards; precise measurement should be ensured with respect to temperature changes, unstability of laser, back reflections;
- Bandwidth shall meet the criteria of spectral characteristics;
- Insertion loss shall ensure the most favourable transmission conditions;
- Crosstalk, the same as in metallic conductors, shall in DWDM installations meet the crosstalk quantities between neighbouring wavelengths. Non-linear effects also cause crosstalk.
- Back reflection may differ in individual channels and its value must be kept within tolerances, mainly with a view to the system stability.
- A very important separate item is the type of the fibre used.

An example of spectral characteristics of four-wave multiplex is shown in Fig. 7.23.

The choice of fibre type can be accommodated to the expected introduction of the DWDM system. This principle is today adopted by many operators in the construction of transport networks using so-called 'Tele-houses'.

Significantly more difficult is the situation as regards the utilization of existing laid fibres for DWDM operation. In the first place, older fibres (ITU-T G.652) are not optimal
for DWDM. The relatively large chromatic dispersion in the lightwave band 1550 nm limits the range of the link and compensation is necessary for longer tracks. The range of link can be increased by inserting optical amplifiers, see Fig. 7.24.

These are so-called EDFA (Erbium Doped Fibre Amplifier), which amplify any optical signal. Their insertion leads to non-linear effects, above all Four Wave Mixing - (FWM) and Self-Phase Modulation - (SPM). Also the values of Polarization Mode Dispersion - (PMD) shall be within the tolerance limits. All the above-mentioned influences affect transmission and they must be considered in the design of networks.

Exploitability of wave multiplexes in the academic computer network

One of the very first applications is the introduction of two-wave multiplex into the experimental network of UTKO. The system demonstrates its functionality, enables element measurement, and a demonstration of its application for the supervision of optical cable was conducted. Its schematic is in Fig. 7.25.

The introduction of 4- or maybe 8-wave multiplex is considered for the Brno network. Preliminary work on the experimental introduction of DWDM in the link Praha-Brno-Olomouc has started. Since an older type of fibre is concerned here, compensation methods will be applied.

Further perspectives of wave multiplexes - DWDM

Increased bit rates will affect the trend of further development. The maximum number of channels increases to 128 or 160. In experimental work up to 1024 channels were achieved. Further parallel bands C and L start being used. The universality of transmission media increases, i.e. Gbit 10 Gbit Ethernet or STM-64.
Increased bit rates of up to 20 Tbit/s can be expected, with systems with 1.6 Tbit/s being currently introduced into backbone networks. As to distance, using the principle of Raman-type of diffusion and soliton transponders, the range of DWDM systems can be enlarged up to thousands of km. Optical cross-connects will significantly enhance the flexibility of networks. They will enable the reconfiguration and back-up of spectral channels in a matter of several ms. These elements are currently implemented as cross-connecting matrix 1024 x 1024, where all connecting operations are performed on a chip using electromechanical micro-mirrors; switching is 16 times faster in comparison with today’s electronic switches. A new conception of network is now being formed using these elements that permeate switching with transmission into a single process back to networks with circuit switching. In conclusion we can say that these new technologies significantly enhance offers of new services as well as transmission chances in optical telecommunications.

Optical access networks

Due to the permanent development of technologies and telecommunication services offered, the demands on bitrates of access networks connecting the terminating point of network, i.e. the end user, to networks providing telecommunication services are steadily increasing. Some subscribers require bitrates of hundreds of Mbit/s or in the order of Gbit/s. Permanently developing optical technologies and investment into Optical Access Network - (OAN) offer the provision of such a needed broad band.

Although optical technology was a specific feature of backbone and metropolitan networks, it is now evident that prospectively they will become standard in access networks too. Optical networks will expand from backbone networks to the end user. This will in particular concern the expansion of optical fibre into the so-called "last mile".

The basic functional units forming an optical access network are as follows:

**Figure 7.25**: Realisation and scheme of WDM in UTKO network.
• **Optical Link Termination** - (OLT) ensuring the functions of network interface between the access network and the network providing telecommunication services,
• **Optical Distributing Network** - (ODN), which is a set of optical transmission means between OLT and ONU,
• **Optical Network terminating Units** - (ONU) having the function of interface between the optical and the metallic sections of access network,
• **Optical Terminating Units** - (OTU) having the function of subscriber interface between the subscriber terminating equipment and the access network (Voice over Internet Protocol - VoIP, video, data).

![Figure 7.26: Block diagram of access network.](image)

From the viewpoint of the position of network terminating units ONU in optical access networks and their design, i.e. the position of optical fibre termination in the network, various types of optical access networks **OAN** are distinguished. The following are regarded as basic:

• **FTTC** (Fibre To The Cabinet), optical fibres are brought to the subscriber cabinet, which the terminating points of network are connected to by metallic cables,
• **FTTB** (Fibre To The Building), optical fibres are brought to the building; individual subscribers are then connected by an internal network,
• **FTTO** (Fibre To The Office), optical fibres are brought to the business subscriber office with enormous requirements for transmission capacity,
• **FTTH** (Fibre To The Home), optical fibres are brought to the subscriber socket.

The main function of access networks is providing transport services in full duplex regime. The transport of signal may be secured by several methods:

• Simplex with **SDM** division (Space Division Multiplex), the transmission in each direction is realised along one optical fibre,
• Duplex with **WDM** division (Wavelength Division Multiplex), the transmission is realised along a single fibre for both directions. Downstream uses a wavelength of 1550 nm and upstream 1310 nm,
• Duplex with **FDM** division (Frequency Division Multiplex), for transport of signals in both directions only one fibre and one wavelength are used; the directions of transmission are frequency divided.

The parameter determining the character of access network corresponds to the type of transmission tracks used in the distribution section of the network:

• **P2P** (Point-to-Point), e.g. direct connection of OLT and ONT,
• **P2M** (Point-to-Multipoint), e.g. passive optical network
Optical networks are classified into two basic groups in accordance with the character of optical elements and units used in the distribution of optical fibre:

- **AON (Active Optical Network)**, which exploits active optical elements in its distribution network (amplifiers, active splitters)
- **PON (Passive Optical Network)**, which utilizes only passive elements.

**Active optical network AON**

This is an access network exploiting active network elements for connecting OLT units with ONU units. AON uses digital equipment generally. The access network is usually realised by **SDH (Synchronous Transfer Hierarchy)** technology configured in ring topology.

AON forms the basic infrastructure of so-called hybrid networks, where other technologies are coupled with the optical part in higher layers. STM-n signals are used. Secondary network levels (xDSL, PON, etc.) are coupled with OAN by synchronous **ADM (Add-Drop Muldex)** via the SMT terminating unit, see Fig. 7.27.

![Block diagram of AON access network](image)

**Figure 7.27**: Block diagram of AON access network.

The main key advantages of active access networks AON are the realisation of substantially larger ranges or spanning of distances between OLT and ONU units than in PON passive optical networks and the possibility of using larger dividing ratios at distribution points. These large distances are reached by the insertion of active elements (amplifiers, splitters, muldaxes) into the optical distribution network. This fact brings a key disadvantage, i.e. the necessity of supplying power to these elements. Minimizing the operational expenses (OPEX) overshadows all above mentioned advantages of PON, and therefore the PON passive access networks are mostly used, first of all for the FTTH architecture.
Passive optical network PON

This network infrastructure is based on utilizing optical network elements. Technical tools for PON completion were developed in university labs, supported financially by Lucent Technologies. The distribution network between OLT and ONU or ONT units consists of only passive elements. This brings a considerable reduction in expenses on both building up access network and subscriber loops, while keeping all advantages of optical communication. PON access networks become economically available also for the residential sector. They penetrate also into the so-called 'last mile', which predetermines them for implementation in FTTH (Fibre To The Home).

Figure 7.28: Topologies used in PON networks, a) bus, b) p2p, c) star, d) ring.

Figure 7.29: Downstream transmission scheme between OLT and ONU units.

Infrastructures of passive optical networks mostly use for distribution of signal the star, ring or bus topology, see Fig. 7.29.

PON networks are mostly realised as a p2mp link, see Fig. 7.29c), where the transmission channel is shared by several users. This method offers the cheapest solution for both the operator (cost of connecting the subscriber), and the subscriber themselves (charges for services). The only disadvantage is the very sharing of transmission bandwidth. In the case of demand for a large bandwidth of transmission band, direct connection between OLT and ONT is chosen. (p2p) see Fig. 7.29b). This method is of course much more expensive than the method mentioned before because there is no division of expenses among more subscribers.
Optical signal in PON networks (p2p) is distributed by splitters, which also operate in opposite direction, that means they are able to link together signals coming from subscribers. There are passive elements which only divide the optical signal into the required number of downstream without any adaptations, including signal amplification. Bi-directional transmission may be realised either by independent fibres or by currently more frequent WDM wave division (Wavelength Division Multiplex). So the transmission of optical signal is realised by a single optical fibre. For downstream a wavelength of 1490 nm is used, for upstream 1310 nm. Downstream transmission is organised such that each ONU termination unit obtains a full multiplexed TDM signal from the OLT unit of link termination, from which it chooses its own channel, see. Fig. 7.30

Upstream transmission uses the method of time division multiplex, TDMA (Time Division Multiplex Access), where each ONU unit inserts its frames into the time slot and sends them to OLT, see Fig. 7.28.

**Figure 7.30:** Upstream transmission scheme between ONU and OLT units.
Table 7.1: Parameters of individual specifications of passive optical networks.

<table>
<thead>
<tr>
<th>Typ</th>
<th>APON (ATM-Based PON)</th>
<th>BPON (Broadband PON)</th>
<th>GPON (Gigabit-Capable PON)</th>
<th>EPON (Ethernet Based PON) or EFM (Ethernet In First Mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommendation</td>
<td>ITU/T.983.1 (amendment 1)</td>
<td>ITU/T G.983.3</td>
<td>ITU/T G.983.1 (amendment 2)</td>
<td>ITU/T G.984.1</td>
</tr>
<tr>
<td>Protocol</td>
<td>ATM</td>
<td>ATM</td>
<td>ATM</td>
<td>ATM a GEM</td>
</tr>
<tr>
<td>Type of optical fibre, number</td>
<td>ITU-T G.652 (1 nebo 2)</td>
<td>ITU-T G.652</td>
<td>ITU-T G.652 (1 nebo 2)</td>
<td>ITU-T G.652 (1 nebo 2)</td>
</tr>
<tr>
<td></td>
<td>max. 32</td>
<td>max. 32</td>
<td>max. 32</td>
<td>max. 64</td>
</tr>
<tr>
<td>Maximal distance [km]</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>a2 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These topologies may be combined arbitrarily when implementing ODN networks (Optical Distribution Network) on condition that the features of used optical interfaces OLT and ONU will be respected. It is necessary to respect several factors when designing PON networks. We start first of all from a spanned attenuation of optical interfaces OLT and ONU; we must respect the types and numbers of splitters, switching parts, connectors and the features of the optical fibre used. Various conflicts in upstream may appear in the timesharing of media due to different distances between ONU and OLT units. These conflicts may be avoided by inserting a protective timeslot between individual time channels. Its magnitude shall be greater than the maximum difference of propagation timeslots; it depends on the difference between the nearest and farthest ONU unit.

FTTH systems, which exploit PON networks, utilise first of all the p2p connection, which is provided for those subscribers who require high transmission bitrates, and p2mp, when the optical fibre is shared by more subscribers. This method is much cheaper for both users and service providers. On the other hand, this solution offers lower transmission bitrates.

**Specification of PON networks for FTTx systems**

In 1995 seven leading world telecommunication operators established an association named **FSAN - Full Service Access Network**, whose goal was the standardisation and deployment of PON networks, see. Table 7.1. These specifications were designed so as to provide for users fully fledged broadband services such as audio, data and video transmission. The following bandwidths were designated by FSAN: 1490 nm for transmission of audio and data from network to user, in opposite direction a bandwidth of 1310 nm is used. For video in downstream a bandwidth of 1550 nm was designated.
**APON, BPON**

Recommendation G.983.1 **APON** (ATM Based PON) was approved by ITU-T (International Telecommunications Union-Telecommunication Standardization Sector) in 1998. It concerns a passive optical network which exploits **ATM** - (Asynchronous Transfer Mode) for information transmission. Bitrates are offered in two variants: symmetric service bitrate 155.52 Mbit/s and asymmetric service in downstream 622.08 Mbit/s and back in upstream 155.52 Mbit/s.

Symmetric service with a bitrate of 622.08 Mbit/s was added later. In 2001 ITU-T accepted Recommendation G.983.3 **BPON** (Broadband PON), which extends the previous standard and uses the same bitrates. One or two optical fibres in accordance with G.652 are used as the transmission media. Bi-directional communication through a single fibre is secured by wave division.

**GPON**

In 2003 ITU-T approved specification G.984.1 **GPON** - (Gigabit Capable PON), which is based on extending specifications G.983.x. Above all, it extends specification G.983.1 as to the bitrate while respecting the principles of access broad band system. ATM cells are used for transmission, but the **GEM** (GPON Encapsulation Method) method is also available for this purpose. This method uses GPON frames for transmission, which are of variable length. ATM cell as well as GEM frames or their fragments are transmitted together in frames of a fixed length of 125 𝜇s. This enables exploiting packet-oriented services such as Ethernet or **IP** (Internet Protocol). Transmission bitrates are offered in two variants: symmetric service with bitrates of 1244.16 Mbit/s and 2488.32 Mbit/s, and asymmetric service in downstream 1244.16 Mbit/s, 2488.32 Mbit/s and in opposite directional (upstream) 155.52 Mbit/s, 622.08 Mbit/s and 1244.16 Mbit/s.

**EPON**

The introduction of Ethernet into access networks was made possible by the acceptance of specification IEEE 802.3ah. This specification is referred to as **EPON** - (Ethernet Based PON) or also **EFMF** - Ethernet In First Mile Fibre. Its goal was the introduction of Ethernet standard down to the user and thus a simplified coupling of local networks. Ethernet frames of a fixed length of 2 ms are exploited for both directions. EPON is designed for multipoint network sharing transmission media, but also **P2PE** - (Point To Point Emulation) communication is targeted. Two types of interface are specified by the IEEE 802.3ah standard, which differ in dynamics and optical power. Type 1000Base-PX10 is designed for usage for distances of up to 10 km with maximum splitting 1:16. Type 1000Base-PX20 is designed for usage for distances of up to 20 km and splitting up to 1:32. Transmission bitrate was specified as 1244.16 Mbit/s symmetric.
Figure 7.31: Transmission bitrates offered to user by symmetric services split 1:32.

Table 7.2: Basic and extended Triple Play services.

<table>
<thead>
<tr>
<th>Data services</th>
<th>Voice services</th>
<th>Video services</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Basic</td>
</tr>
<tr>
<td>High bitrate Internet, High bit rate data transmission</td>
<td>IP telephony VoIP (Voice over Internet Protocol)</td>
<td>Analogue or digital TV transmission, IPTV (TV over Internet Protocol)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extended</td>
</tr>
<tr>
<td>Private data links, Interactive e-learning, monitoring and e-Security systems, Home office</td>
<td>VoIP (Telephone links)</td>
<td>HDTV (High Definition TV), VoD (Video on Demand), Interactive TV, Pay per View, Online games</td>
</tr>
</tbody>
</table>

Triple Play services in FTTH systems

There is a trend among telecommunication operators and providers of broad band services to offer the user the largest possible bandwidth and all the services coupled with it. Steadily intensified competition together with efforts aimed at achieving higher profits lead to the implementation of new services. One of them is "Triple Play Service". It is a new generation of services offering the transmission of voice, data and video. These services may be divided into basic services and extended services, see Table 7.2. The basic services are not charged individually, but they are included in the flat charge for the broad band service. Above-standard services extending the basic services are charged.

Methods of video signal distribution

The main trend among telecommunication operators is to offer a wide choice of video and voice services. This is nothing strange because these services will secure dominant part of their income. Therefore their drive is focused not only on introducing new services, but also on searching for the most suitable transmission method, which will be able to provide more services at the same time without additional upgrade of the transmission
band; this would increase operator’s income. Video services offered in Triple Play are distributed to users via two methods: by so-called overlay PON (video overlay passive optical network) or by IPTV (TV over Internet Protocol).

Overlay PON networks, see Fig. [7.32] use a wavelength of 1550 nm for video transmission, which was reserved for this purpose by ITU-T. The signal is transferred to the user by a single optical fibre together with the data stream (data and voice), for which a bandwidth of 1490 nm is reserved using the WDM wave multiplex. The signal transmitted may be both analogous and digital. On the user side in the ONT unit, the video signal is dropped (by so-called triplexer) and transformed into a radio-frequency signal. This signal, in the case of classical analogous signal, is led from the ONT unit by coaxial cable directly into the TV-set. In the case of digital signal, the Set-top box (STB) is to be used, which transforms digital signal into analogous one. The overlay network offers flexibility to providers and enables them to provide a broad offer of video services. These networks are able to offer residential users capacities beyond their real demands.

![Figure 7.32: Scheme of Triple Play services processing in FTTH systems (source: EXFO).](image)

The other option for video service distribution in the PON networks is IPTV, or switched video. The video signal is transmitted to the user via a packet switching network in this case. The video signal is first digitalized on the side of network termination and subsequently compressed. Binary data are encapsulated in IP data-grams. The signal thus compressed is transferred to ONT together with the data stream (data and voice) using a wavelength of 1490 nm via ATM cells or Ethernet frames. The set-top box with IP interface is inserted into the transmission link between the TV set and the ONT unit. Interconnection of such IP-STB with ONT is realized by CAT-5 structured cabling. The TV set is connected to STB by coaxial cable.

**Optical splitters**

Optical splitters are network elements enabling optical transmission media to be shared by a large number of subscribers. They are usually bi-directional passive elements in FTTH systems, which are operated in PON networks. They are usually bi-directional passive elements equipped with a single input port and several (2 to 64) output ports. The downstream signal of OLT coming to the input port of splitter is divided into the required
number of partial signals. These signals are subsequently distributed to individual ONU units. The splitter merges the upstream signals coming from single ONU units into one common signal, which continues to OLT. These passive network elements ensure only the splitting or merging of optical signal without any other conversion. Depending on the type and manufacturing technology they may work in a defined transmission band or in the whole bandwidth. The insertion loss is added to the optical track the value of which depends on the number of input ports and is given in dB, see Table 7.3.

**Table 7.3**: Inserted loss values for PLC splitter Telcordia GR-1209.

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>1 x 4</th>
<th>1 x 8</th>
<th>1 x 16</th>
<th>1 x 32</th>
</tr>
</thead>
<tbody>
<tr>
<td>1260 - 1650</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inserted loss value [dB]</td>
<td>6,6</td>
<td>9,8</td>
<td>12,7</td>
<td>15,8</td>
</tr>
<tr>
<td>Maximum inserted loss value [dB]</td>
<td>7,1</td>
<td>10,2</td>
<td>13,2</td>
<td>16,6</td>
</tr>
</tbody>
</table>

Splitters may be arranged in cascade, depending on the network topology. ITU-T recommendations concerning the loss values inserted via splitters shall be met.

As to the manufacturing technology, splitters can be divided into two groups:

- **PLC** (Planar Lightwave Circuit)
- **FBT** (Fused Bionic Taper)

PLC splitters are manufactured by planar technology. The required structure is created on a silicon substrate by the technological process. Splitters with up to 32 ports are manufacturable by this technology. This technology is used for splitters with a large number of output ports.

FBT splitters are manufactured by optical fibre splicing at a high temperature and pressure. The fibre cladding is fused and cores of spliced fibres come close together. Beams of 2 to 4 fibres are manufactured by this technology, which are arranged in cascade in order to have a higher number of output ports. This technology is used for splitters with a small number of output ports.

**Figure 7.33**: Exemplification of PLC and FBT splitter structures.

**Choice of suitable transmission method**

As mentioned before, the overlay PON network exploits a wavelength of 1550 nm for the transmission of video signal to the wavelength user, who is thus separated from
the data stream, which is transmitted to the user by a wavelength of 1490 nm. This wavelength was not chosen by ITU-T at random, but due to the insertion loss value being the minimum for this wavelength. Since the video signal was originally transmitted, this feature played a decisive role. To ensure the required quality of transferred signal it is necessary to secure the largest possible CNR (Carrier to Noise Ratio). The minimum CNR value was defined by U.S. FCC (Federal Communications Commission) as 44 dB. This value guarantees the elimination of so-called "snowfall" in the picture. But the value used in FTTH systems should be higher than 47 dB; usually 48 dB is used. Modern ONTs are able to ensure a CNR value of 48 dB for the received signal level from -5 to -6 dBm. To ensure CNR values of 48 dB, it is necessary to use powerful optical sources (lasers, EDFA). So-called Brillouin's effect, i.e. BS (Brillouin Back Scattering) will show up in such light-source powers, when part of reflected light ray returns back to the light source and thus causes disturbance.

This scattering is the result of interaction between light radiation (photons) and the virtual grid, which consists of acoustic waves (phonons) produced by the laser source or EDFA amplifier at huge output powers. This effect could originally be observed already at 7 dBm; today thanks to the continually enhanced technology this margin is shifted beyond 20 dBm. Optical power necessary for the transmission of analogue signal ranges from 10 to 20 dBm (10 - 100 mV). The choice of power depends on inserted loss of transmission path.

Video signal is today transmitted mostly in digital version. Not only because the transmission bandwidth available for this type of transmission will increase several times but also because the picture itself is of higher quality and digital video signal is uncompromisingly more immune against disturbances. The CNR value for digital signal transmission is significantly lower and depends on required error rate. Another factor influencing the quality of digital video is therefore BER (Bit Error Rate). To reduce the BER of transmission channel so called auto-corrective methods are used such as FEC (Forward Error Correction, J.83B). The value of CNR for a required error rate of $10^{-9}$ is 15.5 dB. For the transmission of digital video-signals in binary form much lower optical powers are necessary in comparison with the case mentioned above; powers around 0 dBm are needed. This is given first of all by the much lower value of the signal-to-noise ratio. Non-linear properties of optical fibre may manifest themselves too, such as RS (Raman Scattering) in which there is an interaction between photons and the silicon grid. As a result, photons give up part of their energy and radiation of shorter wavelength appears. Therefore crosstalk may arise between wavelengths in the case of wave multiplex. A minimum spacing of 0.8 nm between channels shall be maintained to prevent this effect.

An advantage of this so-called overlay PON is the separation of video signal from the data stream during transmission. The transmission bandwidth dedicated to video signal distribution is not influenced by the quantity of data transmitted just at this moment. The picture quality cannot thus be degraded by spectral loading of transmission channel. Another advantage can be seen in simpler set-top boxes; in the case of analogous video signal set-top boxes can be excluded at all. The existing network of coaxial cables is exploited for TV signal distribution inside the house. These advantages are outweighed by higher expenses on building up and operating this infrastructure. It is necessary to install wave multiplexes on the side of link termination (inside the exchange) that multiplex the video signal with data stream in downstream, powerful lasers for the video signal and,
last but not least EDFA amplifiers for this signal. It will show up at the user side by expenses on ONT terminating unit, which contains a triplexer for separating individual wavelengths transmitted by optical fibre.

IPTV or switched video is a designation for video signal transmission using a packet network. Video data are inserted into IP data-grams and directed to the user. The digital video signal is transmitted together with the data stream (data and voice) in this case by a wavelength of 1490 nm. Here, too, relatively low optical powers are used. Terminating units on the ONT user site are able to meet the requirements for a CNR of 15.5 dB at a received signal level of -20 to -30 dBm (depending on the type of receiver), which makes really low demands on the power of optical transmitters. Optical power values range from -1 to 5 dBm; optical powers are chosen within this range depending on bitrate and inserted transmission path loss. The Triple Play method of providing complex services is a very economical solution from the viewpoint of both investments (CAPEX) and operational expenses (OPEX). Wave multiplexes and EDFA amplifiers are not necessary in link terminations on the network side as is the case of overlay PON. A diplexer only is used on the user side in the ONT termination unit, which means another cost reduction for the service provider. Maybe the most significant disadvantage of this infrastructure is the transmission bandwidth shared by video signal and data stream.

This method of transmission requires providing a large transmission bandwidth to enable watching the TV and simultaneously downloading large volumes of data. In the case of a great number of TV sets in a household and the desire to watch more TV programmes it may happen that the video signal with higher priority will exploit all the available bandwidth reserved for the user. Another disadvantage consists in set-top boxes, which must support the IP interface. Their price is relatively high and the supply low. On the other hand they enable simpler communication with the video server in upstream. Connecting a new user can be quite a problem for the service provider, especially if more TV sets are to be connected. Existing coaxial distribution networks cannot be used because IP set-top boxes are connected with the ONT unit by CAT-5 structured cabling.
**Table 7.4:** Evaluation of PON in comparison with transmitted optical powers.

<table>
<thead>
<tr>
<th><strong>Optical fibre</strong></th>
<th>G.652 C zero water peak</th>
<th>G.652 C zero water peak</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>1550</td>
<td>1490</td>
</tr>
<tr>
<td><strong>Distance</strong></td>
<td>20 km</td>
<td>20 km</td>
</tr>
<tr>
<td><strong>Insertion loss</strong></td>
<td>4 dB</td>
<td>5 dB</td>
</tr>
<tr>
<td><strong>Splitter 1:32</strong></td>
<td>16,6 dB</td>
<td>16,6 dB</td>
</tr>
<tr>
<td><strong>Connectors</strong></td>
<td>FC</td>
<td>FC</td>
</tr>
<tr>
<td><strong>Number</strong></td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Insertion loss</strong></td>
<td>1,5 dB</td>
<td>1,5 dB</td>
</tr>
<tr>
<td><strong>Links</strong></td>
<td>welded</td>
<td>welded</td>
</tr>
<tr>
<td><strong>Number</strong></td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Insertion loss</strong></td>
<td>0,18 dB</td>
<td>0,18 dB</td>
</tr>
<tr>
<td><strong>Total Insertion Loss</strong></td>
<td>22,28 dB</td>
<td>23,28 dB</td>
</tr>
<tr>
<td><strong>Sensitivity of receiver in ONT</strong></td>
<td>-6 dB (CNR 48 dB)</td>
<td>-24 dB (CNR 15,5 dB)</td>
</tr>
<tr>
<td><strong>Needed optical power of transmitter</strong></td>
<td>16,28 dBm (42,46 mW)</td>
<td>-0,72 dBm (0,85 mW)</td>
</tr>
</tbody>
</table>
7.6 Exercises

A) An optical beam of optical power $P = 0.1 \, \mu W$ and wavelength $\lambda = 1300 \, \text{nm}$ leaves the optical fibre and strikes the photo-detector. Determine the number of photons incident per one second!

B) Optical fibre is characterized by $n_1 = 1.5$. Compute NA (numerical aperture) and angle $\Theta$ under which the light ray can enter the fibre!
8 APPENDIX

8.1 Exercise results of chapter 3.11

A) \( I_1 = U_1/Z_1 = 100 \text{ mA}, a_1 = 2.3 \text{ Np}, a_2 = 20 \text{ dB} \)

B) \( Z = \sqrt{(R + j\omega L)/(G + j\omega C)} = 1310 - j497, \gamma = 0.0165 + j0.0406 \)

8.2 Exercise results of chapter 4.10

A) The capacitance of compound (phantom) circuit is 1.6 times larger in comparison with the capacitance of a pair circuit.

\[
\alpha_k = \frac{R}{2} \sqrt{\frac{1}{L_{pk}}} = \alpha_s = \frac{R}{4} \sqrt{\frac{1}{L_{ps}}}
\]

\[
\frac{1}{L_{pk}} = \frac{1.6}{4} \mu_F,
\]

\[
L_{dk} = 0.4L_{ps}
\]

B) Open line

\[ Z_2 = \infty \]

Reflection factor \( k = \frac{\infty - Z}{\infty + Z} = \frac{U_0}{U_k} = 1 \)

\( U_0 = U_k \) - the voltage wave is reflected equally phased while the current wave is reflected antiphased.

Shortcut line

\[ Z_2 = 0 \]

\[ k = \frac{0 - Z}{0 + Z} = -1 = \frac{U_0}{U_k} \]

\( U_0 = -U_k \) - the voltage wave is reflected in antiphase, the current wave in equal phase.

8.3 Results of chapter 5.7 exercise

A) \( C.l = 38.5.0.230 = 8.85 \text{nF} \)

8.4 Results of chapter 7.6 exercise

A) Photon is a particle with energy defined by relation \( W = h \cdot v \)

\[ h = 6.626.10^{-34} \text{ J.s} \text{ Planck's constant} \]

\( v = \) frequency of radiation

Energy of one photon \( W = h \cdot v = \frac{h \cdot c}{\lambda} = 1.529.10^{-19} \text{ J} \)

Total energy of radiation \( W = P.t = 10^{-19} \text{ J} \)

Within one second stroke \( N = \frac{10^{-7}}{1.529.10^{-19}} = 6.54.10^{11} \) photons strike on the photodetector.

Note: It is advantageous to express the energy of particles by electron-volts, then \( 1 \text{ eV} = 1.6.10^{-19} \text{ J} \)

\( 1 \text{ J} = 6.25.10^{18} \text{ eV} \)

Energy calculated in this exercise is 0.956 \text{ eV}. 
B) from transmission condition

\[ n_2 = 0.99n_1 \]

\[ n_2 = 1.485 \]

\[ \sin \Theta = NA = \sqrt{n_1^2 - n_2^2} = 0.21 \Rightarrow \Theta = 12.2^\circ \]

Result: \( NA = 0.21 \) and the corresponding angle under which the light ray is able to enter the optical fibre equals \( 12.2^\circ \)
References


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