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Cross-polarization effect of radio waves propagation by forest vegetation in wireless communication systems on transport

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Abstract

During the movement of various types of transport (auto, rail) in forest, radio communications in the VHF / UHF bands are sharply disturbed, which is associated with attenuation and a change in the polarization plane (cross polarization effect) of radio waves in the forest. Therefore, this paper reviews the problem of the appearance of the cross-polarization effect appearance in the through propagation of VHF/UHF radio waves in forests. The parameters of cross-polarization are analyzed and the functional dependences XPD {f, ζF, rF}, XPR {f, ζF, rF} are evaluated on the operating frequency, forest vegetation properties and the distance traveled within the forest from the transmitting antenna to the receiving antenna. Rerouted by forward and backward vegetation elements, radio signals contain many cross-polarization components that can have levels comparable to the main (useful) component. An increase in cross-polarization components can be observed in the "forward" region, which can be formed by successively decreasing the useful component, ultimately causing a significant decrease in the XPD value. As a result, the relatively high cross-polarization component can consecutively reduce the level of the useful component, while the cross-polarization effect is random, and the XPD value with fluctuating distance between the transmitting and receiving stations begins to fluctuate relative to XPD = 0. Thus, the influence of forest vegetation on the propagation conditions in VHF/UHF ranges is not only manifested in a random variation of the attenuation coefficient, but also leads to a cross-polarization effect, which ultimately causes deep fading of the radio signal at the receiving point.
This work can be used in assessing the fluctuations of received signals due to the occurrence of cross-polarization during transport traffic in the forest.

Keywords: Electromagnetic waves (EMW); Radio waves propagation; Cross-polarization discrimination (XPD); Cross-polarization ratio (XPR)

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1. Introduction

In Latvia, railway lines are often surrounded by forest, at the same time, radio transmission conditions deteriorate due to the appearance of the cross-polarization effect when radio waves propagate in vegetation. This leads to the fact that the signal level at the output of the antenna devices drops and the radio conditions deteriorate. Therefore, it is advisable to conduct studies of this negative effect.

The absorption, scattering, and cross-polarization effects that occur when radio waves propagate in inhomogeneous absorbing media are important factors that determine the reliability of radio communication channels. Knowing these factors makes it possible to create more adequate models in the design of wireless communication networks [1, 2]. As is known, when electromagnetic waves are emitted by antennas, which acquire a transverse electric type of wave (TEM-Transverse Electric and Magnetic fields) in the far zone, i.e. become practically plane-polarized. When propagating in a vacuum, their plane of polarization (in which the vector E lies) does not change, therefore a plane-polarized Line-of-sight (LOS) regime is observed for electromagnetic waves (EMWs) propagating from the transmitting antenna to the receiving antenna. As a rule, three main types of polarization of coherent EMWs are used in radio communication systems:

- Linear (i.e. polarization is directed perpendicularly to the direction of propagation of the EMW (Pointing vector)) (see Fig. 2b)
- Circular (with a right or left rotation, depending on the direction of rotation of the electric field vector E)
- Elliptic (for which the end of the vector E is described by an ellipse)

It should be noted that the causes of the cross-polarization of EMW are:

- Asymmetric EMW generation in antenna systems
- Inhomogeneity and anisotropy of the EMW propagation medium
- Refraction and reflection of the EMW on the boundary between two media

As an example, Fig. 1 (a, b, and c) shows cases in which the EMW of the corresponding polarization is propagating in space.

Any polarized EMW can be represented as a superposition of two linearly polarized EMWs in two mutually perpendicular directions (see Fig. 1a):

$$\vec{E}(t) = \vec{E}_x(t) + \vec{E}_y(t) \tag{1}$$

In this case, if amplitudes of these components are equal, and they are in-phase, then circular polarization is observed; otherwise (if amplitudes are different) elliptic polarization takes place.

2. Propagation of vertically polarized EMWs through a depolarizing medium

Let's consider the propagation of vertically polarized radio waves through the depolarizing medium (see Fig. 2).

Both components $E_x(t)$ and $E_y(t)$ are known to be coherent for a polarized wave, and incoherent for the unpolarised one. The phase difference between $E_x(t)$ and $E_y(t)$ in the first case is constant, but in the second is a random function of time. To quantify the degree of EMW depolarization, more precisely—the cross-polarization radiation reduction coefficient (Cross-Polar Isolation/Discrimination (denoted as XPI, XPD)) the following parameters are introduced [1-5].

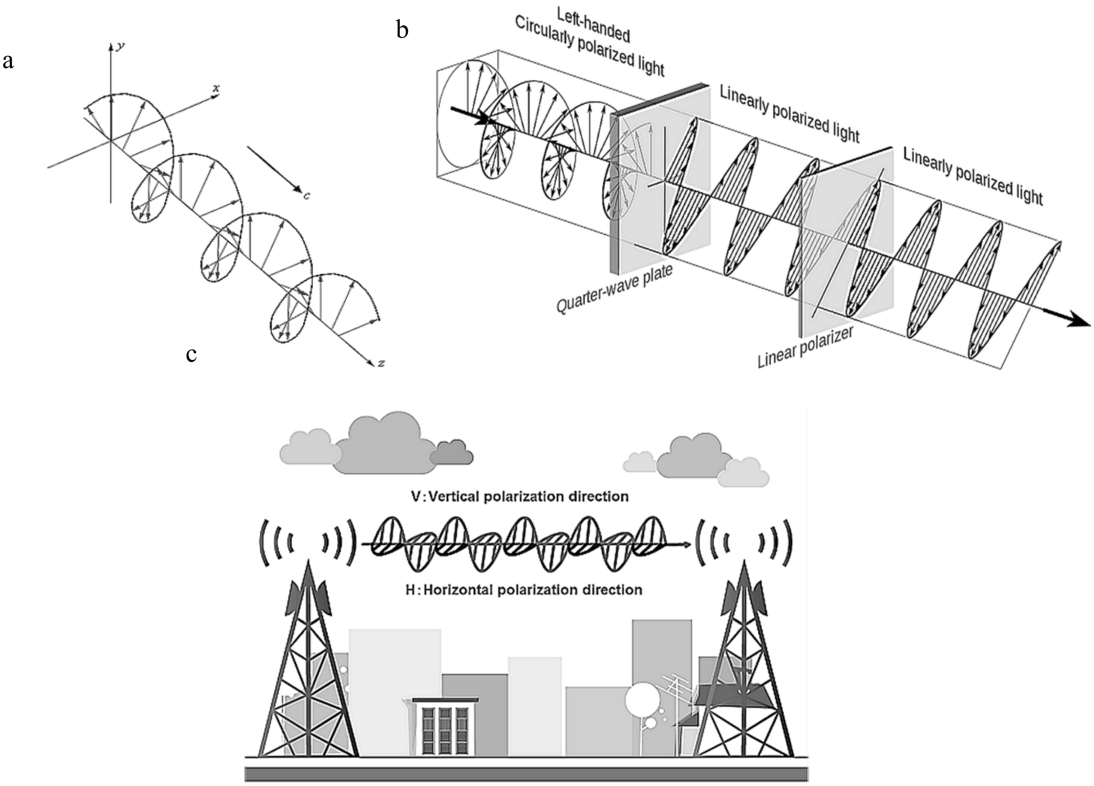

Fig. 1. (a); (b); (c) Examples of corresponding polarization of electromagnetic waves propagating in space.

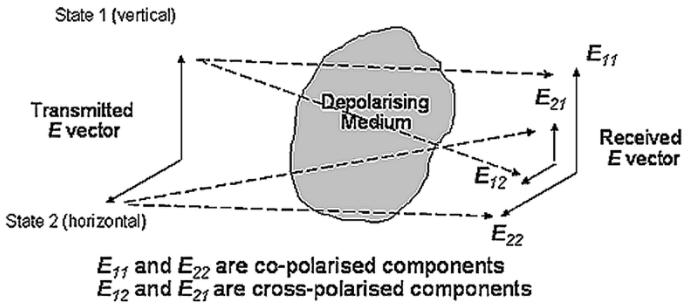

Fig. 2. Depolarizing medium [3].

XPD (Cross-Polarization Discrimination) is defined as the ratio of the amplitude of the electric field strength at the receiving point (EMW power) $E_{11} = E_{xx}$ of the main (useful) polarization to the (interfering) amplitude of field strength (EMW power) $E_{12} = E_{xy}$, which orthogonal to the basic kind of polarization, with propagation of EMW in the forest area and, as a result, cross-polarization in forest vegetation. This parameter expresses the degree of selection (separation) of the main type of the incident electromagnetic wave and is presented as:

$$XPD_{VH} = 20 \cdot lg \left|\frac{E_{11}}{E_{12}}\right| = 10 \cdot lg \frac{P_{11}}{P_{12}}. \quad (2)$$

It should be noted that for antenna systems, expressions for XPD are as follows:
for transmitting antennas:

- with vertical polarization:

$$XPD_{VRx} = 10 \cdot lg \frac{P_{VV}}{P_{VH}}, \tag{3}$$

- with horizontal polarization:

$$XPD_{HRx} = 10 \cdot lg \frac{P_{HH}}{P_{HV}}, \tag{4}$$

for receiving antennas:

- with vertical polarization:

$$XPD_{VRx} = 10 \cdot lg \frac{P_{VV}}{P_{HV}}, \tag{5}$$

- with horizontal polarization:

$$XPD_{HRx} = 10 \cdot lg \frac{P_{HH}}{P_{VH}}, \tag{6}$$

Where P_{VV} and P_{HH} are the powers of the main EMWs (vertically or horizontally polarized) and their cross-polarization components are P_{VH} and P_{HV}.

XPI (Cross-Polarization Isolation) is defined as a ratio of the amplitude of the electric field strength at the receiving point (EMB power) $\boldsymbol{E_{11}}$ of the main polarization to the field strength (EMW power) $\boldsymbol{E_{21}}$, which is interfering and coinciding with the main type of polarization in the propagation of EMW in forest vegetation, resulting in a cross-polarization. This parameter also expresses the degree of selection of the main type of the incident electromagnetic wave and is written as:

$$XPI_{HV} = 20 \cdot \lg \left| \frac{E_{11}}{E_{21}} \right| = 10 \cdot \lg \left| \frac{P_{11}}{P_{21}} \right| > 0 \tag{7}$$

XPR (Cross-Polarization Ratio) is a coefficient (indicator) of cross-polarization:

$$XPR = 10 \cdot lg \frac{P_{ort}}{P_{inc}} < 0, dB \tag{8}$$

where P_{inc}—the power of the incident radio wave, P_{ort}—power of the radio wave, emerging due to cross-polarization, whose component at the receiving point is orthogonal to the component of the incident radio wave.

As shown in [5], $XPR_{Rx} = P_{VH} - P_{VV} (dB)$ under condition of multipath propagation in cellular networks (propagation of vertically polarized EMWs in Paris) can have values in the order of $XPR \sim (-8.7)\ dB$.

BPD (Branch Power Discrimination) - channel power selection (usually specific for transmitting and receiving antennas) [6] is defined as the ratio of the sum of the powers of a vertically-polarized EMW and its horizontal cross-polarized component, to the sum of the powers of a horizontally polarized EMW and its vertical cross-polarized component (9).

$$BPD = \frac{P_{VV} + P_{HV}}{P_{HH} + P_{VH}} \tag{9}$$

For example, for the receiving antenna [4], expression (9) will be written as:

$$BPD_{Rx} = \frac{P_{VV} + P_{HV}}{P_{HH} + P_{VH}} \tag{10}$$

but for the transmitting antenna:

$$BPD_{Tx} = \frac{P_{VV} + P_{VH}}{P_{HH} + P_{HV}} \tag{11}$$

Values of *XPD* and *XPR* are most often determined in practice, which in general are functions of the operating frequency, forest vegetation properties and the distance traveled within the forest from the transmitting antenna to the receiving antenna: *XPD* $\{f, \zeta_F, r_F\}$, *XPR* $\{f, \zeta_F, r_F\}$. A numerical example: $E_{VV} = 10$ *mkV/m*., $E_{VH} = 1$ *mkVm* in the receiving point, thus XPD = 20 dB, XPR = −20 dB. The higher the value of *XPD*, the higher the degree of selection for cross-polarization. While *XPD = 0*, values of the useful and interfering EMW components at the point are equal. Let's consider some results for the definition of *XPD* and *XPR* based on the mathematical modeling and experimental studies for a certain range of radio frequencies.

3. Cross-polarization effect of radio waves propagation in forests

In an inhomogeneous and anisotropic medium (generally, forest vegetation), when electromagnetic waves fall on trees, parts of trees (trunks, branches, leaves) generate currents that create secondary reradiated electromagnetic waves propagating to the receiving antenna (see Fig. 3a and Fig. 3b).

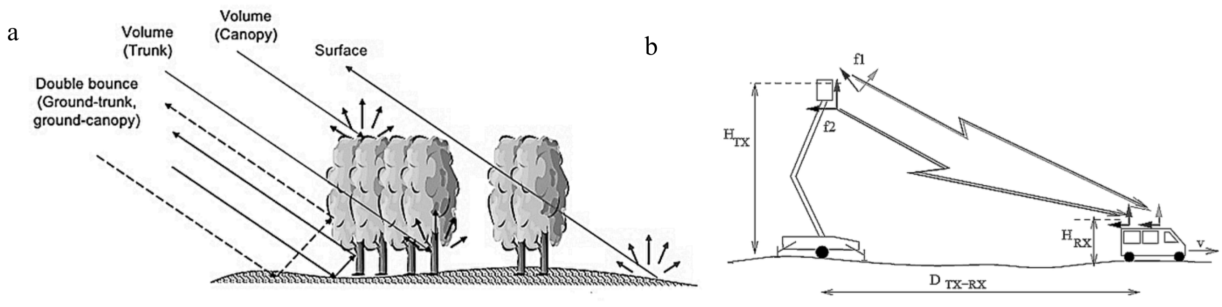

Fig. 3. (a); (b) EMW propagation.

All vertically directed elements of vegetation practically do not change the vertically polarized (useful) falling of EMW - $\boldsymbol{E_{11}} = \boldsymbol{E_{xx}}$ (co-polarised strength), only causing an attenuation and forward scattering, while horizontally and obliquely located vegetation elements create a horizontally directed (interfering) electric field strength vector - $\boldsymbol{E_{12}} = \boldsymbol{E_{xy}}$ (cross-polarized strength), which is also a subject to attenuation and scattering as radio waves propagate in the forest. In addition, the following effects will occur in the propagation of radio waves:

- Lateral wave (LW) will spread above the forest vegetation
- Additional EMW reflected from the forest litter will appear (in which, according to Leontovitch - Rytov [7, 8], the intensity (power P_G) of the EMW will be orthogonal to the useful component

In general, plants in forests are located chaotically in space and the polarization plane of the resulting EMW at the receiving point will differ sharply from the polarization of the EMW falling on the forest area, but the median value of the vector $\boldsymbol{E_{11}}$, in most cases up to a certain distance will exceed the other median components: $\boldsymbol{E_{11}} > \boldsymbol{E_{12}}$, $\boldsymbol{E_{11}} > \boldsymbol{E_{22}}$ and others, Fig. 4b shows a diagram of experiments to determine the effect of cross-polarization on the conditions of the transmission of mobile communication signals during transport traffic (auto).

Thus, the value of *XPD* (or *XPR*) is:

$$XPD_{VH} = 10 \cdot lg \frac{[P_{11}{}^{0} \cdot 10^{-\alpha_{11} \cdot l_F} + P_{LW}(l_{LW})]}{[P_G \cdot 10^{-\alpha_{12} \cdot l_F} + \sum_{r=1}^{r=l_F} P_{12} \cdot 10^{-\alpha_{12} \cdot r}]} \quad (12)$$

where P_{LW} - power at the receiving point of the lateral wave, l_{LW} - distance travelled by the lateral wave, l_F - distance from the transmitting antenna to the receiving antenna, α_{11} - attenuation coefficient of the direct EMW in the forest massif at the given carrier frequency, the distances traveled by the direct cross from different trees that cause EME data, α_{12} - attenuation coefficient of the cross-polarized EMW in the forest area at a given carrier frequency and power, P_G - additional EMW reflected from the forest litter, P_{12} - cross-polarization component of the input power forest vegetation.

4. Experimental studies of XPD and XPR values when radio waves propagate in forests

Experimental studies of cross-polarization effects in forest areas were carried out in [9-11]. Thus, in [10] it was shown that a typical radiation pattern of reemission (scattering) of the EMW by a plant (ficus) in the corresponding plane has a diagram close to the emission of an electric vibrator, but in diagrams of the scattering for twigs and leaf blocks are shown, while depolarization for each scatter has a random character.

Radio signals that are rerouted by the elements of vegetation "forward" and "backward” contain a lot of cross-polarization components, which can have levels comparable to the main (useful) component. An increase in cross-polarization components can be observed in the "forward" region that can be formed by successively decreasing the useful component, ultimately causing a significant decrease of the *XPD* value. As a result, the relatively high cross-polarization component can consistently reduce the level of the co-polarized component.

In [11], the cross-polarization problem is addressed, estimating the *XPR* value of EMWs in VHF/UHF bands (including the 800 MHz frequency) for the propagation conditions of radio waves in the jungle, and a comparison is made for the propagation conditions of radio waves in deciduous trees in Europe. It is shown that the level of *XPR* for the jungle is much higher than *XPR* for deciduous trees (with fallen leaves). In the jungle, as the depth of penetration of the EMW into the forest vegetation increases (from 75 to 2500 m), the level falls and this fall increases according to the frequency of the signal. In addition, it was shown that in the jungle the *VH* component is usually higher than the *HV* component. This is because horizontally polarized EMWs do not induce significant surface currents on vertical parts of the plant, while vertically polarized EMWs induce significant surface currents on inclined parts. At high frequencies and at large distances, the magnitude of *XPR* may even become positive, since the power of the cross-polarization component P_{VH} is converted from the *H* plane to the *V* plane and becomes larger in magnitude, which decays during propagation. It should be noted that when the receiving antenna is moved by less than the wavelength, fluctuations in the level of the received signal in dense jungles increase sharply. This can be interpreted in such a way that for variations in the density of jungle vegetation and conventional forests the variations of the received radio signals are similar to fast fading. It was found that for vertically polarized EMWs at these frequencies, the degree of depolarization is 5-15 dB higher than for horizontally polarized EMWs.

The scheme for the investigation of cross-polarization of EMW is shown in Fig. 4. Vertically polarized EMWs at the frequency of 1.6 GHz are propagating in the high canopy of red pine along two radio paths: Path A - from the transmitting antenna T_x through the forest area to the trihedral reflector *T* and then to the receiving antenna R_x and Path B - from the transmitting antenna T_x to the forest area, reflected from it, and to the receiving antenna R_x.
The measurement procedure consisted of the following:

- Transmitting antenna emitted EMW of two types of polarization: vertical *VV* and horizontal *HH*
- Levels of received signals from the target T and from the forest canopy were measured
- Levels of the received signals without the target T were measured
- P_{VV}, P_{VH}, and $XPR_{Rx} = P_{VV} - P_{VH}$ (dB) were calculated

As shown by experiments, the values are: PVH = 9.15 dB, PVV = 9.58 dB, XPR_{Rx} = -0.23 dB.

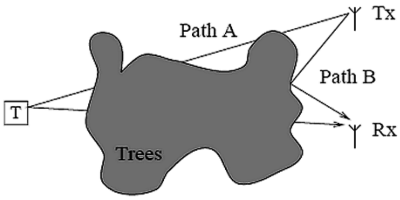

Fig. 4. Scheme for the investigation of cross-polarization of EMW [10].

5. Conclusion

During the propagation of radio waves in forest tracts, radio signals are re-emitted by vegetation elements and contain a multitude of cross-polarization components that can have levels comparable to the main (useful) component. An increase in cross-polarization components can be observed in the "forward" region, which can be formed by successively decreasing the useful component, ultimately causing a significant decrease of the *XPD* value. As a result, the relatively high cross-polarization component can consecutively reduce the level of the useful component, while the cross-polarization effect is random, and the *XPD* value with fluctuating distance between the transmitting and receiving stations begins to fluctuate relative to $XPD = 0$. It is qualitatively possible to describe the change $XPD\ \{f, H_{Tx}, (r_F = D_{Tx-Rx})\}$ for a given operating frequency in the form of an approximate analytical dependence (13):

$$XPD\{f, (r_F = D_{Tx-Rx})\} \sim XPD(r_0) \cdot J_0(kr) \cdot 10^{-\alpha_F \cdot r} \tag{13}$$

where $XPD(r_0)$—*XPD* value at a distance r_0 outside the forest, $J_0(kr)$—zero-order Bessel function that characterizes the *XPD* fluctuations with increasing distance between the transmitting and receiving antennas, and the third term of the formula (13) increase in distance. Thus, the influence of forest vegetation on the propagation conditions of the VHF / UHF bands in mobile communication systems on transport is manifested not only in a random change in the attenuation coefficient, but also leads to a cross-polarization effect, which ultimately causes a deep fading of the radio signal in the receiving point.

This work can be used in assessing fluctuations of received signals of VHF/UHF range due to the occurrence of cross-polarization effect at transport traffic (auto, rail) among forest vegetation.

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