RECOMMENDATION ITU-R S.1555

Aggregate interference levels between closely spaced dual circularly and dual linearly polarized geostationary-satellite networks in the fixed-satellite service operating in the 6/4 GHz frequency bands

(Questions ITU-R 230/4 and 42/4)

(2002)

The ITU Radiocommunication Assembly,

considering

a) that in the 6/4 GHz frequency bands both dual circular polarization (CP) and dual linear polarization (LP) are used by different operational geostationary-satellite fixed satellite service (FSS) networks, and this situation is likely to continue because of the established infrastructure in those networks;

b) that such bands are heavily used resulting in the need for co-frequency and co-coverage networks to operate with relatively small orbital spacing;

c) that the existing ITU-R Recommendations, as well as Appendix 8 to the Radio Regulations (RR), only address the single entry interference between adjacent satellite networks, taking the interfering signal in each polarization at a time;

d) that it is important during coordination to be able to determine the aggregate effect of adjacent satellite interference arising from the simultaneous use of both orthogonal polarizations in each adjacent satellite network, whether the two networks use the same type of polarization (i.e. both CP or both LP) or whether they use different types of polarization (i.e. one using CP and the other using LP);

e) that the magnitude of the two orthogonally polarized signals of the interfered with and/or the interfering networks could be equal or unequal,

recommends

1 that, on the basis of the technical information contained in Annexes 1, 2 and 3, the aggregate interference between closely spaced adjacent satellite networks (up to 6° orbital separation) operating in the 6/4 GHz frequency bands using different types of polarization (i.e. CP in one network and LP in the other) should be assumed to be identical to that which would occur if both networks used the same types of polarization (i.e. both LP or both CP), under the following conditions:

– those networks simultaneously use both orthogonal polarizations co-frequency and co-coverage and the magnitude of the two orthogonally polarized signals of the interfered with and the interfering networks are equal; or

– the magnitude of the two orthogonally polarized signals of the interfered with network are unequal, and the magnitude of the two orthogonally polarized signals of the interfering networks are equal;

2 that, on the basis of the technical information contained in Annex 3, when the magnitude of the two orthogonally polarized signals of the interfering network are unequal, the aggregate interference between closely spaced adjacent satellite networks (up to 6° orbital separation) operating in the 6/4 GHz frequency bands using different types of polarization (i.e. CP in one network and LP in the other) could be assumed to be identical to that which would occur if both networks used the same types of polarization (i.e. both LP or both CP) under the following conditions:

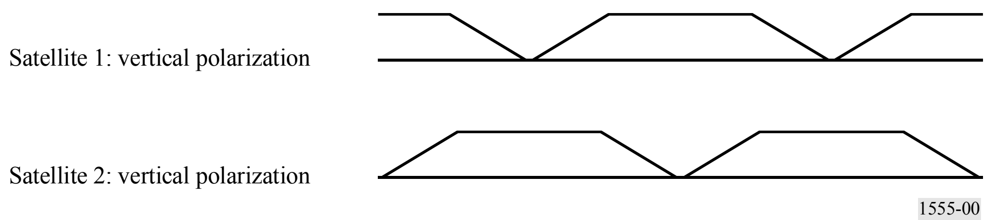
– these networks simultaneously use both orthogonal polarizations co-frequency and co-coverage;

– an additional reduction of the magnitude of the two downlink orthogonally polarized signals of the CP network or an additional reduction of the magnitude of the downlink signal having the highest magnitude of the CP network should be applied.

3 that the technical information contained in Annex 1 should be used to determine the additional reduction of the magnitude of the two orthogonally polarized signals of the CP network when those networks simultaneously use both orthogonal polarizations co-frequency and co-coverage, and the magnitude of the two orthogonally polarized signals of the interfering networks are unequal.

NOTE 1 – When the desired network uses dual LPs with equal magnitudes for the two orthogonal polarized signals and the adjacent network uses dual polarizations with a large difference between the magnitudes for the two orthogonal polarized signals (e.g. greater than 10 dB), the interference environment would differ depending on whether the adjacent satellite uses CP or LP. When LP is used the interference caused to the desired network would be primarily to one polarization (i.e. vertical or horizontal). When CP is used the interference caused to the desired network would be to both polarizations but at a reduced power level compared to the interference from a network using LP.

NOTE 2 – When both the desired and the interfering networks use a staggered channelization plan and when these networks transmit high spectral density in the central portion of the occupied bandwidth of the transponder (e.g. analogue TV/FM), an advantage exists in having adjacent satellites using the same polarization type (i.e. dual LP or dual CP). In these conditions, the signal energy in the centre of the channel falls within the guardband of the co-polarized channel of the adjacent network. The example figure below shows the co-polar channelization plans for one of the polarizations on each adjacent satellite. The interference from the adjacent satellite is mitigated by the angular separation of the satellites and additionally by the frequency separation of the carriers due to filtering of the co-polarized channel of the adjacent satellites.



ANNEX 1

Interference between closely spaced dual circularly and dual linearly polarized satellite networks operating in the 6/4 GHz frequency bands

Abstract

This Annex introduces the issue of the aggregate interference between closely spaced adjacent satellite networks (up to 6° orbital separation) operating in the 6/4 GHz frequency bands when these networks use different types of polarization (i.e. CP in one network and LP in the other), and when those networks simultaneously use both orthogonal polarizations co-frequency and co-coverage. It provides the general expression of the equations which were used to perform the analyses.

It includes the main results of an analysis of the impact on the aggregate adjacent satellite interference levels when neighbouring satellites operating in the 6/4 GHz frequency bands use different types of polarization (i.e. LP versus CP) and when the magnitude of the two orthogonally polarized signals of the interfered with and the interfering networks are equal. In addition, it is assumed that the interfering and interfered with networks operate the same type of carriers at the same frequency. It compares the interference levels in these situations with those that exist when the satellite networks use the same type of polarization, either both using dual LP or both using dual CP. It concludes that in this case, for practical values of satellite and earth station cross-polar discrimination (XPD), the absolute worst-case additional interference, relative to the idealized case where both networks use the same type of polarization and are perfectly aligned, is less than approximately 0.5 dB for the downlink and less than approximately 1.5 dB for the uplink. The earth station antenna off-axis co-polar and cross-polar patterns are the main contributors to the interference. The analysis is worst case and uses simple template envelopes to represent the earth station antenna performance. In practice it is extremely unlikely that worst case conditions will occur on co-polar and cross-polar patterns of each of the two polarization transmitted by the earth station antenna simultaneously.

1 Introduction

6/4 GHz satellites operate co-frequency and co-coverage along the geostationary arc with small orbital spacing between adjacent satellites, typically in the range of 2° to 6°. Coordination between these networks often assumes that they operate co-polar to each other, where no polarization isolation is assumed, such as when both networks use dual orthogonal LP or dual orthogonal CP.

Cases arise where some polarization isolation exists between adjacent networks such as when adjacent networks only use opposite senses of the same type of polarization (e.g. vertical polarization (VP) adjacent to horizontal polarization (HP), or right-hand circular (RHC) adjacent to left-hand circular (LHC) polarization)). With the satellite antenna XPD of the order of 30 dB, the earth station antenna off-axis cross-polar gain will be the dominant cross-polarization effect in these cases. It essentially controls the cross-polar interference between two adjacent satellite networks regardless of whether they are operating in LP or in CP.

Another situation can arise in which adjacent satellite networks use different types of polarization – CP in one network and LP in the other. Such situations occur regularly with networks operating in the 6/4 GHz frequency bands where historical choices of polarization (CP versus LP) made decades ago are still maintained in the current operational networks, a situation that is likely to continue in the future due to the considerable infrastructure investment in these networks. The off-axis polarization isolation between networks in these cases has been studied, but only taking account of one polarization at a time[1]. Paragraph 2.2.3 of RR Appendix 8 provides guidance to administrations in terms of the isolation between a single CP interfering signal and an LP wanted signal (or vice versa) with a recommended worst-case numerical isolation factor of 1.4 times (= 1.46 dB) as an envelope value for all ranges of orbital separation.

The situation that has not been adequately studied, and which is addressed in this Recommendation, is when the interfering network uses both senses of polarization (either CP or LP) and the wanted network uses the other type of polarization (either LP or CP, respectively). In this case it is important during coordination to calculate the aggregate interference resulting from the combined effect of the two orthogonally polarized signals in the interfering network. In fact, this is the case that exists in practice in most situations with currently operational satellite networks, where both are using dual orthogonal polarization for spectral efficiency reasons.

2 Generic vector equations

This section summarizes the general expressions of the equations that should be used to assess the coupling from the two polarization components of the interfering network into one component of the interfered with network. The equations are provided for each possible case of interference (i.e. CP into LP, LP into CP, LP into LP).

2.1 Interference from circularly polarized into linearly polarized antenna systems

In this section we first derive general expressions for the coupling from the two types of circular polarization into a linearly polarized antenna. Then, we consider the two special cases:

– A dual circularly polarized satellite illuminates a linearly polarized earth station.

– A dual circularly polarized earth station illuminates a linearly polarized satellite.

The incident field at the location of the receive antenna is, for each polarization of the circularly polarized transmit antenna:

$$\begin{aligned} \mathbf{e}_R &= e_R\left[\frac{\mathbf{h} - j\mathbf{v}}{\sqrt{2}}\right] + e_{RX}\left[\frac{\mathbf{h} + j\mathbf{v}}{\sqrt{2}}\right]\mathrm{e}^{j\delta_R} \\ \mathbf{e}_L &= e_L\left[\frac{\mathbf{h} + j\mathbf{v}}{\sqrt{2}}\right] + e_{LX}\left[\frac{\mathbf{h} - j\mathbf{v}}{\sqrt{2}}\right]\mathrm{e}^{j\delta_L} \end{aligned} \qquad (1)$$

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[1] See ex-CCIR Reports 555 and 1141 and Recommendation ITU-R S.736.

where:

- $\mathbf{e}_R, \mathbf{e}_L$: incident electric field vectors for the right-hand and the left-hand circularly polarized signals
- e_R, e_{RX}: co-polarized and the cross-polarized field amplitudes of the right-hand circularly polarized signal
- e_L, e_{LX}: co-polarized and the cross-polarized field amplitudes of the left-hand circularly polarized signal
- $\mathbf{h}, \mathbf{v}$: horizontal and vertical unit vectors at the location of the receive antenna
- δ_R, δ_L: unknown phases of the cross-polarized field relative to the co-polarized field for the right-hand and the left-hand circularly polarized signals[2].

Each port of the linearly polarized receive antenna can be characterized by an effective length[3], i.e. for the HP and the VP:

$$\begin{aligned} \mathbf{h}_h &= \sqrt{g}\ \mathbf{h} + \sqrt{g_x}\ \mathbf{v}\ \mathrm{e}^{j\delta} \\ \mathbf{h}_v &= \sqrt{g}\ \mathbf{v} + \sqrt{g_x}\ \mathbf{h}\ \mathrm{e}^{j\delta} \end{aligned} \qquad (2)$$

where:

- g, g_x: proportional to the co-polar and the cross-polar gain of the receive antenna
- $\mathbf{h}, \mathbf{v}$: horizontal and vertical unit vectors at the location of the receive antenna
- δ: unknown phase of the cross-polarization voltage relative to the co-polarization voltage received in a port of the linearly polarized antenna.

The actual values of g, g_x and δ will in general be different for the two receive antenna ports, although the worst-case interference (based on using the gain masks and the appropriate value for δ) will be the same for both antenna ports. The analysis here is of the aggregate interference for one receive antenna port at a time. The received voltages for the two incident signals in equation (1) in the horizontal polarization receive port are therefore:

$$\begin{aligned} v_{Rh} &= \mathbf{h}_h \cdot \mathbf{e}_R \\ &= \sqrt{\frac{g}{2}}\ e_R + \sqrt{\frac{g}{2}}\ e_{RX}\ \mathrm{e}^{j\delta_R} - j\sqrt{\frac{g_x}{2}}\ e_R\ \mathrm{e}^{j\delta} + j\sqrt{\frac{g_x}{2}}\ e_{RX}\ \mathrm{e}^{j(\delta + \delta_R)} \end{aligned} \qquad (3)$$

$$\begin{aligned} v_{Lh} &= \mathbf{h}_h \cdot \mathbf{e}_L \\ &= \sqrt{\frac{g}{2}}\ e_L + \sqrt{\frac{g}{2}}\ e_{LX}\ \mathrm{e}^{j\delta_L} + j\sqrt{\frac{g_x}{2}}\ e_L\ \mathrm{e}^{j\delta} - j\sqrt{\frac{g_x}{2}}\ e_{LX}\ \mathrm{e}^{j(\delta + \delta_L)} \end{aligned} \qquad (4)$$

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[2] As in most antenna analyses, simple carriers with the time factor $\mathrm{e}^{j\omega t}$ are assumed. The carrier and the signal in one polarization are assumed to be uncorrelated with the carrier and the signal in the other polarization.

[3] The concept of "effective length" applied originally to dipole antennas and linear polarization. It has over the years been extended to general polarization states and more general antennas. The effective length of an antenna may be defined as a complex vector so that the received open-circuit voltage is the scalar product of effective length vector **h** and the incident electric field vector **e**, i.e. $v_{oc} = \mathbf{h} \cdot \mathbf{e}$.

The power received in the horizontal polarization port is proportional to the sum of the voltages squared assuming that the two signals are uncorrelated. The last term on the right-hand sides of equations (3) and (4) is the product of the cross-polarization of the two antennas and will therefore be the smallest for practical cross-polar performance values. As a result some of the terms resulting from the squaring of equations (3) and (4) are so small that they can be ignored, and these are the ones involving the product of the last term with any other terms except the first. By simplifying in this way the power in the horizontal polarization receive port is proportional to:

$$\begin{aligned}|v_{Rh}|^2 + |v_{Lh}|^2 = {} & \frac{g}{2}\left(e_R^2 + e_L^2 + e_{RX}^2 + e_{LX}^2\right) + \frac{g_x}{2}\left(e_R^2 + e_L^2\right) + \\ & g\left(e_R\, e_{RX} \cos \delta_R + e_L\, e_{LX} \cos \delta_L\right) + \sqrt{g g_x}\left(e_R^2 - e_L^2\right)\sin\delta - \\ & 2\sqrt{g g_x}\left(e_R\, e_{RX} \sin \delta_R - e_L\, e_{LX} \sin \delta_L\right)\cos\delta\end{aligned} \tag{5}$$

Similarly, the power in the vertical polarization receive port is proportional to:

$$\begin{aligned}|v_{Rv}|^2 + |v_{Lv}|^2 = {} & \frac{g}{2}\left(e_R^2 + e_L^2 + e_{RX}^2 + e_{LX}^2\right) + \frac{g_x}{2}\left(e_R^2 + e_L^2\right) - \\ & g\left(e_R\, e_{RX} \cos \delta_R + e_L\, e_{LX} \cos \delta_L\right) - \sqrt{g g_x}\left(e_R^2 - e_L^2\right)\sin\delta - \\ & 2\sqrt{g g_x}\left(e_R\, e_{RX} \sin \delta_R - e_L\, e_{LX} \sin \delta_L\right)\cos\delta\end{aligned} \tag{6}$$

2.2 Interference from linearly polarized into circularly polarized antenna systems

This section investigates the opposite scenario of that of the previous section. We derive general expressions for the coupling from two orthogonal linear polarizations into a circularly polarized antenna and consider the two special cases:

– A dual linearly polarized satellite illuminates a circularly polarized earth station.

– A dual linearly polarized earth station illuminates a circularly polarized satellite.

The incident field at the location of the receive antenna is for each polarization of the linearly polarized transmit antenna:

$$\begin{aligned}\mathbf{e}_H &= e_H\, \mathbf{h} + e_{HX}\, \mathbf{v}\, \mathrm{e}^{j\delta_H} \\ \mathbf{e}_V &= e_V\, \mathbf{v} + e_{VX}\, \mathbf{h}\, \mathrm{e}^{j\delta_V}\end{aligned} \tag{7}$$

where:

$\mathbf{e}_H$, $\mathbf{e}_V$: incident electric field vectors for the horizontally and vertically polarized signals

e_H, e_{HX}: co-polarized and the cross-polarized field amplitudes of the horizontally polarized signal

e_V, e_{VX}: co-polarized and the cross-polarized field amplitudes of the vertically polarized signal

$\mathbf{h}$, $\mathbf{v}$: horizontal and vertical unit vectors at the location of the receive antenna

δ_H, δ_V: unknown phases of the cross-polarized field relative to the co-polarized field for the vertically and the horizontally polarized signals.

The RHC and LHC polarization ports of the receive antenna are characterized by the effective lengths:

$$\begin{aligned}\mathbf{h}_r &= \sqrt{g}\,\frac{\mathbf{h} + j\,\mathbf{v}}{\sqrt{2}} + \sqrt{g_x}\,\frac{\mathbf{h} - j\,\mathbf{v}}{\sqrt{2}}\,\mathrm{e}^{j\delta}\\ \mathbf{h}_l &= \sqrt{g}\,\frac{\mathbf{h} - j\,\mathbf{v}}{\sqrt{2}} + \sqrt{g_x}\,\frac{\mathbf{h} + j\,\mathbf{v}}{\sqrt{2}}\,\mathrm{e}^{j\delta}\end{aligned} \tag{8}$$

where:

- g, g_x: proportional to the co-polar and the cross-polar gain of the receive antenna
- $\mathbf{h}, \mathbf{v}$: horizontal and vertical unit vectors at the location of the receive antenna
- δ: unknown phase of the cross-polarization voltage relative to the co-polarization voltage received in a port of the circularly polarized antenna.

The received voltages for the two incident signals in equation (7) in the RHC polarization receive port are:

$$\begin{aligned}v_{Hr} &= \mathbf{h}_r \cdot \mathbf{e}_H\\ &= \sqrt{\frac{g}{2}}\,e_H + j\sqrt{\frac{g}{2}}\,e_{HX}\,\mathrm{e}^{j\delta_H} + \sqrt{\frac{g_x}{2}}\,e_H\,\mathrm{e}^{j\delta} - j\sqrt{\frac{g_x}{2}}\,e_{HX}\,\mathrm{e}^{j(\delta + \delta_H)}\end{aligned} \tag{9}$$

$$\begin{aligned}v_{Vr} &= \mathbf{h}_r \cdot \mathbf{e}_V\\ &= j\sqrt{\frac{g}{2}}\,e_V + \sqrt{\frac{g}{2}}\,e_{VX}\,\mathrm{e}^{j\delta_V} - j\sqrt{\frac{g_x}{2}}\,e_V\,\mathrm{e}^{j\delta} + \sqrt{\frac{g_x}{2}}\,e_{VX}\,\mathrm{e}^{j(\delta + \delta_V)}\end{aligned} \tag{10}$$

The power received in the RHC polarization port is proportional to the sum of the voltages squared (neglecting cross-polarization terms of an order higher than two):

$$\begin{aligned}\left|v_{Hr}\right|^2 + \left|v_{Vr}\right|^2 = &\frac{g}{2}\left(e_H^2 + e_V^2 + e_{HX}^2 + e_{VX}^2\right) + \frac{g_x}{2}\left(e_H^2 + e_V^2\right) -\\ &g\left(e_H\,e_{HX}\sin\delta_H - e_V\,e_{VX}\sin\delta_V\right) + \sqrt{gg_x}\left(e_H^2 - e_V^2\right)\cos\delta +\\ &2\sqrt{gg_x}\left(e_H\,e_{HX}\cos\delta_H + e_V\,e_{VX}\cos\delta_V\right)\sin\delta\end{aligned} \tag{11}$$

Similarly, the power in the LHC polarization receive port is proportional to:

$$\begin{aligned}\left|v_{Hl}\right|^2 + \left|v_{Vl}\right|^2 = &\frac{g}{2}\left(e_H^2 + e_V^2 + e_{HX}^2 + e_{VX}^2\right) + \frac{g_x}{2}\left(e_H^2 + e_V^2\right) +\\ &g\left(e_H\,e_{HX}\sin\delta_H - e_V\,e_{VX}\sin\delta_V\right) + \sqrt{gg_x}\left(e_H^2 - e_V^2\right)\cos\delta -\\ &2\sqrt{gg_x}\left(e_H\,e_{HX}\cos\delta_H + e_V\,e_{VX}\cos\delta_V\right)\sin\delta\end{aligned} \tag{12}$$

2.3 Interference from linearly polarized into linearly polarized antenna systems

In this section we consider the interference between two dual linearly polarized systems that may have different polarization alignment angles[4]. We derive expressions for:

– A dual linearly polarized satellite that illuminates a linearly polarized earth station.

– A dual linearly polarized earth station that illuminates a linearly polarized satellite.

The incident field at the location of the receive antenna is, for each polarization of the linearly polarized transmit antenna,

$$\begin{aligned} \mathbf{e}_H &= e_H(\cos\psi\,\mathbf{h} + \sin\psi\,\mathbf{v}) + e_{HX}(-\sin\psi\,\mathbf{h} + \cos\psi\,\mathbf{v})\,\mathrm{e}^{j\delta_H} \\ \mathbf{e}_V &= e_V(-\sin\psi\,\mathbf{h} + \cos\psi\,\mathbf{v}) + e_{VX}(\cos\psi\,\mathbf{h} + \sin\psi\,\mathbf{v})\,\mathrm{e}^{j\delta_V} \end{aligned} \tag{13}$$

where:

$\mathbf{e}_H, \mathbf{e}_V$: incident electric field vectors for the horizontally and vertically polarized signals

e_H, e_{HX}: co-polarized and the cross-polarized field amplitudes of the horizontally polarized signal

e_V, e_{VX}: co-polarized and the cross-polarized field amplitudes of the vertically polarized signal

$\mathbf{h}, \mathbf{v}$: horizontal and vertical unit vectors at the location of the receive antenna

ψ: differential polarization angle between the transmit and the receive antenna

δ_H, δ_V: unknown phases of the cross-polarized field relative to the co-polarized field for the vertically and the horizontally polarized signals.

Equation (2) characterizes the properties of the receive antenna HP and VP ports. The received voltages for the two incident signals in equation (13) in the horizontal polarization receive port are:

$$\begin{aligned} v_{Hh} &= \mathbf{h}_h \cdot \mathbf{e}_H \\ &= \sqrt{g}\; e_H \cos\psi - \sqrt{g}\; e_{HX} \sin\psi\,\mathrm{e}^{j\delta_H} + \sqrt{g_x}\; e_H \sin\psi\,\mathrm{e}^{j\delta} + \sqrt{g_x}\; e_{HX} \cos\psi\,\mathrm{e}^{j(\delta+\delta_H)} \end{aligned} \tag{14}$$

$$\begin{aligned} v_{Vh} &= \mathbf{h}_h \cdot \mathbf{e}_v \\ &= -\sqrt{g}\; e_V \sin\psi + \sqrt{g}\; e_{VX} \cos\psi\,\mathrm{e}^{j\delta_V} + \sqrt{g_x}\; e_V \cos\psi\,\mathrm{e}^{j\delta} + \sqrt{g_x}\; e_{VX} \sin\psi\,\mathrm{e}^{j(\delta+\delta_V)} \end{aligned} \tag{15}$$

The power received in the HP port is proportional to the sum of the voltages squared (neglecting cross-polarization products of order higher than two),

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[4] Satellites with the same polarization alignment, e.g. as defined by the equatorial plane, but operating from different positions along the geostationary arc, will appear to have slightly different polarization orientations at an earth station. For segments of the geostationary arc less than about ±6°, the polarization alignment difference from the central satellite will be less than about 1°.

$$\begin{aligned}|v_{Hh}|^2+|v_{Vh}|^2 = {} & g(e_H^2\cos^2\psi+e_V^2\sin^2\psi+e_{HX}^2\sin^2\psi+e_{VX}^2\cos^2\psi)+g_x(e_H^2\sin^2\psi+e_V^2\cos^2\psi)-\\ & g\sin 2\psi(e_H\,e_{HX}\cos\delta_H+e_V\,e_{VX}\cos\delta_V)+\sqrt{gg_x}\sin 2\psi(e_H^2-e_V^2)\cos\delta+\\ & 2\sqrt{gg_x}\cos^2\psi(e_H\,e_{HX}\cos(\delta+\delta_H)+e_V\,e_{VX}\cos(\delta-\delta_V))-\\ & 2\sqrt{gg_x}\sin^2\psi(e_H\,e_{HX}\cos(\delta-\delta_H)+e_V\,e_{VX}\cos(\delta+\delta_V))\end{aligned} \tag{16}$$

Similarly, the power in the vertical polarization receive port is proportional to:

$$\begin{aligned}|v_{Hh}|^2+|v_{Vh}|^2 = {} & g(e_H^2\sin^2\psi+e_V^2\cos^2\psi+e_{HX}^2\cos^2\psi+e_{VX}^2\sin^2\psi)+g_x(e_H^2\cos^2\psi+e_V^2\sin^2\psi)-\\ & g\sin 2\psi(e_H\,e_{HX}\cos\delta_H+e_V\,e_{VX}\cos\delta_V)+\sqrt{gg_x}\sin 2\psi(e_H^2-e_V^2)\cos\delta+\\ & 2\sqrt{gg_x}\sin^2\psi(e_H\,e_{HX}\cos(\delta+\delta_H)+e_V\,e_{VX}\cos(\delta-\delta_V))-\\ & 2\sqrt{gg_x}\cos^2\psi(e_H\,e_{HX}\cos(\delta-\delta_H)+e_V\,e_{VX}\cos(\delta+\delta_V))\end{aligned} \tag{17}$$

3 Summary of downlink and uplink analysis for dual polarized interfering signals of equal amplitude

The analysis contained in this Annex is based on a rigorous treatment of the field at the output ports of a dual polarized receive antenna (either LP or CP) using a complete representation of the incident signal (either CP or LP, respectively) in terms of their two orthogonally polarized components. This analysis is equally applicable to the uplink and the downlink transmission paths. In this Annex the magnitude of the two orthogonally polarized interfering signals are assumed to be equal.

The analysis uses the generic vector equations given in Section 2 and we present simplified versions for both uplink and downlink. Different combinations of the unknown phase angles, δ_R, δ_L, δ_H, δ_V and δ have been used to derive worst-case, average and best-case results. Separate summary analyses are provided for the uplink and downlink cases of:

– a dual CP network interfering with an LP network

– a dual LP network interfering with an CP network

– a dual LP network interfering with an LP network.

Having addressed the case of a CP network interfering with an LP network, the analysis then deals with the interference in the opposite direction – from an LP network interfering with a CP network.

An important objective of the analysis is to understand the relative impact of the use of different types of polarization in adjacent satellites (CP in one network and LP in the other network) compared to the case where both networks use one type of polarization only (LP in both networks or CP in both networks). Therefore the results are presented in the form of a "Δ" compared to the like polarization case. In order to obtain a true comparison, the same analysis approach is used to determine the reference situation where adjacent networks are both operating using LP.

The results of the comparison are given in Section 5 of this Annex. These results show worst-case interference levels that result from particular combinations of the unknown relative phase angles, δ_R, δ_L, δ_H, δ_V and δ. These worst-case interference levels are given relative to the often-assumed situation where the co-polar and cross-polar signals are assumed to be uncorrelated, and therefore are added in power to determine the aggregate interference level (or average level). The resulting discrepancy between the rigorous worst-case analysis of interference between adjacent LP networks, compared to the simplistic power summation approach, is between 0.05 dB and 0.47 dB. This result should be taken into account when assessing the overall impact of CP networks interfering with adjacent LP networks (and vice versa). The simple power summation approach will provide an average interference level. This average interference is independent of the polarization of the networks. The maximum possible deviation of the worst-case interference from the average interference is slightly larger when the two adjacent networks have different polarization types than when they have the same polarization type.

The conclusions from this analysis are that when the magnitude of the two orthogonally polarized interfering signals is assumed to be equal, the worst-case aggregate downlink interference into an LP system from an adjacent CP system is comparable to that from an adjacent LP system as the interference contributions from the earth station antenna cross-polarization cancel in the earth station antenna receive ports. The worst-case aggregate uplink interference into the LP system from the adjacent CP system is higher than from the adjacent LP system. The interference level depends upon the phase relationship between the co-polarized and the cross-polarized components for the earth station antenna and the satellite antenna. If the interference into the one satellite antenna receive port is increased, the interference into the orthogonal satellite antenna receive port from the same earth station will decrease by a similar amount. Improving the earth station off-axis performance will improve the worst-case aggregate interference. The average interference into dual LP systems from dual CP systems (or vice versa) is identical to the average interference between adjacent dual LP systems or between adjacent dual CP systems.

The aggregate downlink and uplink interference into a CP system from an adjacent LP system is identical to the interference into an LP system from an adjacent CP system.

3.1 CP satellite into LP earth station

We assume:

a) The signal amplitude for each polarization is the same, i.e. $e_R = e_L = e$*.

b) The satellite cross-polarization is defined by the XPD, i.e. $e_{RX} = e_{LX} = e/\sqrt{xpd}$**. XPD is the difference between co-polar and cross-polar gain values of an antenna. In general it is expressed in dB, although in the equations of this note the lower case xpd indicates a linear power ratio.

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* An imbalance between the co-polarization levels from the satellite may be undesirable as it may generate some interference – see the fourth term of equations (5) and (6). However, the first dominant term will be small in the unbalanced case due to the factor, 1/2. The cancellation of the dominant earth station cross-polarization contribution seems to be unique for the downlink interference case. The cancellation takes place if the two polarizations are transmitted from a single satellite or from co-located satellites. Otherwise, this contribution would be a significant downlink contribution for $\delta = \pm 90°$.

** It is a very pessimistic assumption that the cross-polarization peaks occur at the same location and frequency for both hands of CP from the satellite. This point is discussed further in Section 5 of this Annex.

c) The earth station antenna co-polarization and cross-polarization gain are defined by the gain envelopes G and G_x. Typical values for the G_x envelope would be $19 - 25\log(\theta)$ which is 10 dB lower than the typical G envelope of $29 - 25\log(\theta)$. The lower case g and g_x indicate the corresponding numerical values.

The satellite XPD is typically in the order of 27-30 dB while the off-axis earth station XPD close to the main beam can be assumed to be 10 dB. Far away from the main beam, it will be less. Thus, the earth station cross-polarization would be expected to contribute more to the overall adjacent satellite interference than the satellite cross-polarization.

Substitution of these assumptions into equations (5) and (6) provides expressions for the power received by the two earth station antenna ports as functions of the phase differences δ_R, δ_L and δ. These unknown phase differences are generally not considered in the antenna design. However, they are significant for the aggregate interference. Here we only bound the interference for any phase differences and provide the worst-case and the best-case interference:

$$|v_R|^2 + |v_L|^2{}_{worst/best\ case} = (g + g_x)e^2 \pm 2\sqrt{\frac{g(g + 4g_x)}{xpd}}\, e^2 + \frac{g}{xpd}\, e^2 \tag{18}$$

The upper sign applies for the worst case and the lower sign for the best case. The average interference is the sum of the first and the third terms of equation (18). The worst-case interference occurs for the HP port for the phase angles δ, δ_R and δ_L close to 0. Similarly, the best case occurs for the phase angles δ, δ_R and δ_L close to 180°. These two conditions are the best case and the worst case, respectively, for the vertical polarization port. It is significant to note:

a) In average there is no degradation compared to LP systems.

b) If one receive polarization port is degraded, the performance of the other port will be better than in the average case.

3.2 CP earth station into LP satellite

We assume:

a) The signal amplitude for each polarization is the same, i.e. $e_R = e_L = e$.

b) The satellite cross-polarization is defined by the XPD. If the co-polar satellite antenna gain is g_{sat}, the cross-polar satellite antenna gain $g_{sat,\,x} = g_{sat}/xpd$.

c) The earth station antenna co-polarization and cross-polarization gain are defined by the gain envelopes G and G_x. Then, the earth station cross-polarization is $e_{RX} = e_{LX} = e\sqrt{g_x / g}$.

The worst-case and the best-case interference are for the uplink case:

$$|v_R|^2 + |v_L|^2{}_{worst/best\ case} = (g + g_x)e^2 \pm 2\sqrt{\frac{g\, g_x (xpd + 4)}{xpd}}\, e^2 + \frac{g}{xpd}\, e^2 \tag{19}$$

The worst-case interference occurs for the horizontal polarization port for δ, δ_L and δ_R close to 0 as in the downlink case. Since the satellite XPD in general will be large, the worst-case degradation will be larger in the downlink case than in the uplink case.

3.3 LP satellite into CP earth station

We assume:

a) The signal amplitude for each polarization is the same, i.e. $e_H = e_V = e$.

b) The satellite cross-polarization is defined by the XPD, i.e. $e_{HX} = e_{VX} = e/\sqrt{xpd}$.

c) The earth station antenna co-polarization and cross-polarization gain are defined by the gain envelopes G and G_x.

Substitution into equations (11) and (12) gives results that are similar to the results for the interference from a CP satellite into an LP earth station. The worst-case (average and best-case) interference is identical to the worst-case (average and best-case) interference from a CP satellite into an LP earth station given by equation (18). The main difference is that the worst-case interference for the RHC polarization port (and the best-case for the LHC polarization port) occurs for $\delta = 90°$ and $\delta_V = -\delta_H \approx 90°$. Changing the signs of the phase angles interchanges the performance of the receive antenna ports. Obviously, the worst-case phase angles are those that maximize the power transfer from the incident fields from the adjacent satellite equations (1) and (7) into the receive antenna ports characterized by equations (2) and (8).

3.4 LP earth station into CP satellite

We assume:

a) The signal amplitude for each polarization is the same, i.e. $e_H = e_V = e$.

b) The satellite cross-polarization is defined by the XPD. If the co-polar satellite antenna gain is g_{sat}, the cross-polar satellite antenna gain $g_{sat,\,x} = g_{sat}/xpd$.

c) The earth station antenna co-polarization and cross-polarization gain are defined by the gain envelopes G and G_x. Then, the earth station cross-polarization is $e_{HX} = e_{VX} = e\sqrt{g_x/g}$.

Again, the interference is identical to the similar interference from a CP into an LP system. Thus, the worst-case (and best-case) interference from a dual LP earth station into a CP satellite is given by equation (19) and the dependence on the phase angles is as in the downlink case.

3.5 LP satellite into LP earth station

We assume:

a) The signal amplitude for each polarization is the same, i.e. $e_H = e_V = e$.

b) The satellite cross-polarization is defined by the XPD, i.e. $e_{HX} = e_{VX} = e/\sqrt{xpd}$.

c) The earth station antenna co-polarization and cross-polarization gain are defined by the gain envelopes G and G_x.

Substitution into equations (16) and (17) gives that the power received by an LP earth station from a dual LP satellite is proportional to:

$$\begin{aligned}|v_H|^2 + |v_V|^2 = (g + g_x)\, e^2 \mp \frac{g}{\sqrt{xpd}} \sin 2\psi(\cos\delta_H + \cos\delta_V)\, e^2 + \\ 2\sqrt{\frac{g\, g_x}{xpd}}\,(\cos 2\psi(\cos\delta_H + \cos\delta_V)\cos\delta \mp (\sin\delta_H - \sin\delta_V)\sin\delta)\, e^2 + \frac{g}{xpd}\, e^2\end{aligned} \tag{20}$$

The upper sign applies for the HP port and the lower sign for the VP port. The second term, which is the lowest-order satellite antenna cross-polarization contribution, vanishes for perfect cross-polarization alignment, $\psi = 0$. Otherwise, the cross-polarization interference terms depend on 2 ψ, twice the polarization misalignment angle. The worst-case (and the best-case) interference given by equation (24) is for $\psi = 0$

$$|v_H|^2 + |v_V|^2{}_{worst/best\ case,\ \psi = 0} = (g + g_x)e^2 \pm 4\sqrt{\frac{g\, g_x}{xpd}}\, e^2 + \frac{g}{xpd}\, e^2 \tag{21}$$

The worst-case interference occurs for the horizontal polarization port for $\delta_V = -\delta_H = \delta$. Equation (21) also applies for the interference from a CP satellite into a CP earth station. For $\psi = 45°$, the interference becomes identical to that of a dual CP system on an LP system.

3.6 LP earth station into LP satellite

We assume:

a) The signal amplitude for each polarization is the same, i.e. $e_H = e_V = e$.

b) The co-polar satellite antenna gain is g_{sat}, the cross-polar satellite antenna gain $g_{sat,\, x} = g_{sat}/xpd$.

c) The earth station antenna cross-polarization is $e_{HX} = e_{VX} = e\sqrt{g_x/g}$.

Substitution into equations (16) and (17) gives that the power received by an LP satellite from a dual LP earth station is proportional to:

$$\begin{aligned}|v_H|^2 + |v_V|^2 = (g + g_x)\, e^2 \mp \sqrt{g\, g_x} \sin 2\psi(\cos\delta_H + \cos\delta_V)\, e^2 + \\ 2\sqrt{\frac{g\, g_x}{xpd}}\,(\cos 2\psi(\cos\delta_H + \cos\delta_V)\cos\delta \mp (\sin\delta_H - \sin\delta_V)\sin\delta)\, e^2 + \frac{g}{xpd}\, e^2\end{aligned} \tag{22}$$

The upper sign applies for the HP port and the lower sign for the VP port. The second term, which is the lowest-order earth station antenna cross-polarization contribution, vanishes for the perfect polarization alignment, $\psi = 0$. The other terms are identical to the ones in equation (20). Therefore, for perfect polarization alignment, $\psi = 0$, the worst-case downlink performance is given by equation (21). The impact of a polarization angle misalignment of 1° is to increase the worst-case interference by about 0.1 dB.

4 Discussion of the results

4.1 Interference from a CP system into an LP system

Table 1 summarizes the worst-case incremental downlink and uplink interference from an adjacent CP system interfering into an LP system compared to that from an LP system interfering into another LP system versus the satellite antenna XPD and the earth station off-axis cross-polarization.

TABLE 1

Worst-case incremental downlink and uplink interference levels in dB into an LP system from an adjacent CP system (or vice versa) relative to that from an adjacent LP system versus satellite antenna XPD and earth station off-axis cross-polarization G_x, $\psi = 0$

G_x	G – 10 dB			G – 15 dB			G – 20 dB		
XPD (dB)	20	25	30	20	25	30	20	25	30
Downlink	0.31	0.19	0.11	0.52	0.31	0.18	0.62	0.38	0.22
Uplink	1.50	1.70	1.81	1.01	1.12	1.19	0.62	0.70	0.74

With the satellite antenna XPD of the order of 30 dB, the earth station antenna off-axis cross-polar gain will be the dominant cross-polarization effect in these cases. It essentially controls the cross-polar interference between two adjacent satellite networks regardless of whether they are operating in LP or in CP.

The worst-case incremental downlink interference is essentially negligible for low levels of satellite cross-polarization. In addition, no additional degradation was considered for the LP system interfering into the other LP system due to polarization misalignment, antenna yaw effects, Faraday rotation, etc.

The incremental worst-case uplink interference is higher and arises due to the assumed poor off-axis earth station antenna cross-polarization. Even when both satellite and earth station cross-polarization are low, the incremental worst-case uplink interference may not be negligible, but then the average interference will be low.

The worst case occurs when the cross-polarization is in phase with the co-polarization (and a cross-polarization peak coincides with a co-polarization peak) for both earth station polarizations simultaneously. Under these conditions the co-polarization interference and the cross-polarization interference voltages will add in phase in the satellite antenna polarization port. This is considered to be an extremely unlikely event. In other cases, the interference can be less than between LP systems. Further, the average interference from a CP system into an LP system is equal to the average interference between LP systems. The physics of antenna design may naturally constrain the phase-relationship between the earth station cross-polarization and co-polarization. For example, the cross-polarization generated by diffraction in the reflector edges will typically be in quadrature phase with the co-polarization. This would result in some terms to vanish for contributions with $\delta_R = \delta_L = \pm 90°$. The effects of the polarizer, feed, subreflector blockage and strut contributions on the phase relationships of the co-polar and cross-polar components may also contribute but this needs further study and is dealt with in Annex 2. Also, the cross-polarization peaks are unlikely to occur at the location of the co-polarization peaks (see Appendix 1) since cross-polarization generated by reflector edge diffraction typically has peaks in the co-polarization nulls.

4.2 Interference from an LP system into a CP system

The interference from an LP system into a CP system is identical to the interference from a CP system into an LP system. Only the dependence on the phase differences between the co-polarization and the cross-polarization of the earth station antenna and the satellite antenna differs.

5 Conclusions

The conclusions from this analysis are that when the magnitude of the two orthogonally polarized interfering signals are assumed to be equal, the worst-case aggregate downlink interference into an LP system from an adjacent CP system is comparable to that from an adjacent LP system as the interference contributions from the earth station antenna cross-polarization cancel in the earth station antenna polarization ports. This conclusion is valid regardless of the relative phase angles, δ_R, δ_L and δ.

The worst-case aggregate uplink interference into the LP system from the adjacent CP system is slightly higher than from the adjacent LP system. The interference level depends upon the phase relationship between the co-polarized and the cross-polarized components for the earth station antenna and the satellite antenna. The worst-case uplink interference occurs when the cross-polar signal component is in phase with the co-polar one, and when a cross-polar antenna gain peak coincides with a co-polar gain peak, for both of the wanted signal transmissions simultaneously. Such a coincidence of so many factors is considered to be statistically very unlikely. It should be noted that:

– If the interference into one satellite antenna polarization port is increased, the interference into the other satellite antenna polarization port from the same earth station will decrease by a similar amount.

– In practice the earth station off-axis performance is likely to be better than the ITU-R Recommendations', thus the worst-case aggregate interference level will be reduced.

– The physics of antenna design will naturally constrain the phase-relationship between the earth station cross-polarization and co-polarization which tends to lead to the average interference result.

– The actual antenna cross-polar gain peaks are unlikely to occur at the same off-axis angle as the co-polar gain peaks in particular for two polarizations at the same time.

In summary, for practical purposes using realistic antennas, the aggregate interference into dual LP systems from closely spaced dual CP systems (or vice versa) is identical to the aggregate interference between adjacent dual LP systems or between adjacent dual CP systems.

APPENDIX 1

TO ANNEX 1

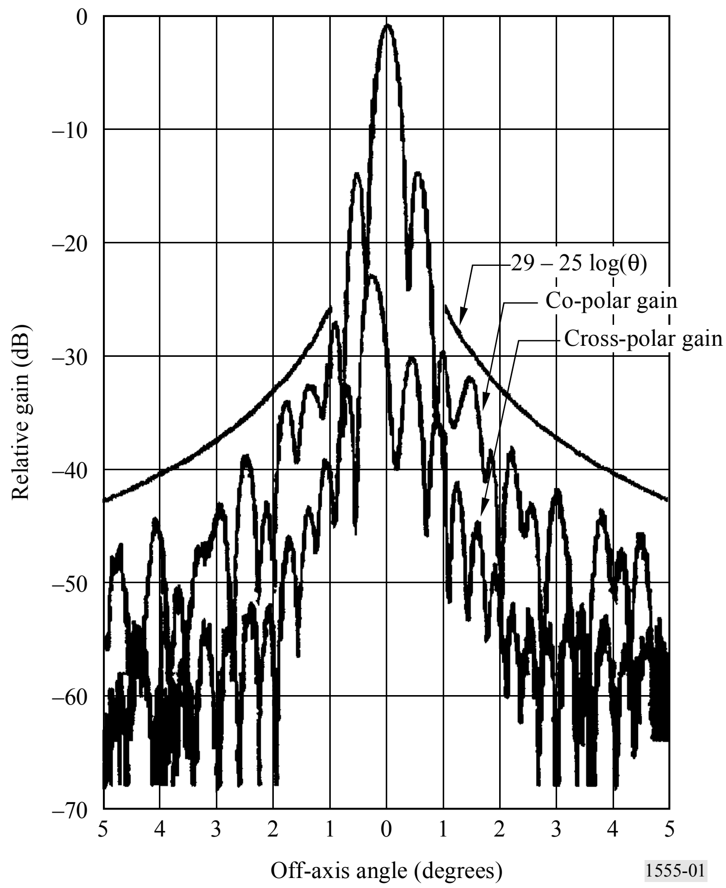
Example measurement data of the cross-polar discrimination of earth station antennas in the direction of closely spaced adjacent satellites

1 Antenna No. 1

Figure 1 gives the measured co-polar and cross-polar gain for a 8.1 m transmit antenna at 6.4 GHz operating in CP. The 29 – 25 log(θ) mask is also shown for off-axis angles greater than 1°. Note that the XPD is greater than approximately 15 dB (relative to 29 – 25 log(θ)) for off-axis angles between 1° and 2°, greater than approximately 18 dB for off-axis angles between 2° and 3°. The noise floor of the measurement does not permit reliable data in this case beyond 3°, although the XPD appears to be well in excess of 10 dB up to 5° off-axis.

FIGURE 1

Measured co-polar and cross-polar gain for 8.1 m transmit antenna at 6.4 GHz (CP)

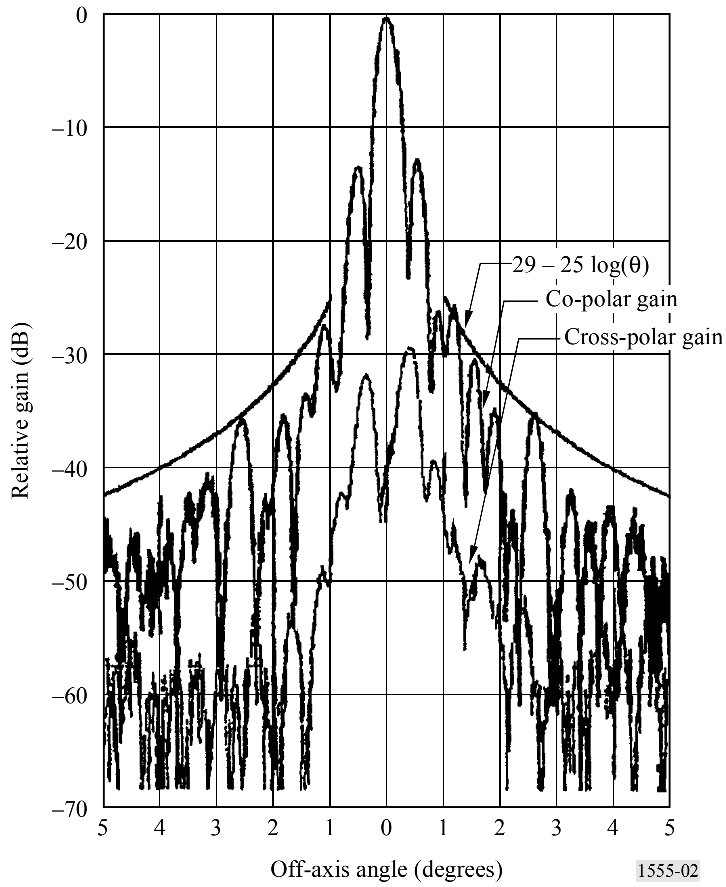


2 Antenna No. 2

Figure 2 gives the measured co-polar and cross-polar gain for a 9.3 m transmit antenna at 6.4 GHz operating in CP. The 29 – 25 log(θ) mask is also shown for off-axis angles greater than 1°. Note that the XPD is greater than approximately 20 dB (relative to 29 – 25 log(θ)) for off-axis angles between 1° and 5°.

FIGURE 2

Measured co-polar and cross-polar gain for 9.3 m transmit antenna at 6.4 GHz (CP)



ANNEX 2

Off-axis cross-polarization of earth station antennas operating in the 6/4 GHz frequency bands

1 Introduction

This Annex investigates the earth station antenna radiation pattern and the factors that contribute to the cross-polarization in further detail. The scattering in the struts supporting the sub-reflector is identified as a potentially dominant source of cross-polarization in the region 2°-10° from boresight. This scattering is only significant in small regions of space. This contribution shows that when it occurs it will mainly degrade the co-polar side lobes for a linearly polarized antenna and mainly the cross-polar side lobes for a circularly polarized antenna.

It shows that for currently available earth station antennas with struts in a quadripod configuration located near the earth station antenna ±45° planes, both the co-polarized and the cross-polarized strut scattering are insignificant in the space away from these planes. In fact, the strut cross-polarization completely cancels in the 0° (and 90°) plane which would normally be aligned with the geostationary arc. In this situation there is no difference between the interference level into an LP system from an adjacent dual CP system compared with that from an adjacent co-aligned dual LP system. In the special cases where the scattering in the struts significantly degrades the earth station CP cross-polarization performance, then the interference from dual CP into LP will be no worse than from dual LP into LP.

2 Summary of the analysis

2.1 Measurement of the phase relationship between the co-polarized and cross-polarized components

The phase relationship between the co-polarized and the cross-polarized components and the off-axis cross-polarization of the earth station antenna could play a role in the difference between the interference level into an LP system from an adjacent CP system compared with that from a perfectly aligned LP system.

Views were expressed that measurements would support the conclusion that the aggregate interference between the networks should be assumed to be identical to that which would occur if both networks used the same types of polarization (i.e. both LP or both CP). The possibility to measure the phase relationship between the co-polarized and cross-polarized components has been analysed. These analyses conclude that this measurement would be difficult if not impossible to perform. The small wavelength and the large size of earth station antennas used in the 6/4 GHz band would require measurements to be performed at several kilometres from the location of the antenna. The measurements would then suffer from severe external perturbations (e.g. ground reflection). The level of the cross-polarization signal is low. Measurement uncertainties would be large and would severely degrade the achievable accuracy. For these reasons the additional studies have concentrate on the analytical approach. This approach yields accurate, more general and reliable results.

2.2 Definition of an earth station radiation pattern model

To further analyse the important role played by the off-axis cross polarization of the earth station antenna, detailed studies have been performed on the earth station radiation pattern. This contribution proposes a model for the radiation pattern of high-efficiency centre-fed dual-reflector antenna systems typically employed as satellite communications earth terminals. This model is presented in Appendix 1 to Annex 2.

2.3 Effect of earth station struts

The struts supporting the sub-reflector are identified as a potentially dominant source of cross-polarization in the region 2°-10° from boresight. At 6/4 GHz band, the strut cross section is comparable to the wavelengths and a special investigation has been carried out. A model of the strut scattering has been developed. It is presented in Appendix 1 to Annex 2.

Scattering in the struts supporting the subreflector is identified as a dominant source of cross-polarization in the region 2°-10° from boresight. Currently available earth station antenna designs use struts in a quadripod configuration located in the earth station antenna ±45° planes to remove the co-polarized strut scattering from the geostationary arc. This configuration cancels the cross-polarization in the principal pattern planes of the earth station antenna both for LP and for CP. Thus, the possible increased uplink interference from a circular polarized network into a linearly polarized network will not occur under standard operating conditions where no strut is perpendicular to the geostationary arc.

Further, should an earth station antenna be operated with a strut perpendicular to the geostationary arc, the interference from CP into LP will be no worse than from LP into LP.

2.4 Simulation and results

Simulations have been performed and numerical results have been obtained. The results are shown in Figs. 3 to 7.

2.5 Offset-fed reflector antenna

The case of offset-fed reflector antennas, commonly used for very small aperture terminal (VSAT), has been considered. These earth station antennas benefit from having no blockage and have very low cross-polarization when used with CP. Thus no further analysis is required to show that the LP and the CP scenarios are identical.

FIGURE 3

Far field amplitude (left) and phase (right) for main reflector and sub-reflector

(D = 9.5 m, d = 1.22 m, 6.425 GHz)

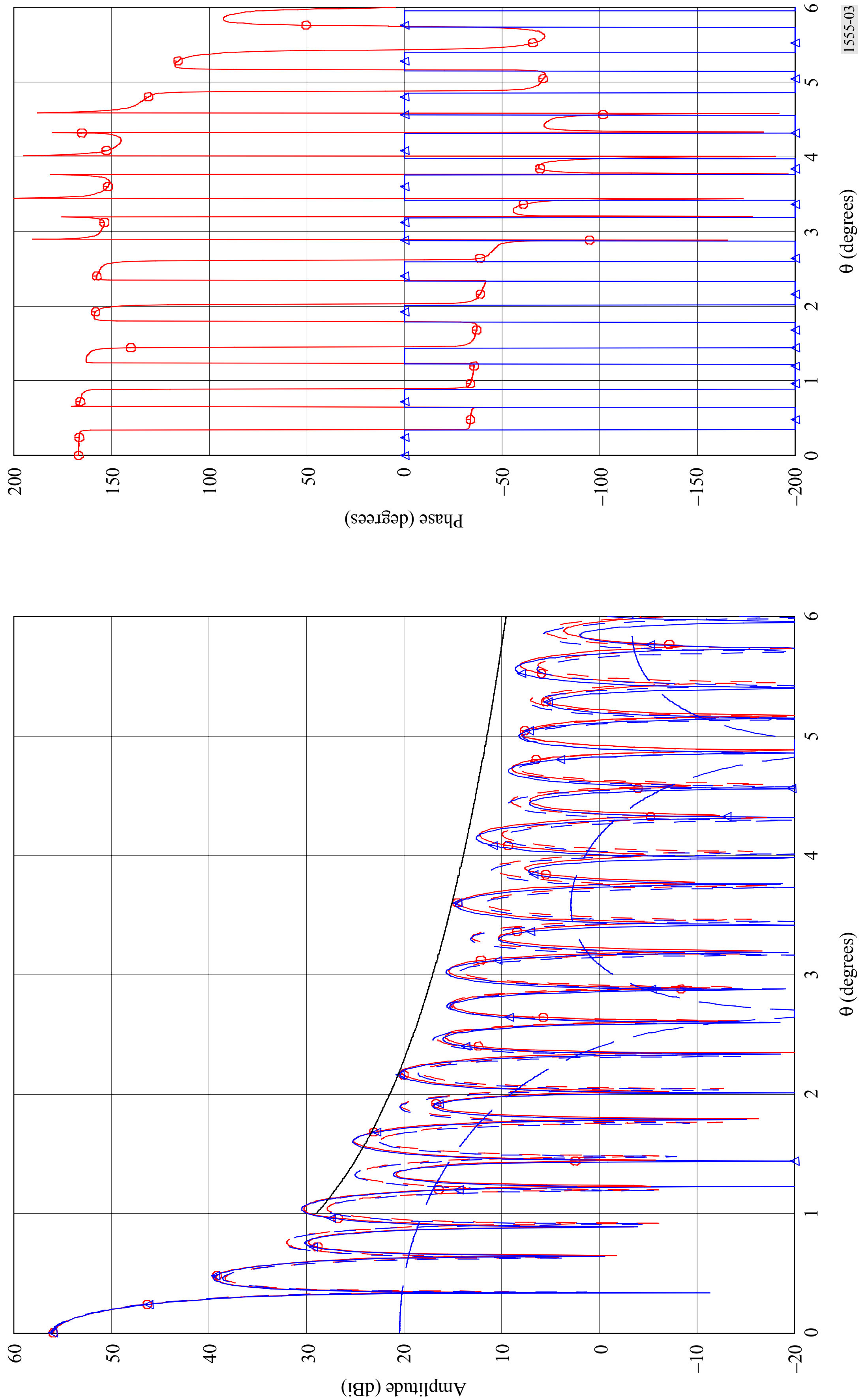


FIGURE 4

Surface tolerance error pattern for r.m.s. of 0.5 mm and correlation length *D*/2 at 6.425 GHz and 14.5 GHz

D = 9.5 m, *d* = 1.22 m

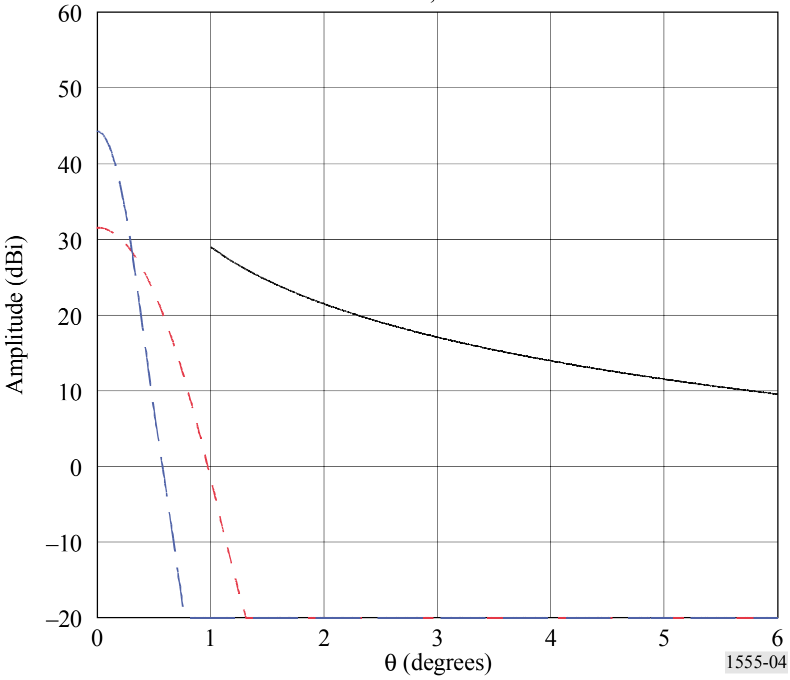


FIGURE 5

Co-polar and cross-polar components from 6 cm circular struts in plane φ = 0°. Strut angle with aperture plane is α = 0°. Comparison between simple model and general reflector antenna software (circles)

(*D* = 9.5 m, *d* = 1.22 m, 6.425 GHz)

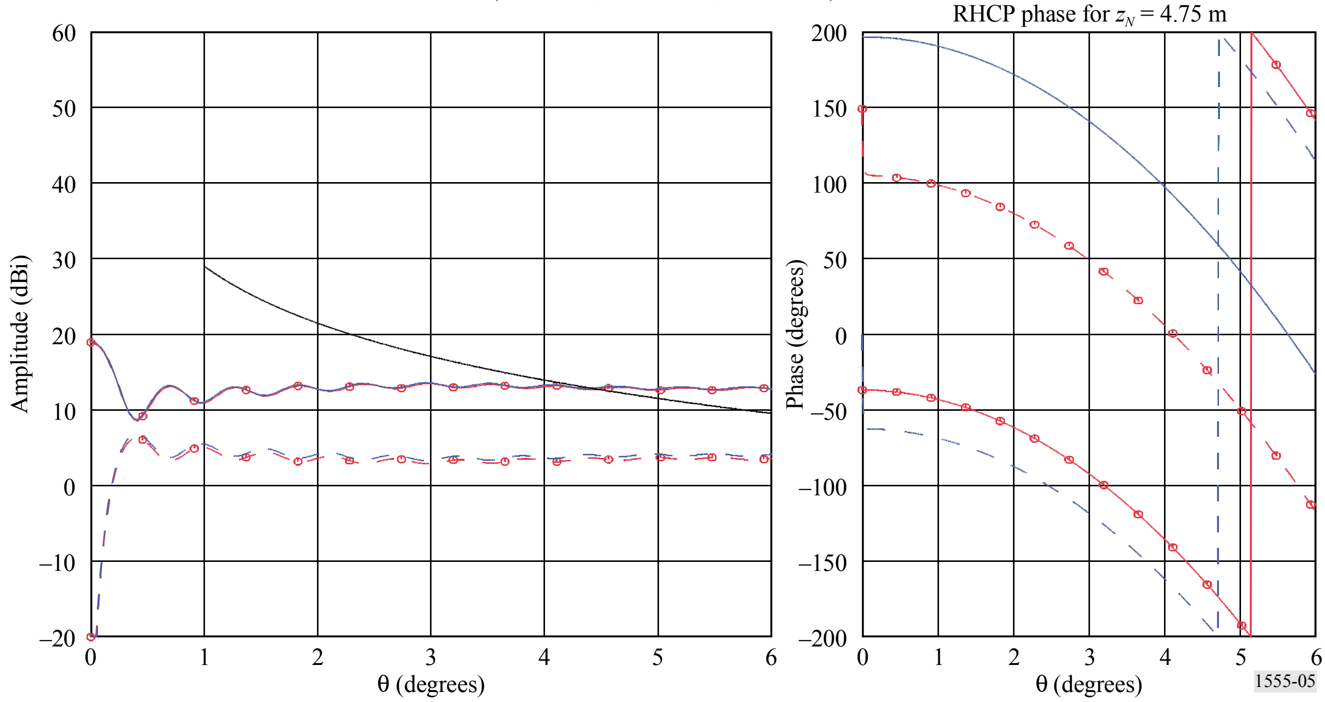


FIGURE 6

Full line curves on left-hand figure compare total co-polar field predicted by simple model and general reflector antenna software (circles) from 6 cm circular struts in plane φ = 0°. Dotted/dashed curves show main reflector field, sub-reflector field, and strut co-polar and cross-polar components prediced by simple model. Right-hand figure shows phase of total co-polar field and cross-polar field predicted by general reflector software. Strut angle with aperture plane is α = 45°

(D = 9.5 m, d = 1.22 m, 6.425 GHz)

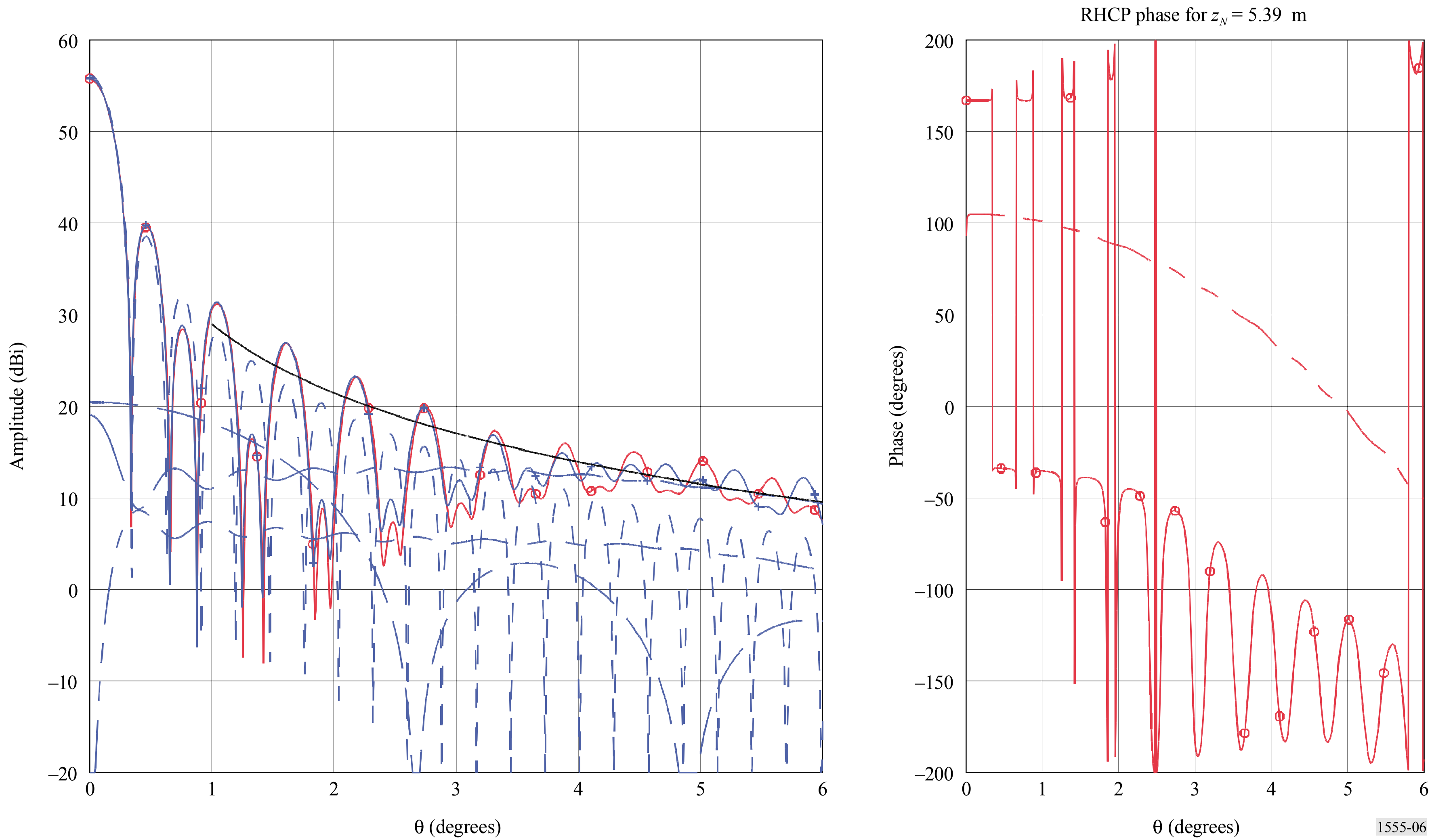
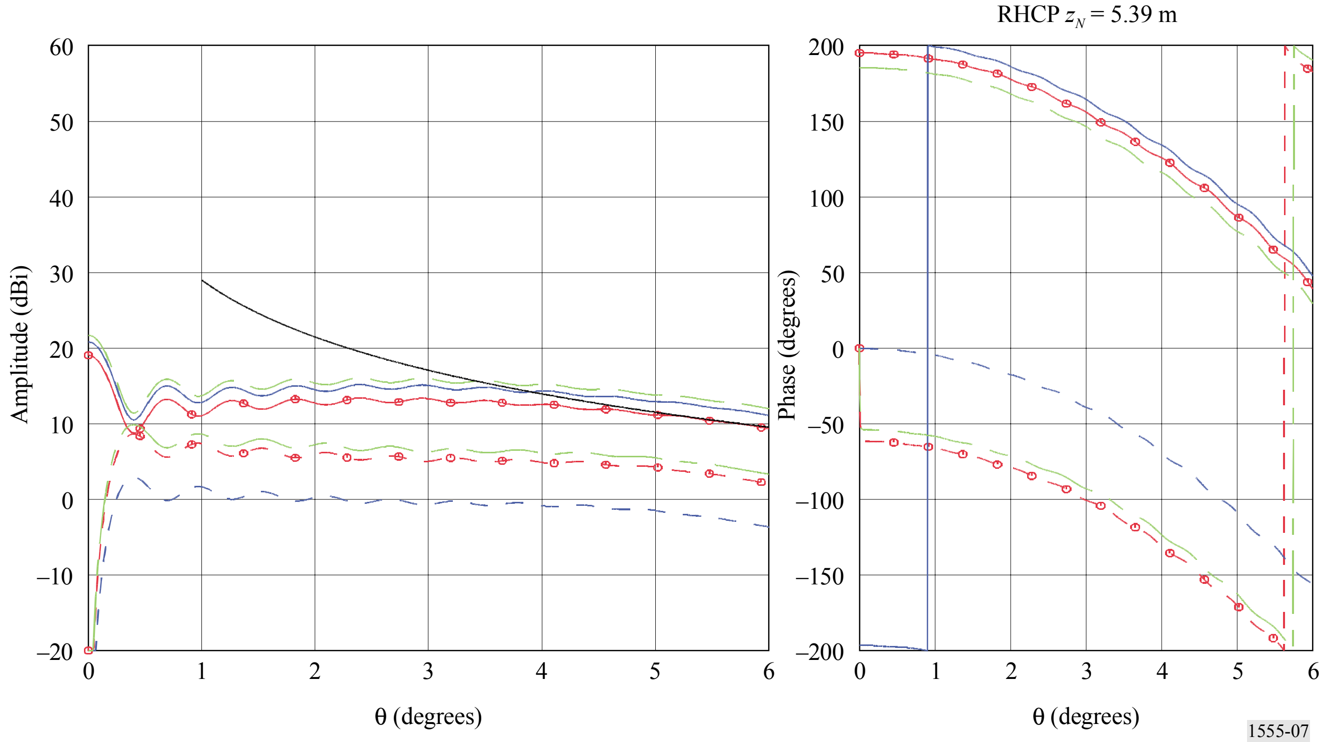


FIGURE 7

Co-polar and cross-polar components from 6 cm circular, 6 cm square and 6 cm/12 cm rectangular struts in plane φ = 0°. Strut angle with aperture plane is α = 45°

(D = 9.5 m, d = 1.22 m, 6.425 GHz)



3 Conclusions

Appendix 1 to Annex 1 indicates that the earth station uplink antenna cross-polarization performance could slightly increase the interference level into an LP system from an adjacent dual CP system compared with that from an adjacent co-aligned dual LP system. The off-axis cross-polarization of the earth station antenna would be a dominant factor in this possible difference.

The practicality to measure the phase relationship between the co-polarized and cross-polarized components, identified as another factor in the possible difference, has been analysed. These analyses conclude that this measurement would be difficult if not impossible to perform. Measurement errors would severely degrade the achievable accuracy. For these reasons the additional studies have concentrated on the analytical approach.

This study investigates the earth station antenna radiation pattern in further detail. In particular scattering in the struts supporting the sub-reflector is identified as a dominant source of cross-polarization in the region 2°-10° from boresight. A simple model for evaluating the co-polarization and the cross-polarization scattering from sub-reflector support struts – including the phase properties – has been developed and validated. It is implemented as a small stand-alone simulation program. Simulations have been performed using this model.

The case of offset-fed reflector antenna has also been considered. When used with CP these antennas have very low cross-polarization. Thus no difference between the interference level into an LP system from an adjacent dual CP system compared with a perfectly co-aligned dual LP system exists in this case.

Extensive studies have been carried on the earth station antenna radiation pattern and the effects that could perturb the cross-polarization performance. For currently available earth station antennas the cross-polarization performance is sufficiently good to dismiss the effects of the phase relationship between the co-polarized and cross-polarized components. Also it is shown that the measurement of this phase relationship is impracticable. It is also one aspect of the issue. An equally important factor is that the same earth station antenna operated with LP can have higher worst case co-polarization side lobes than when operated in CP. The possible increased LP co-polarization side lobes and the possible increased CP off-axis cross-polarization are different manifestations of the same strut scattering problem. The aggregate uplink interference will be no worse for circular than for LP. All the necessary studies on this issue have been performed and the results are conclusive.

The studies conclude that for closely spaced adjacent satellite networks (up to 6° orbital separation) operating in the 6/4 GHz frequency bands with different types of polarization (i.e. CP in one network and LP in the other), when the two networks simultaneously use both orthogonal polarizations co-frequency and co-coverage, the aggregate uplink interference between the networks can be assumed to be identical to the aggregate interference which would occur if both networks used the same types of polarization (i.e. both LP or both CP).

APPENDIX 1

TO ANNEX 2

1 Earth station antenna radiation pattern model

A simple model has been developed for high-efficiency centre-fed dual-reflector antenna systems typically employed as satellite communications earth terminals[5]. It identifies and characterizes the individual contributions. The model includes an accurate diffraction analysis of the strut blockage and all pattern cuts. This is important in the 6/4 GHz band where the dimensions of strut cross sections are comparable to the wavelength. There will be other contributions to cross-polarization, but they will generally be 20-30 dB or more below the corresponding co-polar contributions and will therefore be neglected. Comparisons are made with more accurate analyses by a general reflector antenna analysis software.

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[5] The model is similar to previous models based upon standard aperture field theory, but is extended with a more accurate analysis of the sub-reflector support struts using the so-called induced field ratio (IFR). The strut analysis is simplified to provide closed-form results valid not too far from the earth station antenna boresight. The work is extended to provide phase pattern information and to strut cross sections typically used. Complicated strut cross sections such as space frame structures mainly used only by very large earth station antennas are excluded from the investigation.

1.1 Main reflector and subreflector

This contribution assumes a high-efficiency reflector antenna system in which the sub-reflector and the main reflector are shaped to provide a uniform aperture field illumination. The main reflector diameter and the sub-reflector diameter are termed D and d, respectively.

The sub-reflector contribution is calculated using the standard approximation where the sub-reflector blocks the central part of the main reflector aperture. With this approximation, the blocked part of the main reflector aperture represents lost power. In practical earth station antenna designs, the sub-reflector is often shaped to divert this power to the unblocked parts of the main reflector both to improve the efficiency and to reduce the feed mismatch. Figure 3 shows amplitude and the phase calculated using these standard approximations. The figure on the left-hand side shows the far-field amplitude patterns of the unblocked main reflector aperture in dotted line, the wider sub-reflector blockage pattern in dashed line, and the combined field in full line. The earth station antenna side lobe design goal, $G(\theta) = 29 - 25 \log(\theta)$ dBi, is shown superimposed. In the figure on the right-hand side the lower lobes show the phase of the combined pattern, 0° or 180°. The upper lobes show the phase of the combined pattern calculated by a general reflector antenna software. The more accurate analysis includes a fixed phase offset due to the path length from the feed to the main reflector and a phase change versus angle due to the depth of the main reflector. The simple model assumes a perfect phase centre located at the main reflector apex. Usually, the earth station phase pattern is of no concern and is never measured. The amplitude pattern of the unblocked main reflector and of the combined field calculated by the general reflector antenna software are also shown on the left-hand side figure. But it is very difficult to distinguish the two sets of amplitude patterns from each other.

1.2 Main reflector surface tolerance errors

Reflector surface tolerance can be a potential contributor to co-polar side lobe degradations, but generally not to cross-polarization. Reflectors tend to have surface errors that are correlated with the structural parts such as panels, backing structure and struts. Angular sector panels are popular. This leads to surface errors with a correlation length that is comparable to the reflector diameter. Classical reflector surface tolerance theory predicts a reduction of the nominal gain pattern $g(\theta, \varphi)$ that depends on the r.m.s. surface error ε in wavelengths and a surface error gain pattern that depends upon the r.m.s. surface error and the correlation length c. Figure 4 compares the magnitude of this surface error radiation pattern for an r.m.s. error of 0.5 mm and a correlation length of half the main reflector diameter D at 6.425 GHz in dotted line and at 14.5 GHz in dashed line with the side lobe recommendation. The corresponding on-axis gain losses are 0.08 and 0.4 dB. An r.m.s. error of 0.5 mm is a high accuracy for reflector diameter of almost 10 m. It will not cause significant side lobe problems in the 6/4 GHz band even in the case where azimuthal surface errors due to a large number of radial sector panels have a smaller correlation length and the surface error pattern is shifted away from boresight. The trend is to improve the surface accuracy so that no on-site reflector surface adjustments are required (at least in the 6/4 GHz band).

2 Strut scattering

This Appendix assumes that four struts in quadripod arrangement support the sub-reflector. The quadripod structure is not a circular symmetric structure and will scatter the field in a complicated way. In certain far-field regions, the strut scattering is the dominant field component, and it can generate a significant amount of cross-polarization. In the 6/4 GHz band where the strut cross section may be comparable to the wavelength the usual null-field approximation cannot be used. For such cases, the IFR hypothesis applies. The currents on a strut are approximated by the currents that would flow on an infinite cylinder with the same cross section as the strut and illuminated by an infinite plane wave with the same polarization and direction of incidence as the ray incident locally on the strut. The IFR method modifies the forward scattering properties of the struts and includes polarization effects. It is considered to be an excellent approximation up to at least 15°-20° from the antenna boresight.

In the region not too far away from the antenna boresight, the forward scattering from the struts may be expressed essentially in closed form using a simple forward scattering pattern for each strut with separate terms for the co-polarized and the cross-polarized strut components. For the linearly polarized case with the polarization alignment angle φ_p, the co-polarized and cross-polarized components of the strut scattering from N struts located at the angles φ_n are:

$$f_{sN}^{LP,co}(\theta,\varphi) = \sum_{n=1}^{N} f_s(\theta,\varphi-\varphi_n)\exp(j\Phi(\theta,\varphi-\varphi_n))\left[IFR_M + IFR_D\cos(2(\varphi_n-\varphi_p))\right] \tag{23}$$

and

$$f_{sN}^{LP,cross}(\theta,\varphi) = \sum_{n=1}^{N} f_s(\theta,\varphi-\varphi_n)\exp(j\Phi(\theta,\varphi-\varphi_n))\,IFR_D\sin(2(\varphi_n-\varphi_p)) \tag{24}$$

where:

$$f_s(\theta,\varphi') = \frac{4w}{\pi D}\,\frac{\sin(k(D-d)(\sin\theta\cos\varphi' + (1-\cos\theta)\,\mathrm{tg}\,\alpha)/4)}{\sin\theta\cos\varphi' + (1-\cos\theta)\,\mathrm{tg}\,\alpha}, \tag{25}$$

$$\Phi(\theta,\varphi') = k\,\frac{D+d}{4}(\sin\theta\cos\varphi' + (1-\cos\theta)\tan\alpha) - k(1-\cos\theta)\left(z_N + \frac{d\tan\alpha}{2}\right), \tag{26}$$

$$IFR_M = \frac{IFR_E + IFR_H}{2} \tag{27}$$

and

$$IFR_D = \frac{IFR_E - IFR_H}{2}. \tag{28}$$

and D is the main reflector diameter, d the sub-reflector diameter, w the strut width, and $k = 2\pi/\lambda$ the wave number. The co-polarized and cross-polarized components for the circular polarized cases are:

$$f_{sN}^{CP,co}(\theta,\varphi) = \sum_{n=1}^{N} f_s(\theta,\varphi-\varphi_n)\exp(j\Phi(\theta,\varphi-\varphi_n))\, IFR_M \tag{29}$$

and

$$f_{sN}^{CP,cross}(\theta,\varphi) = \sum_{n=1}^{N} f_s(\theta,\varphi-\varphi_n)\exp(j\Phi(\theta,\varphi-\varphi_n))\, IFR_D \exp(\mp j2\varphi_n), \tag{30}$$

where the upper sign applies to RHC polarization and the lower sign to LHC polarization. The CP expressions are slightly simpler than the LP expressions, equations (23) and (24), and the differences are discussed in the following sections. The strut element pattern, equation (25), is determined as an integral over the projection of the strut in the main reflector aperture plane. The pattern takes into account the angle α the support struts form with the aperture plane so that the peaks of the radiated strut fields occur on diffraction cones, one for each strut.

The diffraction cone of a strut has its axis along the strut and the half angle equal to α. Near antenna boresight, the cone can be approximated by the plane through boresight perpendicular to the projection of the strut, and the scattering from two opposing struts add. The strut width w is assumed to be small so that the radiation from the strut is omni-directional in the perpendicular plane not too far from boresight. The strut scattering pattern is very narrow in the plane of a strut, $\varphi = \varphi_n$, where the first-null-to-first-null width is only a few degrees.

The first term of the strut element-pattern phase, equation (26), can vary very rapidly. But it will vary slowly near the strut scattering peaks and equal to zero on the peak. The parameter z_N in the second phase term is the height of the strut attachment to the sub-reflector rim from the plane containing the main reflector apex. The mean and the difference IFR, equations (27) and (28), replace in the LP and CP field expressions the IFR_E for the electric field vector parallel to the strut axis and IFR_H for the magnetic field vector parallel to the strut axis. Exact solutions for the IFRs exist for the circular cylinders. Otherwise, two-dimensional integral equations must be solved.

3 Discussion of strut scattering

Some earth station antenna designs have their support struts attached to the main reflector well inside the rim. Then, the integration over the strut projections in the main reflector aperture implied in equation (25) should not be extended to the main reflector rim. On the other hand, the blockage by the struts of the sub-reflector field illuminating the main reflector must be added. This so-called spherical-wave blockage is more complicated to analyse accurately. The dominant contribution to this scattering is similar to the plane-wave strut scattering calculated by equations (23) to (30), with changes that depend upon the actual antenna geometry. To avoid this complication, the integration to the main reflector rim in equation (25) was retained combining the plane-wave and the spherical-wave strut scattering contributions. A comparison of LP equations (23) and (24) with the CP equations (29) and (30) shows an important difference between LP and CP. Neglecting the influence of the strut element pattern, the LP co-polarization, equation (23), has an azimuthal variation depending on the IFR difference, IFR_D, between the two linear polarizations whereas the

CP co-polarization equation (29) depends only upon the average IFR_M of the two linear polarizations. At CP, the LP term with co-polarization azimuthal variation is part of the cross-polarization equation (30). Thus, the field addition of the interference contributions, that is suppressed for CP if the phase angles δ_R and δ_L of Annex 1 are equal to ±90°, is an inherent property of the LP co-polarization in equation (23).

Currently available earth station antenna designs have their struts aligned with the ±45° planes where the element pattern of the adjacent struts in the quadripod arrangement are identical, and the cosine term of equation (23) and both the LP and the CP cross-polarization, equations (24) and (30), cancel. Otherwise in the LP case with the polarization parallel or perpendicular to the strut projection, the ±45° planes would be the planes of peak strut cross-polarization. Under normal operating conditions, the geostationary arc should be aligned with the 0° pattern plane considerably favouring the quadripod strut arrangement over the tripod arrangement where one strut would tend to be perpendicular to the geostationary arc.

The model described here has been derived from fields projected into the main reflector aperture and predicts slow phase variations of the significant pattern contributions near the antenna bore-sight. This indicates that the main antenna performance will not be very sensitive to dimensional tolerances which may be unexpected in view of the very large antenna structures in terms of wavelengths typically involved.

4 Typical 6/4 GHz frequency band examples including strut scattering

Figure 5 shows the scattering from a strut quadripod arrangement in the plane containing one of the strut pairs. The reflector dimensions are main reflector diameter $D = 9.5$ m, f/D ratio 0.5, and sub-reflector diameter $d = 1.22$ m. The diameter of the circular struts is 6 cm, the polarization circular, and the frequency 6.425 GHz. The struts are assumed to be located in an aperture plane through the primary focus. Actual earth station antenna struts may be thicker than 6 cm [6]. The figure on the left-hand side shows the amplitude of the co-polar and the cross-polar strut scattering calculated by equations (29) and (30), and by a general reflector antenna software. This software also uses the IFR approximation, but more accurately calculates the field incident on the struts and numerically integrates the strut currents along each strut, as it is located in space. The small circles indicate the results obtained with the general software. There is no significant difference between the two sets of co-polar fields shown in full line and cross-polar fields shown in dotted line. The recommended side lobe template is indicated for reference. The co-polar strut scattering intersects the template at about $\theta = 4°$. It should be borne in mind that outside the plane of Fig. 5, the strut scattering will drop to much lower levels within less than 1°. Nevertheless, Fig. 5 illustrates

[6] Large earth station antennas may have huge struts: a 34 m Cassegrain antenna is reported to have three 10 cm by 76 cm struts including a triangular roof and a sawtooth plate to scatter wide-angle strut radiation. A larger 36.6 m Cassegrain antenna with a 2.8 m sub-reflector has four 12.7 cm by 53.3 cm struts.

that even for small strut cross sections there are regions of space close to the main beam where the strut scattering is the dominant field contribution. In these limited regions of space, it may not be possible to meet the recommended side lobe envelope, and, as will be shown in the next section, dual LP systems will be more gravely affected than dual CP systems. The right-hand side plot shows the corresponding pattern phases. As in Fig. 3, there is a fixed phase offset because the simple model neglects the path length *kf* from the feed to the main reflector apex. Both for the simple model and the general software, the cross-polar strut scattering leads the co-polar strut scattering by about 130° where ±90° would have been desired.

Figure 6 is a repeat of Fig. 5 except that the struts now form angles α of 45° with the main reflector aperture and attach to the sub-reflector rim at the location of the primary focus. The struts intersect the main reflector surface inside the rim, but are allowed to continue in order to account for the spherical-wave strut scattering. The results are very similar to those of Fig. 5 supporting the comment at the end of Section 3 that the model is not very sensitive to the precise strut locations. The strut tilt angle causes a break-up of the scattering from the strut pair perpendicular to the paper plane into two separate cones so that the strut scattering decreases slowly as θ increases and remains below the side lobe template. The phase variation is slightly slower than in Fig. 3, but the 130° phase advance is retained.

The left-hand side plot of Fig. 6 shows the total field calculated by the model in full line and by the general reflector antenna software in full line with small circles. For the sake of the general reflector antenna software, the struts have been moved slightly forward so that they do not intersect the main reflector surface. The main reflector field, the sub-reflector blockage pattern, and the strut co-polarization and cross-polarization are indicated by various dotted and dashed lines. There is a good agreement between the two total fields in full line up to about $\theta = 4°$ where the assumption of a flat main reflector implied in the aperture model is no longer valid. For larger angles θ, the main reflector radiation appears to emanate from the rim region which is located about 1.2 m above the main reflector apex. The right-hand side plot compares the phase of the total field calculated and the strut cross-polarization calculated by the general reflector antenna software. Beyond $\theta = 4°$, the main reflector radiation peaks and the co-polar strut radiation are comparable in magnitude and in phase quadrature so that the pattern nulls are completely filled. Patterns like this are typical for reflectors with struts in the (E-)plane perpendicular to a strut. The preferred solution is to operate the earth station antenna with no strut perpendicular to the geostationary arc. Then the problem is completely avoided. Figure 7 compares the worst-plane strut co-polarization and cross-polarization for quadripod arrangements with three different strut cross sections:

– circular struts with diameter 6 cm (full and dotted line with small circles),

– square struts width side length 6 cm (full and dotted line with small circles), and

– rectangular 6 cm by 12 cm struts with the narrow side facing the main reflector (dashed and dash-dot line).

The square and the rectangular struts have a higher scattering than the circular struts. However, a fairer comparison may have been between struts of the same cross sectional area. The square cross section has the lowest cross-polarization, but its phase is less desirable. As the height of rectangular struts increases, the cross-polarization level increases as well. There is some indication that triangular struts – in particular with the base pointed towards the main reflector – can have excellent RF properties with respect to cross-polarization and antenna temperature.

4.1 Worst-case comparison between uplink strut interference from dual LP and dual CP system

We consider a quadripod strut arrangement with the worst possible alignment with the geostationary arc. We assume circular struts with a diameter of 6 cm, a frequency of 6.4 GHz and that the strut scattering in the vertical pair of struts is the dominant contribution. Approximate values of the IFRs are $IFR_E = -1.22 + j\,0.22$ and $IFR_H = -0.78 - j\,0.22$.

In the dual LP case, the incident electric field vectors are assumed to be aligned with the struts and the scattering fields will be proportional to IFR_H and IFR_E, i.e., $E_{HH} \propto IFR_H$, $E_{HV} = 0$, $E_{VV} \propto IFR_E$ and $E_{VH} = 0$. The scattering from the earth station struts into the HP and VP ports are then proportional to $|E_{HH}|^2 + |E_{VH}|^2 \propto |IFR_H|^2 = 0.66$ and $|E_{VV}|^2 + |E_{HV}|^2 \propto |IFR_E|^2 = 1.54$.

For the dual CP case, the corresponding fields scattered in the struts are proportional to $E_{RH} \propto 1/\sqrt{2}\ IFR_H$, $E_{RV} = -j/\sqrt{2}\ IFR_V$, $E_{LH} \propto 1/\sqrt{2}\ IFR_H$ and $E_{LV} = j/\sqrt{2}\ IFR_H$. The scattering from the earth station struts into the satellite horizontal and vertical polarization ports are then proportional to $|E_{RH}|^2 + |E_{LH}|^2 = |E_{RH}|^2 + |E_{LH}|^2 \propto 1/2|IFR_H|^2 + 1/2|IFR_E|^2 = 1.10$.

The dual CP earth station strut scattering gives identical interference into the two ports of the LP satellite antenna. The dual LP earth station strut scattering into the LP satellite results in one worst-case and one best-case satellite antenna receive port. The average strut interference is equal to that of the adjacent dual CP system. The worst-case port degradation from an adjacent dual LP system is 1.46 dB compared to the average interference. The problem of the adjacent dual LP system arises because the strut scattering in the case considered only affects the copolar fields where it adds on a field level on not on a power level. For the cases considered in Annex 1, the field addition only occurs for adverse combinations of co- and cross-polarization antenna phase patterns.

5 Possibility of measuring of the phase relationship between the co-polarized and the cross-polarized components

The cross-polarization levels that would have to be measured are low compared to the peak co-polar level of the antenna. The antenna is large both physically and in terms of the wavelength. A large measurement distance, at least $2D^2/\lambda$ or about 3.5 km for a 9 m antenna at 6.4 GHz, would be required. Measurement errors such as ground reflections would severely degrade the achievable accuracy of, in particular, phase measurements. No suitable near-field range of the size required is readily available. It does not appear to be practical to use a satellite for phase pattern measurements. New, accurate phase pattern measurement techniques for large antenna systems would have had to be developed. For these reasons, the selected analytical approach was preferred as it also was expected to yield more insight into the physical nature of the effect.

We consider that a stand-alone measurement program could generate more questions than answers. The results obtained could be specific to the antennas measured and not of general validity.

6 Other types of earth station antennas (offset-fed reflector antennas)

Large satellite earth terminals are generally centre-fed dual reflector antenna systems. VSAT terminals use smaller offset-fed reflector antenna systems. Offset-fed reflector antennas benefit from having no blockage and do not suffer from the possible problems addressed above. For LP, the offset geometry degrades the XPD. No cross-polarization degradations occurs for CP, but the beam is squinted to the right for RHC polarization and to the left for LHC polarization.

The opposite situation to some extent exists for centre-fed reflector antennas with narrow struts and for offset-fed reflector antennas with respect to LP and to CP:

– The centre-fed reflector does not suffer from cross-polarization degradations for LP perpendicular or parallel to the struts, but the co-polarized performance is degraded when the polarization is parallel to a strut. For CP and for LP where the polarization vector forms an oblique angle with a strut, both the co-polarization and the cross-polarization are degraded.

– The offset-fed reflector does not suffer from cross-polarization degradations for CP, but the co-polarization beam is squinted in opposite directions for the two senses of CP. For LP, the cross-polarization performance is degraded.

These antennas have very low cross-polarization in the CP case. Thus, there can be no increase of the aggregate interference level into an LP system from an adjacent CP system compared to that from a perfectly aligned LP system.

ANNEX 3

Interference between closely spaced dual polarized satellite networks operating in the 6/4 GHz frequency bands when the magnitude of the two orthogonally polarized signals of the interfered with and/or the interfering networks are unequal (unbalanced case)

1 Scope

This annex details the results of simulations performed to assess the difference between the interference levels caused to a dual linearly polarized network by an adjacent dual linearly polarized network and an adjacent dual circularly polarized network when the magnitude of the two orthogonally polarized signals of the interfered with and/or the interfering networks are unequal (unbalanced case). The unbalanced case may occur in practice when the interfered with and/or the interfering network transmit high power density carriers on one polarization and low power density carriers on the other polarization.

2 Analysis

The generic vector equations defined in Annex 1 to this Recommendation have been used to assess the level of the incident electric field vectors at the uplink and downlink antenna output ports. Various cases of difference in the magnitude of the signals of the interfered with and/or the interfering networks have been considered. The assumptions used in these simulations correspond to typical values of earth stations and satellites operating in the 6/4 GHz bands and are summarized in Table 2.

TABLE 2

Analysis parameters

Spacecraft orbital separation(1) (degrees)	2
Uplink centre frequency (GHz)	6.175
Downlink centre frequency (GHz)	3.950
Ground station antenna diameter (m)	4.5
Ground station antenna gain (dB)	$[20 \log_{10}(\pi D/\lambda)] - 1.5$
XPD (aggregate of transmit and receive antennas) (dB)	28
Ground antenna co-polarization side lobe pattern (dBi)	$29 - 25 \log \theta$
Ground antenna cross-polarization side lobe pattern (dBi)	$19 - 25 \log \theta$

(1) The actual topocentric orbital separation between the space stations as seen from the ground station has been considered to be 2.2º.

Two cases were considered:

– Firstly, the case where the magnitude of the two orthogonally polarized signals of the interfered with network and of the interfering network are unequal.

– Secondly, the case where only the magnitude of the two orthogonally polarized signals of the interfered with network are unequal.

For both cases, the polarization of the interfered with network is assumed linear and the interference levels were calculated for both a dual linearly and a dual circularly polarized interfering network. The interference level has been assessed with respect to the lowest magnitude signal of the interfered with network. When the magnitude of the two orthogonally polarized signals of both the interfered with and the interfering network have been assumed unequal and it has been considered that the polarization of both networks are linear, it has been assumed that the signal with the lowest magnitude was on the same polarization in both networks. The interference level has been calculated for the uplink and the downlink separately.

3 Results

The simulation results are shown graphically in Figs. 8 to 11 below.

FIGURE 8

Aggregate uplink carrier-to-interference (*C/I*) ratios caused to a dual linearly polarized network by an adjacent dual linearly polarized network and an adjacent dual circularly polarized network when the magnitude of the two orthogonally polarized signals of both the interfered with and the interfering networks are unequal

(Unbalanced wanted and interfering uplink networks)

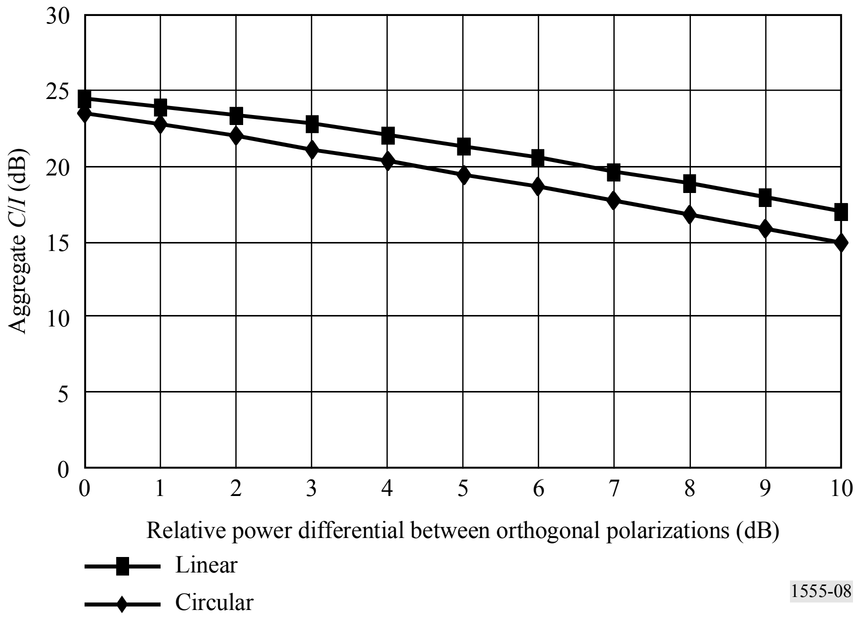


FIGURE 9

Aggregate downlink *C/I* ratios caused to a dual linearly polarized network by an adjacent dual linearly polarized network and an adjacent dual circularly polarized network when the magnitude of the two orthogonally polarized signals of both the interfered with and the interfering networks are unequal

(Unbalanced wanted and interfering downlink networks)

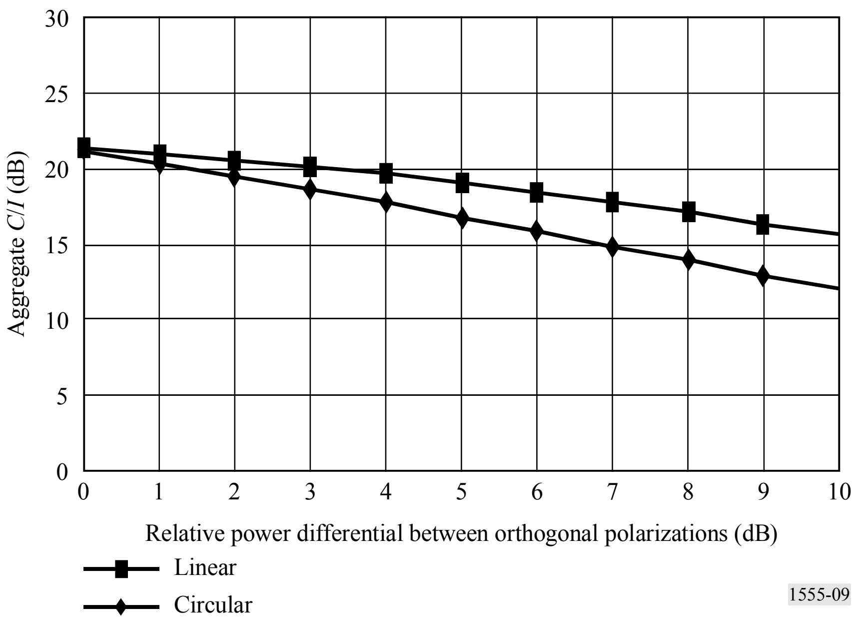


FIGURE 10

Aggregate uplink *C*/*I* ratios caused to a dual linearly polarized network by an adjacent dual linearly polarized network and an adjacent dual circularly polarized network when the magnitude of the two orthogonally polarized signals of the interfering network are equal and the magnitude of the two orthogonally polarized signals of the interfered with network are unequal

(Uplink unbalanced wanted levels only)

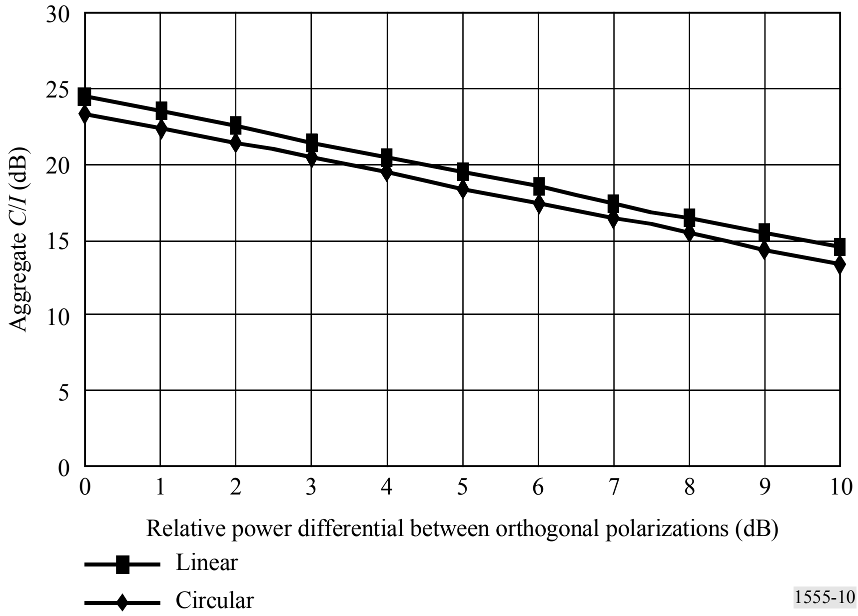
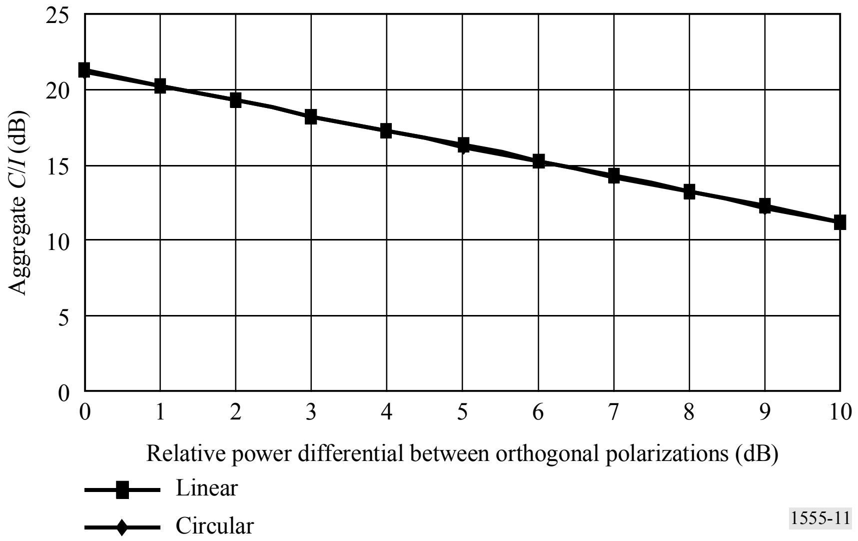


FIGURE 11

Aggregate downlink *C*/*I* ratios caused to a dual linearly polarized network by an adjacent dual linearly polarized network and an adjacent dual circularly polarized network when the magnitude of the two orthogonally polarized signals of the interfering network are equal and the magnitude of the two orthogonally polarized signals of the interfered with network are unequal

(Downlink unbalanced wanted levels only)



Inspection of the results implies the following:

– For the uplink, there is no significant difference between the aggregate interference levels caused to a linearly polarized network by an adjacent linearly polarized network or an adjacent circularly polarized network in all the cases considered.

– For the downlink, there is no significant difference between the aggregate interference levels caused to a linearly polarized network by an adjacent linearly polarized network or an adjacent circularly polarized network, when the magnitude of the two orthogonally polarized signals of the interfering network are equal. This is independent of the relative magnitude of the two orthogonally polarized signals of the interfered with network.

– For the downlink, when there is a difference in the magnitude of the two orthogonally polarized signals of both the interfering network and the interfered with network, there is a difference between the aggregate interference level caused to a linearly polarized network by an adjacent linearly polarized and an adjacent circularly polarized network. The aggregate interference level caused to the lower power signal in the wanted, linearly polarized network by an adjacent circularly polarized network would be higher than the one caused by a linearly polarized network.

In this last case, further simulations have been performed to assess how this difference could be compensated. The transmit power of the circularly polarized interfering network was reduced to cause the same level of interference in the wanted network as for a dual linearly polarized interfering network. This was approached in two ways: firstly, the magnitude of the two orthogonally polarized signals of the circularly polarized interfering network were both reduced maintaining the same relative power differential as the two polarizations on the interfered with network. Secondly, the magnitude of both signals in the interfering network was reduced equally, maintaining the same power level on both polarizations. The required reduction in transmit power versus the relative power differential of the two orthogonally polarized signals is shown graphically in Fig. 12.

4 Conclusion

By applying the equations developed previously, the relative interference caused by a dual circularly and dual linearly polarized interfering network to a dual linearly polarized network has been assessed. For all cases, except for the downlink when both wanted and interfering networks are operating with differential powers between their two orthogonal polarizations, it has been shown that there is little or no difference to the level of interference caused. For that one case it has been shown that the interference caused by the circularly polarized network can be restored to the same level as for a linearly polarized interfering network by reducing the transmit power of the two signals of the interfering network. This reduction can be implemented whilst either maintaining the same relative power differential between the two orthogonally polarized signals of the interfering network as for the interfered with network, or with equal powers on the two polarizations of the interfering network.

FIGURE 12

Required reduction in transmit power versus the relative power differential of the two orthogonally polarized signals to cause the same level of interference in the wanted network as for a dual linearly polarized interfering network