

Cross-polarisation discrimination-induced interference in dual-polarised high-capacity satellite communication systems

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Abstract: The design of spectrally-efficient, high-throughput satellite (HTS) systems with capacity approaching one terabit per second requires operating at Ka-band frequencies and above, where there are several gigahertz of allocated radio spectrum, using multiple spot beams with dual orthogonal polarisation mode. At these high frequencies, rain attenuation poses a major obstacle to the design of high-availability satellite links which are needed for the realisation of ubiquitous broadband multimedia communication services including high-speed Internet access at rural and remote locations. Furthermore, depolarisation-induced interference in such systems could have a performance-limiting impact if a co-channel cross-polar signal combines with system noise to drive the carrier-to-noise-plus-interference ratio (CNIR) below an acceptable threshold. This paper employs real measurement data to investigate the impact of depolarisation-induced interference on dual-polarised HTS systems for temperate and tropical climatic regions. Scenarios that cause significant system performance degradation are analysed, including the effects of signal frequency, antenna size, and regional rainfall rate. The impact of depolarisation on system performance is quantified by the reductions in the CNIR and link availability of a dual-polarised system when compared with those of a similarly-dimensioned single-polarised system.

1 Introduction

Satellite communication systems are an indispensable means of providing telecommunication services to large geographical areas, difficult terrain, and locations where conventional terrestrial communication infrastructures are not suitable. The proliferation of new applications and services in the terrestrial telecommunication sector, together with the evolution in related technologies, has translated into a manifest surge in demand for satellite communication applications and services. These advances have brought satellite communication systems to the forefront in terms of providing much-needed broadband and Internet services. This situation has stimulated the emergence of high-throughput satellite (HTS) systems, advancing toward terabits/second capacity, in order to cope with steadily increasing user-demand.

To enhance capacity in satellite systems, several issues have to be contended with – especially the orbital and spectral congestion in the legacy frequency bands allocated for satellite services. This has necessitated a gradual transition to the use of higher frequencies such as the Ka (20/30 GHz) and *Q/V* (40/50 GHz) bands in order to exploit the large capacity these spectral segments offer. To achieve even more capacity, various frequency reuse techniques such as spatial isolation (SI) and dual orthogonal polarisation (DOP) have been adopted for use in the design of the latest operational and proposed future HTS systems [1].

Notwithstanding the anticipated capacity benefit the transition into the higher frequency bands could offer, systems operating above 10 GHz are adversely affected by atmospheric propagation impairments. These propagation effects degrade the transmitted signal, with consequent impact on the quality of service (QoS) and link availability. Most prominent amongst these atmospheric factors are the rain attenuation and the interference induced by hydrometeor (mainly ice and rain) depolarisation [2]. For systems operating below 10 GHz, rain attenuation is usually very small – even under severe rain conditions. Depolarisation is the most significant propagation impairment of concern in this case [3]. The situation is different for systems operating at higher frequencies: at 30 GHz, rain attenuation is the most

significant propagation impairment. Between these two frequency limits, attenuation and/or depolarisation can be the propagation impairment limiting the system's performance, depending on the frequency, elevation angle, polarisation, and climate [4].

Frequency reuse techniques are employed in order to expand the capacity of communication systems by up to an order of magnitude. Using SI, the available bandwidth is divided into smaller portions which are used repeatedly for sending signals to different locations that are adequately separated [5]. The channels using the same portion of the bandwidth are called *co-channel*, whereas the inherent energy leakage amongst them is referred to as *co-channel interference* (CCI). CCI has been identified as one of the factors which has significant system performance-limiting potential. It is a major issue to be addressed in HTS system design [6–10]. Systems that reuse frequency by adopting DOP transmission are prone to system- and medium-induced depolarisation, which introduces interference power into the corresponding orthogonal channel, with consequent effects on system performance [11]. Atmospheric depolarisation occurs when some of the power transmitted in the desired polarisation (the co-polar signal) is converted into the undesired, orthogonal polarisation (cross-polar signal) as a result of propagation through an anisotropic medium [12].

In this paper, an illustrative analysis of the impact of depolarisation on the performance of dual-polarised satellite communication systems is presented. The analysis utilises a database of Ka-band satellite beacon attenuation measurements recorded at the University of South Wales (USW) in Pontypridd, United Kingdom. To also determine the impact of depolarisation on similar systems in tropical locations, a hypothetical analysis, based solely on the ITU-R model [13], was undertaken for Lagos, Nigeria. This paper further extends the investigation to the uplink, so as to determine the influence of depolarisation on the overall carrier-to-noise-plus-interference ratio (CNIR_o). In addition, the impact of the increase in received system noise power due to rain (ΔN_{rain}) on the downlink in the tropical region is considered. The analysis incorporates the effect of antenna sizes on link performance, so as to provide a guide for link design and dimensioning.

The remainder of this paper is organised as follows: in Section 2, the theoretical basis of hydrometeor depolarisation is presented. Satellite link measurements and data extraction are summarised in Section 3. The effect of antenna inherent cross-polarisation isolation (XPI) is discussed in Section 4. The method of estimating CCI due to depolarisation is presented in Section 5. The results from simulation of satellite communication links in the temperate and tropical locations are discussed in Section 6. Finally, Section 7 concludes this paper.

2 Hydrometeor depolarisation

The extent of hydrometeor depolarisation depends on the link frequency [gigahertz (GHz)], path elevation angle (degrees), and the co-polar rain attenuation [decibels (dB)] that occurs concurrently due to the same rain event. It also depends on the polarisation tilt angle, τ (degrees) of the linearly polarised electric field vector, which describes its orientation with reference to the local horizontal at the Earth-station, and is given by [12]

$$\tau = 90^\circ - \tan^{-1} \left(\frac{\tan(L_e)}{\sin(l_s - l_e)} \right) \quad (1)$$

where L_e is the Earth-station latitude ($^\circ\text{N}$), l_e is the Earth-station longitude ($^\circ\text{E}$), and l_s is the sub-satellite point longitude ($^\circ\text{E}$).

It is well known that, in dual-polarised satellite communication systems, the XPI level is the measure used to determine the degree of interference. It compares the co-polarised power with the cross-polarised power received in the same polarisation state. However, the cross-polarisation discrimination (XPD) is representative of the XPI for all practical purposes. The XPD for linearly polarised waves, for both vertical (E_1) and horizontal (E_2) directions, is defined by [3]

$$\text{XPD}_{1,2} = 20 \log_{10} \left(\frac{E_{11,22}}{E_{12,21}} \right) \text{ dB} \quad (2)$$

$E_{11,22}$ are the co-polar received electric field vectors, whereas $E_{12,21}$ are the corresponding cross-polar received vectors. Fig. 1 illustrates the depolarisation principle.

3 Experimental satellite link measurements and data extraction process

The experimental data used in this paper were recorded at Pontypridd in South Wales, United Kingdom (latitude 51.59°N , longitude 3.33°W) along an Earth-space path of elevation 29.30° to the Eutelsat Hot Bird 13 A (formerly Hot Bird 6) satellite

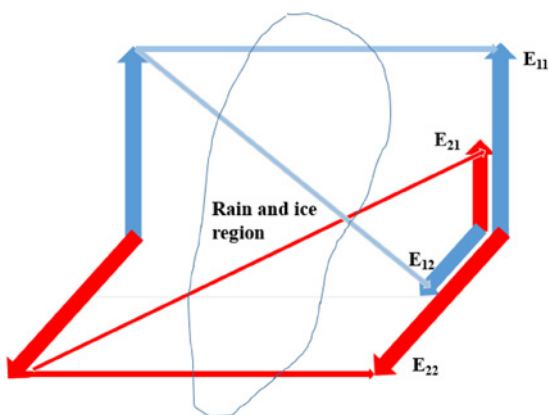


Fig. 1 Depolarisation component of linearly polarised waves

located in geostationary orbit at 13.0°E . The received signal strength (dBm) of a 19.7 GHz beacon transmitted on Eutelsat's downlink was recorded at five samples per second over a three-year period (July 2010–July 2013) (Fig. 2). The 19.7 GHz beacon was received through a Gregorian-type antenna of 1.2 m diameter mounted on a roof at 86 m above mean sea level. Full details of the installation are presented in [14].

The output signal of the receive antenna was fed into a low-noise block (LNB) which accepts signals of a specific polarisation and down-converts them from 19.7 GHz to an intermediate frequency (IF) of 1.451 GHz. This first IF output from the LNB is fed via a multiplexer to a further down-converter which produces a second IF frequency of 70 MHz. This second IF output is then connected to a tracking receiver, which follows the Doppler-shifted satellite beacon signal carrier frequency and measures its amplitude.

Many propagation and non-propagation effects contribute to variations in the recorded beacon signal level (or raw data). Changes in the received beacon signal level can be caused by atmospheric effects, diurnal variations due to satellite movements in geostationary orbit, thermal shifts, and power fluctuations. To remove the diurnal variation from the recorded beacon data, a reference level, known as the 'zero dB reference', has been set. This reference level is used to extract the total attenuation, which includes scintillation, gaseous, cloud, rain, and other atmospheric attenuation components. The resulting total attenuation time-series (expressed in dB) is processed to exclude scintillations by passing the data through a fifth-order Butterworth low-pass filter with a cut-off frequency of 0.04 Hz. The meteorological data simultaneously measured at the receiving station are used in conjunction with the ITU-R P.676 model [15] to generate gaseous attenuation time-series containing 86,400 samples per day. Finally, rain attenuation is extracted from the smoothed total attenuation time-series by subtracting the gaseous attenuation time-series. The extracted measured rain attenuation time-series at 19.7 GHz is then scaled to produce a corresponding time-series of rain attenuation at 30 GHz by using [13].

Collectively, these data provide a reliable estimation of the instantaneous propagation conditions and carrier-to-noise ratio (CNR) on the Ka-band beacon downlink and uplink. The cumulative distribution of the measured data was used as the accompanying co-polar rain attenuation, A_{rain} , from which to compute the strength of the contemporaneous depolarisation-induced interference power using the ITU-R depolarisation model.

The ITU-R model [13] provides a method for deriving the long-term statistics of hydrometeor-related depolarisation interference due to atmospherically induced XPD. Figs. 3 and 4 illustrate the dependence of atmospheric XPD, denoted XPD_{atm} , on

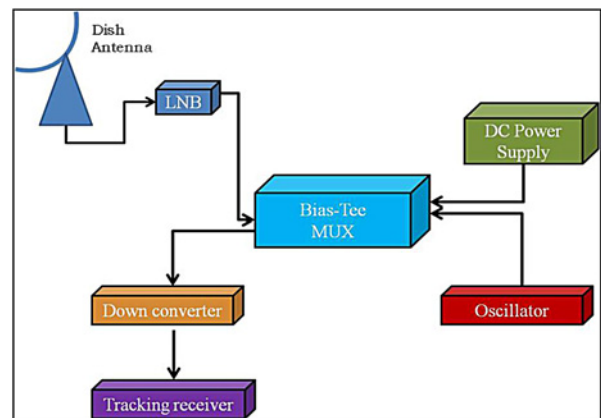


Fig. 2 Block diagram of satellite beacon receiver system

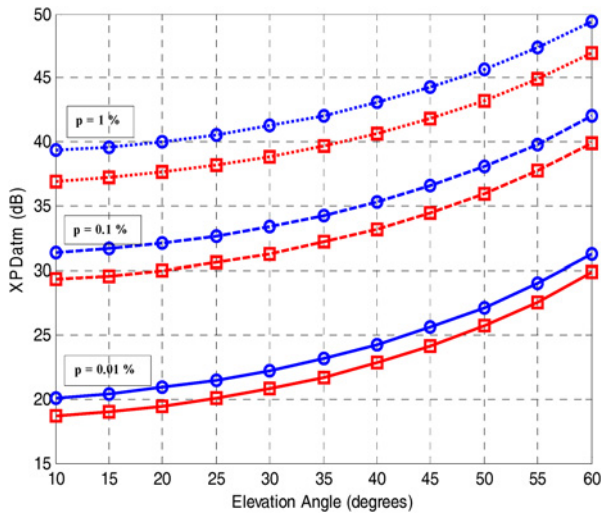


Fig. 3 Dependence of 30 GHz (squared lines) and 19.7 GHz (circled lines) links XPD_{atm} on elevation angle for 0.01% (solid lines), 0.1% (dashed lines), and 1% (dotted lines) of time [tilt angle = 7.59°]

path elevation and polarisation tilt angles, respectively, at various time-percentages, p (%). Fig. 3 shows that, for a fixed polarisation tilt angle, XPD_{atm} improves with increasing elevation angle, whereas Fig. 4 shows that, for a fixed elevation angle, XPD_{atm} decreases with increasing polarisation tilt angle. The XPD_{atm} values for polarisation tilt angles in the range 45°–90° can be obtained by noting that the curves are symmetrical about the value $\tau = 45^\circ$.

4 Effect of antenna imperfections

Real antennas have finite XPI. Therefore, the Earth-station and satellite antenna XPDs (XPD_{es} and XPD_{sat}), of typical values 30 and 25 dB, respectively [16], must be combined with XPD_{atm} in order to ascertain their overall impact. The combination is carried out using (3) for the best-case (XPD_{bc}), where the cross-polar fields are incoherent. This assumes that there is no phase correlation between the respective interfering signal components arising from each XPD term [11]. Equation (4) represents the worst-case combination (XPD_{wc}), where the cross-polar fields are added in-phase [17]. In this paper, both the best- and worst-case analyses are carried out

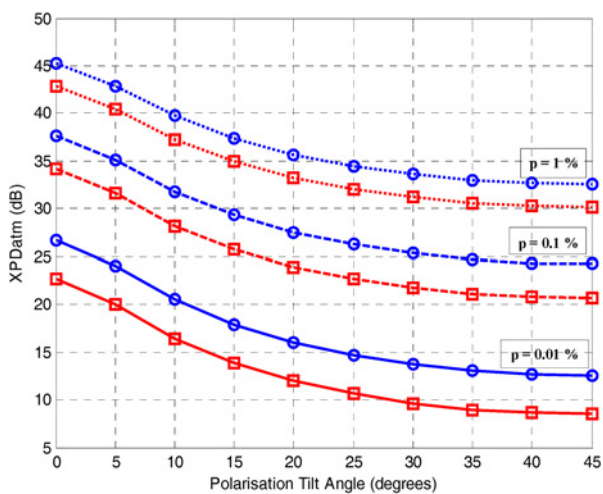


Fig. 4 Dependence of 30 GHz (squared lines) and 19.7 GHz (circled lines) links XPD_{atm} on polarisation tilt angle for 0.01% (solid lines), 0.1% (dashed lines), and 1% (dotted lines) of time [elevation angle = 29.30°]

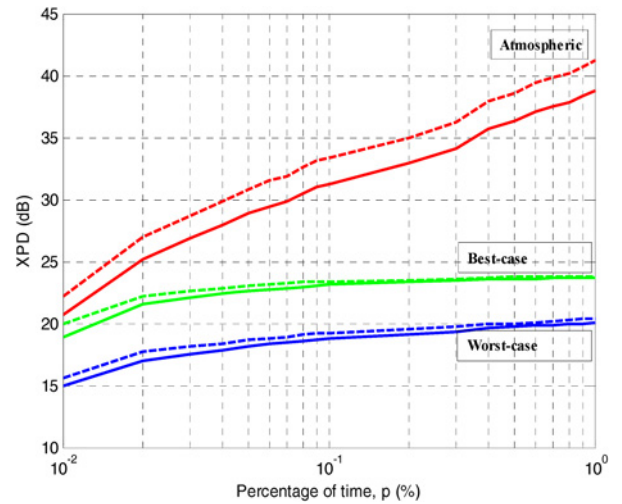


Fig. 5 Temperate location: 30 GHz (solid lines) and 19.7 GHz (dashed lines) links XPD_{atm} , XPD_{bc} , and XPD_{wc} at various percentages of time, p [tilt angle = 7.59° and elevation angle = 29.30°]

and compared

$$XPD_{bc} = -10 \log_{10} \left(10^{-(XPD_{atm}/10)} + 10^{-(XPD_{es}/10)} + 10^{-(XPD_{sat}/10)} \right) \text{ dB} \quad (3)$$

$$XPD_{wc} = -20 \log_{10} \left(10^{-(XPD_{atm}/20)} + 10^{-(XPD_{es}/20)} + 10^{-(XPD_{sat}/20)} \right) \text{ dB} \quad (4)$$

Fig. 5 compares XPD_{atm} with XPD_{bc} and XPD_{wc} as a function of p for the Pontypridd measurement data. It can be observed that, for the 19.7 GHz link at $p = 0.01\%$, the antennas imperfection contributes 2.5 dB reduction in XPD for the best-case, whereas the worst-case causes a 6.5 dB reduction. For the 30 GHz link, the XPD is further reduced by 1 dB in both cases. While the XPD_{atm} of both links show significant improvement with increasing p , the

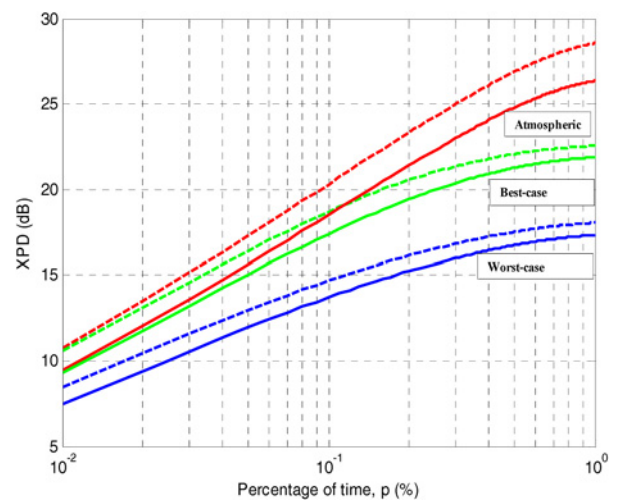


Fig. 6 Tropical location: 30 GHz (solid lines) and 19.7 GHz (dashed lines) links XPD_{atm} , XPD_{bc} , and XPD_{wc} at various percentages of time, p [tilt angle = 76.29° and elevation angle = 30.0°]

improvement of XPD_{bc} and XPD_{wc} are less significant, indicating that antenna depolarisation dominates over atmospheric depolarisation in such situations. The result also shows a 4 dB difference between XPD_{bc} and XPD_{wc} .

Fig. 6 presents the result of a similar analysis for a tropical region, using [13]. It can be observed that the difference between XPD_{atm} and XPD_{bc} for both links up to $p=0.02\%$ is not significant, whereas a 2.5 dB difference is observed with respect to XPD_{wc} at $p=0.01\%$. However, the difference between XPD_{atm} and XPD_{bc} becomes more obvious with increasing p . The results also indicate that, at higher values of p , XPD_{atm} improves significantly as compared with both XPD_{bc} and XPD_{wc} which are limited by the effect of the antennas' imperfections. In terms of the variation in XPD with link operating frequency, both XPD_{bc} and XPD_{wc} degrade by around 1 dB on changing from 19.7 to 30 GHz, while, for XPD_{atm} , the degradation increases with increasing p from 1 dB up to about 2.5 dB. It is, therefore, clear that, in operational systems with real antennas, the atmospherically induced XPD only contributes to system performance impairment at very low time-percentages.

5 Method of estimating CCI

The noise-like depolarisation-induced CCI power component, $I_{(h, v)}$, [dB watt (W)] introduced into the respective channels, horizontal and vertical, from the orthogonal counterpart is quantified by

$$I_{(h, v)} = P_{rain(v, h)} - XPD_{(v, h)} \text{ dBW} \quad (5)$$

where $P_{rain(v, h)}$ (dBW) is the power received in rain conditions and $XPD_{(v, h)}$ is the XPD in respective orthogonal (vertical and horizontal) channels. Therefore, the total noise power, $n_{I(h, v)}$ (W), in the respective channels is the sum of the thermal noise power received in rain, $N_{rain(h, v)}$ (dBW), and the CCI power component, $I_{(h, v)}$ (dBW), introduced by the corresponding orthogonal channel. The total noise power is, thus

$$n_{I(h, v)} = 10^{(N_{rain(h, v)}/10)} + 10^{(I_{(h, v)}/10)} \text{ W} \quad (6)$$

Hence, the respective channels CNIR is given by

$$\begin{aligned} CNIR_{(h, v)} = & CNIR_{(ca)} - A_{rain(h, v)} - \Delta N_{rain(h, v)} \\ & - 10 \log_{10} \left(10^{(N_{rain(h, v)}/10)} + 10^{(I_{(h, v)}/10)} \right) \text{ dB} \end{aligned} \quad (7)$$

where $CNIR_{ca}$ is the clear-sky CNIR, $A_{rain(h, v)}$ is the respective channel co-polar rain attenuation, and $\Delta N_{rain(h, v)}$ is the increase in system thermal noise power due to rain in respective channels (dB). The results obtained are consistent with the findings of [11]. However, they are modified by the inclusion of ΔN_{rain} , to take into account the increase in effective antenna temperature (and consequent additional thermal noise) due to rain on the satellite downlink.

6 Results, analysis and discussion

In this section, an assessment of the impact of various link parameters on dual-polarised system performance is carried out. Table 1 shows the satellite system link parameters used in this analysis. First, the procedures presented in Sections 4 and 5 are applied to determine the temperate location's downlink, uplink, and overall link CNIRs for different antennas and for the atmospheric, best- and worst-case antenna effects of XPD. Then a similar analysis is carried out for the tropical region using the ITU-R prediction model. For both climatic scenarios, the impact of depolarisation-induced interference on single- and dual-polarised systems are computed, presented, and compared.

Table 1 Satellite system link parameters

| | |
|-------------------------------------|--|
| Frequency (downlink/uplink) | 19.7 GHz/30.0 GHz |
| Satellite EIRP | 61.5 dBW |
| Earth-station antenna diameter | 0.6, 2, 4, 6 m |
| Modulation | uncoded QPSK (CNR = 13.6 dB for BER of 10^{-6}) |
| Earth-station antenna XPD_{es} | 30 dB |
| Satellite antenna XPD_{sat} | 25 dB |
| Pontypridd, UK (temperate location) | |
| location | 51.59° N, 3.33° W, 86 m a.m.s.l |
| elevation angle | 29.30° |
| polarisation tilt angle | 7.59° |
| Lagos, Nigeria (tropical location) | |
| location | 6.45° N, 3.39° E, 78 m a.m.s.l |
| elevation angle | 30.0° |
| polarisation tilt angle | 76.29° |

6.1 Analysis of the impact of depolarisation-induced interference on system performance in a temperate location

In this section, we present an analysis of the impact of depolarisation on a dual-polarised system in a temperate location. In this analysis, we consider the following scenarios for the downlink, uplink, and the overall link: (i) atmospheric depolarisation alone, where both satellite and Earth-station antennas are assumed to be ideal, with infinite isolation; (ii) atmospheric plus best-case antenna effects combination; and (iii) atmospheric plus worst-case antenna effects combination. We consider equal effective isotropically radiated power (EIRP) in the two orthogonally polarised transmissions from the satellite. The two transmissions are assumed to occupy the same frequency spectrum, but to contain different information, i.e. the cross-polar interference is noise-like.

6.1.1 Temperate location downlink: This analysis is based on attenuation measurement data from USW, Pontypridd, UK:

Single-polarised system: The baseline single-polarised system is only affected by rain attenuation – unlike the dual-polarised system, which is affected by both rain attenuation and

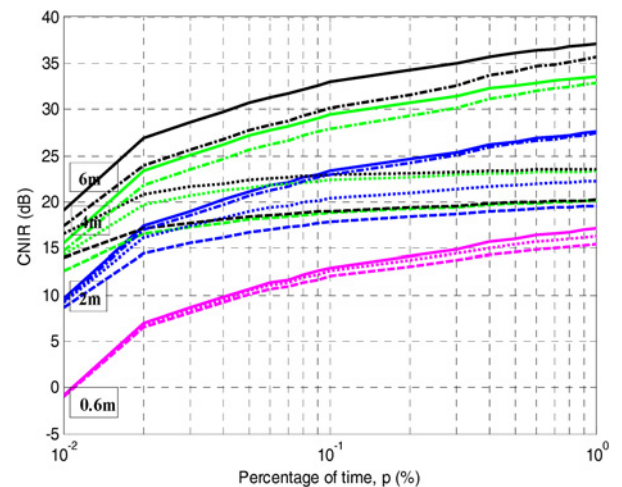


Fig. 7 Temperate location: CNIR of 19.7 GHz link single-polarised system (solid lines), dual-polarised system: atmospheric depolarisation alone (dashed-dotted lines), atmospheric and antennas effect, best-case (dotted lines), and atmospheric and antennas effect, worst-case (dashed lines) for various antenna sizes (0.6, 2, 4, and 6 m) at various percentages of time, p

depolarisation. For the 2 m antenna, it can be observed that, at $p = 0.01\%$, the CNIR (note that, for the single-polarised system, CNIR reduces to CNR as $I=0$ in this case) is 4 dB below the threshold (i.e. the uncoded quadrature phase shift keying (QPSK) CNR threshold of 13.6 dB required for bit error rate (BER) 10^{-6} [18]). At $p = 0.02\%$, the CNIR is 3 dB above the threshold. However, for larger Earth-station antennas, the single-polarised link CNIR increases significantly. At $p = 0.01\%$, the CNIRs for 4 and 6 m antennas are 2 and 6 dB above the threshold, respectively. It is also worth noting that the CNIR of a single-polarised system increases with increasing values of p . However, using a small Earth-station antenna of 0.6 m diameter, it is observed that, at 0.1% of the time, the single-polarised system is 0.6 dB below threshold due to rain attenuation. These results are shown in Fig. 7.

Dual-polarised system: atmospheric depolarisation alone: Here, we consider the impact of depolarisation exclusively due to hydrometeors. We assume that both satellite and Earth-station antennas are ideal, having infinite isolation. The result for a 2 m antenna indicates that, at $p = 0.01\%$, the system CNIR is comparable with that of the single-polarised system, and, therefore, the impact of atmospheric depolarisation is observed to be negligible. The dual-polarised system's CNIR is below the threshold, leading to system outage due to the dominance of rain attenuation. However, increasing the Earth-station antenna size brings about an improvement in dual-polarised system CNIR. Though the dual-polarised system CNIRs are 1 and 2 dB below the single-polarised system CNIR, respectively, for the 4 and 6 m antennas at $p = 0.01\%$, their respective CNIR are 1.5 and 4 dB above the threshold. Similarly, using a small Earth-station antenna of 0.6 m diameter, results indicate that the atmospheric depolarisation has a negligible effect. Therefore, XPD_{atm} is insignificant for all antenna sizes. These results are also shown in Fig. 7.

Dual-polarised system: atmosphere and best-case antenna effects: In reality, the satellite and Earth-station antennas have typical XPD values of 25 and 30 dB, respectively, as mentioned elsewhere in this paper. These XPDs must be combined with the atmospheric XPD in order to take into account the impact of the antennas on the overall system performance. It can be observed in Fig. 7 that, at $p = 0.01\%$, the impact of the best-case antenna effects combination is still negligible for the 2 m Earth-station antenna, as the CNIR compares closely with the atmospheric depolarisation case. At $p = 0.02\%$, the system CNIR is 2 dB above the threshold, but it is 1.5 dB below the single-polarised system's CNIR. Increasing the

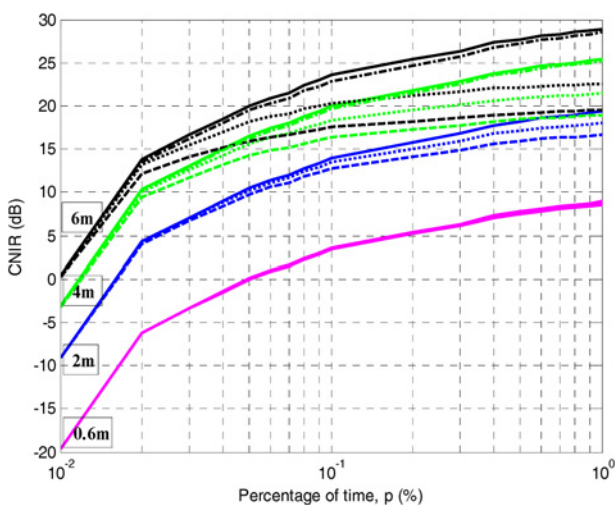


Fig. 8 Temperate location: CNIR of 30 GHz link single-polarised system (solid lines), dual-polarised system: atmospheric depolarisation alone (dashed-dotted lines), atmospheric and antennas effect, best-case (dotted lines), and atmospheric and antennas effect, worst-case (dashed lines) for various antenna sizes (0.6, 2, 4, and 6 m) at various percentages of time, p

Earth-station antenna diameter to 4 m yields an improvement in system CNIR at all values of p . Using a 6 m Earth-station antenna, the results indicate that depolarisation is no longer an issue, as the system's CNIR is well above the threshold. It is also evident from the results that, at higher values of p , increasing the antenna diameter for a dual-polarised system above 2 m offers no substantial benefits in system performance relative to the single-polarised system. However, using a small Earth-station antenna of 0.6 m diameter, the results indicate that the best-case combination of antenna effects leads to only a 0.5 dB degradation in link CNIR at $p = 1\%$, relative to the single-polarised system.

Dual-polarised system: atmosphere and worst-case antenna effects: Considering the worst-case combination of antenna effects for the 2 m Earth-station antenna, at $p = 0.01\%$, this leads to an additional 0.5 dB requirement above the 4 dB that would have been provided in the case of the single-polarised system. Though the result in Fig. 7 shows that, at $p = 0.02\%$, the system's CNIR is above the stated threshold, it is, however, indicated that the worst-case antenna effects caused the dual-polarised system's CNIR to degrade by 3 dB relative to that of the single-polarised system, due to antenna imperfections. Using a 4 m Earth-station antenna leads to a 1 dB degradation below threshold at $p = 0.01\%$. With a 6 m Earth-station antenna, the results indicated that even the worst-case scenario of antenna effects presents a 0.5 dB extra link margin at $p = 0.01\%$. However, using a small Earth-station antenna of 0.6 m diameter, the results indicate that the worst-case combination of antenna effects leads to a 1 dB degradation in link CNIR at $p = 0.1\%$, relative to the single-polarised system. It is interesting to note that, at $p = 0.2\%$, the single-polarised system is 0.6 dB above CNIR threshold, whereas the worst-case combination of antenna effects leads to further 0.6 dB degradation exclusively due to depolarisation. This suggests that rain attenuation is mostly the dominant propagation impairment in dual-polarised systems using small antennas.

6.1.2 Temperate location uplink: This analysis is based on frequency-scaled attenuation measurement data from USW, Pontypridd, UK:

Single-polarised system: For the 30 GHz uplink, rain attenuation is the most significant propagation impairment of concern. The results in Fig. 8 show that, for a 2 m diameter Earth-station antenna, the single-polarised system CNIR is above the threshold at $p = 0.09\%$. Increasing the Earth-station antenna size to 4 m improves the system's performance such that it is not affected by rain attenuation at $p \geq 0.03\%$. Using a 6 m Earth-station antenna, the single-polarised system is not affected by rain attenuation at $p \geq 0.02\%$. This demonstrates that, for a single-polarised system, increasing the Earth-station antenna size brings about the expected improvement in link CNIR.

Dual-polarised system: atmospheric depolarisation: The results in Fig. 8 show that, for all the Earth-station antenna sizes considered in this investigation, at this frequency, the impact of atmospheric depolarisation is negligible relative to the single-polarised system. For the 0.6, 2, and 4 m diameter Earth-station antennas, the results show no difference between the single-polarised and dual-polarised systems' performance for all values of p . For the 0.6 m antenna, the system is severely affected by rain attenuation, with the CNIR 4.5 dB below the specified threshold at $p = 1\%$. The results demonstrate that, in terms of their effect on CNIR, rain attenuation dominates over depolarisation in the dual-polarised system at this frequency.

Dual-polarised system: best-case antenna effects: Taking into account the depolarisation effect of the antennas, for the best-case scenario, the impact of depolarisation on CNIR is not significant for the 0.6 and 2 m diameter Earth-station antennas – as shown in Fig. 8. However, as the Earth-station antenna size increases to 4 m, the effect of depolarisation becomes clear at values of

$p \geq 0.04\%$ where the CNIR values are above the threshold. A similar condition is observed for the 6 m diameter Earth-station antenna.

Dual-polarised system: worst-case antenna effects: Considering the worst-case antenna effects combination, the results show that, for the 2 m Earth-station antenna, the dual-polarised system is 2 dB below threshold at $p = 0.08\%$, which is 1 dB below the single-polarised system's CNIR. At $p = 0.1\%$, the dual-polarised system is 1 dB below threshold due to depolarisation, whereas the operation of the single-polarised system is unaffected by rain attenuation. Using a 4 m diameter Earth-station antenna, the effect of depolarisation on the dual-polarised system's CNIR is observed to be 0.5 dB worst for $p = 0.03\%$ with respect to that of the single-polarised system. For a 6 m Earth-station antenna, at $p = 0.02\%$, the dual-polarised system is 1 dB below the CNIR threshold, whereas the single-polarised system's CNIR is 0.5 dB above the threshold. Fig. 8 depicts the results discussed above.

6.2 Analysis of the impact of depolarisation-induced interference on system performance in a tropical location

Here, we present an analysis of the impact of depolarisation on a dual-polarised system in a tropical location. The analytical approach is similar to that used for the temperate location in Section 6.1. We consider the following scenarios: (i) atmospheric depolarisation alone, where both satellite and Earth-station antennas are assumed to be ideal (with infinite isolation); (ii) atmospheric plus best-case antenna effects combination; and (iii) atmospheric plus worst-case antenna effects combination. The assumptions regarding the satellite transmission characteristics detailed in Section 6.1 also apply here.

6.2.1 Tropical location downlink: For the tropical location analysis, the results presented in Fig. 9 are based on the hypothetical statistics provided in [13]:

Single-polarised system: For the reference single-polarised system that is only affected by rain attenuation, using a 2 m diameter Earth-station antenna, at $p = 0.1\%$, the system is 1 dB below the CNIR threshold. The system only overcomes the effect of rain attenuation at $p = 0.2\%$. The curve indicates an improvement in link CNIR with higher values of p . For a 4 m diameter antenna, the single-polarised system's CNIR improves with antenna size and higher values of p . In this case, the system is 0.5 dB below the CNIR threshold at $p = 0.04\%$. At $p = 0.05\%$, the single-polarised

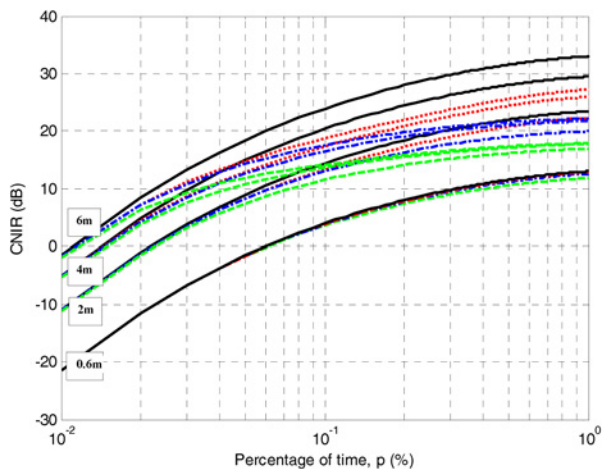


Fig. 9 Tropical location: CNIR of 19.7 GHz link single-polarised system (solid lines) and dual-polarised system: atmospheric depolarisation alone (dotted lines), atmospheric and antennas effect, best-case (dashed-dotted lines), and atmospheric and antennas effect, worst-case (dashed lines) for various antenna sizes (0.6, 2, 4, and 6 m) at various percentages of time, p

system has 1.4 dB extra link margin above the CNIR threshold. Increasing the Earth-station antenna diameter to 6 m further improves the system's CNIR performance. In this case, at $p = 0.02\%$, the single-polarised system is 5 dB below the CNIR threshold. At $p = 0.04\%$, the single-polarised system's performance is not limited by rain attenuation. However, using a small Earth-station antenna of 0.6 m diameter, the system CNIR is 1.5 dB below the threshold at $p = 1\%$.

Dual-polarised system: atmospheric depolarisation alone: Similarly to the temperate location analysis, in order to investigate the impact of atmospheric depolarisation on dual-polarised link performance, we initially assume that both Earth-station and satellite antennas are ideal. Using a 2 m Earth-station antenna, the atmospheric depolarisation degrades the system CNIR by 1 dB relative to the single-polarised system at $p = 0.08\%$. At $p = 0.09\%$, the single-polarised system is no longer in outage, but the dual-polarised system is degraded by 1 dB due to atmospheric depolarisation. However, when a 4 m diameter Earth-station antenna is used, the impact of atmospheric depolarisation on the dual-polarised system causes a 1.5 dB degradation in CNIR with respect to the single-polarised system at $p = 0.04\%$. At $p = 0.05\%$, the single-polarised system has 1.4 dB extra link margin above the CNIR threshold, but the dual-polarised system is 0.5 dB below CNIR threshold. The atmospheric depolarisation ceases to have effect on the dual-polarised system only at $p \geq 0.07\%$. Increasing the Earth-station antenna to 6 m diameter further improves both systems' CNIR at all values of p . At $p = 0.03\%$, the single-polarised system is 0.5 dB above the CNIR threshold, but the dual-polarised system is 1.5 dB below threshold. The dual-polarised system overcomes the effects of atmospheric depolarisation at $p \geq 0.04\%$ with 0.5 dB above threshold at $p = 0.04\%$. When a small Earth-station antenna of 0.6 m diameter is used, the impact of atmospheric depolarisation is negligible relative to the single-polarised system for all values of p , as shown in Fig. 9.

Dual-polarised system: atmosphere and best-case antenna effects: Here, we consider the best-case effect of the antennas. For a 2 m diameter Earth-station antenna, it is shown in Fig. 9 that the performance of the dual-polarised system presents a 0.5 and 1 dB degradation relative to the atmosphere-alone scenario and the single-polarised system, respectively, at $p = 0.08\%$. The dual-polarised system is 1 dB below the CNIR threshold up to $p = 0.1\%$. However, when a 4 m diameter Earth-station antenna is used, at $p = 0.04\%$ the dual-polarised system is 2.5 dB below the CNIR threshold. At $p = 0.05\%$, the single-polarised system appears to have 1.4 dB extra above threshold, the dual-polarised system still requires 1 dB extra to overcome the effect of depolarisation. Obviously, the dual-polarised system only overcomes the effect of depolarisation at $p = 0.06\%$.

For a 6 m diameter Earth-station antenna, at $p = 0.02\%$, the dual-polarised system's CNIR is 1.5 dB below the single-polarised system's CNIR. The single-polarised system is not in outage at $p = 0.03\%$, but the dual-polarised system is 2.5 dB below the CNIR threshold. The dual-polarised system only overcomes the effect of depolarisation at $p \geq 0.05\%$. Using a small Earth-station antenna of 0.6 m diameter, the impact of depolarisation on dual-polarised system CNIR is only observable at $p = 1\%$, with a 0.5 dB degradation relative to the single-polarised system. At this value of p , the single-polarised system is 0.5 dB below the CNIR threshold due to rain attenuation, whereas the dual-polarised system requires 1 dB extra to overcome the effect of depolarisation.

Dual-polarised system: atmosphere and worst-case antenna effects: For the 2 m Earth-station antenna, the impact of antenna effects on the performance of the dual-polarised system very clear such that the system's CNIR is degraded by 1.5 dB relative to the atmospheric depolarisation scenario at $p = 0.08\%$. This implies 2.5 dB degradation with respect to the single-polarised system. The single-polarised system is not affected by rain attenuation at $p \geq 0.09\%$, but the dual-polarised system is in outage by 2.6 dB below CNIR

threshold up to $p \leq 0.1\%$. With a 4 m diameter Earth-station antenna, the dual-polarised system's CNIR is 3.5 dB below the threshold at $p = 0.04\%$. In general, the dual-polarised system only overcomes the effect of depolarisation at $p \geq 0.1\%$. Further increase in the Earth-station antenna diameter to 6 m improves the system's performance. At $p = 0.02\%$, the dual-polarised system's CNIR is degraded by 2.5 dB relative to the single-polarised system. However, while the single-polarised system is not in outage at $p = 0.03\%$, the dual-polarised system is 3.5 dB below the threshold. The dual-polarised system overcomes the effect of depolarisation at $p \geq 0.08\%$. Using a small Earth-station antenna of 0.6 m diameter, at $p = 1\%$ a 1.5 dB degradation in system's CNIR with respect to the single-polarised system is observed. At this value of p , the dual-polarised system requires 2 dB extra to overcome the effect of depolarisation. Fig. 9 shows the results.

Effect of variation in system noise power due to rain on downlink: The effect of variation in receiving system noise due to rain, ΔN_{rain} , on the downlink is investigated for the tropical location using a 2 m Earth-station antenna. The results are presented in Fig. 10 below. Radiometric noise caused a 4 dB difference for the single-polarised system, as compared with the case where its effect is not taken into account. However, for the dual-polarised system, this value is observed to decrease with increasing values of p for the atmospheric, best- and worst-case antenna effects combinations.

When ΔN_{rain} is not taken into account, the worst-case scenario depolarisation results in a CNIR which is 0.5 dB below threshold at $p = 0.09\%$. This is the exact level of degradation that the atmospheric depolarisation alone produced when the effect of ΔN_{rain} is taken into account. This situation holds for a tropical region using the ITU-R depolarisation model. Therefore, the effect of thermal noise emission from intense rain should be taken into consideration when designing dual-polarised satellite communication systems in the tropics.

6.2.2 Tropical location uplink: Similarly to the downlink analysis, Fig. 11 presents results of the uplink analysis performed for the tropical location based on the hypothetical statistics provided in [13]. Using a 0.6 m Earth-station antenna on the uplink, the results show no observable difference between the performances of the single- and dual-polarised systems (for both the best- and worst-case antenna effects). This shows that the impact of depolarisation is insignificant in this case.

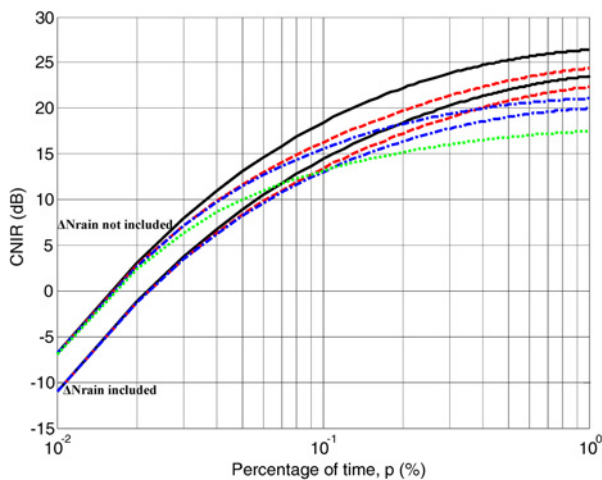


Fig. 10 Tropical location: impact of ΔN_{rain} on 19.7 GHz link CNIR for single-polarised system (solid lines) and dual-polarised system: atmospheric depolarisation alone (dotted lines), atmospheric and antennas effect, best-case (dashed-dotted lines), and atmospheric and antennas effect, worst-case (dashed lines) for a 2 m Earth-station antenna at various percentages of time, p

Increasing the Earth-station antenna diameter to 2 m produces no significant difference between the performance of the single- and dual-polarised systems, except at $p = 1\%$, where the single-polarised system is not affected by rain impairment (being slightly above the CNIR threshold), whereas the dual-polarised system with the worst-case antenna effects combination leads to a 1 dB degradation below threshold due to depolarisation.

Using a 4 m Earth-station antenna, the single-polarised system is not affected by rain attenuation at $p = 0.3\%$, but the dual-polarised system with the worst-case antenna effects is 0.5 dB below the CNIR threshold. Increasing the Earth-station antenna diameter to 6 m slightly improves the performance of both systems, such that, at $p = 0.2\%$, the single-polarised system is not affected by rain attenuation, whereas the dual-polarised system with the worst-case antenna effects is 0.5 dB below threshold.

6.3 Overall link CNIR analysis

The analyses in the previous sections were carried out on the downlink and the uplink separately. The end-to-end CNIR_o analysis is carried out in order to account for the effect of both uplink and downlink impairments on system performance. Figs. 12 and 13 show the result of these analyses using 4 m uplink and 2 m downlink Earth-station antennas for both the temperate and tropical locations, respectively.

The impact of rain attenuation and depolarisation on the overall link depend on whether the downlink or the uplink is affected by rain. The CNIR_o is degraded most when the uplink is affected by rain. This is due to the higher frequency of the uplink. The CNIR_o, in terms of the link condition on the uplink, CNIR_u, and on the downlink, CNIR_d, is given by

$$\text{CNIR}_o = \left[(\text{CNIR}_u)^{-1} + (\text{CNIR}_d)^{-1} \right]^{-1} \text{ dB} \quad (8)$$

6.3.1 Temperate location: For the temperate location, it can be seen in Fig. 12 that, for the dual-polarised system with only the downlink affected by rain, the CNIR_o at $p = 0.01\%$ is 4.5 and 5 dB below threshold for the best- and worst-case scenarios, respectively. However, for the single-polarised link, the CNIR_o is 4.0 dB below the threshold. This indicates that depolarisation is responsible for 0.5 and 1 dB further degradation in the dual-polarised system relative to the single-polarised system for the best- and worst-case combinations, respectively.

The situation is not the same when only the uplink is affected by rain, in which case the dual-polarised system is 1 and 2 dB below

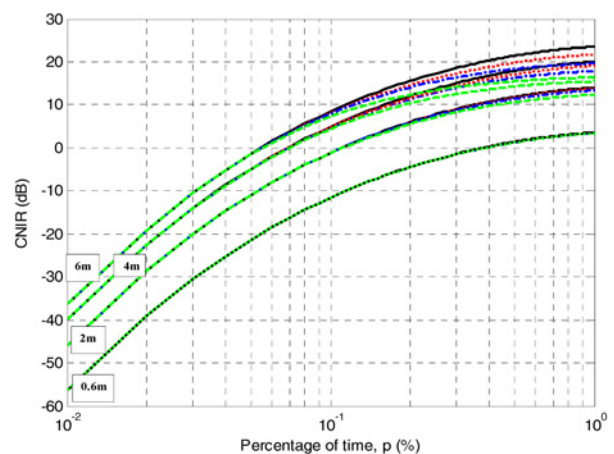


Fig. 11 Tropical location: CNIR of 30 GHz link single-polarised system (solid lines) and dual-polarised system: atmospheric depolarisation alone (dotted lines), atmospheric and antennas effect, best-case (dashed-dotted lines), and atmospheric and antennas effect, worst-case (dashed lines) for various antenna sizes (0.6, 2, 4, and 6 m) at various percentages of time, p

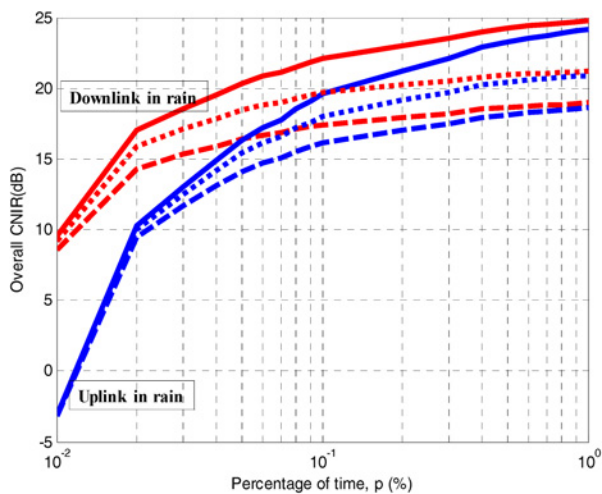


Fig. 12 Temperate location: overall CNIR of 30/19.7 GHz links for single-polarised system (solid lines) and dual-polarised system: atmospheric and antennas effect, best-case (dotted lines), and atmospheric and antennas effect, worst-case (dashed lines) at various percentages of time, p . [4 m uplink/2 m downlink antenna]

the threshold at $p = 0.03\%$ for the best- and worst-case conditions, respectively, whereas the single-polarised system is 0.5 dB below the threshold. The worst-case is 0.5 dB below threshold at $p = 0.04\%$.

6.3.2 Tropical location: For the tropical location analysis, and with the dual-polarised system downlink only affected by rain, it can be observed in Fig. 13 that, for the best-case scenario, the $CNIR_o$ at $p = 0.08\%$ is 1 dB below the threshold, whereas, for the worst-case scenario, the $CNIR_o$ at $p = 0.1\%$ is 2 dB below threshold. However, the single-polarised system is not notably affected.

With regard to the situation where only the uplink is affected by rain, the difference between the performance of both systems is only observable from $p = 0.2\%$, where both systems' $CNIR_o$ is below threshold, but the dual-polarised system is further degraded by 1 and 2 dB for the best- and worst-case scenarios, respectively, relative to the single-polarised system. At $p = 0.3\%$, the single-polarised system is no longer affected by rain attenuation, but the dual-polarised system is below the $CNIR$ threshold by 0.5 dB for the best-case, and by 1.5 dB for the worst-case, scenarios.

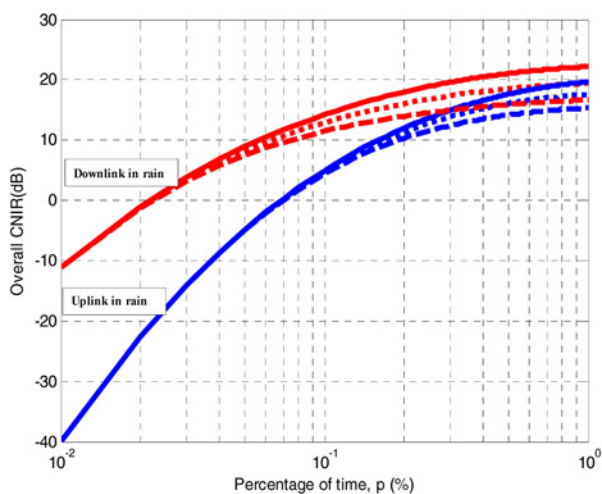


Fig. 13 Tropical location: overall CNIR of 30/19.7 GHz links for single-polarised system (solid lines) and dual-polarised system: atmospheric and antennas effect, best-case (dotted lines), and atmospheric and antennas effect, worst-case (dashed lines) at various percentages of time, p . [4 m uplink/2 m downlink antenna]

Note that the condition whereby heavy rain exists on both the uplink and downlink simultaneously is not considered here, since this scenario occurs with only a very low probability.

7 Conclusions

The objective of this paper has been to present an analysis of the impact of depolarisation-induced interference in dual-polarised, high-capacity satellite communication systems in different climatic regions. The impact of the depolarisation on system performance was quantified by the reduction in CNIR for various link dimensions, as compared with the corresponding single-polarised system (which is only affected by rain attenuation). The analysis made use of real measurement data for a temperate location, while data derived from an ITU-R model were used for the tropical location. The results from both locations were then compared.

On the basis of our measurements and analyses, it is clear that, in operational systems with real antennas, the atmospherically induced depolarisation only contributes to the system performance impairment at very low time-percentages. Taking into account the effect of the antennas' XPI for the best- and worst-case combinations further exacerbates the system performance degradation with respect to that of the corresponding single-polarised system.

For the temperate location, on the downlink, at $p = 0.01\%$, the impact of the atmospherically induced depolarisation and the best-case antenna effect combination on system performance is negligible for small antennas, whereas the worst-case antenna effect combination leads to a 0.5 dB degradation in CNIR. For relatively large antennas, the impact of the atmospheric depolarisation became more pronounced relative to the single-polarised system. It is also evident from the results that, at higher values of p , increasing the Earth-station antenna diameter for a dual-polarised system offers no further improvement in CNIR as compared with relatively small Earth-station antennas.

Similarly, for the tropical location, rain attenuation is dominant over depolarisation, especially for smaller Earth-station antennas. Therefore, the impact of the atmospheric depolarisation and best-case antenna effect scenario is not significant. It is also evident that the impact of ΔN_{rain} on downlink CNIR is manifest in this case, and it must be taken into consideration when designing dual-polarised satellite communication links in the tropics. Antenna size obviously plays a key role in improving the link CNIR, especially for the single-polarised system. The results indicated that, due to their lower gains, smaller antennas render the system more susceptible to both rain attenuation and depolarisation. Note also that the downlink performance in all the systems analysed is better than that of the corresponding uplinks, due to the frequencies of operation.

Consequently, it may be concluded that depolarisation is a performance-limiting factor in dual-polarised HTS systems. Its impact leads to more frequent system outages, which require an increase in the fade margin in order to sustain the link availability and QoS, as compared with the corresponding single-polarised system (for a given operating frequency and link dimensioning). Further research to develop techniques for mitigating the effect of depolarisation-induced CCI in dual-polarised satellite communication systems is, therefore, required.

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