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TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU

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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Transmission media characteristics – Submarine cables

Co-location longitudinally compatible interfaces for free space optical systems

ITU-T Recommendation G.640

ITU-T

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ITU-T Recommendation G.640

Co-location longitudinally compatible interfaces for free space optical systems

Summary

This Recommendation provides a procedure for establishing that two co-located Free Space Optical (FSO) transmission systems will not interfere with each other. Calculations of the conditions required to be met to prevent interference in some examples of co-located FSO systems are also included.

Source

ITU-T Recommendation G.640 was approved on 29 March 2006 by ITU-T Study Group 15 (2005-2008) under the ITU-T Recommendation A.8 procedure.

FOREWORD

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The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

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Compliance with this Recommendation is voluntary. However, the Recommendation may contain certain mandatory provisions (to ensure e.g., interoperability or applicability) and compliance with the Recommendation is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the Recommendation is required of any party.

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

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ITU-T Recommendation G.640

Co-location longitudinally compatible interfaces for free space optical systems

1 Scope

This Recommendation defines optical interfaces for "co-location longitudinally compatible" free space optical transmission systems thereby enabling interference-free coexistence of more than one point-to-point free space optical system at a location.

This Recommendation also includes definitions of parameters that are relevant for the characterization of free space optical systems.

Free space optical systems are commonly referred to as "FSO" systems.

2 References

2.1 Normative references

The following ITU-T Recommendations and other references contain provisions, which through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

– ITU-T Recommendation G.957 (2006), *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy*.

– IEC 60825-1 (2001), *Safety of laser products – Part 1: Equipment classification, requirements and user's guide*.

– IEC 60825-2 (2005), *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)*.

– IEC 60825-12 (2005), *Safety of laser products – Part 12: Safety of free space optical communication systems used for transmission of information*.

2.2 Informative references

– ITU-T G-series Recommendations – Supplement 39 (2006), *Optical system design and engineering considerations*.

3 Terms and definitions

3.1 Definitions

This Recommendation defines the following terms:

3.1.1 acceptance angle: The acceptance angle (of an FSO receiver) is the angle between the lines at which the power detected by the receiver falls to $1/e^2$. This parameter is also called the Field of View (FOV) of an FSO receiver and is commonly defined to be where the power density falls to $1/e^2$, 1/e or 50%.

3.1.2 beam divergence: The beam divergence is the angle between the lines at which the power density of an FSO beam falls to $1/e^2$.

NOTE 1 – This parameter is also commonly defined to be where the power density falls to either 1/e or 50%.

NOTE 2 – The beam divergence should be measured at a distance at least five times the Rayleigh distance from the lens (see 3.1.8) to ensure that it is measured under far field conditions.

3.1.3 inter-channel crosstalk: The ratio of the disturbing optical power to the wanted optical power detected by the receiver where the wanted and disturbing signals are at different wavelengths.

3.1.4 inter-channel crosstalk penalty: The penalty assigned in the system budget to account for inter-channel crosstalk.

3.1.5 interferometric crosstalk: The ratio of the disturbing optical power to the wanted optical power detected by the receiver where the wanted and disturbing signals can be at the same wavelength.

3.1.6 interferometric crosstalk penalty: The penalty assigned in the system budget to account for interferometric crosstalk.

3.1.7 transmitter (or receiver) setting error: The maximum angle between the axis of the transmitter (or receiver) and a straight line joining the transmitter and receiver together.

3.1.8 Rayleigh distance: This is defined as:

$$\text{Rayleigh distance} = \frac{2D^2}{\lambda}$$

where:

D is the diameter of the transmitter lens

λ is the wavelength

3.2 Terms defined in other Recommendations

This Recommendation uses the following term defined in ITU-T Rec. G.957:

– Extinction ratio.

4 Abbreviations

This Recommendation uses the following abbreviations:

FOV Field Of View

FSO Free Space Optical

R_{fso} Reference plane just before the optical receiver input lens

Rx Receiver

S_{fso} Reference plane just after the optical transmitter output lens

Tx Transmitter

5 Reference points

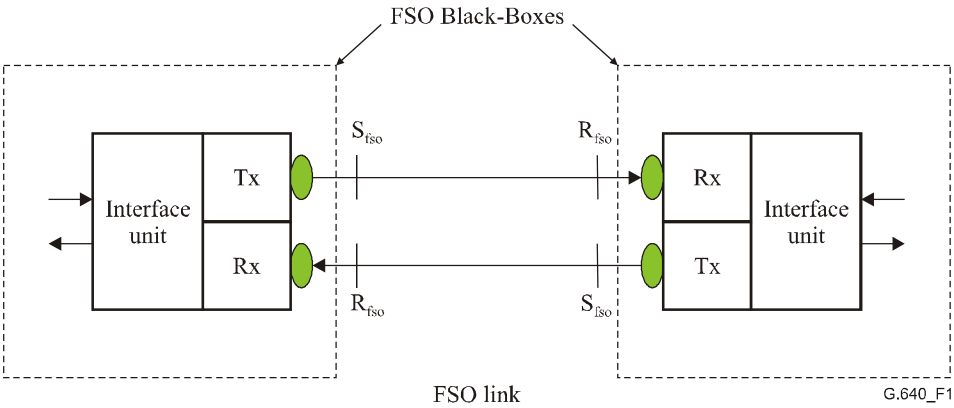

Figure 5-1/G.640 – Free space optical link reference diagram

The reference planes in Figure 5-1 are defined as follows:

– S_{fso} is a reference plane just after the optical transmitter output lens;

– R_{fso} is a reference plane just before the optical receiver input lens.

6 Co-location longitudinal compatibility

The free space between the S_{fso} and R_{fso} reference planes in an FSO system is a shared medium employed by many other users for a variety of different purposes. In order to establish criteria for the co-location of FSO systems, the crosstalk ratio C generated by one system interfering with another is described in 6.1 and the effect of the weather on this crosstalk ratio is considered in 6.2. The optical power penalty caused by this crosstalk is then defined for two cases:

– Case A – where the two systems can be at the same wavelength (see 6.3).

– Case B – where the two systems can **not** be at the same wavelength (see 6.4).

The difference between these two cases is illustrated in Figure 6-1.

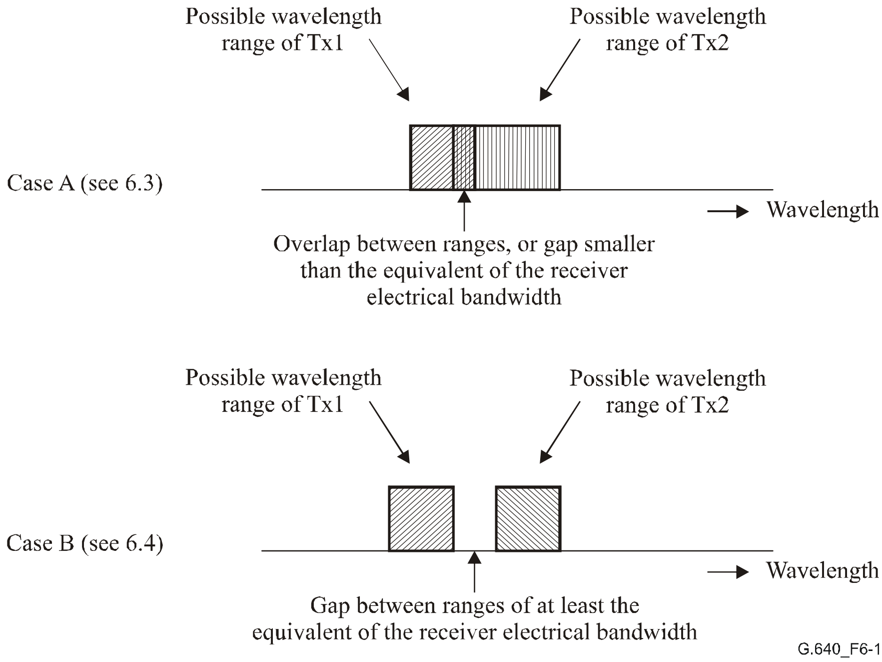

Figure 6-1/G.640 – Illustration of the difference between the cases covered by clauses 6.3 and 6.4

For bidirectional systems the two directions have to be considered separately.

NOTE 1 – For some FSO systems the source coherence is sufficiently low (especially in the case of LED-based systems) that even when the wavelengths are the same, interferometric crosstalk is not observed. For these co-located FSO systems, case B always applies.

NOTE 2 – Even for some laser-based FSO systems, the assumption of interferometric crosstalk may be pessimistic because the laser coherence may be largely destroyed by the atmosphere at some wavelengths.

6.1 Crosstalk ratio between two FSO systems

On the assumption that the beam produced by an FSO transmitter can be approximated by a Gaussian beam, Figure 6-2 contains a reference diagram for a general FSO transmitter.

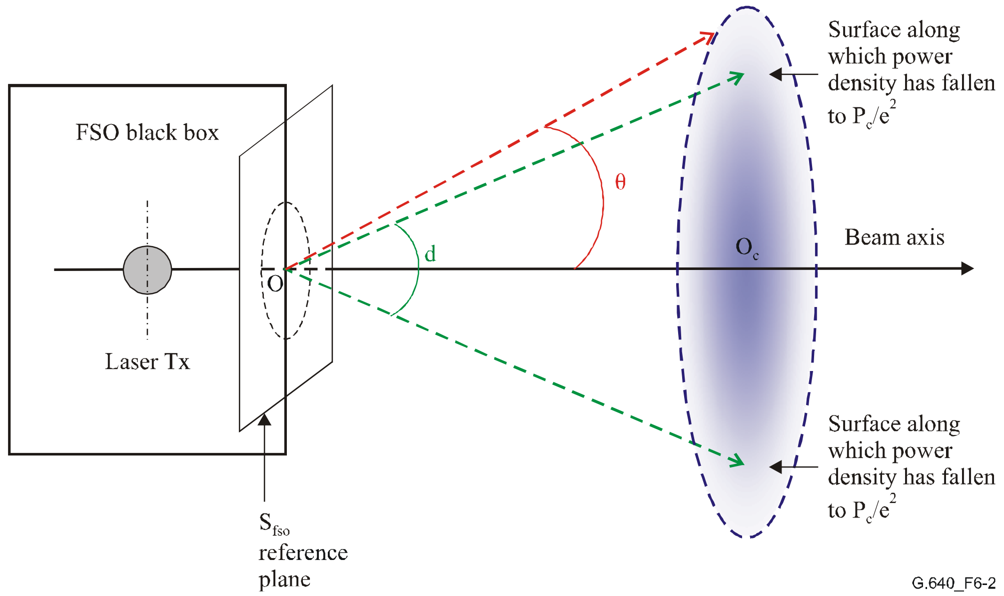

Figure 6-2/G.640 – Gaussian beam reference diagram for an FSO transmitter

The optical power density of this beam at an angle θ to the beam axis is given by:

$$O = O_c e^{\frac{-8\theta^2}{d^2}} \qquad (6\text{-}1)$$

where:

- O_c is the optical power density at the centre of the beam
- d is the beam divergence (the angle between the lines at which the power density falls to $1/e^2$) and
- θ is the angle between the beam axis and the measurement point

If the curve of optical power density vs angle is known for a particular FSO system, then values from the curve should be used in place of the approximation from Equation 6-1. An example measured curve is shown in Figure 6-3.

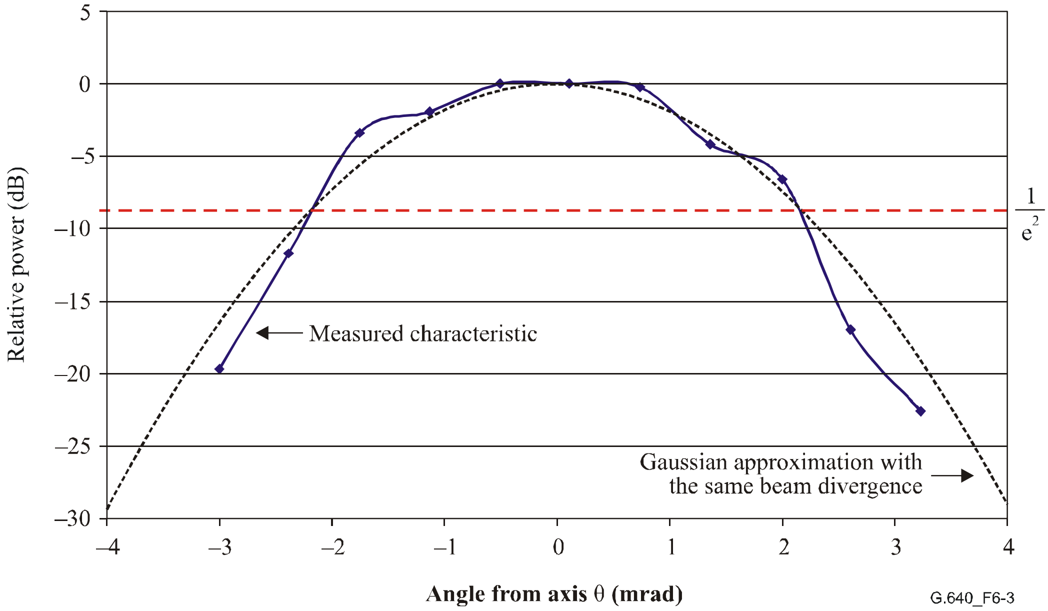

Figure 6-3/G.640 – Example measured curve of power density vs angle

The corresponding reference diagram for the FSO receiver is given in Figure 6-4.

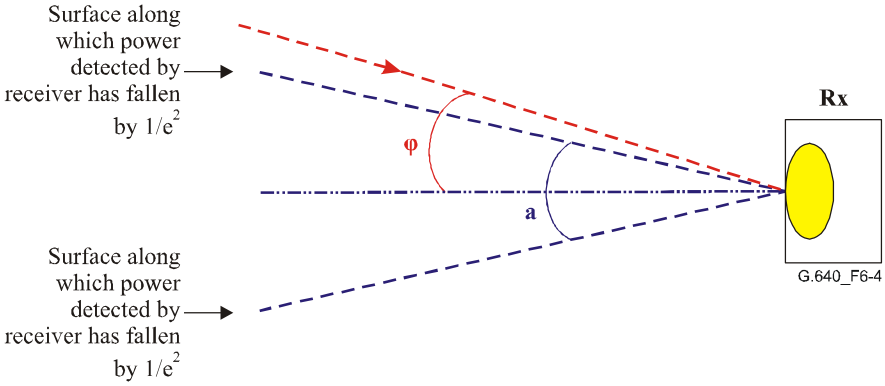

Figure 6-4/G.640 – Reference diagram for an FSO receiver

The characteristic of detected power vs angle for an FSO receiver depends on a number of parameters including the focal length of the lens, the lens quality, and the diameter of the detector.

If the diameter of the spot formed by the lens is smaller than the diameter of the detector, then the characteristic is approximately rectangular. However, if the diameter of the spot is approximately the same as the diameter of the detector, then the characteristic is an approximately Gaussian curve where the optical power (incident at an angle φ to the receiver axis) detected by the receiver is given by:

$$R = R_a e^{\frac{-8\varphi^2}{a^2}} \tag{6-2}$$

where:

R_a is the optical power detected by the receiver when the light is incident along the receiver axis

a is the acceptance angle (the angle between the lines at which the power detected by the receiver falls to $1/e^2$)

φ is the angle between the incident light and the axis of the receiver

The two cases defined above are illustrated in Figures 6-5 and 6-6.

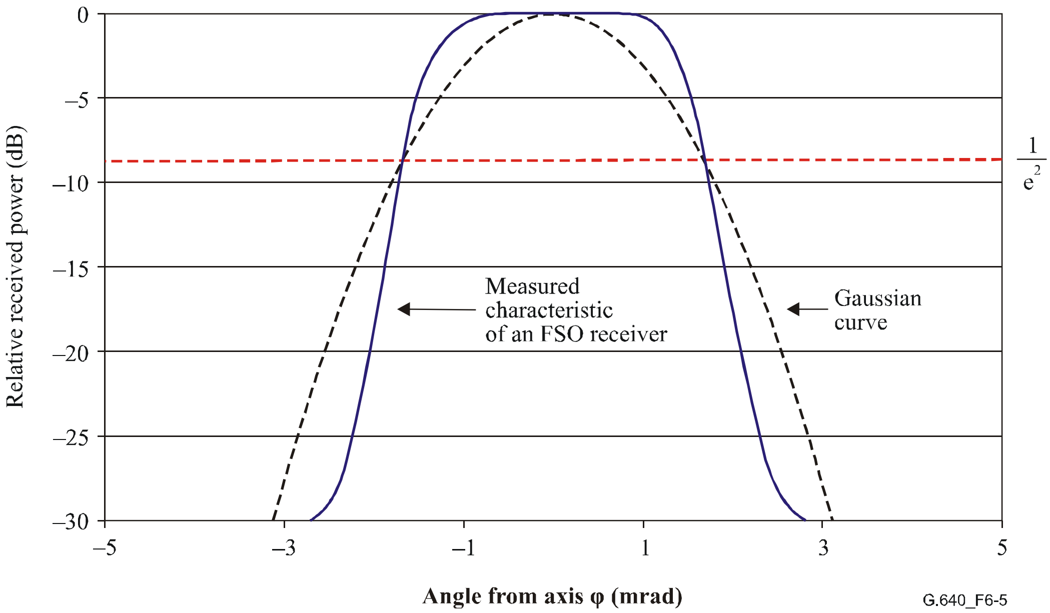

Figure 6-5/G.640 – Example measured curve of received power vs angle showing a rectangular shape

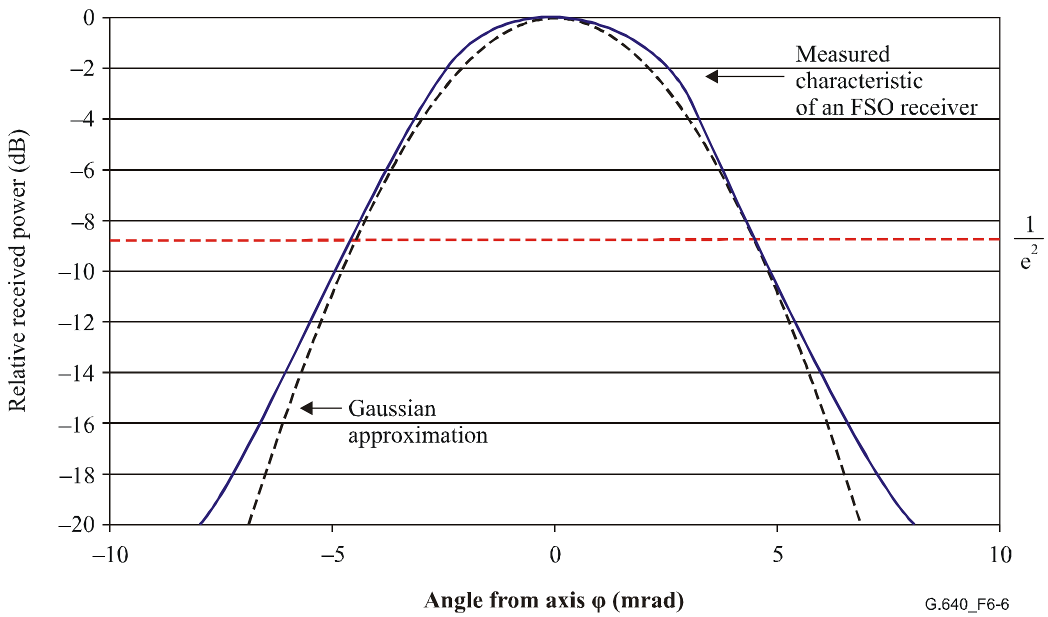

Figure 6-6/G.640 – Example measured curve of received power vs angle showing a Gaussian shape

As can be seen from Figure 6-5, the fit between the measured characteristic and the Gaussian curve is not very good for the rectangular case.

Consequently, if the curve of optical power detected by the receiver vs angle is known for a particular FSO system, then values from the curve should be used in place of the approximation from Equation 6-2.

For the case where the two systems cannot be at the same wavelength, optical filtering at the receiver may further reduce the amount of interfering power detected with respect to the wanted power. This effect is illustrated in Figure 6-7.

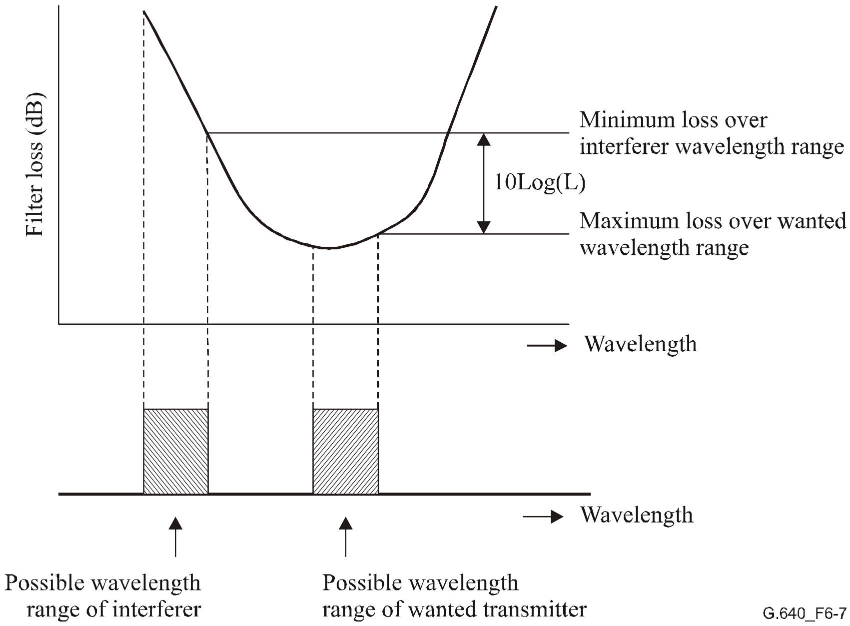

Figure 6-7/G.640 – Illustration of reduction of the interfering power due to optical filtering

Figure 6-8 shows the general case of one FSO system interfering with another.

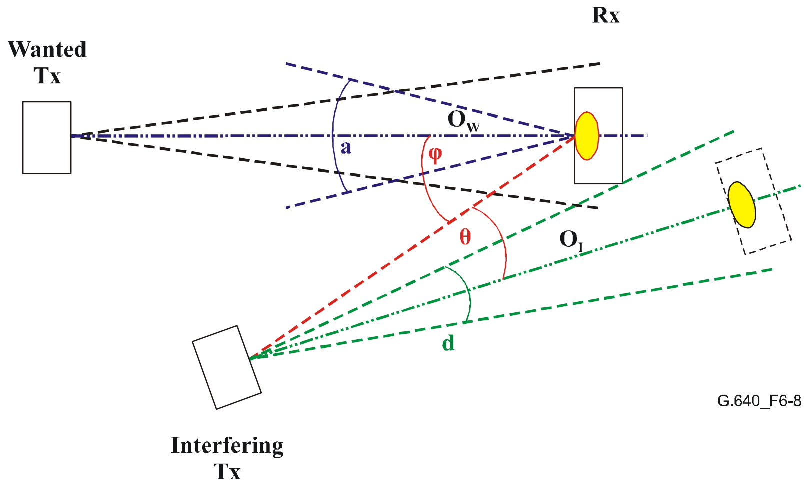

Figure 6-8/G.640 – FSO system crosstalk reference diagram

This leads to an equation for the crosstalk ratio C:

$$C = L\frac{O_I}{O_W} e^{\frac{-8\theta^2}{d^2}} e^{\frac{-8\varphi^2}{a^2}} \tag{6-3}$$

where:

- L is the ratio of optical filter loss between the wanted and interfering wavelength ranges as illustrated in Figure 6-7 (this would be 1 if the ranges overlap (Case A) or if both ranges are within a flat region of the filter characteristic)
- O_W is the minimum power density at the centre of the wanted beam
- O_I is the maximum power density at the centre of the interfering beam at the same distance from the interfering transmitter as the receiver
- θ is the angle between the interfering beam axis and a line between the interfering transmitter and the receiver
- d is the beam divergence (the angle between the lines at which the power density falls to $1/e^2$) of the interfering transmitter
- φ is the angle between the receiver axis and a line between the interfering transmitter and the receiver
- a is the receiver acceptance angle (the angle between the lines at which the power detected by the receiver falls to $1/e^2$)

If the curve of optical power density vs angle is known for the interfering transmitter, then the term $e^{\frac{-8\theta^2}{d^2}}$ in Equation 6-3 should be replaced by the (linear) value from the curve.

Likewise, if the curve of optical power detected by the receiver vs angle is known, then the term $e^{\frac{-8\varphi^2}{a^2}}$ in Equation 6-3 should be replaced by the (linear) value from the curve.

6.2 Effect of the weather on crosstalk ratio

Practical FSO systems are typically designed to be able to accommodate a wide variety of weather conditions. The two main effects due to the weather that must be taken into consideration in the calculation of crosstalk ratio are attenuation and beam divergence.

6.2.1 Attenuation change

In applying Equation 6-3 to calculate crosstalk ratio, care must be taken in the evaluation of the factor $\frac{O_I}{O_W}$ to ensure that the value used is the worst that can occur for any weather conditions that the wanted link must tolerate. Specifically, in the case where the interfering transmitter is closer to the receiver than the wanted transmitter, the worst-case ratio between the interfering power density and the wanted power density at the centre of their respective beams will be when the attenuation of the wanted link is at its maximum (i.e., in the worst weather conditions that it is required to tolerate). For an example of this, see Example 3 in Appendix I.

6.2.2 Beam divergence change

A second effect of the weather on FSO links is that the effective beam divergence may increase somewhat due to some adverse weather conditions. This effect should be taken into account in setting the value of *d* used in Equation 6-3 to calculate the crosstalk ratio.

In the case where the two co-located links operate at different wavelengths, the attenuation of the wanted and interfering beams due to the weather may be different. The degree of the attenuation difference, however, depends on a number of parameters such as the water droplet size.

6.3 Case A – interference between two systems that can be at the same wavelength

When the wavelengths of two co-located FSO systems can be the same, then to prevent mutual disturbance, each FSO system must claim some physical space. The space that they must claim is dependent on the level of interferometric crosstalk generated by the interferer.

The interferometric crosstalk penalty from ITU-T G-series Recommendations – Supplement 39 (and including the effect of imperfect extinction ratio) is:

$$P_I = 10\log_{10}\left(\frac{\dfrac{r-1}{r+1}}{\dfrac{r-1}{r+1} + 10^{\frac{C_I}{10}} - 4\sqrt{\dfrac{r}{r+1}10^{\frac{C_I}{10}}}}\right) \quad [\mathrm{dB}] \qquad (6\text{-}4)$$

for an average power decision threshold, and:

$$P_I = -10\log_{10}\left(1 - 2\left(\frac{\left(1+\sqrt{r}\right)\sqrt{10^{\frac{C_I}{10}}(r+1)}}{r-1}\right)\right) \quad [\mathrm{dB}] \qquad (6\text{-}5)$$

for an optimized decision threshold.

where:

P_I is the interferometric crosstalk penalty (dB)

$C_I = \log_{10}(C)$ is the interferometric crosstalk (dB) i.e., the ratio of the disturbing power to the wanted power detected by the receiver

r is the linear extinction ratio of the wanted signal

The interferometric crosstalk penalty for an ideal wanted signal and one with 6 dB extinction ratio is plotted in Figure 6-9.

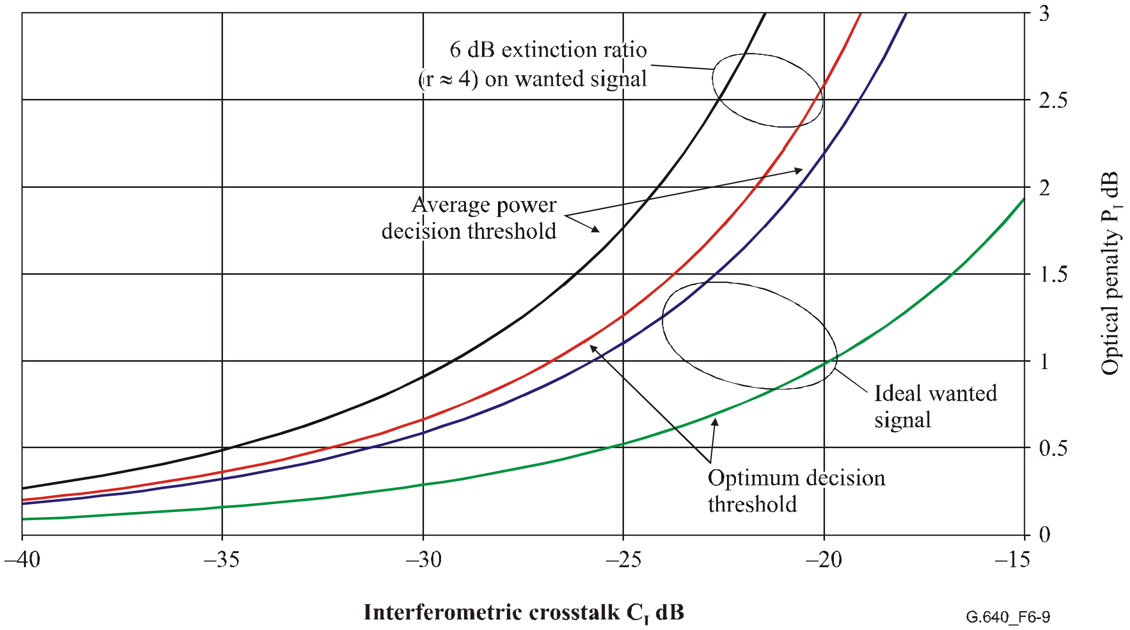

Figure 6-9/G.640 – Graph of optical penalty vs interferometric crosstalk for a single interferer (bounded model)

6.4 Case B – interference between two systems which cannot be at the same wavelength

When the wavelengths of two co-located FSO systems **cannot** be the same (as illustrated in Figure 6-1 Case B) then the crosstalk generated by the interferer is inter-channel crosstalk.

The inter-channel crosstalk penalty from ITU-T G-series Recommendations – Supplement 39 (and including the effect of imperfect extinction ratio) is:

$$P_C = 10\log_{10}\left(1 - 10^{\frac{C_C}{10}}\frac{r+1}{r-1}\right) \quad [\text{dB}] \tag{6-6}$$

where:

P_C is the inter-channel crosstalk penalty (dB)

$C_C = \log_{10}(C)$ is the inter-channel crosstalk (dB), i.e., the ratio of the disturbing power to the wanted power detected by the receiver

r is the linear extinction ratio of the wanted signal.

The inter-channel crosstalk penalty for an ideal wanted signal, and one with 6 dB extinction ratio, is plotted in Figure 6-10.

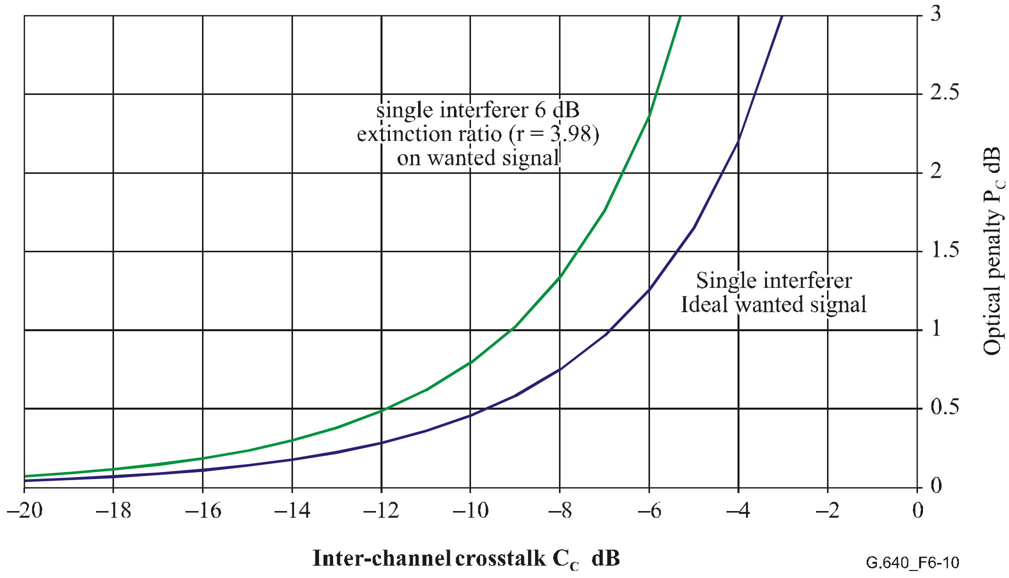

Figure 6-10/G.640 – Graph of optical penalty vs inter-channel crosstalk for a single interferer

6.5 Procedure for establishing whether the conditions for co-location longitudinal compatibility are met

When it is required to site two FSO systems in close proximity to each other, the following procedure allows an assessment to be made as to whether the two systems will produce unacceptable interference with each other. The procedure must be completed twice for each pair of FSO systems, once with one system as the wanted and the other as interferer and then again with the roles reversed.

1) Establish the optical penalty due to crosstalk that is allowed for in the power budget of the wanted system. For example this might be 0.5 dB.

2) Determine which of the two cases illustrated in Figure 6-1 applies. If there is a gap between the possible wavelength ranges of the two transmitters of at least the equivalent of the receiver electrical bandwidth then it is Case B and the crosstalk is inter-channel, otherwise it is Case A – interferometric crosstalk.

3) Calculate the crosstalk ratio. This is different depending upon the result of step 2.

   a) Case A. For interferometric crosstalk, use Equation 6-4 or 6-5 (depending on whether the receiver decision point is optimized or not) to calculate what value of crosstalk would generate the maximum penalty found in step 1. For example, a wanted transmitter with 6 dB extinction ratio, and a receiver with an average power decision threshold, will have a 0.5 dB penalty for a C_I of approximately –35 dB (see Figure 6-9).

   b) Case B. For inter-channel crosstalk, use Equation 6-6 to calculate what value of crosstalk would generate the maximum penalty found in step 1. For example, a wanted transmitter with 6 dB extinction ratio will have a 0.5 dB penalty for a C_C of approximately –12 dB (see Figure 6-10).

4) Using Equation 6-3 and values for the physical parameters of the two FSO systems, calculate whether the physical locations proposed for the two systems will allow the maximum crosstalk levels found in step 3 to be met under all conditions. The information provided in 6.2 should be taken into account to make sure that the parameter values used correspond to the worst case that may be encountered for any weather conditions under which the wanted system is expected to operate satisfactorily.

Examples of the use of this procedure in practical FSO systems can be found in Appendix I.

7 Optical safety considerations

Information on optical safety considerations relevant to FSO systems can be found in IEC 60825-1, IEC 60825-2 and IEC 60825-12.

IEC 60825-12, *Safety of free space optical communication systems used for transmission of information*, in particular, gives details of the classification of locations where FSO systems might be operated and specifies the requirements on equipment operated in each of them.

Appendix I

Example crosstalk calculations

I.1 Example 1

Two FSO systems of the same design are needed to be installed between the same pair of buildings resulting in two parallel free space links. The characteristics of the individual systems are:

- Distance between transmitter and receiver 400 m.
- Overall transmitted power maximum 8 mW and minimum 5 mW.
- Maximum transmitter beam divergence under worst weather conditions (d) 4 mrad.
- Transmitter minimum extinction ratio 8.2 dB.
- Maximum receiver acceptance angle (a) 5 mrad.
- Receiver has an average power decision threshold.
- Transmitter and receiver setting accuracy 1 mrad.
- Maximum crosstalk penalty 0.5 dB.

What is the minimum separation of the two systems? A reference diagram for this example is shown in Figure I.1.

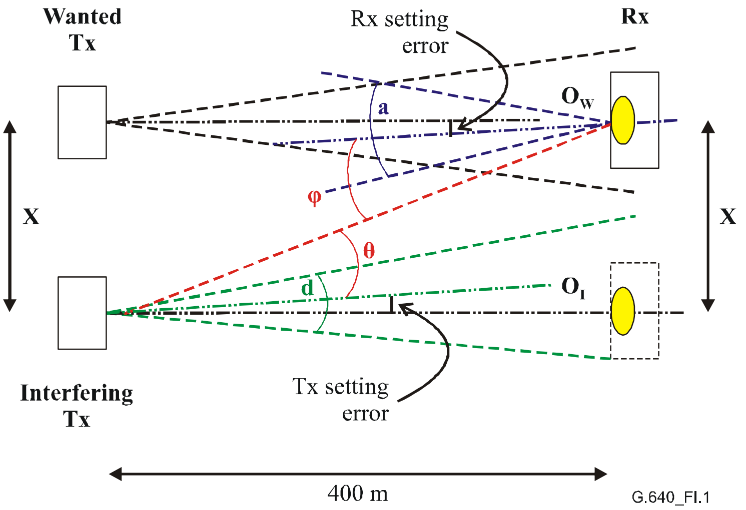

Figure I.1/G.640 – Example 1 crosstalk reference diagram

Following the procedure in 6.5 gives:

1) The maximum optical penalty due to crosstalk is 0.5 dB.

2) Because the two systems are the same design, the wavelengths can be the same so it is case A – interferometric crosstalk.

3) Calculate the crosstalk ratio for case A.

   a) Case A. For interferometric crosstalk with an average power decision threshold, use Equation 6-4 to calculate that C_I = –33.3 dB would generate a 0.5 dB penalty with an extinction ratio of 8.2 dB. In linear terms this is C_I = 0.000463.

4) Because, in this example, the links are parallel and the setting errors for the transmitter and receiver are the same, the angles θ and φ are the same for all values of separation X. Because the two links are the same length, the ratio of O_I to O_W is the same as the ratio of the maximum to minimum transmitted power (since the interfering transmitter could be at the maximum power and the wanted transmitter at the minimum). Also, because the wavelengths are the same, L = 1. Equation 6-3 therefore becomes:

$$0.000463 = \frac{8}{5} e^{\frac{-8\theta^2}{4^2}} e^{\frac{-8\theta^2}{5^2}}$$

This equation is satisfied when θ (and therefore φ) is 3.06 mrad.

From the geometry of the links:

$$\tan\left(\frac{1+3.06}{1000}\right) = \frac{X}{200}$$

which is satisfied for a separation X = 1.6 m.

I.2 Example 2

This example is the same as example 1 except that the worst-case characteristics of the transmitter beam are known to be inside the curve in Figure I.2, and the worst-case values of the optical power detected by the receiver vs angle are inside the curve in Figure I.3.

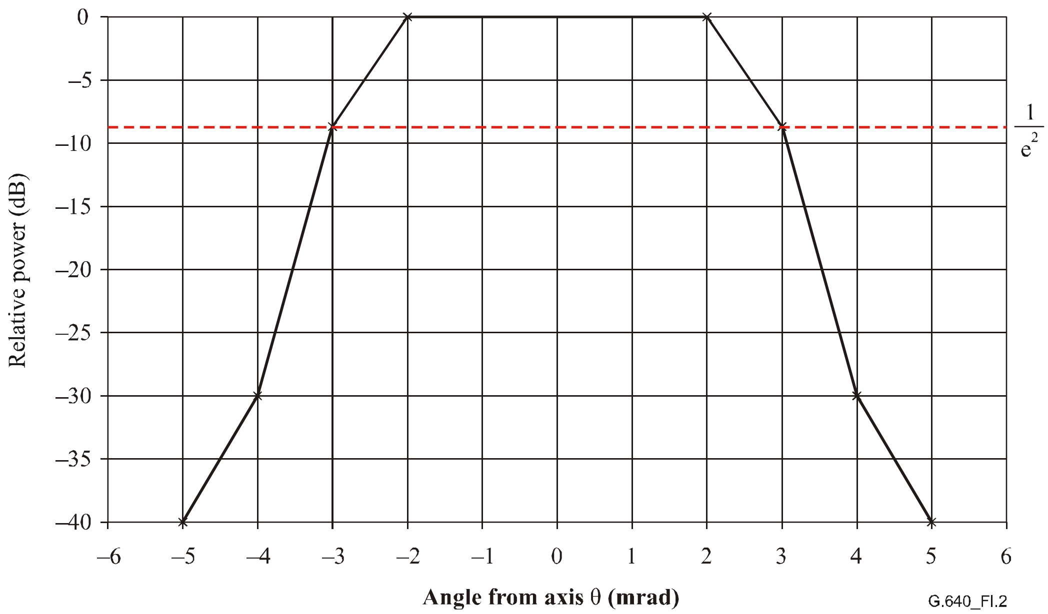

Figure I.2/G.640 – Worst-case curve of power density vs angle for the transmitters

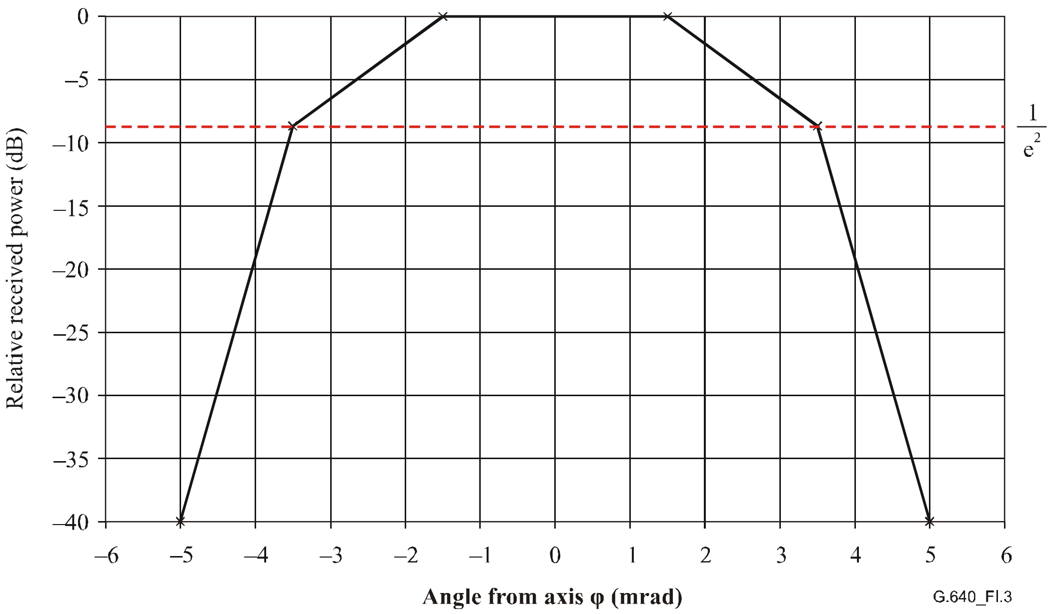

Figure I.3/G.640 – Worst-case curve of optical power detected by the receiver vs angle

The procedure for this example is identical to that of example 1, up to step 4. Now Equation 6-3 becomes:

$$0.000463 = \frac{8}{5} \textit{ (value from Figure I.2} \times \textit{value from Figure I.3)}$$

This equation is satisfied when θ (and therefore φ) is 3.82 mrad.

From the geometry of the links:

$$\tan\left(\frac{1+3.82}{1000}\right)=\frac{X}{200}$$

which is satisfied for a separation X = 1.9 m.

I.3 Example 3

Two FSO systems of the same design are needed to be installed in the arrangement shown in Figure I.4.

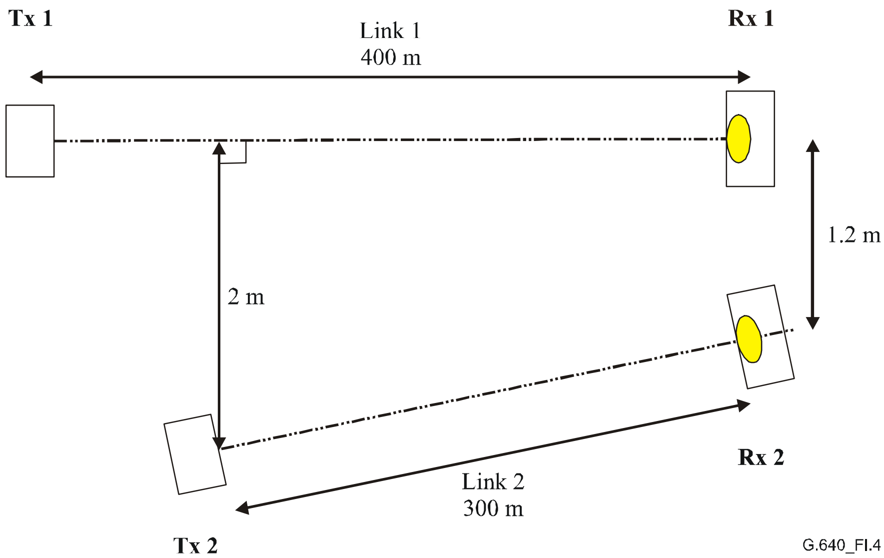

Figure I.4/G.640 – Example 3 configuration

The characteristics of the two systems are:

- Overall transmitted power maximum 8 mW and minimum 5 mW.
- Maximum transmitter beam divergence under worst weather conditions (d) 4 mrad.
- Transmitter minimum extinction ratio 10 dB.
- Maximum receiver acceptance angle (a) 6 mrad.
- Receiver has an average power decision threshold.
- Transmitter and receiver setting accuracy 1 mrad.
- Maximum crosstalk penalty 0.5 dB.
- Link 1, distance between transmitter and receiver 400 m.
- Allocation in Link 1 budget for atmospheric attenuation 25 dB.
- Link 2, distance between transmitter and receiver 300 m.

Will the crosstalk penalty be acceptable for both systems?

A reference diagram with link 1 as the wanted system is shown in Figure I.5.

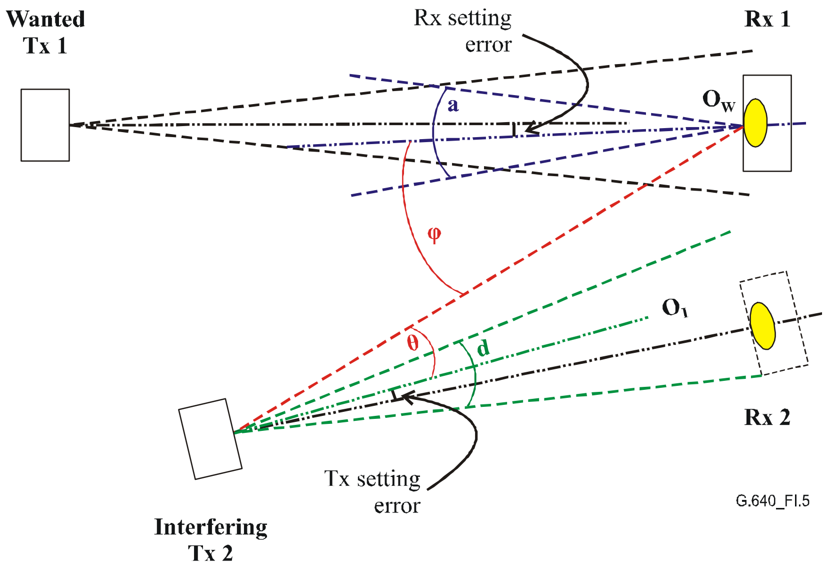

Figure I.5/G.640 – Example 3 crosstalk reference diagram for link 1

Following the procedure in 6.5 for Tx 1 as the wanted transmitter and Tx 2 as the interferer gives:

1) The maximum optical penalty due to crosstalk is 0.5 dB.

2) Because the two systems are the same design, the wavelengths can be the same so it is Case A – interferometric crosstalk.

3) Calculate the crosstalk ratio for Case A.

   a) Case A. For interferometric crosstalk with an average power decision threshold use Equation 6-4 to calculate that C_I = –32.6 dB would generate 0.5 dB penalty with an extinction ratio of 10 dB. In linear terms this is C_I = 0.000545.

4) From the geometry defined in Figure I.4, the angle φ ≈ 1000 × arctan(2/300) – 1 mrad which is 5.67 mrad, and the angle θ ≈ 1000 × arctan(1.2/300) – 1 mrad which is 3.0 mrad. Because link 2 is shorter than link 1, the ratio of O_I to O_W depends on the square of the link distances, the weather conditions, and the ratio of the maximum to minimum transmitted power (since the interfering transmitter could be at the maximum power and the wanted transmitter at the minimum power). This ratio is therefore:

$$\frac{O_I}{O_W} = \frac{8}{5}\frac{400^2}{300^2}10^{\frac{\left(25-25\frac{300}{400}\right)}{10}} = 12$$

with the last term taking account of the atmospheric attenuation in link 2 in conditions where there is 25 dB of attenuation in link 1. Because the wavelengths can be the same, L = 1. Equation 6-3 therefore becomes:

$$C = 12\,\mathrm{e}^{\frac{-8\times 3.0^2}{4^2}}\,\mathrm{e}^{\frac{-8\times 5.67^2}{6^2}} = 0.0000106 = -39.7\ \mathrm{dB}$$

Since this level of crosstalk is below the value of –32.6 dB, which is the maximum the receiver can tolerate, the proposed geometry of the links is acceptable to link 1.

A reference diagram with link 2 as the wanted system is shown in Figure I.6.

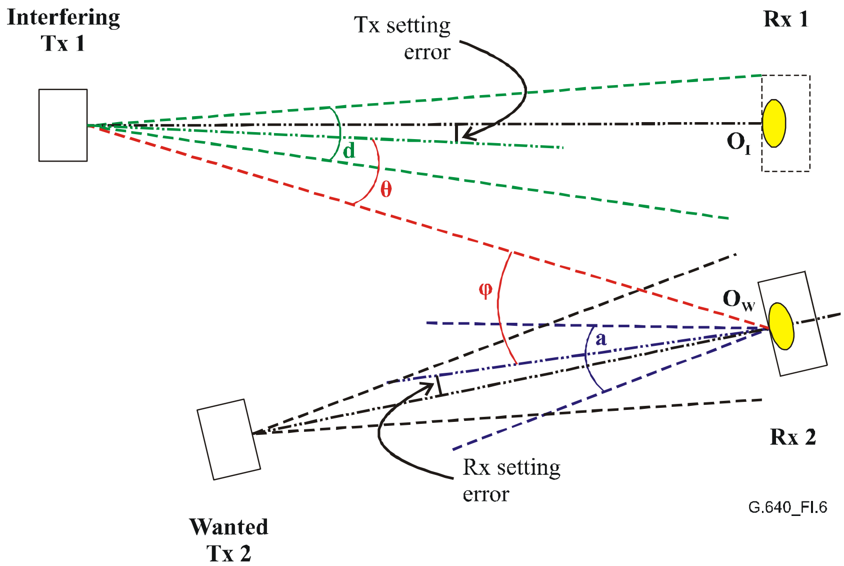

Figure I.6/G.640 – Example 3 crosstalk reference diagram for link 2

Following the procedure in 6.5 for Tx 2 as the wanted transmitter and Tx 1 as the interferer gives:

1) The maximum optical penalty due to crosstalk is 0.5 dB.

2) Because the two systems are the same design, the wavelengths can be the same so it is Case A – interferometric crosstalk.

3) Calculate the crosstalk ratio for Case A.

   a) Case A. For interferometric crosstalk with an average power decision threshold, use Equation 6-4 to calculate that C_I = –32.6 dB would generate a 0.5 dB penalty with an extinction ratio of 10 dB. In linear terms this is C_I = 0.000545.

4) From the geometry defined in Figure I.4 the angle φ ≈ 1000 × (arctan(0.8/300) + arctan(1.2/400)) – 1 mrad which is 4.67 mrad, and the angle θ ≈ 1000 × arctan(1.2/400) – 1 mrad which is 2.0 mrad.

   Because link 2 is shorter than link 1, the ratio of P_I to P_W depends on the square of the link distances, the weather conditions, and the ratio of the maximum to minimum transmitted power (since the interfering transmitter could be at the maximum power and the wanted transmitter at the minimum). The crosstalk will be worst for clear conditions, so the worst ratio is therefore:

$$\frac{P_I}{P_W} = \frac{8}{5}\frac{300^2}{400^2} = 0.9$$

   Because the wavelengths can be the same, L = 1. Equation 6-3 therefore becomes:

$$C = 0.9\, e^{\frac{-8\times 2.0^2}{4^2}}\, e^{\frac{-8\times 4.67^2}{6^2}} = 0.000964 = -30.2\text{ dB}$$

   Since this level of crosstalk is above the value of –32.6 dB, which is the maximum the receiver can tolerate, the proposed geometry of the links must be changed in order to avoid link 1 exceeding its maximum crosstalk penalty. This can be achieved by increasing the separation of the receivers to at least 1.4 m.

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