Multimode Fibre Launch Conditions

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Documents

- The discussions relate to the following documents
- 86C_1004_ IEC 61282-11
- 86B/3265/CD 61755-2-3
- 86B_3136e_CD IEC 61755-1-1
- 10.7 406 Multimode Interface Standard, Multimode optical interface – random mate loss Simulation, Tom Hanson, James Luther, Steve Swanson, Taormina, Sicily – 2011-04

- We would like to honour the substantial and high quality modelling work of contributors to these documents including Tom Hanson and Bob Conte
- The suggestions in this talk aim only to refine the earlier work.

Experimental Validation and Error

- All numerical modelling methods must be validated by comparison with experiment before they can be trusted.
- An assessment of the error, uncertainty or accuracy of the results of the modelling method compared to experiment should be quoted for a range of cases.
- In the case of statistical modelling methods the experimental validations must be carried out at regular intervals across the full positive and negative expected range of all variables
- In this case the main variables are the lateral offset, the core diameter (CD) and the numerical aperture (NA) with the result being the loss. Additional variables may be the type of connector, the type of fibre, the manufacturer

Experimental Validation

- In addition, in the case of statistical modelling the actual probability distributions and not just the mean and standard deviation of each variable must be established and if reproducible between connector and fibre manufacturers must then be used in the calculations.

Different Probability Distributions

- If connector or fibre manufacturers have different means and standard deviations for each of the variables or even completely different probability distributions then these must be used in the modelling which makes the results specific to just that manufacturer.
- The modelling method can still be put into a standard it is just that the results will not be generally applicable and so it would not make sense to put general graphs or equations into the standard except as specific examples.

Different Probability Distributions

- In such a case a large number of different expected cases for different means, standard deviations and probability distributions could all be run and stored and for any new case within the ranges interpolated values could be obtained.
- Alternatively, the modelling program could be made available for manufacturers to input their own particular values for means, standard deviations and probability distribution functions.
- In this case the program may need to have a user friendly interface which need not give access to all the functionality of the program.
- A means for users to pay a licence fee to gain access to the program would be reasonable to pay for development and maintenance costs.

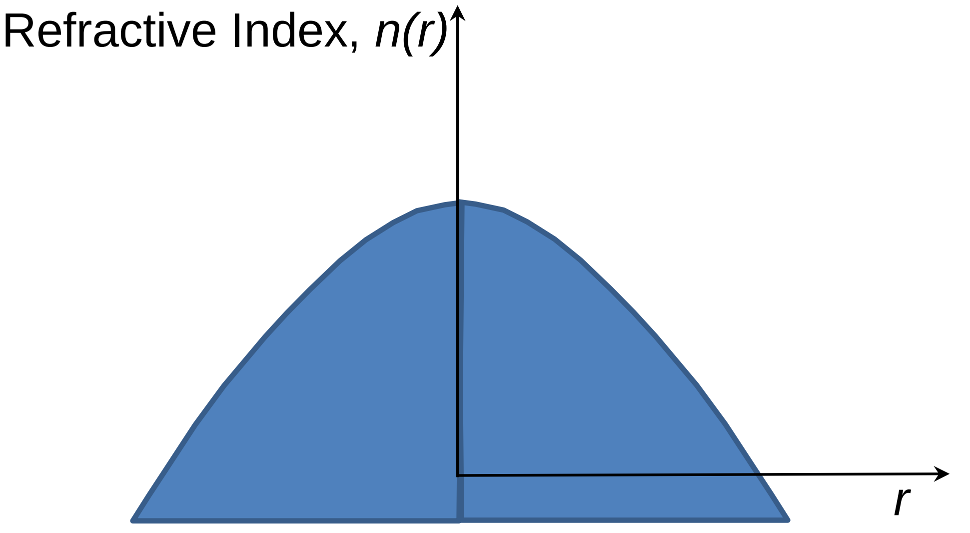
Monte Carlo Simulations

- When there is a non-linear relationship so that cascading two multimode fibre patchcords do not give twice the loss of one then more detailed mathematical modelling must be performed.
- When the variables have statistical distributions then one approach is to carry out the simulations at small regular intervals across the full positive and negative expected range of all variables to fully characterise the performance but this can be time consuming
- If the dependence on the variables is smooth and slowly varying then larger intervals across the variable ranges can be used to reduce calculation time which may be possible in this case given the slow smooth variation in figure 5 of 86B/3265/CD 61755-2-3

Validity of Monte Carlo Simulations

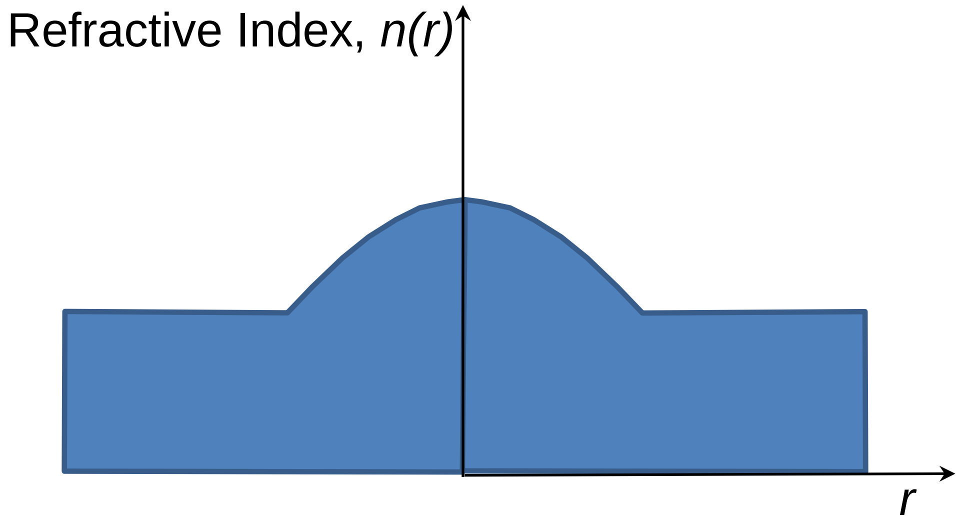
- However, if the statistical distributions vary from one manufacturer to another and/or if the dependence on the variables is not known to be smooth and slowly varying then a reasonable approach is to use a Monte Carlo simulation.
- However, a graph should be plotted of the output result, in this case for loss, versus the number of Monte Carlo simulations. Such a graph usually varies and then saturates becoming stable after a certain number of Monte Carlo simulations. This number or a number slightly higher for safety can then be used as the minimum number required
- As a rough guide we use 100,000 runs to simulate coupling to multimode waveguides whereas the simulations performed here used 4000 on line 286 86B/3265/CD. 4000 may be sufficient if the output graph has saturated for that value but this must be checked.

Laguerre-Gauss Functions



- Laguerre-Gauss functions are the exact orthogonal mode eigenfunction solutions for an infinitely extended parabolic refractive index profile in cylindrical waveguides.
- That is fibres with no cladding and just a parabolic graded refractive index core.

Graded core, constant cladding index Multimode Fibres

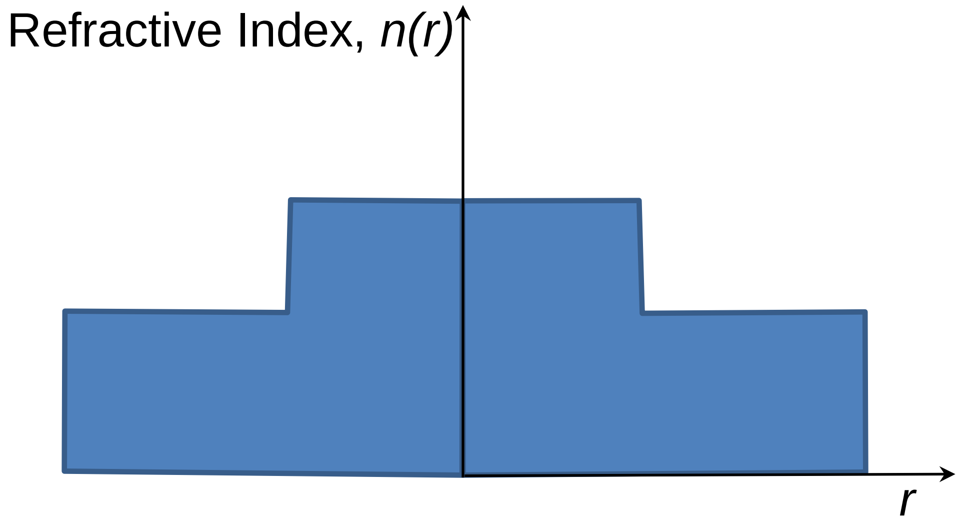


- Laguerre-Gauss functions are not the actual modes but are approximate solutions for a parabolic core index and a fixed cladding index. 86C_1004_ IEC 61282-11 document says:

NOTE Real fibres are neither exactly parabolic nor circular. However, the simplified theory has been found to yield reasonable results on limiting the effects of launching cord near field variations to variance in measured attenuation.

The infinite parabola model is defined as

Step index Multimode fibres



- Laguerre-Gauss functions are not ideal and are further from the actual modes of the step index fibre.

Improved accuracy

- However, there is no need to assume that the modes are Laguerre-Gauss functions which are approximate.
- Instead the exact modes can be calculated and expressed as a weighted sum of a set of an orthonormal complete set of functions such as Laguerre – Gauss.
- When we sum all of the more accurate modes we will still end up with a sum of Laguerre – Gauss functions as in IEC61282-11 method BUT there will be different weighting coefficients.
- There are several papers which describe how to calculate these weights which can be followed.

Relevant Research Papers

- Jean Pierre Meunier and Shaikh Iqbal Hosain, An Efficient Model for Splice Loss Evaluation in Single-Mode Graded-Index Fibers, Journal of Lightwave Technology, Vol. 9, No. 11, pp 1457 November 1991
- Evaluating the splice losses between two identical arbitrarily graded index single-mode fibers caused by transverse and angular misalignments. The power transmission coefficients at the splice are expressed as **weighted** sum of simple Laguerre-Gaussian functions, the weight factors being computed by solving a linear matrix eigenvalue problem.

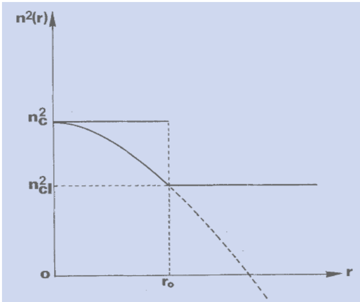
Relevant Research Papers

- R. L. Gallawa, A. Kumar, A. Weisshaar, Fibre splice loss: a simple method of calculation, Optical and Quantum Electronics 26 (1994) S165-S172
- We use Galerkin's method, but **expand the field of both fibres in terms of the same set of basis functions**, leading to considerable simplicity: the overlap integral is simply the inner (dot) product of the eigenvectors. Integration is thus avoided.

Relevant Research Papers

- R. Mussina, B.P. de Hon, R.W. Smink, A.G. Tijhuis, Modal Modeling Strategies for the Design of Optical Fibers, IEEE/LEOS Benelux Symposium, November 27 and 28, 2008
- This paper shows how to use the Galerkin method to calculate **the weights for the sum of Laguerre – Gauss functions to represent the modes** for any arbitrary radial, circularly symmetric refractive index distribution in single mode fibres.
- The advantages are a very fast convergence, the number of basis functions N in the range 14 to 20 is a good compromise between accuracy and computation time
- The technique is valid for multimode fibres but to our knowledge has not yet been used for them.

Infinite Parabola Model



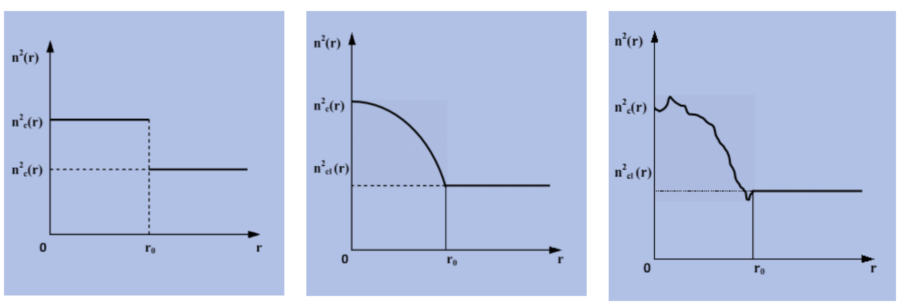
Eigensolutions:

Laguerre-Gauss polynomials

$$\psi_{mn}\left(x(r)\right) = \sqrt{\frac{V}{\pi}}\exp\left(-x(r)/2\right)x(r)^{m/2}L_n^m\left(x(r)\right)$$

Fibre Model with Arbitrary Refractive Index Profile

Guided modes: $$\psi_m(r,\theta) = \sum_{n=1}^{\infty} c_n \psi_{nm}(r)\exp(-im\theta)$$



coefficients c_n are defined by the Galerkin method

step-index
truncated parabolic
arbitrary profile

Galerkin Method

$$\left[\frac{d^2}{dr^2}+\frac{1}{r}\frac{d}{dr}+k_0^2n^2(r)-\frac{m^2}{r^2}-\beta^2\right]\psi_{mn}(r)=0$$

$$Ax=\beta^2x$$

The matrix eigenvalue problem

- *A* is symmetric
- has purely discrete real eigenvalue spectrum
- the eigenvalues provide the propagation coefficients β for guided modes
- components of the eigenvectors represent the expansion coefficients c_n

Weak Guiding Limitation

- The scalar wave equation solution depends on there being weak guiding with a refractive index difference of $\Delta < 0.05$
- The cases analysed are for $\Delta < 0.010$, $\Delta < 0.019$ so are fine.
- Note that the method may not work for silica core and polymer cladding multimode fibres unless $\Delta < 0.05$

Orthonormal Condition 86C_1004_ IEC 61282-11

411 The mode field is scaled for unit power $\int_0^{2\pi}\int_0^{\infty} r\left(\psi(r,\theta)\right)^2 dr\, d\theta = 1.$

- This formula appears to be in essence correct. It is the condition for orthonormal basis functions which is normally required in calculations.
- However, there is usually a π constant in the equations on line 411 or line 407.

86C_1004_ IEC 61282-11 Typos

- Line 214 Delete the each
- Line 296 a reference is missing
- There is a misprint in line 407 equation 15: there should be a ξ instead of ε.
- Line 430 Equation 18 Ψ should be squared
- A reference is missing in line 549
- Line 590 50 microns spectral width should be 50 nm

86B/3265/CD 61755-2-3

- 86B/3265/CD 61755-2-3 Table 1 line 119 Bm is 0.30 presumably dB mean attenuation whereas in 86B_3136e_CD IEC 61755-1-1 line 188 Table 2 and in 10.7 406 Multimode Interface Standard, Bm is 0.35 dB mean. Which one is correct?
- Both tables specify >=97% but 2 sigma is 95.4% so would that be a better figure to use?
- Lines 229-230 are the core diameters and NA varied about the same values for all connectors? However, the mean value may vary from manufacturer to manufacturer and still have the same tolerances.

86B/3265/CD 61755-2-3

- Line 225 figure A.1 says the reference connector has nominal core diameter and NA and line 134 says it has a nominal fibre. Is it better for the reference grade termination to be an independent standard or to have the most probable values for NA, CD and offset in the batch of patchcords to be measured?
- Line 185 Figure 5 If the curve represents the average loss at 97% (not defined) is the loss lower below the curve?
- Two curves are needed for Bm and Cm and each should be split into two - mean and 97%-tile.
- Are these simulations for GI or SI fibre and which of these types of fibre is used in the reference connector? Curves should be provided for both types.

Assumptions
86B/3265/CD 61755-2-3

These questions can only be answered by making assumptions about:

- The distributions of CD and NA.
- An assumption about the launching mode group power distribution.
- An assumption about the shape/form of the offset distribution.

The assumptions are:

- CD/NA are Gaussian random variables with standard deviation equal to 1/3 of the Standard specification tolerance.
- The launching mode group power distribution is the one that is close to the lower EF limit.
- The distribution of connection 0 offset is Rayleigh, or the square root of the sum of squares of two independent Gaussian random variables, which can be considered as x/y displacements of the optical center inside connector B from the optical center of the launching reference connector (connector A).

- These assumptions must be validated experimentally.

86B/3265/CD 61755-2-3

- Line 307 change height, Δ to refractive index difference, Δ
- Line 445 change decrease to increase

Concatenation

- If a cascade of many terminated fibre patchcords are chosen from the same batch and joined together then even if the various random distributions of CD and NA are not Gaussian the combination of them all will tend towards Gaussian by the Central Limit Theorem.
- This suggests the Gaussian distribution modelling is accurate for a cascade of many fibre patchcords so this is how they should be measured so that any one having extreme values does not unduly influence the final measurements.

Concatenation

- In 86B/3265/CD 61755-2-3 Table A.4 and Figure A.6 show a non-linear relationship between loss and number of concatenated fibres.
- However, they also show that after about 5 connectors the remainder of the curve is much more linear than for one or two connectors. It could even be approximated by a linear curve beyond about 5 connectors.

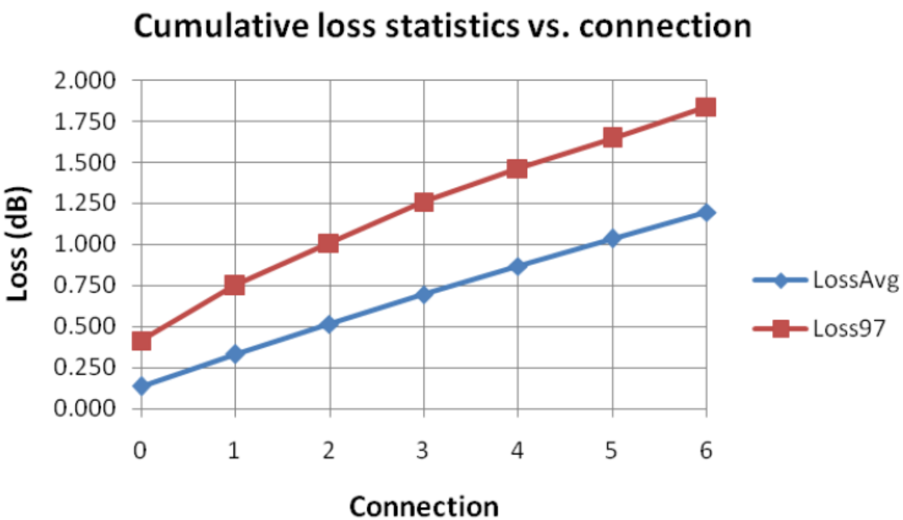


Table A.4 – Cumulative loss vs. connection

	Cumulative		Cum Normalized		Difference	
connection	LossAvg	Loss97	LossAvg	Loss97	LossAvg	Loss97
0	0.136	0.415	0.136	0.415	-	-
1	0.330	0.748	0.165	0.374	0.193	0.333
2	0.517	1.007	0.172	0.336	0.187	0.259
3	0.697	1.257	0.174	0.314	0.180	0.251
4	0.868	1.462	0.174	0.292	0.172	0.204
5	1.034	1.648	0.172	0.275	0.165	0.186
6	1.196	1.838	0.171	0.263	0.162	0.190

Concatenation

- The use of a reference grade termination at the first connector is not typical of practical use and may lead to unrealistic results.
- However, after about 5 terminations the effect of the first reference grade termination is being lost within the results dominated by the actual patchcords themselves. So this is a better region in which to carry out measurements likely to give more reproducible results.
- All of the documents seem to suggest that two fibre patchcords should be concatenated after the reference grade termination.
- However, it seems to be better to concatenate at least about 5 fibre patchcords.
- Indeed Table A.1 in 86B/3265/CD 61755-2-3 says that 6 or 9 concatenations were used in simulations.

Reproducible Results

- To get similar measurement results in different laboratories one method is to use similar high quality reference grade terminations at connection 0.
- However, perhaps a better method is to use at least 5 concatenated fibre patchcords chosen from the same batch so that individual fibre and connector characteristics are averaged out.
- Indeed it may even be possible to omit the first reference grade termination and just to use connectors and patchcords chosen from a batch. This would need to be confirmed by further modelling.

Probability Distribution Functions

- The document 10.7 406 Multimode Interface Standard, recommends that Gaussian distributions are not used for offsets but instead raised cosine distributions.
- In document 86B/3265/CD 61755-2-3 lines 228 – 229 it says Gaussian random distributions were used for CD, NA and lateral offset. However, later in the same document on line 368 it says Rayleigh random distributions are used for the offset. Non of these are the raised cosine distributions apart for the case of simulating a broadband source.
- The actual probability distribution functions of each variable should be measured experimentally and after removal of outliers used in the modelling.

86B_3136e_CD IEC 61755-1-1

- Document 86B_3136e_CD IEC 61755-1-1 does not mention that outliers with loss of more than 0.5 dB are excluded so needs updating.
- In document 86B_3136e_CD IEC 61755-1-1 Line 132 The measured numerical aperture of the core. Should replace core by core and cladding.

Detectors

- Non of the documents mention detectors
- Are the detectors large area intercepting all diverging free space light from the last connector?
- Are the detectors integrating sphere types which would be normal for averaging out speckle and spatial non-uniformities on the detector?
- Does the detector have a fibre attached to it and if so what kind of connector is on that fibre. Does the detector have another reference grade termination?

Graphs and Equations

- Are the graphs plotted and equations given the most useful ones for the industry users?
- If not what would the industry users like to see as it may be easy to present the same data in another way?

Optical Launched Field

- For a single wavelength the optical launched field is fully characterised

1) If the amplitude and phase of the spatial near field are known as a function of *r*, θ or *x, y*, OR
2) If the amplitude and phase of the angular far field distribution are known as a function of ϕ, θ

Note that 1) and 2) can be found from each other by a 2D Fourier Transform so either is sufficient to have full knowledge

- However, finding the amplitude and phase requires use of interferometers which require stable laboratory conditions for use.

Optical Launched Field

- For a single wavelength the optical launched field is almost known apart from knowledge of phase

1) If the intensity of the spatial near field is known as a function of *r*, θ or *x, y* OR
2) If the intensity of the angular far field distribution is known as a function of ϕ, θ

Note that 1) and 2) can be found from each other by a 2D Fourier Transform by Parseval's Theorem so either is sufficient

- If the azimuthal variation is averaged the intensity $I(r)$ or $I(\phi)$ are obtained which can be used to calculated spatial encircled flux or angular encircled flux.
- So either spatial encircled flux or angular encircled flux can be used but there is no need for both.

Optical Launched Field

- However, if the optical source has a broad range of wavelengths and if they are not separated out at the power detector by spectral analysis and treated separately as before then their individual power distributions add losing information and the Fourier transform relationship between near and far field breaks down so they contain different information. In this case the most knowledge about the launched field is found by recording both of

1) The intensity of the spatial near field as a function of r, θ or x, y AND
2) The intensity of the angular far field distribution as a function of ϕ, θ

- So both the azimuthally averaged intensities $I(r)$ and $I(\phi)$ are required which can be used to calculate both spatially encircled flux and angularly encircled flux.