Propagation Delay Skew in Multimode Channels

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Overview

- Estimate the worst-case magnitude of various propagation delay skew factors due to transmission over parallel OM3 fibers
  - to provide guidance for de-skewing buffer depth and
  - circuits that must handle dynamic skew variation
- Establish an upper bound by summing worst-case values of the various factors
  - some static, some dynamic
  - result exceeds actual measured skew by wide margin
- Convert skew into baud rate unit intervals as a function of distance
  - Allows examination of trade-off of buffer depth vs. distance

Skew contributors

- Numerical Aperture (NA) range
- Fiber strand length difference
- Cabling stress effects
- Differential Mode Delay (DMD)
- Group delay difference over operating wavelength range (relative group delay)

NA range

- **Fiber standards define the max and min NA**
  - **For a given cladding Index of Refraction (IoR), the NA specs bound the range of IoR at the center of the core**

by definition $NA = (IoR_{core}^2 - IoR_{clad}^2)^{1/2}$

rearranging $IoR_{core} = (NA^2 + IoR_{clad}^2)^{1/2}$

where:

NA max (std) = 0.215

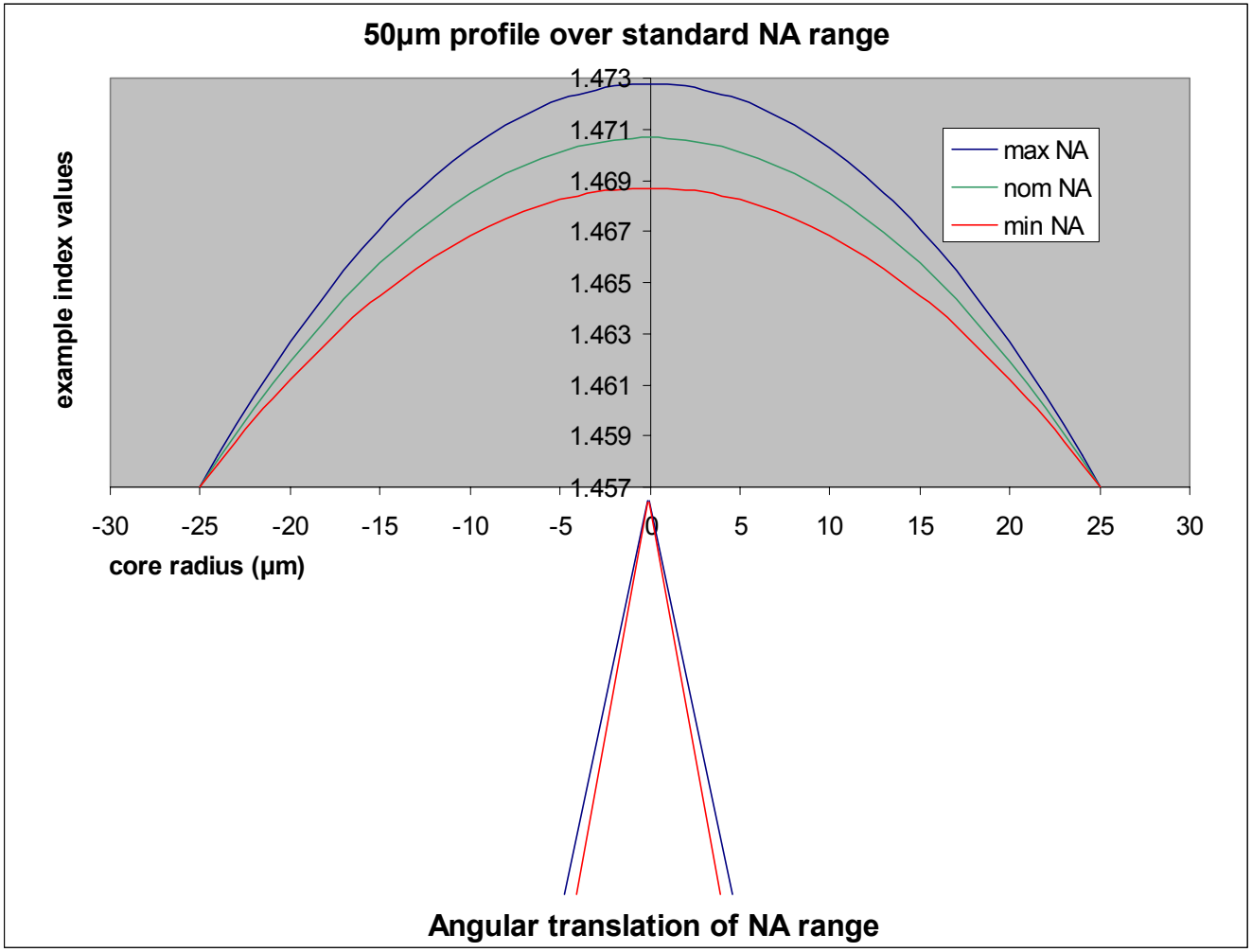
NA min (std) = 0.185

IoR_{clad} nom = 1.457

- **IoR_{core} range translates directly to propagation delay range, i.e. maximum skew due to NA**

Max NA Skew = ($IoR_{core,max}$ - $IoR_{core,min}$) / speed of light = 13.6 ps/m

Index profile range and associated NA



Strand length difference

- **Fiber strands within a section of cable can be of different length depending on construction, stranding**
- **Skew contribution is proportional to length difference**

  skew (ps/m) = differential length factor × propagation delay factor (ps/m)
- **Chosen differential length factor should be conservative estimate based on factory data & stranding knowledge**
  - **Suggest 0.005 (0.5%), illustrated here:**

- **Propagation delay factor should be conservative to account for variation in cladding IoR**
  - **5000 ps/m is conservative relative to that associated with nominal cladding IoR and maximum NA (4913 ps/m)**
- **With these values:**

Strand Length Skew = 0.005 × 5000 = 25.0 ps/m

Cabling stress effects

- Mechanical stress changes the IoR of the glass, and therefore affects propagation delay
- Stress differences between strands is a source of skew
- Proof test standard: ≥ 100 kpsi (0.69 GPa), i.e. ~1% strain
- Cables impart less than this strain under max rated tensile load†
  - Assume residual post-installation strain is 50% of max† (very conservative)
  - Imparted to at least one strand, while at least one other at zero (worst-case difference)
- Stress-refraction coefficient estimated as†† 2.6×10^{-5} ($kpsi^{-1}$)

Max Stress Skew = [(50 – 0) × 2.6×10^{-5}] / speed of light = 4.4 ps/m

†Telcordia GR-20 recommends installation strain at ≤ 60%, and residual at ≤ 20%, of proof

††J. R. Simpson et.al. "A single-polarization fiber" JLT Vol LT-1, No 2, June 1983, pp 370-374

DMD imparted skew

- DMD is the difference in propagation delay between fastest and slowest modes in a multimode fiber
- A source of skew if launch conditions from the transmitter or upstream fiber change, exciting different modes
  - Laser heating or aging
  - Connection alignment shift from mechanical load
- For transmitters compliant to -SR launch, power is concentrated within inner 19µm radius corresponding to inner mask of DMD templates
  - Maximum inner mask DMD for OM3 = 0.33 ps/m

Max DMD Skew = 0.33 ps/m

Group delay

- **Propagation delay depends on wavelength**
  - **Known as group delay, and cause of chromatic dispersion**

$$\text{Relative Group Delay} = A + S_0/8 \left[\lambda^2 \left(1 + (\lambda_0 / \lambda)^4 \right) \right]$$

where:
A = arbitrary number, usually chosen to set RGD to 0 when $\lambda = \lambda_0$
S_0 = zero dispersion slope
λ = operating wavelength
λ_0 = zero dispersion wavelength

- **Skew arises from the difference in group delay across the operating wavelength range (relative group delay)**
  - **Wavelength range assumed to follow -SR**

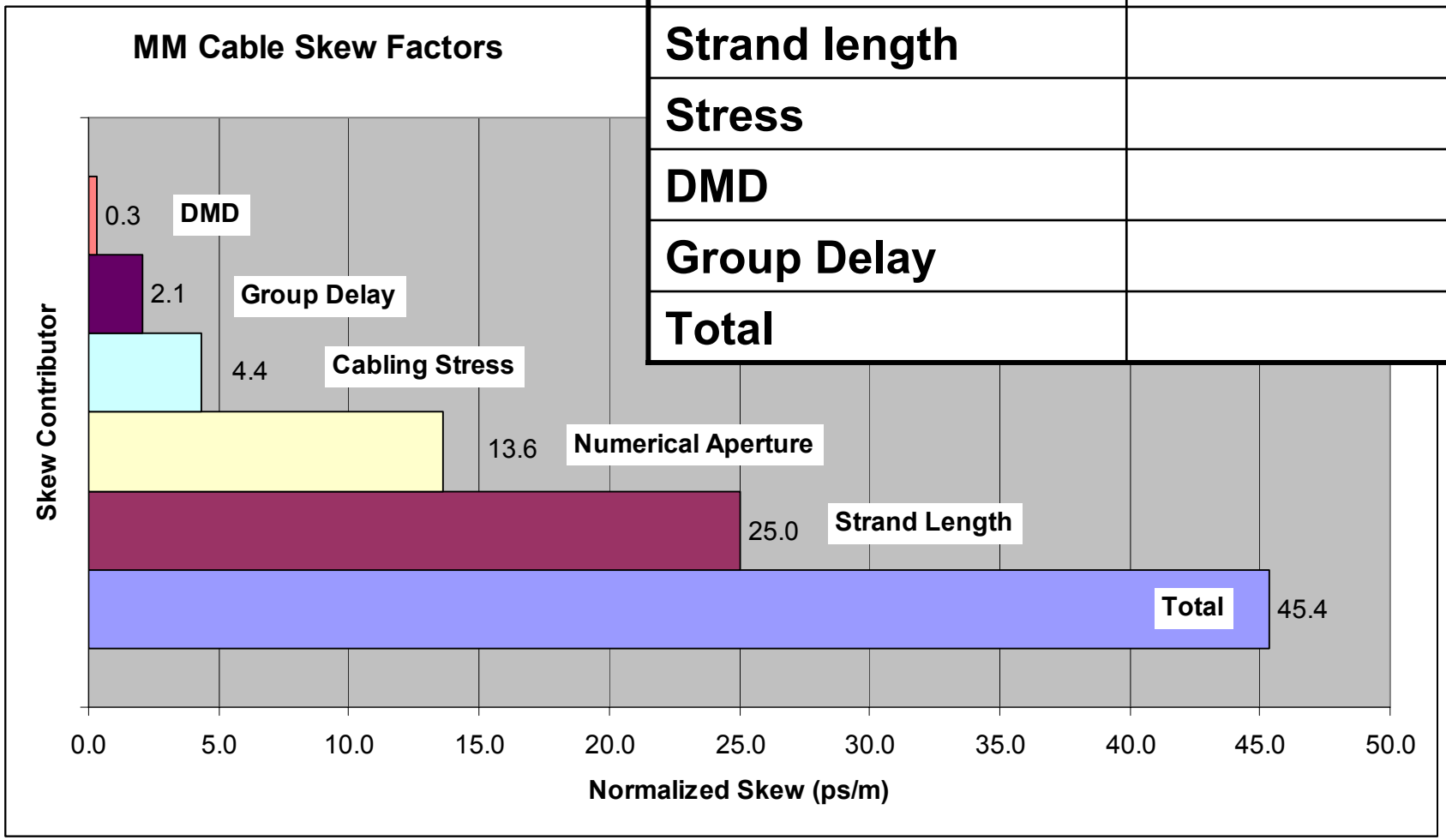
$$\text{Skew (ps/m)} = S_{0skew}/8000 \left\{ \left[\lambda_{min}^2 \left(1 + (\lambda_{0skew} / \lambda_{min})^4 \right) \right] - \left[\lambda_{max}^2 \left(1 + (\lambda_{0skew} / \lambda_{max})^4 \right) \right] \right\}$$

where:
S_{0skew} = worst-case zero dispersion slope to maximize skew (0.102 ps/nm^2•km)
λ_{0skew} = worst-case zero dispersion wavelength to maximize skew (1318 nm)
λ_{min} = minimum operating wavelength (840 nm)
λ_{max} = maximum operating wavelength (860 nm)

Max Group Delay Skew = 2.1 ps/m

Skew contributor magnitude summary

Contributor	Magnitude (ps/m)
NA	13.6
Strand length	25.0
Stress	4.4
DMD	0.3
Group Delay	2.1
Total	45.4



Dynamic skew contributors

- **Dynamic contributors are those that can change over time**
  - **NA: fixed by glass, not dynamic**
  - **Strand length: fixed during manufacturing & terminating, not dynamic**
  - ☑ **Stress: variable due to relaxation & temperature, dynamic**
  - ☑ **DMD: variable due to launch & coupling variation, dynamic**
  - ☑ **Group delay: variable due to laser wavelength shift with temperature and wavelength drift over time, dynamic**

Skew contributor summary

Contributor	Worst-Case Magnitude (ps/m)	Max Dynamic Magnitude (ps/m)
NA	13.6	0
Strand length	25.0	0
Stress	4.4	4.4
DMD	0.3	0.3
Group Delay	2.1	2.1
Total	45.4	6.8

The worst-case magnitude overshadows the dynamic magnitude.

Under the assumptions made herein, the worst-case skew is ~1% of propagation delay.

The actual skew observed in real cables is far lower.

Skew vs. Length

link length (m)	worst-case skew (ps)	worst-case skew (UI)	dynamic skew (ps)	dynamic skew (UI)
0	0	0.0	0	0.0
25	1134	11.7	169	1.7
50	2268	23.4	338	3.5
75	3402	35.1	507	5.2
100	4537	46.8	676	7.0
125	5671	58.5	845	8.7
150	6805	70.2	1014	10.5
175	7939	81.9	1183	12.2
200	9073	93.6	1352	13.9
225	10207	105.3	1521	15.7
250	11342	117.0	1690	17.4
275	12476	128.7	1858	19.2
300	13610	140.4	2027	20.9

UI calculation for 10.3125 Gbaud

Multimode Skew Model Spreadsheet

OM3 cable skew model — Paul Kolesar, Pete Anslow — 6-May-08 rev 0_5

OM3 multimode fiber cable skew factors	parameter 1	parameter 2	parameter 3	normalized skew (ps/m)
numerical aperture (NA) difference	NA, max (unitless) **0.215**	NA, min (unitless) **0.185**	cladding IoR, nom (unitless) **1.457**	13.6
strand length difference	differential length factor **0.0050**	propagation delay (ps/m) **5000**	n.a.	25.0
cabling stress difference	stress, max (kpsi) **50**	stress, min (kpsi) **0**	stress-refraction coef ($kpsi^{-1}$) **2.61E-05**	4.4
DMD difference for OM3 at 850 nm (inner mask)	DMD, max (ps/m) **0.33**	DMD, min (ps/m) **0**	n.a.	0.3
relative group delay for worst-case wavelength range	wavelength, max (nm) **860**	wavelength, min (nm) **840**	n.a.	2.1
total worst-case skew at 850 nm				45.4
total maximum dynamic skew				6.8

Other inputs		
speed of light in vacuum	**299,792,458**	m/sec
zero dispersion wavelength for max skew @ 850 nm	**1318**	nm
zero dispersion slope at zdw, max	**0.102**	ps/nm^2-km
baud rate	**10.3125**	Gbaud
initial link length	**0**	m
link length increment	**25**	m

link length	worst-case skew		dynamic skew	
(m)	(ps)	(UI)	(ps)	(UI)
0	0	0.0	0	0.0
25	1134	11.7	169	1.7
50	2268	23.4	338	3.5
75	3402	35.1	507	5.2
100	4537	46.8	676	7.0
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Summary

- Calculated worst-case skew for parallel multimode transmission on OM3 at ~850 nm
- Created a skew model for committee use
  - As was done for the singlemode skew model, expect a motion to adopt the model during the closing session