IEEE802.3 4P Study Group
Predicting Cable P2P Resistance Unbalance (P2PRunb) from existing cabling parameters

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Terminology

- P2P = Pair to Pair
- P2PRunb = Pair to Pair Resistance Unbalance.
- Runb=Pair Resistance Unbalance

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Objectives

- To investigate the possibility of predicting **Cable** Pair to Pair Resistance Unbalance (P2PRunb) which is currently not specified, by using specified cable parameters such as:
  - Propagation Delay[2] and / or,
  - Delay skew[2,]
  - Characteristic impedance requirements[3]
  - Or others.

- *Having the cable P2PRunb will allow us to complete the work on the entire channel P2PRunb from July 2013.*

Notes:

1. The final decision of maximum P2PRunb will be taken based on cabling vendors inputs. This work meant to get an idea of what is expected in order to allow us to move forward in our analysis for the entire CHANNEL for P2PRunb until formal specifications from TIA will be available.

2. See Annex A1 for propagation delay and skew definitions and Annex C for specifications. See Annex E for transmission line model and its main parameters

The need for **Cable** P2P resistance unbalance spec.

- In 4P operation, the total load current is divided between Alternative A pairs and Alternative B pairs.

- If channel resistance in all pairs is not equal, then the load current in Alternative A pairs and Alternative B pairs will be different from each other. The resulting difference in current may affect channel components (e.g. magnetics and/or other) and, as a result, may limit the usable power at the PD input

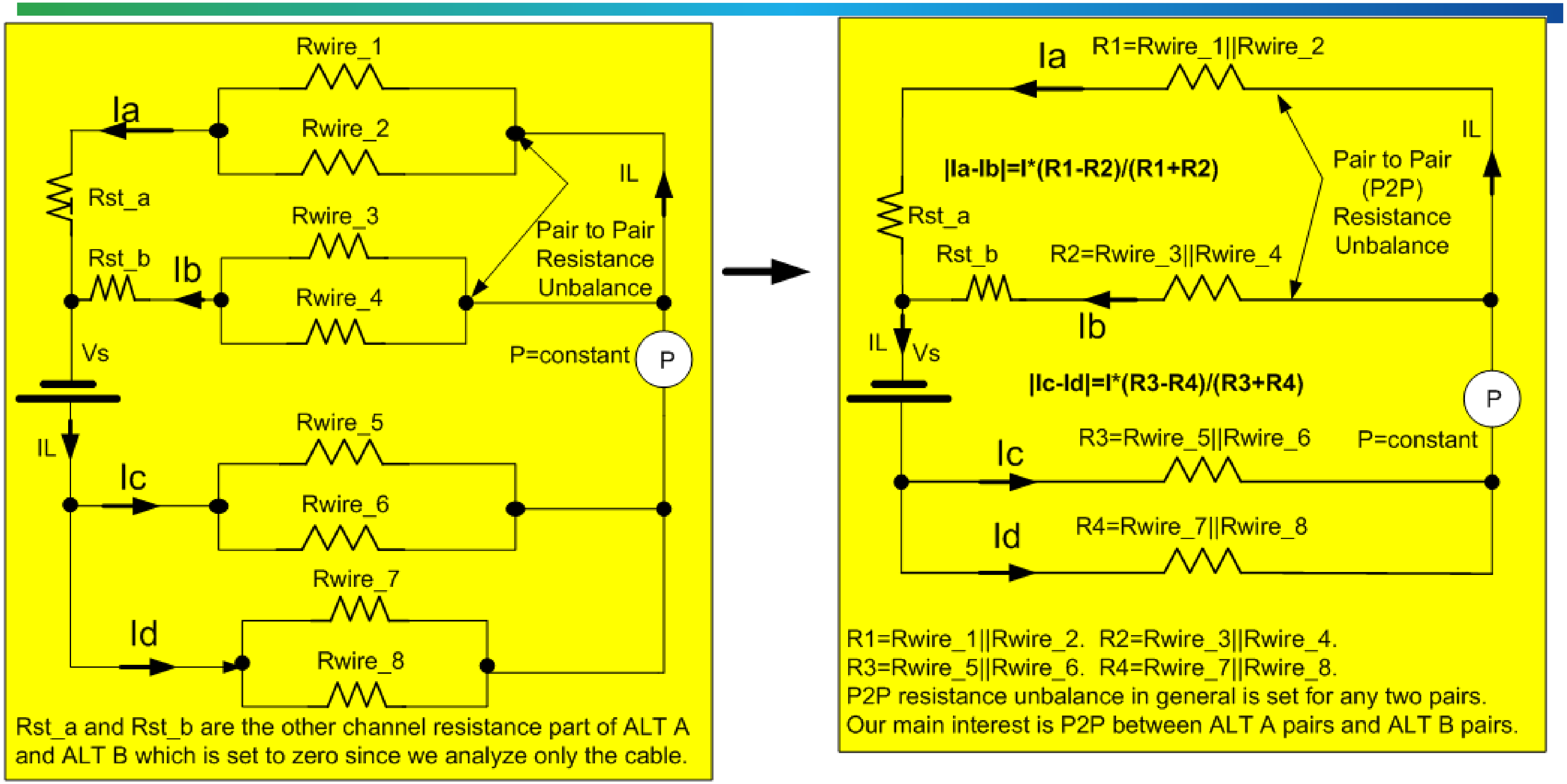
- **See more details at:**

http://grouper.ieee.org/groups/802/3/4PPOE/public/jul13/darshan_2_0713.pdf

http://grouper.ieee.org/groups/802/3/4PPOE/public/jul13/beia_1_0713.pdf

See also updated presentations of the above sources in future meetings.

P2P **Cable** resistance unbalance[1] Model



Rst_a and Rst_b are the other channel resistance part of ALT A and ALT B which is set to zero since we analyze only the cable.

R1=Rwire_1||Rwire_2. R2=Rwire_3||Rwire_4.
R3=Rwire_5||Rwire_6. R4=Rwire_7||Rwire_8.
P2P resistance unbalance in general is set for any two pairs.
Our main interest is P2P between ALT A pairs and ALT B pairs.

Figure 1

1. Ia, Ib, Ic and Id may not be equal. P2PRunb=(Ri-Rj)/(Ri+Rj). i,j=1,2..4. i<>j.
2. Rst_a=Rst_b=0 for finding Cable P2PRunb unbalance only. See more details in Annex B2
1. See Annex F, for calculation of Ri, Rj for any pair and definition of P2PRunb

Equation Derivation Strategy

- ***See Annex A for working assumptions.***
- Our Starting point $P2PRunb \equiv \dfrac{R2 - R1}{R2 + R1}$
- Converting to pair wire parameters:

$$P2PRunb \equiv \frac{\dfrac{L_2}{D_2^2} - \dfrac{L_1}{D_1^2}}{\dfrac{L_2}{D_2^2} + \dfrac{L_1}{D_1^2}}$$

- *L1 and L2 are the pair 1 and pair 2 real length (meters) including twist rate effect.*
- Replacing pair length (Li) with a function of propagation delay and/or other cable parameters, f(Li).

$$P2PRunb = \frac{\dfrac{f(x_2)}{D^2{}_2} - \dfrac{f(x_1)}{D^2{}_1}}{\dfrac{f(x_2)}{D^2{}_2} + \dfrac{f(x_1)}{D^2{}_1}}$$

- We will see that $f(X_i) = f(L_i) = \dfrac{t_i}{n_i \cdot \beta_i}$
- See annex B and B1 for derivation of f(Xi) =f(Li) and its parameter definitions .

Proposed Equation based on exiting cable parameters

$$P2PRunb = \frac{\dfrac{t_2}{n_2 \cdot D^2{}_2 \cdot \beta_2} - \dfrac{t_1}{n_1 \cdot D^2{}_1 \beta_1}}{\dfrac{t_2}{n_2 \cdot D^2{}_2 \cdot \beta_2} + \dfrac{t_1}{n_1 \cdot D^2{}_1 \cdot \beta_1}}$$

$$\beta_i = \sqrt{\alpha_i \cdot \cos(\theta_i)}$$

$$\alpha = 1$$

$$\theta_i \approx \arctan(2Dout_i / T_i)$$

Notes:

1. D1 and D2 ($D_i^2 = d_{i1}^2 + d_{i2}^2$, d1 and d2 are the pair wire diameters) are the equivalent wire diameters in pair 1 and pair 2 represented by R1 and R2. See Annex F and F1.

2. Measured propagation Delay t1 and t2 of pair 1 and pair 2 respectively: See Figure 2 in Annex A1.

3. The term ß_i is for compensating the measured propagation delay time to reflect the true pair length including twist rate effects. ß_i is a complex function. α=1 for the purpose of this work. See Annex B1 for first order approximation for ß_i.

4. n=light index of the wire insulating material. See annex B for details.

5. Dout_i is the outer diameter of the wire in pair_i (copper + insulation). T_i is the twist period length. See Annex B1.

Important observations

- P2PRunb can be zero (see numerator) if $$\frac{t_2}{n_2 \cdot D_2^2 \beta_2} - \frac{t_1}{n_1 \cdot D_1^2 \beta_1} = 0$$ which happens at: $$t_2 \cdot n_1 \cdot D_1^2 \cdot \beta_1 = t_1 \cdot n_2 \cdot D_2^2 \cdot \beta_2$$
- P2PRunb is highly sensitive to Pair diameter D1 and D2. See Annex F.
- Different wire diameters between pairs and different twist ratios can zero the P2PRunb even if |t2-t1|=skew>0 due to different insulating material (affects light velocity v=c/n by different n between pairs).
- t2 and t1 that are function of pair length differences (not only) due to different twist rates that cause P2PRunb.
- The above are validated in the lab tests presented in Annex G.
- It means that cable construction can be implemented in many ways to optimize performance in terms of pair resistance unbalance,P2P resistance unbalance, propagation delay, skew, Zo etc. by cable construction parameters such copper diameters d1, d2, D1, D2, Dout, Twist Rate, insulation material and insulation thickness etc.
- The equations demonstrated that a lower P2PRunb is possible for different wire diameters between pairs when balancing techniques are used to compensate for different pair twist ratios. See Annex D and D1 for details

P2P resistance unbalance prediction process - 1

- MATLAB was used to run a set of parameter on the adjacent equation and filter the P2PRunb results by the following list of filters:

$$P2PRunb = \frac{\dfrac{t_2}{n_2 \cdot D^2_2 \cdot \sqrt{\cos\theta_2}} - \dfrac{t_1}{n_1 \cdot D^2_1 \cdot \sqrt{\cos\theta_1}}}{\dfrac{t_2}{n_2 \cdot D^2_2 \cdot \sqrt{\cos\theta_2}} + \dfrac{t_1}{n_1 \cdot D^2_1 \cdot \sqrt{\cos\theta_1}}}$$

$$D_i^2 = d_{i1}^2 + d_{i2}^2$$

- Each pair meets Runb=2% maximum per specifications. which limits d1/d2 ratio to 0.98 or 1/0.98. See Annex F1.
- Running for d1/d2=1 for reference. See Annex B, part B-6.
- Running pair to pair equivalent diameter difference D1/D2 0.99 to 1 and from 1 to 1/0.99 for reference.
- Running filter from for d1/d2 ratio from 0.98 to 1 and 1 to 1/0.98 for reference.
  - Between pairs we may have a pair with 1 AWG difference from other pair
  - Zo is tuned to meet RL when terminated with precise 100Ω
    - Alert when Zo<>100Ω by 2,4,5,10,15% by changing all Zo affecting parameters (See Annex E)

P2P resistance unbalance prediction process - 2

- Pair Length=100 meter
- skew_max=45ns. To check for 36ns and 25nsec as well.
- Insulation material: Fixed 0.7=1/n1=1/n2 since the effect of different values is already embedded in the resulting numerator ("skew") and Zo limits.
- Propagation delay t2_min=ß*100m/(c/n)=0.97*100m/(3*10^8*0.7)=462ns. 570ns max. t1=t2-skew.
- Running for $\beta = \sqrt{\frac{\cos\theta_1}{\cos\theta_2}}$ together with skew limits. This will filter Twist ratio maximum differences between pairs vs skew max.

The above process resulted with P2PRunb for a cable <5%

Conclusions

$$P2PRunb = \frac{\dfrac{t_2}{n_2 \cdot D_2^2 \cdot \sqrt{\cos\theta_2}} - \dfrac{t_1}{n_1 \cdot D_1^2 \cdot \sqrt{\cos\theta_1}}}{\dfrac{t_2}{n_2 \cdot D_2^2 \cdot \sqrt{\cos\theta_2}} + \dfrac{t_1}{n_1 \cdot D_1^2 \cdot \sqrt{\cos\theta_1}}} \cong \frac{R2 - R1}{R2 + R1}$$

- P2PRunb Measured < 4.4%.

  Predicted ≤ 5%.
- The proposed equation covers the main contributors to P2PRunb.
- Due to other cable parameters e.g. Zo, Propagation time delay, skew, wire diameters and other cable performance requirements Runb in the pairs and between pairs (P2PRunb) are actually tightly controlled.
  - Very high sensitivity to different wires diameters between pairs.
  - The value of D1/D2 if it is <1 or >1 increase or decrease P2P resistance unbalance. It can be zeroed by L1*D2^2=L2*D1^2.
    - It can be used to balance resistance between wires in the pair
    - It can be used to balance resistance between pairs.
- Equation confirms that Cables with:
  - Lower resistance per meter will have higher P2PRunb, e.g. CAT6A with AWG23 wires will have higher P2PRunb than CAT5e with AWG24 wires.
  - Higher twist rate differences between pairs will have higher P2PRunb. This may also be resolved by balancing with different pair wire diameter.

Next Steps

- It is proposed that the cable P2P maximum resistance unbalance will be set to ≤5% max for the purpose of completing the channel P2P resistance unbalance worst-case analysis.
  - The "maximum" value cannot be lower than 2%. (It cannot be better than pair unbalance which is 2%max.)
- To start the liaison process to request formal P2P resistance unbalance limits from TIA and/or ISO/IEC asking to approve P2PRunb limits preferably <5% or proposing other cost effective P2PRunb limit.

Thank You

Annex A: Working Assumptions.

- Pair Z0 is kept within specification for any cable length.
- Propagation delay which is function of Z0 components (L,C,R,G) is ~linear increasing function of pair length. See Annex E for details.
- The differences in pair twist ratio is embedded in actual pair length that affects wire resistance.
- The propagation delay time increased or decreased due to twist rate ratio that affect the inductance and capacitance of the transmission line. See Annex B1 for details.
- Insulation dielectric material of all pairs are assume to be ~the same.(in reality it may not e.g. on pair 3,6 if use higher twist rate, so propagation delay need to be compensated to meet skew requirements). The general case is addressed as well.
- Wires in a cable may have different diameters. Diameter difference are expected to be < 1 AWG between pairs See Annex D and D1.
- *Wires diameter difference within a pair is controlled to be below 2% since overall 2% maximum pair resistance unbalance need to be met.*
- *Equivalent pair wire diameter (Ri, Figure 1) is defined and addressed for the purpose of P2PRunb analysis.*
- *For lab measurement accuracy requirements, see Annex K.*
  - Propagation delay test frequency<=10MHz.

Annex A1- Propagation Delay and skew definitions

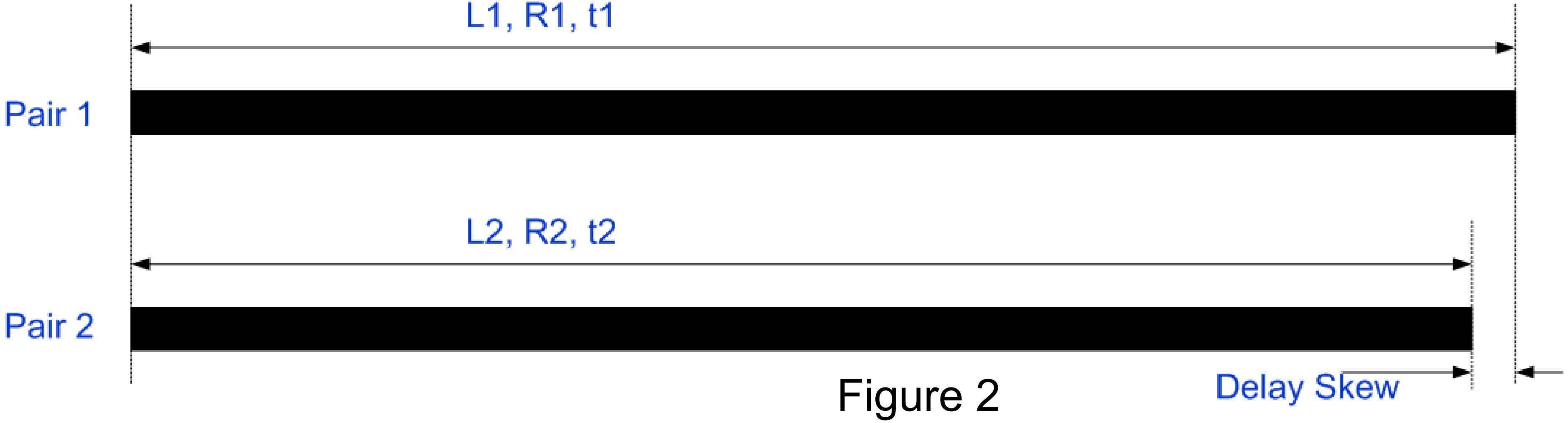


Figure 2

First cable with length of L1, resistance of R1 [Ω] (two wires in parallel) and propagation delay time t1, the time it takes the signal to propagate from end to end.

Second cable with length of L2, resistance of R2 [Ω] (two wires in parallel) and propagation delay time t2, the time it takes the signal to propagate from end to end.

Pair 1 and Pair 2 are the designation of any one of the 4 pairs compared to any other pair.

- The delay skew is the difference in time required by a signal to propagate through conductors in the same cable due to differences in the physical lengths of the pairs caused by different twist ratios.

Annex B:Calculation of P2PRunb from the Propagation Delay -1

- P2PRunb is defined as (see Figure 1):

Eq-1 $$P2PRunb \equiv \frac{R2-R1}{R2+R1}$$ Eq-2 $$R_i = \rho\frac{L_i}{s_i} = \rho\frac{L_i}{0.25\cdot\pi\cdot D^2{}_i}$$

D1 and D2 are the equivalent pair diameter. **See Annex F for details**

R1 and R2 are the equivalent pairs resistance (defined in figur 1)

with their equivalent pair length l_1 *and* l_2 .

ρ is the conductor resistivity [Ω/m].

- As a result, P2PRunb can be written as follows:

Eq-3 $$P2PRunb \equiv \frac{\rho\frac{L_2}{0.25\cdot\pi\cdot D^2{}_2} - \rho\frac{L_1}{0.25\cdot\pi\cdot D^2{}_1}}{\rho\frac{L_2}{0.25\cdot\pi\cdot D^2{}_2} + \rho\frac{L_1}{0.25\cdot\pi\cdot D^2{}_1}} \equiv \frac{\frac{L_2}{D^2{}_2} - \frac{L_1}{D^2{}_1}}{\frac{L_2}{D^2{}_2} + \frac{L_1}{D^2{}_1}}$$

L_1 *and* L_2 are pair 1 and pair 2 length (meter) and include the effect of twist rate that increases the pair wire length.

Annex B:Calculation of P2PRunb from the Propagation Delay -2

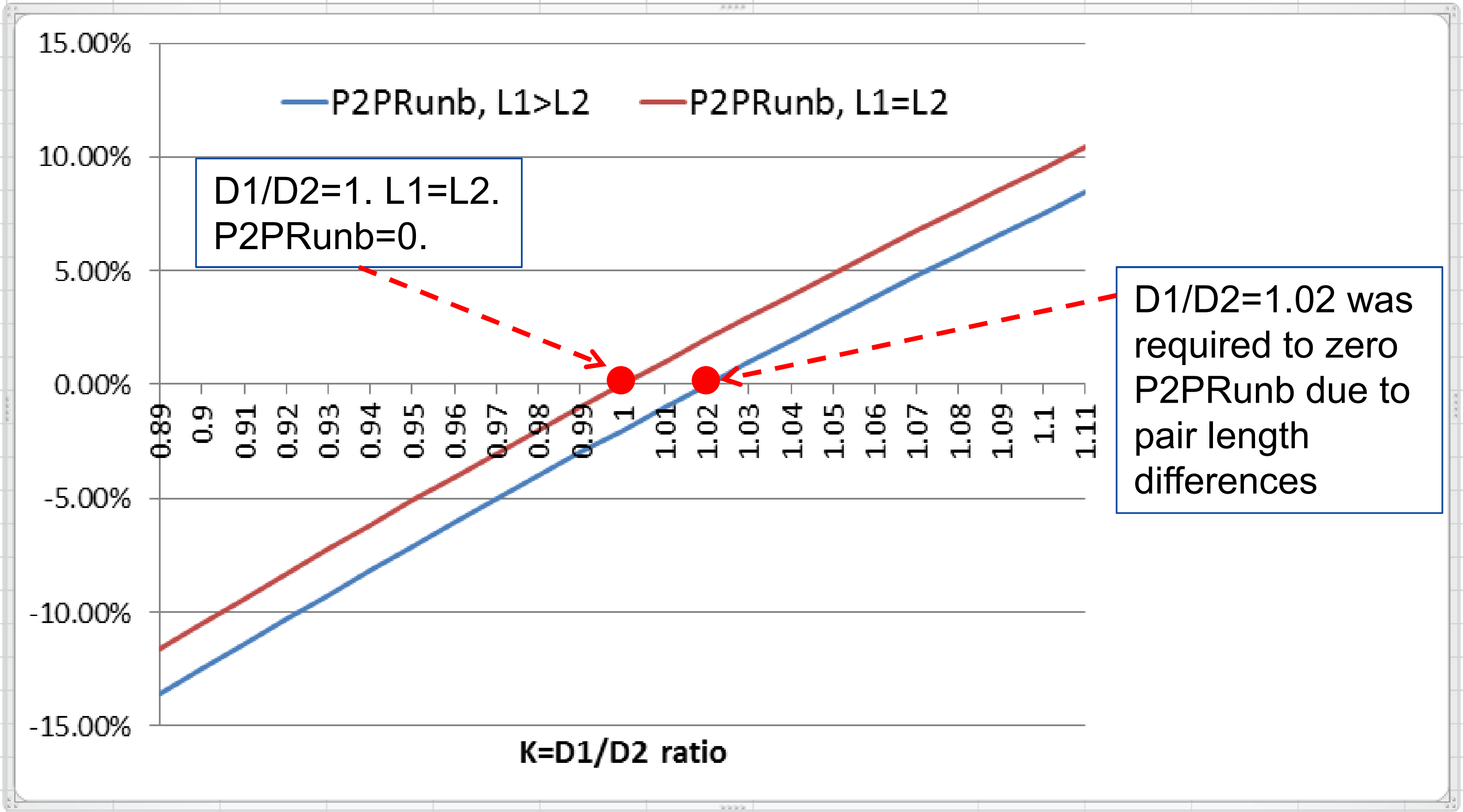
- Resulting with:

Eq-4 $$P2PRunb \equiv \frac{\frac{L_2}{D^2{}_2} - \frac{L_1}{D^2{}_1}}{\frac{L_2}{D^2{}_2} + \frac{l_1}{D^2{}_1}}$$

- Equation 1 represent the resulted P2PRunb as if we measured it in the lab. (Shorting the pair ends, at each end, and measuring the resistance).
- Equation 4 is identical to Equation 1 with physical parameters of the pairs.
- This is important observation. P2PRunb is not depend on conductor material and other constants as in eq-3. It depends only on pair length differences and wire diameter differences.
- *We already can see that wire diameter affects significantly P2PRunb.*
- The pair length differences are due to the different twist rate that each pair has for reducing cross talk.

Annex B–Calculation of P2PRunb from the Propagation Delay -3. P2PRunb max limits vs. D1/D2 and D2/D2 ratio.

- Example: Case 1: L1=50m+2%. L2=50m-2%. Case 2:L1=L2. D1/D2 is changed from 0.89 to 1.11 representing maximum 1AWG difference in diameter between pairs



D1/D2=1. L1=L2. P2PRunb=0.

D1/D2=1.02 was required to zero P2PRunb due to pair length differences

Annex B:Calculation of P2PRunb from the Propagation Delay -4

- The objective is to replace the pair length with a function f(x) that depends on defined pair parameters.

Eq-5 $$L_i = v_i \cdot \frac{t_i}{\beta_i} = \frac{c}{n_i} \cdot \frac{t_i}{\beta_i}$$

Eq-6 $$\beta_i \approx \sqrt{\frac{\cos(\theta_i)}{\alpha_i}} = \sqrt{\cos(\theta_i)}$$

$$\theta = arcTan\cos(Dout/(T/2))$$

$$\alpha = 1$$

- t_i is the measured propagation delay with additional correction factor ß_i. First order estimation of ß is ß =(cos(θ)/ α)^0.5. θ and α are function of the twist rate parameters. See annex B1 for α_i and ß_i first order estimation details.
- vi is the light velocity in material (wire insulation). Vi=c/n_i.
- c is light velocity in vacuum=3*10^8m/sec.
- n_i is material index. Typical n_i=1.427 used in this analysis. 1/n_i=0.7.

Annex B:Calculation of P2PRunb from the Propagation Delay -5

- Replacing the pair length with eq-5 resulted with

$$P2PRunb \equiv \frac{\frac{L_2}{D^2{}_2} - \frac{L_1}{D^2{}_1}}{\frac{L_2}{D^2{}_2} + \frac{L_1}{D^2{}_1}} \cong \frac{\frac{t_2}{n_2 \cdot D^2{}_2 \cdot \beta_2} - \frac{t_1}{n_1 \cdot D^2{}_1 \cdot \beta_1}}{\frac{t_2}{n_2 \cdot D^2{}_2 \cdot \beta_2} + \frac{t_1}{n_1 \cdot D^2{}_1 \cdot \beta_1}}$$

Eq-7

$$P2PRunb \cong \frac{\frac{t_2}{n_2 \cdot D^2{}_2 \cdot \beta_2} - \frac{t_1}{n_1 \cdot D^2{}_1 \cdot \beta_1}}{\frac{t_2}{n_2 \cdot D^2{}_2 \cdot \beta_2} + \frac{t_1}{n_1 \cdot D^2{}_1 \cdot \beta_1}}$$

Eq-7 can be investigated for 3 use cases.

a) n1=n2. The two pairs are with the same insulation material.

b) D1=D2. The pairs have the same equivalent diameter which means that the resistivity of the pair when both pair wires are shorted at their edges, are equal.

c) n1=n2 and D1=D2

Annex B:Calculation of P2PRunb from the Propagation Delay -6

a) n1=n2. The two pairs are with the same insulation material.

Eq-8 $$P2PRunb \cong \frac{\dfrac{t_2}{D^2{}_2 \cdot \beta_2} - \dfrac{t_1}{D^2{}_1 \cdot \beta_1}}{\dfrac{t_2}{D^2{}_2 \cdot \beta_2} + \dfrac{t_1}{D^2{}_1 \cdot \beta_1}}$$

- If all pairs have the same insulating material i.e. n1=n2.
  (Typical case when twist rate is not high (in pairs 3,6 or others) so no need to compensate for meeting skew requirements with other pairs)

- In this case all the information for P2PRunb is embedded in t1, t2, D1,D2 and θ1 and θ2.

Annex B:Calculation of P2PRunb from the Propagation Delay -7

b) D1=D2. The pairs have the same equivalent diameter which means that the resistivity of the pair when both pair wires are shorted at their edges, are equal.

Eq-8.1 $$P2PRunb \cong \frac{\frac{t_2}{n_2 \cdot \beta_2} - \frac{t_1}{n_1 \cdot \beta_1}}{\frac{t_2}{n_2 \cdot \beta_2} + \frac{t_1}{n_1 \cdot \beta_1}}$$

- In this case all the information for Run is embedded in the transmission line parameters and not in the pairs resistivity (since they are equal). It means that it is actually function of L, C and R(frequency) parameters which are function of d, Dout, er and twist rate. See annex B1 and E for more details.

Annex B:Calculation of P2PRunb from the Propagation Delay -8

c) If n1=n2 AND D1=D2. all pairs have the same insulating material and the same equivalent pair wire diameter Di (may not be a typical case) then we get:

Eq-9 $$P2PRunb \cong \frac{\frac{t_2}{\sqrt{\cos\theta_2}} - \frac{t_1}{\sqrt{\cos\theta_1}}}{\frac{t_2}{\sqrt{\cos\theta_2}} + \frac{t_1}{\sqrt{\cos\theta_1}}}$$

- Eq-9 now can be described in terms of skew as well.
- We can see the information on Run is embedded at the compensated skew and propagation delay as would be expected in ideal (t2_ideal) parallel (non twisted) transmission line

$$\frac{t_2}{\sqrt{\cos\theta_2}} - \frac{t_1}{\sqrt{\cos\theta_1}} = Skew \Rightarrow \frac{t_1}{\sqrt{\cos\theta_1}} = \frac{t_2}{\sqrt{\cos\theta_2}} - Skew$$

$$P2PRunb \cong \frac{\frac{t_2}{\sqrt{\cos\theta_2}} - \frac{t_1}{\sqrt{\cos\theta_1}}}{\frac{t_2}{\sqrt{\cos\theta_2}} + \frac{t_1}{\sqrt{\cos\theta_1}}} = \frac{\frac{t_2}{\sqrt{\cos\theta_2}} - \frac{t_2}{\sqrt{\cos\theta_2}} + Skew}{\frac{t_2}{\sqrt{\cos\theta_2}} + \frac{t_2}{\sqrt{\cos\theta_2}} - Skew} =$$

$$\cong \frac{Skew}{\frac{2\cdot t_2}{\sqrt{\cos\theta_2}} - Skew} \cong \frac{Skew}{2\cdot t_2^{ideal} - Skew}$$ Eq-10

See interesting example on next page

Annex B:Calculation of P2PRunb from the Propagation Delay -9

Eq-10
$$P2PRunb \cong \frac{Skew}{\frac{2 \cdot t_2}{\sqrt{\cos\theta_2}} - Skew}$$

- **Example for the case of n1=n2 and D1=D2 so P2PRunb is caused mainly by pair length differences):**
- If the nominator (The compensated skew) of Equation 9 is 45nsec max then for:
- 1/n1=1/n2=0.7 , L=100m, v=0.7*c,
- D1=D2.
- t2=476ns.
- Cos(θ1) is embedded in the skew max.
- Cos(θ2)>cos(θ1)
- P2PRunb max. is:
- α= 1 for simplify this use case.

$$P2PRunb = \frac{45ns}{\frac{2 \cdot 476.2ns}{\sqrt{\cos\theta_2}} - 45ns} = $$

$$= \left\{ \begin{array}{l} 4.91\% \; for \sqrt{\cos\theta_2} = 0.99 \\ 4.86\% \; for \sqrt{\cos\theta_2} = 0.98 \\ 4.81\% \; for \sqrt{\cos\theta_2} = 0.97 \end{array} \right\}$$

- This is for skew max. Normally skew is lower resulting with lower P2PRunb. On the other hand P2PRunb may increase again due to different D1 and D2. We will see later that d1/d2 in pair level and D1/D2 between pairs, need to be controlled (and other parameters as well) with pair real length for meeting Zo which will reduce P2PRunb below this numbers. See Annex E for details.

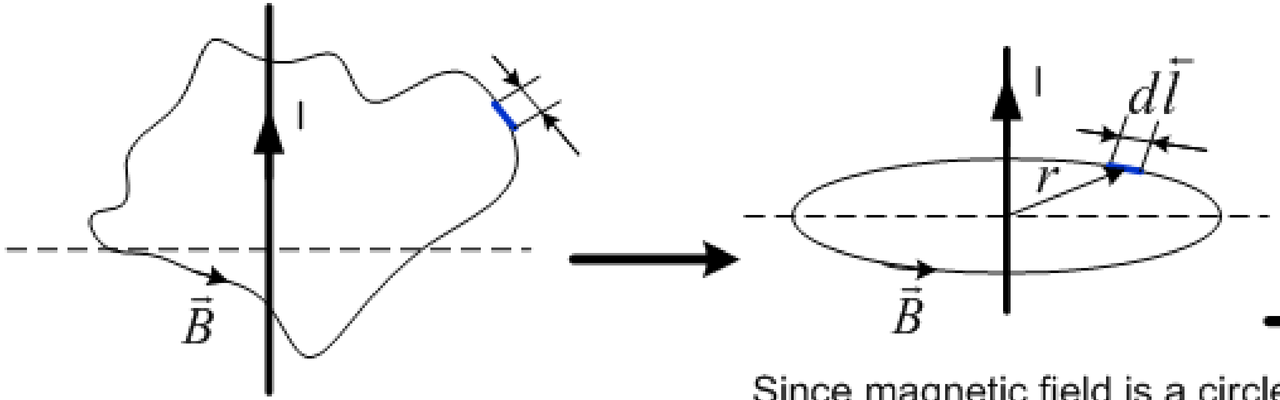
Annex B1 – twist ratio effect on propagation time - 1

- Real pair has a twist ratio (i.e. twisted pair).
- Each pair has different twist ratio. The twist ratio within a pair is constant (our working assumption).
- It increases the pair physical length by a factor of ~1/cos(θ) which increases the propagation delay time which serves our objective to use propagation delay time as a tool to measure the real pair length which is part of the pair resistance equation. However, twist ratio affects the inductance (and capacitance) through different mechanisms that increase or decrease the propagation delay time. As a result we may need to compensate the measured propagation delay time t1 and t2 to reflect the actual pair physical length.
- How twist rate affects the inductance and in general the twisted pair transmission line parameters?
- The twisting action increases the pair inductance due to increasing number of turns per unit length by a factor of α (moving from ideal parallel transmission line to loosen solenoid like inductor model). As a result, propagation time will increase by factor of α^0.5 .
- The twisting action reduces the magnetic field between the wires (the angle of the magnetic field is no longer 90° to the surface between the wires), causing to reduction in inductance by a factor of cos(θ) and as a result to lower propagation time by factor of (cos(θ))^0.5.
- The following slides show the analysis of the twist ratio effect on propagation delay and how to use the findings in the equation developed in Annex B.

Annex B1 – twist ratio effect on propagation time - 2

- Magnetic field density at a distance r from a straight infinite wire carrying a current I, over single infinite wire is:

$$\oint \vec{B} \bullet d\vec{l} = \mu_0 \cdot I$$ I is the total current crossing the loop l



$$H = \frac{I}{2 \cdot \pi \cdot r}$$

$$B = \mu_0 \cdot H = \frac{\mu_0 \cdot I}{2 \cdot \pi \cdot r} \hat{a}_\phi$$

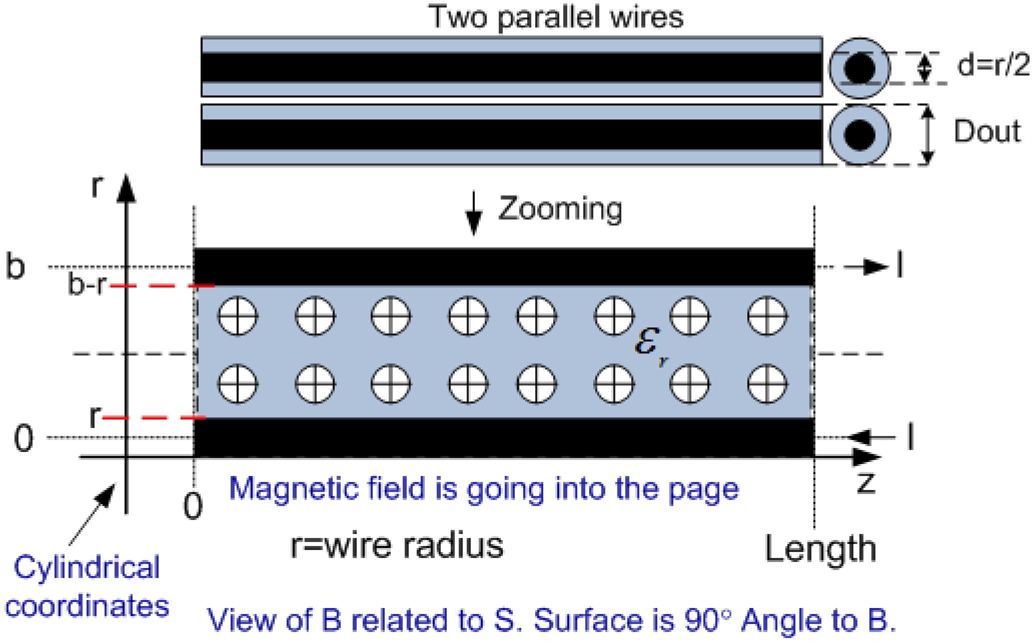
Since magnetic field is a circle around the wire and the loop (Amper's loop) can be a circle as well, it makes it easier to calculate the integral.

$\hat{a}_\Phi$ = unit direction vector of the magnetic flux density

$\mu_0 = 4 \cdot \pi \cdot 10^{-7}$

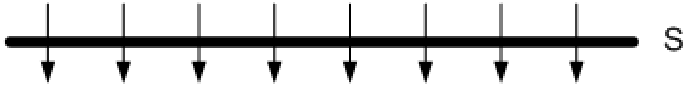
- Magnetic flux crossing enclosed area S: $\Phi = \int_s d\vec{B} \bullet d\vec{S} = L \cdot I$
- For propagation Delay per unit length, see Annex E for details.

Annex B1 – twist ratio effect on propagation time - 3

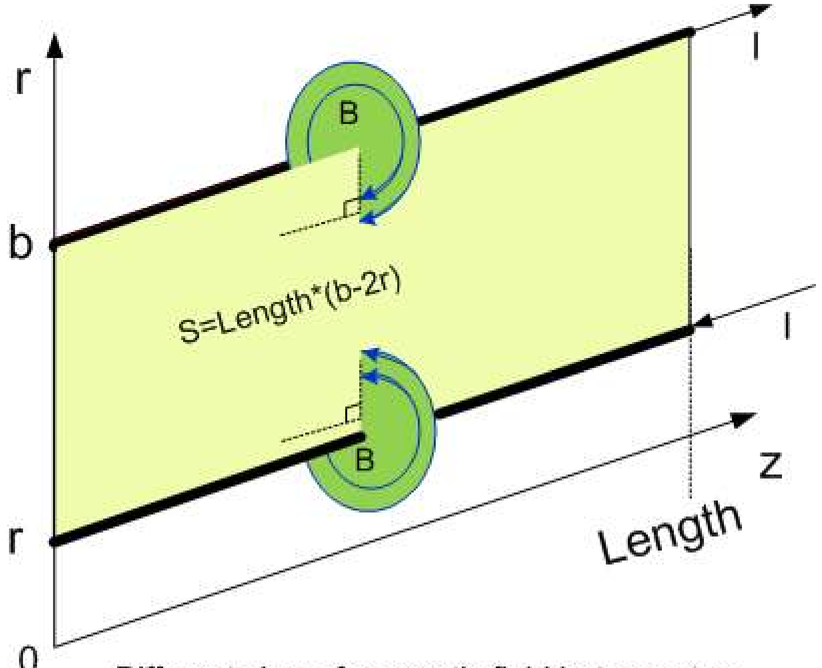


Magnetic field is going into the page

View of B related to S. Surface is 90° Angle to B.



(d-a) is the distance between the two wires. S is the surface between the wires in which the magnetic field is crossing it so the magnetic flux can be computed by the dot product of B and dS



Different view of magnetic field between two parallel wires

$$\varphi_m = L \cdot I = 2 \cdot \int B \bullet dS$$

Annex B1 – twist ratio effect on propagation time - 4

$$\varphi_m = L \cdot I = 2 \cdot \int B \bullet dS = \int_r^{b-r} \frac{2 \cdot \mu_0 \cdot I}{2 \cdot \pi \cdot r} dr \int_0^{Length} dz = \frac{\mu_0 \cdot I \cdot Length}{\pi} \cdot LN\left(\frac{b}{r} - 1\right)$$

-We have two wires hence B is doubled between wires.
-The magnetic flux is crossing the area between the edges of the two wires i.e. from distance r to distance b-r. r is the wire radius and b is the distance between the centers o the two wires. For two wires that touch each other at their insulation edges, b=Dout/2+Dout/2=Dout. Dout is the wire outer diameter (copper + insulation).
-The above equation assumes uniform flux density between the two wires, Length>>r, b>r and high frequency operation (current through wires is concentrated on the wire surface).

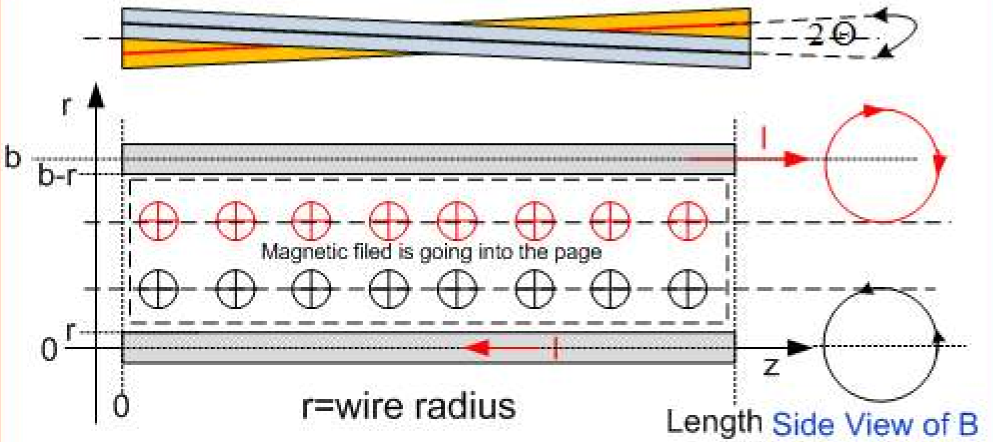
Solving for L (self and mutual inductance, for parallel transmission line, twist rate=0)

$$L = \frac{\mu_0}{\pi} \cdot LN\left(\frac{b}{r} - 1\right)$$

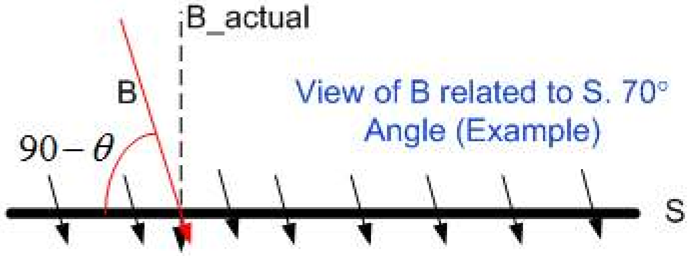
For parallel long transmission line twist rate=0

This expression is approximation for L under the above conditions. The equation became highly accurate when b>>r which is not the case for UTP where b/r<4. There are much accurate approximation however it is not needed for the purpose of our work.

Annex B1 – twist ratio effect on propagation time - 5

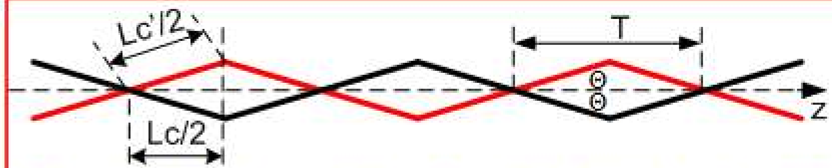


Side View of B around the wire



View of B related to S. 70° Angle (Example)

S is the surface between the wires in which the magnetic field is crossing it so the magnetic flux can be computed by the dot product of B and dS



T=period (e.g. in==unit length) and # of twists per in=1/T (=twist rate).
Example: Dout=0.06, T/2=0.15. T=0.3=period, 1/T=twist rate=3.3 twists/in.
Lc, Lc'=length of wire piece in the relevant direction.
Dout is the outer diameter of the wire

$$B' = B \cdot \beta$$

$$\beta \approx \alpha \cdot \cos(\theta)$$

$$\theta \cong arcTan(n \cdot D_{out} / T)$$

$$\alpha = 1$$

$$\theta = 21.8^\circ$$

$$B' = 0.928 \cdot B$$

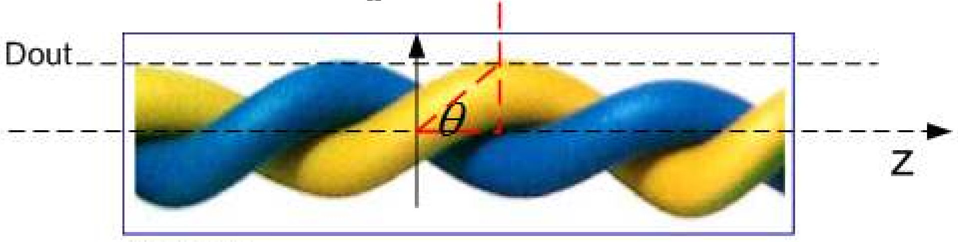
n = model constant (2 to π).
The increase in pair length due to particular twist rate can be found from:

$$\cos(\theta) = \frac{Lc}{Lc'}$$

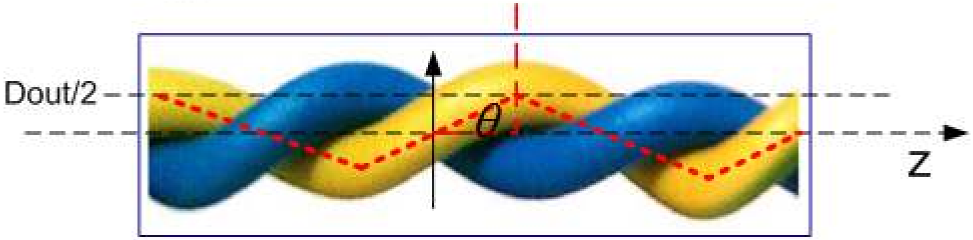
Note: The accurate result is more complex however the above is good first order approximation.

Annex B1 – twist ratio effect on propagation time - 6

- The twist angle is affecting the transmission line parameters L and C and evaluated as follows:
- Option 1 simplified) The helix generated by the twisting action has a thickness of Dout from the helix center to the edge of the wire. The peak of the height is at Dout at half of the twist periode forming the angle θ. As a result, the angle is Atan(Dout/(T/2))=Atan(2*Dout/T).
- Option 2: The center lines of two twisted wires form a helix. The helix diameter is one wire diameter. It forms a sine wave in the longitudinal plane e.g. z direction. Looking at the twisted pair as a with a sine wave shape: y=(Dout/2)*sin(2*π*z/T). T is the twist period=1/twists_per_unit_length. z is the distance and Dout is the wire outer diameter. As a result θ can be derived as θ=Atan(pi*Dout/T).
- The differences between the models are the factor n which could be between 2 to π. Hence the general form is θ =Atan(n*Dout/T), n=2 to π.
- Through out this work we will use n=2. The accuracy of the results as function of n will be evaluated in later research due to the fact that it didn't change our main conclusions.



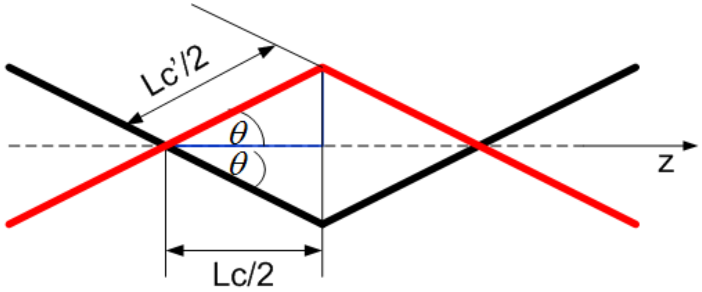
Model A



Model B

Annex B1 – twist ratio effect on propagation time - 7

- The propagation delay is affected by 3 derivatives of the twisting action:
- a) The propagation time is increased due to the increase of the pair physical length by a factor of ~1/cos(θ) by the approximation Lc'/Lc/(cos(θ)). This part of increasing pair length and resulting with longer propagation delay, is embedded in the pair resistance hence it is not a source for error.
- b) Due to the twist rate>0 (turns per unit length>0), the inductance is increased by a factor of α compared to parallel transmission line which is a function of the twist rate per unit length (turns per unit length), due to the fact that the twisting pair is approaching to loosen solenoid model which has higher inductance (resulting with higher propagation delay by a factor of a^05. *For low twist rate values, b=Dout and b/r<4,* α *may be neglected.*
- c) The inductance is decreased due to reduction of magnetic field caused by the twisting action (resulting from <90deg magnetic field vector (also function of θ =f(twist rate, Dout) that crosses the plane between the two wires) The reduction of the magnetic field is by a factor of ~cos(θ) which is a first order estimation. The approximation for cos(θ) is more complex. Typically Inductance may increase due to solenoid effect higher than the reduction by cos(θ) so the net effect on inductance may increase. At low twist ratio both factors are negligible or cancel each other.



Annex B1 – twist ratio effect on propagation time - 8

The measured propagation delay time t1 and t2 is shorter or longer than the value that accurately represents the pair true length. i.e:

$$t_i = tp_i \cdot \sqrt{\alpha_i \cdot \cos(\theta_i)}$$

t_i is the measured propagation delay time and tp_i is the objective.

As a result, in order to reflect the true pair length,
the measured propagation time need to be divided by: $\sqrt{\alpha_i \cdot \cos(\theta_i)}$

Resulting with $tp_i = \dfrac{t_i}{\sqrt{\alpha_i \cdot \cos(\theta_i)}}$ or $tp_i = \dfrac{t_i}{\sqrt{\beta_i}}$

$$\beta_i = \sqrt{\alpha_i \cdot \cos(\theta_i)}$$

Annex B1 – twist ratio effect on propagation time - 9

- In parallel transmission line cos(θ)=1

- Why if B is reduced to ß3*B, the inductance is reduced by (1-ß3) ^0.5?
  - If B is reduced due to twist rate>0 to ß3*B, e.g. ß3=0.9
  - Inductance is decreased from L to ß3 *L
  - t1=(L*C)^0.5 (propagation delay for twist rate=0)
  - t2=(ß3 *L*C)^0.5 (propagation delay for twist rate>0)
  - t2/t1= ß3 ^0.5 ➔ t2=t1* ß ^0.5
  - Reduction in propagation delay is t1-t2=(1- ß ^0.5)*t1 i.e. (1- ß ^0.5)=1-0.948=0.051 from t1. ➔=~5%.

Annex B1 – twist ratio effect on propagation time - 10

Example analyzed per possible error source for the propagation delay time:

a) Pair actual length was increased by 5% due to twist rate>0. As a result propagation delay will increase by 5% . This part is not needed to be compensated in the proposed P2PRunb due to the fact that it will be accounted by the pair resistance (higher length , higher resistance)

a) α: As a result of the twist rate above, **<u>if</u>** inductance was increased due to the solenoid effect *(compared to the parallel two wire transmission line. For equation that represents the effect of twist rate on inductance, α =1)* by 7%. The propagation delay will increased by 7%^0.5=~2.65%.

b) As a result of the twist rate above, inductance will decrease due to the reduction of the magnetic field by 5% (same of (a) since it is function of the same θ). The propagation delay will decreased by 5%^0.5=~2.23%.

c) As a result, the net effect on propagation delay time is 5%+2.65%-2.23%=5.42% which is 0.42% away from the 5% time delay increase from the value that represents the true pair length.

- See Annex J1 for twist rate vs. cos(θ)^0.5 curve <u>for example.</u>
- *The values for α* are not addressed in details in this work and it is to be the subject of a future research. As first order estimation it has negligible effect on the main conclusions and resulted from this work.

Annex B1 – twist ratio effect on propagation time - 11

Finding inductance L when pair is twisted:

$$\varphi_m = L \cdot I = \int 2 \cdot B \cdot \beta \cdot dS$$

We have two wires hence B is doubled between wires and we add the factors of magnetic field reduction and magnetic field increase due to solenoid effect.

$$= \int_r^{b-r} \frac{2 \cdot \mu_0 \cdot I \cdot \beta}{2 \cdot \pi \cdot r} dr \int_0^{Length} dz = \frac{\mu_0 \cdot I \cdot Length \cdot \beta}{\pi} \cdot LN\left(\frac{b-r}{r}\right)$$

Solving for L (Inductance) per unit length)

12. $$L = \frac{\mu_0 \cdot \beta}{\pi} \cdot LN\left(\frac{b}{r} - 1\right)$$

13. $$\theta = arcTan\cos(Dout/(T/2))$$

$$\beta = \sqrt{\alpha \cdot \cos(\theta)}$$

Annex B1 – twist ratio effect on propagation time – 12

Summary

For α=1 (negligible effect for the purpose of this work) and that the twist rate effect on capacitance (through equivalent er, is embedded in the target Zo in order to meet the specification of the cable):

1. Length’, L’ and Tp’ are the values of pair length, inductance and propagation delay respectively for twisted pair.

2. Length, L and Tp are the values of pair length, inductance and propagation delay respectively for untwisted pair (parallel transmission line.

3. The increase in pair length due to particular twist rate is about: $Length' = \frac{Length}{\cos(\theta)}$

4. The reduction in the inductance due to the twist rate is: $\frac{L'}{L} = \cos(\theta)$

5. The reduction in propagation delay due to the reduction in the inductance L is: $\frac{Tp'}{Tp} = \sqrt{\cos(\theta)}$

6. Since the propagation delay is used to measure the pair length, we need to compensate it to reflect the real length.

7. As a result the measured Tp, need to be replaced with: $\frac{Tp}{\sqrt{\cos(\theta)}} = \frac{Tp}{\sqrt{\cos(arcTan(2D_{OUT}/T))}}$

8. From (7), t1 and t2 (propagation delay t1 and t2 for pair 1 and pair 2 respectively) in P2PRunb Equation in Annex B need to be replaced with: $\frac{t_i}{\sqrt{\cos(\theta_i)}}$

Teta is derived from wire outer diameter and twist rate:

$$\theta_i \approx arcTan\,(n \cdot Dout_i / T_i)$$

$$n = 2 \ \ to \ \ \pi$$

Annex B2 – Interpretation of P2PRunb definition -1

In the general case for <u>the channel</u>
(All the components in the channel are summed for their maximum and minimum value (true for Runb and P2PRunb):

$$P2PRunb/Runb \equiv \frac{\sum R\max - \sum R\min}{\sum R\max + \sum R\max}$$

Separating cable resistance from the above sums of all channel components including connectors, transformers, PSE output resistance and PD input resistance and input diodes results with:

$$P2PRunb/Runb \equiv \frac{(\sum R\max^{1} - \sum R\min^{2}) + (Rc_{\max} - Rc_{\min})}{(\sum R\max^{1} + \sum R\min^{2}) + (Rc_{\max} + Rc_{\min})}$$

Since we are checking only cable P2PRunb, removing all the other components and remaining with Only cable resistance will significantly increase the P2PRunb[%] in short cables and as a result with higher pair to pair current unbalance.

$$P2PRunb/Runb \equiv \frac{(\sum R\max^{1} = 0 - \sum R\min^{2} = 0) + (Rc_{\max} - Rc_{\min})}{(\sum R\max^{1} + \sum R\min^{2}) + (Rc_{\max} + Rc_{\min})} =$$

$$= \frac{Rc_{\max} - Rc_{\min}}{Rc_{\max} + Rc_{\min}}$$

In our work, we use the terms R1 and R2 instead of Rc_max and Rc_min to describe the pair CM resistance by paralleling the two wires in the pair.

$$P2PRunb/Runb = \frac{Rc_{\max} - Rc_{\min}}{Rc_{\max} + Rc_{\min}} =$$

$$= \frac{R_2 - R_1}{R_2 + R_1}$$

Annex B2 – Interpretation of P2PRunb definition -2

P2PRunb can be positive or negative pending if R2>R1 or R1>R2.

$$P2PRunb\,/\,Runb \equiv \frac{R2-R1}{R2+R1}$$

What is the ratio between R1 and R2 to get the desired P2PRunb or Runb?
Defining k as:

$$k=\frac{R1}{R2} \longrightarrow R1=k\cdot R2 \longrightarrow Runb \equiv \frac{R2-k\cdot R2}{R2+K\cdot R2}=\frac{(1-k)}{(1+k)}$$

Or finding k as function of P2PRunb/ or Runb:

$$k \equiv \frac{(1-Runb)}{(1+Runb)}$$

If Rmax (R2) is given, Rmin (R1) is:

$$R\min = R\max\cdot\frac{(1-Runb)}{(1+Runb)}$$

Example 1:
P2PRunb=5%
k=(1-0.05)/(1+0.05)=0.95/1.05=0.904
R2=10Ω
R1=10Ω*0.904=9.04 Ω.
OR:
P2PRunb= -5%
k=(1-(-0.05))/(1+(-0.05))=1.05/0.95=1.105
R2=10 Ω, ➔ R1= 10Ω*1.105=11.05
So k can vary from 0.904 to 1.105 ➔20.1% pp in order to have |P2PRunb|=5%, |k_max|~=10%
Example 2:
P2PRunb=5%
Rmax=10Ω
Rmin=10Ω*0.95/1.05=9.04Ω

Annex B2 – Interpretation of P2PRunb definition -3

- Alternative A to Alternative B power unbalance equation:
- Will be addressed in future work

Annex C1: Propagation Delay and skew Specifications

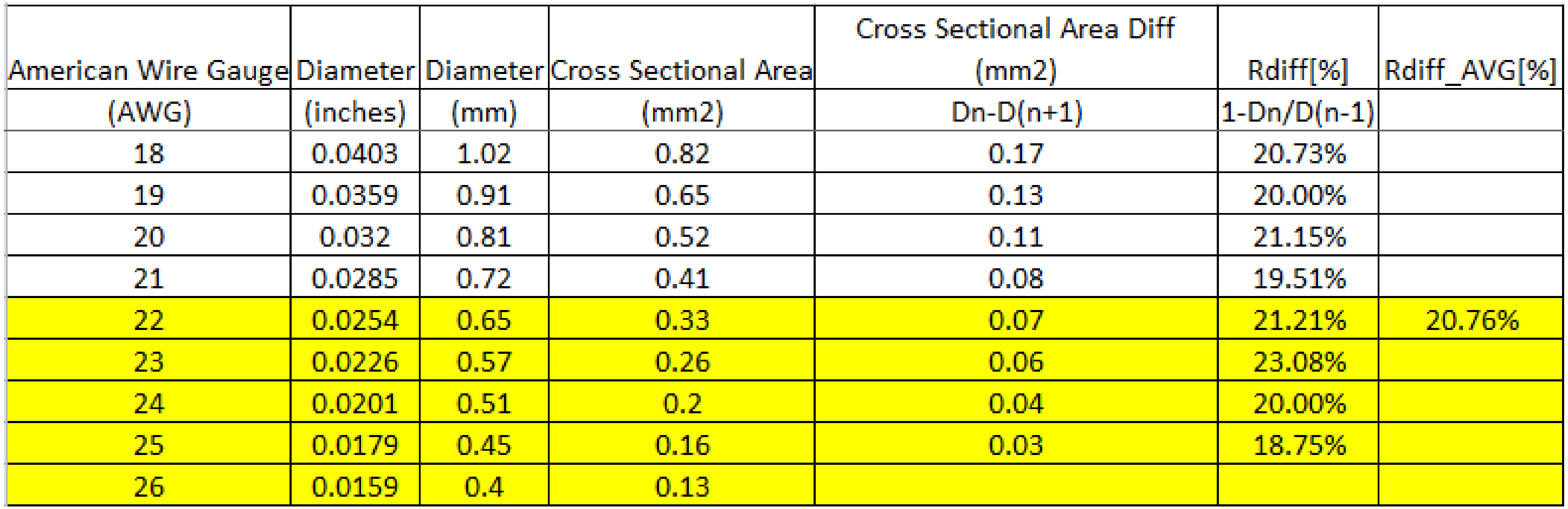
	Category 5e/Class D	Category 6/Class E	Category 6A/Class EA	Class F	Class FA
Propagation Delay (ns)	$534+\frac{36}{\sqrt{f}}$, f [MHz]				
Delay skew (ns)	50	50	50	30	30

- Source: ANSI/TIA-568-C.2
- The above maximum limits (for the channel) can be used for predicting the maximum P2P resistance unbalance together with additional information. (See Annex B and B1).
- 1.25ns per connector need to be reduced for getting only the cable spec.➔45nsec
- In good cables skew has margin of 25 to 50% from specification.
- Propagation delay is also less than spec limits by ~15-25% margin.
- There are cables that are close to spec limits.

Annex C2: Additional ANSI/TIA-568-C.2 data

- From ANSI/TIA-568-C.2:
  - Clause 5.3 Horizontal cable shall consist of four balanced twisted-pairs of 22 AWG to 24
  - 5.3.1 Insulated conductor
  - The diameter of the insulated conductor shall be 1.53 mm (0.060 in) maximum.
- **Clause 5.5** Cord cable shall consist of four balanced twisted-pairs of 22 AWG to 26 AWG.

Annex D – 1AWG wire diameter difference from AWG26 to AWG18.



American Wire Gauge	Diameter	Diameter	Cross Sectional Area	Cross Sectional Area Diff (mm2)	Rdiff[%]	Rdiff_AVG[%]
(AWG)	(inches)	(mm)	(mm2)	Dn-D(n+1)	1-Dn/D(n-1)	
18	0.0403	1.02	0.82	0.17	20.73%	
19	0.0359	0.91	0.65	0.13	20.00%	
20	0.032	0.81	0.52	0.11	21.15%	
21	0.0285	0.72	0.41	0.08	19.51%	
22	0.0254	0.65	0.33	0.07	21.21%	20.76%
23	0.0226	0.57	0.26	0.06	23.08%	
24	0.0201	0.51	0.2	0.04	20.00%	
25	0.0179	0.45	0.16	0.03	18.75%	
26	0.0159	0.4	0.13			

- What if wire diameter between pairs may be up to 1 AWG difference?
- (Within a pair wire diameter differences are very small in order to meet pair 2% Runb.)
- 1AWG difference is ~20.8% difference in wire resistance **for 22 to 26 AWG range**
- It means that D1/D2 range may be ~=0.89 to 1/0.89.
- Using larger wires diameter in long pairs and lower wire diameter in shorter pairs is probably used as a technique to have Zo=100Ω±TBD% in all pairs which actually helps reducing P2PRunb.

Annex D1 - 1 AWG wire diameter difference rare or common use case?

- Is it possible that in a cable, a wire in pair 1 and another wire in pair 2 will have a difference of 1AWG?
  - Analysis:
  - 1AWG difference between pairs will cause 11.5% P2PRunb even if pair 1 and pair 2 length are equal. Due to actual different twist rates it will be 15% or higher.
  - Over 1100 tested samples (CAT5e, CAT6, CAT6A) showed that P2PRunb max=4.4% which means that 1 AWG wire diameter difference is a rare use case.
  - It is impossible that two wires in a pair will have 1AWG difference since 2% Runb can't be met (d1/d2 range can be 0.98 to 1 or 1 to 0.02). (confirmed by cabling expert).
  - The possibility of 1 AWG difference between wires in the same cable vs. calculations and vs. lab tests can be explained by the following:
    - The wire diameter is controlled within the pair and between the pairs to be much less than 1AWG, and/or
    - The cabling MFGs do use the balancing technique shown in the proposed equation by compensating larger pair length with larger wire diameter compared to the other pairs resulting with lower P2PRunb. <u>As a result, the above question became non issue.</u>
    - To control Zo to be nearly the same on all pairs suggest much lower differences than 1AWG.

    (The above possibilities were confirmed by cabling experts.)

Annex E–Transmission line model parameters -1

- In transmission line per unit length:

Zo = Characteristic impedance

$$Z_0[\Omega] = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

$$for\ G << j\omega L$$

$$Z_0[\Omega] = \sqrt{\frac{R + j\omega L}{j\omega C}}$$

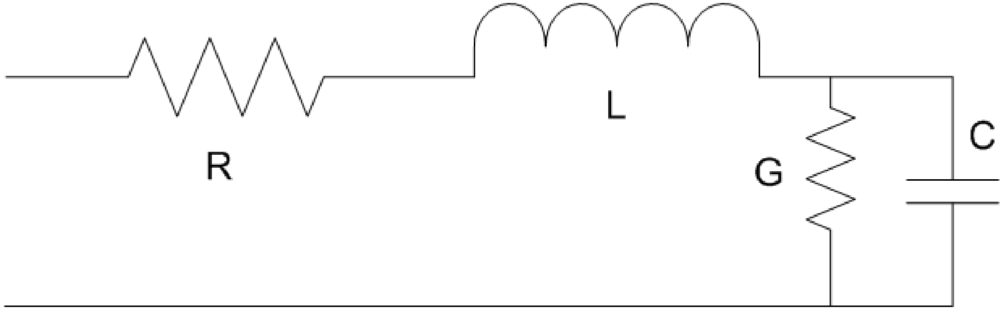
Propagation Delay time

$$delay[\sec] = \sqrt{(R + j\omega L)\cdot(G + j\omega C)}$$

$$for\, G << j\omega C$$

$$delay[\sec] \approx \sqrt{(R + j\omega L)\cdot(j\omega C)}$$

- For an ideal line (evenly distributed L and C and (ignoring skin effect) the delay increases linearly with its length, while its impedance remains constant.
  - For a given length, the phase difference between the input and output will increase with the frequency.



Annex E–Transmission line model parameters -2

- Components L,C and R (G assumed to be negligible) in Zo equation each has its own contribution to Zo accuracy which need to be connected to accurate 100 ohm termination and meet cable requirements e.g. return loss, PSNEX etc.).

$$Z_0[\Omega]=\sqrt{\frac{R+j\omega L}{j\omega C}}$$

$$L=\frac{\mu_0\cdot\beta}{\pi}\cdot LN\left(\frac{b}{r}-1\right)=\frac{\mu_0\cdot\beta}{\pi}\cdot LN\left(\frac{2\cdot b}{d}-1\right)$$

The factor beta accounts for the inductance increase due to twist rate>0 due to the solenoid effect and inductance reduction due to lower magnetic field resulted by twist rate angle.

$$C=\frac{\pi\cdot\gamma\cdot\varepsilon_0\cdot\varepsilon_r}{LN\left(\frac{b}{r}-1\right)}=\frac{\pi\cdot\gamma\cdot\varepsilon_0\cdot\varepsilon_r}{LN\left(\frac{2\cdot b}{d}-1\right)}$$

See Annex B1 for addressing ß. The factor gamma in the equation for C is accounting for the twisting rate that affects the equation parameters values e.g. er. Derivation of gamma is not addressed here.

- For copper at 20°C

$$skeen\_depth[mm]\approx\frac{2.063}{\sqrt{f[KHz]}}=\frac{0.065234}{\sqrt{f[MHz]}}$$

- For T≥ 20°C

$$\boxed{\delta[mm,T[C^\circ]\approx 0.065234\cdot\sqrt{\frac{(1+(T-Ta)*0.003862)}{f[MHz]}}}$$

$$R\approx\frac{Length\cdot\rho}{\pi(r^2-(r-\delta)^2)}$$

Annex E–Transmission line model parameters -3

- Running $Z_0[\Omega] = \sqrt{\dfrac{R + j\omega L}{j\omega C}}$ for the following parameters:
  - R including Skeen Effect
  - L(d,Dout),
  - C(er, d,Dout),
  - Beta(twist rate, Dout, twist_period)
  - Er
  - f=1MHz to 100/250/500MHz (CAT5e/CAT6/CAT6A)
  - At cable operating temperature (20°C to 60 °C)

Shows that Zo need to be tightly controlled to meet Zo limits that controls return loss and as a result the wire parameters (e.g. d^2*pair length) are controlled. Since all pairs need to meet 100Ω±ΔZo it forces relatively tight pair to pair resistance unbalance. (Similar analysis can be done for PSNEXT)

Annex E–Transmission line model parameters -4

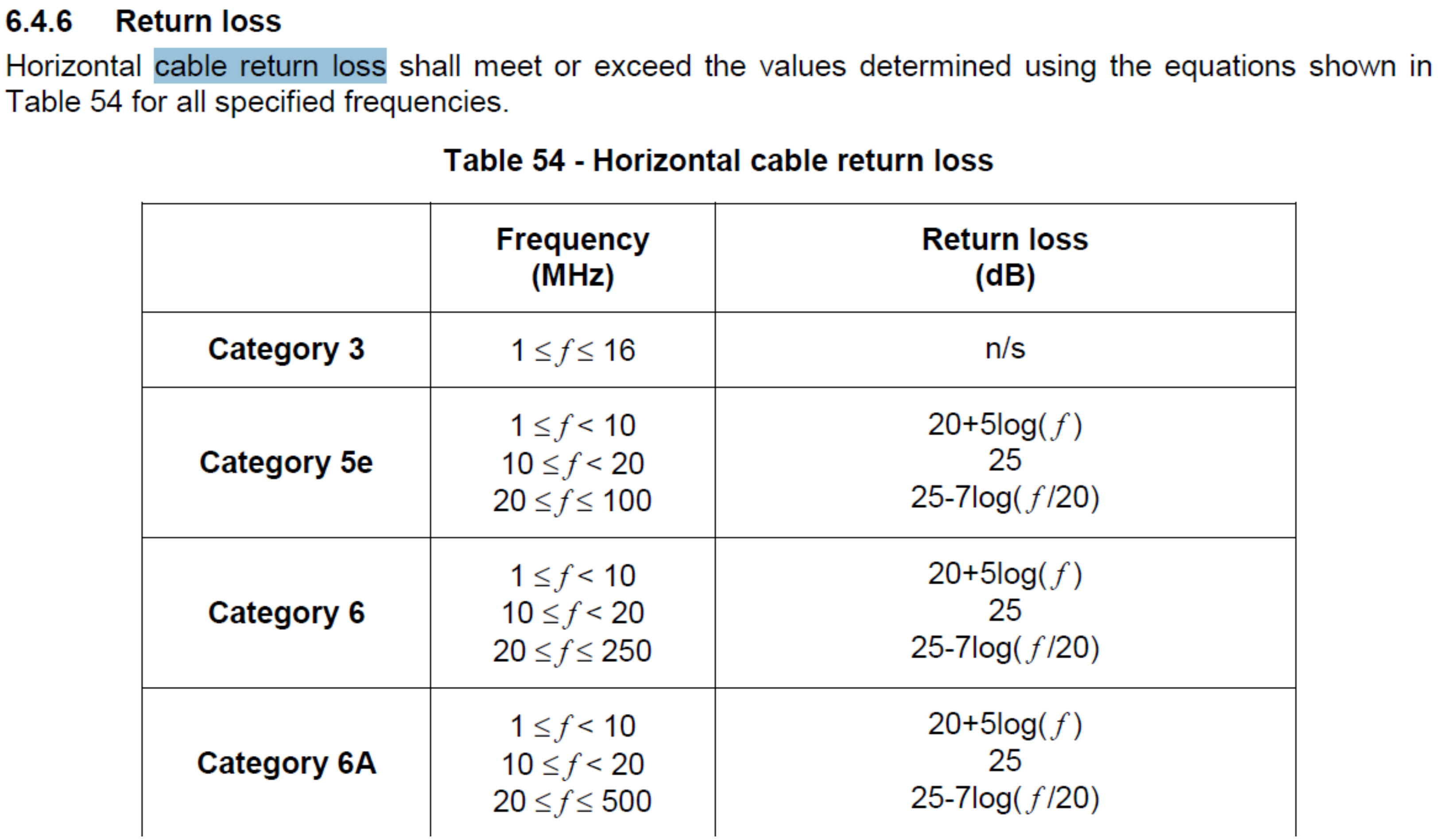
- MATLAB was used in the following example to filter results of P2PRunb based on Zo results that is going off the specifications.
  - Initial numbers:
  - Er=1.345, d=0.405mm, Dout=0.725mm,beta=0.98,L=422uH/m, C=35.45pf/m, f=1MHz, R(row,d,f)=R, R(DC)=0.13Ω/m.
  - Resulted with Zo=100.039Ω at 1MHz.
- Sensitivity Analysis
  - Changing d by -5% ➔Zo=107.12 Ω and
  - Changing Dout by +5% ➔Zo=113.74 Ω and
  - Changing er by -5% ➔Zo=116.74 Ω and
  - Changing beta by -5% ➔Zo=116.74 Ω and
  - Changing the above with reverse polarity resulted with Zo=83.59 Ω
- So far without accounting for:
  - Operating temperature range and
  - Operating frequency range and
  - Measurement errors and other design margins

Annex E–Transmission line model parameters -5

- We got already > ±16.7% deviation from pure Zo=100Ω
  ➔Return Loss=~21dB which is close to 20dB limit at 1MHz.
- As a result, wire diameter with the other wire parameters is tightly controlled (better than **5%**). Specifically wire diameter within a pair is tightly controlled.
- The tight control of the wire diameter for meeting Zo was confirmed by cabling experts.

Annex E–Transmission line model parameters - 6

- Return Loss requirements which is a function of Zo



6.4.6 Return loss

Horizontal cable return loss shall meet or exceed the values determined using the equations shown in Table 54 for all specified frequencies.

Table 54 - Horizontal cable return loss

	Frequency (MHz)	Return loss (dB)
Category 3	$1 \le f \le 16$	n/s
Category 5e	$1 \le f < 10$ $10 \le f < 20$ $20 \le f \le 100$	$20+5\log(f)$ 25 $25-7\log(f/20)$
Category 6	$1 \le f < 10$ $10 \le f < 20$ $20 \le f \le 250$	$20+5\log(f)$ 25 $25-7\log(f/20)$
Category 6A	$1 \le f < 10$ $10 \le f < 20$ $20 \le f \le 500$	$20+5\log(f)$ 25 $25-7\log(f/20)$

Annex F – Pair equivalent resistance calculation - 1

- Wire resistance of a pair (two wires in parallel) as function of different wire diameters within a pair wires.
- For R1: d1, l1 and d2,l2 are Rwire_1 and Rwire_2 diameter and wire length respectively. See figure 1 for reference.

$$Rwire_1 = \frac{\rho \cdot l_1}{0.25 \pi d_1^2}$$

$$Rwire_2 = \frac{\rho \cdot l_2}{0.25 \cdot \pi \cdot d_2^2}$$

$$R1 = \frac{Rwire_1 \cdot Rwire_2}{Rwire_1 + Rwire_2}$$

$$= \frac{\left(\frac{\rho \cdot l_1}{0.25 \cdot \pi \cdot d_1^2}\right) \cdot \left(\frac{\rho \cdot l_2}{0.25 \cdot \pi \cdot d_2^2}\right)}{\left(\frac{\rho \cdot l_1}{0.25 \cdot \pi \cdot d_1^2}\right) + \left(\frac{\rho \cdot l_2}{0.25 \cdot \pi \cdot d_2^2}\right)} =$$

$$= \frac{\left(\frac{\rho \cdot l_1 \cdot l_2}{0.25 \cdot \pi \cdot d_1^2 \cdot d_2^2}\right)}{\left(\frac{l_1 d_2^2 + l_2 d_1^2}{d_1^2 d_2^2}\right)} = \frac{\rho \cdot l_1 \cdot l_2}{0.25 \cdot \pi \cdot \left(l_1 d_2^2 + l_2 d_1^2\right)}$$

$$for \;\; l1 = l2 = l_{eqv} \,, \;\; or \;\; l_{eqv} = \frac{l_1 + l_2}{2}$$

$$R1 = \frac{\rho \cdot l_{eqv}}{0.25 \cdot \pi \cdot \left(d_2^2 + d_1^2\right)}$$

$$= \frac{\rho \cdot l_{eqv}}{0.25 \cdot \pi \cdot D_1^2}$$

$$D_1^2 = d_2^2 + d_1^2$$

$$D_1 = \sqrt{d_2^2 + d_1^2}$$

Annex F – Pair equivalent resistance calculation - 2

- In general $R_i = \frac{\rho \cdot L_i}{0.25 \cdot \pi \cdot D_i^2}$ $D_i = \sqrt{d_{i1}^2 + d_{i2}^2}$
- Example for R1. Same calculation can be used for any pair. Leqv is the pair length of Rwire_1 and Rwire_2 which can be at 1st order ~=(Lwire_1+Lwire_2)/2. D1 is the equivalent diameter of the two wires in the pair.
- D1=d*2^0.5 for d1=d2=d case.
- |d1-d2|=0.02 maximum in order to met 2% pair resistance unbalance specifications.

  See annex F1 for details.

$$R1 = R_{wire\_1} \| R_{wire\_2} = \frac{\rho}{0.25 \cdot \pi} \cdot \left(\frac{L_{eqv}}{D^2{}_1} \right)$$

$$R1 = \frac{\rho}{0.25 \cdot \pi} \cdot \left(\frac{L_a \cdot L_b}{D_b^2 \cdot L_a + D_a^2 \cdot L_b} \right) = \frac{\rho}{0.25 \cdot \pi} \cdot \left(\frac{L_{eqv}}{d_1^2 + d_2^2} \right)$$

Annex F1 – Pair maximum diameter difference

$$Rwire_1 = \frac{\rho \cdot l_1}{0.25\pi d_1^2}$$

$$Rwire_2 = \frac{\rho \cdot l_2}{0.25 \cdot \pi \cdot d_2^2}$$

$$R_{UNB} = \frac{Rwire_1 - Rwire_2}{Rwire_1 + Rwire_2} = 0.02 =$$

$$= \frac{\left(\frac{\rho \cdot l_1}{0.25 \cdot \pi \cdot d_1^2}\right) - \left(\frac{\rho \cdot l_2}{0.25 \cdot \pi \cdot d_2^2}\right)}{\left(\frac{\rho \cdot l_1}{0.25 \cdot \pi \cdot d_1^2}\right) + \left(\frac{\rho \cdot l_2}{0.25 \cdot \pi \cdot d_2^2}\right)} =$$

$$= \frac{\left(\frac{l_1}{d_1^2}\right) - \left(\frac{l_2}{d_2^2}\right)}{\left(\frac{l_1}{d_1^2}\right) + \left(\frac{l_2}{d_2^2}\right)}$$

$$l_1 = l_2$$

$$R_{UNB} = \frac{\left(\frac{1}{d_1^2}\right) - \left(\frac{1}{d_2^2}\right)}{\left(\frac{1}{d_1^2}\right) + \left(\frac{1}{d_2^2}\right)} = \frac{d_2^2 - d_1^2}{d_2^2 + d_1^2} = 0.02$$

$$1.02\, d_1^2 = 0.98\, d_2^2$$

$$\frac{d_1^2}{d_2^2} = \frac{0.98}{1.02} = 0.96$$

$$\frac{d_1}{d_2} = \sqrt{\frac{0.98}{1.02}} = 0.979 \approx 0.98$$

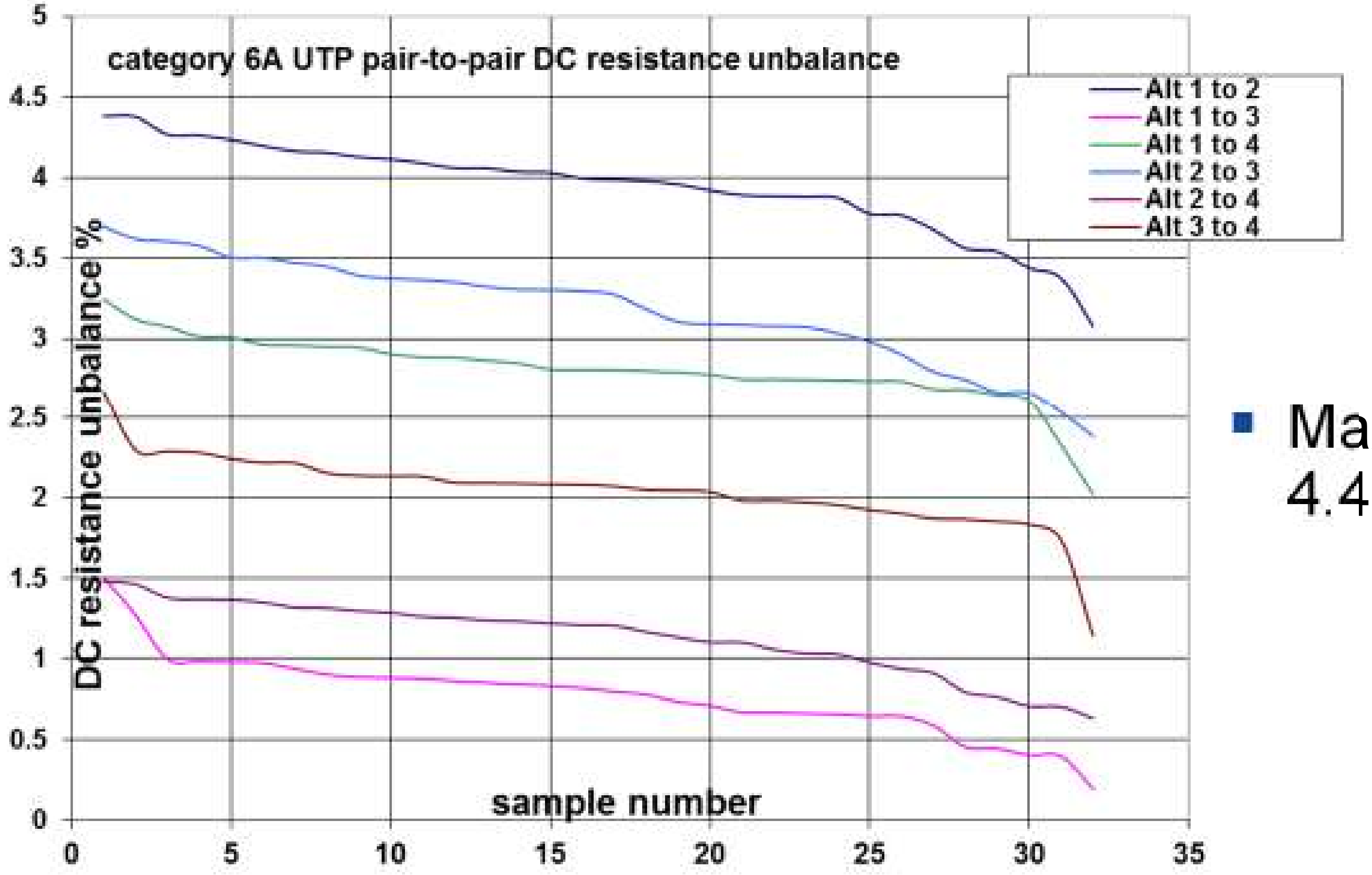
- Conclusion: for the same wire length in a pair, wire diameter maximum difference is 2%. Practically it will be better due to Zo requirements and other error factors.

Annex F2 – How to define and present P2PRunb

- Proposed setup to define P2PRunb in all pairs in a cable:
  - Test 100m/TBD cable for improved test resolution.
  - Find the pair with the minimum resistance e.g. pair 4,5.
  - Find the P2PRunb between the other pairs to pair 4,5.
  - The results are presented as follows:
    - P2PRunb 1,2 to 4,5: X1
    - P2PRunb 3,6 to 4,5: X2
    - P2PRunb 4,5 to 4,5: 0
    - P2PRunb 7,8 to 4,5: X3
  - Requirement: |X1|, |X2|, |X3| ≤5%

Annex G1: CAT6A, P2P DC resistance unbalance

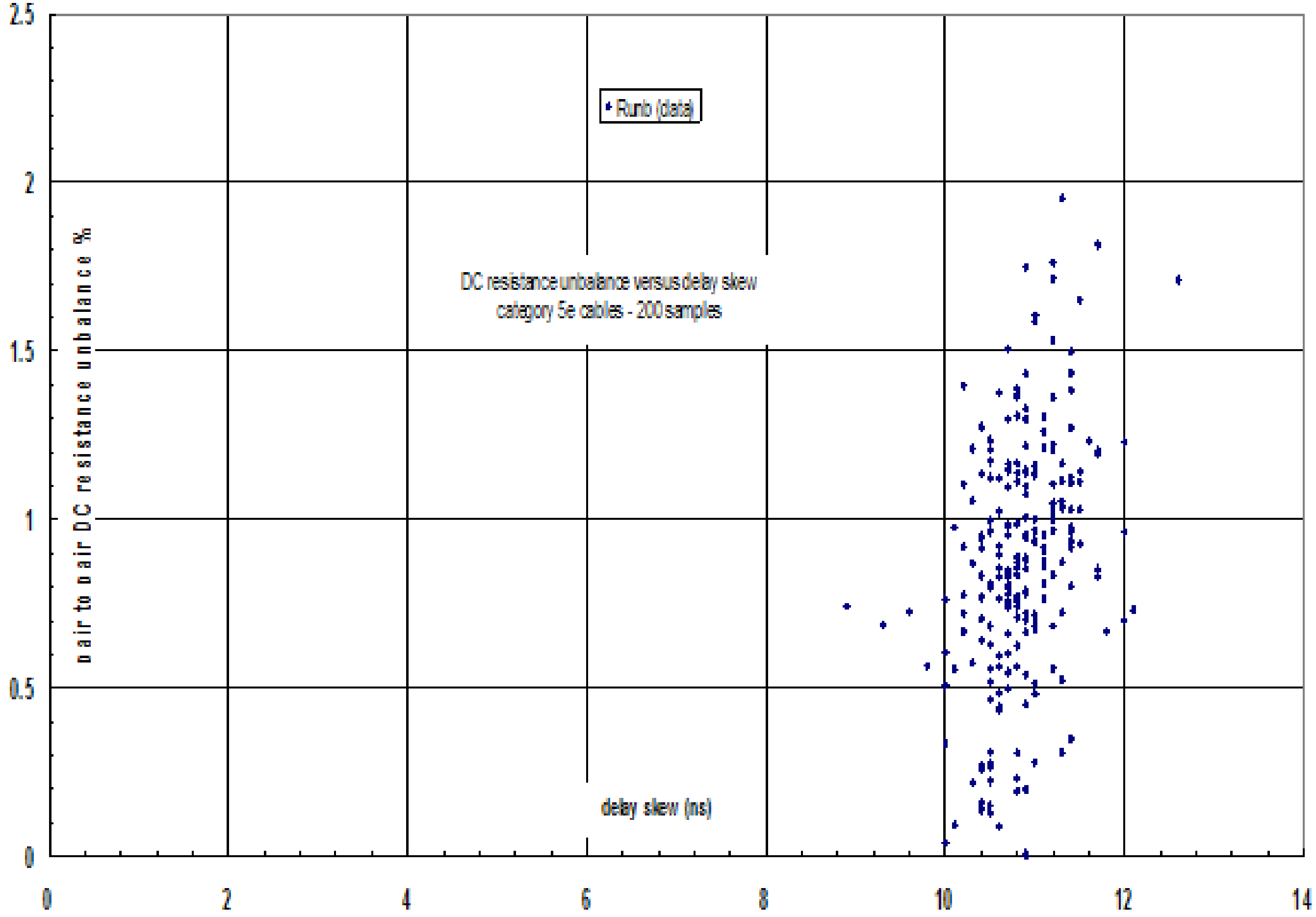
Source: Wayne Larsen / Commscope



- Max P2PRunb: 4.4%

The sample number is a unique number given to each sample. 32 samples were measured, and they were sorted by pair combination, largest DC resistance unbalance to smallest.

Annex G2: Cat5e, 200 samples: P2P DC resistance unbalance (P2PRunb) variations vs. skew due to differences in wire diameter and twist rates.



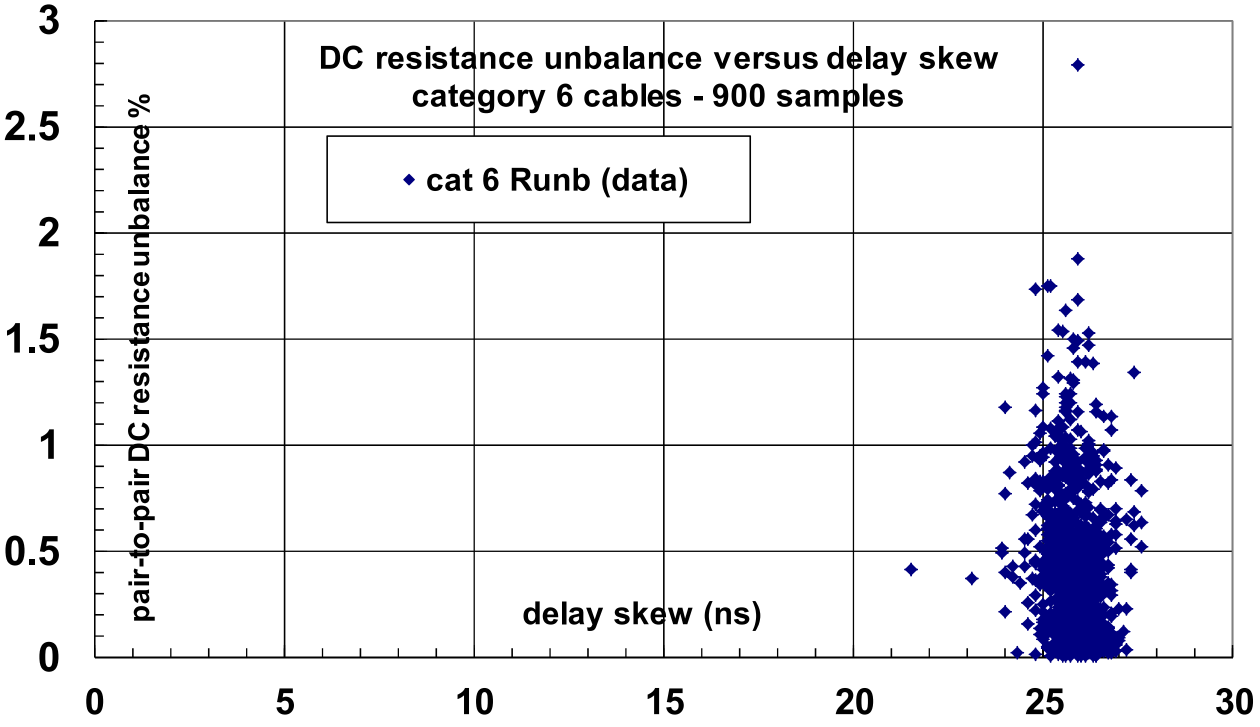
Tests:
Wayne Larsen/Commscope
Analysis:
Yair Darshan/Microsemi.

$$Runb \equiv \frac{\dfrac{t_2}{n_2 \cdot D^2_2 \cdot \sqrt{\cos\theta_2}} - \dfrac{t_1}{n_1 \cdot D^2_1 \cdot \sqrt{\cos\theta_1}}}{\dfrac{t_2}{n_2 \cdot D^2_2 \cdot \sqrt{\cos\theta_2}} + \dfrac{t_1}{n_1 \cdot D^2_1 \cdot \sqrt{\cos\theta_1}}}$$

- Max Resistance unbalance for 200 samples of CAT5e: < 2%.
- *The lab results validates the possibility of different P2PRunb for the ~same skew due different wire diameters.*

Annex G3: Cat6, 900 samples: P2P DC resistance unbalance (P2PRunb) variations vs. skew due to differences in wire diameter and twist rates.

$$Runb \equiv \frac{\dfrac{t_2}{n_2 \cdot D_2^2 \cdot \sqrt{\cos\theta_2}} - \dfrac{t_1}{n_1 \cdot D_1^2 \cdot \sqrt{\cos\theta_1}}}{\dfrac{t_2}{n_2 \cdot D_2^2 \cdot \sqrt{\cos\theta_2}} + \dfrac{t_1}{n_1 \cdot D_1^2 \cdot \sqrt{\cos\theta_1}}}$$



Tests: Wayne Larsen/Commscope
Analysis: Yair Darshan/Microsemi.

- Max Resistance unbalance for 900 samples of CAT6: < 3%.
- *The lab results validates the possibility of different P2PRunb for the ~same skew due different wire diameters.*

Annex G4: Additional information

- The skew measurements were all made on all frequencies from 1-500 MHz, and the reported number is the largest skew at any of those frequencies.
- All the skew and DC resistance measurements were made on 100m cable lengths.

Tests: Wayne Larsen/Commscope.

Annex G5: Propagation delay vs. P2PRunb

- The data base used to generate Annex G1-G4.
- To be added later.

Annex G5: Cat5e, Cat 6A: P2P DC Resistance unbalance

- Cat 5e: 30 samples, P2PRunb < 2%.
- Cat 6A: 10 samples, P2PRunb < 2%.

- Source: Yair Darshan/Microsemi.

Annex G6: CAT6A skew measurements

- skew < 10nsec for 30 samples (100m).
- (Source: Yair Darshan/Microsemi tests)

- From cables data sheet
  - CAT6A skew max≤45nsec
  - CAT6 skew max ≤25nsec

Annex H: Equation validation. Lab tests vs. Calculation - 1.

(**Tested** with cable pairs with the same insulating material, d1=~d2 per pair)

- Details for one of the lab tests.
  - Other lab tests (13) showing same behavior.

$$\left|\frac{d(P2PRunb)}{dt=1n\sec}\right|\approx 0.1\%$$

$$\left|\frac{d(P2PRunb)}{d(k)=1\%}\right|\approx 1\%$$

$$\left|\frac{d(P2PRunb)}{d(\alpha)=1\%}\right|\approx 0.7\%$$

$$k=D1/D2$$

$$\alpha=(1/n_1)/(1/n_2)$$

Correction factor K → to compensate for measurements error of<1%.

	P2P diameter factor, k	**Pairs**	Real Measurements of R1 and R2. P2PRunb	P2PRunb based on final equation
Real results	1	1,2	2.38%	3.25%
	1	3,6	1.12%	2.11%
	1	4,5	0.66%	0.36%
	1	7,8	0.00%	0.00%
Correcting factors required to match real results	1.0087	1,2	2.38%	2.38%
	1.01	3,6	1.12%	1.12%
	0.9970	4,5	0.66%	0.66%
	1	7,8	0.00%	0.00%

- Conclusion: Good correlation with systematic error which is function of test measurement accuracy (not a surprising result if f(x) replace length!

Annex H: Equation validation. Lab tests vs. Calculation – 2

(cable pairs with the same insulating material)

Before correction factor

Pair	Pair Length[m] for reference , not used.	Pair Res.(Ω)	tp [nsec]	skew[ns] for reference , not used.	wire diameter, d(m)	P2P diameter factor, k	equivalent pair diameter D1[m], D2(m)=d*2^0.5	External wire diameter (copper+ insulation) Dout[m]
1,2	107.6	6.453	520	29	0.000405	1	0.000573	0.000900
3,6	105.5	6.292	510	19	0.000405	1	0.000573	0.000900
4,5	102.2	6.235	494	3	0.000405	1	0.000573	0.000900
7,8	101.6	6.153	491	0	0.000405	1	0.000573	0.000900
1,2	107.6	6.453	520	29	0.000405	1.0087596	0.000578	0.000900
3,6	105.5	6.292	510	19	0.000405	1.01	0.000578	0.000900
4,5	102.2	6.235	494	3	0.000405	0.9970545	0.000571	0.000900
7,8	101.6	6.153	491	0	0.000405	1	0.000573	0.000900

After correction factor

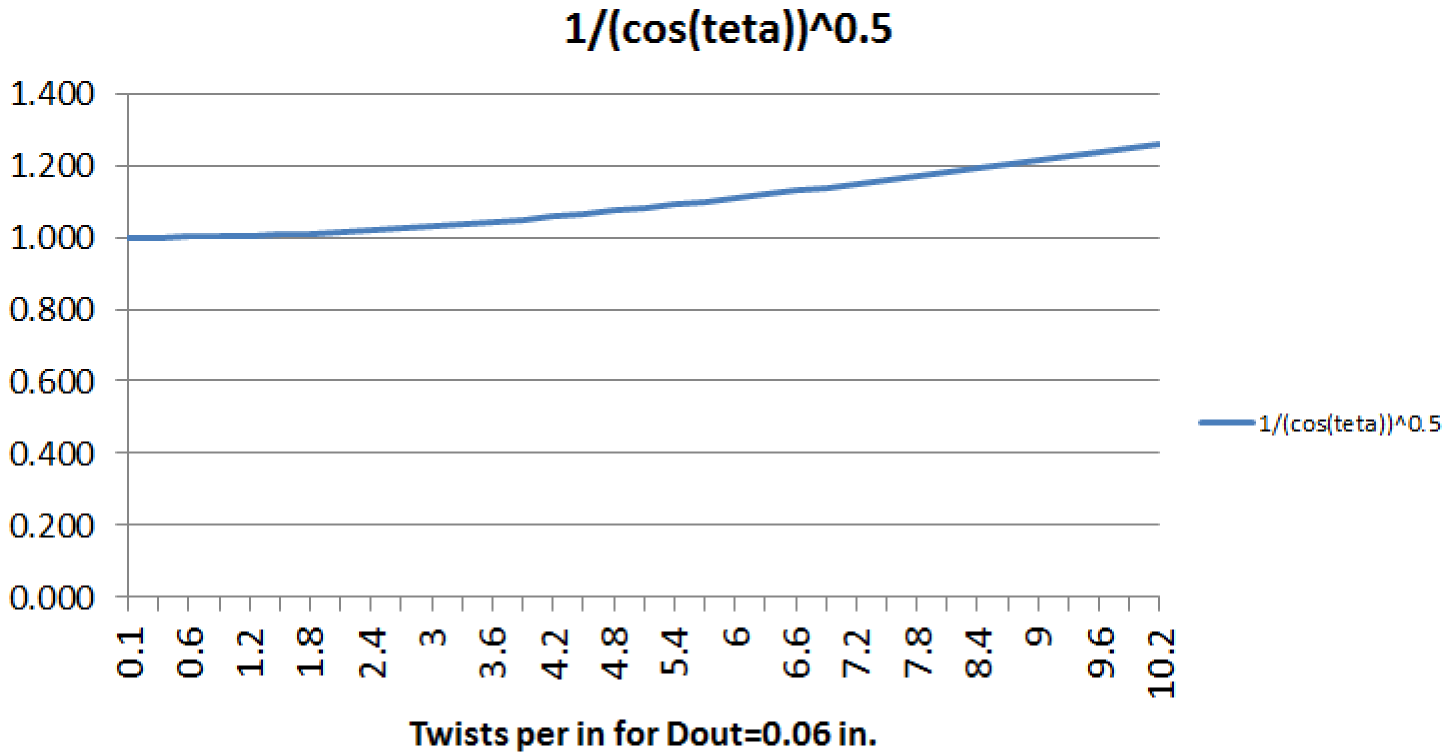
Twists/m=1/T	**T**	**twist rate ratio**	**cos(θ)**	**(cos(θ))^0.5**	**Real Measurements UNB(R)**	**P2PRunb based on final equation**
127.273	0.008	1.591	0.97475	0.987	2.38%	3.25%
109.091	0.009	1.364	0.98126	0.991	1.12%	2.11%
88.889	0.011	1.111	0.98744	0.994	0.66%	0.36%
80.000	0.013	1.000	0.98979	0.995	0.00%	0.00%
127.273	0.008	1.591	0.97475	0.987	2.38%	2.38%
109.091	0.009	1.364	0.98126	0.991	1.12%	1.12%
88.889	0.011	1.111	0.98744	0.994	0.66%	0.66%
80.000	0.013	1.000	0.98979	0.995	0.00%	0.00%

Before correction factor

After correction factor

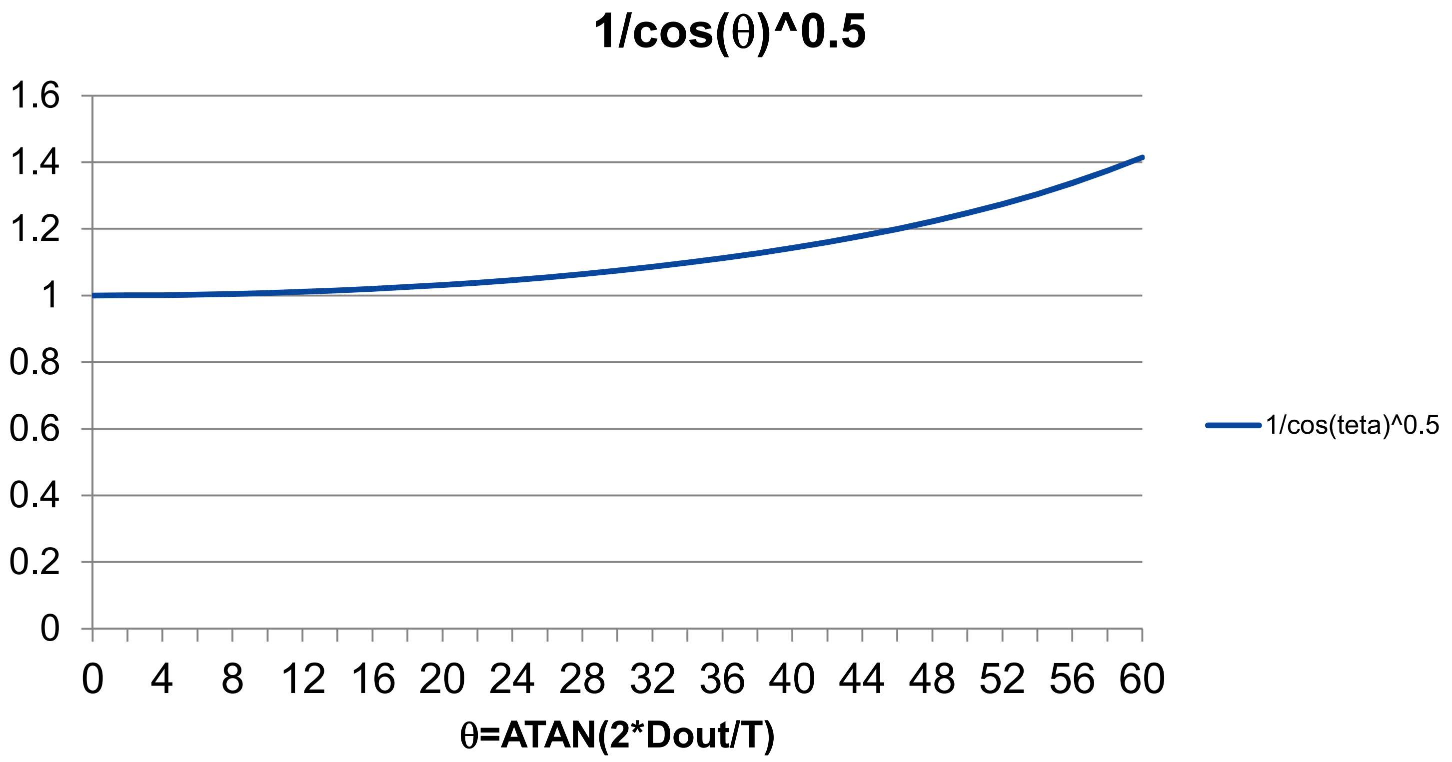
Annex J-1: for $\sqrt{cos(\theta)}$ vs. twist rate. (Example)

- Dout=0.06 in. Note that in low twists/in, cos(θ)➔1, no effect on propagation delay.
- Note that what is important is the difference between the twist rate in pair i and pair j.



Annex J-2: $\sqrt{cos}(\theta)$ vs.θ. Example

- θ (function of twist rate parameters) vs. 1/(cos(θ))^0.5 (propagation delay compensation factor).



Annex N – Some wire data used in this work

- Most common conductor diameters:
  - Copper: 0.4 mm (AWG26), 0.65 mm (AWG22)
  - With Insulation: 0.5 mm, 0.9 mm. (0.06 in max)

- Notes.
- The wire type used in the mathematical analysis in Annex B and B1 is solid.
- The effect of stranded wire type was not addressed in this work and it is to be the subject of a future research. As first order estimation it has negligible effect on the main conclusions resulted from this work.

Annex K: Lab test accuracy requirements

- Cable Length
  - Tests should be done on long cables e.g. 100m. (make connectors effect insignificant and improved resolution of (Ri-Rj) part of P2PRunb definition and propagation delay measurements.
  - Cable Length measurements accuracy better than 1cm.
- Resistance Measurements
  - Cable wires resistance resolution measurements <5 mili-ohms. Accuracy<5%.
- Propagation delay
  - Resolution <0.1nsec. (Currently 1nsec granularity test equipment were used which affects measurements accuracy by 50-100% for good cables with low skew and P2PRunb<1%). Each 1nsec affects ~0.1-0.2% on P2PRunb.
  - Test Frequency:<10MHz for minimizing errors. Propagating delay vs. test frequency change =~35nsec/700MHz

References

- http://www.physics.princeton.edu/~mcdonald/examples/twisted_pair.pdf
- http://microe.udea.edu.co/~alince/recursos/lineas/Twisted_Magnet_Wire_Tx.pdf

Revisions

Rev	Subject	Date		
00	Annex B2 was divided to two slides with derivation of P2PRunb or Runb from Channel level to cable level	Nov-8-2013		