Intra-Pair skew: About wave propagation in screened single pair

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Abstract

We show that intra-pair skew cannot be properly defined on a single screened pair, as the signal launched in a single wire does not propagate as such along the pair due to inter-wire coupling.

This coupling and propagation behaviour is illustrated using an analogy with the coupled pendulum system.

The measurement results can be described using a combination of the common and differential propagation modes. This is confirmed by TDR results of signal propagation.

Keywords: Wire; Cable; Single-Pair; Skew

1. Introduction

In-Pair skew is defined as the difference of the propagation time between the signal travelling in one wire and the other wire of a pair (cf. IEC 62783-1-1:2022). This time difference is expected to affect the differential signal and hence perturb the integrity of the communication.

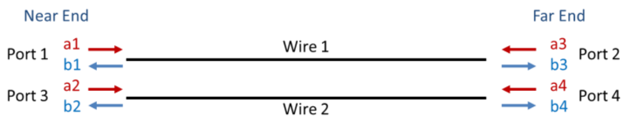
However, literature is not clear about this topic and different publications highlight the difficulty in interpreting the measurement results [3].

This paper gives a more thorough physical understanding of the signal propagation and clarifies the fact that Intra-Pair skew cannot be defined as such.

2. Ports definition for single pair

Measurements performed for this paper are done using a four port vector network analyser (VNA).

The cable is connected according to the scheme here below. As usually defined, “a” and “b” are the incoming and reflected waves, respectively.



- S_{mn} represents the response at port “m” of a signal send on port “n”

Hence:

- S_{21} represents the response at the far end of the first wire of a signal sent from its near end
- S_{43} represents the response at the far end of the second wire of a signal sent from its near end

As per IEC 62783-1-1:2022, Intra-pair skew is defined as propagation time (phase) difference between S_{21} and S_{43}.

3. Single wire measurements on pair

As S_{21} represents the signal propagation in one wire of the pair, it is expected to be a smoothly decreasing curve. However, measurement does not show the expected behaviour (cf. Figure 1). Measured S_{21} is a “bumped” curve with dips falling to zero (or close to) at regular frequency intervals.

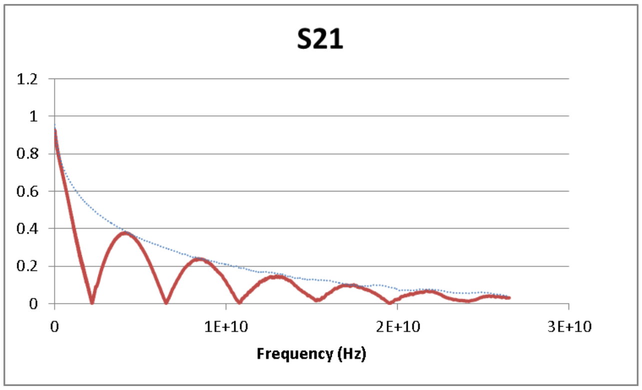


Figure 1: Measured S_{21} on a single pair (red curve) and its expected behaviour (blue dotted line)

Owing to the noise disturbance, phase computation at frequencies where the amplitude is close to zero is difficult. Moreover, closely looking at the dips where the signal amplitude falls close to zero (cf. Figure 2), the phase curve shows jumps of π. These jumps lead to a non-linear curve when unwrapping the phase (cf. Figure3)

This observation is not compatible with the common understanding of single wire signal propagation.

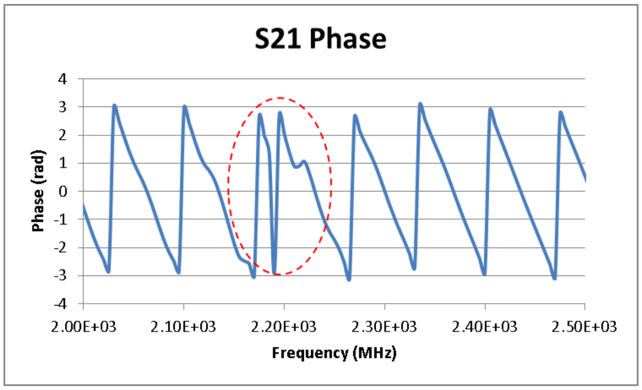


Figure 2: Phase of S_{21} around a point where the module of S_{21} is close to zero. One can see a phase distortion and a jump of π in the absolute value of the phase

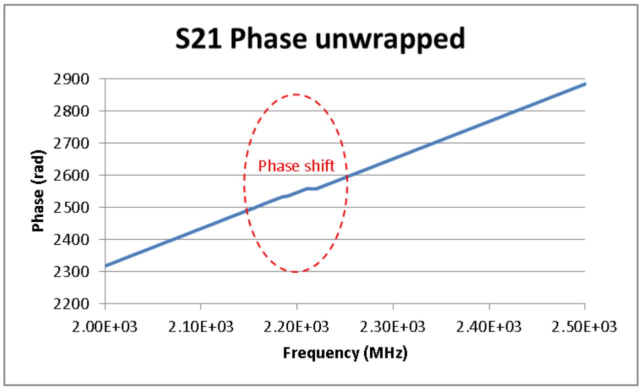


Figure 3: The phase distortion of figure 2 shown in the unwrapped phase representation. A phase jump of π is clearly visible

S_{41} (signal sent on the same wire but measured on the other wire) measurements are also surprising (cf. Figure 4). Instead of being close to zero, the signal shows similar amplitude behavior, but with dips at frequencies where S_{21} is maximal. This confirms the presence of inter-wire coupling i.e. signal is present on the wire where no signal was launched. It suggests that the signal does not propagate solely on a single wire.

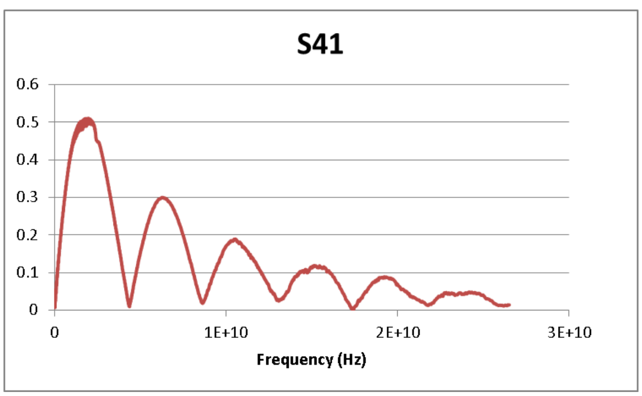


Figure 4: Measured S_{41} on a single pair

Note: S_{43} and S_{23} are similar to S_{21} and S_{41} respectively.

4. Data interpretation – the coupled pendulum

In order to get a tangible picture of coupled modes propagation in a screen pair, a direct analogy with the behaviour of a coupled pendulum is used.

The model: Two equivalent pendulums are coupled with a spring.

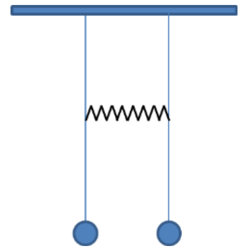


Figure 5: The coupled pendulum model

In this mechanical example, a stable oscillation corresponds to the situations where both pendulum are excited (oscillate) in phase or 180° out of phase. These modes are called “eigenstates”.

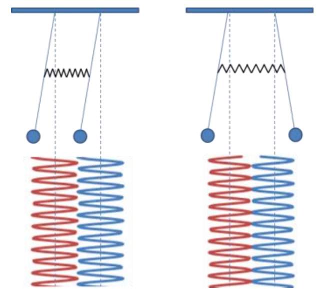


Figure 6: In phase and 180° out of phase modes

In our screened pair system, this can be related to the common and differential modes of propagation, which represent the eigenstate of the pair excitation. The displacement amplitudes of the pendulum correspond to the voltage amplitude on the wires.

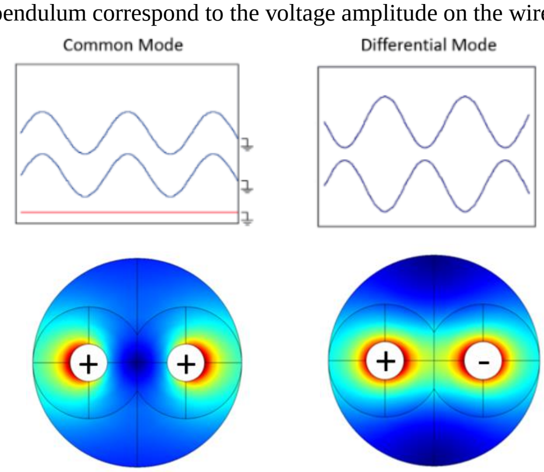


Figure 7: The common and differential propagation modes in a screened pair and associated electrical field distributions

When exciting only one pendulum, it is well known and understood that the energy of the system is periodically transferred over time from one pendulum to the other.

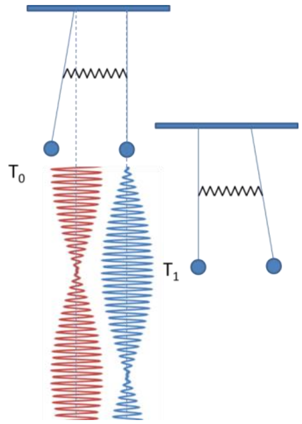


Figure 8: The coupled pendulum when one single pendulum is excited at time T_0. After a while (T_1) all the energy is transferred to the other pendulum

The periodic movement of the pendulums over time is shown in the following figure.

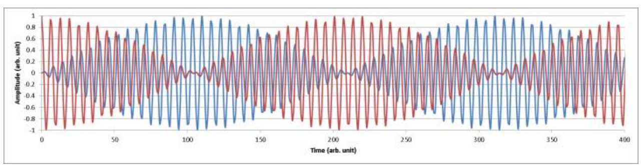


Figure 9: Oscillations of both pendulums over the time

5. Interpretation in the case of the screened pair

As both wires are electromagnetically coupled to each other, launching a signal in a wire of a screened pair is exactly like exciting one pendulum in the state described above.

The signal will propagate along the pair length and its energy will be transferred back and forth between both wires.

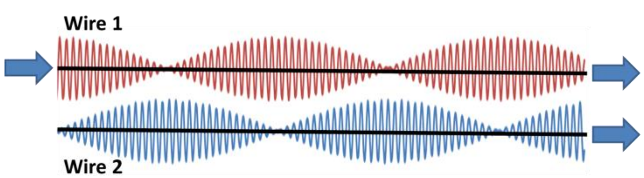


Figure 10: Signal propagation in a screened single pair when only one wire is excited

Any excitation mode can be described as a linear combination of the eigenmodes of the system.

Assuming a perfect cable, a single wire excitation can be constructed by the linear superposition of the common and differential modes with identical amplitudes.

Hence, assuming a perfect connector, by injecting a signal into a single wire, both propagation mode occur with equal amplitudes.

These 2 modes will then propagate through the pair. Measuring a single wire at some place along the pair will reveal the superposition of the state of these 2 modes at that position.

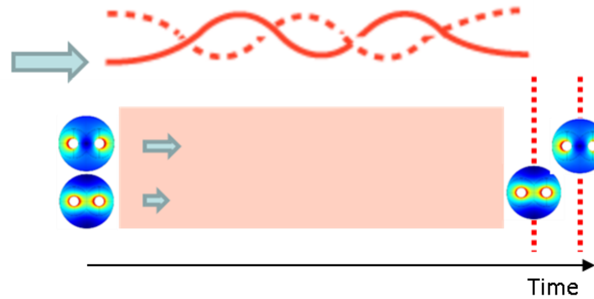


Figure 11: Decomposition of a single wire excitation into common and differential mode signals and their propagation. The propagation speed of both modes is different, so they will not reach the cable end simultaneously

This can be easily simulated by the sum of 2 sine waves with different propagation speeds and attenuation, as it is the case for common and differential modes.

Doing so, one can perfectly fit the measured curves.

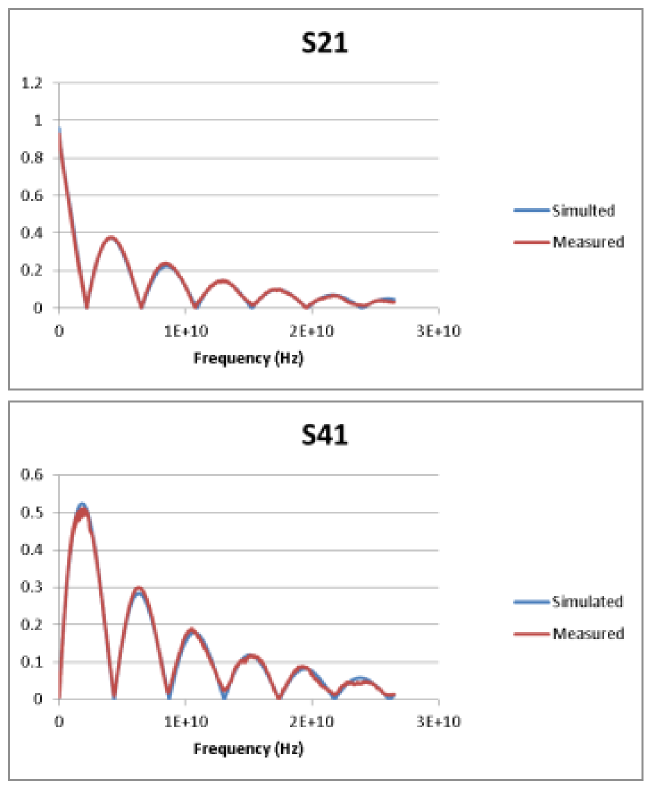


Figure 12: Comparison between measured S parameters and calculated ones using Common and Differential mode propagation with different speeds and attenuations

Note: Using mixed mode theory, S_{dd21} and S_{cc21} (the differential and common mode signals respectively) can be calculated from the single wire measurements. These two signals show the expected monotonic power decrease with frequency.

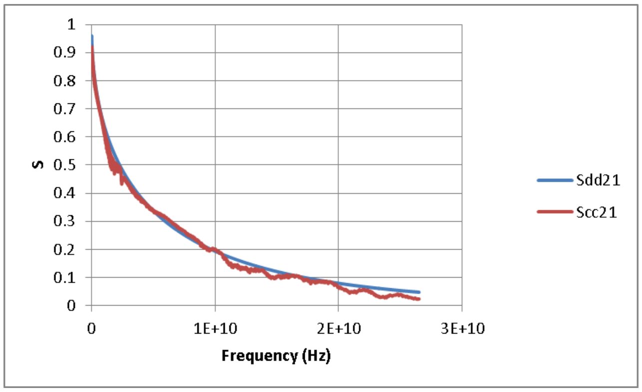


Figure 13: S_{dd21} and S_{cc21}

6. Time domain curves – propagation speeds

When looking at the calculated TDR of S_{21}, one gets 2 distinct reflection peaks (cf. Figure 14). The propagation speeds of differential and common mode can be computed from measured S_{cc21} and S_{dd21} respectively. The product of propagation speed and cable length result in the exact time where both peaks appear.

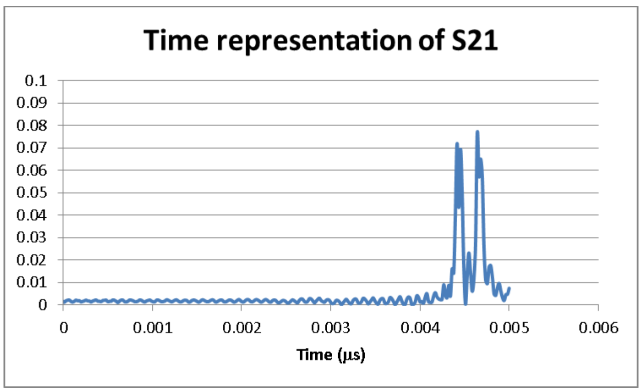


Figure 14: Time domain representation of S_{21} showing dual propagation times of the signal corresponding to common and differential modes

This corroborates our interpretation of wave propagation based on the superposition of common and differential modes.

7. Notes

The theoretical description given above corresponds to a situation using perfect connectors and cable.

In the real world, the transfer of the signal from the connector to the wire may not be perfect and may thus result in different amplitudes of the differential and common modes. This will lead to S21 and S_{43} parameter that do not completely reach "zero" amplitude at dips. If the cable is perfect, this property might be used to characterize the connector.

In the real world also, the cable is not ideal and the eigenmodes may deviate slightly from the differential and common modes shown in Figure 7. These new eigenmodes are called "quasi-differential" and "quasi-common modes" by J.Poltz "[4]. This will not significantly affect our analysis, except that both modes will not be populated with equal amplitude using a perfect connector.

Eigenmodes are by definition orthogonal and hence propagate without interaction through the cable.

Irregularities along the cable length will however lead to alteration of the quasi-eigenmodes and hence to mode coupling.

For short cable length or low frequencies, when the transfer of power on the second wire remains low, the "usual" description of in-pair skew may still be appropriate.

8. Conclusion

Single wire wave propagation in screened single pair is not possible due to existing coupling between both wires. Energy is hence continuously transferred from one wire to the other.

This can be interpreted in terms of common/differential modes (which represent the eigenmodes) excitation and propagation. Modelling this behaviour perfectly reflects the measured curves.

Intra-pair skew as defined in the standards is hence not a relevant parameter. It is moreover obvious that the measured signals will strongly depend on the position of the measurement i.e. the length of the cable.

Perturbing effects like mode coupling must then rather be looked at using differential to common mode conversion parameters.

9. Annex

9.1 Modified mixed mode representation of Intra-Pair skew

Another description of intra-Pair skew has been proposed in [1] using modified mixed mode S-parameters.

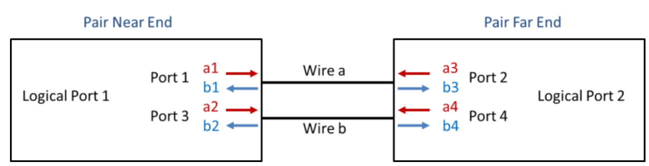
In this representation, intra-pair skew is defined as the difference in the propagation time (phase difference) of a differential signal sent at differential Port 1 and received respectively at single wire ports 2 (S_{2d1}) and 4 (S_{4d1}).

One can show that

$$S_{2d1} = \frac{1}{\sqrt{2}}(S_{21} - S_{23}) \qquad (1)$$

$$S_{4d1} = \frac{1}{\sqrt{2}}(S_{41} - S_{43}) \qquad (2)$$

Where d1 stand for "differential mode at logical port 1"



One can however also show (using mixed mode parameters description) that

$$S_{2d1} = \frac{1}{\sqrt{2}}(S_{dd21} + S_{cd21}) \qquad (3)$$

$$S_{4d1} = \frac{1}{\sqrt{2}}(-S_{dd21} + S_{cd21}) \qquad (4)$$

Considering for ease of interpretation that

$$S_{dd21} \gg S_{cd21} \qquad (5)$$

(which is the case for the measured cable), the phase difference between these 2 new S parameters will be π (minus sign of S_{dd21}) plus some oscillations which amplitude is related to the ratio between TCTL (S_{cd21}) and differential IL (S_{dd21}) and phase related to the difference in propagation speed of both differential and common modes.

Exchanging the sign of S_{4d1} as suggested in [1] to take into account the 180° phase difference between both "signals" of the differential mode will only move the curve by π down to around 0.

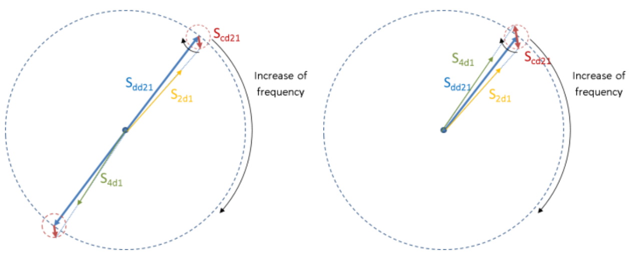


Figure 15: Graphical representation of S_{2d1} and S_{4d1} calculated from S_{dd21} and S_{cd21}

This is what is observed in the measurement.

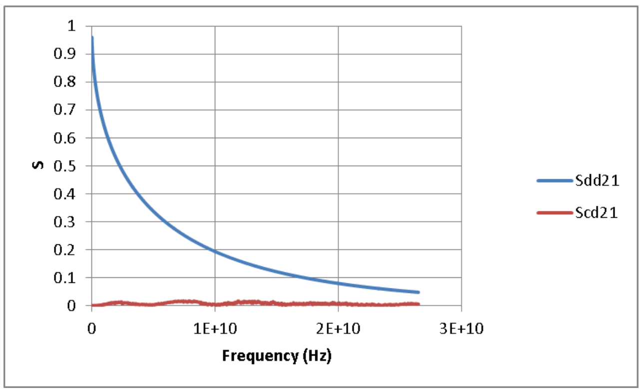


Figure 16: S_{dd21} and S_{cd21}

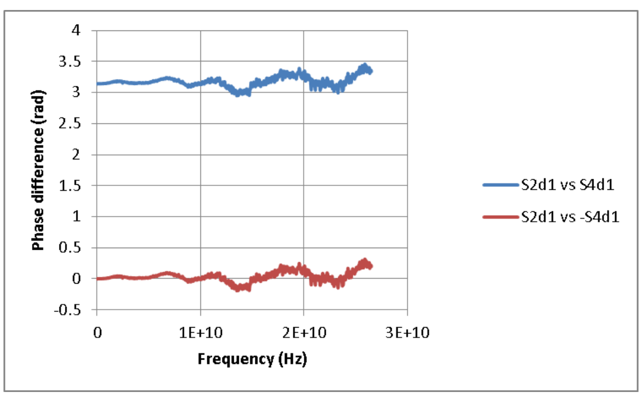


Figure 17: Phase difference between S_{2d1} and $\pm S_{4d1}$

This is then obviously not related to some propagation speed difference between both wires, but the envelope of the curve reflects the relative importance of TCL as compared to IL.

10. References

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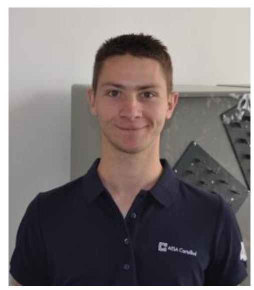
11. Authors

Boris Dardel obtained his PhD in physics in 1994 at the University of Neuchatel (Switzerland) in Condensed Matter Physics. He then joined the cable manufacture of Nexans Suisse SA in Cortaillod (Switzerland) where he managed different technical departments linked with materials, cable designs, testing and R&D. In 2016, Dr. Dardel came to AESA SA in Colombier (Switzerland) as R&D Manager, responsible for designing and leading R&D processes, specifically linked to the measurement of electrical resistance for energy cables.



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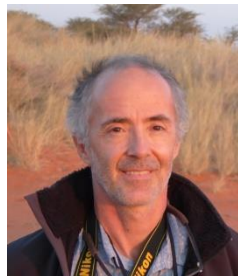
Wolfgang Klein holds a degree of Dipl.-Ing. (TH) Information Technology from RWTH Aachen University (Germany). During and after his university education he worked in the testing department of the German cable manufacturer Kerpenwerk.

His responsibilities connected with central IT were related to networking and automating test equipment. In 1994, he joined M.E.A. (Mauf und Rudow) where he used his practical experience to design the Quality Management System CIQ 3.0. He also developed the foundation of some modern telecom automatic test equipment such as the balunless data cable measurement systems “Cobalt”. Since the merger of M.E.A. and AESA, he continues his role as head of the System Development Department.

Denis Milz is the Area Sales Manager at AESA. He joined the company in June 1997. Owner of a Bachelor of Science in Electronics and electrical engineering from the Ecole d’Ingénieurs du Locle, Neuchâtel, he began his career at AESA as a software developer. He was then put in charge of the after-sales service department for a few years before moving to a more commercial position.

Denis Milz is in parallel responsible for the product line of automated test equipment (ATE) for Copper communication cables.

Vincent Arbet-Engels is the CEO/Managing Director of AESA, a leading manufacturer of test equipment for the cable industry. Prior to AESA, he held various scientific and management positions at CERN, IBM, and Abilis Systems, in both the USA and Europe.



Dr Arbet-Engels graduated from the University of California, Los Angeles (UCLA) in 1992, with a Ph.D. in Electrical Engineering. He also earned a M.S. from UCLA, as well as a M.S. and B.S. from the Swiss Federal Institute of Technology in Lausanne (EPFL) in Microengineering.