Comparing Various Measurement and Simulation Techniques for Estimating Crosstalk

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Abstract—**A comparison between crosstalk measurement techniques is made to investigate their applicability and efficiency for determining crosstalk between cables above a ground plane made of copper or carbon-fibre reinforced plastic (CFRP). Cost effectiveness, accuracy, speed and complexity of the methods are evaluated. All measurements are performed on two PCBs containing two pairs of copper traces. The techniques that are considered include balanced Vector Network Analyzer (VNA) measurements, balanced Spectrum Analyzer (SA) measurements, balanced EMI receiver (EMI-R) measurements, single-ended VNA measurements converted to mixed-mode S-parameters, and finally measurements with a signal generator (SG) and an oscilloscope (OSC). For verification, measured results are also compared to three simulation techniques, involving a Method of Moments simulation and two different transmission line models.**

Keywords—crosstalk, measurement, simulation, multiconductor transmission line

I. INTRODUCTION

In a race towards sustainable flight, the aviation industry is focussed on the development of More Electric Aircraft (MEA), including hybrid or fully electrical propulsion. These are necessary developments for emission free aviation, but they also drastically increase the amount of on-board electrical wiring. Therefore, attempts are made to optimise Electrical Wiring Interconnection Systems (EWIS) of aircraft in terms of weight, volume and costs, while keeping compliancy with safety (e.g. EMC) regulations. In such optimisations, crosstalk is one of the essential topics to address. Crosstalk measurements and simulations can be used to test new EWIS designs, as well as to identify possible margins in an existing EWIS design that can be utilised to optimise the design.

In literature various crosstalk measurement techniques have been used. For starters, the combination of a tracking generator (TG) and a spectrum analyzer (SA) is broadly used for the generation of culprit signal and measurement of victim signal, respectively. For instance in [1] near-end crosstalk (NEXT) between two wire pairs was measured with this method. This method requires the use of baluns to connect the balanced wire pairs to the unbalanced measurement equipment, restricting the frequency band in which measurements can take place. In [2] current clamps were used to measure crosstalk currents in cable bundles, yielding frequency restrictions dictated by the current clamps. Finally, in [3] single-ended S-parameter measurements were converted to the mixed-mode S-parameters for the estimation of electromagnetic (EM) coupling between cables. In this case the frequency range is only limited by the Vector Network Analyzer (VNA).

The current paper compares results between several measurement techniques to investigate advantages and applicability to two different crosstalk situations. Key in this comparison is not showing that one can measure the exact crosstalk levels, as there is no novelty in this. Moreover, both uncertainties and incomplete data in a EWIS design make exact prediction of crosstalk in practical cabling configurations on-board aircraft unthinkable. Therefore, in EWIS optimisation, efficiency of the measurement setup is in favour of accuracy, since the engineer is most likely to repeat crosstalk measurements or computations for several EWIS designs. This paper would serve as a practice and application guide. The techniques that are compared are: direct measurement by VNA, single-ended VNA measurements converted to mixed-mode S-parameters, (tracking) generator with EMI receiver (EMI-R) or with Spectrum Analyzer, and function generator with oscilloscope (OSC). For verification, measurements are also compared to simulation results obtained with Feko and two different Multiconductor Transmission Line (MTL) models.

All measurement techniques are applied to two PCBs, one with copper and one with Carbon-Fibre Reinforce Plastic (CFRP) ground plane. Carson already studied influences of lossy ground (e.g. soil) on transmission line behaviour, in particular for overhead lines [4]. In more recent years advanced transmission line models for overhead lines [5], [6], as well as coupling between lossy lines have been developed [7]. As discussed in [8], modern aircraft contain many composites such as CFRP, thereby replacing aluminium fuselage panels by lossy ground planes. This affects crosstalk behaviour [8]. Therefore, the second PCB with CFRP ground plane is used to experiment with the various measurement techniques and investigate their applicability to more complex ground plane behaviour.

Section II discusses the crosstalk configuration and a corresponding theoretical baseline obtained from simulation. Sections III and IV discuss the measurement setup and results, respectively. Finally, section V discusses three different simulation models and their results, after which conclusions are given in section VI.

II. THEORETICAL BASELINE

Two PCBs have been designed, as opposed to wires hovering [3], to increase measurement stability and repeatability. Both PCBs have four traces divided in two pairs, which are separated by a distance of 10 mm. The trace thickness is 35 μm. All other dimensions are shown in the cross-sectional sketch shown in Fig. 1 (mind that it is not at scale). The difference between the two PCB layouts is that one of the PCBs has a copper ground plane as bottom layer, while the other lacks a bottom layer but is placed on top of a

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CFRP ground plane. The goal is to determine both near-end and far-end crosstalk between the two wire pairs, named NEXT and FEXT respectively. Consider the numbering of the conductors of the PCB in such a way, that traces 1 and 2 form the aggressor or culprit wire pair, while conductors 3 and 4 form the victim wire pair. In that case, common-mode (CM) NEXT and FEXT are defined as follows:

$$NEXT_{CM} \,/\, FEXT_{CM} = \frac{V_{v,CM,NE/FE}}{V_{c,CM}}, \tag{1}$$

in which:

$$\begin{aligned} V_{v,CM,NE/FE} &= \left(V_{3,NE/FE} + V_{4,NE/FE}\right)/2 \\ V_{c,CM} &= \left(V_{1,NE} + V_{2,NE}\right)/2 \end{aligned}. \tag{2}$$

Subscripts v and c indicate victim and culprit wire pair, respectively. Differential-mode (DM) crosstalk is defined in the same way, except that DM voltages are used.

Fig. 1 shows the cross-sectional dimensions and the 3D model of the boards, with SMA type connectors at each end of the conductors. The cross-sectional dimensions are constant over a length of 50 cm. This means that the well-known long line effects (quarter wavelength) should start to appear from approximately 50 MHz [9], [10]. Below this the 20 dB/dec slope of crosstalk is expected until, possibly, resistive crosstalk becomes dominant over the capacitive and inductive crosstalk, causing a plateau in the crosstalk curve. This is caused by a voltage drop over the resistance in the common return path. Fig. 2 and Fig. 3 show simulated NEXT and FEXT for the PCB with copper ground plane, of which the Feko simulation acts as a theoretical baseline to which results of all measurement techniques are compared and validated. More details on the different simulation results that are shown in these figures are given in section V.

Important evaluation criteria can be observed from the simulation result. The resonance frequency is for FEXT slightly below and for NEXT slightly above 300 MHz. The long line effect starts approximately at 150 MHz, while the crosstalk at 10 MHz is approximately -62 dB and -58 dB, for FEXT and NEXT respectively. Note that there is no resistive plateau at the lower frequencies, as the simulation is performed with an ideal return path, i.e. PEC.

In the following section multiple measurement setups are described to obtain the “same” results. Emphasis lies on accuracy, speed, cost effectiveness and complexity of measurement.

III. MEASUREMENT METHODS AND SETUPS

This section describes the various methods that were used to estimate crosstalk between the traces on both PCBs. Due to the vastness of unique combinations of measurement equipment and processing techniques, this paper presents a limited subset of the results. In case results show deviations from the expected result an explanation was sought.

In general for each measurement, the common-mode measurements were performed using a ZFRSC-123-S+ power splitter (applicable from DC – 12 GHz), to directly measure either NEXT or FEXT. In Fig. 4 this can be seen as replacing adapter “A” with a resistive network with three ports. This figure gives a general sketch of all measurement setups, with indication of the port numbering when representing the system as 8-port or 4-port.

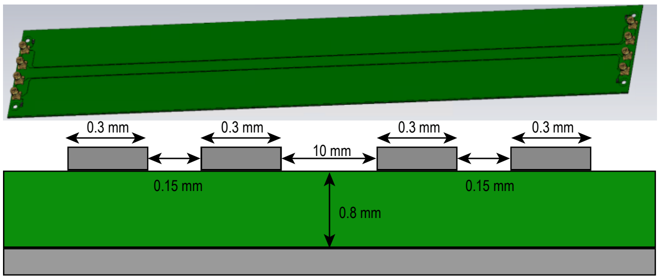

Fig. 1. Top figure shows the general overview of the PCB designs. Lower figure shows the cross-sectional dimensions (cross-section not at scale).

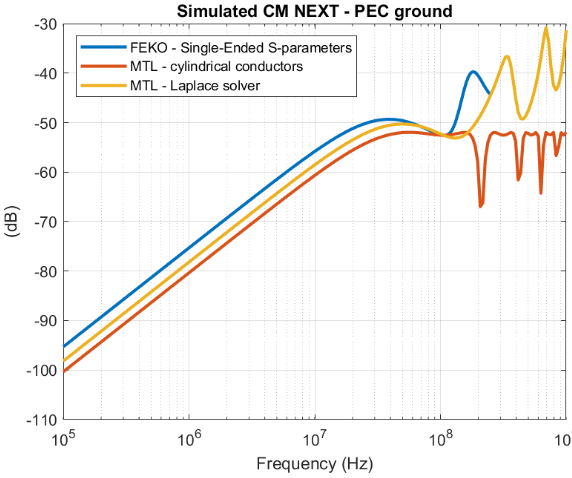

Fig. 2. Simulations of CM NEXT on a PCB with PEC ground. Blue line serves as theoretical baseline and is computed with Feko. The two other results are computed with MTL models, one for cylindrical conductors and one with a Laplace solver in which the exact PCB dimensions were included. Section V will provide more details on the simulations.

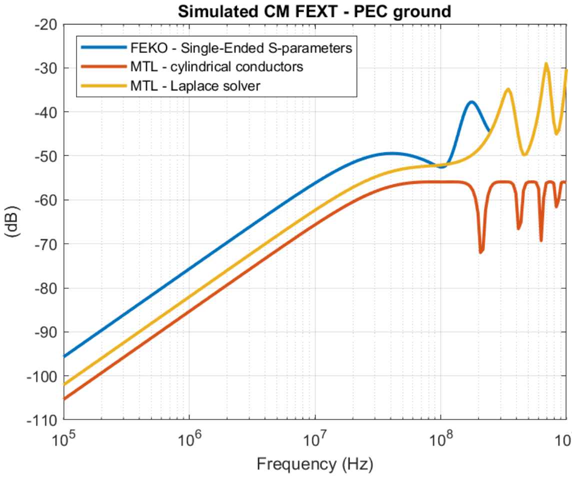

Fig. 3. Simulations of CM FEXT on a PCB with PEC ground. Blue line serves as theoretical baseline and is computed with Feko. The two other results are computed with MTL models, one for cylindrical conductors and one with a Laplace solver in which the exact PCB dimensions were included. Section V will provide more details on the simulations.

A. EMI receiver and (tracking) generator

Measurements performed with the Rohde & Schwarz EMI Test Receiver ESS (frequency range: 5 Hz – 1 GHz) are very much in line with the pure definition of crosstalk given in (1). The tracking generator poses a voltage upon the CM adapter that is connected to ports 1 and 2 on the PCB, while the receiver port is connected via a similar CM adapter to ports 3 and 4 for NEXT (and ports 7 and 8 for FEXT). Internally the transfer ratio is determined and given in dB.

In Fig. 5 a simplified block diagram of the receiving port is given. It is shown that the "RF" input is down-mixed and heavily filtered, to assure no spectral leakage between adjacent frequency observation points. Settings that can affect measurement results are dwell time, frequency steps and bandwidth. In case of crosstalk, the used EMI detector will always be the peak detector as it will show the worst case. Using the build-in tracking generator will circumvent possible mismatch between the TG and the receiver as a result of set observation frequency and dwell time. In case of using a signal generator, the sweeping rates should mismatch to ensure proper crosstalk detection.

Benefits of using EMI test receivers are the large dynamic range (DNR), low noise floor and large observational frequency range. In a crosstalk measurement setup, the noise floor is relevant for low-frequency evaluation and in this case it was approximately -90dB.

B. *Vector Network Analyzer*

A second way to measure EM coupling between cables is by using a VNA. In this paper, a Keysight E5061B Network Analyser (frequency range: 5 Hz – 3 GHz) was used. All measurements were performed with the VNA set to 1601 measurement points, 0 dBm power and 10 times averaging. Typical sweep time in the measurement setup was around a second. Averaging lowers the noise floor, and increases measurement accuracy especially for low-frequency analysis. However, it also introduces a larger measurement time. One can trade-off accuracy versus speed, but in general the VNA measurements of crosstalk are slow as they also require open short terminated (OST) calibration steps. These are also quite complex in case baluns are used, as these are three port devices and thus not straightforward in being calibrated out.

Another option is to perform single-ended measurements and use conversion to obtain mixed-mode S-parameters [3]. The calibration step becomes less complex since baluns are not required, however the number of measurements to be performed increases in case one is interested in mixed-mode parameters. Benefit of this procedure is that one will acquire DM, CM and the conversion characteristics of the setup.

C. *Spectrum Analyzer and (tracking) generator*

A third and often used measurement setup includes a spectrum analyser in combination with a tracking generator. The SA used in this paper was a Siglent SVA1015X (frequency range: 9 kHz – 1.5 GHz) and was set to use a resolution bandwidth (RBW) of 120 kHz and a video bandwidth (VBW) of 100 kHz. The pre-amplifier was turned on to reduce the effect of noise in the results. The tracking generator was set to 0 dBm power in order to be consistent with the VNA. The selected filter was the EMI filter and the attenuator was automatically set to 30 dB.

One issue here was the measurement time and accuracy at the lower frequency range. The RBW of 120 kHz already required a long measurement time (tens of seconds to minutes), and reducing its size would increase this drastically into the sub-hour range. A reduced RBW is however necessary to measure the crosstalk accurately in the lower frequency range, i.e. below 1 MHz.

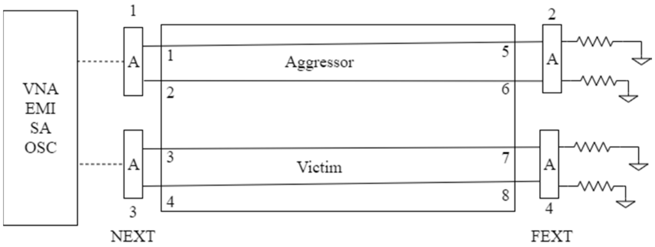

Fig. 4. Sketch of measurement setups - A is a possible Balun adapter for either CM/DM or just a through. The dashed lines can be a varying number of coaxial cables depedent on the measurment technique used.

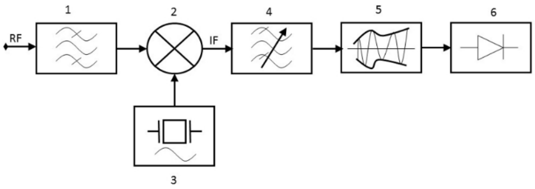

Fig. 5. Simplifed block diagram adopted from [11]. 1 Input filter, 2 Mixer, 3 Local oscillator, 4 Tuneable IF bandpass filter, 5 Envelope detector, 6 EMI detectors.

D. *Signal Generator and Oscilloscope*

A fourth and final measurement setup that is evaluated in this paper consists of a USB powered oscilloscope in combination with a two-channel output signal generator. The scope used was a Picoscope 5442D, with upper frequency limit of 60 MHz due to its bandwidth. Sampling frequencies depend on the set A/D conversion resolution, ranging from 62.5MS/s to 1 GS/s for 8 to 16 bit respectively.

In [12] it was already shown that this equipment can be used as an EMI test receiver that basically observes all frequencies of interest in parallel. By applying a short-time fast Fourier transform (STFFT) and max holding the envelope of the resulting time dependent frequency information in every frequency, one will eventually end up with a worst case crosstalk level. Conventionally the SG will generate a continuous wave of a specific frequency, while the OSC is used to compare input and output voltages. Whether it is peak-to-peak or root mean square (RMS) voltages, its ratio will still be the same and thus the measure of crosstalk. The novel approach used in these measurements is using a linear chirp signal, i.e. a continuous waveform linearly increasing in frequency. Parameters to be set are sweep time and frequency range. Using digital signal processing (DSP) one can accurately retrieve the low-frequency crosstalk levels in sub-second measurements. The DSP is in this case the bottleneck for speed, however this depends heavily on processing power. Trade-offs can be made between number of sweeps performed, and with it observational time and the measurement noise.

IV. MEASUREMENT RESULTS

A. *Near-end crosstalk*

Fig. 6 shows the measurement results for NEXT on the PCB with copper ground plane. Clearly, all measurement techniques yield similar results that also match with simulations, until the noise floor of the different setups is reached below 1 MHz. The evaluation criteria introduced in Section II are very well met. Just as in the theoretical baseline, in all measurements the long line effects start around 150 MHz and the NEXT level at 10 MHz is roughly -60 dB (except with the OSC, for which the maximum frequency was 60 MHz). The OSC measurement using a picoscope starts deviating above 10 MHz, which can have several origins, like path-length differences, reflections due to impedance mismatches or even timing issues in the synchronous measurement of the input and output channel. Moreover, the results with SA are noisy, and especially for lower frequencies the deviations become large. The cause is a RBW that is still too large. Decreasing it will give results equal to the other methods, but also yields very long measurement times.

The measured NEXT for the PCB on a CFRP ground plane is shown in Fig. 7 (OSC measurement is missing for this case). Clearly, this is a more complex case, since the measurement techniques now show some deviations. Measured results for the VNA with baluns, EMI receiver and SA (except below 0.1 MHz) are still relatively in agreement, by having an expected 20 dB/dec and a slight offset of 5 dB, up to about 2 MHz. For higher frequencies the results deviate slightly. The single-ended S-parameter measurements are not useful in this case, if low-frequency crosstalk levels are required. For these frequencies the resistive component of the CFRP (with conductivity much lower than copper) seems to be too high for this method to work well.

B. *Far-end crosstalk*

Fig. 8 and Fig. 9 show similar results for FEXT measurements. In case of a copper ground plane results of all measurement techniques match very well, except that the same observations for the NEXT measurements with OSC and SA hold. Comparing the other results to the theoretical baseline in Fig. 3 shows good agreement. In case of CFRP the results are shown in Fig. 9, showing the measurement techniques involving the VNA, EMI receiver and SA are in very good agreement. However, the single-ended S-parameter method deviates, albeit less than for NEXT. Nonetheless it does show the expected 20 dB/dec crosstalk behaviour, as well as some transition behaviour around 10 MHz (elaborated on in section V). One of the reasons for the change in behaviour for this measurement technique when compared to NEXT might be the anisotropic properties of the CFRP. Using an LCR bridge the impedance of the material in different directions was checked, and it showed higher impedance in the transversal direction compared to the direction of the PCB traces. This might explain the lack of the resistive crosstalk behaviour in the single-ended measurements of FEXT. However, due to the fact that these properties can vary for various CFRP ground planes, this measurement technique is marked not suitable for crosstalk situations with lossy ground planes.

C. *Comparison of Measurement setups*

Four measurement equipment setups were described, with five possible measurement techniques. Combining or interchanging several components between setups, like TG and SG, will increase the number of techniques rapidly. Nevertheless the techniques described are some of the most common methods for determining crosstalk, while the accuracy, speed, cost or complexity will likely not vary too much by interchanging several components. An overview of all pros and cons of the measurement techniques in this paper is given in TABLE I. (table also indicates applicability to crosstalk in free space (FS), of which results are not shown in this paper). In general, from comparing the measurements it can be seen that low-frequency (below 10 MHz) crosstalk can be estimated with all of these setups. However, in case the spectrum analyser is used, the RBW should be decreased with respect to the settings in this paper. The EMI-R + TG shows the least amount of noise, while the OSC + SG and SA show the highest amount of noise. The applicable frequency range depends mainly on the measurement equipment, which for our crosstalk measurements implies only a limitation for the OSC+SG (up to 60 MHz). However, when switching to DM crosstalk, different baluns will be required, yielding more stringent frequency limitations (in [1] 100 kHZ – 400 MHz). In such a case VNA-SE measurements could be a useful alternative, however for lossy ground planes their frequency limits depend on conductivity of the ground plane. The OSC+SG yields by far the cheapest setup (by approximately an order of magnitude), and also measurement duration is the shortest for OSC+SG, which is only limited by the sweep time of the SG. In this case it was a sub-second measurement time. For the VNA and EMI-R setup, the measurement time is highly dependent on the IF BW, but in general will take several tens of seconds. The SA measurement is dependent on the RBW, but is often in the order of minutes in this frequency range. When adopted towards a duration of seconds, the low-frequency range is completely off due to a too high RBW, as is shown in the results. The EMI-R and OSC setup do not require OST calibration, which is the case for VNA and SA. This reduces pre-setup complexity, as with baluns it is a non-trivial task being three port systems.

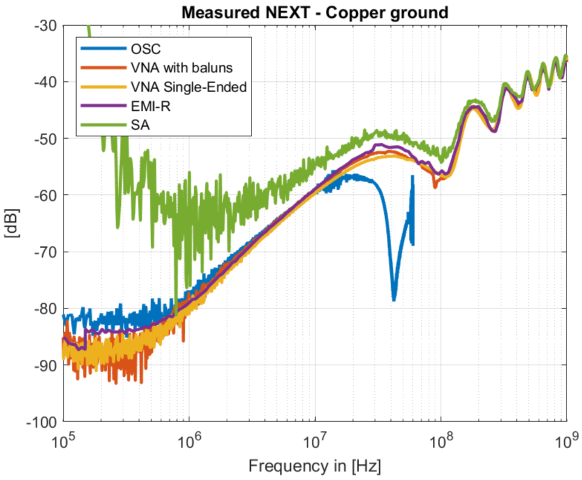

Fig. 6. Measured CM NEXT for the PCB with copper ground plane.

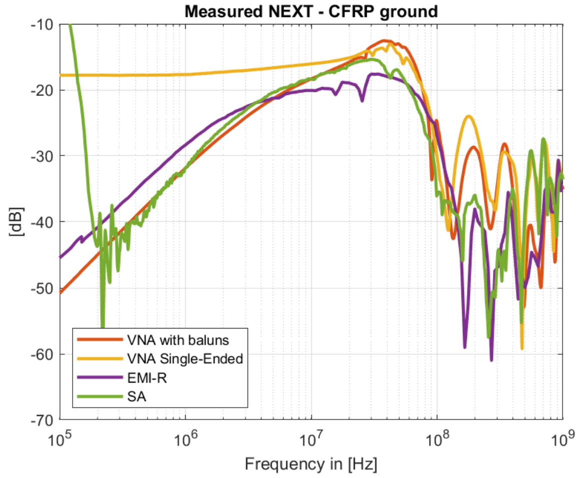

Fig. 7. Measured CM NEXT for the PCB with CFRP ground plane.

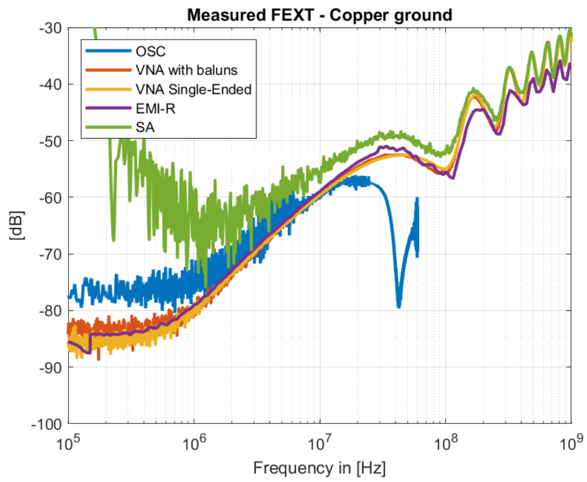

Fig. 8. Measured CM FEXT for the PCB with copper ground plane.

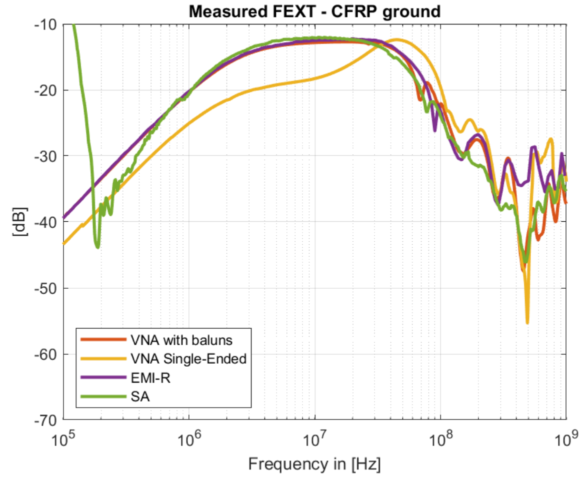

Fig. 9. Measured CM FEXT for the PCB with CFRP ground plane.

TABLE I. OVERVIEW OF MEASUREMENT TECHNIQUES AND THEIR PROS/CONS

	PEC	FS	CFRP	Pros/cons
VNA + Bal	x	x	x	+ Accurate over entire Freq. Range + No post-processing - use of Baluns, limits freq. range. - OST calibration
VNA-SE	x		x	+ no Baluns, so limit of freq. range due to VNA - Needs a "PEC" return path - OST calibration - Complex processing
EMI-R	x	x	x	+ no calibration + no post-processing - slow
SA + TG	x	x	x	+ no post-processing - Very slow - Balun calibation
OSC + SG	x	x		+ Cheap + no calibration - Only low-freq. - Complex post-processing

V. CROSSTALK SIMULATIONS

Apart from measuring crosstalk, simulations are also very useful to predict crosstalk in a certain EWIS design, or to develop new design rules that enable the optimisation of EWIS. In this paper, simulations of the given PCBs are performed with Feko and the MTL method.

For the MTL modelling two options are considered. If a very quick and rough estimate of crosstalk is desired, the simplest option is to model the PCB strips by cylindrical conductors that have a radius of $r_w = w/4$. Here w is the width of the PCB traces. In that case a rough crosstalk estimate is obtained by using Paul's [10] analytical expressions for the inductance and capacitance matrices. By using these equations an error due to the fact that the PCB strips are actually not widely separated is accepted. After solution of the MTL equations crosstalk can be obtained from the voltages of all conductors by applying (1).

A more accurate solution is obtained by computation of the inductance and capacitance matrix with a Laplace solver. This includes the actual behaviour of rectangular strips, as well as the dielectrics, the finite ground plane and proximity effects. These per-unit-length parameters can then again be used while solving the MTL equations, yielding a more accurate crosstalk result.

Finally, the most accurate simulated estimate of crosstalk is obtained by using a commercially available full-wave solver such as Feko. Therefore, the PCB layout is created in Feko. In Feko, several solution methods are available. The details in this model, being imposed mostly by the thin substrate layer, make the choice for the hybrid FEM/MoM solution method the most efficient one. In that case the CFRP can be modelled as a thin dielectric sheet with the properties of the CFRP. In our case, the CFRP has a thickness of roughly 2 mm, while the conductivity and permittivity are chosen equal to those used in [8].

NEXT and FEXT results for these three simulation methods for the PCB with PEC ground are shown in Fig. 2 and Fig. 3. The solutions by Feko match well with the corresponding measurements in Fig. 6 and Fig. 8. Both simulated and measured NEXT are roughly equal to -62 dB at 1 MHz. For FEXT this value is -58 dB, both in measurement and simulation.

Comparing the different simulation techniques, Feko yields the results that match best with measurements. However, this is also the most computationally expensive method (solved on Linux server with Intel(R) Xeon(R) Gold 6148 CPU @ 2.40GHz, 80 cores available, 6.8 hours when using single core, 10.5 GB RAM per core required). Fig. 2 and Fig. 3 also show the results obtained by MTL simulation. When the PCB traces are approximated by cylindrical conductors solutions are obtained within a second on a simple laptop (1 core, Intel i5, 8GB RAM), while low-frequency crosstalk levels are already quite accurate for both NEXT and FEXT. However, at high frequencies errors in the inductance and capacitance by assuming cylindrical conductors, an infinite ground plane and a homogeneous dielectric material start to show, since above 100 MHz the difference with respect to the Feko solution starts to increase. Using the capacitance and inductance matrices computed by a Laplace solver changes the high-frequency crosstalk behaviour and yields levels that are closer to the Feko results. This computation by the Laplace solver increases computation time and needs to be performed once for each cable cross section.

Finally, Fig. 10 shows simulated results for the PCB with CFRP ground plane. Simulation results show a clear influence of the CFRP ground plane. There is a clear shift in

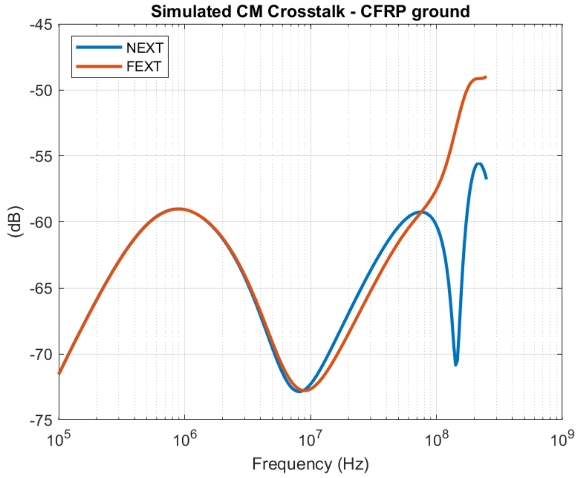

Fig. 10. Simulated CM NEXT and FEXT for the PCB with CFRP ground.

TABLE II. OVERVIEW OF SIMULATION TECHNIQUES AND THEIR PROS/CONS

	PEC	FS	CFRP	Pros/cons
MTL cylindrical	x	x		+ Fast - Inaccurate, especially for higher frequencies
MTL with Laplace	x	x		- Laplace solver takes effort, but only computed once
FEM	x	x	x	+ Accuracy - Time & memory consuming

crosstalk behaviour in the frequency area from roughly 1-10 MHz, where the skin depth of the CFRP becomes less than the actual thickness of the ground plane. For higher frequencies the crosstalk levels are comparable to those given in Fig. 2 and Fig. 3 for a PEC ground plane. In the lower frequency area crosstalk levels are higher than those for the PCB with copper ground plane. Such observations are very similar to conclusions drawn about differential-mode crosstalk above a CFRP ground plane in [8]. In the measurements however, these observations are less visible. Measured common-mode crosstalk levels are much higher than those for the PCB with copper ground plane, and also larger than simulated values. Most likely some unforeseen differences between the simulated and measured setup for the CFRP case are the cause. This can include errors in the estimation of the CFRP properties and bad connections of the PCB traces to the CFRP ground plane (in which case CM crosstalk will be completely different). Moreover, even though for DM crosstalk modelling with an isotropic layer is sufficient, including directionality (if this info is present) could improve the model.

VI. CONCLUSIONS

This paper contains a comparison between various crosstalk measurement techniques. All measurement techniques are applied to two PCBs containing four traces used in pairs, while the ground planes are either copper or CFRP. Common-mode crosstalk is measured and compared between all methods. The focus in this comparison is on accuracy, speed, cost effectiveness and complexity of the measurement. Finally, simulations are performed with FEKO and the MTL method to compare to all measurement results.

The measurement results for the PCB with copper ground plane coincide well over all measurement techniques, with some differences for the setup with spectrum analyzer due to too high RBW, as well as some differences for the Picoscope. In general, the measured results also match very well with simulations. Therefore, the measurement techniques can be evaluated on all properties but accuracy. A detailed overview of pros and cons is given, which can be used as a practical guide.

When the copper ground plane is replaced by the CFRP ground plane, differences start to appear between the various measurement methods, as well as between measurements and simulations. The latter is most likely formed by differences between the modelled versus practical properties of the CFRP, including connections to ground. With regard to the measurement methods, results of SA, balanced VNA and EMI receiver measurements match well, while the mixed-mode VNA measurements deviate significantly. The latter is clearly not applicable to such lossy material.

Finally, measured results have been compared to three different simulation methods. For the copper ground plane, the full-wave solution by Feko proved to be both the most accurate and the most computationally expensive method. Even though MTL models are require additional assumptions that can introduce errors, especially in the low-frequency area the obtained results are very reasonable. This justifies the use of such models to obtain a quick estimate for crosstalk levels, or in optimisation of EWIS in which computational efficiency is essential.

REFERENCES

[1] J. Lansink Rotgerink, H. Schippers, and F. Leferink, "Low-frequency analysis of multiconductor transmission lines for crosstalk design rules," IEEE Trans. Electromagn. Compat., vol. 61, no. 5, pp. 1612–1620, 2019.

[2] C. Jullien, P. Besnier, M. Dunand, and I. Junqua, "Advanced modeling of crosstalk between an unshielded twisted pair cable and an unshielded wire above a ground plane," IEEE Trans. Electromagn. Compat., vol. 55, no. 1, pp. 183–194, 2013.

[3] J. Lansink Rotgerink, N. Moonen, and F. Leferink, "Mixed-Mode S-Parameter Measurements for Determination of Cable Coupling," in ESA Workshop on Aerospace EMC, 2018.

[4] J. R. Carson, "Wave Propagation in Overhead Wires with Ground Return," Bell Syst. Tech. J., vol. 5, no. 4, pp. 539–554, 1926.

[5] M. D'Amore and M. S. Sarto, "A new formulation of lossy ground return parameters for transient analysis of multiconductor dissipative lines," IEEE Trans. on Power Del., vol. 12, no. 1, pp. 303–314, 1997.

[6] F. Rachidi, S. L. Loyka, C. A. Nucci, and M. Ianoz, "A new expression for the ground transient resistance matrix elements of multiconductor overhead transmission lines," Electr. Power Syst. Res., vol. 65, no. 1, pp. 41–46, 2003.

[7] T. Demeester and D. De Zutter, "Quasi-TM transmission line parameters of coupled lossy lines based on the Dirichlet to Neumann boundary operator," IEEE Trans. Microw. Theory Tech., vol. 56, no. 7, pp. 1649–1660, Jul. 2008.

[8] J. Lansink Rotgerink, F. Happ, and J. J. P. van Es, "Crosstalk between wire pairs above a composite ground plane," in IEEE International Symposium on Electromagnetic Compatibility, 2016, vol. 2016-Novem, pp. 89–93.

[9] C. R. Paul, Introduction to Electromagnetic Compatibility. Wiley Interscience, John Wiley & Sons Inc., 2006.

[10] C. R. Paul, Analysis of Multiconductor Transmission Lines, New York, John Wiley & Sons, 1994.

[11] T. Karaca, B. Deutschmann, and G. Winkler, "EMI-receiver simulation model with quasi-peak detector," in IEEE International Symposium on Electromagnetic Compatibility, 2015, vol. 2015-Septm, pp. 891–896.

[12] T. Hartman, N. Moonen, and F. Leferink, "Direct Sampling in Multi-channel Synchronous TDEMI Measurements," in 2018 IEEE 4th Global Electromagnetic Compatibility Conference (GEMCCON), 2018, pp. 1–5