Noisy ElectroMagnetic Fields

A Technological Platform for Chip-to-Chip
Communication in the 21st Century

NEMF21

Final Report

Executive Summary

March 7, 2019

Executive Summary

NEMF21 (Noisy Electromagnetic for the 21st centuries) was a project funded by the European Commission through its Horizon 2020 Future Emerging Technologies (FETopen) program. It brought together eight partners from across Europe with the common objectives to provide the design tools and evaluation criteria for building wireless chip-to-chip (C2C) communication systems in the presence of noise and interference and thus introducing wireless C2C as an alternative to wired connections.

Working in the 10 – 100 GHz and using spread-band spectrum technology allows for large data transfer rates and low power consumption. This would enable completely new ways of communication between all components on a chip level as well as new and compact 3D designs. Still, the wireless chip-to-chip pathway carries substantial risks and challenges, which need to be carefully investigated. Receivers can pick up unwanted EM radiations in an environment that has many radiating RF components in close proximity sending and receiving complex, coded and potentially noisy signals which scatter from and interact with the surrounding ICs and their housing. Wireless C2C implementation can only become reality if the increased sensitivity to Electromagnetic Interference (EMI) can be handled successfully and the electromagnetic energy can be routed efficiently through complex network topologies – including the IC components themselves. NEMF21 set out to provide the fundamental research and the necessary numerical and experimental advancements to start thinking seriously about wireless C2C architectures.

Within the NEMF21 framework, we have developed analytical and numerical tools to identify and assess the impact of noise on wireless communication and to model and mitigate the interaction of EMI with the signal and its influence on the channel capacity and data rates. In parallel, we have developed experimental setups to demonstrate our design protocol, as well as the analytical and numerical tools.

Progress can be summarised along the following lines, (where [D] denotes design protocol; [H] is hardware implementation; [M] is modelling toolbox):

[D] Design protocol for optimal Multiple-Input Multiple-Output (MIMO) antenna system in the near field.
[D] Signal processing and coding techniques, which utilize the information theoretic gains of MIMO systems with very-low to moderately-low resolution signal quantization.
[D] Design principles for low-latency channel-matched codes are provided for general frequency selective MIMO channels.
[H] A 2.4 GHz Liquid Cristal Polymer (LCP) antenna (appropriated for direct integration of antennas in packaging) combined with a 2.4 GHz front-end module. LCP smart antenna incorporate tuning and matching components.
[H] A 2.4 GHz-5.8 GHz bi-band fractal antenna combined with front-end ICs. Operations for evaluating MIMO functionalities in the near and far field.
[H] A millimetre wave 26 GHz -29 GHz antenna on package solution integrating beam-forming IC and antenna arrays.
[H] Integrated power combiners and closely coupled on-chip antennas which support stochastic approaches accounting for uncertainties in critical design parameters and implementation of multi-physics BIST solutions for real-time monitoring, tracking and optimisation of system-level performances including energy harvesting (EM-Thermal).
[M] An efficient numerical implementation of dynamical energy analysis (DEA) [Tan09] in three dimensions.
[M] Application of Wigner function (WF) concept to transform the two-point correlation functions of the currents or emitted fields into functions of the phase-space coordinates.
[M] Development of phase space propagators based on classical, multi-reflection ray dynamics.
[M] Bootstrapping simulation method to predict statistical properties of fluctuations brought about by multi-path interference in highly reverberant environments.

This document gives an overview summarising the progress made during the project. A detailed *Final Report* and the project deliverable reports are available from the project web-page – www.nemf21.org – for further reading. A summary regarding access to data (*Deliverable report D9.1*) and the C2C guidelines (*Deliverable Report D9.2*) can also be accessed from the web-page. In addition, further information such as contact emails and a list of relevant publications (all open access) is available from the web-page.

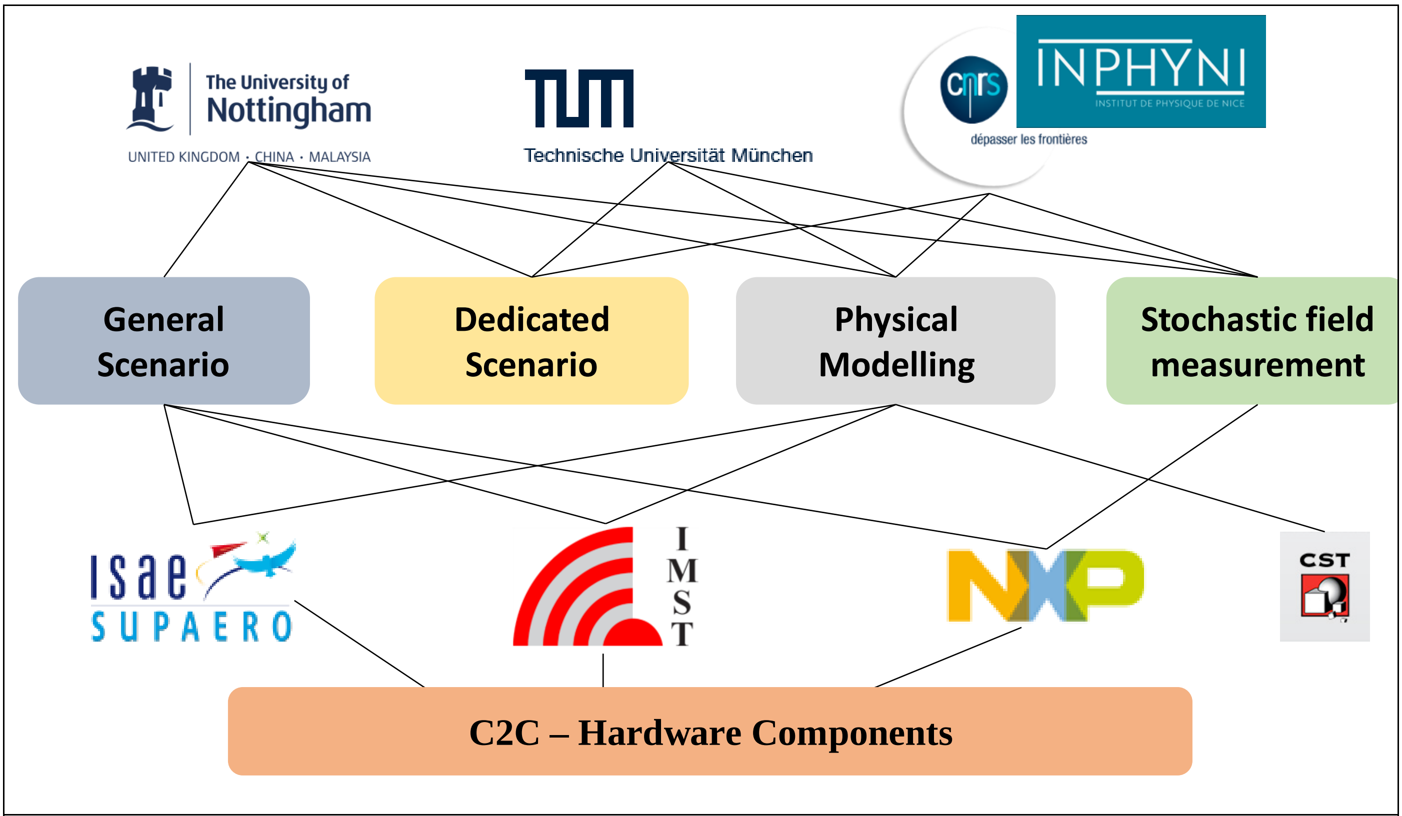

Figure 1. Schematic of the NEMF21 work program

Context

The miniaturizing of wireless transceivers has brought about the development of very efficient and miniaturized system-on-chip (SoC) devices. These systems achieve high integrability and flexibility at a low price [YPR16]. The high integration is facilitated by complementary metal oxide semiconductor (CMOS) technology. Traditionally, RF frontends are not integrated with the antennas in the same technology, but there is a push towards integrated RF-SoC devices. The need for integrated antennas is in particular driven by the advent of the internet of things (IoT), applications in radar sensing for autonomous driving, in medical or in 5G applications. There are severe challenges when integrating millimetre wave antennas on CMOS circuits. Chip surface is a cost factor and should not be wasted for antennas. In addition, in multiconductor, or wireless multiantenna interconnects, used for high-speed on-chip or chip-to-chip communication, the assumption of having available high-resolution ADC and DAC components, cannot be made. However, ADC and DAC components are an integral part of the MIMO system.

On a physical layer lever, operating a multitude of antennas in close proximity and the presence of other electronic components and in confined spaces is challenging from a design and safety point-of-view. Both, simulation tools and experimental verification methods are not readily available, especially in the high GHz regime.

In NEMF21 these fundamental limitations and possible ways to overcome them in the context of near-field MIMO set-ups are explored. A powerful tool is here multiport communication theory [IN10b, IN14] which provide the necessary framework ensuring that applications of signal processing and information theory actually do encompass the underlying physics of electromagnetic fields. Circuit theory provides the perfect link to bridge the gap between electromagnetic theory, information theory, and signal processing. Circuit theory is therefore not only of fundamental importance for the detailed design of individual components of a communication system, but it is crucial for the overall conceptual design. This insight, based on the work in [IN14], became the guiding principle of the work done in NEMF21 and it forms the basis of the near-field and far-field MIMO concepts. In addition, statistical considerations describing EM field fluctuations based on insight from random matrix theory as well as short wavelength asymptotics have been used to develop a simulation toolbox for modelling C2C communication scenarios. Hardware prototypes advancing RF-SoC architectures have been designed and tested.

The NEMF21 consortium consists of 7 partners, four universities (University of Nottingham – UoN, Technical University of Munich – TUM, University of Nice (Nice) and the Insitute Superieur de l'Aronautique de l'Espace – ISAE) and three industrial partners (IMST GmbH – IMST, NXP Semiconductors – NXP and CST AG – CST) taking on the challenges in a collaborative research effort as shown in Fig 1. The main research efforts developed along the 4 research strands indicated in Fig 1 – namely, (1) general and (2) dedicated benchmarking scenarios for differing C2C environments and challenges as well as physical wave field modelling (3) and stochastic field measurements (4). Developing the hardware components guided by the input of the 4 research strands has been done mainly by partner NXP in close collaboration with ISAE and support from IMST.

Findings from NEMF21 and recommended Guidelines

The NEMF21 has mapped out the potential for wireless data transfer on a chip and component level. This project represents one of the most comprehensive research efforts on assessing wireless C2C technologies carried out until today. It has identified the main challenges and bottlenecks of such an approach and has provided a range of solution strategies and novel methodologies to tackle and assess these challenges. Compared to wired interconnects on the one hand and conventional wireless communication on the other hand, the following major issues have been identified:

- *Design constraints*: Antenna structures and associated components need to fit in with a series of other design parameters
- *Near-field communication*: Wireless communication and data transfer is often in the near field and includes a high antenna density
- *Far-field communication*: In case of high frequencies or inter PCB communication the data transfer might be in the far-field regime
- *Noise and EMI*: Communication will generally be in a reverberant environment and in the presence of radiating components
- *Physical modelling*: Modelling wireless communication needs to take into account the physical layer (coupling), as well as stochastic parasitic signals
- *Integrated MIMO antennas*: Hardware components need to integrate multiple antennas on a chip level including MIMO, Decoupling and Matching Networks (DMN) and beam-forming set-ups for different frequency ranges

Below, we will summarise briefly the main achievements of NEMF21 regarding the challenges listed above:

Design constraints

- Analysis of C2C application scenarios, resulting in the separation between general scenario (GS) and dedicated scenario (DS) approaches – see workflow, Figure 2.

For the GS discussed also in detail in the Final Report it is assumed, that the C2C communication link is added to an already existing, highly integrated layout of a printed circuit board (PCB). The impact on the established infrastructure should be minimised, so introducing new wired connections across the PCB, adding new PCB layers or using too much space is not an option. The DS on the other hand, describes the case where there are more degrees of freedom for designing the wireless C2C communication link and where optimal transmitter/receiver array architectures can be considered. The overall design of the PCB can then be chosen to optimise C2C data exchange and more versatile approaches e.g. distance-optimised nearfield MIMO can be considered. The characterisation of noise and interference as it may arise due to noisy signals, noisy fields emanating from radiating components on, for example, the PCB or EMI due to scattering of signals on nearby objects is discussed; the influence of these stochastic field components on the communication channels is also considered for different scenarios.

The important questions are: "Am I going to design a new PCB?" and (if this is not the case) "Can the existing PCB design be easily/flexibly changed?".

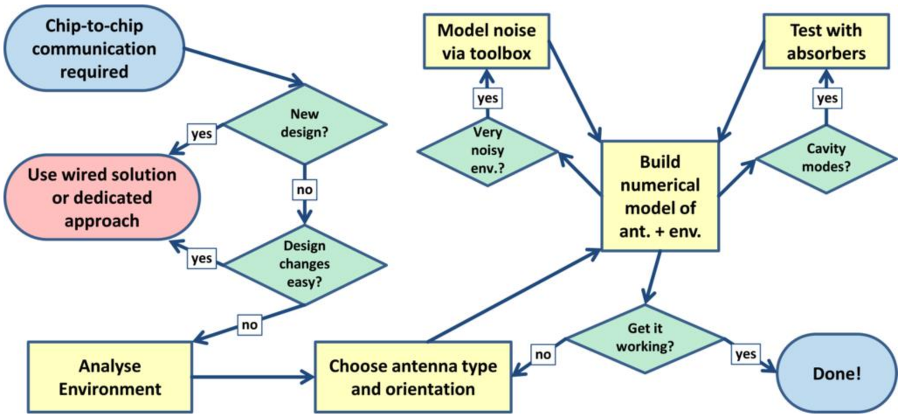

Figure 2 Proposed workflow for designing a wireless C2C communications link in the General Scenario

Lessons learned from the GS

Specific guidelines have been formulated in the Final Report and are also summarised in the Deliverable Report D9.2. The decision process and design pathways are outlined in Figure 2.

<u>*General aspects:*</u> In general, it can be concluded, that it is not possible to find one single configuration for C2C communication that performs best in all possible cases. Instead, the given constraints and environmental conditions need to be analysed carefully to find a suitable configuration for the current problem.

<u>*Optimisation criteria*</u>: When planning C2C communication in the sense of the GS, the corresponding optimisation criteria should be considered first. A good starting point is the figure of merit for the C2C communication link (e.g. bandwidth, noise and signal strength). Based on the idea of maximising the channel capacity, the benchmarks were mainly analysed with respect to the S parameters, i.e. the transmission coefficient S_{21}. From the results it can be concluded that transmission coefficients do not fall below 60 dB (at the target frequency) for any of the different benchmark configurations considered. It can therefore be expected that there is some margin for achieving a high channel capacity.

<u>*Antenna types:*</u> The choice of the antenna type, position and orientation is an important degree of freedom for matching the configuration of the C2C communication link to the problem at hand. For example, if the PCB is located in free space the monopole antenna clearly outperforms the other antenna types in the benchmark. But if the PCB is within a box or an enclosure, the reflections from the lid may result in a better performance of patch antennas. Another example would be a 2 × 1 patch array configuration which radiates sideways in θ-direction, but not in Φ- direction, so its orientation (rotation) on the PCB is clearly important. Therefor it is required that all important features of the PCB and its environment are already taken into account in early stages of the design phase.

Outcome:

The analysis for a given PCB design can be done based on the *Inverse Local Imaging* (ILI) method implemented in IMST's EM-field solver software *Empire* and supports the design decisions. For an in-depth analysis of noisy environments, the tools developed as part of the physical layer modelling need to be employed supported by noisy-field measurements as described below.

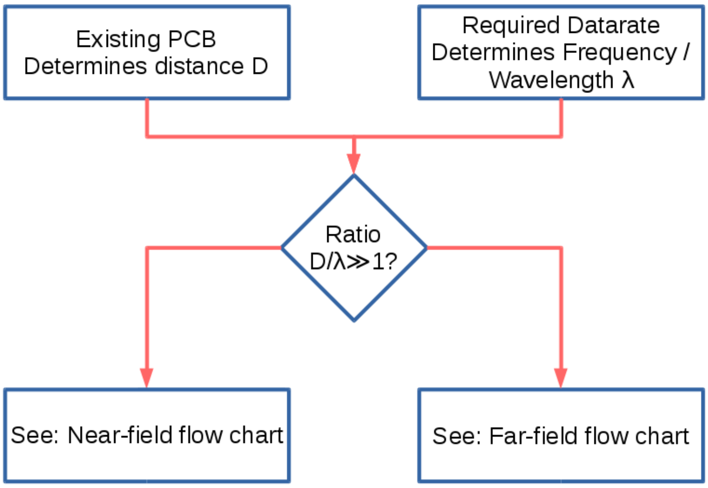

Figure 3 Proposed workflow for designing a wireless C2C communications link for the DS

Lessons learned from the DS

For the operation in DS, it is advantageous to distinguish between a near-field and far-field scenario with a decision tree s indicated in Figure 3. The following techniques have been developed and tested in NEMF21:

Near-field communication

- Optimal operation of MIMO communication links with maximal power transfer and noninterfering channels using joint DMNs have been suggested.
- DMNs achieving optimal channel capacity in free-space near-field scenarios and for a moderate density of resonances in the far-field scenarios within enclosures have been designed both for DMNs including realistic networks for linear MIMO arrays and a cross-over-free three-port design.
- Joint DMN networks are realisable practically by lumped-components.
- Wigner Function methods have been adapted to describe near-field, reactive fields around circuit boards and to provide bounds on communication capacity available in confined geometries.

In particular, the design and implementation of DMNs plays a crucial role in the Near-field scenario. Unlike in the far-field, DMNs act non-local here, which provides a challenge for the design process. The workflow for the design cycle as proposed by NEMF21 is depicted in Figure 4 below.

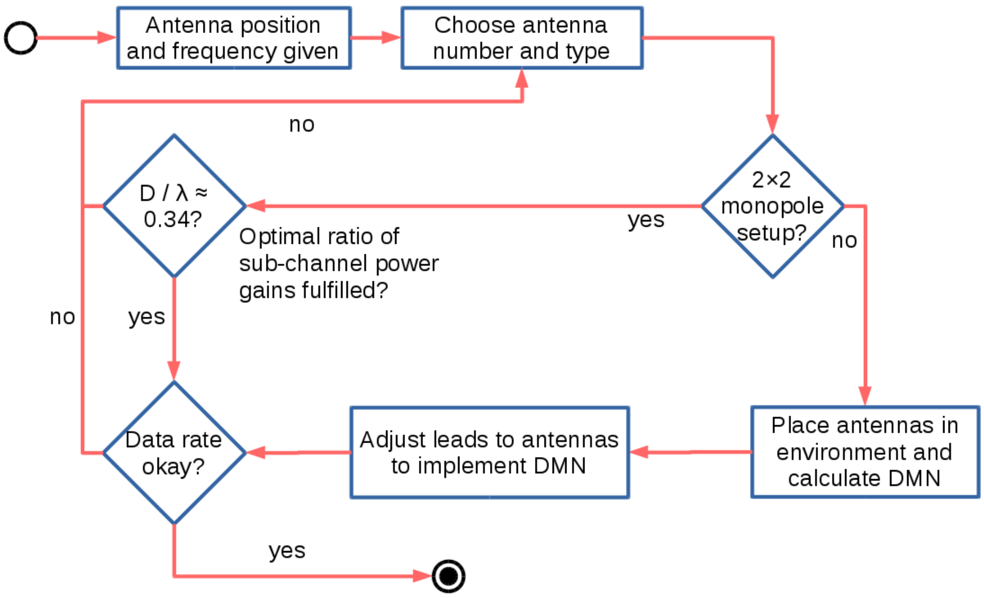

Figure 4 Proposed workflow for designing a near-field DMN

Far-field communication

- Beam-forming techniques have been designed to achieve high transmission channels and stable communication.
- Analytic predictions for the distribution of transmission using the random coupling model and the effective Hamiltonian method including directed antenna or beam-forming effects.
- Analytic results have been derived in the strong absorption regime and for SIMO and MISO situations.

Noise and EMI

- The channel transfer function between transmit and receive arrays has been determined including the radiation impedance of the chip/package antenna in the front-end as a system-specific feature: arbitrary antenna types can be considered in digital link performance studies.
- The channel transfer matrix statistics of the MIMO interconnect in irregular environments are predicted through universal laws of RMT: high losses - Gaussian ensembles; low losses - modified transfer matrix ensemble based on t-student distributions.
- For operation inside electrically large shielding enclosures implying a far-field scenario, the density of resonances involved in the energy transfer process plays an important role in the statistics of the transmitted signal
- The mutual information statistics based on RMT channel transfer matrix predicts high data rates in the presence of a low density of resonances and low losses. It can be obtained in closed mathematical form for a high density of resonances and high losses: the density of resonances becomes a penalty for the signal-to-noise ratio
- Shannon-type upper bounds of the channel capacity for MIMO interconnects operating inside a reverberant enclosure can be obtained through DEA simulations.
- The average data-rates of MIMO interconnects for moderate resonance densities is increased in the presence of line of sight
- A multi-probe measurement strategy and how to configure and perform the measurement run has been established. Data handling and complexity reduction have been addressed.

Physical Modelling

- Strategies to model noisy electromagnetic field propagation based on considerations of electromagnetic field correlations have been demonstrated. New analytic techniques and numerical implementations have been presented which can be pipelined with existing numerical EM full wave solvers to compute noisy EM field problems in complex environments
- DEA-based simulations provide a means of simulating stray emissions in environments with non-universal, geometry-specific response.
- DEA-based simulations provide a means of estimating bounds for the communication capacity in reverberant environments that are too large for effective simulation using full-wave solvers. When the environment has highly non-universal features so that RMT methods are not directly applicable, this provides a means of accounting explicitly for geometry-specific response
- A C2C toolbox based on the Finite-Difference Time-Domain (FDTD) method, the Finite Element Method (FEM), the Transmission Line Modelling (TLM) method and Dynamical Energy Analysis (DEA) method has been implemented.

Integrated MIMO antennas

- Communication links and the pertaining new hardware components have been designed, fabricated and measured, i.e., integrated antennas in front-end-IC modules for 2.4 GHz, 5.8 GHz, 28 GHz near-field MIMO as well as on-chip for near-field MIMO.
- Modelling tools for coupled integrated antennas in the near field have been tested.
- Performance of demonstrator in Reverberation Chamber (RC) has been conducted.

Guidelines for the DS:

The DS is an idealised scenario – but it seemed desirable as part of NEMF21 to develop this scenario in some detail to assess whether wireless C2C communication is feasible and advantageous even under such ideal conditions. We have thus developed detailed step-by-step guidelines for C2C communication setups in the DS given in terms of a workflow description considering in particular:

- Required preliminary information.
- Analysis of possible problems caused by environment.
- Iterative process of building a numerical model.
- Obtaining a functional C2C design.

A toolbox, resulting from the present document, supports the design decision process.

Following on from the work flow diagrams for the DS is distinguishing between near- and far-field DS as shown in Figure 3 and the workflow diagram for designing DMNs for the near-field DS as shown in Figure 4, we developed a flow diagram for far field connections as shown in Figure 5. This scenario is in particular prone to noise and EMI complications, which need to be assessed in greater detail here as shown in the diagram.

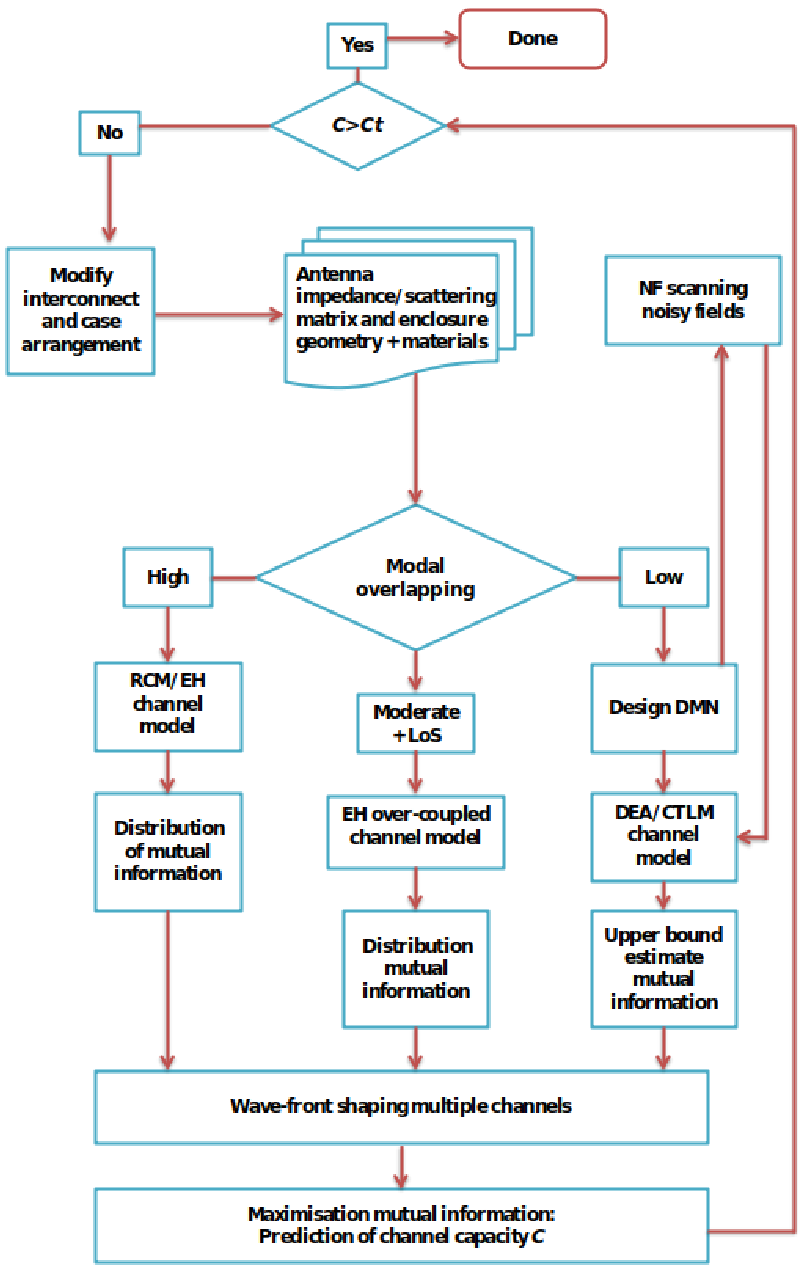

Figure 5 Workflow chart for far-field C2C communications link in enclosures

Combining full-wave EM simulations and measurements for complex circuits and systems for C2C configurations:

In designing fully integrated hardware components, advanced simulation tools have been developed. The complexity of the task leads to the necessity to develop efficient partitioning methodologies applied to practical scenarios. The objective of partitioning strategies is to segment a complex circuit into sub-partitions to analyse separately and then combine, later on, with active parts/sources for global performances analysis/optimisation. The following partitioning rules and guidelines have been applied for properly dividing complex circuits and systems into sub-partitions:

- No (or very little) EM coupling between the dividing planes
- The current at the location of the divider should be traveling perpendicular to the plane of the divider. This includes the ground return current
- The port should be well away from the DUT. If not, reference planes should be used. This rule is needed because a single mode of propagation should be on the line connected to the port. Otherwise, circuit theory does not work
- Any ports that are close to each other need to be calibrated together (i.e., co-calibrated/de-embedded)
- At each divider, the ground reference for the ports needs to be clearly defined. When connecting the pieces back together with circuit theory, the circuit theory program will assume that the grounds are perfectly connected together with no discontinuity between them
- Incorporation of measurement results in modelling can be achieved by using field-field correlation information

Summary and Conclusions

NEMF21 has for the first time established a framework in which the application of wireless C2C communication can be analysed and assessed in a systematic and controlled way. Different scenarios have been established and corresponding assessment criteria have been put together being specific for each scenario. This makes it now possible to get answers to the question whether a conventional wired approach is favourable or a wireless approach may be feasible. Details are provided in this summary report and in more detail in the Final Report.

It is acknowledged that both the decision process and the implementation may be costly – something we have not factored into our analysis. On the plus side, there may be distinct advantages in the C2C approach due to more flexibility and diversity in the chip or PCB design space such as placement and interconnectivity of single chip components – again, these factors have not been incorporated in our analysis. Instead we have focussed mostly on the physical layer of the design and identifying possible complications. Considering a Beyond NEMF21 scenario, the natural next step is now to systematically search for specialised application – based on the design guidelines developed here – where the advantages outweigh the potential complications. For the time being, the conclusion must be that wired connections are the preferred option compare to wireless C2C design due to the complexity and the potential risks of the latter approach.

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