Deep integration: fusing antennas with electronics

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A worldwide objective is to develop next generation technology enabling Tbit/s high speed communication links, wirelessly. One obvious way to reach this goal is to make electronic systems operate at higher frequencies where larger frequency bandwidths are available, but then several fundamental problems must be solved. Some of these problems are outlined in this presentation, after which the following question is asked: how to overcome these problems?

We may very well need to think of new ways of designing integrated antenna systems. One such approach introduced herein is called: DEEP INTEGRATION.
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Abstract

The direct integration of antennas with nonlinear electronics dates back to the late 50s, where transistorized antennas were proposed and later realized, even arrays thereof, think e.g. of the so-called antennafier arrays. They were typically constructed at low frequencies using discrete semiconductor devices. Nowadays, one develops advanced monolithic integrated circuits (ICs) operating at mm-wave frequencies. This is possible thanks to the great strides made in photolithographic processes, the advent of powerful computers in conjunction with fast circuit and multiscale electromagnetics solvers using highly realistic semiconductor device models. This worldwide trend has opened up new research avenues; concepts of the past are being re-thought in the light of these new technological developments with the objective to overcome the wireless system integration challenges of the future.

DEEP INTEGRATION is the ultimate abstraction of spatially integrating small-scale electronics with large-scale antennas using quasi-optical methods. It promises to address the challenges of the future. Multiscale numerical synthesis techniques must be developed.

This presentation identifies some of these challenges, discusses some of the lessons that we have learned, introduces the concept of DEEP INTEGRATION, and provides a very simple example of a Deeply Integrated antenna to showcase its principles.

Keywords – Deep Integration, active integrated antennas, millimeter wave antennas, spatial power combining, contactless connections, characteristic basis function method
Rob Maaskant was born in the Netherlands on April, 14th, 1978. He received his MSc degree (cum laude) in 2003, and his PhD degree (cum laude) in 2010, both in Electrical Engineering from the Eindhoven University of Technology, The Netherlands. From 2003-2010 he was employed as a Researcher at the Netherlands Institute of Radio Astronomy (ASTRON), The Netherlands, and from 2010-2012 as a postdoctoral researcher at the Chalmers University of Technology, Sweden, for which he received a Marie-Curie (Rubicon) postdoctoral fellowship from the Netherlands Organization for Scientific Research (NWO). He won the 2nd best paper prize (best team contribution) at the 2008 ESA/ESTEC workshop, Noordwijk, and has been awarded the prestigious prize of the best PhD project in 2010 of the TU/e Electrical Engineering Department. He has published more than 100 journal and conference papers, and is holder of 8 patents or patent applications. He is the primary author of the CAESAR software; an advanced integral-equation based solver for the analysis of large antenna array systems, which is being used by several international research institutions. As an Assistant Professor he received the "Young Researcher" grant from the Swedish Research Council (VR) in 2011. He is currently an Associate Professor in the Antenna Group of the Electrical Engineering Department at Chalmers (Sweden) as well as in the Electromagnetics Group of the Eindhoven University of Technology (TU/e, The Netherlands). He has received a Vidi grant from NWO in 2016 for realizing novel mm-wave integrated antenna and microwave structures in collaboration with NXP and Ericsson. He has been elevated to Senior Member IEEE in 2013, and served the AP community as an Associate Editor for the IEEE Transactions on Antennas and Propagation, the IEEE Antennas and Wireless Propagation Letters, and the Forum for Electromagnetic Research Methods and Application Technologies (FERMAT, http://www.e-fermat.org).

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Goal: Tbit/s wireless systems

Traditional Bottom-Up Design Flow

- System
- Sub-systems
- Devices
- Semiconductors

![Diagram showing design flow]

- Globally optimum solution is NOT possible
- Interconnection losses and packaging resonances, Cross-talk effects
- mm-wave power generation
- Miniaturization limit in ~2024 [1]


If one follows a traditional *bottom-up* design flow, subsystems are locally optimized in isolation from each other in a well-defined reference impedance environment, typically 50 Ohm. Then these subsystems are interconnected to form an entire wireless system. This leads to interconnection losses, package resonances, cross talk effects, and so on... and these problems get more severe at higher frequencies.

Mm-wave power generation becomes problematic too, since semiconductor components are miniaturized down to the atomic scale in an attempt to reduce parasitic effects, but then they will generate less power. More of them will be needed in conjunction with efficient power combining schemes. Moreover, over-the-air propagation and material losses increase with frequency, requiring even larger output powers. This is why smaller communication cells are foreseen. This will lead to more base station antennas and collectively causes a major energy problem, not to speak about the cost of active cooling.

As academics we must think of radically new approaches to overcome these problems.
Before proposing a unified solution, let us look at some of the lessons that we have learned.
Lesson #1: think quasi-optically, keep fields distributed

Potential to be more compact, reduced losses, increased bandwidth

Lesson 1: think in terms of extended field modes along with wave amplification techniques. Quasi-optical power combining can be done in (air) dielectrics without having to handle large currents along transmission lines that are going to increase the Ohmic losses.

On the left one observes a conventional power amplifier (PA) integrated circuit (IC) which power-combines the signal first on the IC itself. This requires chip area and leads to on-chip combiner losses. The signal is then transported to a 50-Ohm microstrip line which is then impedance tapered to feed a substrate integrated waveguide (SIW) mode. This is a large structure with losses at different transitions and is potentially limited in bandwidth due to various impedance transformations.

On the right, however, the SIW mode is directly amplified, spatially. Neither tapered lines nor the use of on-chip power combiners are necessary. The structure has become smaller and less lossy. Equal 50-Ohm input impedances are seen from the 4 PA outputs by choosing different microstrip line widths. Impedance matching is done in active mode (for uniform array excitation), by minimizing the corresponding active reflection coefficients at each of the coupled microstrip lines: \( \Gamma_m = \sum_{n=1}^{4} S_{mn} \) for \( m = 1, ..., 4 \). More details are given in A. Roev, R. Maaskant, A. Höök and M. Ivashina, "Wideband mm-Wave Transition Between a Coupled Microstrip Line Array and SIW for High-Power Generation MMICs," forthcoming in IEEE Microwave and Wireless Components Letters.
Lesson #2: reduce transition losses, let EM fields couple in air dielectrics

Lesson 2: overcome the transition losses through contactless connections; EM fields can couple directly from an IC to an external transmission line or waveguide structure. This avoids the losses associated with solderballs or bondwires, as well as an impedance matching network to compensate for the transition reactance.

The slide shows a Silicon IC that is placed inside a waveguide. An array of on-chip microstrip lines is used to excite a metal cavity mode at both ends of the IC. The cavity powercombines the microstrip modes in air dielectrics whose field then exits through a ridge waveguide. The entire IC is floating for RF, while DC biasing is accomplished using conventional techniques (solderballs, bondwires). AMC-PEC surfaces are used to suppress undesired substrate modes in the (P-doped) bulk substrate of the IC; RF fields couple into the backend metallization layers through so-called gap waveguide technology.
Lesson #3: direct impedance matching via circuit + EM co-simulation

Lesson 3: use direct impedance matching of devices to their optimal load and source impedances. This avoids using 50-Ohm matching networks.

The slide highlights the PCB circuitry of a center array element. The output drain pad of a GaN FET (tiny Qorvo IC in green next to the slot) is bonded directly over the slot antenna. The slot antenna is optimized to represent the optimal load impedance seen from the drain bondpad of the transistor IC. The optimal load impedance of the transistor is found through a load-pull simulation. Once the optimal load impedance has been realized, an ADS-EM co-simulation is performed and the overall performance is assessed, which includes the design of the input matching circuit. It is seen that the gain, the total output power and the drain efficiency are close to the optimal load-pull source-pull results taken from the datasheet of this specific transistor. The integrated design has been optimized further and will be published after the measurements have been completed.
A Wide Net of Concepts in the Literature

High-power quasi-optical grid amplification and techniques (Cal Tech since 1990, Univ of Colorado, TU Delft, Uni of Rennes,...)

In/on-antenna power combining, load modulation, Doherty antennas (Karlsruhe, Georgia Inst Tech, Princeton, Univ. California, Calgary, KU Leuven,...) last decade

In addition to these recent developments, a lot of work has happened in the last 10-20 years. That is, a wide net of literature can be identified that helps to provide a path to the future, with wireless components closely integrated with Very-Large Scale Integration (VLSI) and active devices at higher frequencies.

From quasi-optical grid amplification and antenna beamforming to in- or on-antenna power combining techniques. Active devices are directly embedded in a spatially extended EM field (e.g. waveguide or antenna). These active devices are coupled through the external EM field or share the same support for the current distribution (leading to in/on-antenna power combining). This results in strong coupling and leads to so-called load modulation seen by these devices, which is a change in the active impedances due to multiple simultaneously used active devices. This will affect the nonlinear characteristics of these devices. The latter is exploited to design high-efficiency Doherty transmitters, which are power amplifiers that are co-integrated with multi-port antennas. Concepts to synthesize the desired antenna current distribution through multi-fed antennas and multiple PAs are currently being explored by various groups.
Several books have been written on active integrated antenna systems. The term “Integrated Circuit Antenna Modules” was introduced in the 90s as a unifying term encompassing a large class of integrated antenna-circuit concepts (book 1 and 2). The optimal design criteria of active receiving antenna systems, where noise couples from low-noise-amplifier inputs via antenna mutual coupling back into the beamformed antenna system, has only been understood recently (e.g. book 3 and earlier research papers). New antenna terms have been adopted by the IEEE because the existing standard terms for single port antennas were inadequate. High power generation solutions in inexpensive (but lossy) Silicon have been provided in book 4, where a future outlook direction is proposed similar to Deep Integration discussed hereafter. Book 5 describes the state-of-the-art in co-design and co-integration of active components with antennas. Book 6 treats active and passive multifunctional antennas, among which reconfigurable, self-oscilating and amplifying antennas.

It is pointed out that some of these books are edited volumes containing research papers from a vast amount of researchers and research groups that cannot be all mentioned here due to space contraints.
Can we combine the previously learned lessons into a single unified solution?

This is where DEEP INTEGRATION comes in.
In DEEP INTEGRATION, microwave functions such as filtering, amplification, radiation, and so on, get merged into a single multifunctional component. This goes beyond strong integration in which we e.g. connect amplifiers directly to antenna structures (middle figure). In DEEP INTEGRATION, semiconductor components are merged with antennas. It is the combination that makes the antenna, PA, filter, and so on. That means that antenna currents are affected by removing the semiconductors from it, and hence the antenna radiation characteristics are affected. It also means that the power amplifier characteristics are affected if the (passive linear) antenna materials are removed, because the antenna makes up the external parasitic impedance environment to the transistors. It also means that the DC and RF currents both flow through the antenna structure. The whole gets function-inseperable. Hence the term DEEP INTEGRATION.

Note that, antenna-circuit modules have been considered, grid amplifiers, and so on. But these typically still separate the amplifiers from the radiating antenna currents. So, what if we generalize the integration concept and formulate an alternative design flow? How will it look like?
DEEP INTEGRATION is an extreme form of electronic system integration where conducting, semiconducting and non-conducting materials are fused into a single inhomogeneous material distribution having the multifunctional properties of an entire antenna system.

The slide shows a passive linear material distribution which embeds localized nonlinear semiconductor devices – in this case elementary FETs. There is no local ground, FETs are characterized as 3-terminal nonlinear electrodynamic devices. Both DC (biasing) and RF (+harmonic) currents flow throughout the multifunctional medium. Interior subsystems can no longer be identified, therefore detrimental cross-talk effects no longer exist. In fact, interior field interference effects are exploited; signals propagate as waves throughout the material while being amplified, combined spatially to yield high power and are modulated, all at the same time.
To enable DEEP INTEGRATION, a *top-down* design flow is proposed, which is opposite to the traditional bottom-up design flow. That is, we start from a single inhomogeneous material at macro scale level, which can be many wavelengths in size representing the entire system, and then synthesize the optimal material distribution to meet the system-level requirements.

The material is adjusted during each iteration, which e.g. means that FETs are moved and metals are redistributed. This modifies both the DC(-biasing) and RF currents. It will therefore affect both the antenna and amplifier behavior, or the multifunctional properties in general. It is the optimization algorithm that needs to synthesize the optimal material distribution.

The optimization is very nonlinear (NP hard), but by imposing constraints, by reducing the degrees-of-freedom to e.g. planar structures and discrete locations of transistors and metal patches only, and by relaxation of the optimization it is believed that the material synthesis becomes tractable.
Nonetheless, the major challenge is the time-efficient global synthesis of such multi-scale structures. To tackle this, we first separate the electromagnetic modeling of the passive linear parts from the localized nonlinear parts of the material (see the slide).

The multiscale passive linear part is characterized through fast domain decomposition techniques such as the Characteristic Basis Function Method. This yields a multiport S-parameter model of the structure + corresponding field solutions. This is imported in a circuit simulator. The nonlinear electrodynamic (DynaFET) models are attached to the localized interior ports and the voltage current relations are solved through e.g. a harmonic balance simulation. Once the port currents (or voltages) are known, they are used as excitation currents in the EM simulation to e.g. determine the field that is being radiated by the integrated structure.

The domain decomposition technique allows to solve problems exceeding a million degrees-of-freedom in terms of the number of current (or field) modes, using moderate computing power.
Toy Example: 1 Ring + 1 FET @ 3GHz

- Loop antenna = DC feed for GaN Qorvo FET
- Loop antenna = RF parasitic optimal load for FET
- Loop above GND is 1 lambda in circumference (dipole mode radiation)

The above structure illustrates DEEP INTEGRATION in its simplest form — a toy example. The planar passive linear material is composed of PEC metal and air only. The FET has no local ground and is placed inside the antenna conductor, which constitutes a loop antenna (circumference is 1 lambda) placed lambda/4 above a PEC gnd-plane.

It is Deeply Integrated because the loop antenna is a DC feed for the FET (see DC sources on the left), but also makes up the external parasitic environment to the FET. Removing one of them destroys both the PA and antenna performance, the PA-antenna structure becomes inseparable.

The passive linear structure is analyzed as a 5-port, whose S-matrix is imported in e.g. ADS. The circuit simulation is performed with the FET and external sources attached. This yields the circuit currents and voltages from which we can compute the radiated fields, dissipated powers, and so on.

Thanks Oleg Iupikov (generating results, Matlab) & Corné van Puijenbroek (help with ADS)
Toy Example: 2 Rings + 2 FETs

Stacking loops: scalable solution, higher power, load modulation (Doherty),...

Stacking two loops (in CST) would give rise to a 10-port S-matrix. Exciting both of the loop antennas in-phase allows to spatially power-combine the radiated field in air dielectrics. The loops are strongly coupled and allow for load modulation techniques to e.g. Increase the efficiency (Doherty power combining). It represents a scalable solution in terms of power generation, while an array of such elements would increase antenna directivity. The improvement of the output power, power gain, and efficiency with respect to single loops are shown. As well as the Effective Istropic Radiated Power (EIRP) pattern is shown after exciting the 10-port antenna in CST by the ADS-computed currents.

This is simply an example illustrating the basic ideas of DEEP INTEGRATION without overcomplicating the matters at this point.
One could also think of merging existing circuit solutions into existing antenna designs, rather than designing them in isolation and cascading them in a conventional fashion.

The above slide (on the left) shows how stacking of CMOS transistors is used to increase the voltage swing over the load impedance. This is done to overcome the low breakdown voltage of CMOS transistors. When combined with a planar inverted F-antenna one can derive a Deeply Integrated PIFA. This allows the voltage swing over the PIFA to increase and to generate more power. This is still at concept level and yet to be realized, but it qualitatively visualizes the DEEP INTEGRATION concept and the line of thought.
10 Years Outlook – Deep Integration

Merging semi-conducting, non-conducting, and conducting materials into a single inhomogenous material capable of emulating an entire antenna system

- DEEP INTEGRATION potentially allows
  - Higher power (quasi-optical power combining)
  - Improved heat spreading
  - More optimal global RF system solutions
  - Singly integrated multifunctional component
  - New cross departmental research directions
  - Low-cost low-loss solutions
  - Design of ACTIVE: reflect arrays, metamaterials, antennafiers, ...

Challenges:

This slide summarizes the DEEP INTEGRATION paradigm as a research umbrella unifying the electromagnetics, microelectronics and material science fields. It has the promise to overcome several fundamental bottlenecks and has great potential as listed on the slide.

For research opportunities, research collaborations, research visits and joint research applications, both/either at Chalmers (Sweden) and/or the TU/e (Netherlands),

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- Caltech High-speed Integrated Circuits Lab
- Georgia Tech Electronics and Micro-System Lab (GEMS)
- Princeton Integrated Micro-Systems Research Lab
- University of California, High Speed Electronics Lab

(and the list goes on...)
**Selected References**


(and the list goes on...)