10 years of Silicon mm-Waves: from Oxymoron to Reality


California Institute of Technology
The Paradigm Shift

- Die area and the number of transistors per die is increasing.
- The transistor maximum operation wavelength is shrinking.

Systems, Circuits, EM and device physics cannot be abstracted separately anymore.
Classical circuit theory is based on the fundamental assumption of $d \ll \lambda$

- These conditions result in almost no radiation
- Energy is stored in inductors and capacitors or dissipated in resistors
- Kirchhoff's Laws (KVL and KCL) provide a systematic approach for analyzing large-scale non-radiating circuits
- Smaller integrated device dimensions pushed the circuit abstraction to the GHz range
A limited number of problems can be addressed by separating the design of circuits and radiating elements.

An electromagnetic simulator solves Maxwell’s PDEs for the radiating elements.
Design approaches confined to no-longer relevant sub-disciplines result in sub-optimal solutions.

Need to meet siblings of Carver Mead’s tall and skinny computer scientists in this domain.
Today we can integrate large-scale circuits that operate in wavelengths that are (much) smaller than the die size.

Results in a very relevant, complex multi-disciplinary problem, waiting for efficient, elegant mathematical solutions. (Attention theoreticians)

There is currently no efficient systematic approach for analyzing these large-scale radiating integrated circuits.
Co-design of circuits and radiating elements.

Integrated circuits bring an unprecedented level of reconfigurability to the world of *inflexible* radiating elements.

Poses a truly challenging real-world optimization problem.
The near-field and far-field of the antenna can be manipulated by changing the impedance of the lumped elements.

The key question: how can we find the values of the impedances for any desired far-field pattern and antenna input impedance?
Completely intractable problem to solve by changing the values of the impedances and solve the new field problem (run a new EM simulation to solve Maxwell’s PDEs)

- 20 impedances, 2 discrete values for each one: $2^{20} \sim 10^6$ EM simulations
- Not a practical solution for large problems (10 or more variables)
A receiver in far-field captures the radiated power at a specific angle

The receiver, transmitter, and varactors are replaced by lumped differential ports

Only one EM simulation is required to extract the scattering parameters of the whole structure

---

Circuit Model of the EM Problem

\[ \tilde{Y}_{EM} : (n+1) \times (n+1) \]

From EM simulation

\[ \mathbf{V} = \begin{bmatrix} v_1 & v_2 & \ldots & v_n \end{bmatrix} \]

\[ \mathbf{I} = \begin{bmatrix} i_1 & i_2 & \ldots & i_n \end{bmatrix} \]

\[ \begin{bmatrix} \mathbf{I} & i_{n+1} \end{bmatrix} = - \begin{bmatrix} \mathbf{V} & 1 \end{bmatrix} \times \begin{bmatrix} \tilde{Y}_T & 0 \\ 0 & -y_{in} \end{bmatrix} \]

\[ \begin{bmatrix} \mathbf{I} & i_{n+1} \end{bmatrix} = \begin{bmatrix} \mathbf{V} & 1 \end{bmatrix} \times \tilde{Y}_{EM} \]

- Objectives:
  \( v_1 \) : far-field at a desired angle
  \( y_{in} \) : input conductance of the antenna

- Variables:
  \( \tilde{Y}_T \) : conductance matrix of the terminations

---

Convex Representation

- Find $\tilde{Z}_{\text{new}} = (\tilde{W}_{11} + \tilde{Y}_T)^{-1}$ such that:
  \[
  \left| \text{Re}(v_1 - v_1^d) \right| \leq \varepsilon_1 \quad \left| \text{Im}(y_{\text{in}} - y_{\text{in}}^d) \right| \leq \varepsilon' \\
  \left| \text{Im}(v_1 - v_1^d) \right| \leq \varepsilon_1 \quad \left| \text{Re}(y_{\text{in}} - y_{\text{in}}^d) \right| \leq \varepsilon'
  \]

- Equations:
  \[
  \tilde{V} = -\tilde{W}_{21} (\tilde{W}_{11} + \tilde{Y}_T)^{-1} = -\tilde{W}_{21} \tilde{Z}_{\text{new}} \\
  y_{\text{in}} = -\tilde{W}_{21} (\tilde{W}_{11} + \tilde{Y}_T)^{-1} \tilde{W}_{12} + w_{22} = -\tilde{W}_{21} \tilde{Z}_{\text{new}} \tilde{W}_{12} + w_{22}
  \]

- It can be proved that for reciprocal problems the passivity constraint is equivalent to a Linear Matrix Inequality (LMI) condition\(^1\):
  \[
  \text{Re}\left(\tilde{Z}_{\text{new}}^{-1} - \tilde{W}_{11}\right) > 0 \quad \begin{bmatrix} \text{Re}(\tilde{W}_{11}) - \text{Re}(\tilde{Z}_{\text{new}}) & \text{Im}(\tilde{Z}_{\text{new}}) \\ \text{Im}(\tilde{Z}_{\text{new}}) & \text{Re}(\tilde{Z}_{\text{new}}) \end{bmatrix} \prec 0
  \]

Global Optimum Can Be Calculated!!!
A Remarkable System in Year 2000

Our vision at Caltech was highly revolutionary in the late 90’s.
The vision led to substantially more advanced systems today.
Led to a very active (and central) area of research for integrated circuits, with many practical implications in real life.
We have come a LONG WAY from this picture.
Complete Self-Contained TRX in Silicon (Radar/Communication System)

Highest level of mm-Wave integration in silicon (~15,000 transistors)
- A completely new modulation scheme offering directional security, concurrency, and energy efficiency.
- Truly integrated system, propagation, antennas, analog, and digital circuits.
Applications in Biosensing

- Opens the door for single molecule, label free detection of bio-molecules, using high frequency silicon systems.
- Tested with real DNA samples and highest sensitivity.
- Will serve as a faster, cheaper, smaller, and much more sensitive replacement for existing DNA and protein microarrays.
Acknowledgements

• Lee Center for Advance Networking for providing the right framework targeting true relevant yet long term research.

• All present and former members of the CHIC group who have made this possible and continue to provide leadership in the academia and industry for additional innovative solutions to relevant problems.

• Members of Lee center for constructive feedback and discussions.

• Other sponsors (NSF, IBM, DARPA, Sony, ONR, Intel, Toshiba, AFRL, Conexant, Raytheon, Fujitsu, Infineon, and others)
Circuit Model of the EM Problem

\[ v_{n+1} = v_{in} = 1 \]

\[ Y_{EM} : (n+1) \times (n+1) \]

From EM simulation

- No need to run an EM simulation for each iteration
- A simple MATLAB program can be used to sweep the elements of the matrix \( \tilde{Y}_T \) and calculate \( v_1, y_{in} \)
- 20 variables, 2 discrete values for each one: \( 2^{20} \sim 10^6 \) iterations in MATLAB

\[ \tilde{Y}_T : n \times n \]

---

The Reverse Problem

Find $\tilde{Y}_T$ such that:

$$
\begin{align*}
|\text{Re}(v_1 - v_1^d)| &\leq \varepsilon_1 \\
|\text{Im}(v_1 - v_1^d)| &\leq \varepsilon' \\
|\text{Im}(v_1 - v_1^d)| &\leq \bar{\varepsilon}_1 \\
|\text{Re}(y_{in} - y_{in}^d)| &\leq \varepsilon'
\end{align*}
$$

For practical reasons and to avoid oscillation problems, a passivity constraint is imposed on the termination matrix $\tilde{Y}_T$:

- $\text{Re}(\tilde{Y}_T)$ is a positive definite matrix: $\text{Re}(\tilde{Y}_T) > 0$
Defining the Optimization Problem

- **Find** \( \tilde{Y}_T \) such that:

\[
\begin{align*}
&\text{Re}(v_1 - v_1^d) \leq \varepsilon_1 \\
&\text{Im}(y_{in} - y_{in}^d) \leq \varepsilon'
\end{align*}
\]

\[
\begin{align*}
&\text{Im}(v_1 - v_1^d) \leq \varepsilon_1 \\
&\text{Re}(y_{in} - y_{in}^d) \leq \varepsilon'
\end{align*}
\]

- **Equations:**

\[
\begin{align*}
\vec{V} &= -\bar{W}_{21}(\bar{W}_{11} + \bar{Y}_T)^{-1} \\
y_{in} &= -\bar{W}_{21}(\bar{W}_{11} + \bar{Y}_T)^{-1}\bar{W}_{12} + w_{22}
\end{align*}
\]

\[
\tilde{Y}_{EM} = \begin{bmatrix} \bar{W}_{11} & \bar{W}_{12} \\ \bar{W}_{21} & w_{22} \end{bmatrix} \quad \bar{W}_{11} : n \times n \quad \bar{W}_{21} : 1 \times n
\]

\[
\bar{W}_{12} : n \times 1 \quad w_{22} : 1 \times 1
\]

- **Passivity condition:**

- \( \text{Re}(\tilde{Y}_T) \) is a positive definite matrix: \( \text{Re}(\tilde{Y}_T) > 0 \)
A conducting ground plane is placed 10µm (λ/150) above the transmitter to block the signal and reduce the radiation efficiency by almost shorting the antenna.

A passive termination network maximizes the received power by manipulating the electromagnetic properties of a patch array.

- All-short terminations: $P_r/P_t=1.45\times10^{-5}$, Radiation Efficiency=2.12%
- All-open terminations: $P_r/P_t=8.37\times10^{-6}$, Radiation Efficiency=2.03%
- Optimum network: $P_r/P_t=4.23\times10^{-4}$, Radiation Efficiency=41.85%
- Required time for finding the optimum solution: 8.5 seconds (2.3GHz quad-core)
The convex optimization algorithm finds a passive termination matrix that maximizes the received power.

The radiation efficiency of the optimum solution is 41.85%. This is around 2% for the all-short or all-open terminations.

The optimum solution improves **Directivity \times Efficiency** by a factor of 29.

Optimum solution causes a strong near-field resonance between the antenna and the reconfigurable surface.