Accurate and Fast RFI Prediction Based on Dipole Moment Sources and Reciprocity

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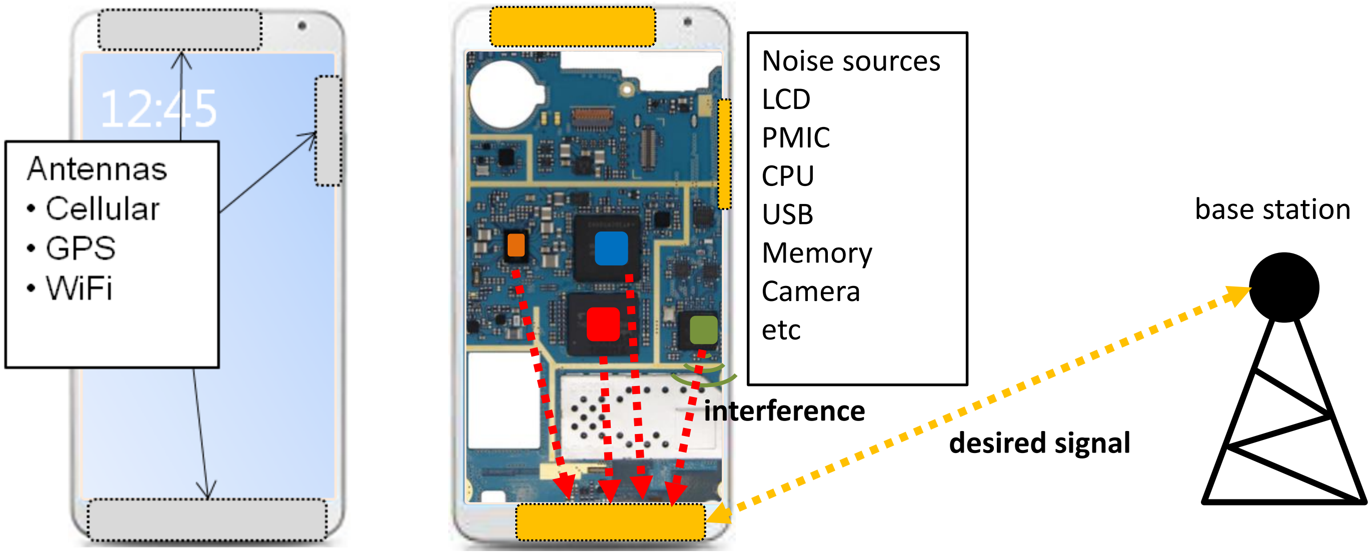
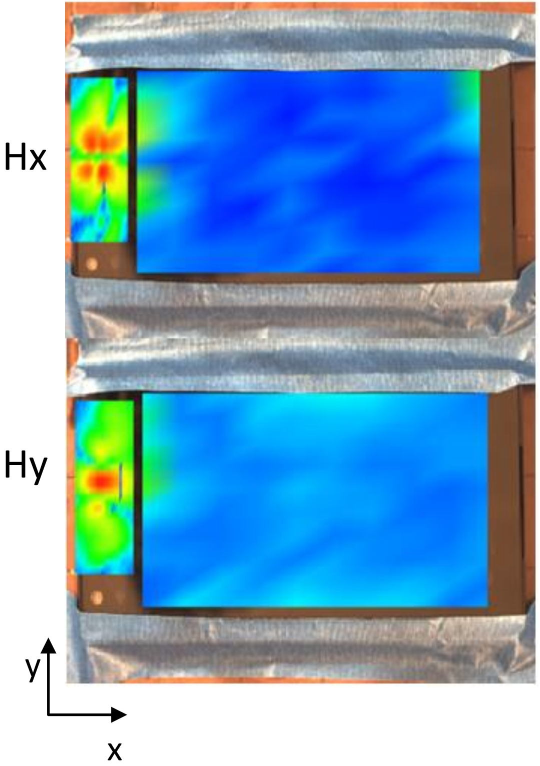
RF Desense: EMI within a Wireless Device

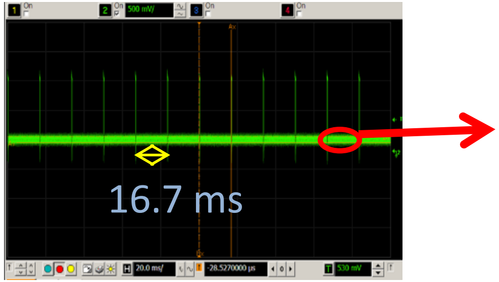


Noise generated by ICs gets picked up by RF antennas nearby and degrades RF sensitivity

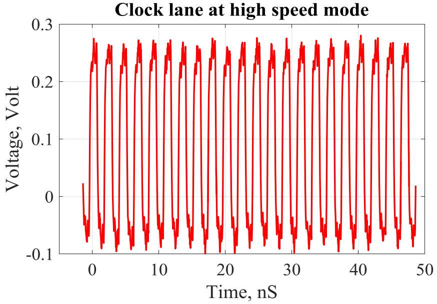
LCD MIPI Noise-to-GSM Interference



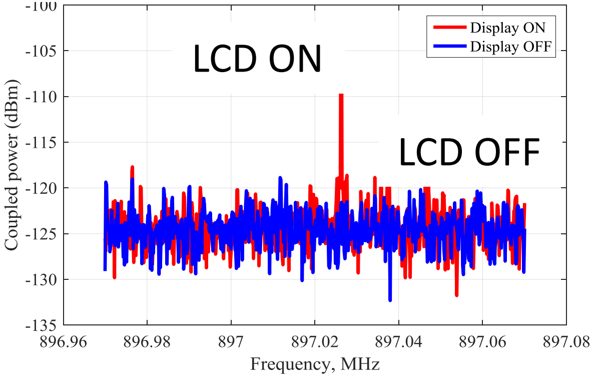
MIPI signal



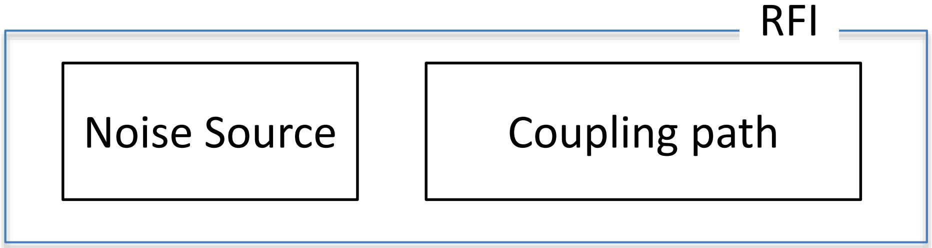
High speed clock



Coupled noise on antenna



Divide and Conquer



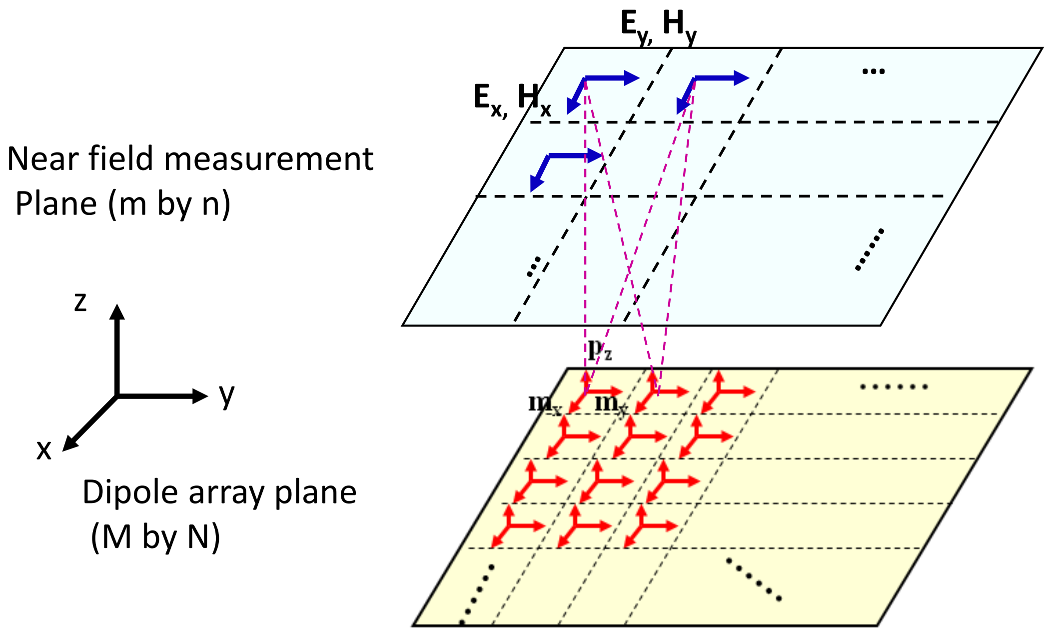
Noise source

- AP, DDR, PMIC, high-speed traces (data or clock), etc.
- Generally independent of system design (e.g. modulation)

Coupling path

- Characteristics of system; namely board and antenna design
- Noise sources sit on a “part of antenna”

Near-Field Scanning Based Dipole Reconstruction



Reconstructed sources (dipoles) are located on the ground plane

Least Square Method

EM fields from dipoles (an example)

$$E_x = K_e \Big\{ \Big[-\frac{y^2+(z-h)^2}{r_1^2} g_1(r_1) + g_2(r_1) + \frac{y^2+(z+h)^2}{r_2^2} g_1(r_2) - g_2(r_2) \Big] P_x + \Big[\frac{xy}{r_1^2} g_1(r_1) - \frac{xy}{r_2^2} g_1(r_2) \Big] P_y + \Big[\frac{(z-h)x}{r_1^2} g_1(r_1) + \frac{(z+h)x}{r_2^2} g_1(r_2) \Big] P_z + \Big[\frac{(z-h)}{r_1} g_3(r_1) + \frac{(z+h)}{r_2} g_3(r_2) \Big] k_0 M_y + \Big[-\frac{y}{r_1} g_3(r_1) + \frac{y}{r_2} g_3(r_2) \Big] k_0 M_z \Big\}$$

f_1 (E_x); x_1 (P_x); x_2 (P_y); x_3 (P_z); x_4 ($k_0 M_y$); x_5 ($k_0 M_z$)

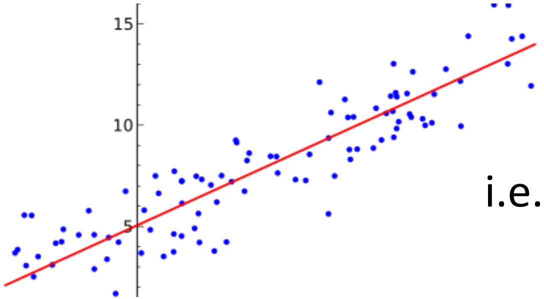
☞ $f_1 = T_{11} x_1 + T_{12} x_2 + \cdots + T_{1k} x_k$

E & H fields from dipole moment source

$$\begin{aligned} f_1 &= T_{11}x_1 + T_{12}x_2 + \cdots + T_{1k}x_k \\ f_2 &= T_{21}x_1 + T_{22}x_2 + \cdots + T_{2k}x_k \\ &\vdots \\ f_n &= T_{n1}x_1 + T_{n2}x_2 + \cdots + T_{nk}x_k \end{aligned}$$

$$\begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1k} \\ T_{21} & & & \\ \vdots & & \ddots & \vdots \\ T_{n1} & & \cdots & T_{nk} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix}$$

Find the approximate solution of overdetermined systems (# of equations > # of unknowns)



i.e. Data fitting

Physical Dipole Source Reconstruction

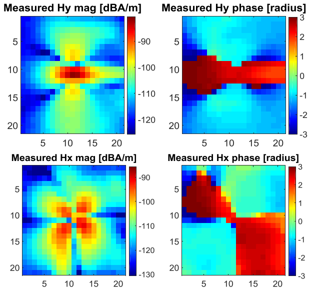
Least square method is known to be particularly prone to having too many variables

$$\begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1k} \\ T_{21} & & & \\ \vdots & & \ddots & \vdots \\ T_{n1} & & \cdots & T_{nk} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix}$$

Minimizing number of dipoles provides much better stability

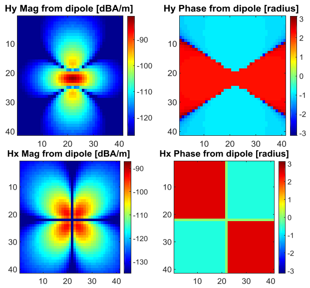
Minimize the variable (dipoles) through near field pattern recognition

scanned fields



Determine source type, location

Source magnitude

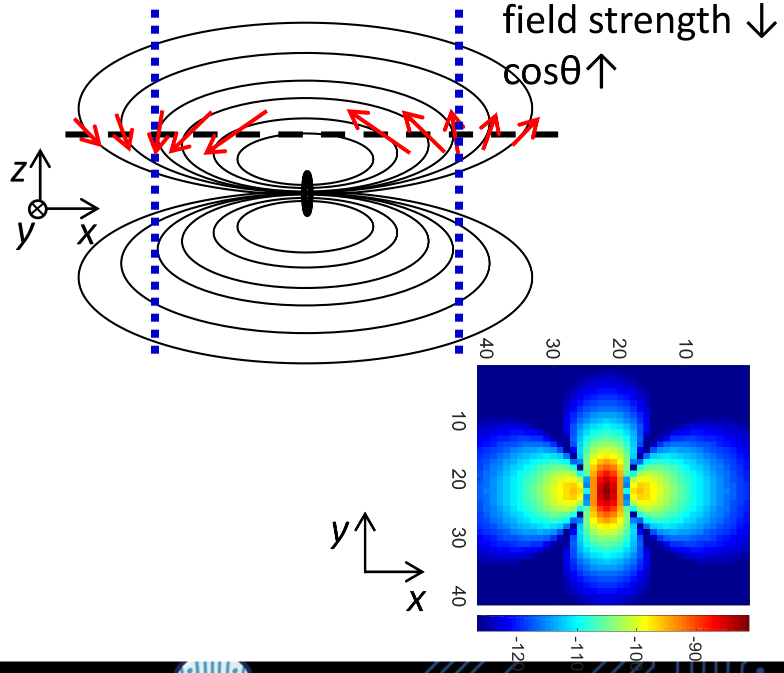


reconstructed fields

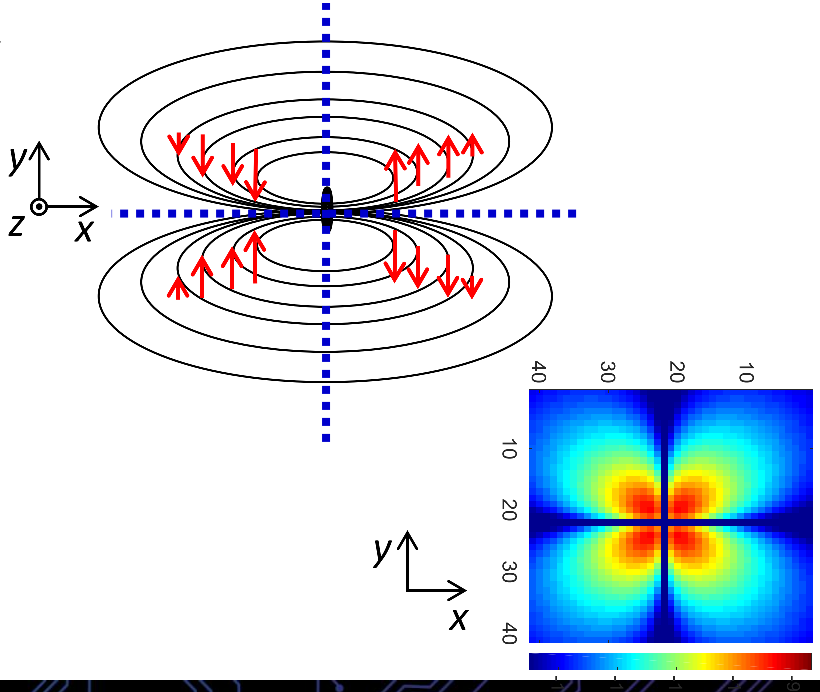
Educated guess → machine learning algorithm

Recognizing Dipole Type from Radiation Pattern

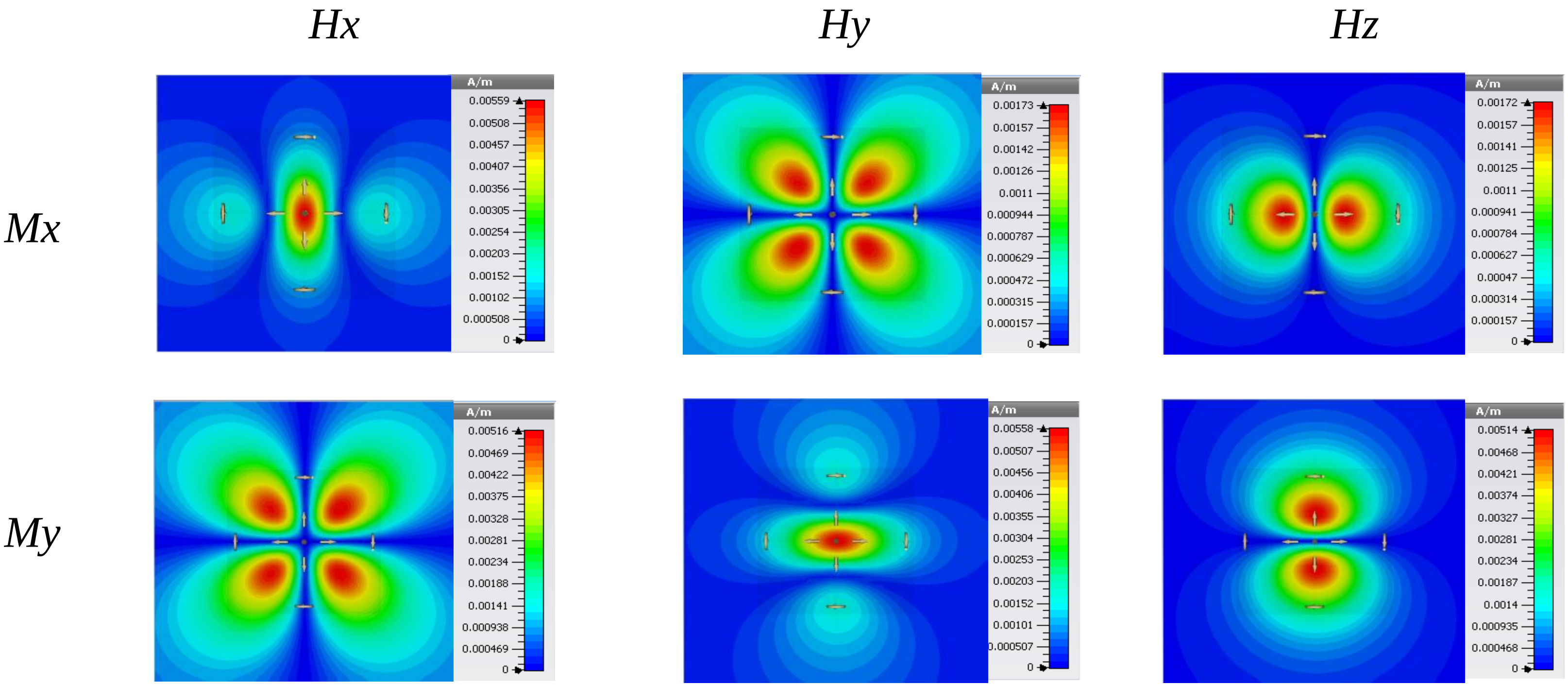
H_x plot (on *xy*-plane) for M_x source



Hy plot (on *xy*-plane) for M_x source

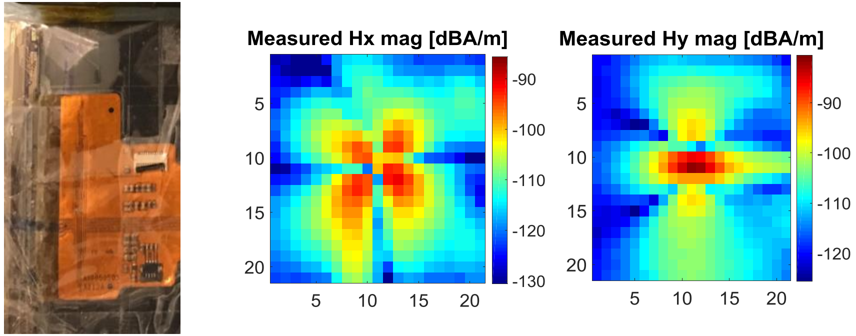


Near Field Pattern From Each Dipoles

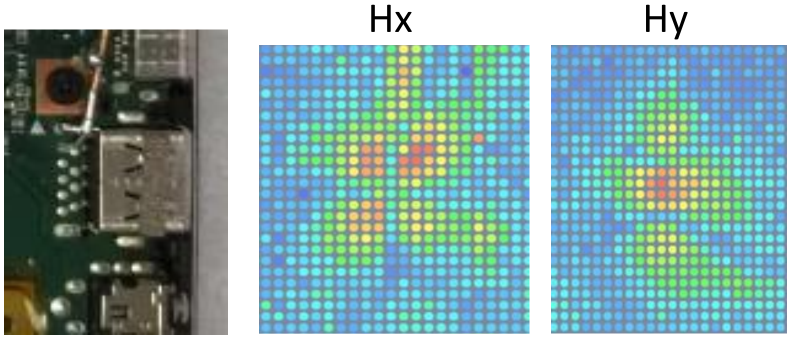


Noise Source Scanning Examples

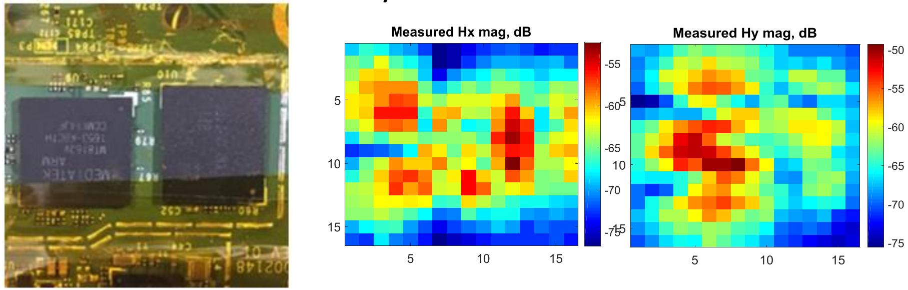
Display Driver IC (actually FPCB bending part) (900 MHz)



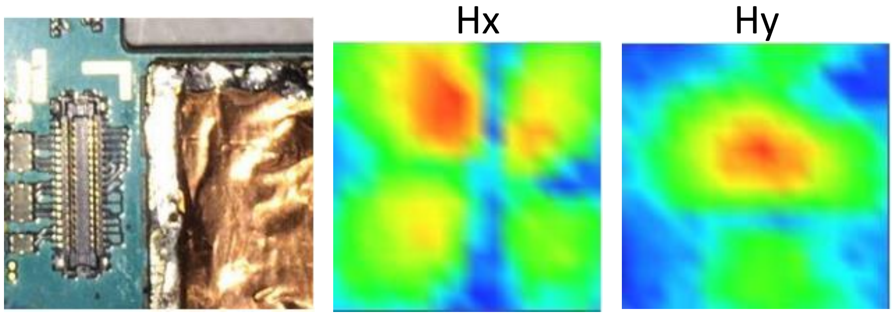
USB connector (2.4GHz)



AP and DRAM (2.4GHz)

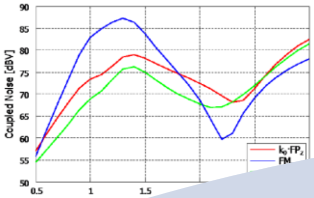


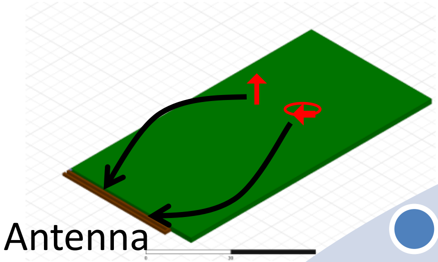
Common mode choke

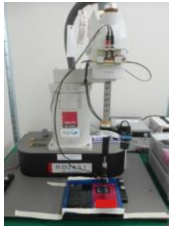


Fast and Intuitive RFI Estimation

Numerical simulation is for validation, not for design





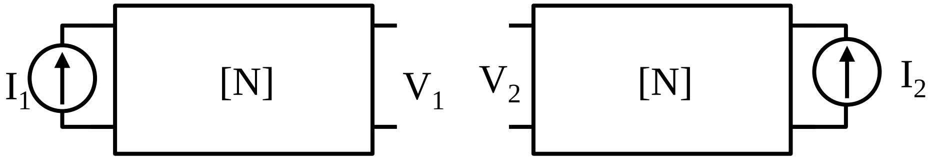


- Dipole moment source extraction
- Numerical simulations
- Coupled voltages

An Insightful RFI model is needed to answer "What if" questions

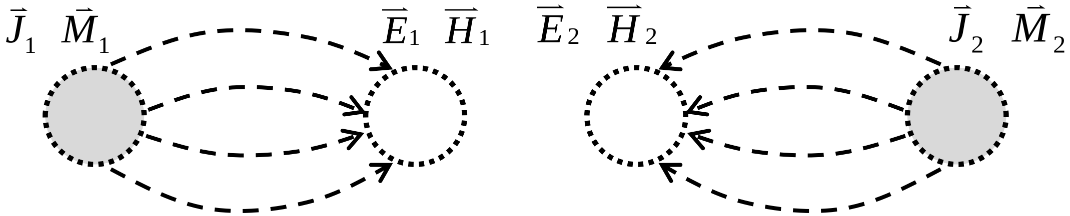
Reciprocity Theorem

Reciprocity in a reciprocal network



$$I_1 V_2 = I_2 V_1$$

Reciprocity in electromagnetics



$$\left\langle (\vec{J}_1, \vec{M}_1), (\vec{E}_2, \vec{H}_2) \right\rangle = \left\langle (\vec{J}_2, \vec{M}_2), (\vec{E}_1, \vec{H}_1) \right\rangle$$

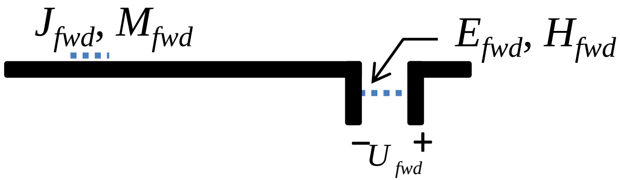
$$\iiint_V \left(\vec{E}_1 \cdot \vec{J}_2 - \vec{H}_1 \cdot \vec{M}_2 \right) dv = \iiint_V \left(\vec{E}_2 \cdot \vec{J}_1 - \vec{H}_2 \cdot \vec{M}_1 \right) dv$$

(simplified integral form)

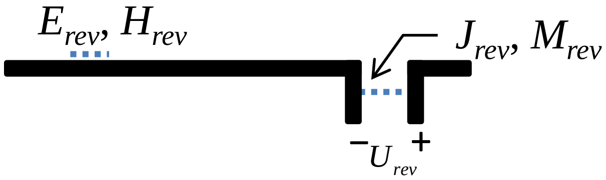
Derivation

Original problem

Forward problem (noise radiates)



Reverse problem (antenna radiates)



Reciprocity theorem

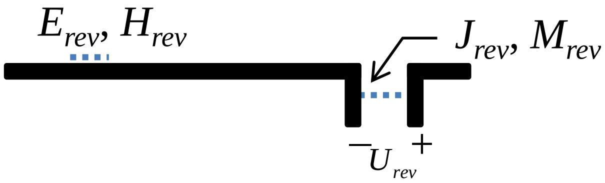
[redacted]

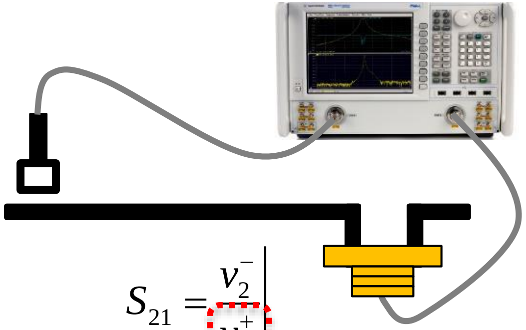
$$U_{fwd} = \frac{Z_L}{2U_{rev}^{+}}\left(\sum_{i=1}^{N} -\vec{E}_i^{rev}\cdot\vec{P}_i + \sum_{i=1}^{N}\vec{H}_i^{rev}\cdot\vec{M}_i\right)$$

$\vec{P}_i$ $\vec{M}_i$: Reconstructed dipoles

Derivation

Reverse problem (antenna radiates)





$$S_{21} = \left.\frac{v_2^-}{v_1^+}\right|_{v_2^+=0}$$

We actually measure S-parameters

$$U_{fwd} = \frac{Z_L}{2U_{rev}^+}\left(\sum_{i=1}^{N} -\vec{E}_i^{rev}\cdot\vec{P}_i + \sum_{i=1}^{N}\vec{H}_i^{rev}\cdot\vec{M}_i\right)$$

$\frac{E_i^{rev}}{U_{rev}^+}, \quad \frac{H_i^{rev}}{U_{rev}^+}$: S21 x probe factor

Single Dipole (M_y) Case – Often Happens!

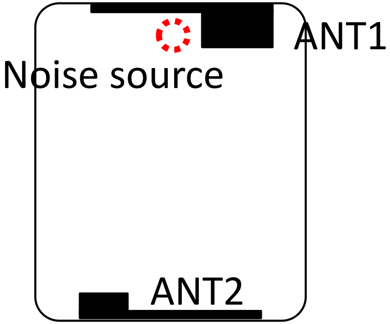
$$U_{fwd} = \frac{Z_L}{2U_{rev}^{+}}\left[H_y M_y\right] = f_M M_y$$

$$f_M = \frac{Z_L}{2}\frac{H_y}{U_{rev}^{+}}$$ transfer function (S21 x probe factor)

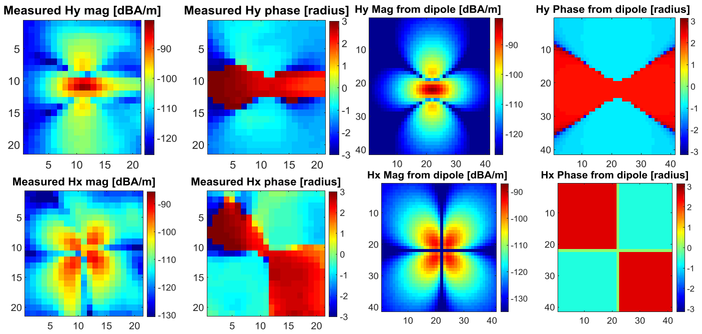
☞ Source type determines which field quantities to look at $\begin{cases} M_x \rightarrow H_x \\ M_y \rightarrow H_y \\ P_z \rightarrow E_z \end{cases}$

LCD MIPI Noise in Cell Phone

DUT

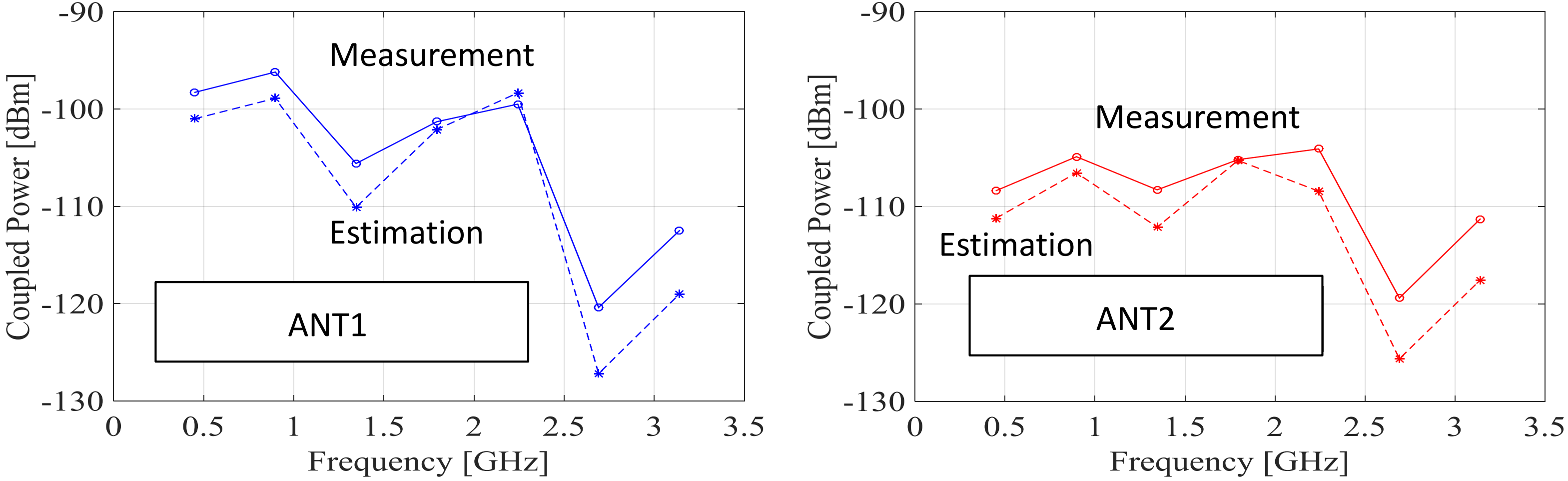


Dipole reconstruction (using VNA)



Correlations

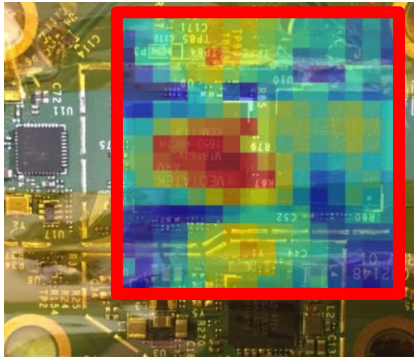
Coupled noise power at the antenna ports

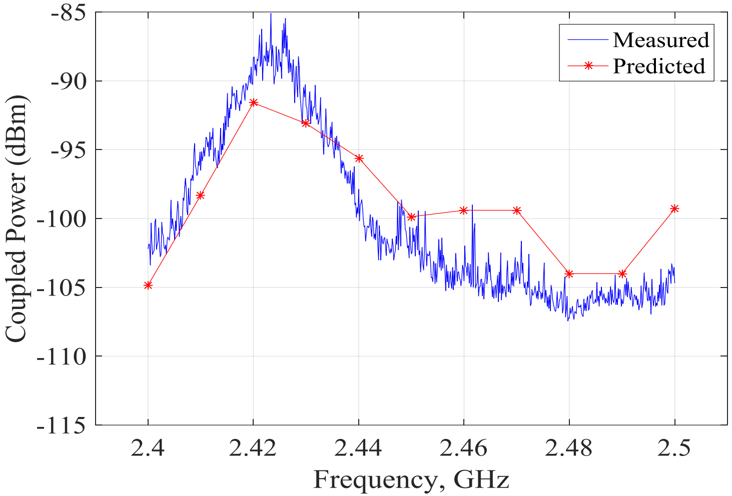


Measurement: direct measurement using SA

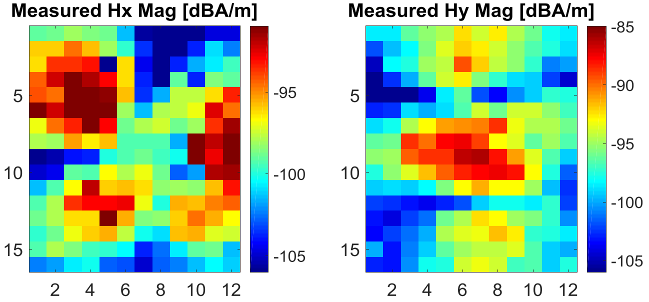
Estimation: reconstructed dipole × antenna near field scanning

AP Noise





Dipole reconstruction using SA



Errors < 5dB, average error ≈ 3 dB

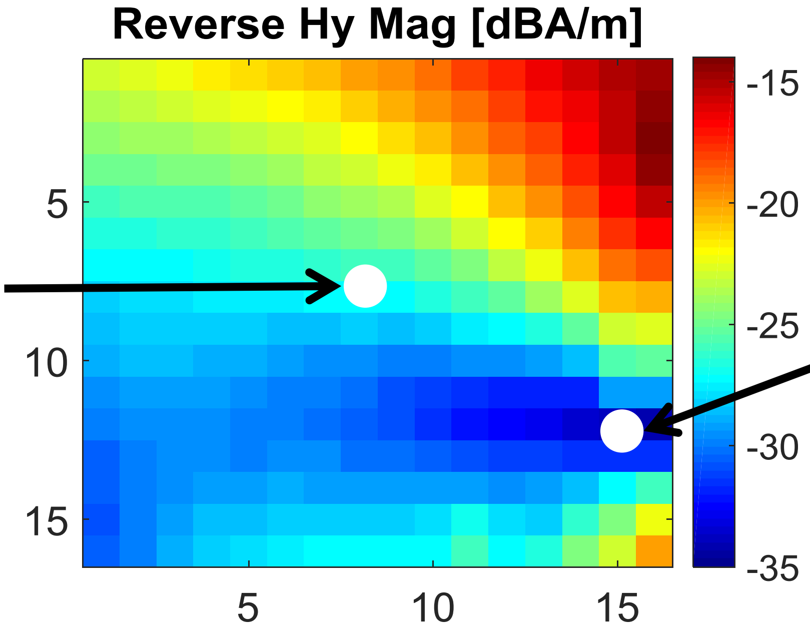
Challenges: time-varying nature of signals (measurement, algorithm)

Reducing H_y

Move the noise source to a location with minimal H_y component

Smartly changing antenna geometry can also reduce H_y

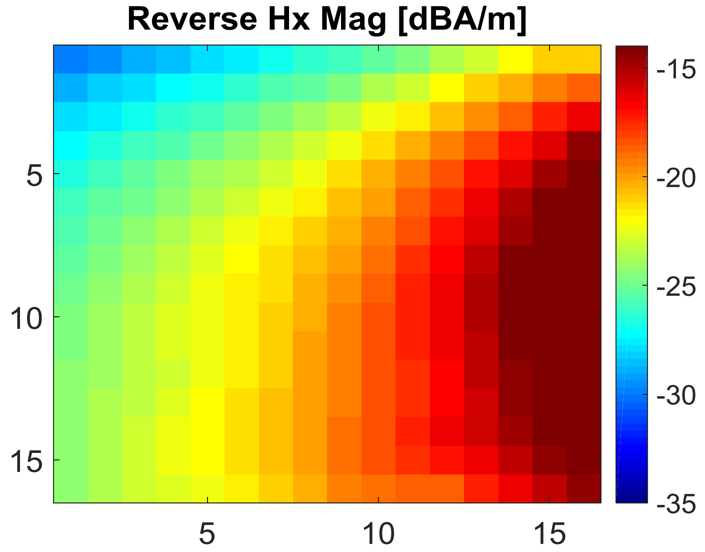
Originally, My dipole is here

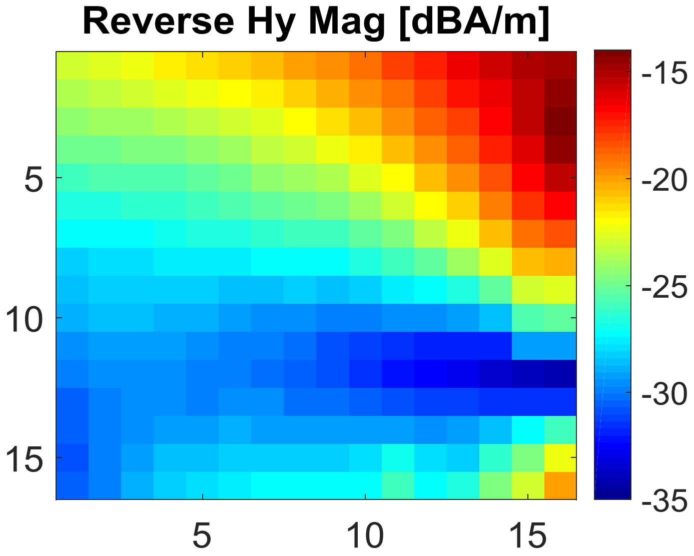


Move My dipole to this Hy-min place

What if Rotating IC by 90 Degree

By exciting the antenna in reverse problem, generally H_y is weaker than H_x. So keeping the noise source as magnetic dipole M_y is a better choice.



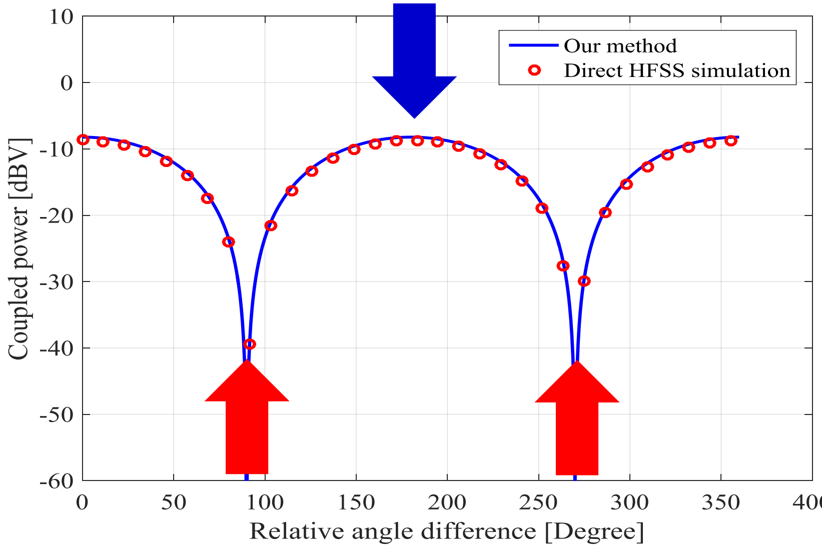


What if Rotating a M dipole At a Arbitrary Angle

The coupled noise is a function of angle between H field (reverse problem) and magnetic dipole (forward problem)

$$U_{fwd} = \frac{Z_L}{2U_{rev}^{+}} (\vec{H}_{\tan}^{rev} \cdot \vec{M}_{\tan}^{fwd})$$

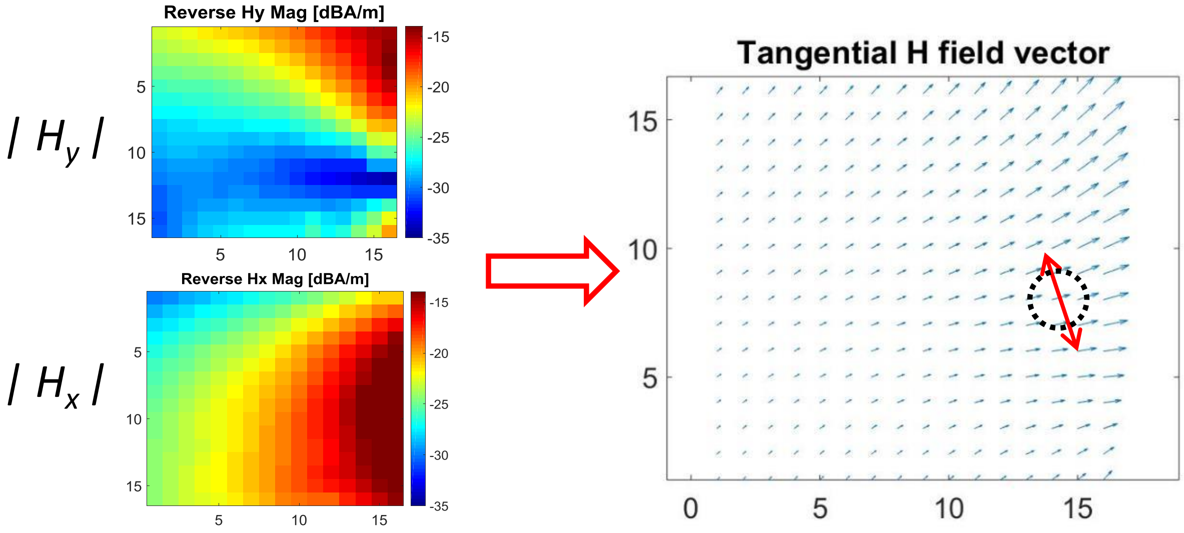
$$= \frac{Z_L}{2U_{rev}^{+}} |\vec{H}_{\tan}^{rev}||\vec{M}_{\tan}^{fwd}| \hat{a}_{M_{\tan}} \cdot \hat{a}_{H_{\tan}}$$



Using Rotation Effect on This DUT

Tangential H field vector is plotted based on H_x and H_y

CPU IC can be rotated to be orthogonal to H field



Conclusion

- Fast and accurate RFI model by diving RFI into two parts
  - Source:
    - Dipole (near field or TEM cell based reconstruction)
  - Coupling:
    - Transfer function (S21 x probe factor)
    - Make the victim antenna radiate and measure the field at the IC location
- Many possible applications
  - Pre-layout decision or RFI-aware design optimization
  - Efficient numerical simulations

Thank you!

QUESTIONS?