Wireless Power Transfer through MRC: from theory to implementation

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Agenda

- Introduction and history of Wireless Power at Qualcomm
- EM fields in metals, thermals and ISM Bands
- System-level analysis for Multi-device charging
  - EM Field, Impedance and the Secret Sauce
- A metal case can help efficiency?
- Charging small devices
- Lessons learned
- EMI and Desense (time permitting)

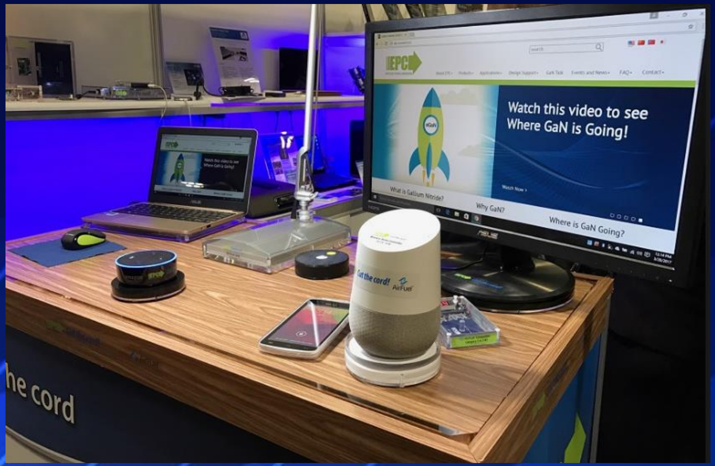
We will not talk about…
(but if you really want, we can have a webinar on each topic!)

- Tesla, Marconi and friends: it took a hundred years to make it work (kind of…)
- Safety: term mostly used by competitors to generate F.U.D.
- Compliance: this is what matters (and no product is approved if it doesn't comply)
- Neither WPT nor 5G cause COVID-19 (we are not sure about 6G yet)
- Class D Vs. Class E Transmitter*: both have pros and cons.
- Do you need OOB communication (e.g., Bluetooth)?
  No, but you can make the system a lot smarter with it!

* If your background is Power Management, you will design a Class D; if you are an RF engineer, you will build a Class E/F. Both of you will make it work… with a lot of effort!

What does “wireless” mean?

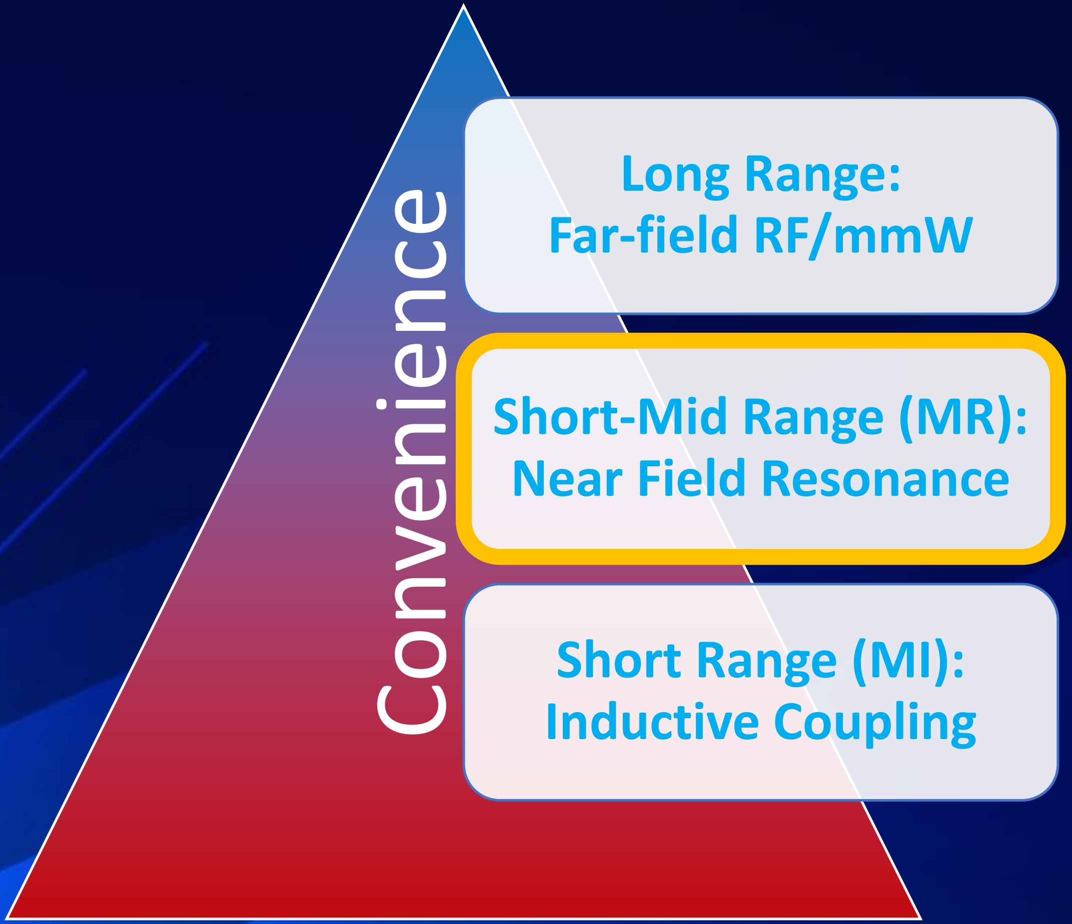
Wireless:
No wires – Any device



1 wire:
works with most devices

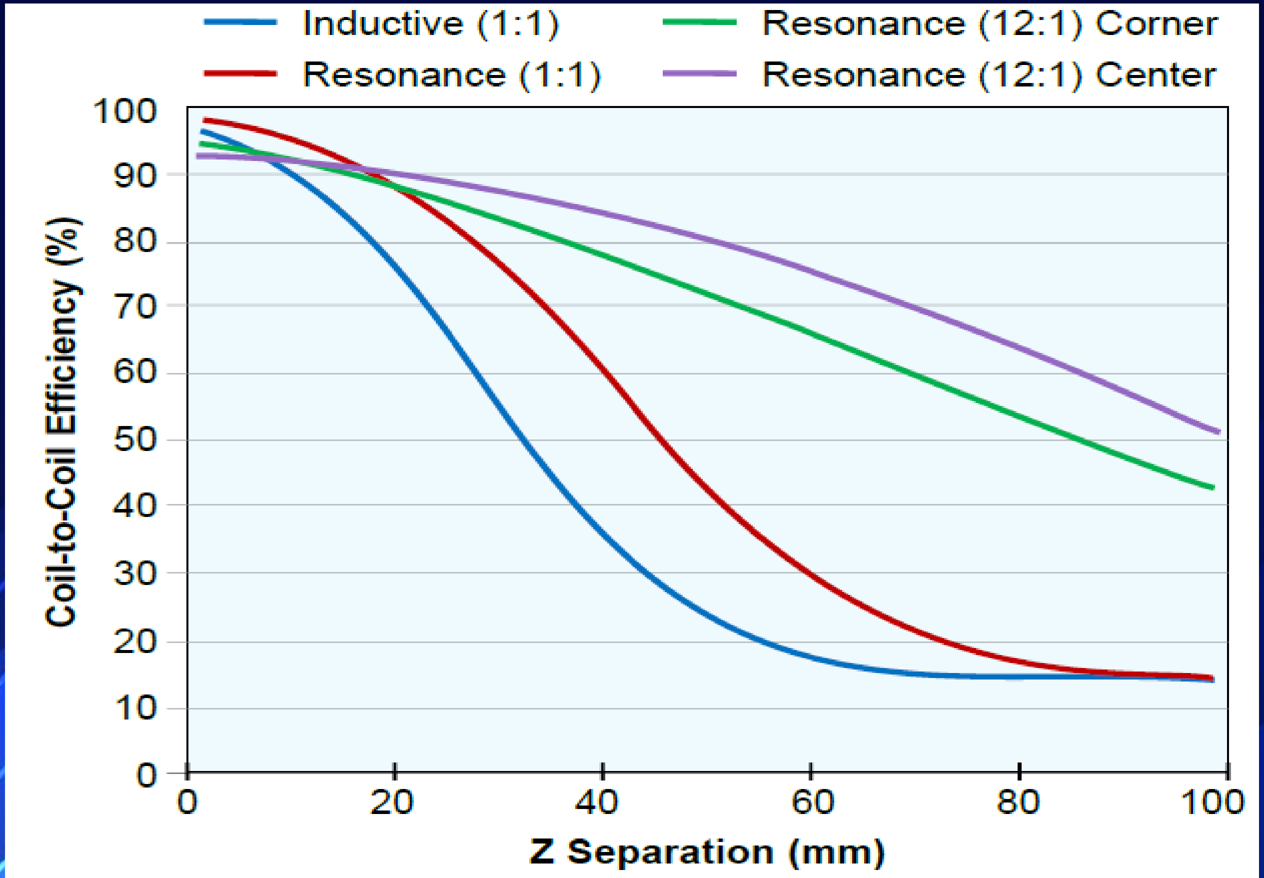
Many wires + pucks:
one per device type

Wireless Charging Technologies



Wireless-Charging Efficiency

F. Carobolante "Resonant Wireless Power Transfer Technology & Integration Roadmap" CICC 2015



- At close range, coil-to-coil efficiency (power transfer across the air gap) is greater than 90% for both tightly and loosely coupled systems.

The ratios represent charging coil to receiving coil size; 12:1 means the charging coil is 12x larger in diameter than the receiving coil.

(Source: MediaTek)

The Wireless System design challenge: a non-linear system with too many variables

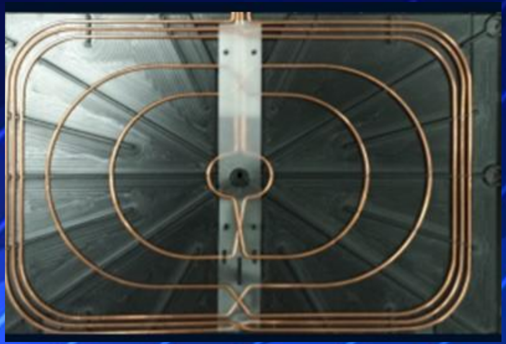
- A three-device charger must concurrently, safely and reliably deliver power to each receiver:
  - **Tolerance stack of more than 60 elements in a chain of resonant circuits**
  - A variable supply with a 5:1 voltage range
  - Load: 10 to 10,000 Ohms per receiver; reflected reactance from –j200 to +j200 Ohm
  - Resonant elements affected by handset materials
  - Highly variable coupling of each receiver (X-Y-Z)
  - Conflicting feedback requirement from each receiver

→ **~10^{75} simulations? Impossible**

History of wireless power at Qualcomm

- 2007: 10MHz demo system (500 x 500mm at 1m distance)
- 2008: 13.56MHz systems
  - 2.5 watts max to load based on regulatory limits at 13.56MHz
  - Time division multiplexed (so 2 receivers get 1.25 watts each)
- 2009: Move to 6.78Mhz (higher power, better efficiency)
  - In-band signaling
  - Inherent (impedance based) power control and power sharing among multiple devices
  - Learned a lot about complex impedance!

History of wireless power at Qualcomm (cont'd)

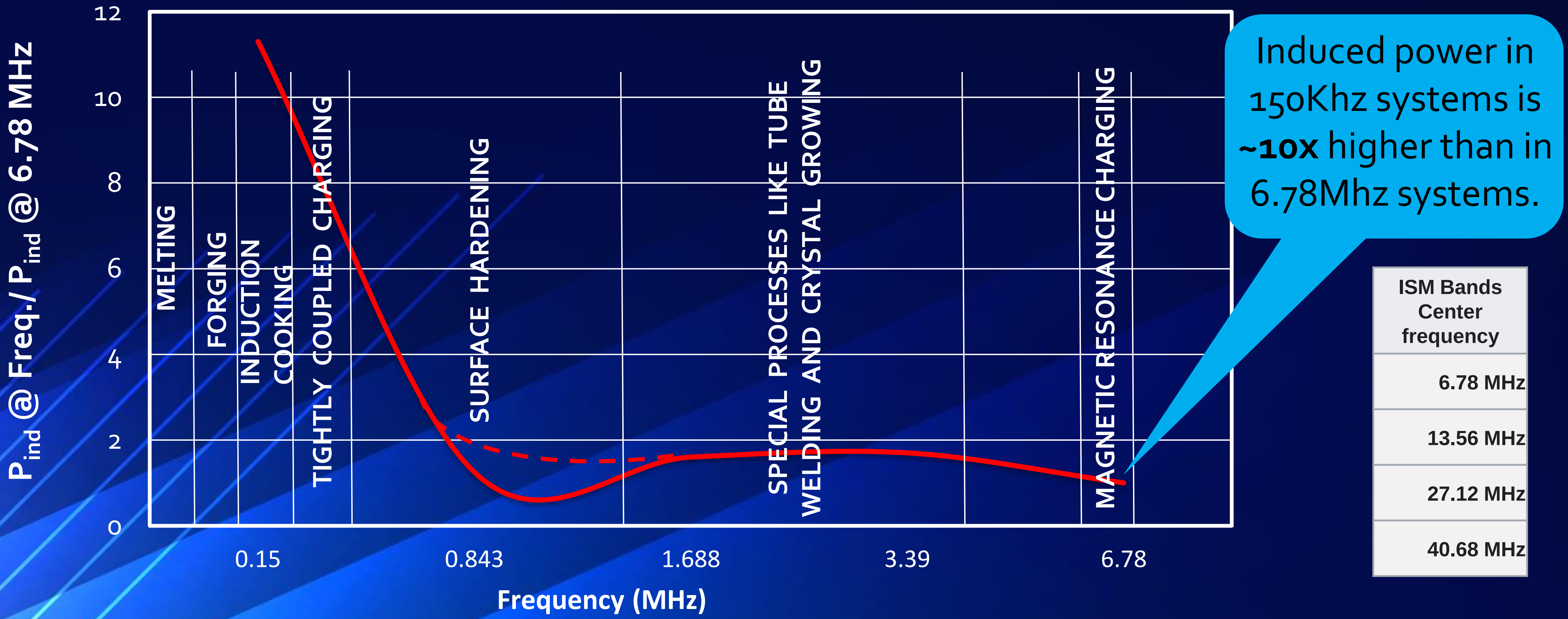


- 2010: WiPower acquisition (500KHz system)
  - Refined H-Field uniformity and understood effects of E-Field
  - Regulatory/heating problems – abandoned
- 2011: In-band communication finalized
  - System used reverse communication to adjust power for efficiency, detect lost power
  - Proved adaptive tuning for multi-chargers
- 2012: Switch to BLE for communications
  - Required by A4WP partners

Induced Power Loss Over Frequency

Frequency selection's impact on losses in conductive materials within the charging field (e.g., all metallic elements in the device being charged)F.

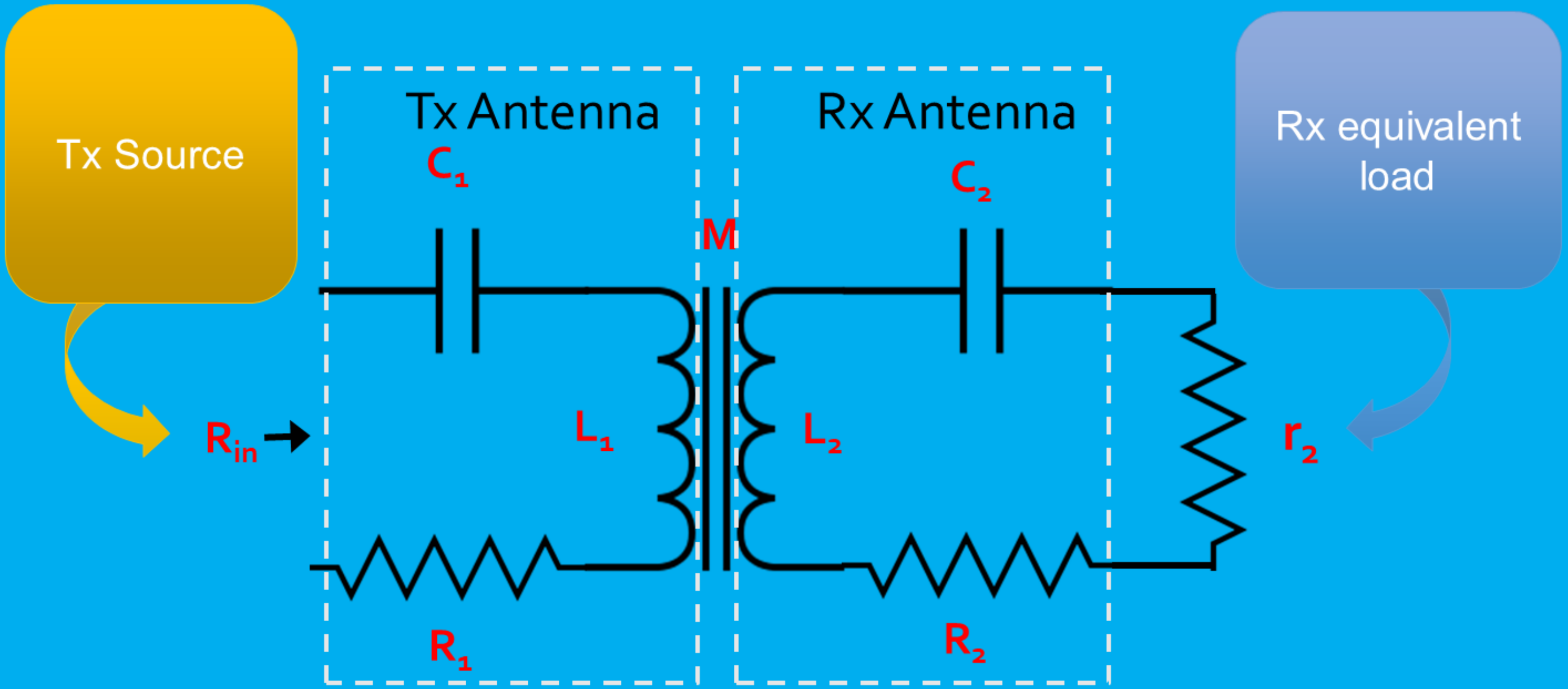
F. Carobolante "Magnetic Resonant Charging and the A4WP Standard" ISSCC 2015



ISM Bands Center frequency
6.78 MHz
13.56 MHz
27.12 MHz
40.68 MHz

Key parameters

F. Carobolante “Magnetic Resonant Charging and the A4WP Standard” ISSCC 2015



$$R_{in} = R_1 + \frac{\omega^2 M^2}{R_2 + r_2}$$

$$M = \frac{\sqrt{(R_2 + r_2)(R_{in} - R_1)}}{\omega}$$

$$\eta = \frac{r_2}{R_2 + r_2}\left[\frac{1}{1 + R_1 \frac{R_2 + r_2}{\omega^2 M^2}}\right]$$

The Field Perspective

F. Carobolante "Magnetic Resonant Charging and the A4WP Standard" ISSCC 2015

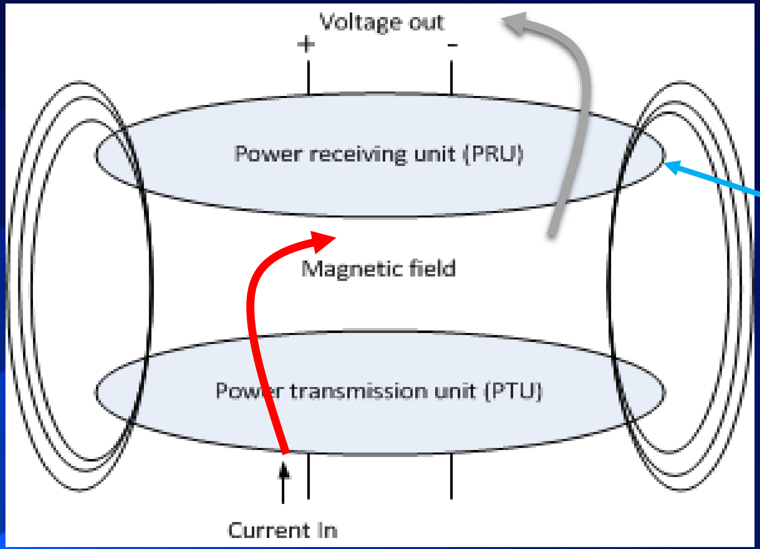
	Integral form	Differential Form
Gauss's Law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho \, dV$	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's Law of Magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$	$\nabla \cdot \mathbf{B} = 0$
Faraday's Law of Induction	$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampere's Circuit Law	$\oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \iint_{\Sigma} \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}\right) \cdot d\mathbf{S}$	$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}\right)$

$$V = \oint E \cdot dl = i\omega\mu_0 \int H \cdot da$$

The voltage induced on a receiving coil depends directly on the time rate of change of magnetic field strength and the total cross sectional area.

$$\int H \, dl = NI$$

Ampere's law



Faraday's law

$$V = N \cdot \frac{d\varphi}{dt}$$

N: RX coil turns

A: RX area

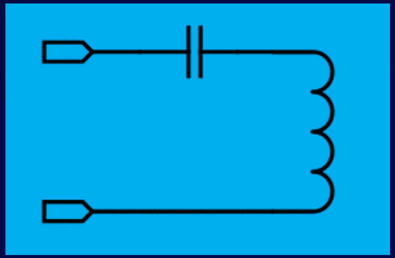
Φ: Flux through coil area

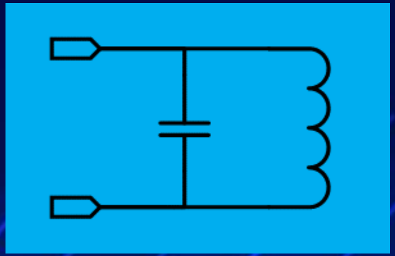
$$M = N_{RX} A_{RX} \frac{\mu H_{TX}}{I_{TX}}$$

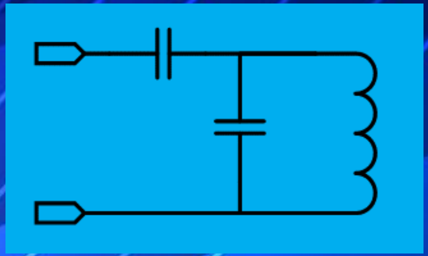
RX resonator design

TX resonator design

Resonator tuning



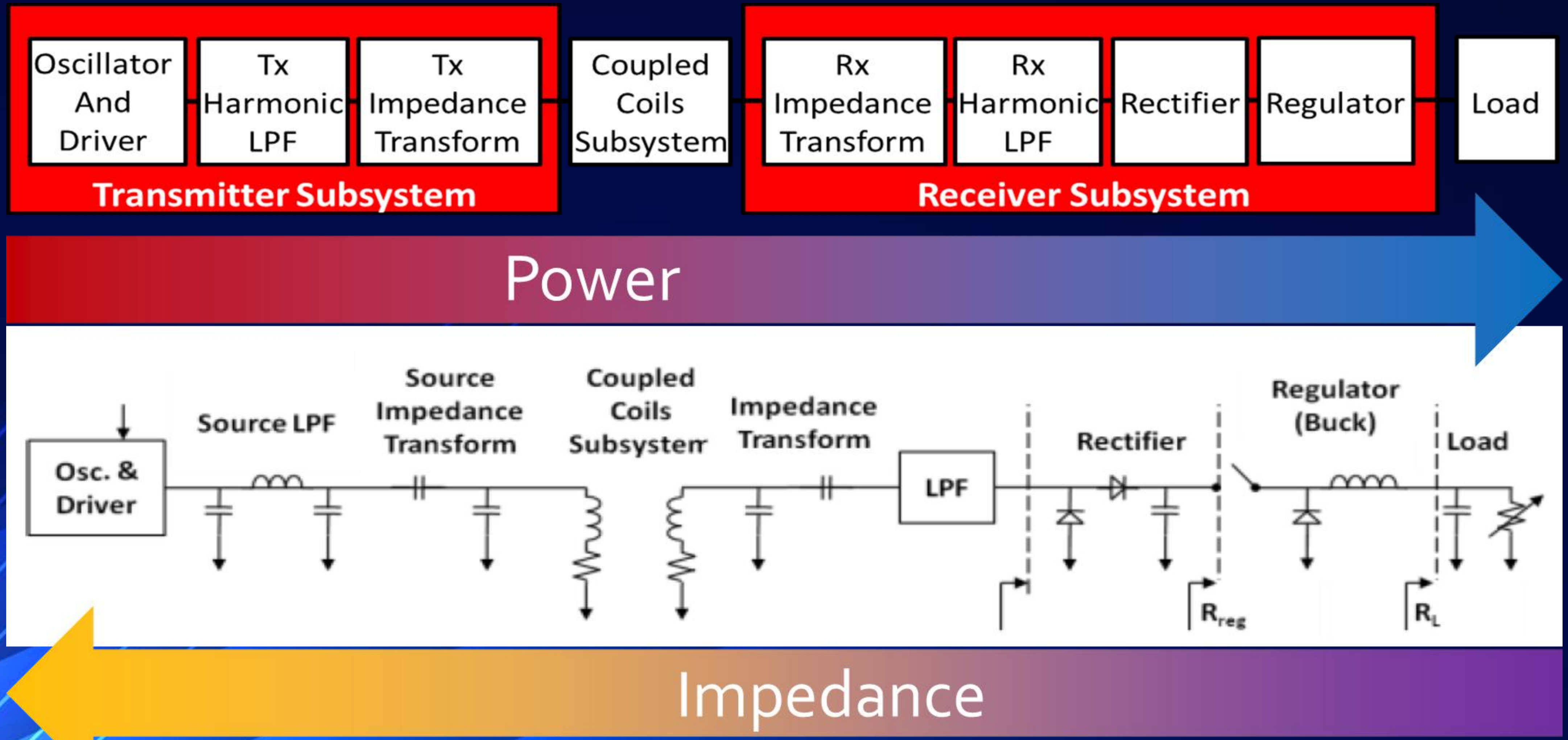




- Series
  - Carries same current in the resonator as output by the TX
  - Multiple load devices add in series
  - Ideally suited to be driven by a current source
- Shunt
  - Current ratio changes based on load
  - Multiple devices add in parallel
  - Imaginary part of impedance seen by PA changes with receiver load
- Hybrid
  - Predominantly series-tuned
  - Small shunt capacitor can be used to transform (match) a low impedance to a higher impedance

Lesson #1: Build an End-to-End System Diagram

F. Carobolante “Magnetic Resonant Charging and the A4WP Standard” ISSCC 2015



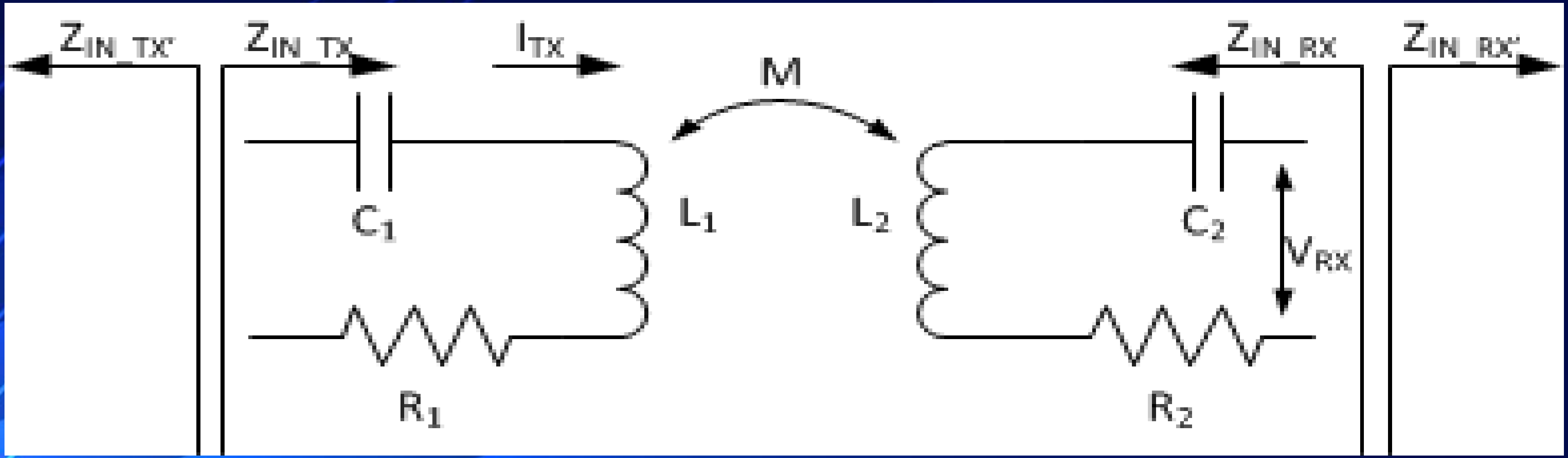
Lesson #2: Series resonance allows for automatic control of the load

F. Carobolante "Magnetic Resonant Charging and the A4WP Standard" ISSCC 2015

$$j\cdot\omega\cdot L_1 + \frac{1}{j\cdot\omega\cdot C_1} = 0 \qquad j\cdot\omega\cdot L_2 + \frac{1}{j\cdot\omega\cdot C_2} = 0$$

$$Z_{IN\_TX} = R_1 + \frac{\omega^2\cdot M^2}{R_2 + Z_{IN\_RX'}}$$

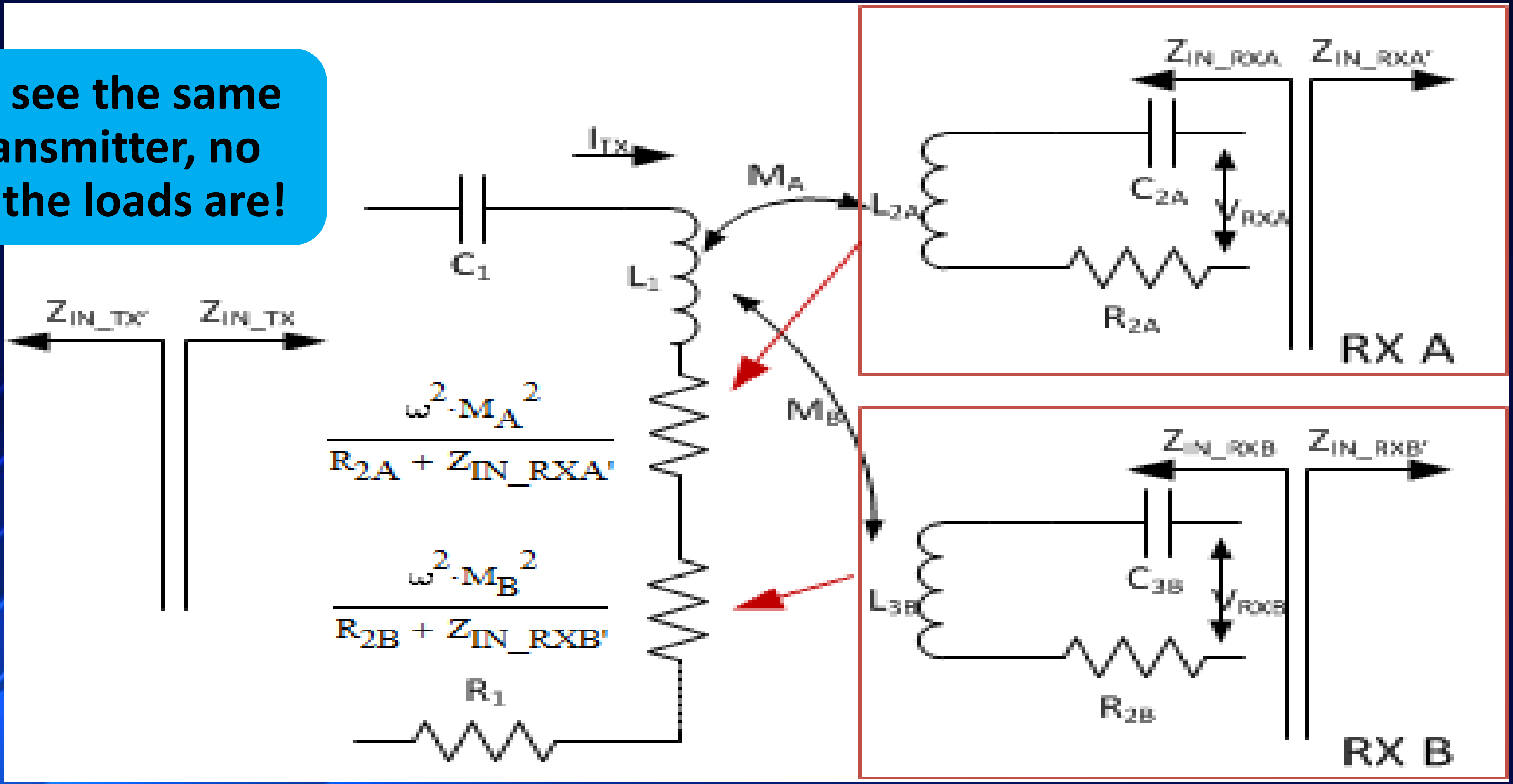
Receiver load resistance is inverted on the Transmitter side!



Lesson #3: The TX current must be constant. Multiple Receivers add in series on the Transmitter side

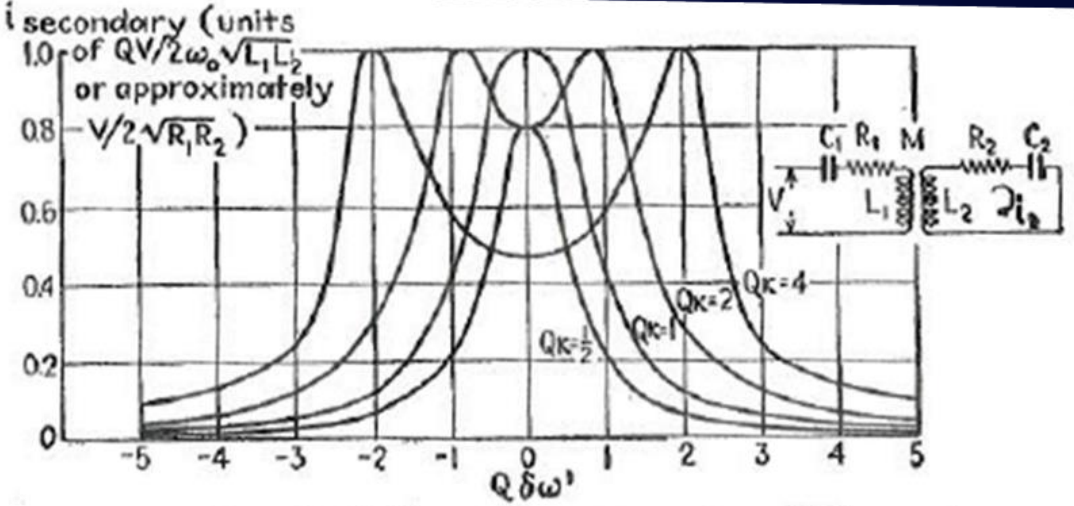
F. Carobolante "Magnetic Resonant Charging and the A4WP Standard" ISSCC 2015

All Receivers see the same I_{TX} in the Transmitter, no matter what the loads are!



Lesson #4: Don't operate "at resonance"

- If you design for exact resonance… you will never operate at the right point!



$M = k\sqrt{L_1L_2}$ $\quad Q = \omega L/R \quad$ $\omega' = \sqrt{LC}\,\omega$

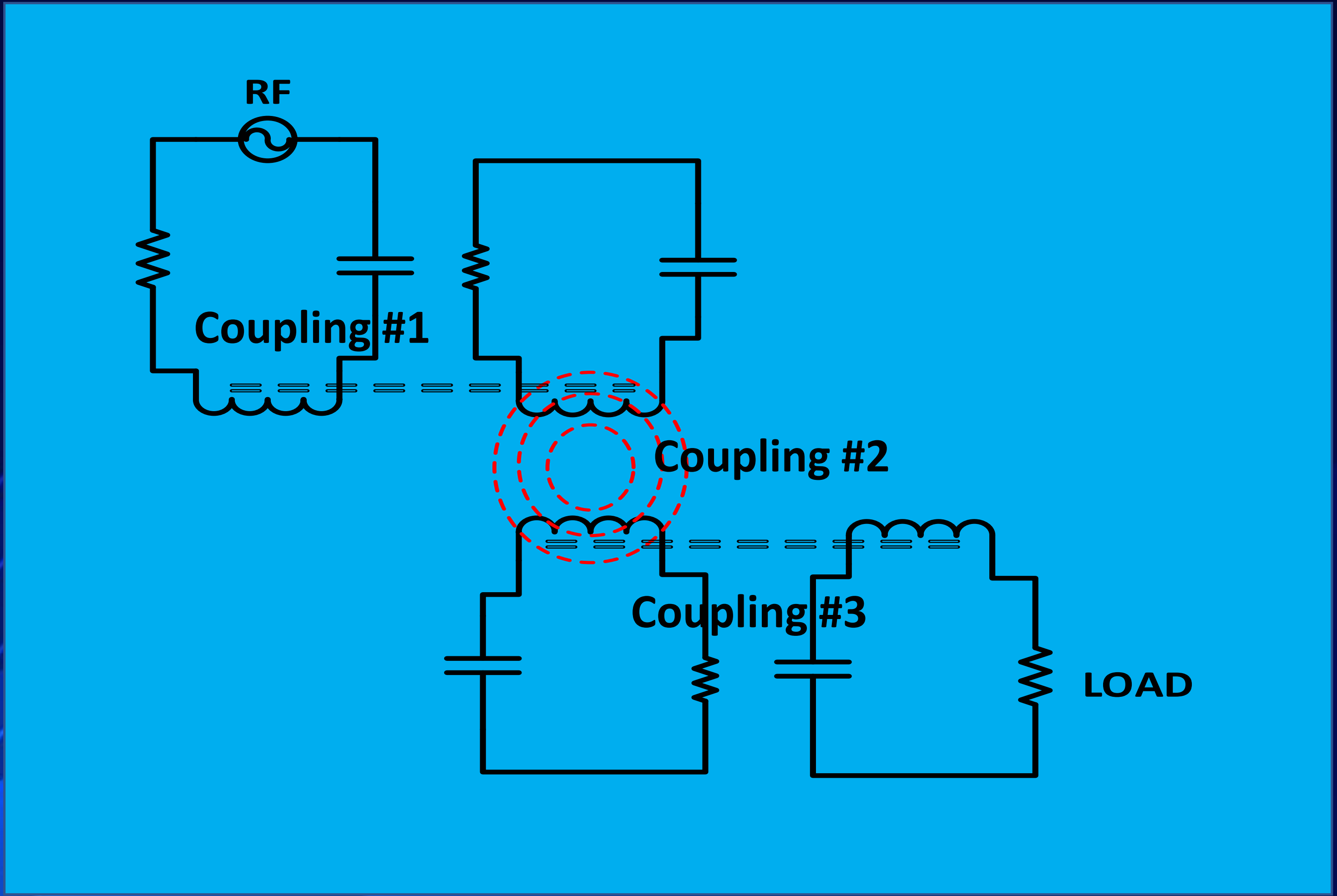
Maxima separated a distance

$$\delta\omega' = \frac{1}{Q}[(Qk)^2 - 1]^{1/2} \text{ for small } \delta\omega'.$$

Fig. 14.8.—Typical resonance curves for coupled systems.

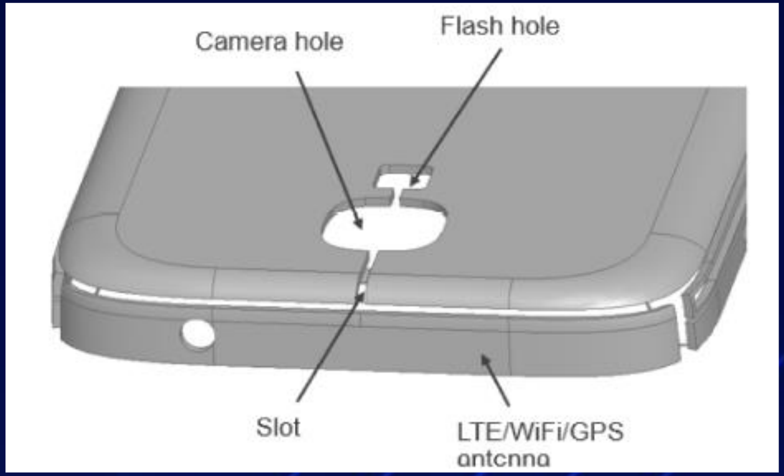
Gaylord P. Harnwell: "Principles of Electricity and Electromagnetism", McGraw Hill, 1949, page 500.

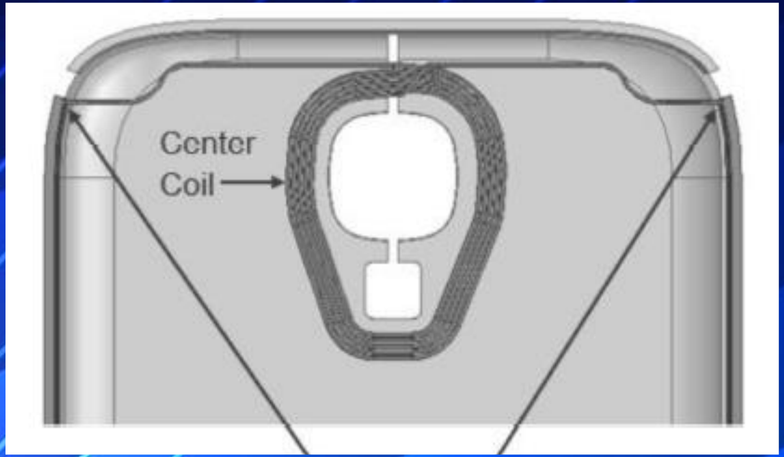
Other Interesting configurations
(3- and 4-coil systems)

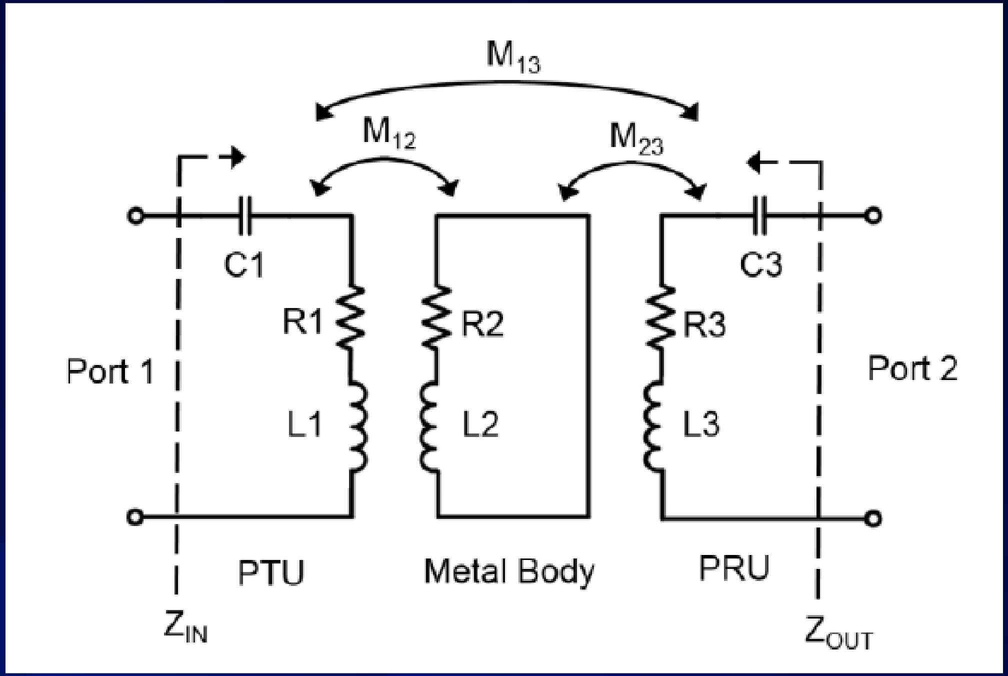


Who said “never use an odd number of coils?”

N. Jeong et al. "Wireless Charging of a Metal-Body Device," IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 65, NO. 4, APRIL 2017







The metal back-cover of a device can be utilized as an intermediate (2nd) coil, which is tightly coupled to an internal receiver coil

Wireless Power Transfer for small devices: Less than 0.5mm thick includes all electronics!

F. Carobolante et al. "A Novel Charger Architecture for Resonant Wireless Power Transfer," IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS 2017

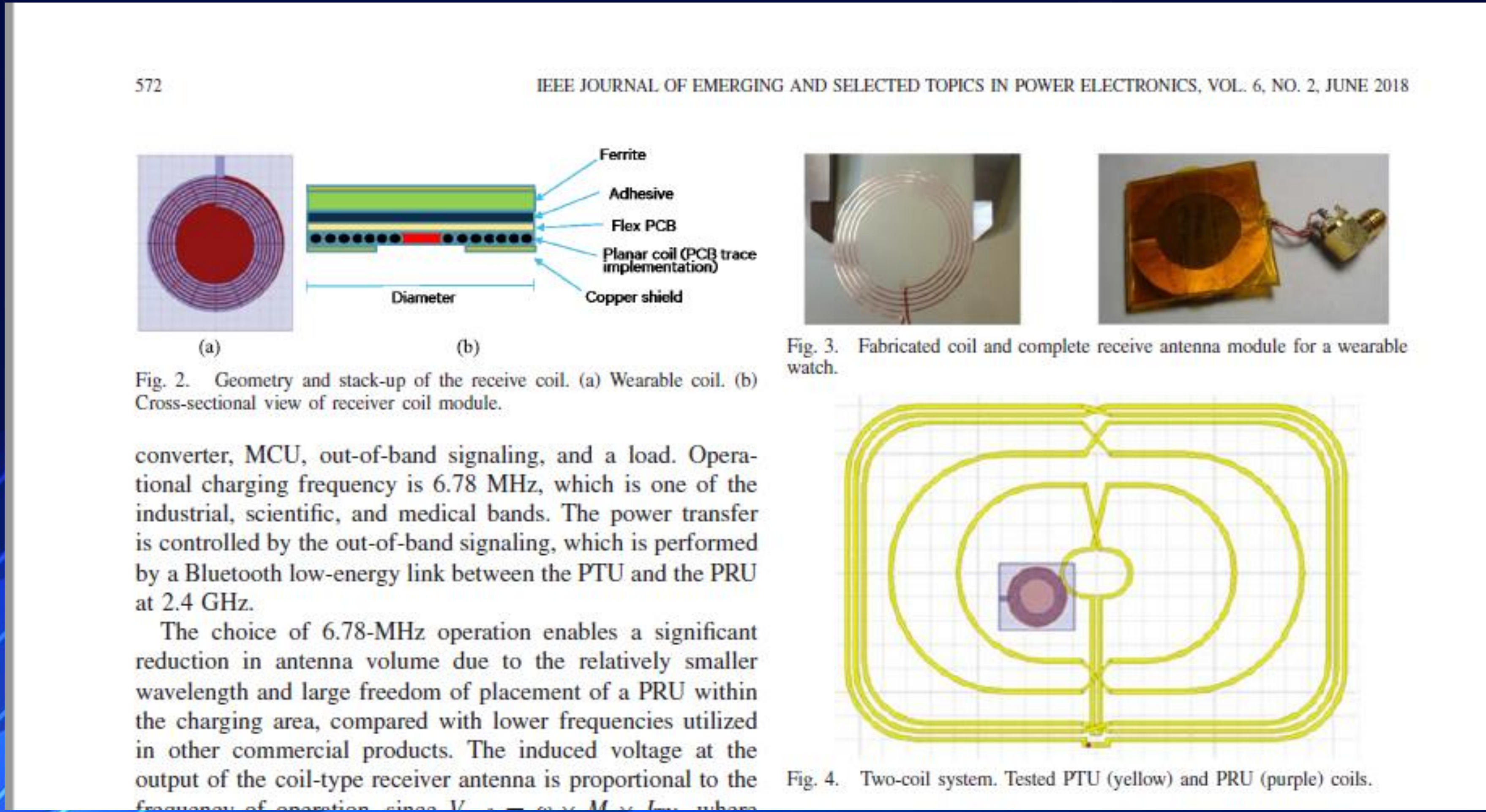

572 IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, VOL. 6, NO. 2, JUNE 2018

Fig. 2. Geometry and stack-up of the receive coil. (a) Wearable coil. (b) Cross-sectional view of receiver coil module.

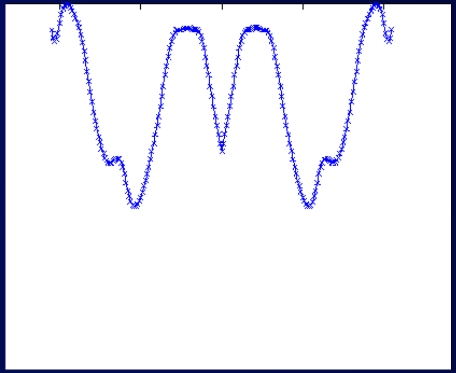
converter, MCU, out-of-band signaling, and a load. Operational charging frequency is 6.78 MHz, which is one of the industrial, scientific, and medical bands. The power transfer is controlled by the out-of-band signaling, which is performed by a Bluetooth low-energy link between the PTU and the PRU at 2.4 GHz.

The choice of 6.78-MHz operation enables a significant reduction in antenna volume due to the relatively smaller wavelength and large freedom of placement of a PRU within the charging area, compared with lower frequencies utilized in other commercial products. The induced voltage at the output of the coil-type receiver antenna is proportional to the

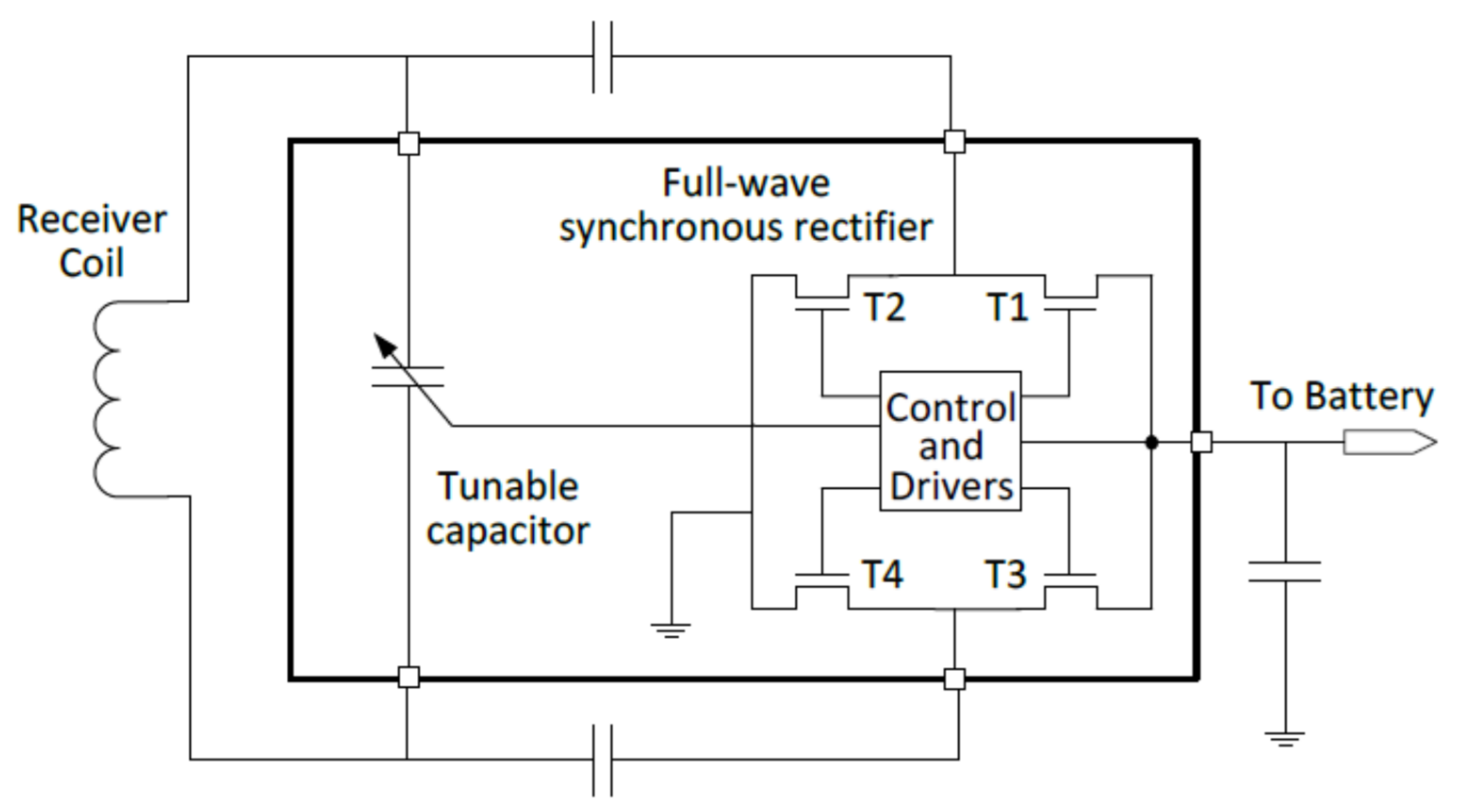
Fig. 3. Fabricated coil and complete receive antenna module for a wearable watch.

Fig. 4. Two-coil system. Tested PTU (yellow) and PRU (purple) coils.

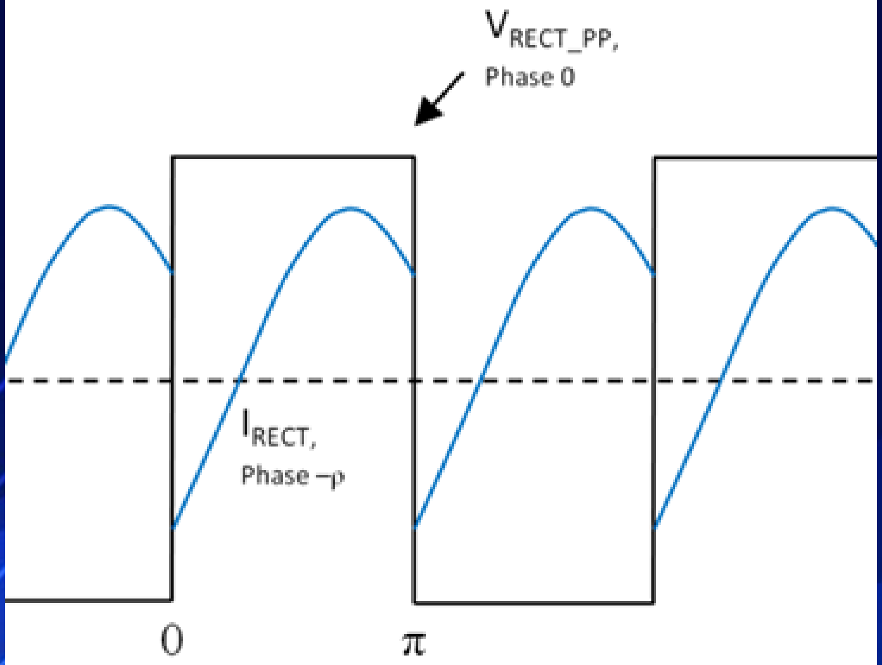
Problem with field uniformity

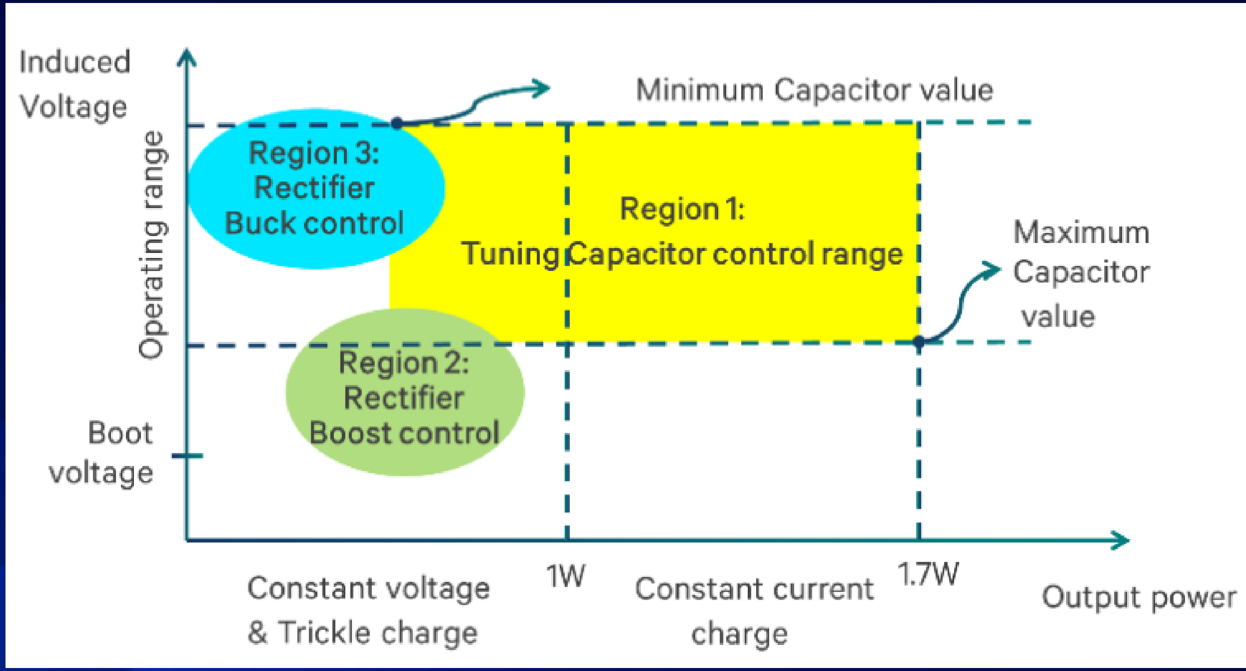


Complete receiver in one chip!

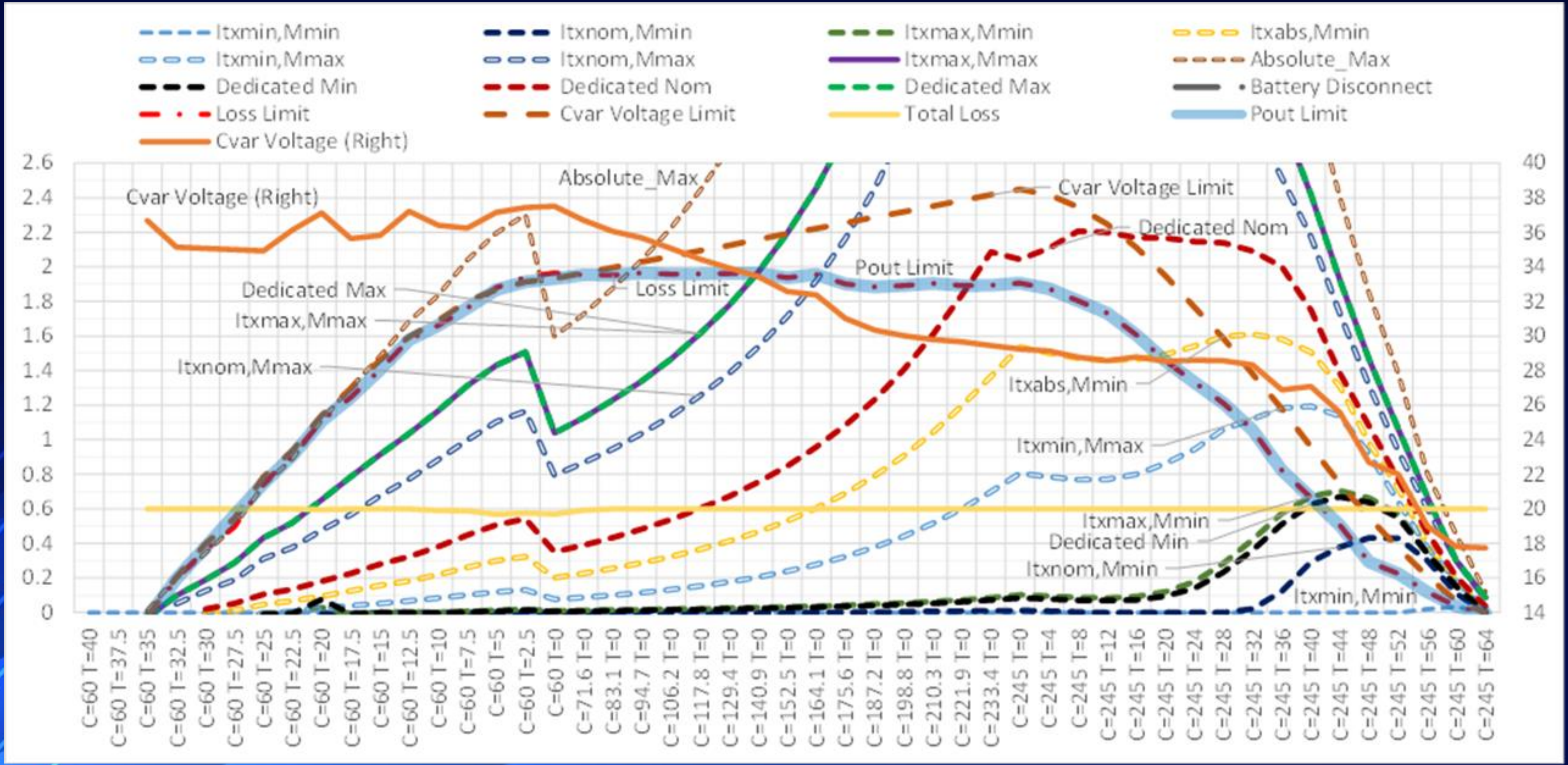


Buck and Boost operations…
by controlling the residual reactance





…and graphing what happens in all three regions of operation makes for colorful plots



EMI is caused by harmonic content
Desense is caused by in-band noise *and* shielding

- Rectifier is main source of noise:
  - Fully-differential implementation
  - Notch/bandpass filter can be built-into rectifier
- The noise from rectifier is also re-broadcasted by the transmitter antenna. Need to kill that path!
- Coil Density Impacts Cellular (WWAN) antenna sensitivity
  - Copper and ferrite are excellent shields
  - 6.78MHz antenna → **-2dB**
  - 150KHz bed of coils and ferrite → **-12dB!**

Patent Application Publication

Jeong et al.

(10) Pub. No.: US 2017/0373538 A1

(43) Pub. Date: Dec. 28, 2017

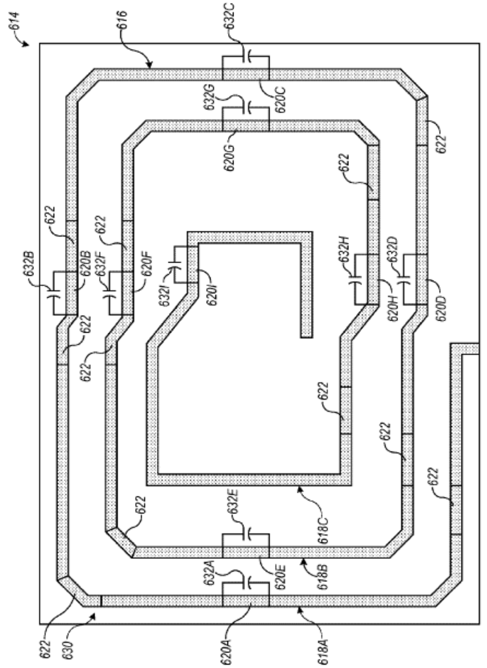


FIG. 6

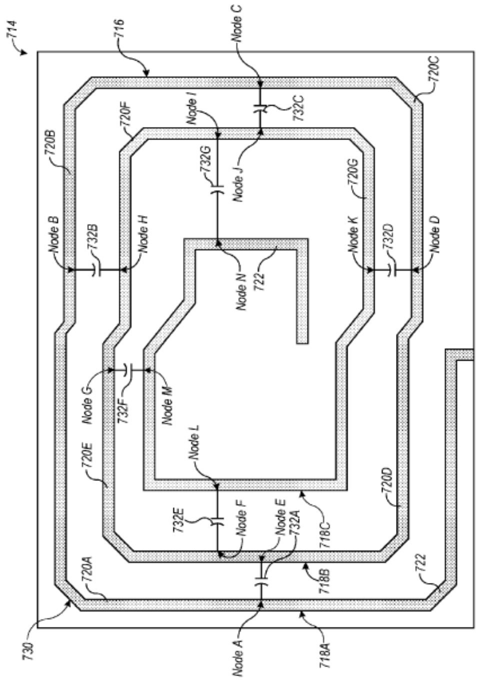


FIG. 7

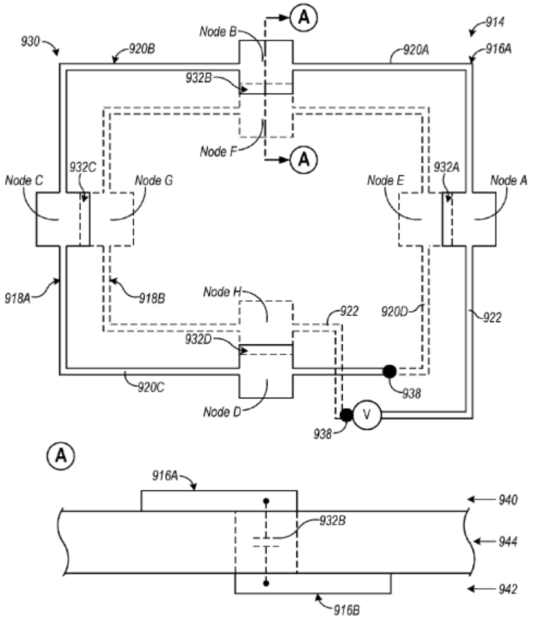


FIG. 9

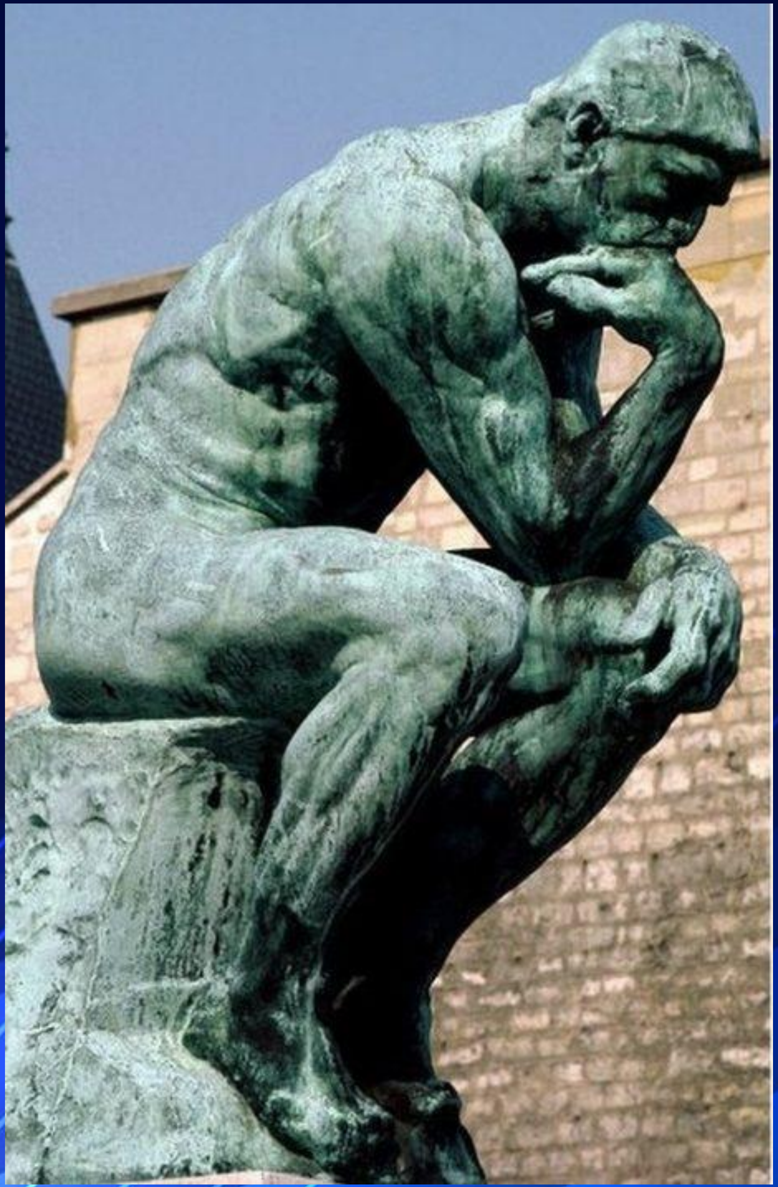
Notch Filter built into the antenna structure

Key concepts
Lessons (painfully) learned

- Frequency choice determines heat dissipated in metals: if you want to power differently sized objects in the same field, the frequency must be at least 1MHz
- Efficiency in the Receiver is more important than overall efficiency because of temperature limits: touch and battery.
- Operating "at resonance" is not important: tolerance of all components and operating conditions will not allow it anyway!

Key concepts (cont'd)
Lessons (painfully) learned

- What matters is optimizing end-to-end efficiency by analyzing Power flow from PA to Load and Reflected Impedance from Load to PA.
- System design must ensure that Power delivery and Power sharing by multiple loads is inherently achieved by the impedance behavior.
- Your life will be easier if you make everything differential (transmitter and receiver): common mode noise is the most difficult one to eliminate!



Questions?

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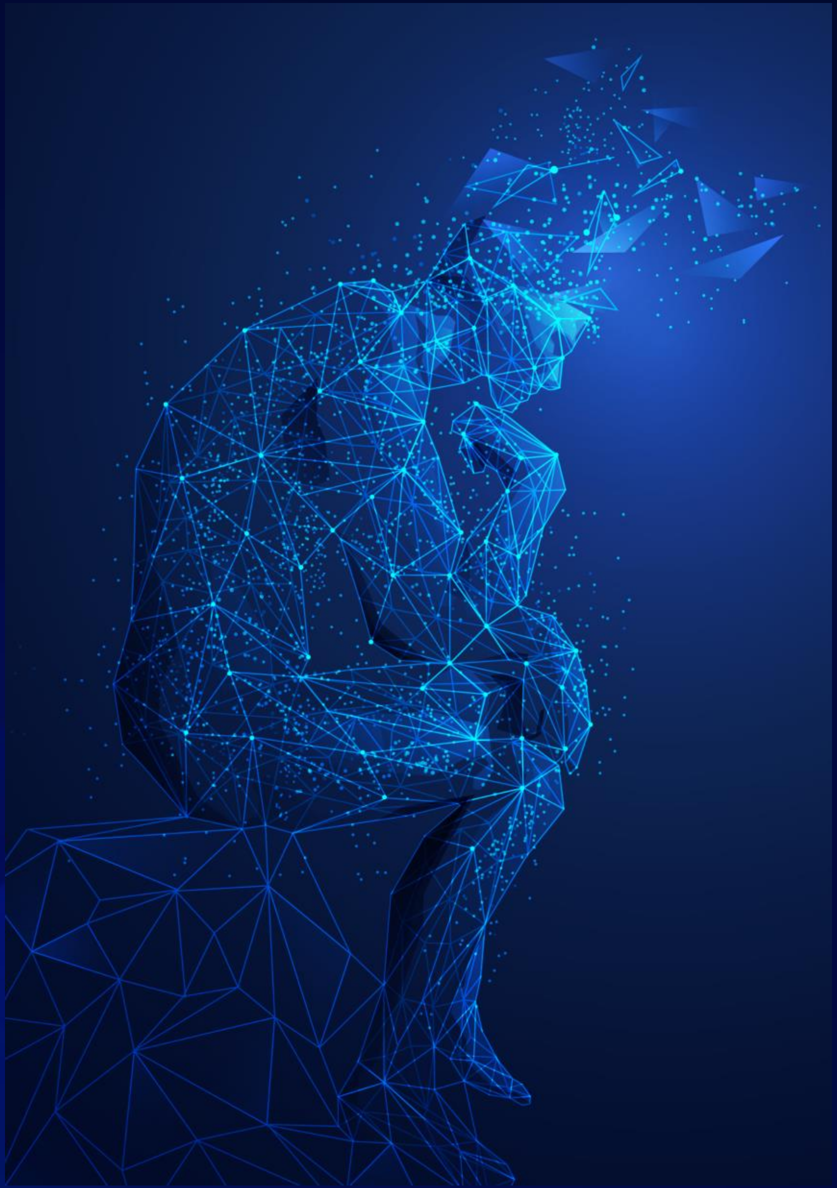

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