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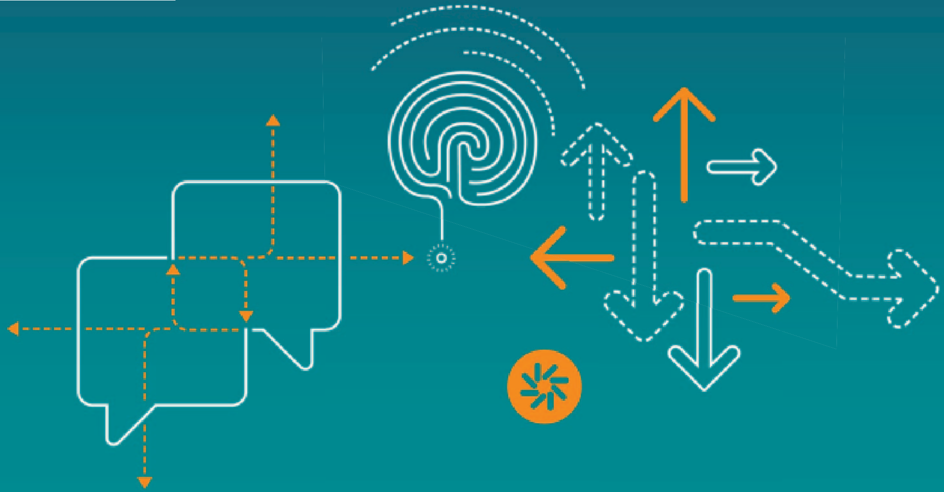
Resonant Wireless Power Transfer Technology & Integration Roadmap



Agenda

1. Introduction
2. Magnetic Resonant Wireless Power System
3. Standardization Requirements
4. Coexistence & Regulatory Requirements
5. Design Considerations
6. Integration Trends

Introduction

Life is Mobile

Wireless Charging

What Consumers Want and Care About

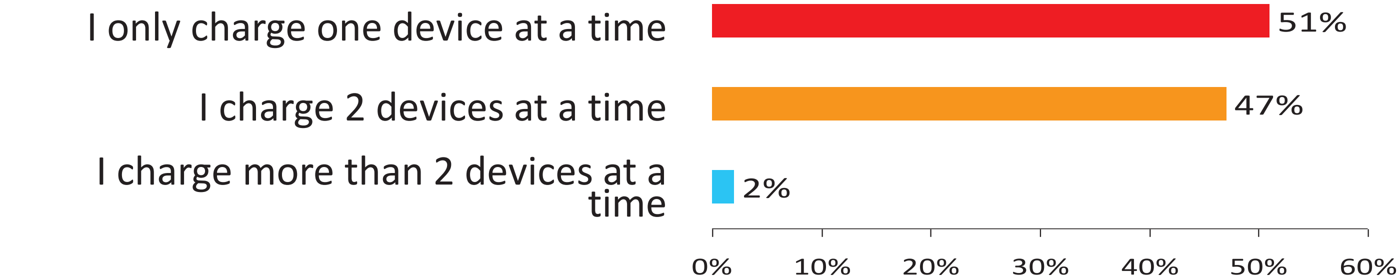
- Easy and convenient charging of *multiple devices*
- Colors, patterns & shapes that match décor
- Streamlined, *integrated device enablement*
- Cool, thin, portable and sleek designs
- *Works with portfolio of CE devices*
- True wireless charging experience
- *Ubiquitous charging locations*

- Consensus from the "Mobile" generation: freedom from cords
  - *Save time (ideally):* simultaneous charge of multiple devices
  - *Simplify:* fewer cords, one charger "fits all"
  - *Relax:* less hunting for the right cord or outlets

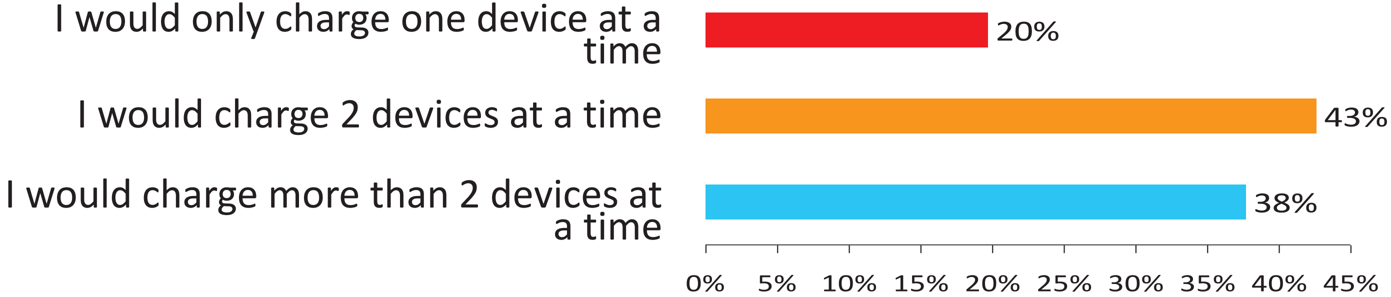
Consumers Want To Charge Multiple Devices

How many devices do/would you charge at the same time?

Current Users



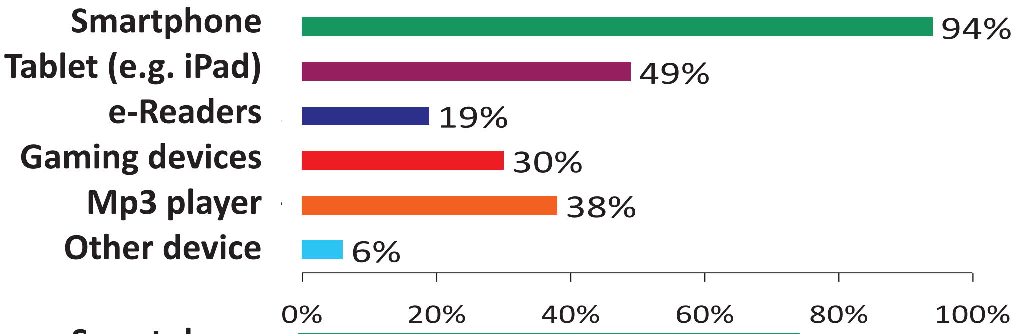
Intenders/ Rejecters



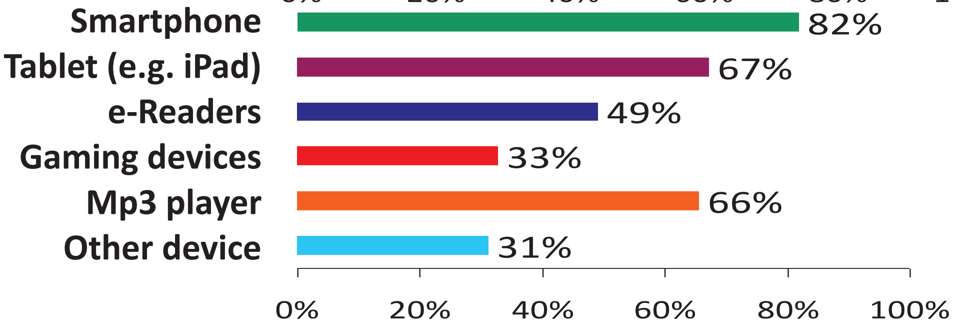
And They Want To Charge More Than Just Smartphones…

Which type of device(s) do you currently/would you intend to charge with your wireless charger?

Current Users



Intenders/Rejecters



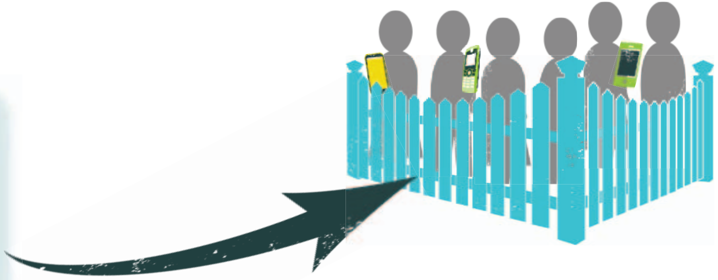
Strong Consensus

Motivation to adopt wireless charging

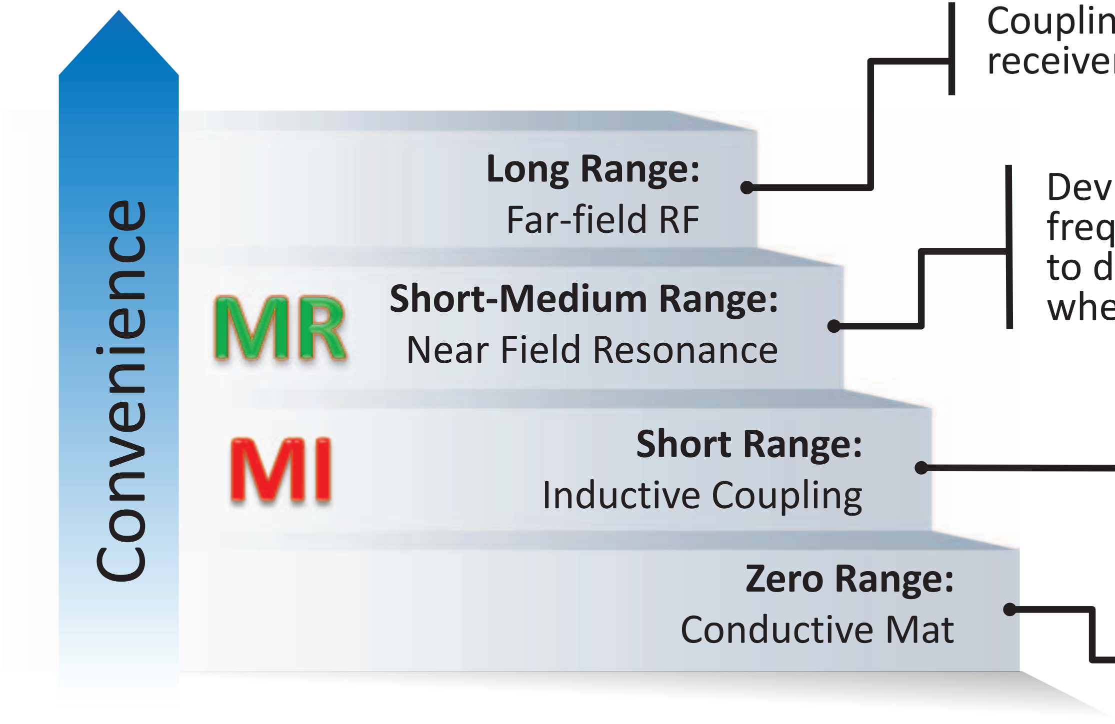
- Portability: charging devices when away from home
- Multiple device charging and charging beyond Smartphones
- Adaptive to multiple devices (phones, tablets, handheld game)
- Fast charge time; aesthetically appealing to blend in with home décor
- Flexible device placement and charge range

Implication

Current wireless charging systems are not keeping pace with consumers' growing needs to charge many portable devices



Wireless Charging Landscape



Coupling of RF energy to a device with a small receiver antenna with device in the RF far field

Device is brought within near field of a low frequency Tx antenna. RF energy couples to device with small receive antenna where it is rectified for device charging

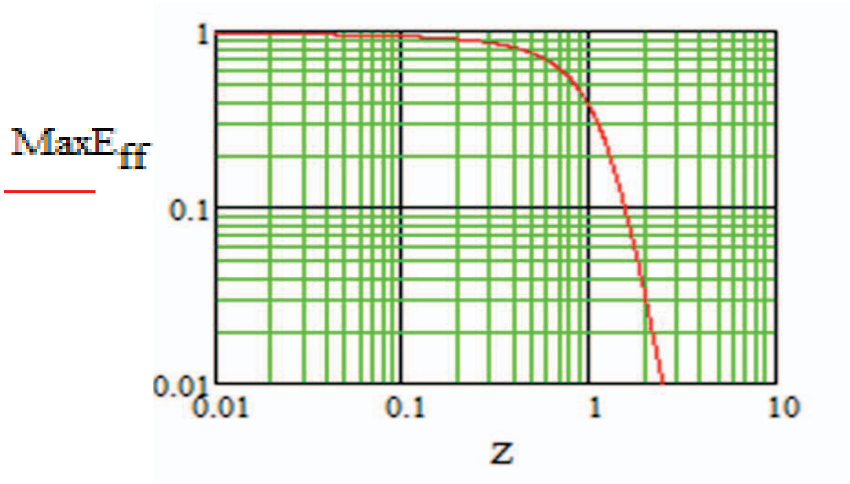
Coupling of RF energy when a device with a small receive antenna is placed on a “charging surface” containing the transmit elements

Current flows through the pad to a conductive adapter in the device

Near Field vs Far Field

Near field offers significant advantages to efficient power transfer

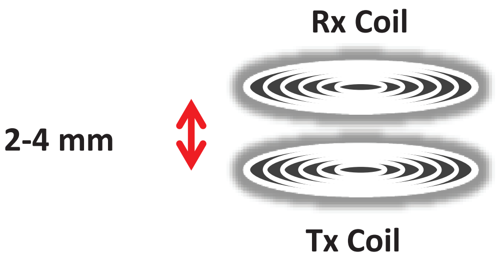
- **Near field: ~linear decrease in energy**
  - Near the TX pad, minimal reduction in coupling with Z-distance increase
  - On large pads small devices have highest Z freedom, but also lowest coupling
- **Far field: energy decreases with (distance)^2**
  - Amplitude decreases linearly with distance, thus areal energy decreases with (distance)^2
  - Far field systems are typically very low power



Max Power Transfer Efficiency of two loops vs spacing between them (Z distance relative to coil diameter)

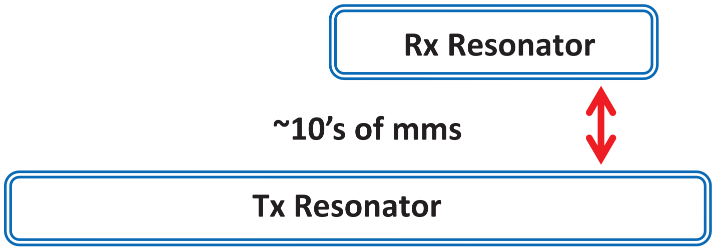
Magnetic Induction (Tight Coupling) vs Magnetic Resonance

Key Distinctions – Size, Separation and Orientation



Magnetic Induction (Coupling Coefficient K is close to 1)

- Tx and Rx coils generally: have a 1:1 ratio, are closely matched in size and shape, are in close proximity, and utilize magnets or other mechanism to maintain precise alignment

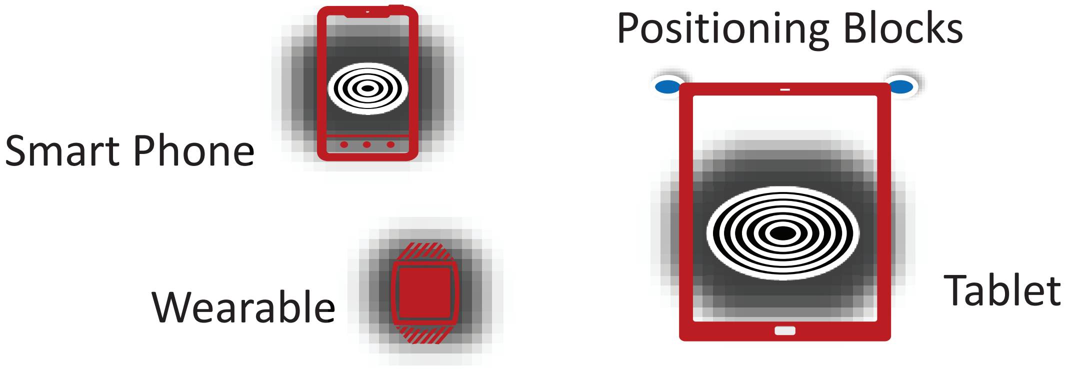


Magnetic Resonance (K<<1)

- Tx antennas are designed to: create a CHARGING FIELD, require no precise alignment, and allow devices to be separated by 10's mm
- Frequency choice >1MHz allows for presence of metal objects

Freedom of Placement

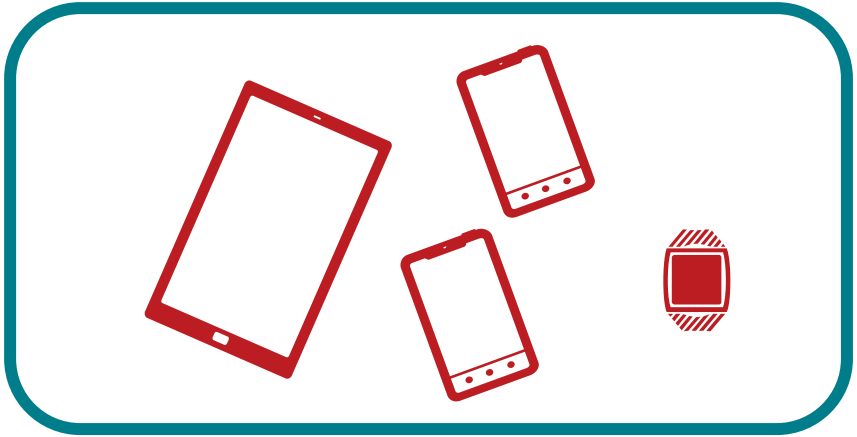
Magnetic Induction



- Many tightly coupled solutions utilize positioning devices, such as magnets or physical constraints such as blocks or ‘posts’ to insure alignment.
- One cannot place a BT Headset on the tablet charging spot, and cannot place the tablet on the smart phone spot and expect them to charge. Wearable devices cannot easily be placed on a flat charging surface.

Freedom of Placement

Magnetic Resonance

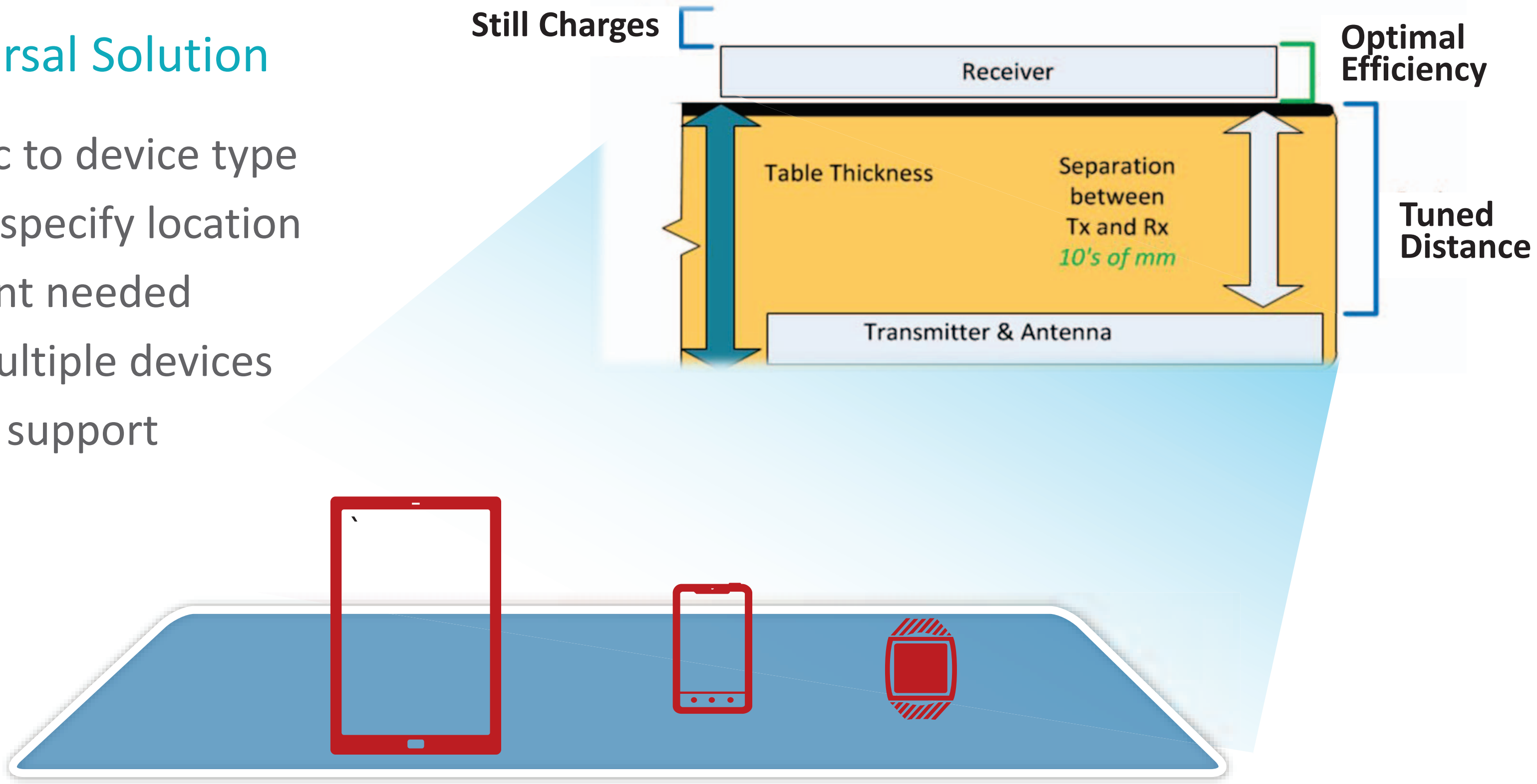


- Magnetic Resonant solutions do NOT require any alignment of devices
- One transmitter ‘field’ can charge wearables, smart phones, & tablets.

Magnetic Resonance

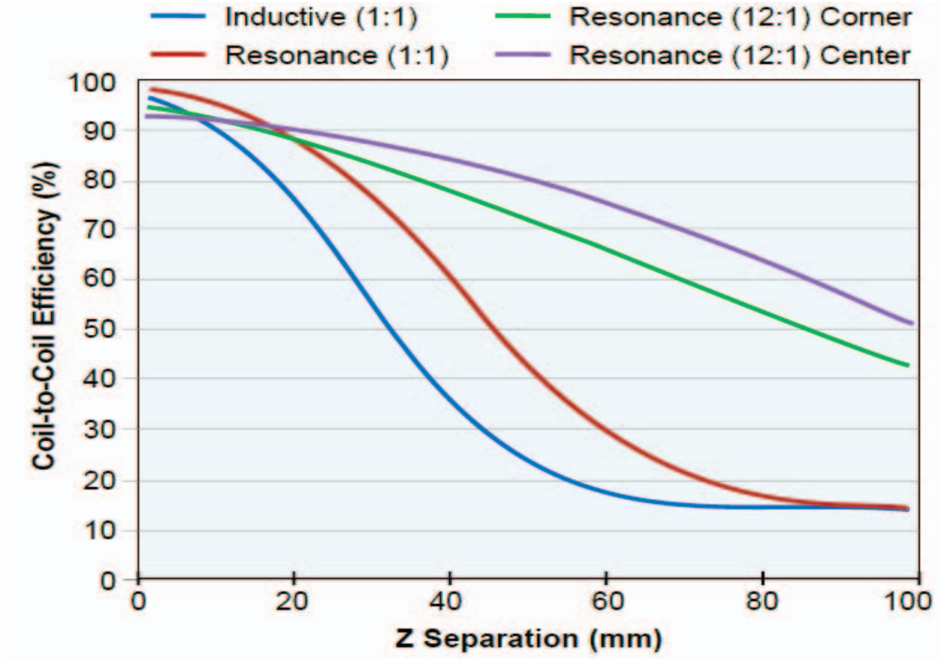
A Truly Universal Solution

- NOT specific to device type
- No need to specify location
- No alignment needed
- Supports multiple devices
- High power support



Wireless-Charging Efficiency

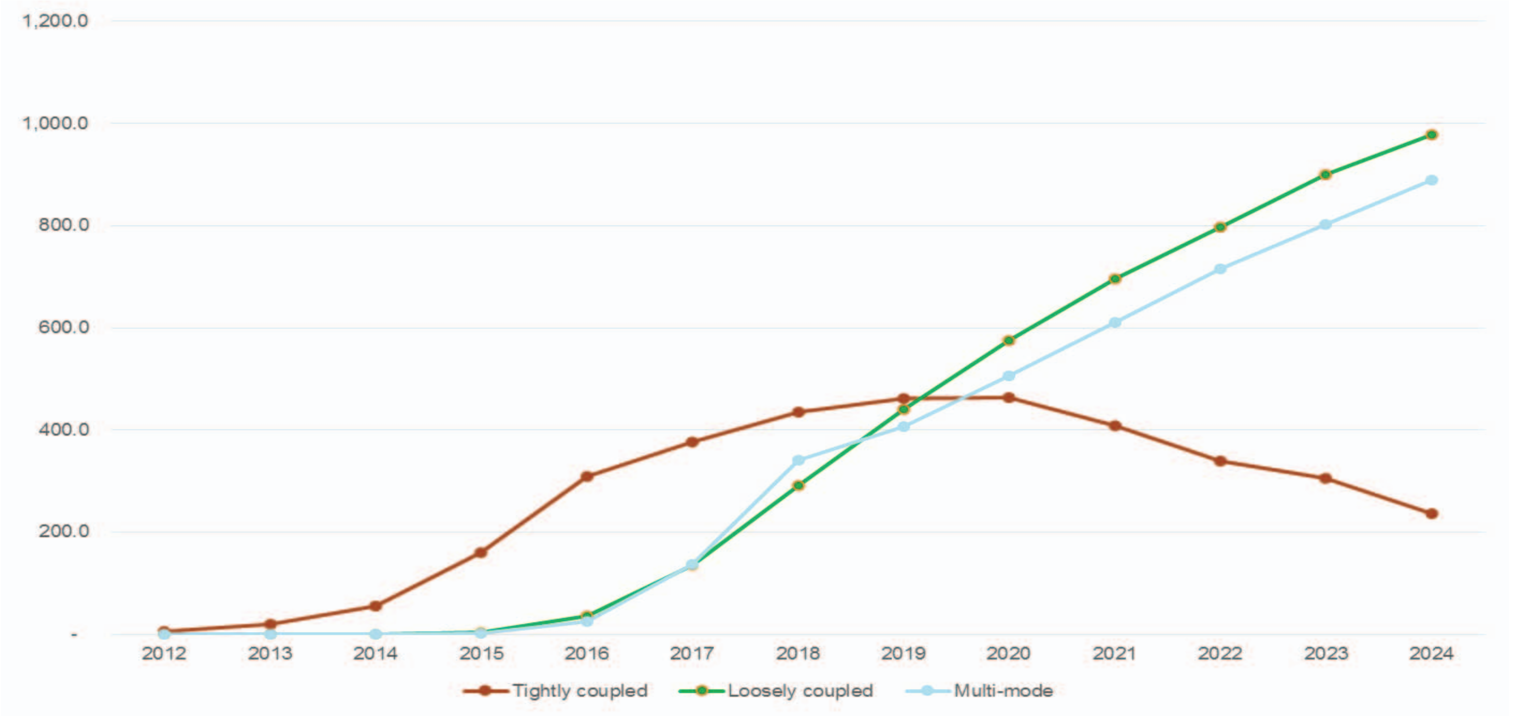
- At close range, coil-to-coil efficiency (power transfer across the air gap) is greater than 90% for both tightly and loosely coupled systems.



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)

Total Wireless Charging Market

Technology Adoption – Resonant vs. Tightly Coupled



Source: IHS Research Feb.15

Magnetic Resonant Wireless Power System – Basic Concepts

The Field Perspective

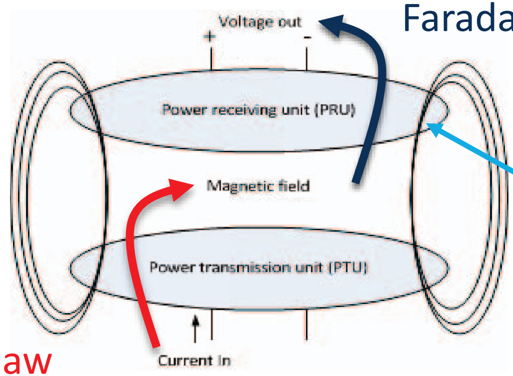
	Integral form	Differential Form
Gauss's Law	$\oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega} \rho\, dV$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's Law of Magnetism	$\oiint_{\partial\Omega} \mathbf{B}\cdot d\mathbf{S} = 0$	$\nabla\cdot\mathbf{B}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

$$V = \oint \boldsymbol{E}\cdot d\boldsymbol{l} = i\omega\mu_0 \int H\cdot da$$

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.

$$\boxed{\int \mathrm{H\, dl} = \mathrm{NI}}$$

Ampere's law



Faraday's law

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

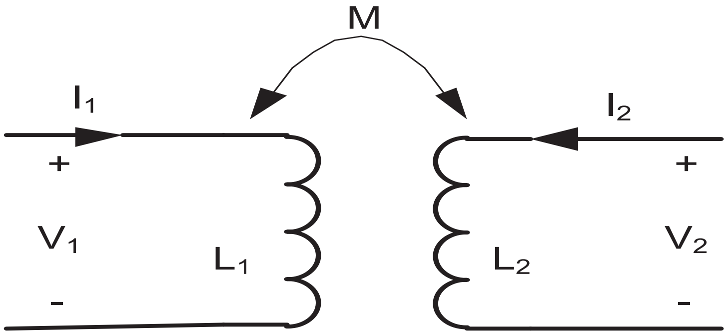
N: RX coil turns
A: RX area
Φ: Flux through coil area

Magnetic Coupling Details

- Induced voltage is proportional to B field
  - H field is magnetizing field, created by Itx
  - B field is magnetic flux density, created by H * (μ/μ_0)
  - Flexibility: modify μ (permeability) to modify voltage
- Without resonance, power transfer is determined largely by area ratios A_{TX}/A_{RX}
- With resonance, field density is much higher in receive coil area
  - Resonance effectively concentrates flux, increases coupling, thus generating higher voltages
  - Problem: resonance causes complex loads
- Good coupling → Receiver impedance reflected to transmitter → Challenges and opportunities for the control of power delivery

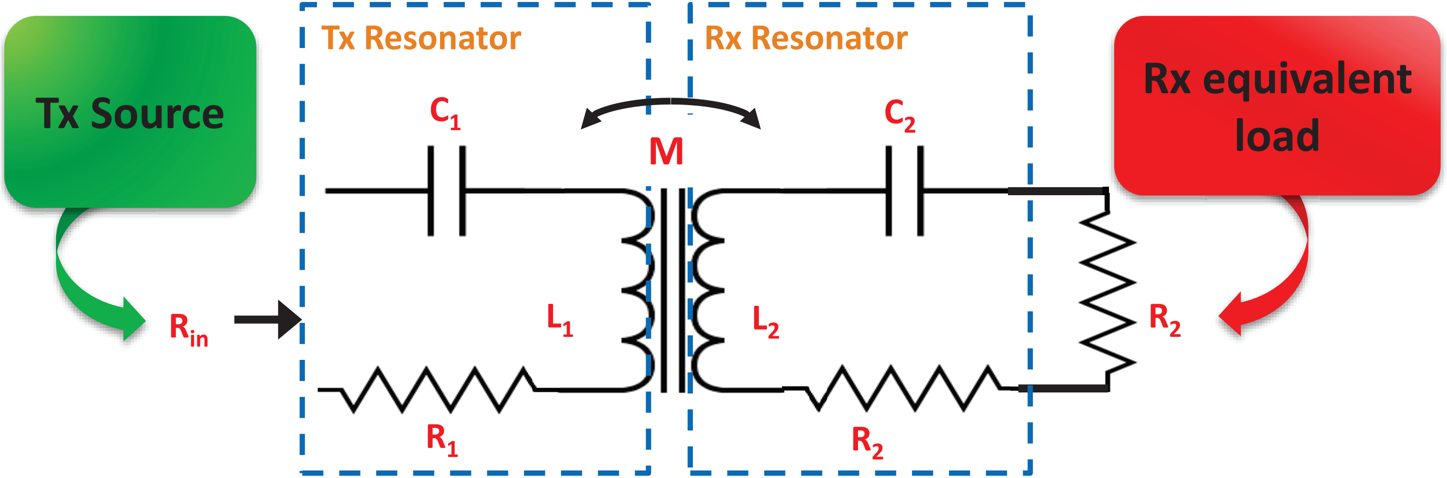
The Circuit Perspective

Mutual Inductance



- The wireless power transfer system can be simply described by the two-port network system:
  - $V_1 = Z_{11}I_1 + Z_{12}I_2$
  - $V_2 = Z_{21}I_1 + Z_{22}I_2$
- For a pair of closely coupled lossless coils, the equations can be further transformed to
  - $V_1 = i\omega L_1 I_1 + i\omega M I_2$
  - $V_2 = i\omega M I_1 + i\omega L_2 I_2$

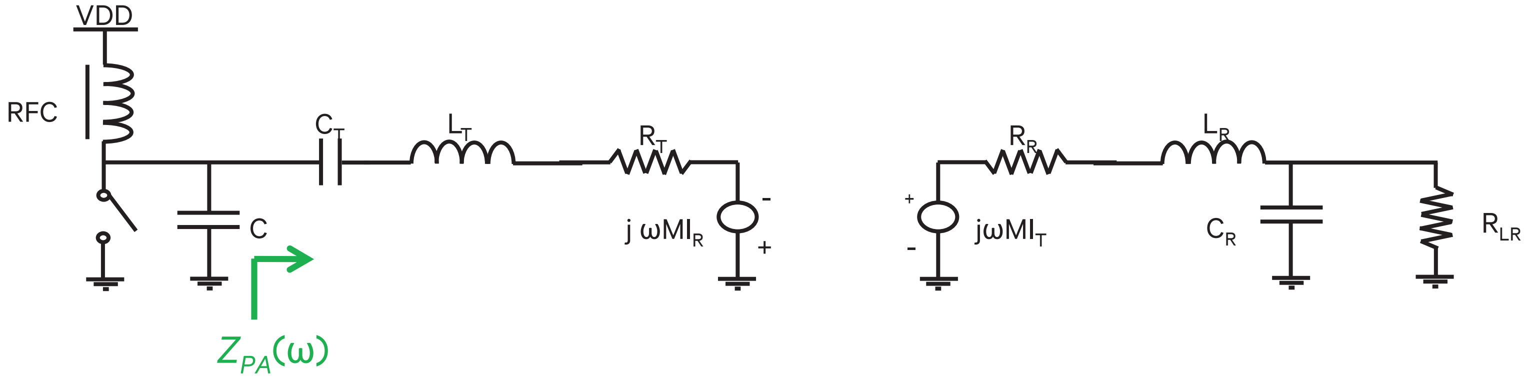
System Description – Key Parameters



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

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

Example: Resonance in a Series/Shunt Configuration



$$Z_{PA}(\omega) = R_T + jX_T + \frac{\omega^2 M^2}{R_R + j\omega L_R + \dfrac{R_{LR}}{1 + j\omega C_R R_{LR}}}$$

$$\omega_0 = \sqrt{\frac{1}{L_R C_R} - \frac{1}{R_{LR}^2 C_R^2}}$$

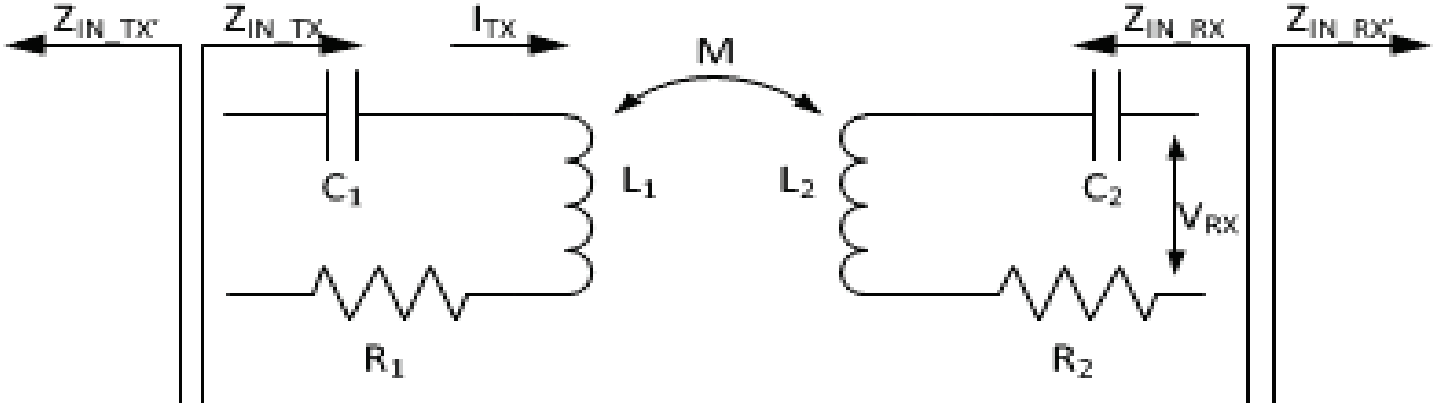
Resonant condition is a function of load
Multiple receivers condition further complicates the system description

When both Tx and Rx are series-resonant…

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

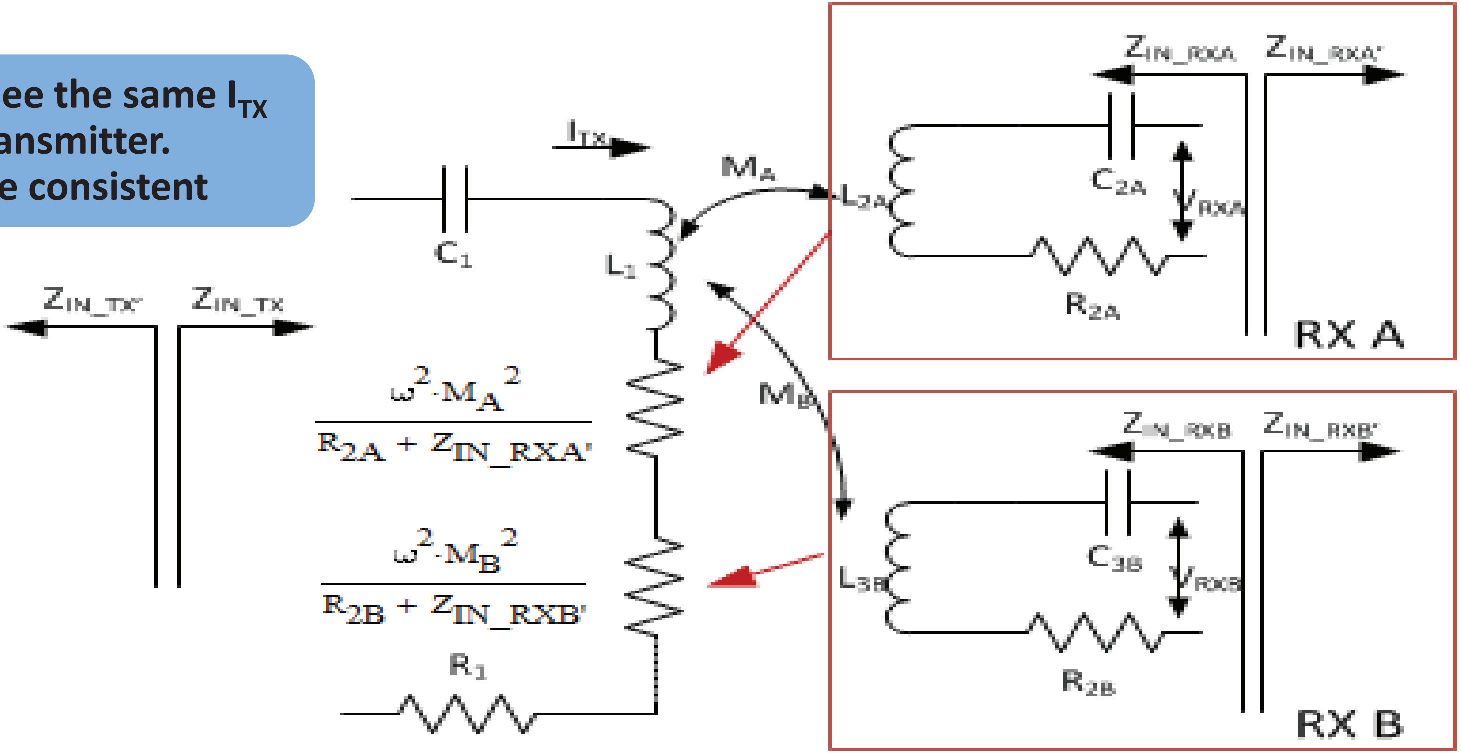
$$Z_{IN\_TX} = R_1 + \frac{\omega^2 \cdot M^2}{R_2 + Z_{IN\_RX'}}$$

Receiver load resistance is inverted on the Transmitter side!



Multiple Receiver devices add in series on the Transmitter side

All Receivers see the same I_{TX} in the Transmitter.
M_N must be consistent



Standardization Requirements

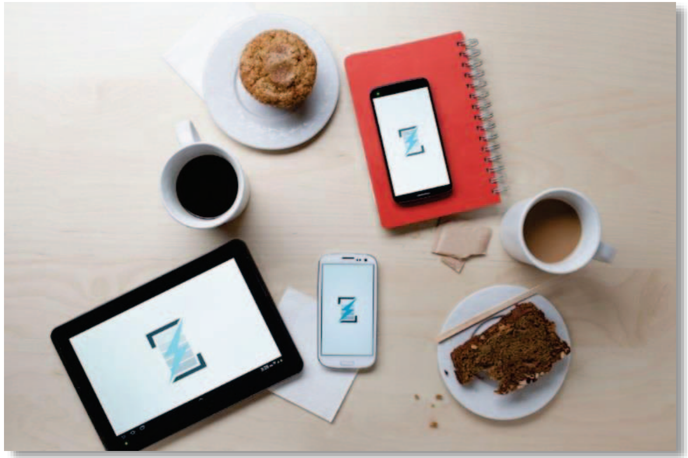
rezence

Alliance for Wireless Power

Alliance for Wireless Power

rezence
Alliance for Wireless Power

- Qualcomm Inc. co-founded in 2012
- Certified products entering the market in 2015
- Rapid member growth, over 180 today, including
  - Carriers, OEMs, consumer devices, components, furniture, automotive and more
- A4WP and PMA merger consolidates the standards landscape

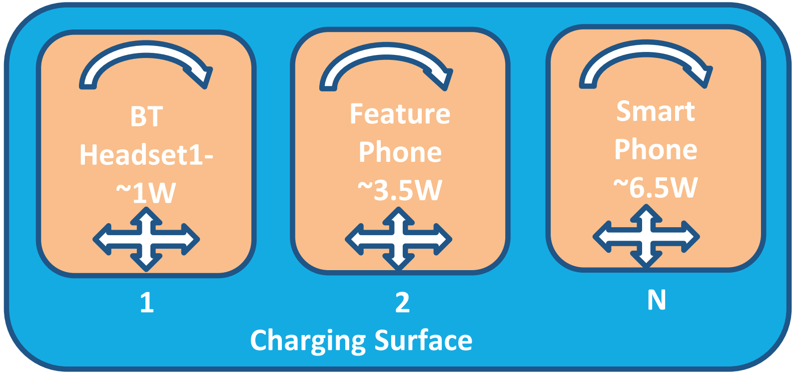


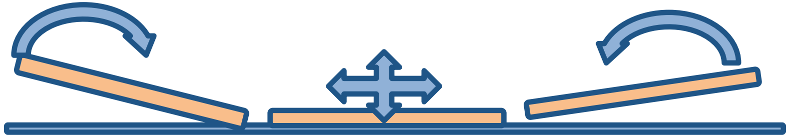
Advantages of A4WP Technology

"Bowl" design:
throw all devices to be charged in the bowl

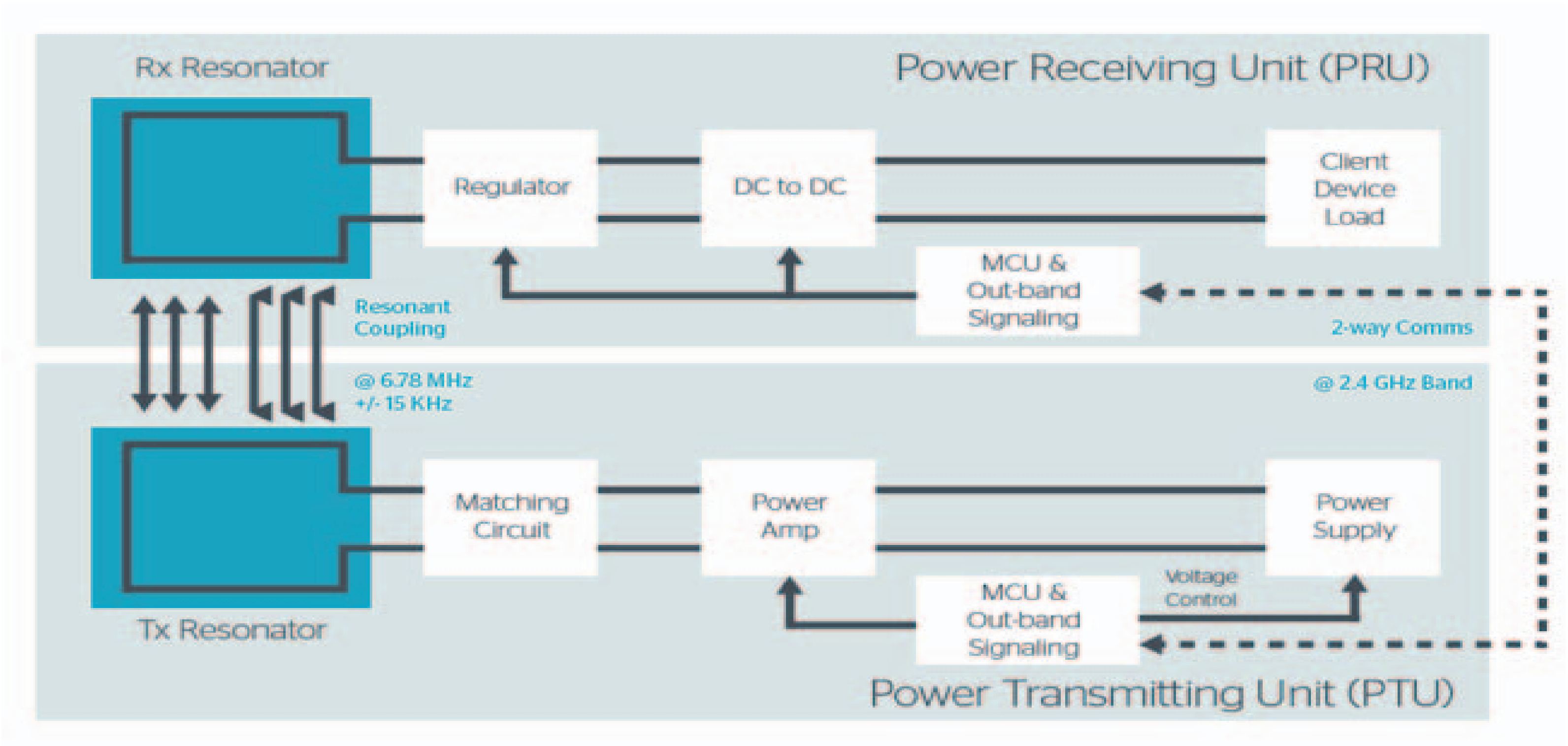
WPT user experience

- Spatial freedom as simultaneous charging of multiple devices in a "drop & go" experience
- Horizontal, vertical and angular position tolerance (mm-cm)



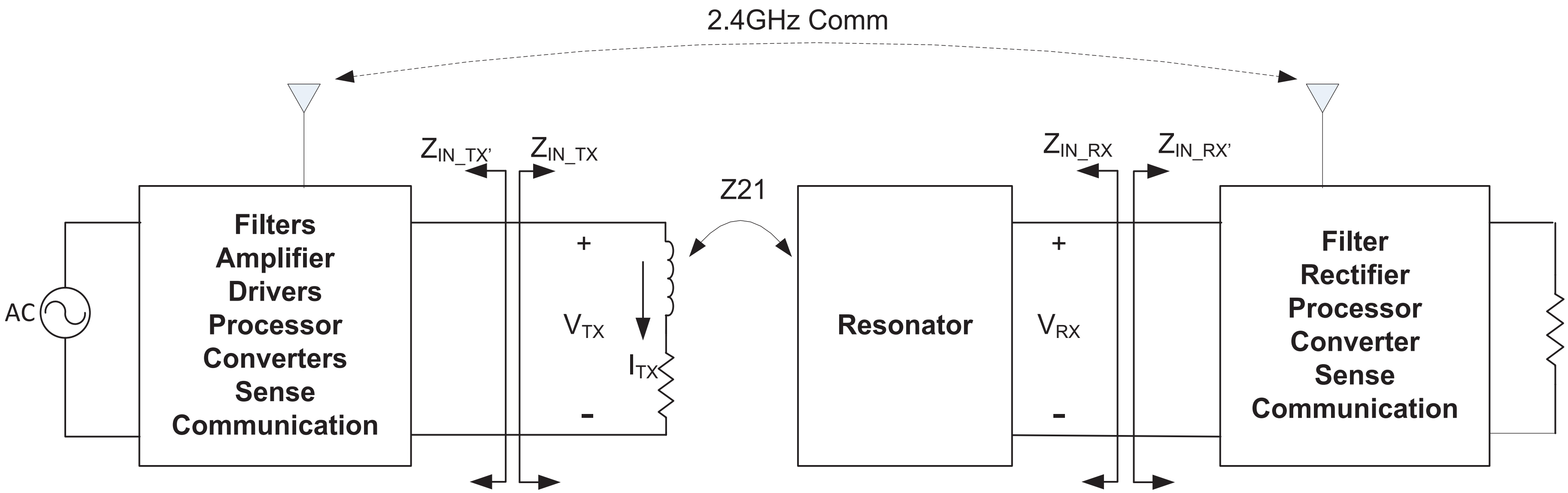


A4WP System Block Diagram



Only Key Interfaces Are Constrained

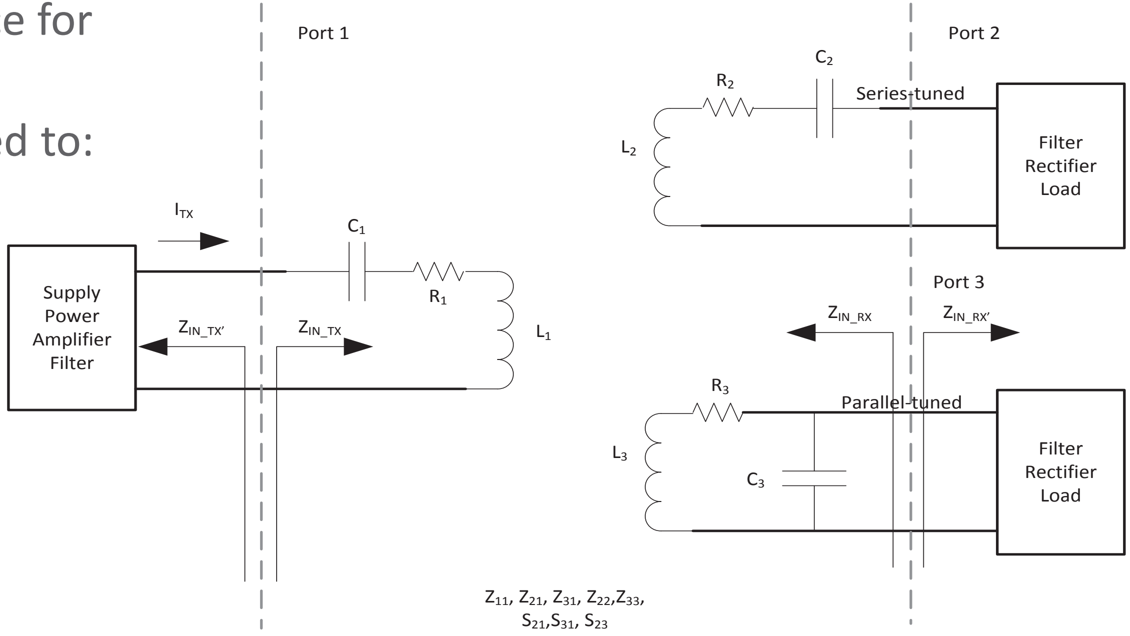
Many opportunities for innovation and differentiation



Power Transfer Specifications

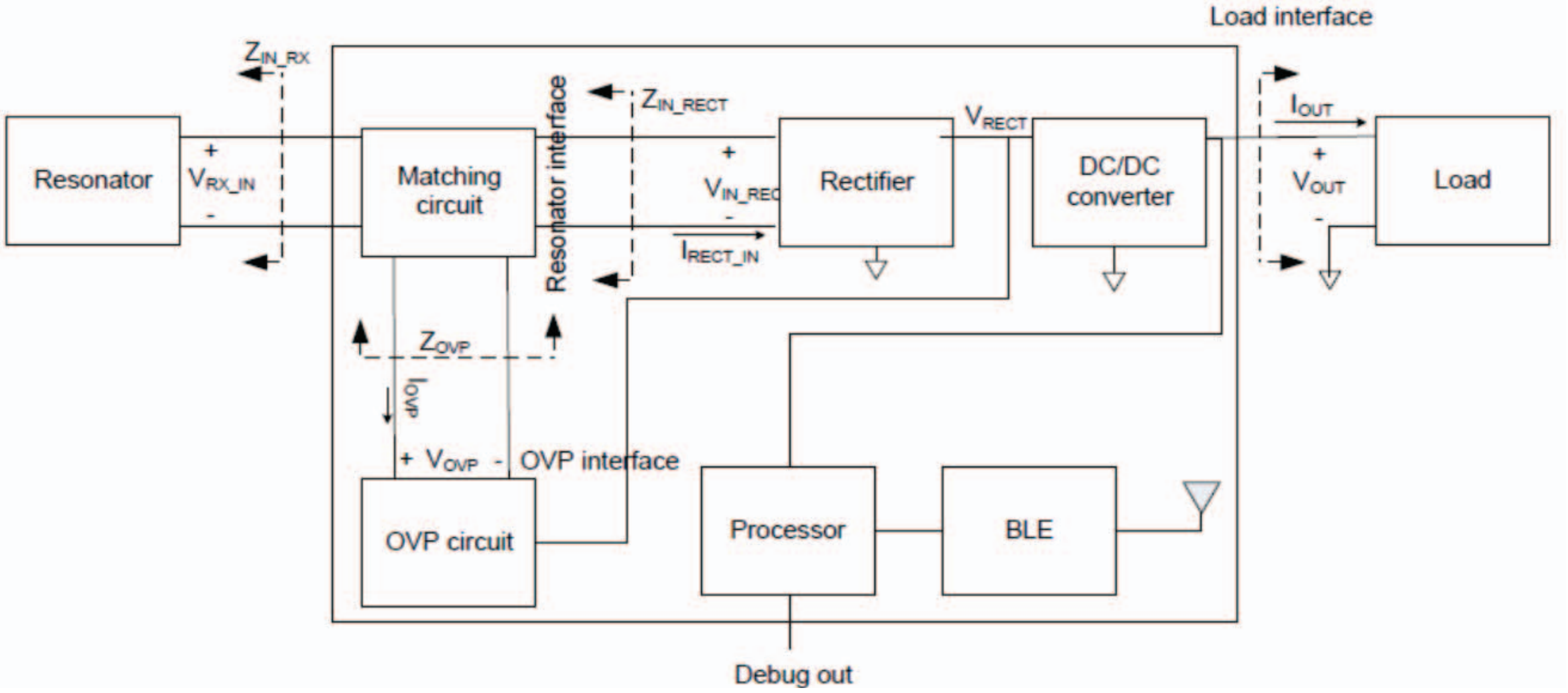
Interoperability parameters and measurement points

- PTU and PRU physical interface for power transfer.
- The requirements are designed to:
  - Support concurrent multi-device charging
  - Ensure stability by minimizing reliance on the control system
  - Provide approved PTU resonator designs



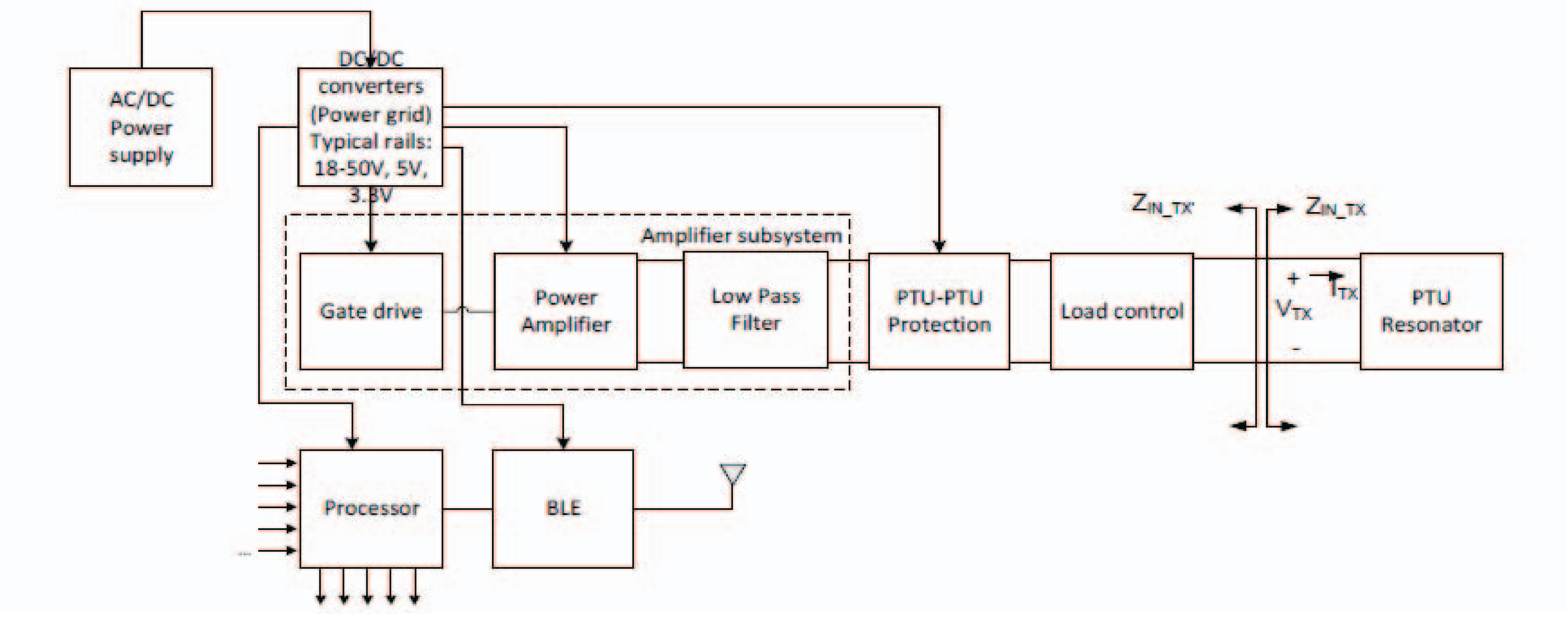
Power Receiving Unit (PRU)

A4WP does not specify implementation details



Power Transmitting Unit (PTU)

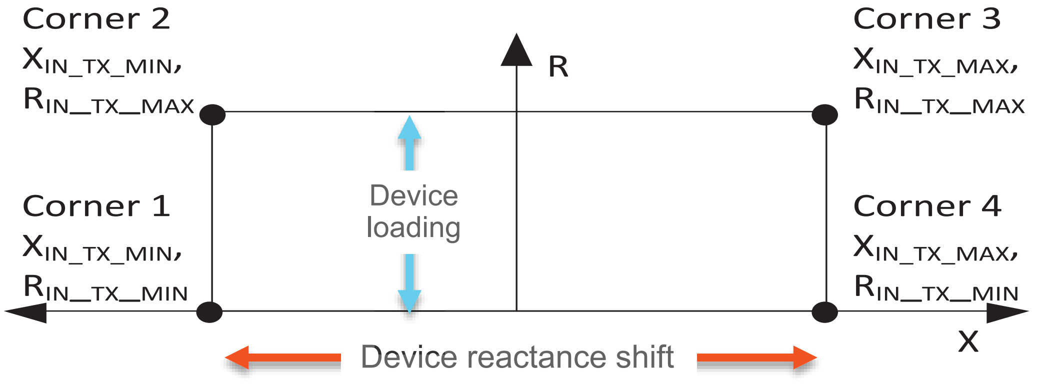
A4WP does not specify implementation details



PTU Resonator Requirements

PTU amplifier must meet impedance requirements across a wide range of chargeable devices

- Resonator coupling efficiency limits are established
- Current levels injected into PTU resonator are defined:
  - ITX_MIN
  - ITX_NOMINAL
  - ITX_ABS_MAX
- Source impedance at PTU resonator interface is defined
- PTU Resonator impedance interface is defined
- PRU load reflected to PTU resonator interface is defined



Coexistence & Regulatory Requirements

Coexistence: Reference Specifications

Applications	TIS[1] Specs for Phone by Carriers	TIS Specs by UE Vendors or Std	OEM Specs for Degradation by Accessory	Derived Min TIS Due to Interference by WiPower	Source Docs
CDMA 850	Spec. Provided		Spec. Provided	Spec. Provided	Carrier specs
CDMA 1900	Spec. Provided		Spec. Provided	Spec. Provided	Carrier specs
GSM 850	Spec. Provided	Spec. Provided	Spec. Provided	Spec. Provided	Carrier specs
GSM 900	Spec. Provided	Spec. Provided	Spec. Provided	Spec. Provided	3GPP TSG RAN WG4-#52
GSM 800/1900	Spec. Provided	Spec. Provided	Spec. Provided	Spec. Provided	
UMTS 2100	Spec. Provided	Spec. Provided	Spec. Provided	Spec. Provided	GSMA SE.43 v3.0
GPS	Spec. Provided				OEM accessory specs
WLAN		Spec. Provided, based on data rate			802.11x standard
BT		Spec. Provided			BT RF Specs

[1] TIS = Total isotropic sensitivity (average over the whole sphere)

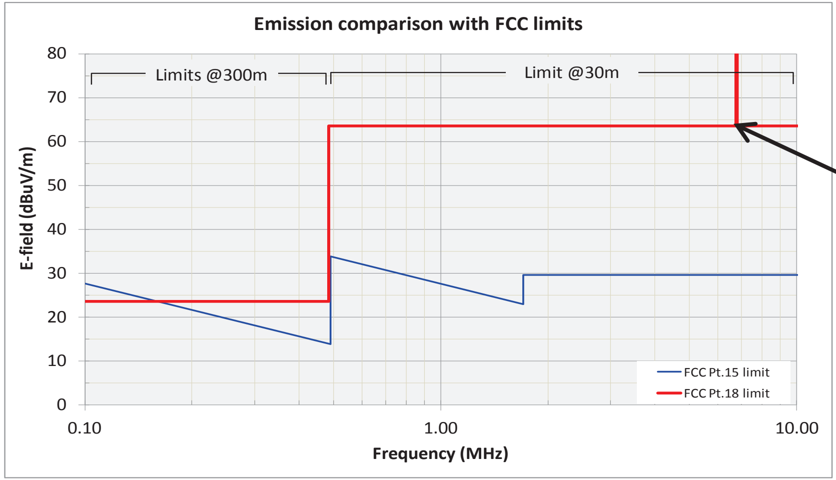
Managing RF Coexistence

There are more than 10 radios in a Smartphone!

- NFC: although both transmissions cannot occur at the same time, implementations can use the same antenna for both systems via appropriate matching networks.
- WWAN and WLAN: well known procedures are utilized. Link budgets are analyzed and coexistence is ensured by appropriately positioning antennas and tuning the filters. The small amount of metal in the TX minimizes issues.
- Bluetooth: in integrated solutions, the same BT HW is used by adding a dedicated profile for Wireless Power Transfer, which has been created by the Bluetooth SIG.
- GPS: there are no special requirements (besides typical care on antenna placement). Often, the TX antenna acts as a reflector thus improving GPS sensitivity.

Regulatory (Emission)

Applicable Requirements



Part 18 ISM limit allows unrestricted emissions at ISM* frequency (6.78MHz shown)

*ISM: Industrial Scientific and Medical

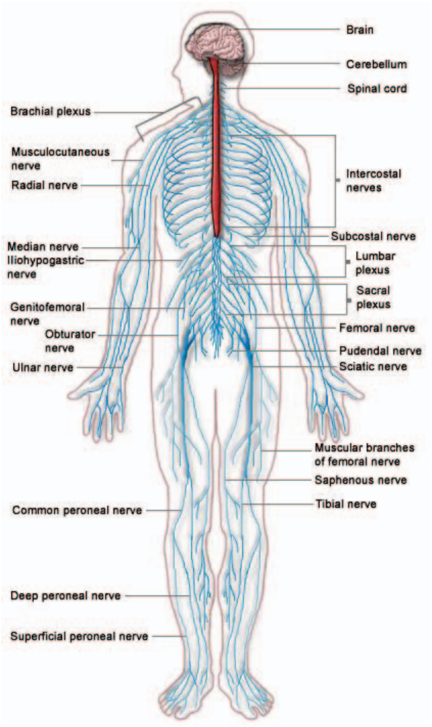
- The fundamental operating frequency and the signal characteristics determine the regulatory categorization
  - In the US wireless power can fall into the category of ISM* equipment under Part 18 and/or intentional radiators under Part 15 of the FCC rules, thus operating frequency is critical

Regulatory (Safety)

Applicable Requirements (continued)

- RF Exposure Requirements for WPT systems
  - All wireless charging systems should be assessed in accordance with “Basic Restrictions” specified in ICNIRP* 1998/ICNIRP 2010 as well as FCC requirements.
- Restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields that are based directly on established health effects are termed “Basic Restrictions.”
- Depending upon the frequency of the field, the physical quantities used to specify these restrictions are current density (J), specific energy absorption rate (SAR), and induced electric field (E).

*** International Committee for Non Ionizing Radiation Protection. ICNIRP is the International recognized body that sets guidelines for protection against adverse health effects of non-ionizing radiation.**



Regulatory Requirements for Charging Function at 6.78 MHz

No.	Requirement	US	Canada	EU
1	6.78 MHz ISM alloc.	FCC Pt.18	ICES-001-V4 (CISPR11) RSS-216	EN55011
2	EMC emissions [1], [2]	FCC Pt.18 FCC KDB 680106	ICES-001-V4 (CISPR11) RSS-216	EN55011
3	EMC immunity [3]	N/A	N/A	EN61000-6-1
4	RF exposure by simulation [4]	FCC Pt.1/2 FCC KDB 680106	RSS-102-V4	EN62311 (ICNIRP)
5	Product safety	UL60950	CSA 60950-1	EN60950
6	WEEE/ROHS/REACH	Yes	Yes	Yes
7	Certification type	DoC	DoC	DoC

EUT setup note:
[1] Use dummy PRU loads to qualify PTU emission
[2] Use a clean PTU to qualify emission from a PRU (iPhone sleeve or USB dongle)
[3] Use the standard system configuration (PTU and PRU) to qualify system immunity for both WPT and BT
[4] RF exposure will be assessed by simulation approach against basic limit if the reference limit can not be met

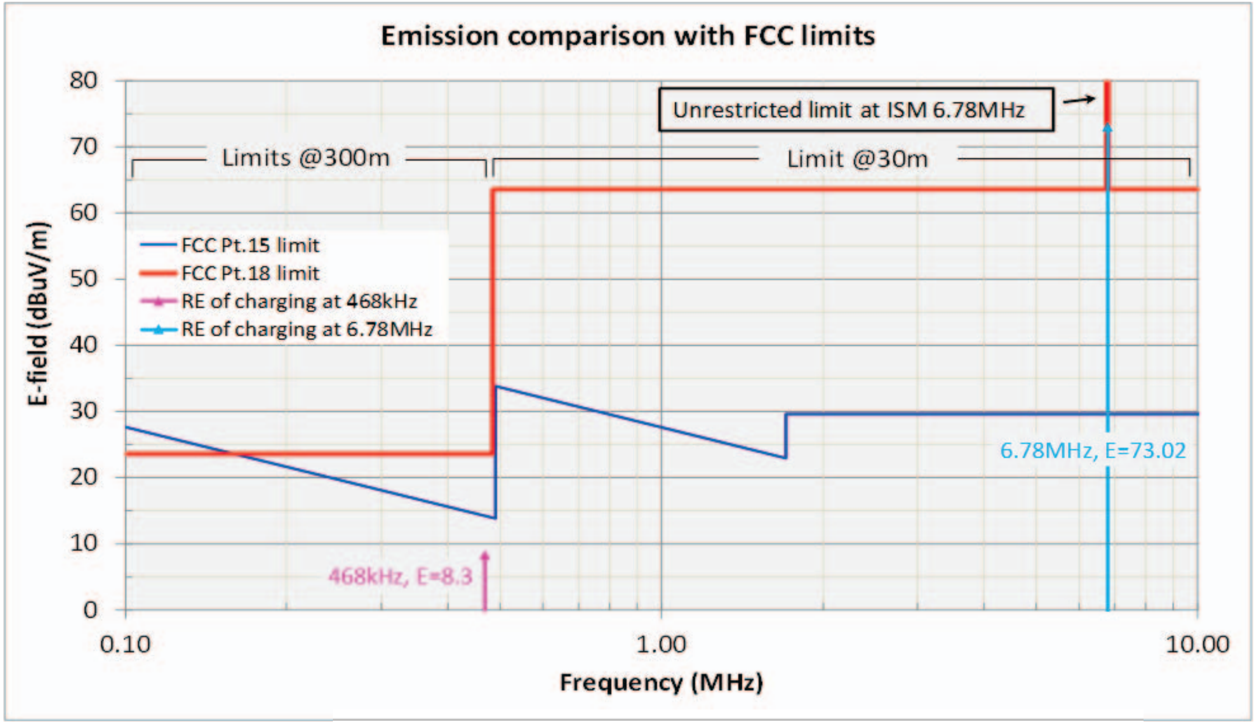
Regulatory Requirements for BT Communication at 2.4 GHz

No.	Requirement	US	Canada	EU
1	Radio spectrum emissions	Part 15.247	RSS-210-V8	EN 300 328
2	EMC Emissions [1], [2]	FCC Pt.18	RSS-210-V8	EN301 489-1/-17
3	EMC immunities [2]	N/A	N/A	EN301 489-1/-17
4	RF exposure	FCC Pt.1/2	RSS-102-V4	EN62311 (ICNIRP)
5	Product safety	UL60950	CSA 60950-1	EN60950
6	WEEE/ROHS/REACH	N/A	N/A	Yes
7	Certification type	FCC ID Cert	IC ID Cert	DoC

EUT setup note:
[1] BT emission under operational mode can be assessed under system charging platform (PTU and a PRU)
[2] BT emission from PTU can be tested with dummy PRU load (w/o BT)
[3] Use the standard system configuration (PTU and PRU) to qualify system immunity for both WPT and BT
[4] RF exposure assessment can be assessed by EIRP measurement and assessment

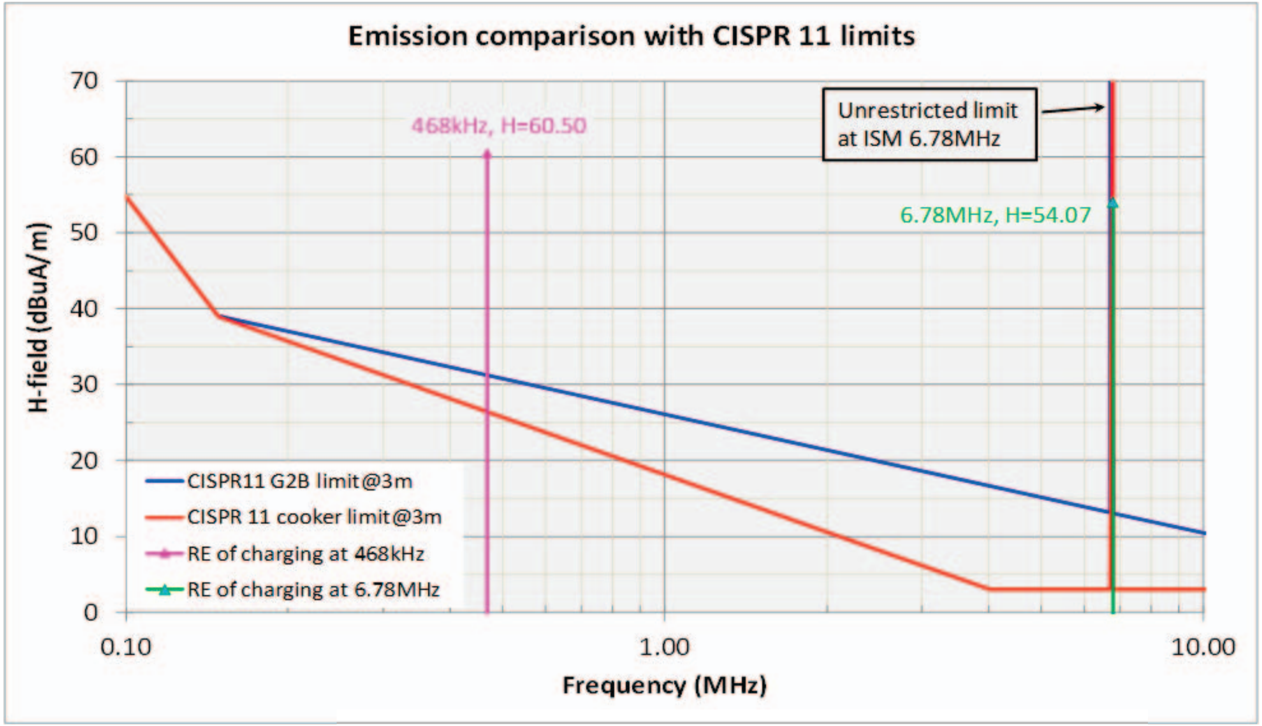
Radiated Emissions Assessment per FCC Pt.15/18 US Limits

Comparison of 6.78MHz and 468KHz



Radiated Emissions Assessment per CISPR 11

Comparison of 6.78MHz and 468KHz



Human Exposure Limits

RF Exposure Limits for General Population (100 Khz–10 Mhz)

	SAR [W/kg] (Whole Body Average)	**SAR [W/kg]** (Head/Trunk)	**SAR [W/kg]** (Limbs)	**Induced E** (2x2x2 mm3-avg) [V/m] (CNS and PNS)	**Induced J** (1 cm^2 - avg) [mA/m^2] (Head/Trunk)
ICNIRP 1998	0.08	2 (10-g)	4 (10-g)	–	f/500
ICNIRP 2010	0.08	2 (10-g)	4 (10-g)	1.35×10^{-4} f	–
FCC	0.08	1.6 (1-g)	4 (10-g)	–	–

Note: f is in Hz

- FCC[1] limit of 1.6 W/kg on 1g SAR[2] to prevent tissue heating for f > 100 kHz
- ICNIRP[3] 1998 and 2010 standards for induced current density (J) and induced electric field (E) between 1 Hz and 10 MHz to prevent nerve stimulation in both central and peripheral nervous systems (CNS and PNS)
  - 2010 standard specifies the E limits for both CNS and PNS
  - 1998 standard was based on effects seen in CNS from biological studies but specifies the induced J limits for all tissues in head and trunk regions
- As of today, ICNIRP 2010 standard has not been adopted by regulatory bodies. Hence, human exposure should be qualified for all exposure quantities in 100 kHz to 10 MHz frequency range

[1] Federal Communications Committee
[2] Specific Absorption Rate
[3] International Commission on Non-Ionizing Radiation Protection

RF Exposure Estimation in Typical Usage Scenarios

Home/office environment

Simulation model 1

- Duke sitting with Qualcomm® WiPower™ embedded in center or corner
- Hands resting on the table (25 mm separation distance above Tx)

Simulation model 2

- Duke sleeping with WiPower at center of table
- Cheek resting on the top surface of 25 mm-thick table

Simulation model 3

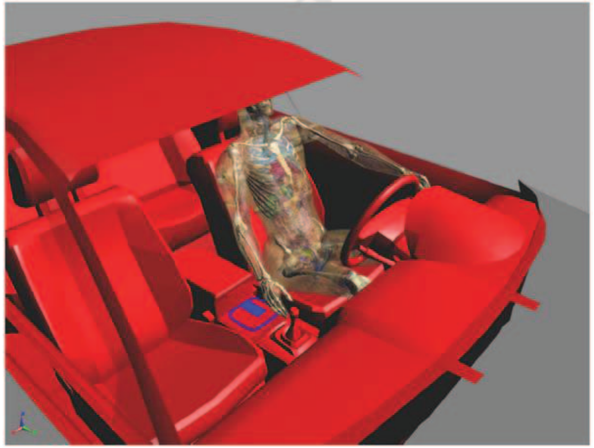
- Duke Standing along X and Y sides of WiPower module embedded in the corner of table
- 50 mm separation distance

- Duke anatomical model was evaluated for the typical usage scenarios
- Table dimensions: Height = 740mm, Thickness of the top surface = 25mm

Qualcomm WiPower is a product of Qualcomm Technologies, Inc.“

RF Exposure Estimation in Typical Usage Scenarios

Automotive environment

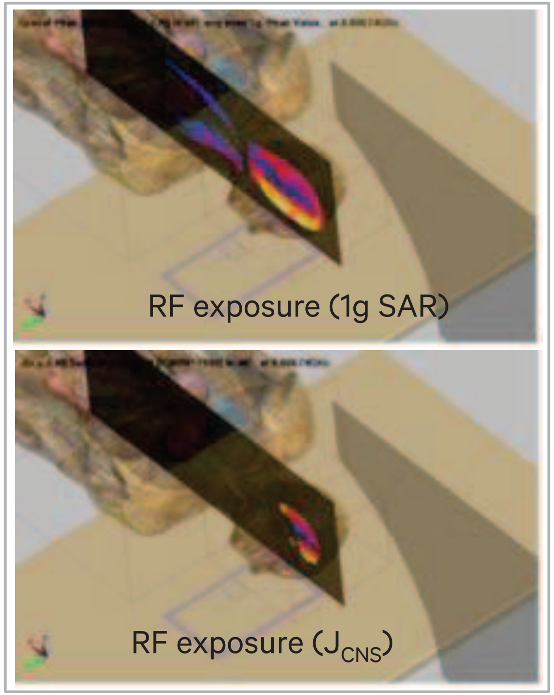
Simulation model 1 **Hands on the driving wheel**	Simulation model 2 **One hand near the gear shift**
	
RF exposure (1g SAR)	RF exposure (10g SAR)

RF Exposure Estimation in Typical Usage Scenarios

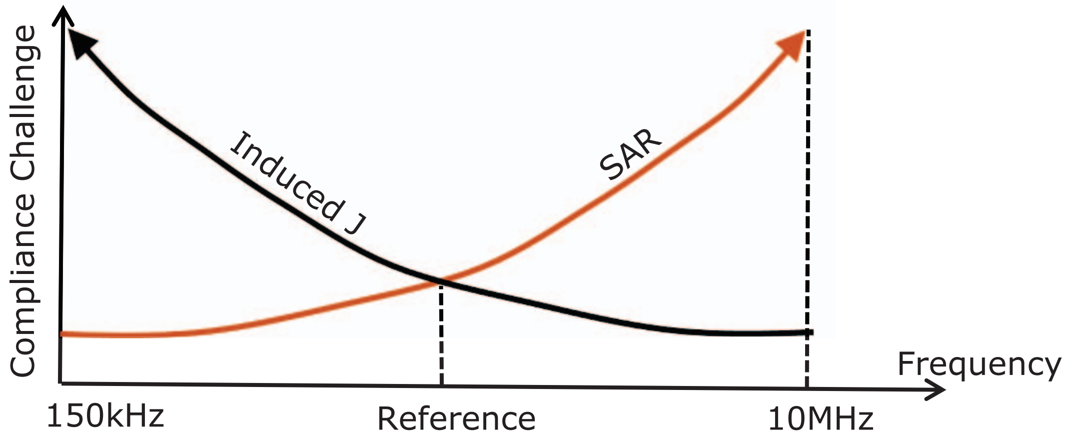
- Numerous wireless power use cases have been evaluated to assess RF exposure with respect to ICNIRP basic restrictions. A few examples:
  - Next to a tray placed on a table
  - Next to a nightstand
  - Working at a desk with embedded Tx and standing at various positions close to the desk
  - Hands on a driving wheel
  - One hand on driving wheel and the other on a gear shift
- In each use case evaluated, the results are far below the regulatory requirements

Simulation Model Example

Duke Sleeping



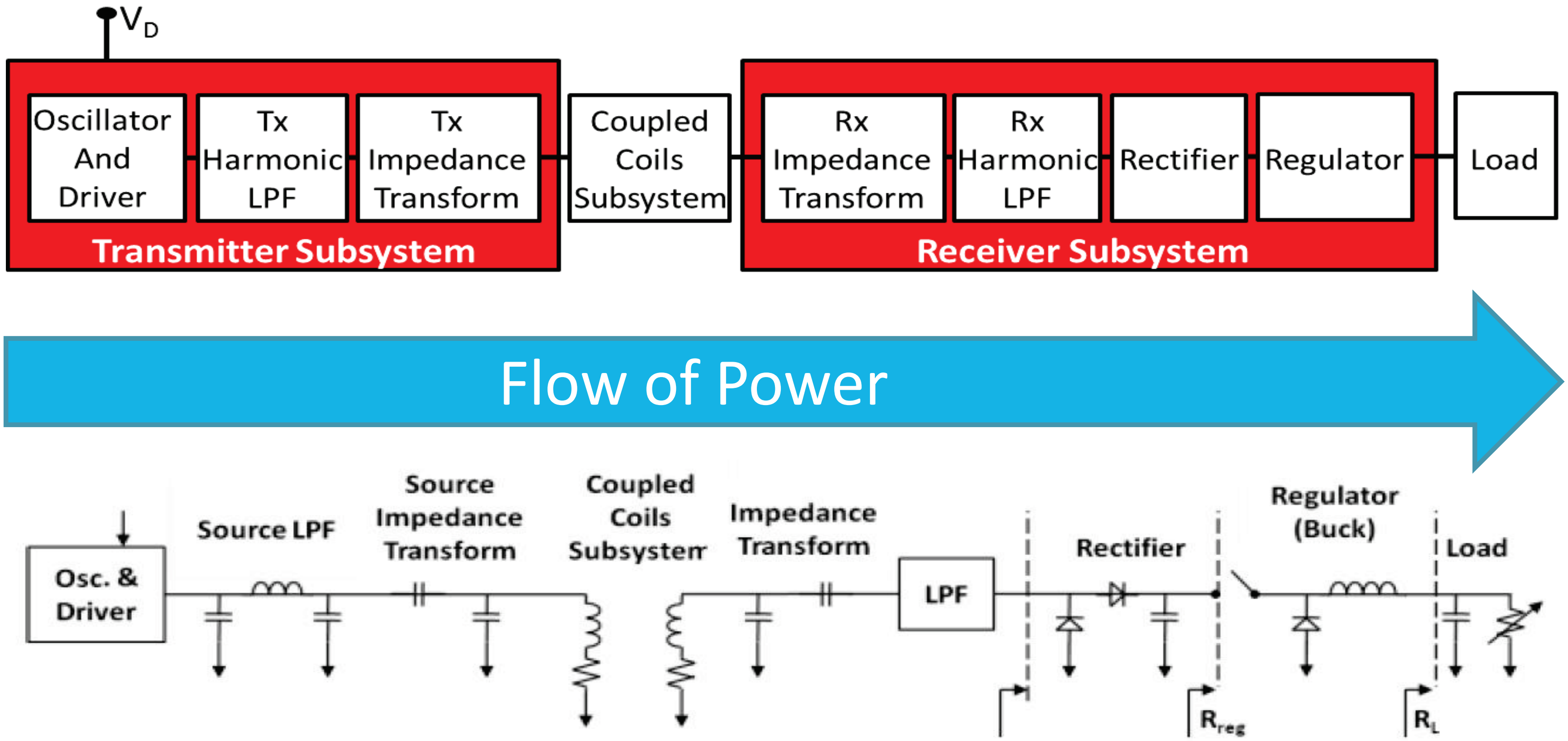
RF Exposure Frequency Dependency



- Depending on the frequency of operation used by the wireless power system, only one of the basic restriction parameters may dictate compliance
- The chart highlights the frequency dependency for the “Basic Restrictions” of SAR and induced current density (J). For a given design and use case definition: (i) the lower the frequency the more challenging it is to comply with induced current density (J); (ii) the higher the frequency the more challenging it is to comply with SAR.

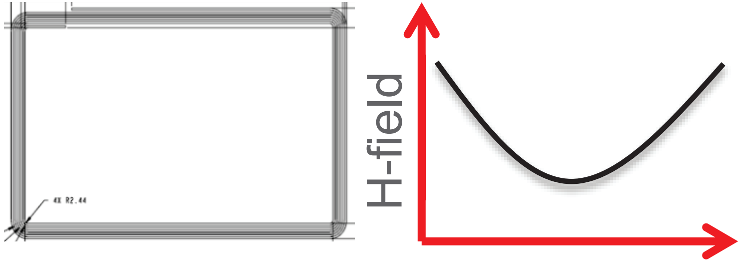
Design Considerations

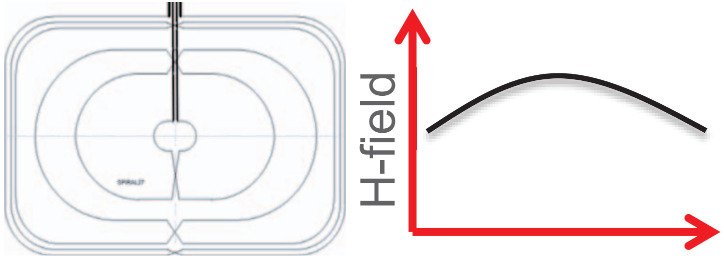
End-to-End System Diagram



Typical TX Resonator Architectures

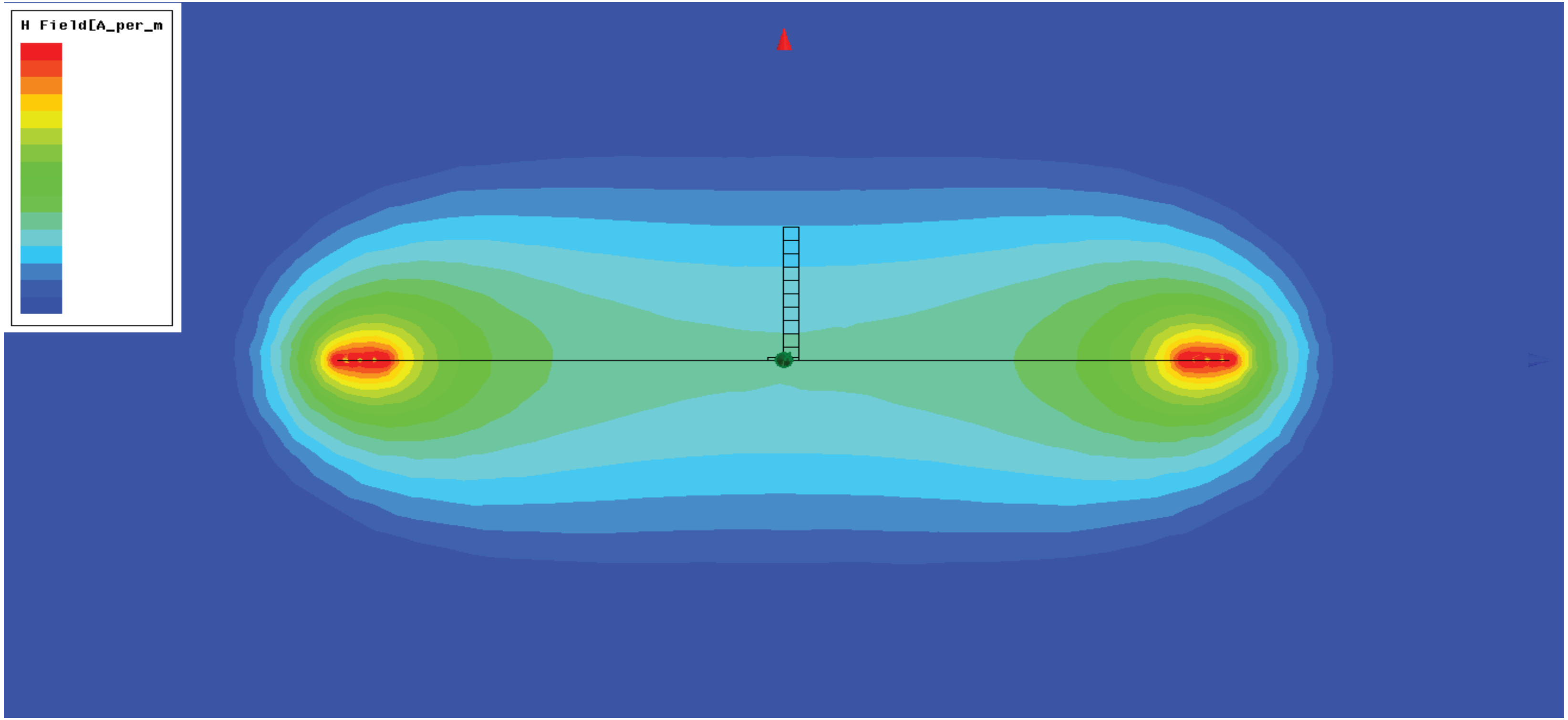
Two basic types of resonators



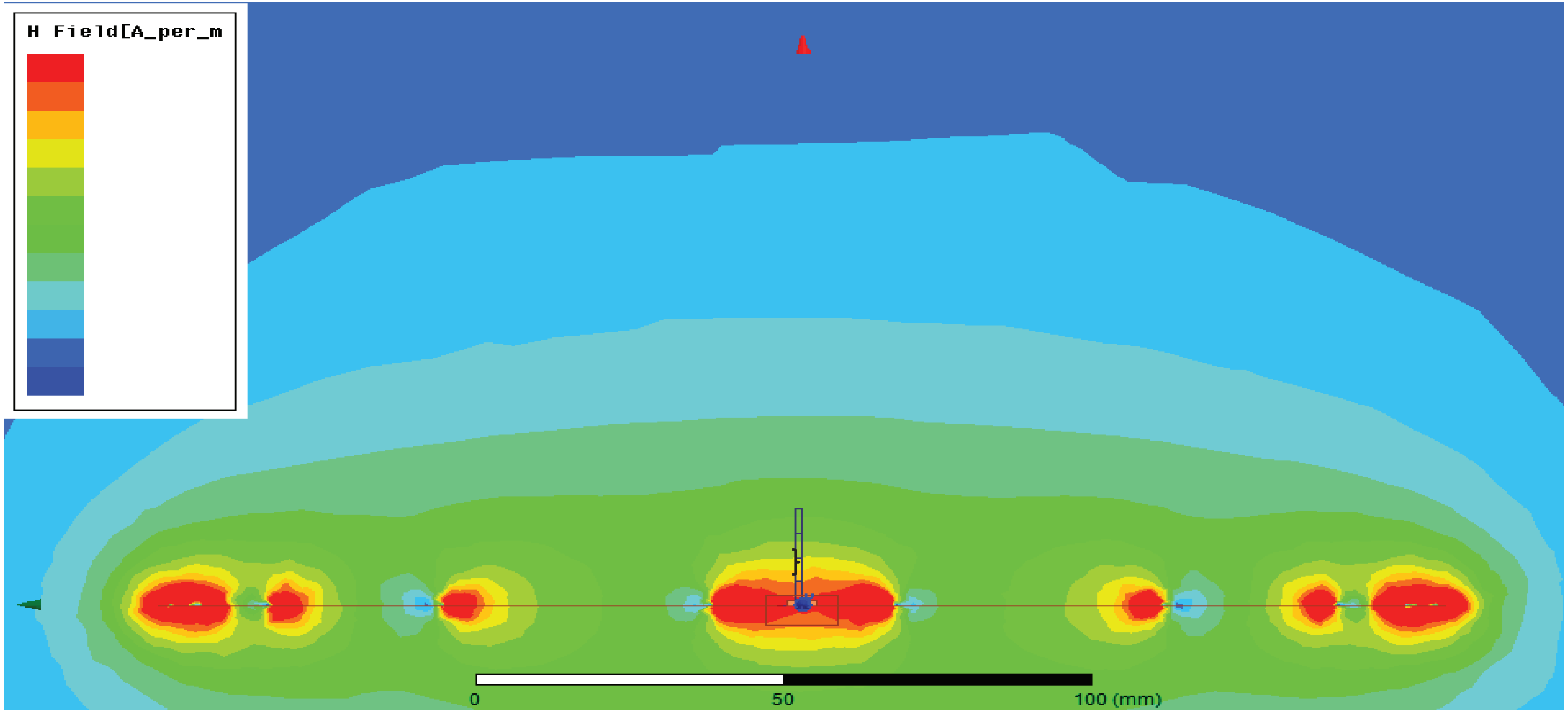


- Loop
  - Typical field pattern: strong at the edges, weak at the center
  - Low metal density in active area → less impact on RX radios
  - Downside: higher loss, non-uniform field
- Spiral
  - Typical field pattern: weak at the edges, strong at the center
  - It can be optimized for low losses and uniform field
  - Downside: potentially higher impact on RX other radios

Example: Loop Resonator



Example: Spiral Resonator

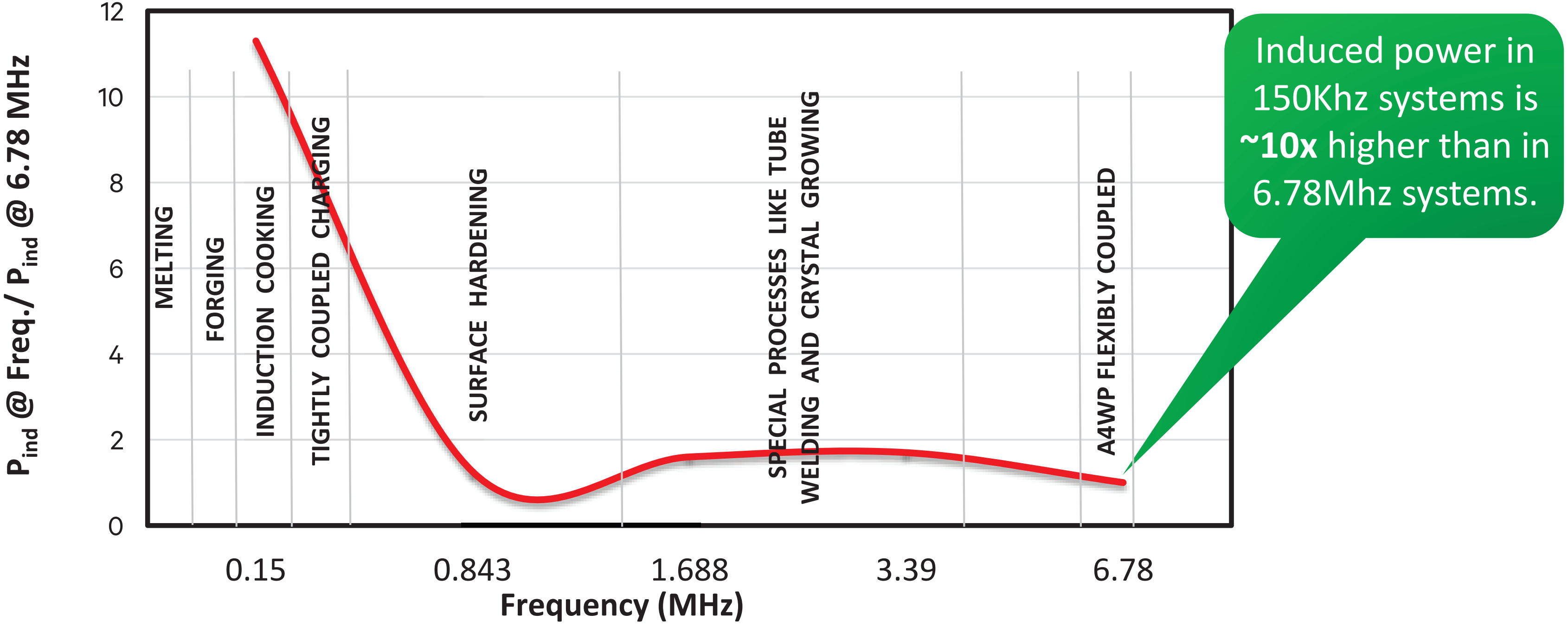


Effect of Receiver(s) Material Composition on TX Resonator

- Properties of RX materials change the H field seen by the receiver and the impedance reflected back to the TX.
- Typical devices (phones, tablets, etc.) contain significant amounts of metallic parts as well as other materials (diamagnetic, paramagnetic, ferromagnetic, etc.)
- The design of the receiver needs to take into account the effect of such materials:
  - Metal structures modify the H field distribution, creating “null” points
  - Ferromagnetic structures increase the flux density and modify the direction of the H field
  - Other materials react differently to the field, may absorb energy and dissipate it into heat

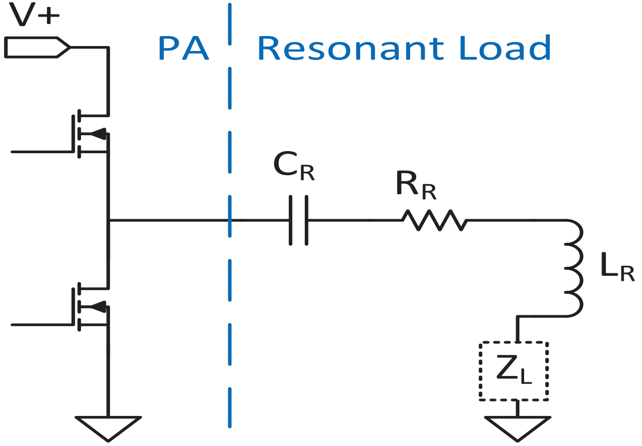
Induced Power Loss Over Frequency

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

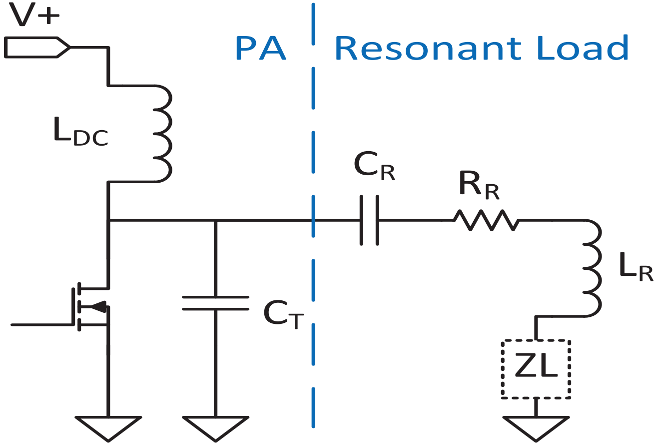


Resonant PA Configurations

- **Class D**
  - No over-voltage on FETs
  - More complex pre-driver (to optimize dead-time)
- **Class E**
  - Peak voltage undefined
  - Simpler pre-driver (can easily be made resonant)



Note:
Z_L=reflected Load impedance



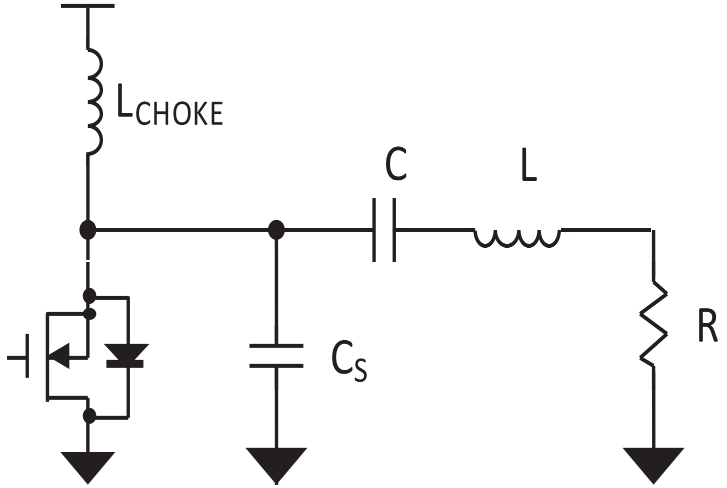
Both PA's: (i) can be made differential, (ii) require a (Pi-type) low-pass filter to reduce harmonics and (iii) can tolerate a limited range of load reactance variation

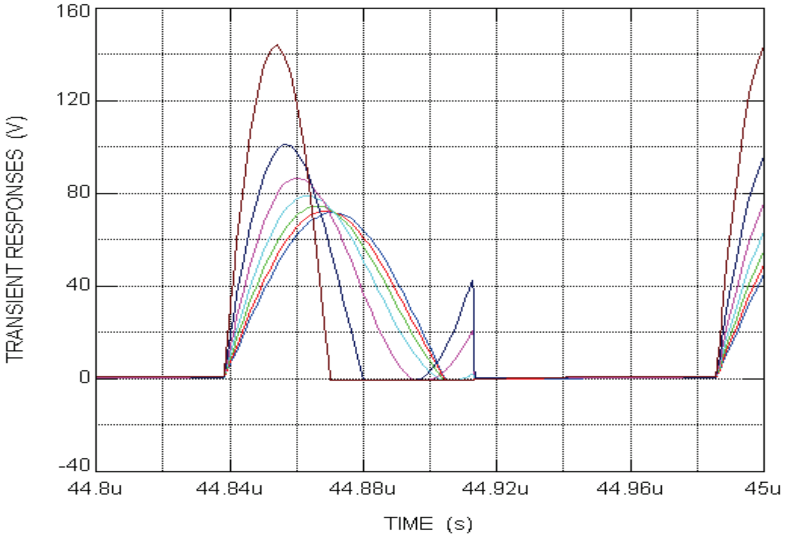
Comparison of Class D and E

- At the same supply voltage:
  - Class-E operation requires its switching transistor to have a 3.562× higher breakdown voltage than that of the class D operating
  - The output power of an optimized ideal single-ended class-E transmitter is 2.847× higher than that of typical optimized ideal class-D transmitter
- Efficiency:
  - For Class E, Drain and Gate capacitances of the FET can be absorbed into the resonant input and load circuits. For a Class D, such sources of loss are difficult to overcome: GaN offers some advantages to Class D topology, due to reduced output capacitance.

Load Effects on Class E Driver

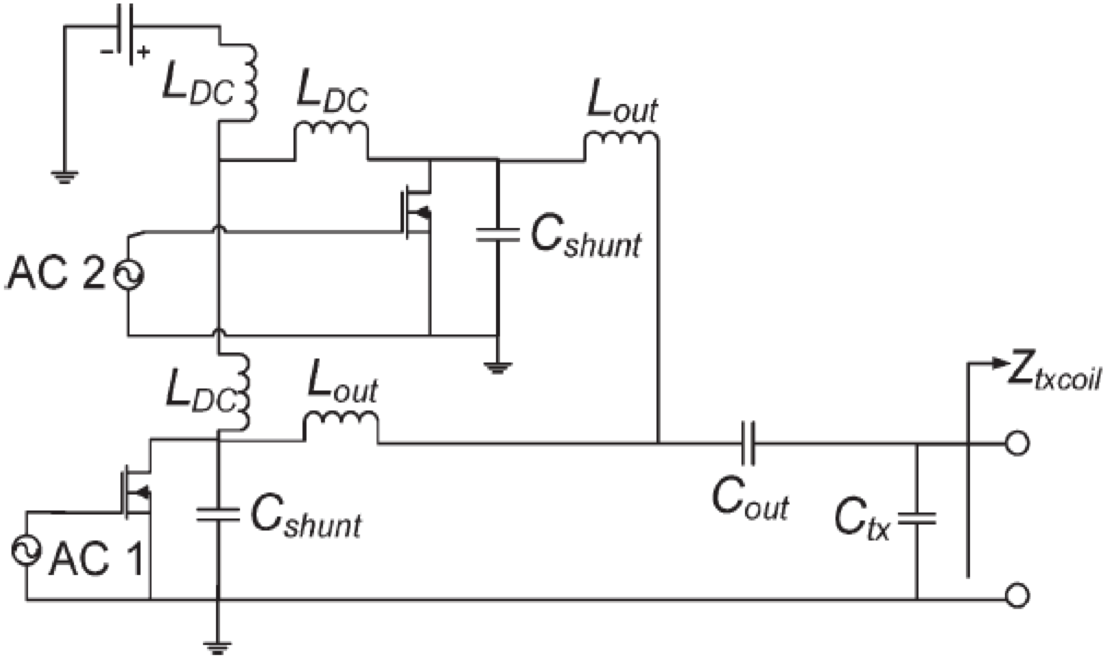
- Drain to source time domain response of the switch when phase angle of load impedance is changed from the nominal resonant point.



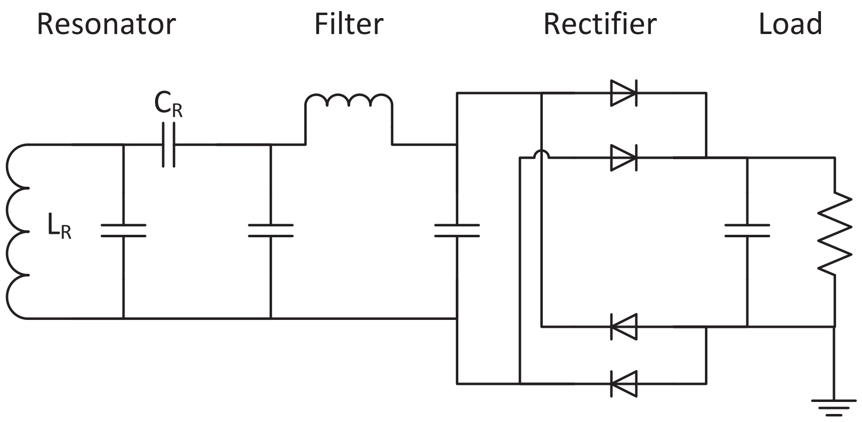


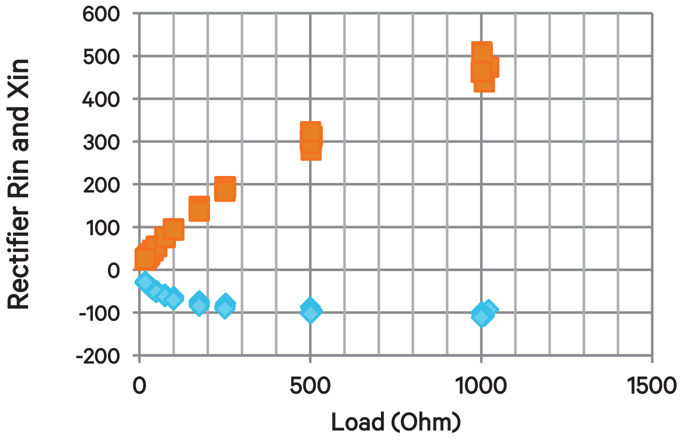
Efficiency Improvement of a Class E Amp

Dual Class-E driver (Zhen Ning Low et al.)



Receiver Architecture

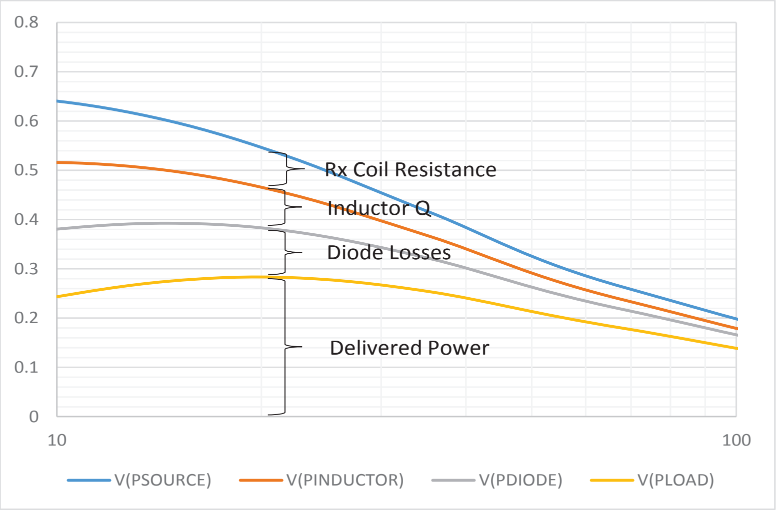


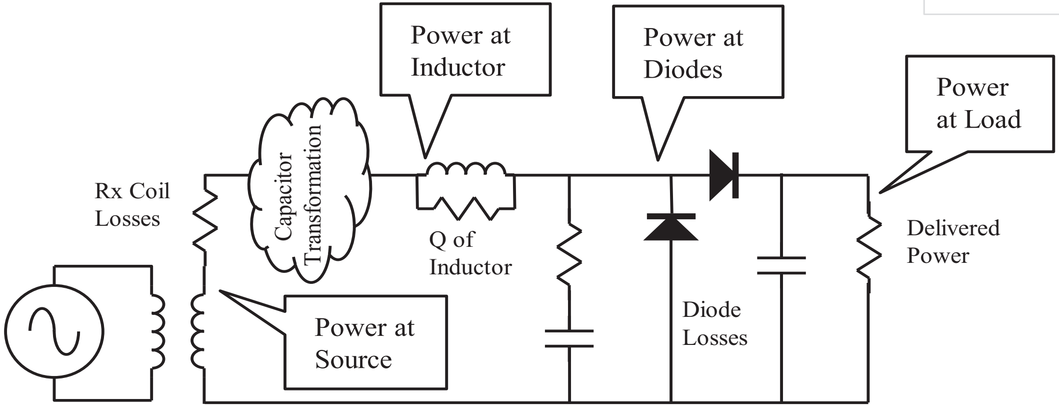


- EMI Filter (typically a Pi L-C structure) is required to reduce harmonics generated by the rectification, which would otherwise be injected in the resonator.
- A typical diode rectifier exhibits a shift in its input impedance depending on the load value, on both its real and imaginary component. This effect needs to be considered when optimizing the resonator reactance.

Power Loss Segmentation

- Power loss segmentation is characterized at the input of each major stage:
  - Power coupled into coil
  - Power into power inductor
  - Power into Rectifier
  - Power Delivered to load



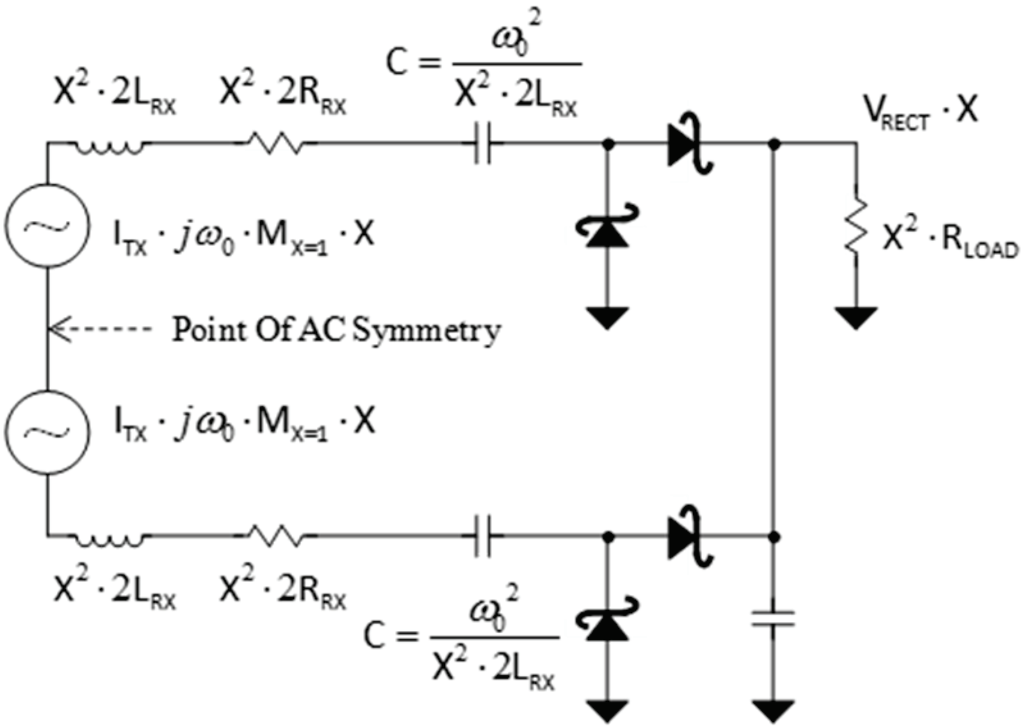


Receiver Rectification Options

- Shottky Diode rectification Vs. Synchronous FET rectification
  - Synchronous FET design is typically more efficient and compact, but care needs to be placed to control maximum voltage and avoid breakdown
  - At 6.78 MHz, FET turn-on and turn-off timing as well as slew rate needs to be accurately controlled to minimize unwanted losses, cross-conduction, and related generation of harmonics
- Full-wave rectification Vs. half-bridge “doubler” rectification
  - The “doubler” approach provides twice the output voltage, but generates larger third harmonic noise, which needs to be suppressed.

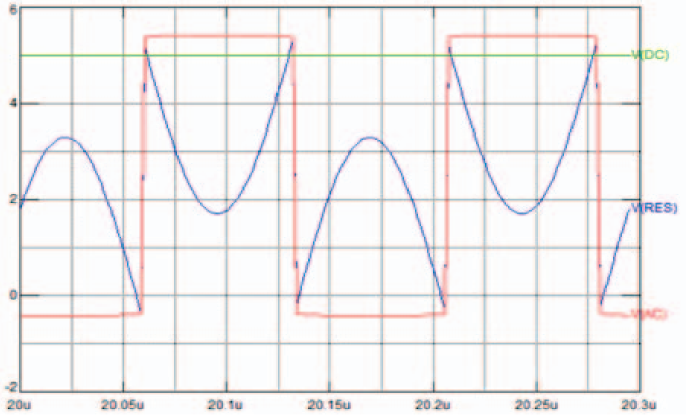
Equivalency of Half and Full Wave Rectifiers

- Compared to the Half bridge, at equivalent output voltages and power, AC voltages are doubled, AC current is halved and AC impedances are quadrupled.
- Diode losses for both configurations are equivalent as the two legged versions carry half the current on each set of diodes but have twice as many diodes.

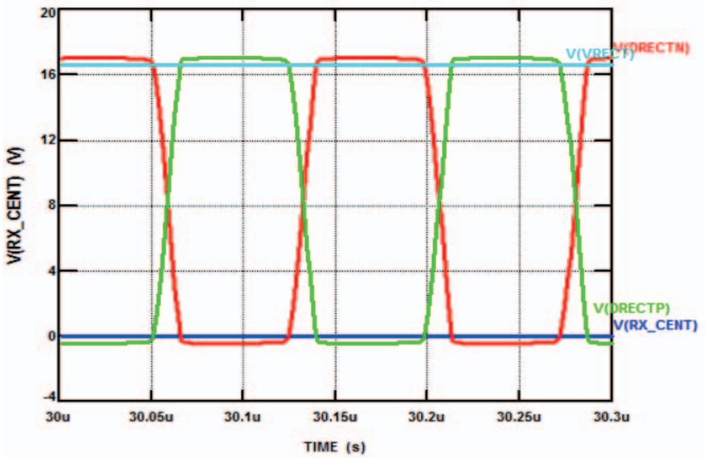


Half-wave Vs. Full-wave Rectifier

- Half-wave rectifier
- Blue = Voltage across Resonator
- Red = Voltage at Diode Inputs
- Green = Voltage at Diode Output

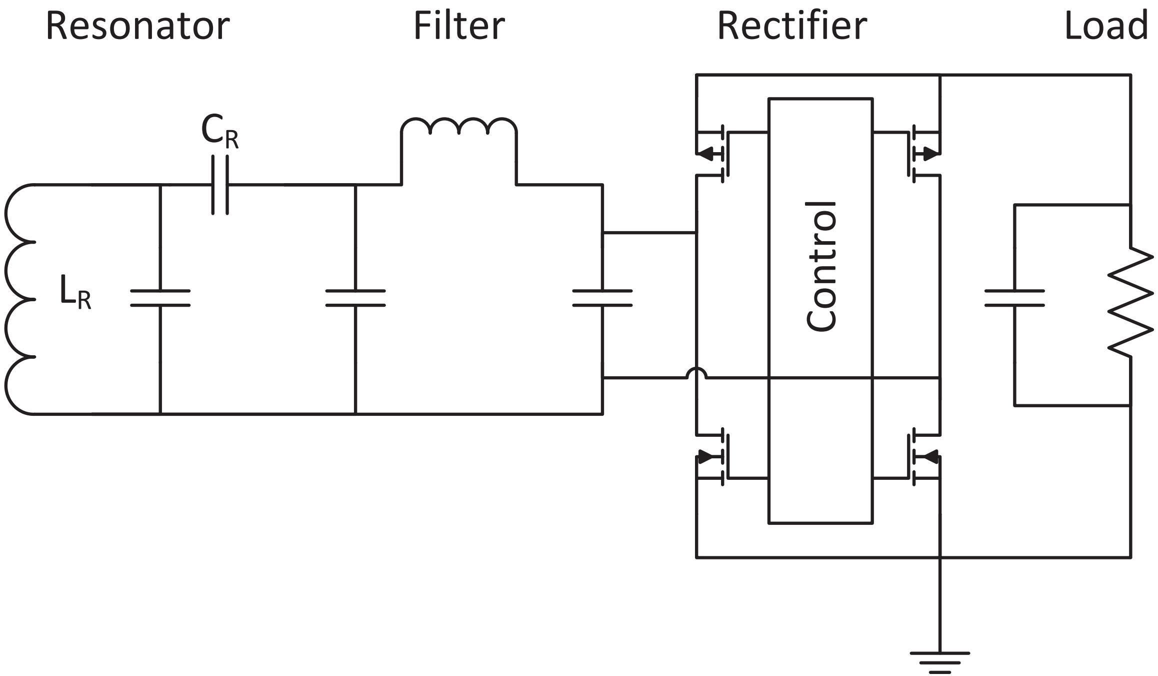


- Full-wave rectifier
- Dark Blue = Reference Ground
- Light Blue = Rectifier Output
- Red, Green = AC Voltage at Diode Inputs



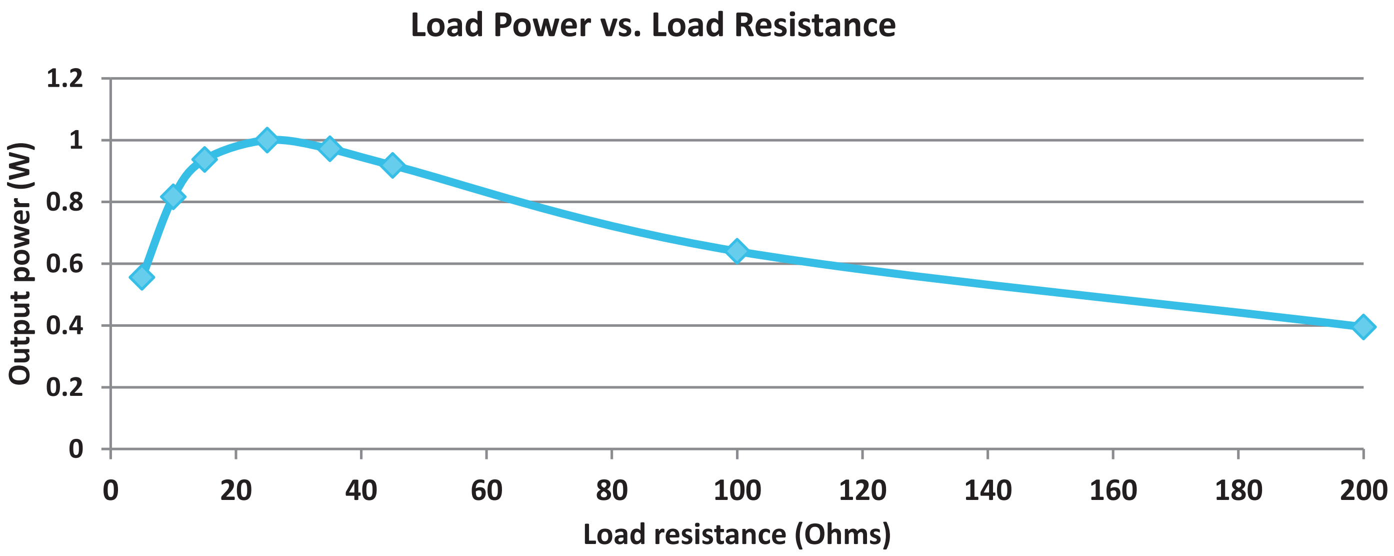
Synchronous rectifier

- Can be N-Channel/ P-Channel at low voltage or N-Channel/N-Channel at higher voltages
- Can be controlled "out of phase", thus implementing a DC-DC conversion, but operating outside ZVS/ZCS causes additional losses and EMI generation



Load Requirements

- The minimum value of the Load Resistance needs to be controlled and always be greater than the Maximum Power Point Resistance in order to avoid “collapse”



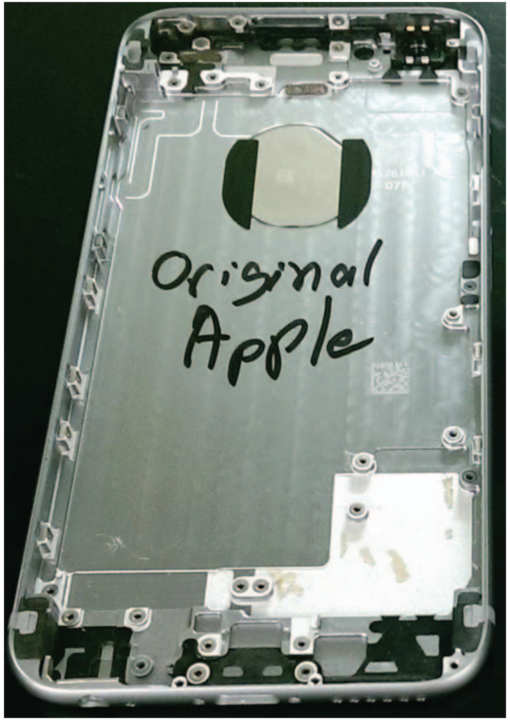
Many Premium Products Have Metal Cases

…and now can be wirelessly charged at 6.78MHz

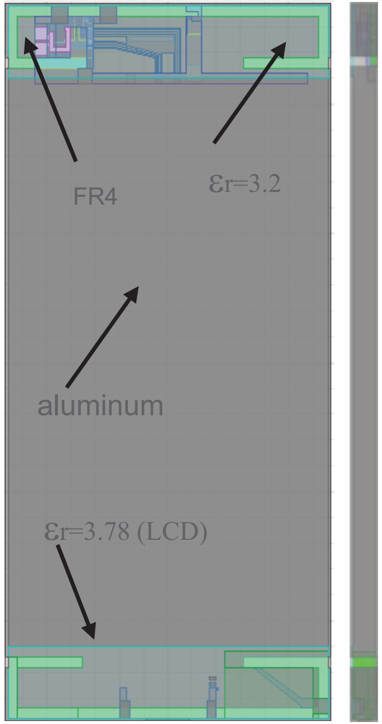
WiPower enables wireless charging for metal devices

- Designed to be compliant with the Alliance for Wireless Power's Rezence standard

Study of iPhone 6

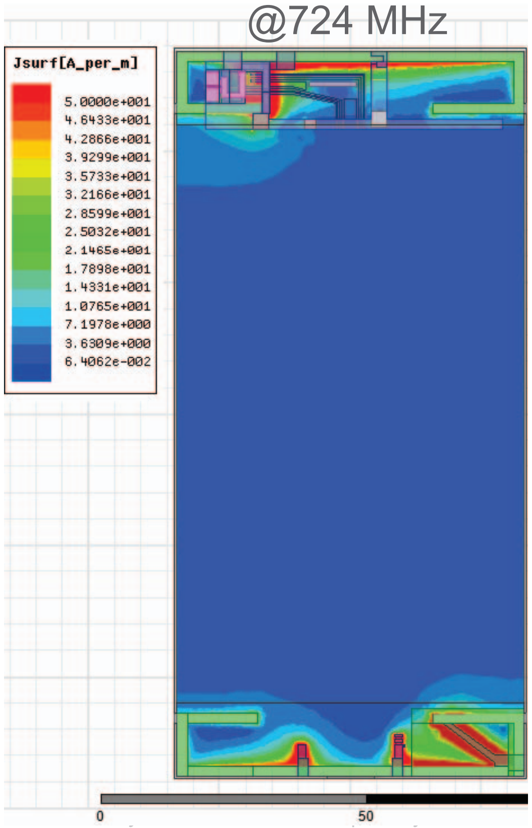


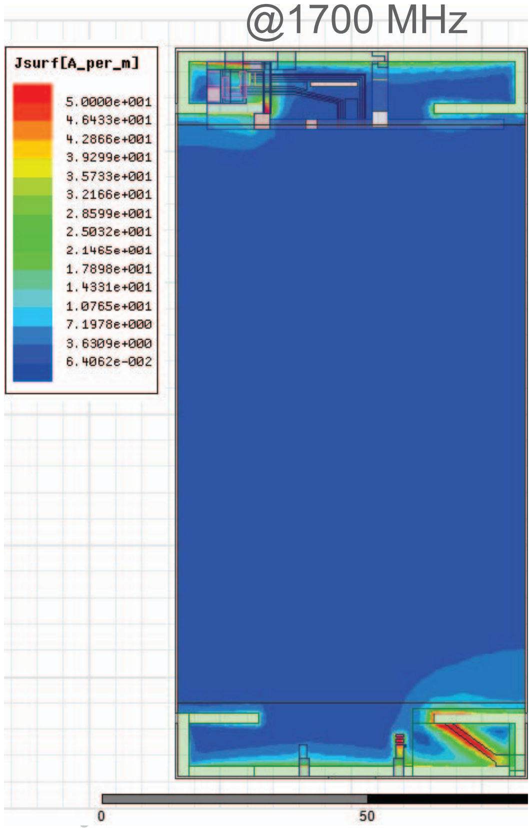
HFSS Model



Current Distribution – WWAN Lower Bands

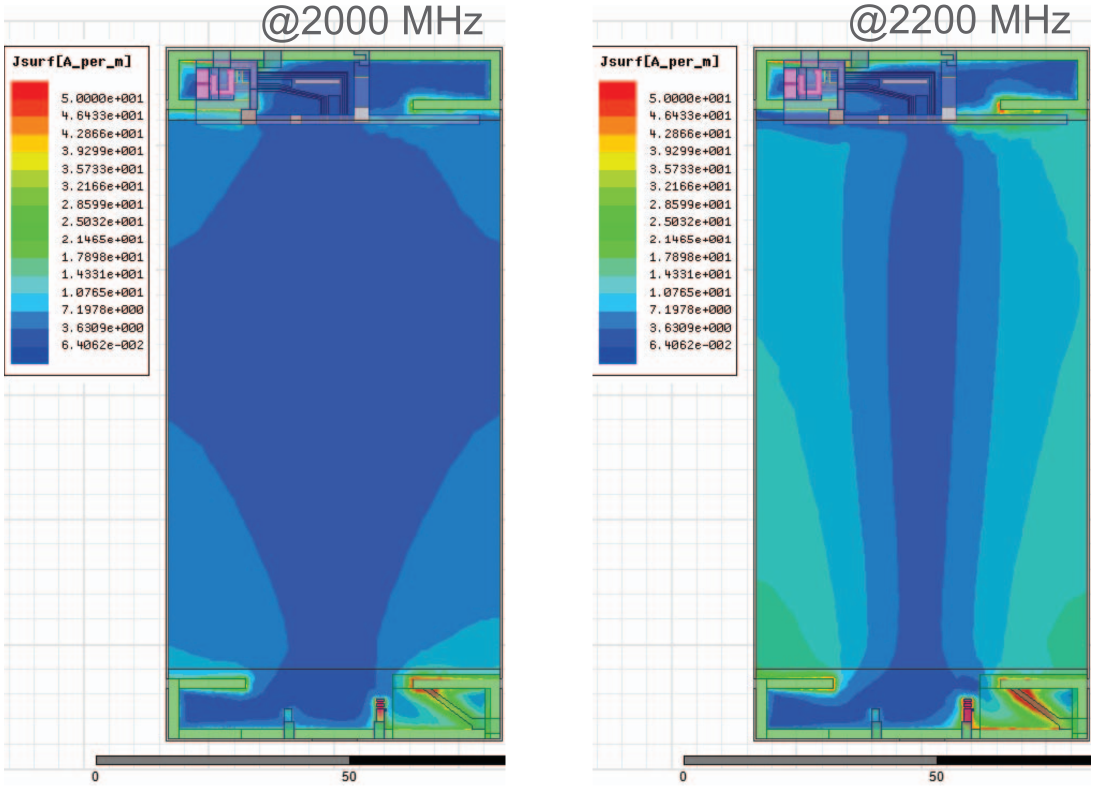
- RF current distribution is assessed to evaluate potential interference between antennas, to ensure that the wireless charging will not degrade the communication performance





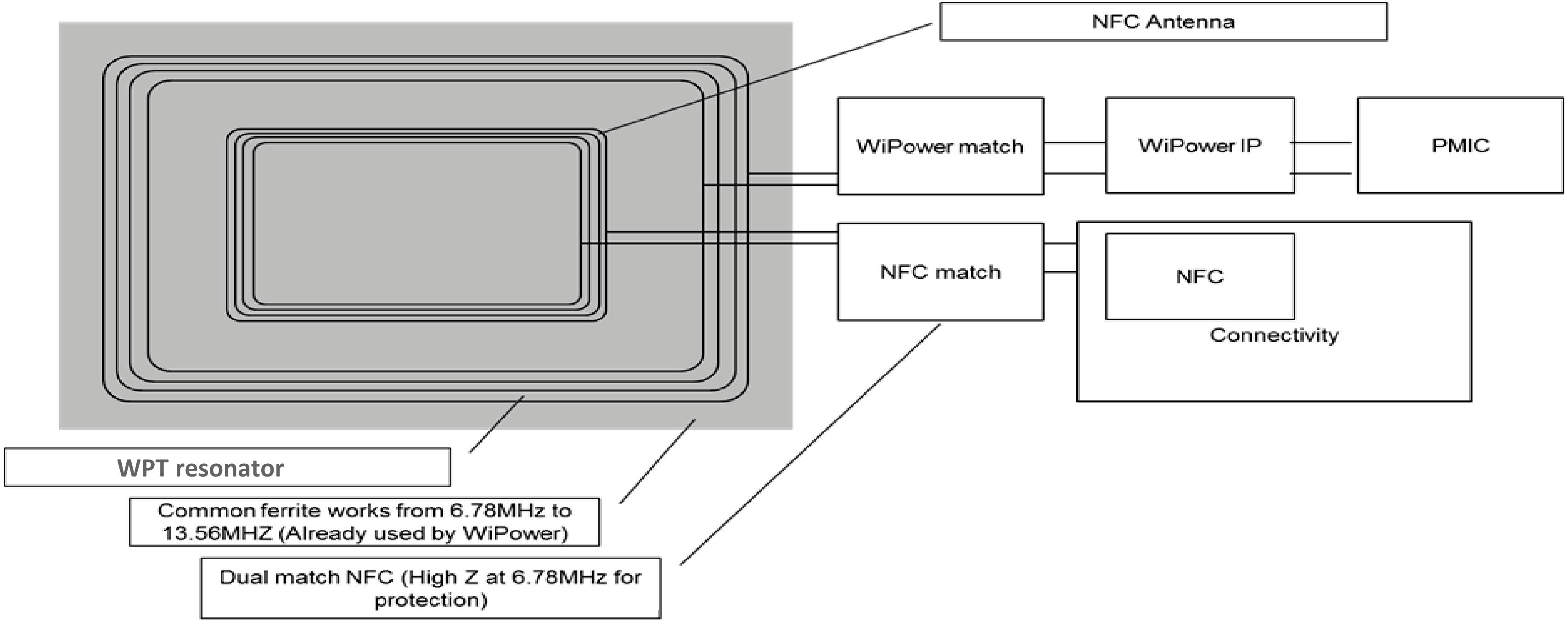
Current Distribution – WWAN Higher Bands

- Higher frequencies show very different RF current patterns: all cases are evaluated prior to finalizing a product design, including WiFi, BlueTooth and GPS



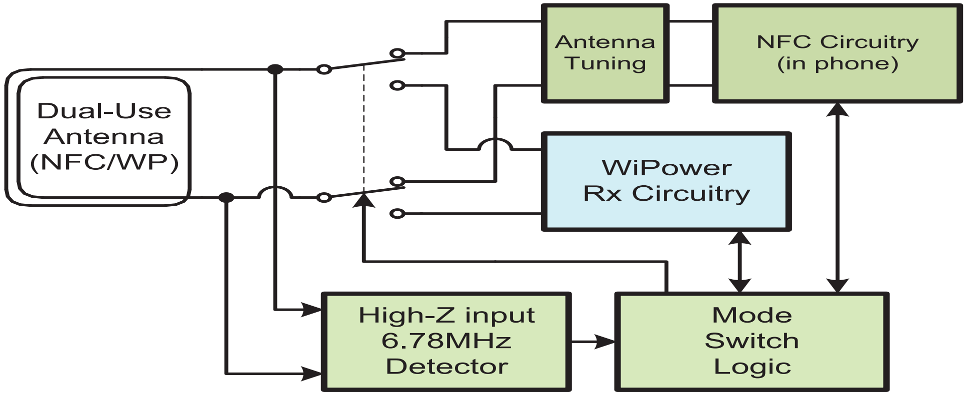
NFC and WPT (A4WP) in the Handset

- Dual Antenna Approach
  - Coupling between the WPT coil and the NFC coil needs to be minimized



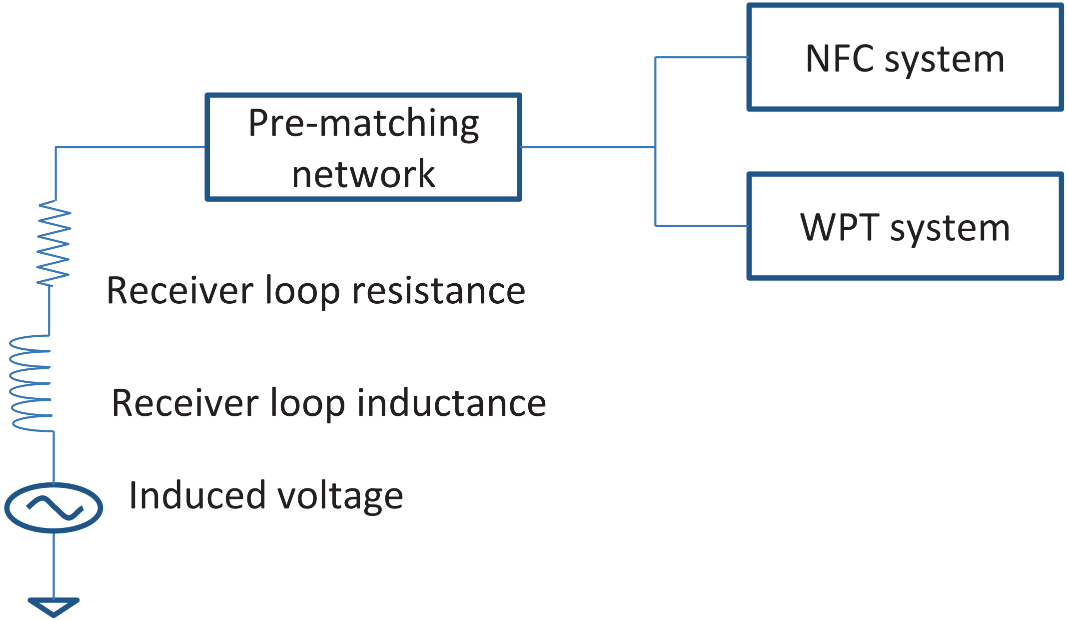
Shared Antenna option #1: switched antenna

- Advantages
  - Larger antenna for both systems—better performance
  - Removed interaction between two antennas
- Disadvantages
  - System design effort
  - Less flexibility of antenna placement for NFC



Shared Antenna option #2: dual-port matched filter

- Advantages
  - No losses on switches
- Disadvantages
  - Circuit design effort and larger filter



Bluetooth Low Energy (BLE)

- Two-way communication is accomplished with BT release 4.1 (dubbed BLE or "Bluetooth Smart"), which provides considerably reduced power consumption and cost, relative to prior implementations.
- A dedicated BT Profile has been assigned by the Bluetooth Special Interest Group (Bluetooth SIG) to the wireless charging functions as specified by A4WP (Alliance for Wireless Power).
- BLE Connection can be established within 150 ms from the time a chargeable device is placed on the transmitter.
- Built-in multiple Receivers' communication is accomplished by frequency hopping and unique registered Bluetooth address (public and static).
- Cross-connection is avoided by timing differential and Receiver placement detection, with additional software algorithms to detect and resolve potential anomalous cases.

Managing RF Coexistence

There are more than 10 radios in a Smartphone!

- NFC: although both transmissions cannot occur at the same time, implementations can use the same antenna for both systems via appropriate matching networks.
- WWAN and WLAN: well known procedures are utilized. Link budgets are analyzed and coexistence is ensured by appropriately positioning antennas and tuning the filters. The small amount of metal in the TX minimizes issues.
- Bluetooth: in integrated solutions, the same BT HW is used by adding a dedicated profile for Wireless Power Transfer, which has been created by the Bluetooth SIG.
- GPS: there are no special requirements (besides typical care on antenna placement). Often, the TX antenna acts as a reflector thus improving GPS sensitivity.

Integration Trends

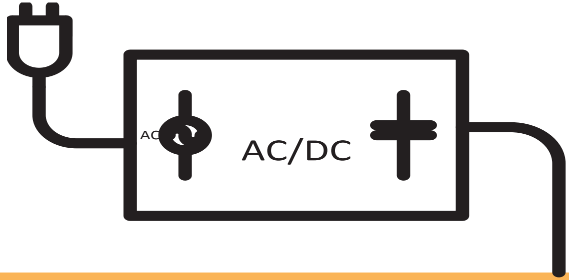
Power levels in A4WP - Rezence specifications

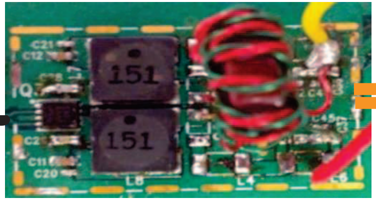
Levels are based upon typical applications

PTU Classes	
Class 1	TBD (~2.5W)
Class 2	10W
Class 3	16W
Class 4	22W
Class 5	TBD (~33W)
Class 6	TBD (~50W)

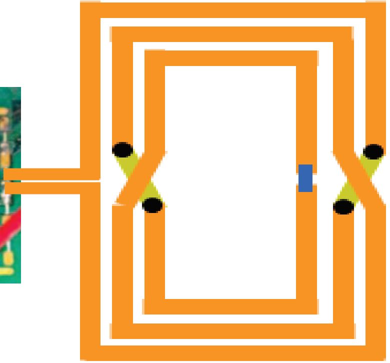
PRU Categories		
Category 1	TBD (~1.75W)	Wearables
Category 2	3.5W	Feature Phones
Category 3	6.5W	Smartphones
Category 4	TBD (~13W)	Tablets
Category 5	TBD (~25W)	Thin Notebooks
Category 6	TBD (~40W)	Notebooks

Block Diagram for PTU Integration





PA and Filter

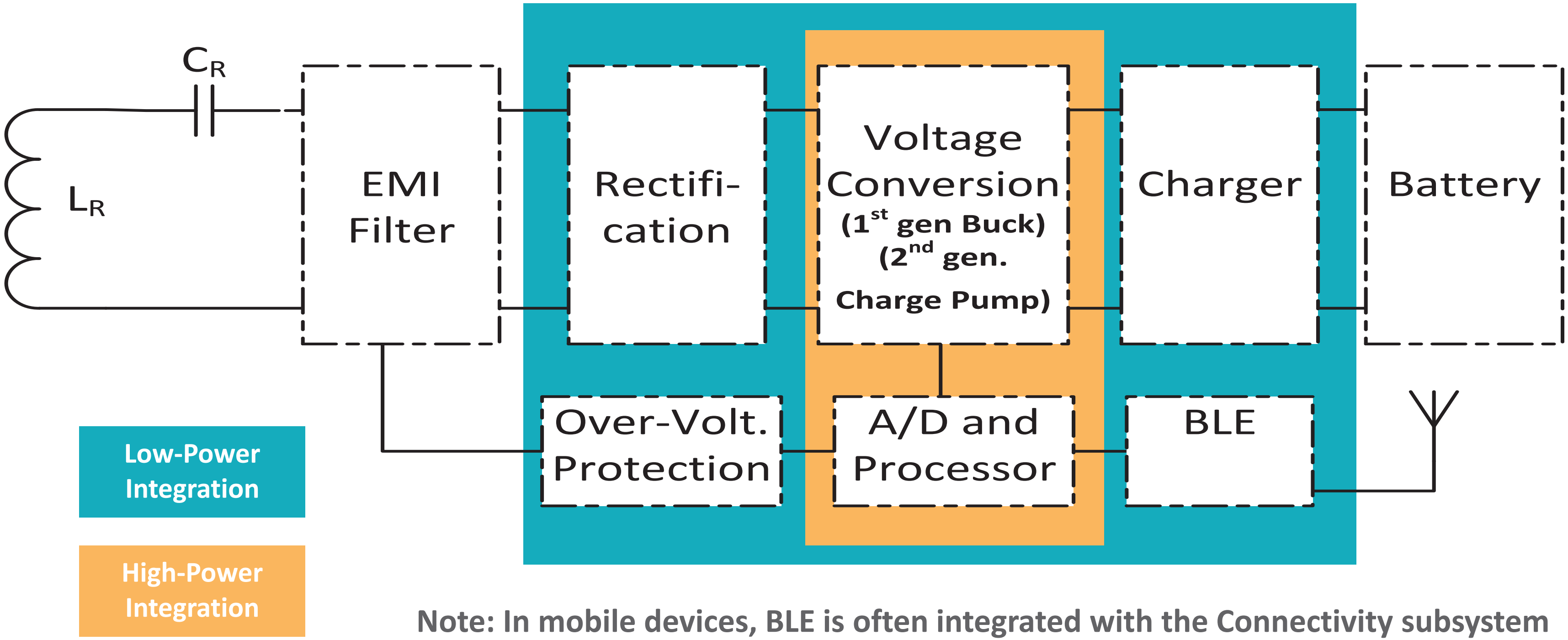


Resonator

- PA Power Supply
- Housekeeping Supplies
- RF PA Drivers
- RF Voltage and Current Measurement
- Oscillators and Clocks
- I2C and other I/O’s
- OV, OC, OT Protections
- Controller
- Temp. Sensing
- Impedance Control
- Bluetooth * **Communication**
- Power and Impedance Calculation

* May be separate IC

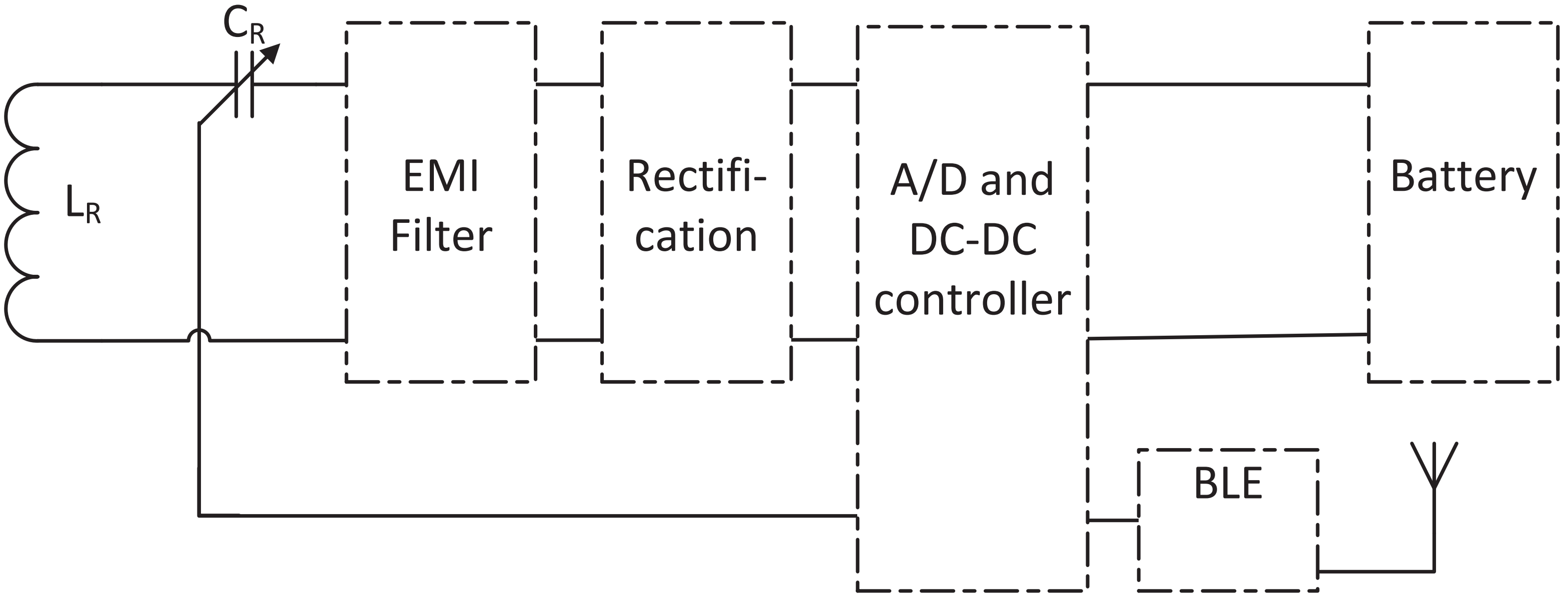
Receiver Integration



Note: In mobile devices, BLE is often integrated with the Connectivity subsystem

Novel architectures

Controlling resonance allows for optimization of battery charging



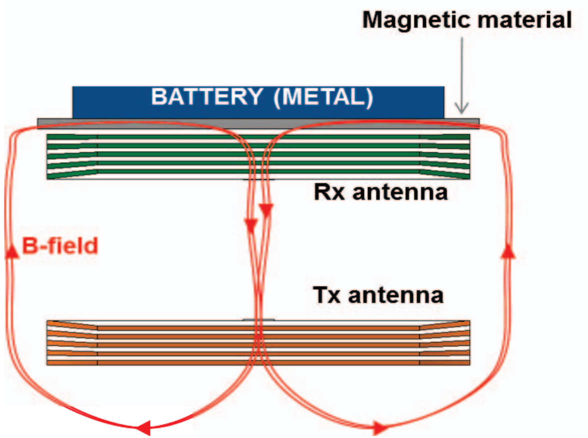
Electronic components' challenges

- Transmitter: High efficiency, resonant Power Amplifiers from 10 to 50+ Watts
  - Low average dissipation, but large instantaneous power loss when off-resonance
  - GaN shows some advantage, but thermal capacitance can pose challenges if dynamic conditions are not properly addressed at system design level
- Receiver: Rectification at 6.78MHz
  - Challenges: high efficiency, low EMI generation
  - Synchronous rectification presents some advantages but high voltages and power dissipation challenge integration for devices that require >>10W
- EMI filters:
  - Low losses at 6.78MHz and high rejection at the lower harmonics and all the way to LTE and WWAN bands: not many components available in this frequency range

Technology challenges

What it takes to operate at 6.78MHz

- Ferrite and antenna structures miniaturization: thickness vs. permeability
  - Magnetic reluctance is given by $R = \frac{l}{\mu w t}$, where μ is the permeability of the material
  - Hysteresis losses (given by $\mu"$), which contribute to heating of the assembly
  - Complex permeability: $\mu = \mu' - j\mu“$
  - Magnetic loss tangent $\tan \delta = \frac{\mu"}{\mu\prime}$
  - Current production materials have μ = 100~200 and $\mu“$ = 1~5 allowing for thickness of **0.2mm or less**



Silicon Integration

- Qualcomm® Snapdragon™ 808 and 810 processors support Qualcomm® WiPower™ technology.
  - Qualcomm WiPower* is a honoree of the 2015 CES Best of Innovation Award for portable power.
  - WiPower also made the Top 10 Product Designs of 2014 list from TIME
- Many other silicon vendors support and have A4WP-compliant solutions, including:
  - Broadcom
  - IDT
  - Intel
  - MAPS
  - MediaTek
  - Nordic Semiconductor
  - NXP
  - ON Semiconductor
  - Qualcomm/CSR
  - Renesas

Premium mobile computing devices, including smartphones and tablets

rezence
Alliance for Wireless Power

Note: WiPower is Qualcomm's Wireless Power Transfer technology, fully A4WP/Rezence compliant
Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc.

SmartWatch Constraints are driving integration

Battery life is the most challenging goal

- Challenges:
  - Week-long Battery life
  - Restricted Physical Size
  - Always-on Display / Modern Touch UI
- Opportunities:
  - Integration of Wireless Power and NFC antennas
  - Integration of antenna structure in Wearables
  - Integration in SiP

SmartWatch Hardware Features

Memory/Storage

Wireless Battery Charging

Microphone

Connectivity:
BT and WWAN

Vibe and/or
Speaker

Display and
Lighting

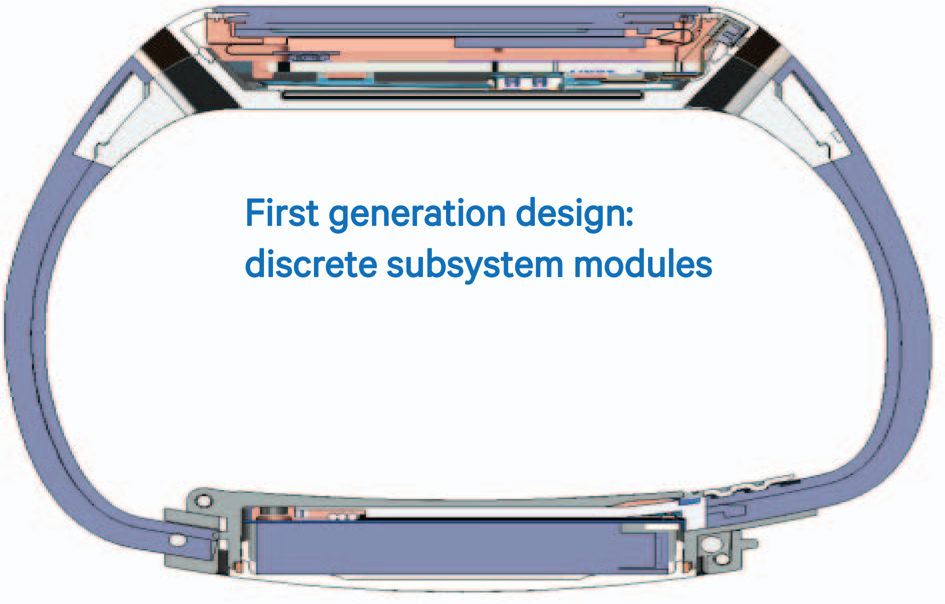
Debug/Expansion/
FW Updating

User Interfaces:
buttons, dials, touch

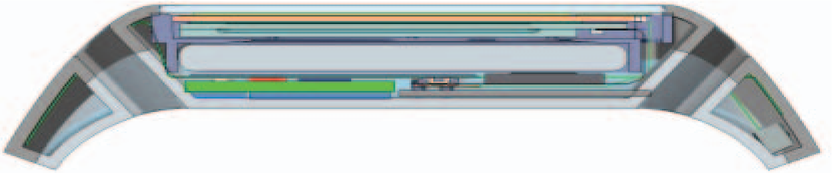
Design Objectives

- Enable sleeker form factors.
  - Seek reduction in both overall area and thickness.
  - Emphasis on achieving high level of integration by using cutting edge technologies.
- Reduce overall system cost while increasing reliability and ecosystem development options.
  - Create highly integrated modules.
  - Enhance device flexibility by enabling accessories and connected devices.
- Provide modular hardware solutions to facilitate models differentiation.
  - Create highly flexible functional platforms that reduce time-to-market.
- Increase manufacturability and simplify construction
  - Move all subsystems into a single volume that can easily be integrated in different industrial designs.

Smartwatch Integration Evolution



First generation design:
discrete subsystem modules



Second generation design:
battery takes up most of the volume

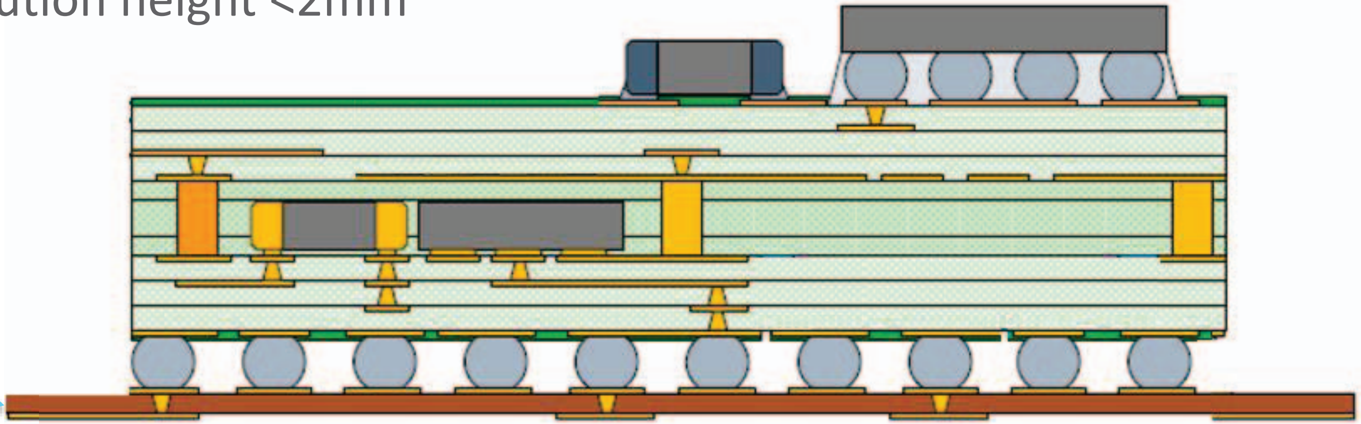
- Both Display Housings have less than 10mm Thickness
- Overall shape and volume are maintained

System in Package implementation

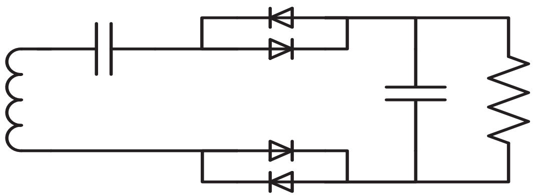
Current Solutions

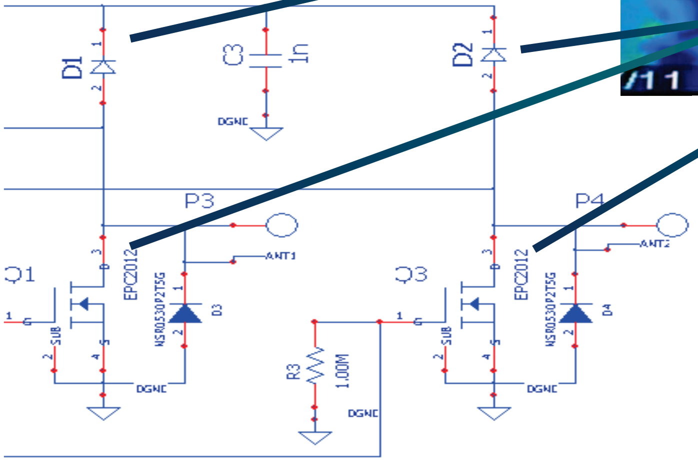
- High Level of Integration: Embedded Passive and Active Die using 2.5D and 3D process
- Requires a Flex Base to solder SiP module using BGA or LGA style contacts
- Total system solution height <2mm

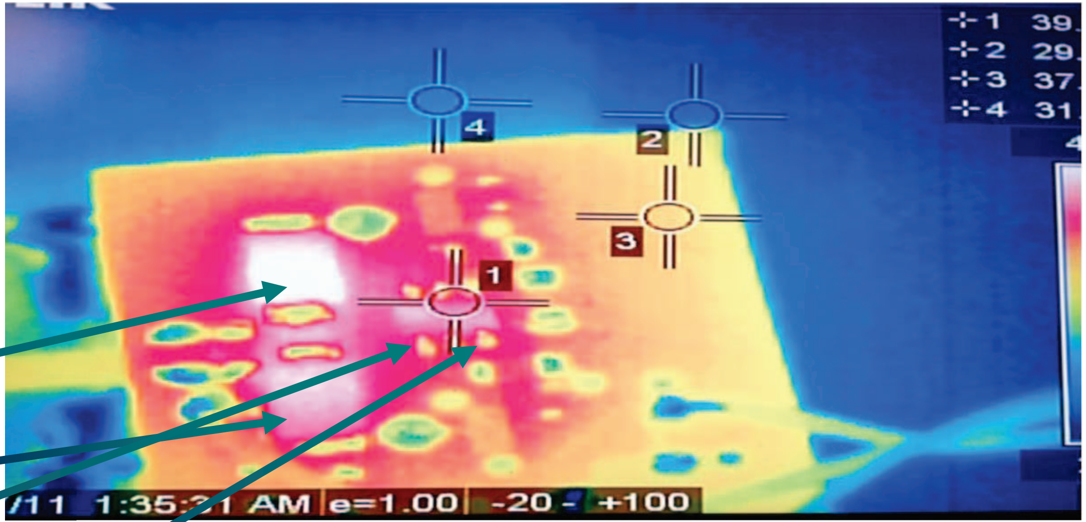
The Wirelesss Power Transfer antenna can be implemented in the Flex circuit



Efficiency: GaN Vs. Si







When voltage rating of diode bridge is relatively high, GaN FETs provide more efficient rectification. While at lower voltages Silicon FETs offer a more cost-effective solution for synchronous rectification, for higher power/voltage applications the GaN technology can provide substantially superior efficiency. Similar conclusions apply to the TX PA.

CONCLUSIONS

A Few “Lessons Learned”

- Operating “at resonance” is not the Holy Grail
  - Optimizing end-to-end (E2E) efficiency requires considering the system as a whole: Power flow from PA to Load and Reflected Impedance from Load to PA.
  - The design of the system must take into consideration the combined effect of all components’ tolerance, thus it is not always operating “at resonance”
- The system needs to be architected so that Power delivery and Power sharing by multiple loads is inherently achieved by the impedance behavior: it is impractical to realize a control loop, which is fast enough to react to the dynamic variations of multiple loads.
- Operating frequencies below 1MHz cause unacceptable losses in metal structures that enter the TX field
- Efficiency in the Receiver is more important than “E2E”, because of “touch” temperature
- GaN provides valuable efficiency improvements in both Transmitter PA and Receiver Rectification, but its higher cost makes it practical only for medium-high power applications, where integration of power devices is not optimal

A4WP High-Level Roadmap

	2013	2014	2015
Usage Progression	Home, Business, Automotive	Public Infrastructure & Services	Enhanced Services
Features	**Positional Freedom, 1:N charging, Bluetooth Smart Communications, Scalable Power**		
Specification (BSS)	BSS 1.2	**BSS 1.3**	BSS 1.4
1:N PTU Power	10 – 16W	**10 – ~50W**	~1 – ~50W
PTU Devices (examples)	Mats, Furniture, In-Vehicle Accessories	Furniture, PCs, In-Vehicle*	Consumer Electronics
PRU Power	3.5 – 6.5W	**<3.5 – 30W**	~1 – ~30W
PRU Devices (examples)	Smartphones	Laptops, Tablets, Peripherals	Consumer Electronics
Apps		Power Management, Location	Social Media, Gaming

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