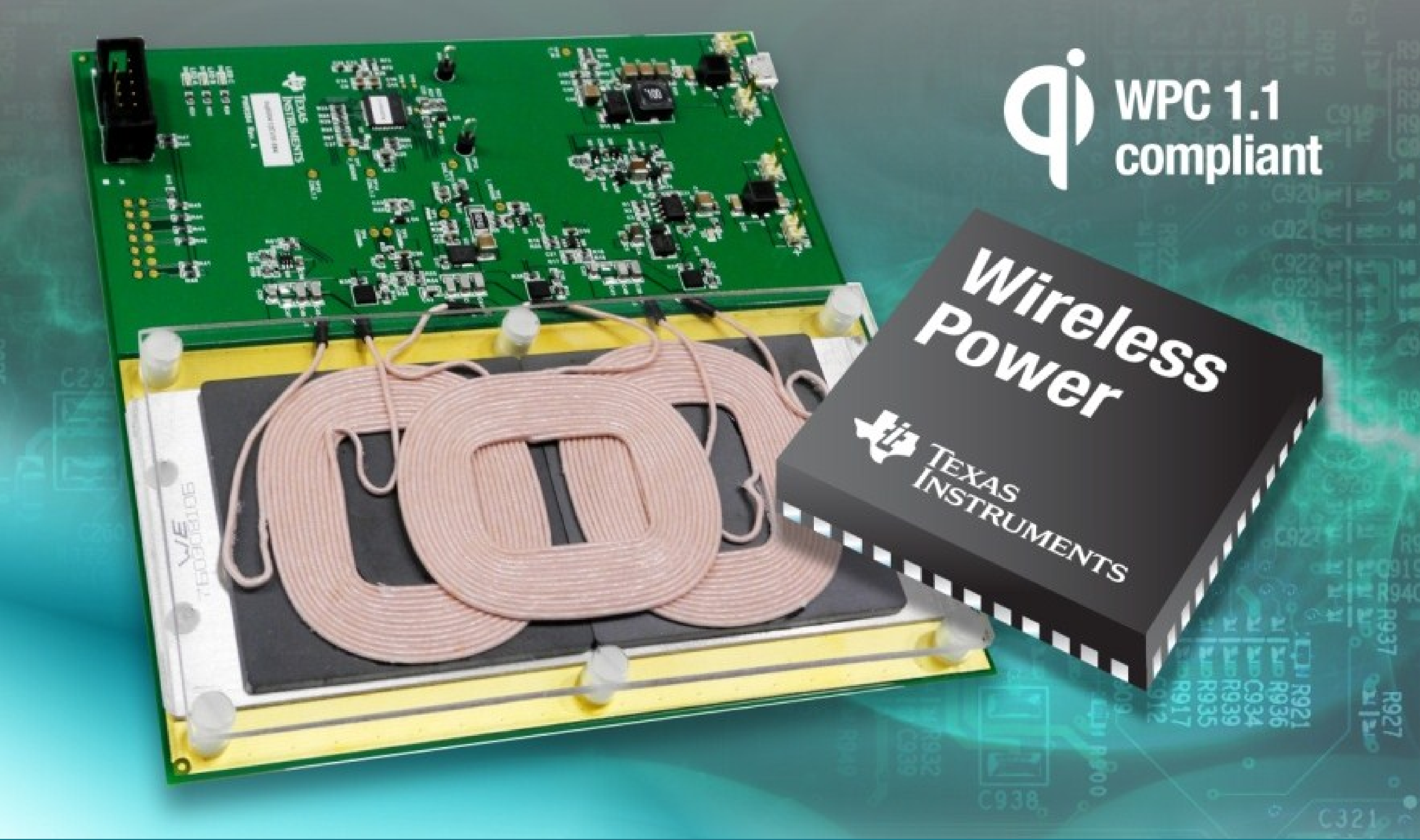


Introduction to Wireless Power

Texas Instruments

Wireless power – basic concept

Wireless power… why?

- **<u>Convenience</u> – end-users can charge multiple devices (camera, phone, tablet, headset, other accessories) on a common charging pad or table without carrying cables or adapters**
  - <u>Infrastructure</u> (charging station) is needed in public places: offices, hotels, vehicles, to drive growth – starting now
  - Compare to the growth of wireless LAN ~ 10 years ago
  - Users will not need to carry chargers while traveling!
- **Longer term, wireless charging enables portability in other applications e.g. medical, wearable, that need to be sealed / waterproof**

Overview / Agenda

- Brief wireless power market / standards overview
- Theory of operation: Near Field / Inductively Coupled Wireless Power Systems (in widespread use today)
- Evolution of the WPC standard & new features
  - Foreign Object Detection
  - Constant Voltage vs. Direct Battery Charge RX
  - Dual Mode Compatible RX
  - Free Positioning
  - Automotive Application Considerations
  - Wearable (low power) applications

TI Leadership in Wireless Charging

Texas Instruments

History of TI's Wireless Power Innovation

2010
- First Qi-compliant system
- WPC member

2011
- World's smallest receiver
- Highly integrated second-generation solutions

2012
- WPC 1.1-compliant solutions
- First integrated receiver with Li-Ion battery charger
- First ICs to support A1, A5, A10, A11, and A6 transmitters

2013
- PMA and A4WP member
- Sampling Automotive and dual-mode solutions
- Next-generation WPC 1.1 Tx and Rx solutions

2014
- Magnetic resonance solutions
- WPC medium-power solution
- Automotive transmitter solutions
- WPC and PMA dual-mode solutions

Wireless Power Consortium (WPC)

Proprietary Solutions

Interoperability key to adoption

WPC

- Industry wide standard for delivering wireless power up to 5W
- Aimed to enable interoperability between various charging pads and portable devices
- Standard continues to gain traction with increasing list of members (105+)
- Compatible devices will be marked with a Qi logo

Power For A Wireless World

Broad Industry Support

Best Buy, Belkin, Compal, Continental, Denso, Energizer, Ever Win International Corp., Haier, Johnson Controls, LG, Motorola, NEC, Nokia Connecting People, Orange, Panasonic, Philips, Primax, RRC, Samsung, SoftBank, Sony Ericsson, StanleyBlack&Decker, Texas Instruments, Verizon wireless

and more…

Various Product Concepts

Module

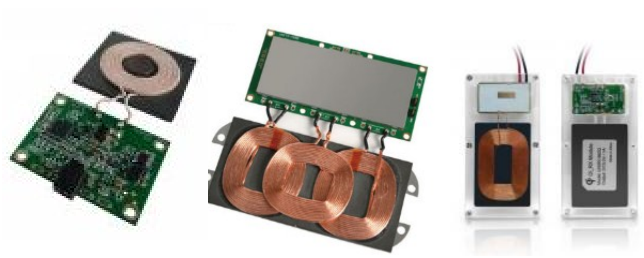


Table Mount Automotive

Built in

Accessories

The Evolving Wireless Power Market

- Standardization, Ecosystem, and Interoperability Drive Growth
- Estimate 15 M+ units shipped in 2012 → **40M+** in 2013
- Verizon and AT&T driving adoption in US; DoCoMo in Japan

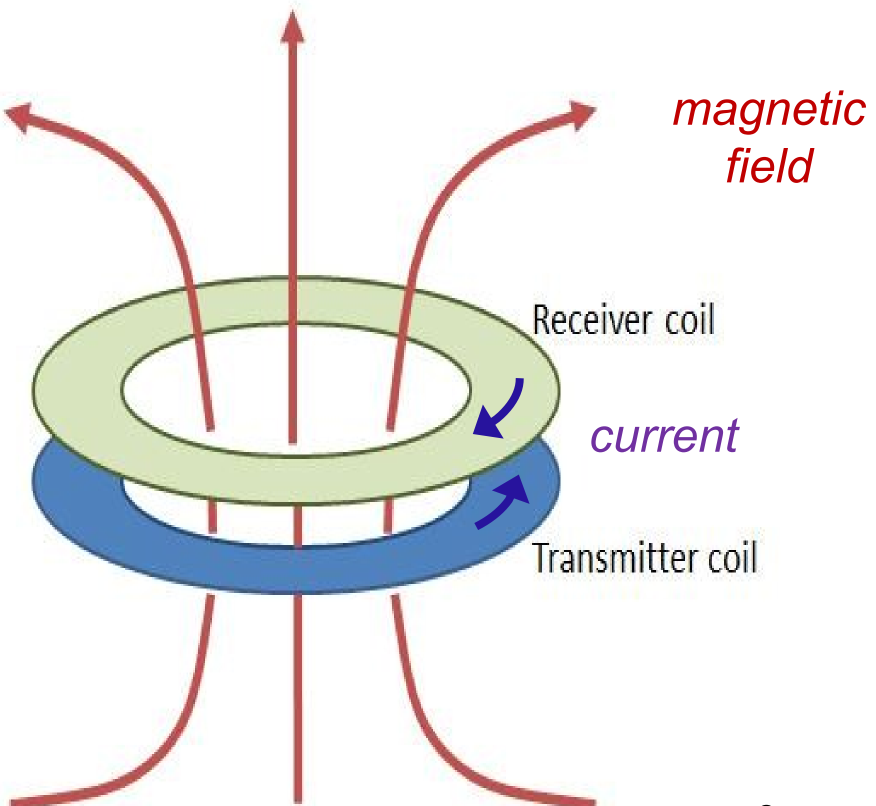
  - www.wirelesspowerconsortium.com
  - http://www.powermatters.org
  - www.a4wp.org

Wireless Power Interface Standards

	WPC / Qi 1.1	PMA	A4WP
Coupling	Tightly Coupled	Tightly Coupled	Loosely Coupled
Approximate Operating Frequency Range	100 – 200 KHz	200 – 300 KHz	6.78 MHz
Communication Path	In-Band (signaling over the power path)	In-Band (signaling over the power path)	BLE / out-of-band (separate channels for power & control)
System level Efficiency	> 70%	> 70%	
Spatial Freedom with existing standard	Medium	Lowest	Highest
Future enhancements planned	Qi 1.2 spec extension will add loosely coupled / resonant capability to WPC Standard	Adopted A4WP as resonant spec; next steps TBD	

HOW DOES IT WORK?

Inductive Coupling

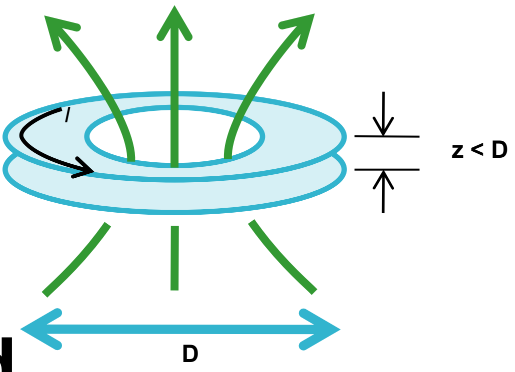


Source: www.wirelesspowerconsortium.com

- *Current in primary coil (transmitter) generates magnetic field*
- *Magnetic field induces current in secondary coil (receiver)*
- *Received current is used to charge battery or power load device*

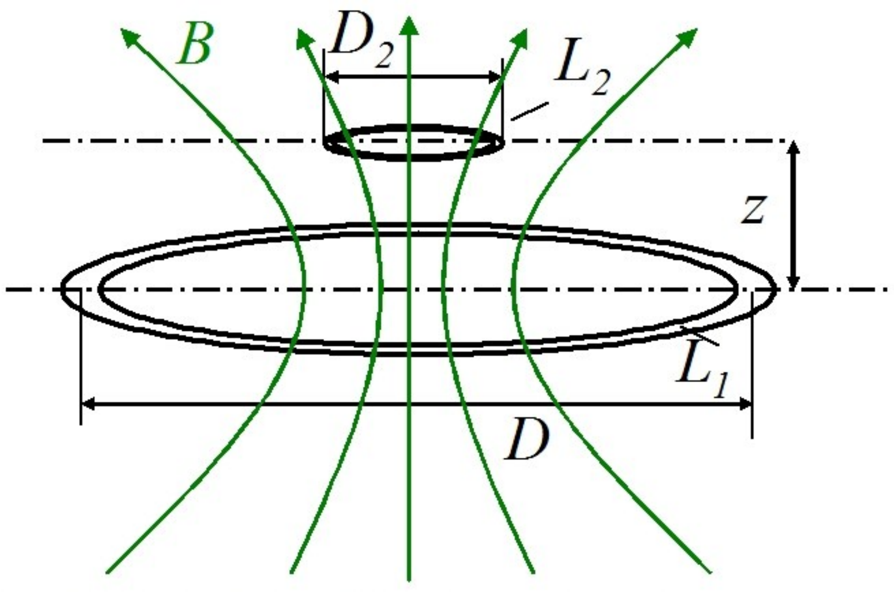
Wireless charging beyond the toothbrush:

Intelligent Control of Inductively Coupled Power Transfer



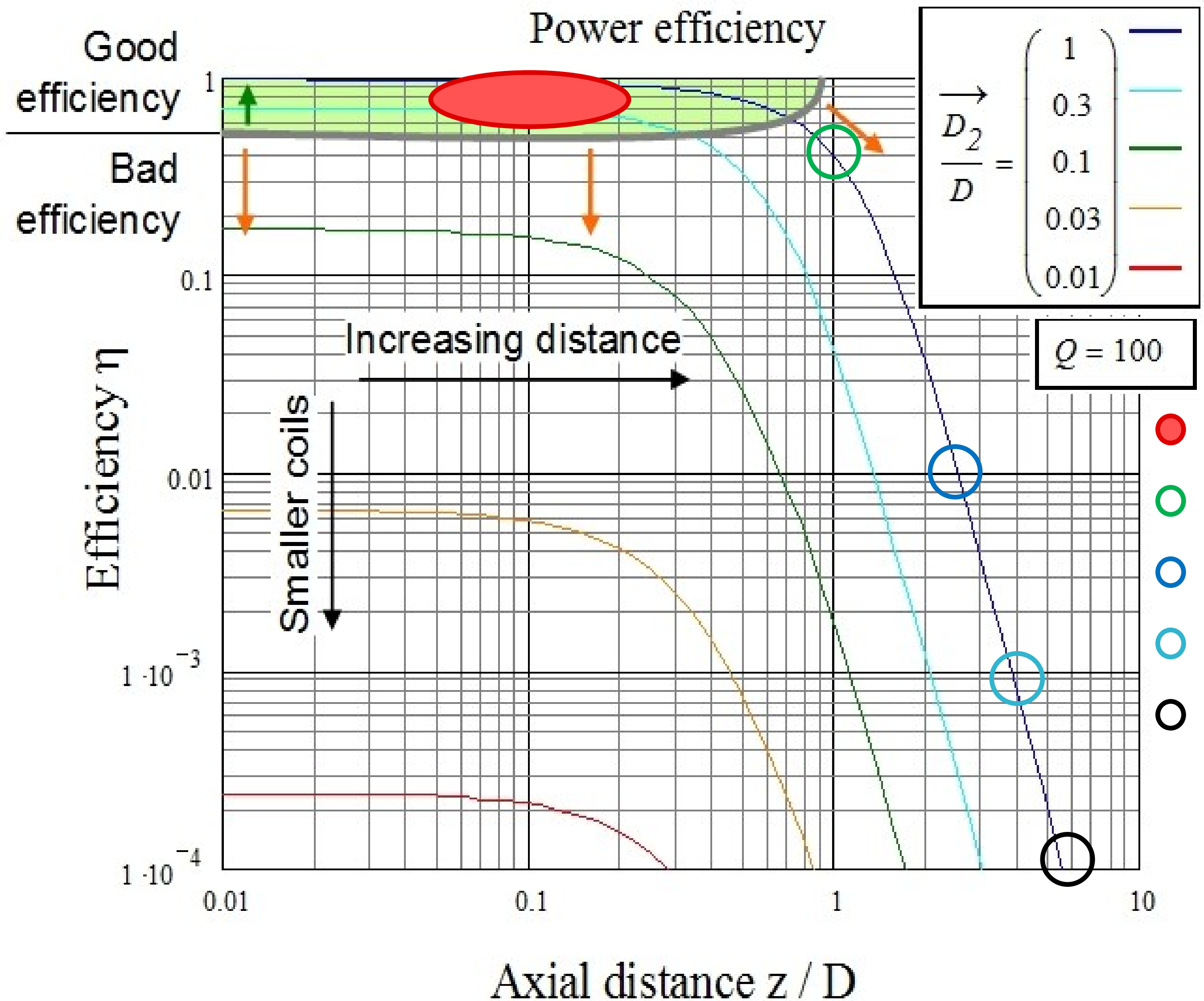
- **Power transmitted through shared magnetic field**
  - Transmit coil creates magnetic field
  - Magnetic field induces current in receiver coil
  - Shielding material below TX and above RX coils
- **Power transferred only when needed**
  - Transmitter waits until its field has been perturbed
  - Transmitter sends seek energy and waits for a digital response
  - If response is valid, power transfer begins
- **Power transferred only at level needed**
  - Receiver constantly monitors power received and delivered
  - Transmitter adjusts power sent based on receiver feedback
  - If feedback is lost, power transfer stops

Factors Affecting Coupling Efficiency



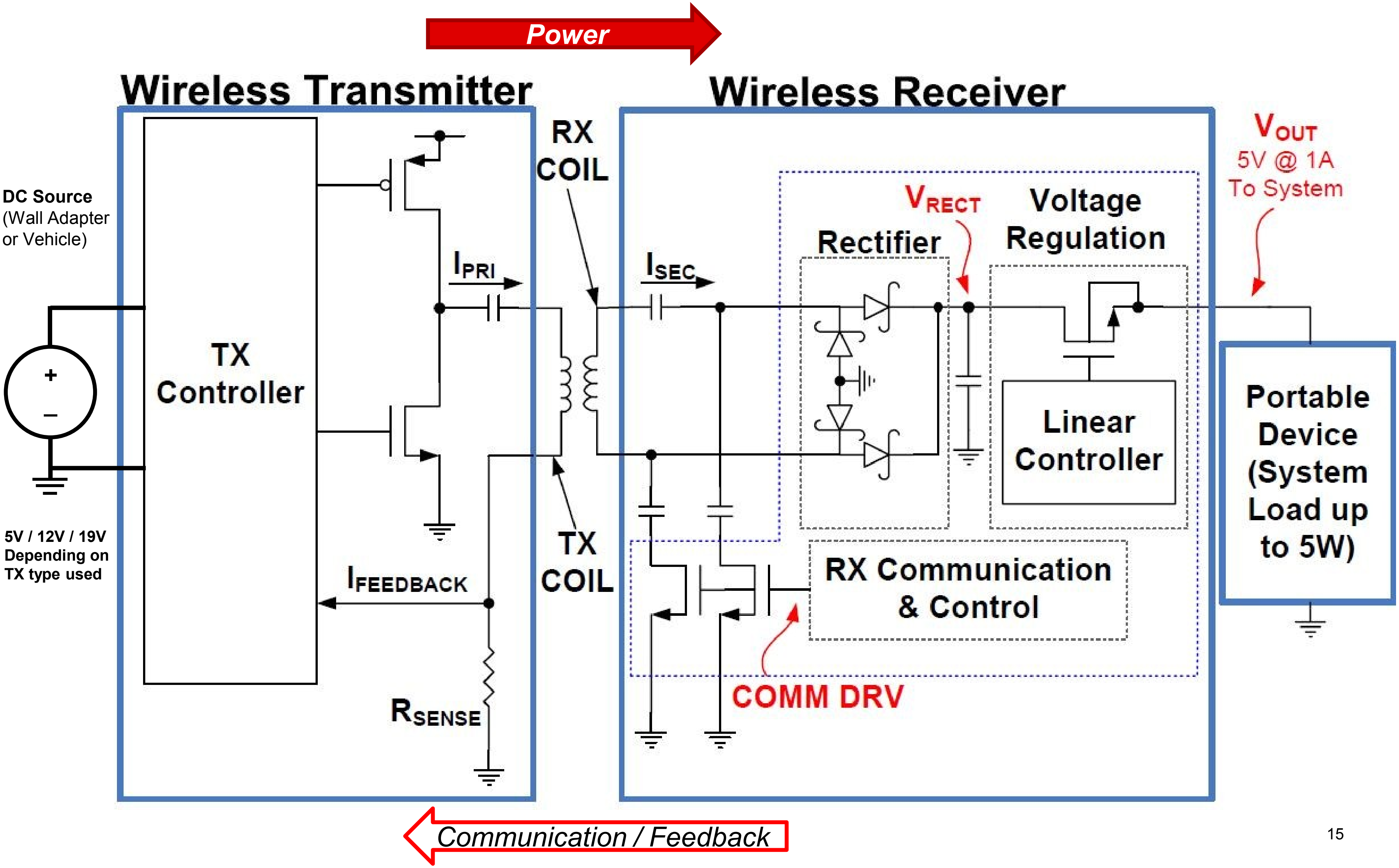
- **Coil Geometry**
  - Distance (z) between coils
  - Ratio of diameters (D_2 / D) of the two coils → *ideally D2 = D*
  - Physical orientation
- **Quality factor**
  - Ratio of inductance to resistance
  - Geometric mean of two Q factors
- **Near field allows TX to "see" when RX is present**
- ***Good Efficiency when coils displacement is less than coil diameter (z << D)***

Factors Affecting Coupling Efficiency



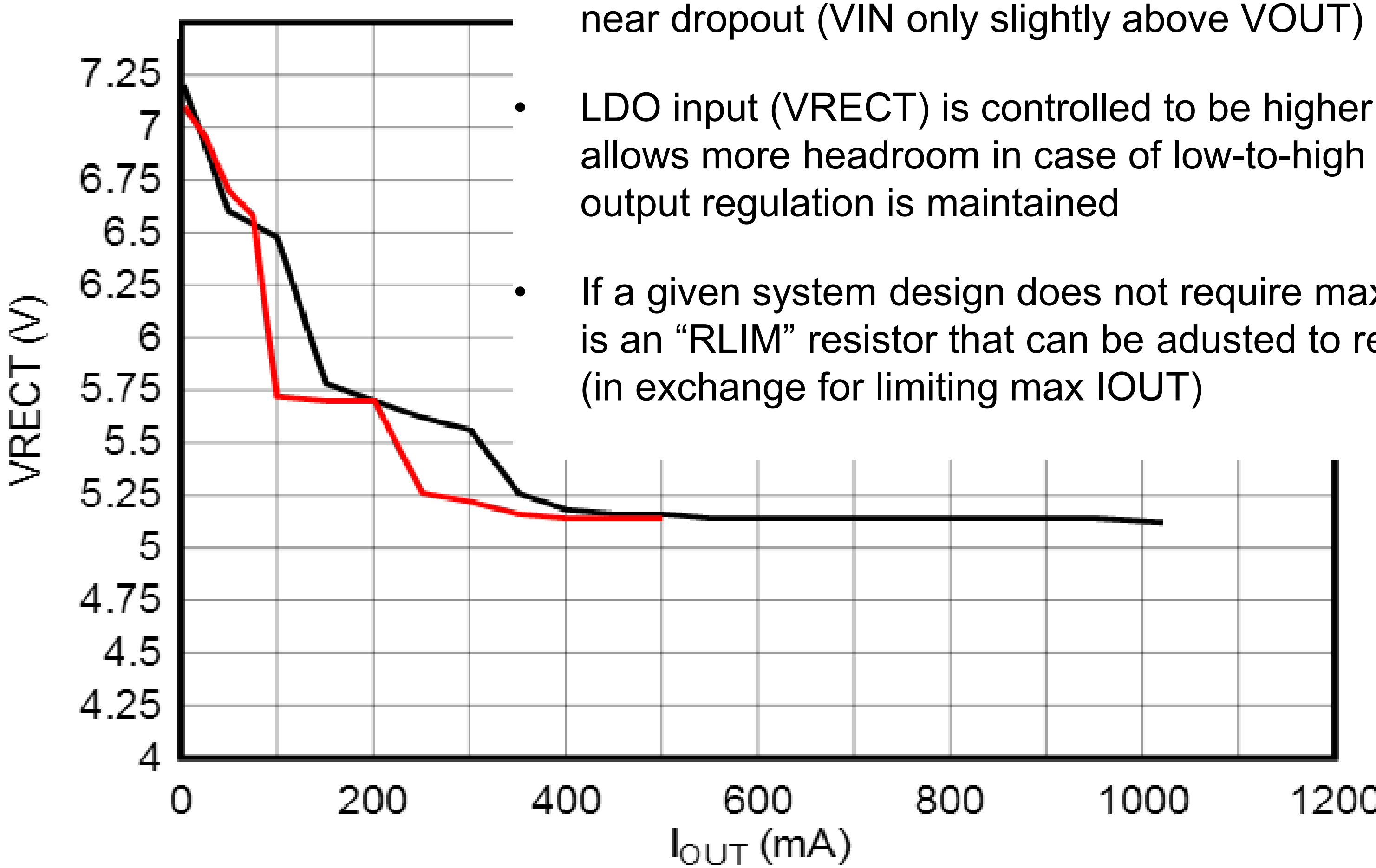
- Optimal operating distance
- 40% at 1 diameter
- 1% at 2.5 diameters
- 0.1% at 4 diameters
- 0.01% at 6 diameters

TI Solution: bq50xxx + bq51xxx chipset



Optimizing Efficiency & Load Transient Response

- RX has linear regulator stage, but the overall system (TX+RX) acts as a feedback-controlled switch mode regulator
- LDO output stage can be efficient if linear regulator is operated near dropout (VIN only slightly above VOUT)
- LDO input (VRECT) is controlled to be higher at light loads – allows more headroom in case of low-to-high load transient so output regulation is maintained
- If a given system design does not require max output power, there is an “RLIM” resistor that can be adusted to reduce the LDO input (in exchange for limiting max IOUT)

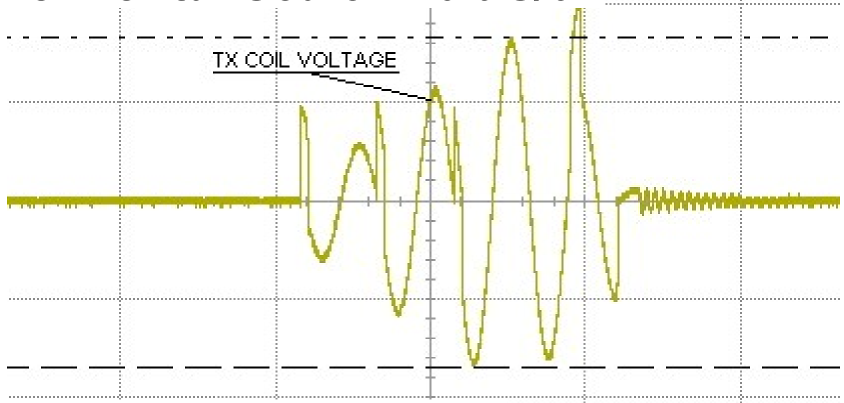


Communication - Basics

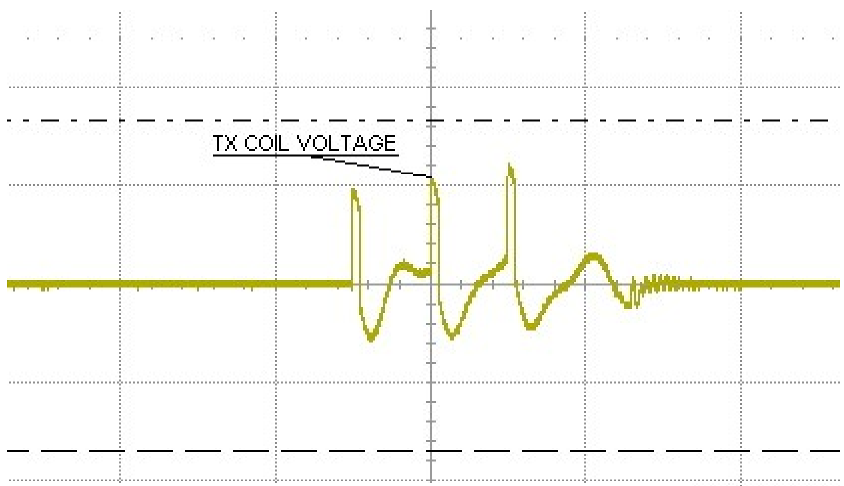
- **Primary side controller must detect that an object is placed on the charging pad.**
  - When a load is placed on the pad, the primary coil effective impedance changes.
  - "Analog ping" occurs to detect the device.
- **After an object is detected, must validate that it is WPC-compatible receiver device.**
  - "Digital Ping" – transmitter sends a longer packet which powers up the RX side controller.
  - RX side controller responds with signal strength indicator packet.
  - TX controller will send multiple digital pings corresponding to each possible primary coil to identify best positioning of the RX device.
- **After object is detected and validated, Power Transfer phase begins.**
  - RX will send Control Error Packets to increase or decrease power level
- **<u>WPC Compliant protocol ensures interoperability.</u>**

Analog Ping with and without object on pad

Vertical Scale: 20V/div
Horizontal Scale: 20 uS/div

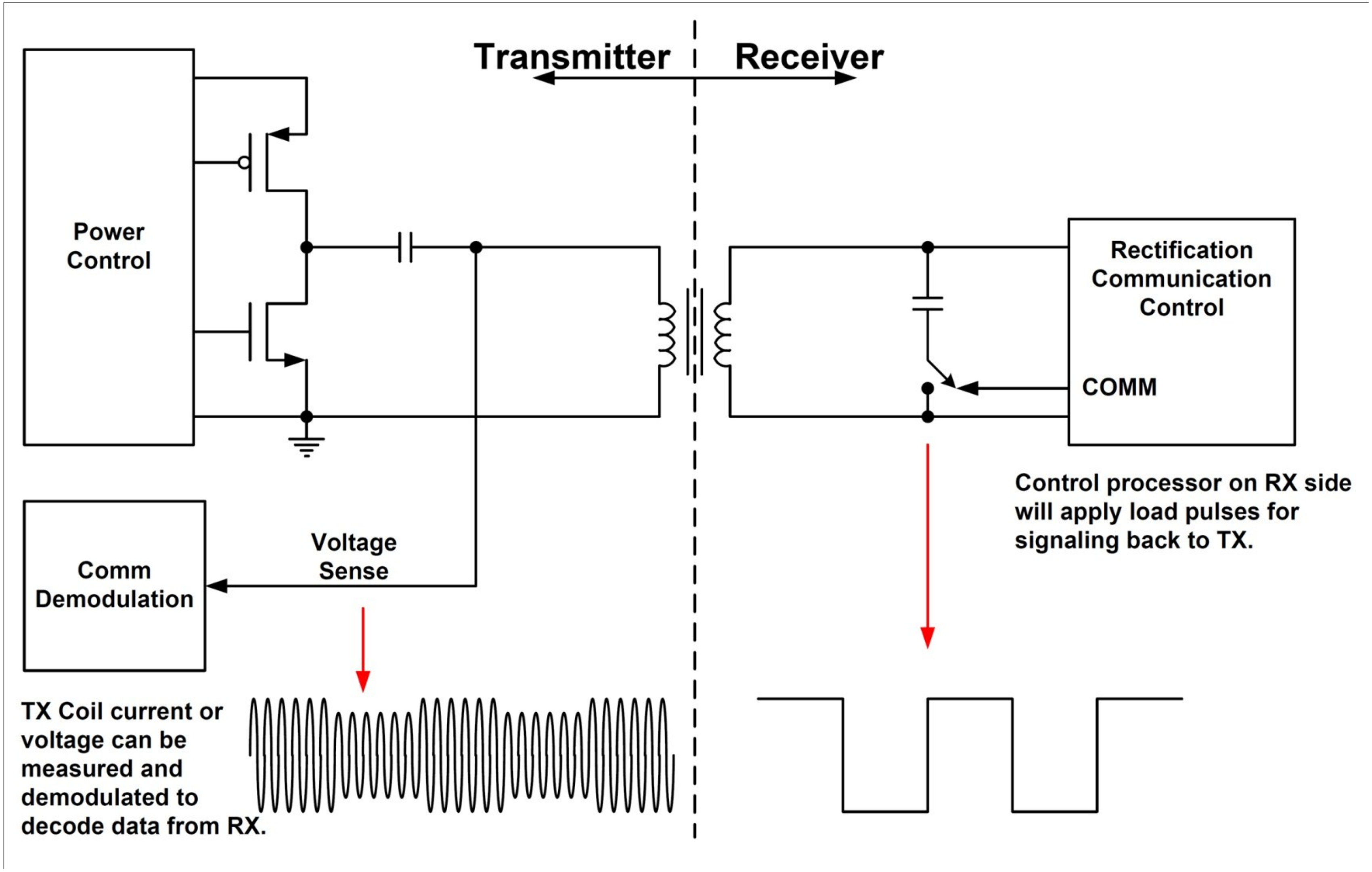


(a) No object on pad

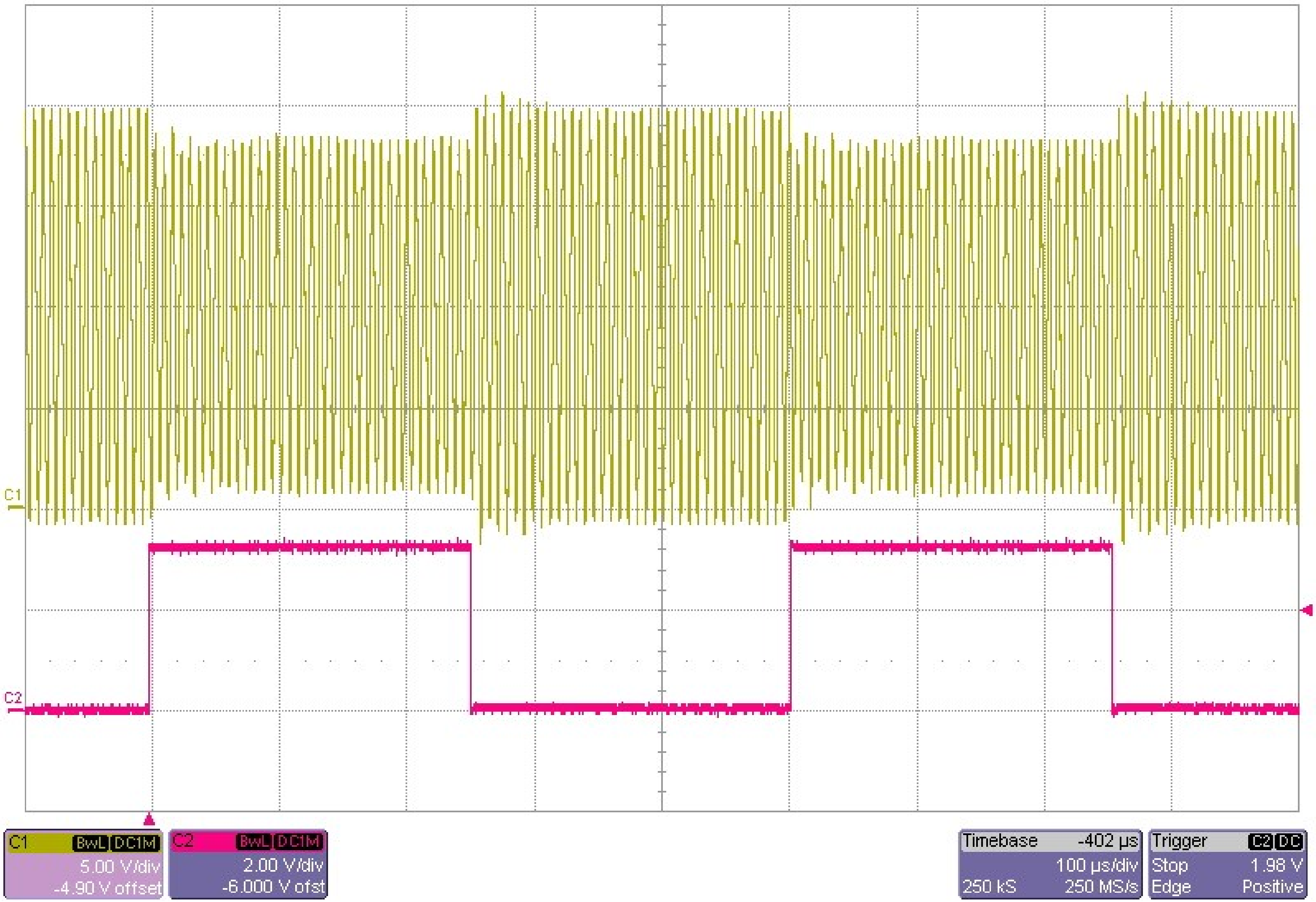


(b) RX Device placed on pad

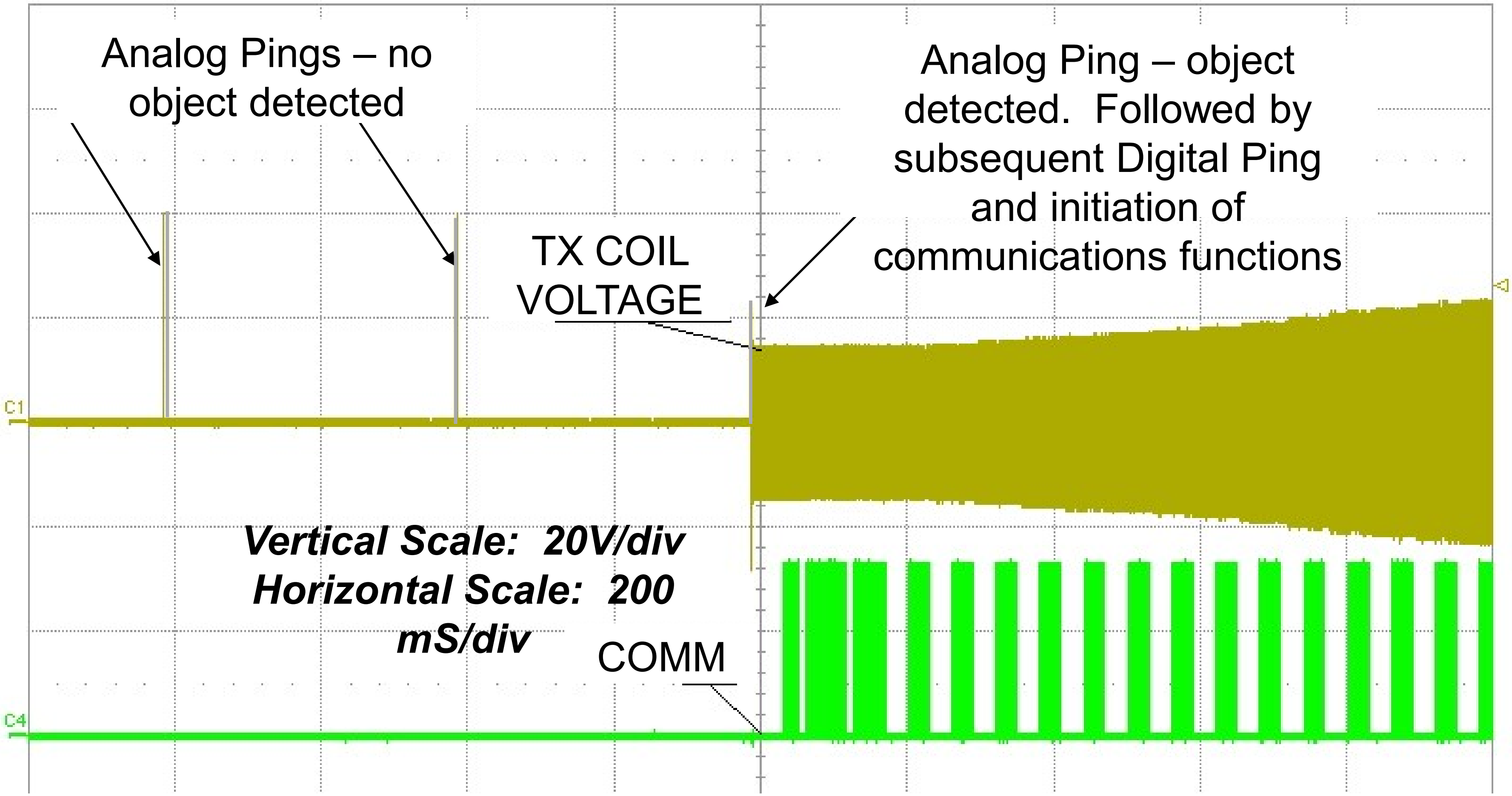
Communication – Implementation



Communication – actual waveform

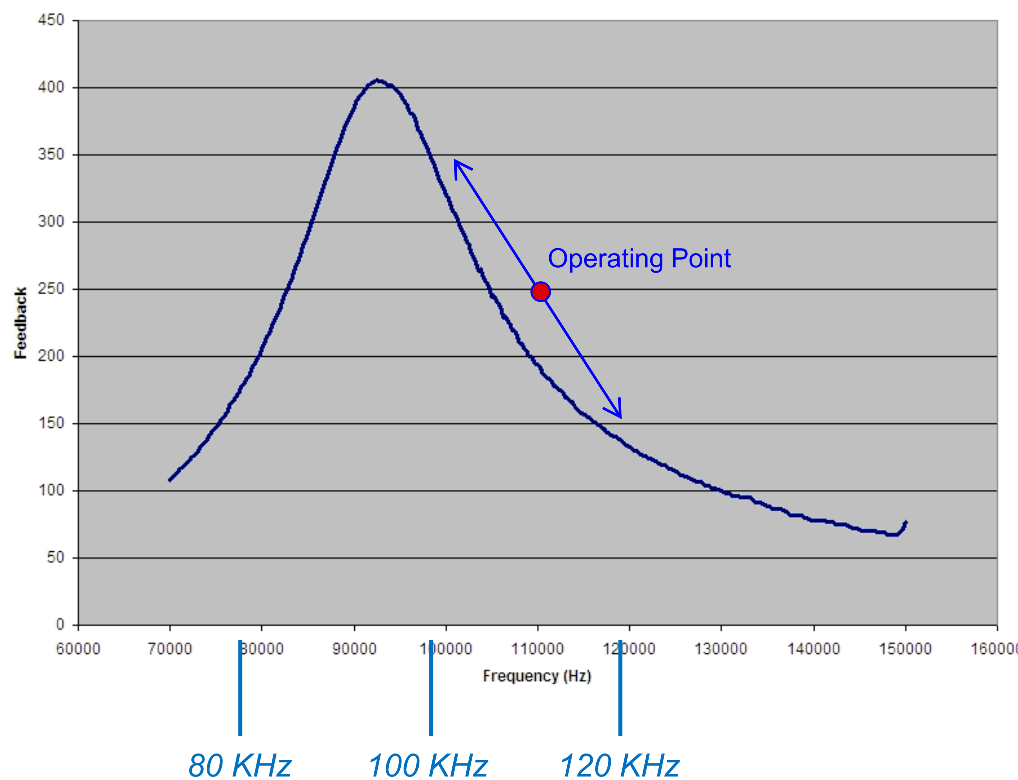


Analog Ping / Digital Ping / Startup



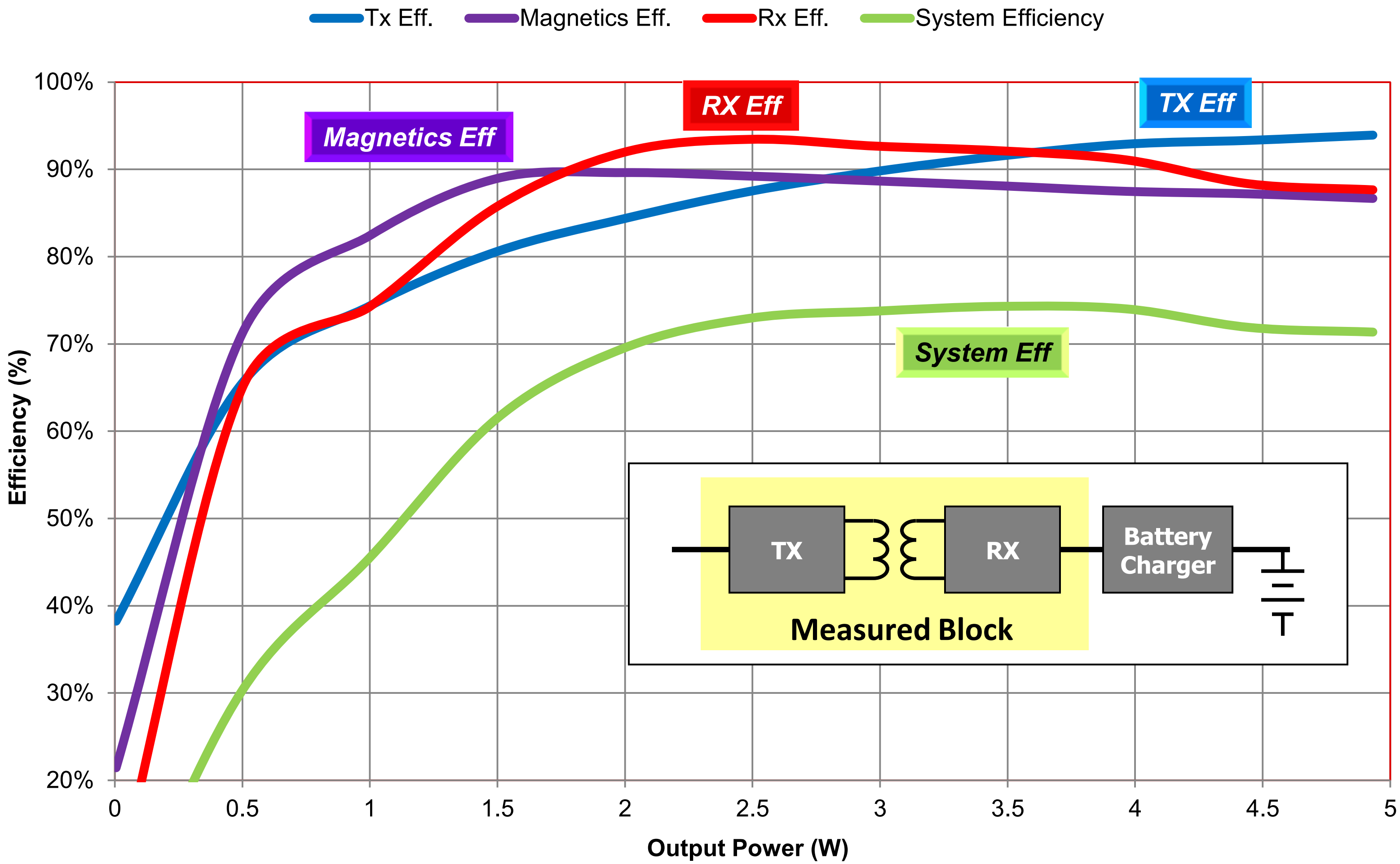
Resonant Power Transfer – Switching Frequency Variation

- **5W Capable System operates near resonance for improved efficiency.**
- **Power control by changing the frequency, moving along the resonance curve; about 100 – 200KHz for Qi**
- **Modulation using the power transfer coils establishes the communications.**
- **Feedback is transferred to the primary as error.**

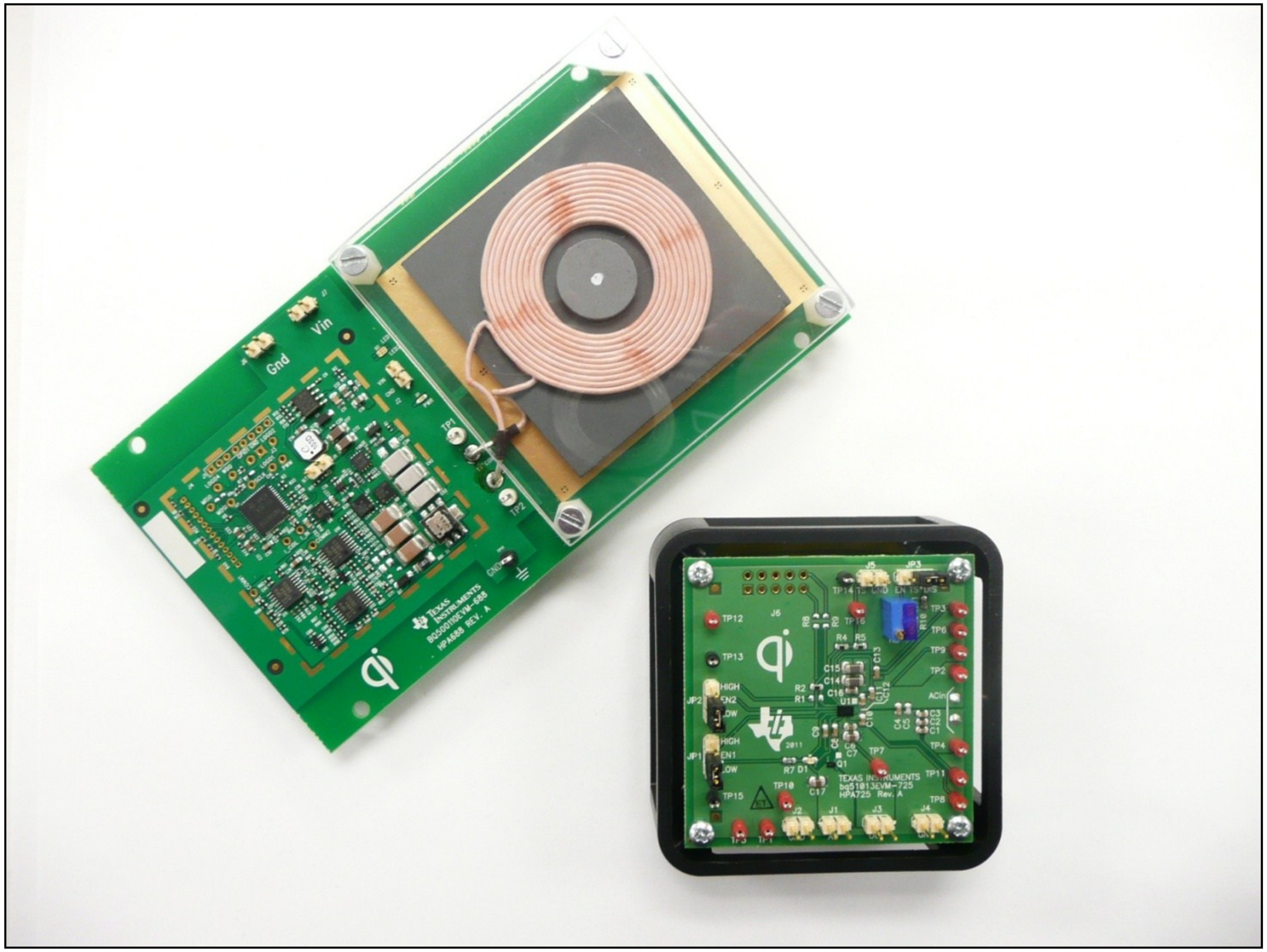


bqTesla System Efficiency Breakdown

- **Efficiency is RX Coil design dependent**
- **Measured from DC input of BQ500210 TX to DC output of BQ51013 RX @ 5V out**
- **<u>Net efficiency to battery</u> can be higher using direct charge vs. 2-stage charge architecture**

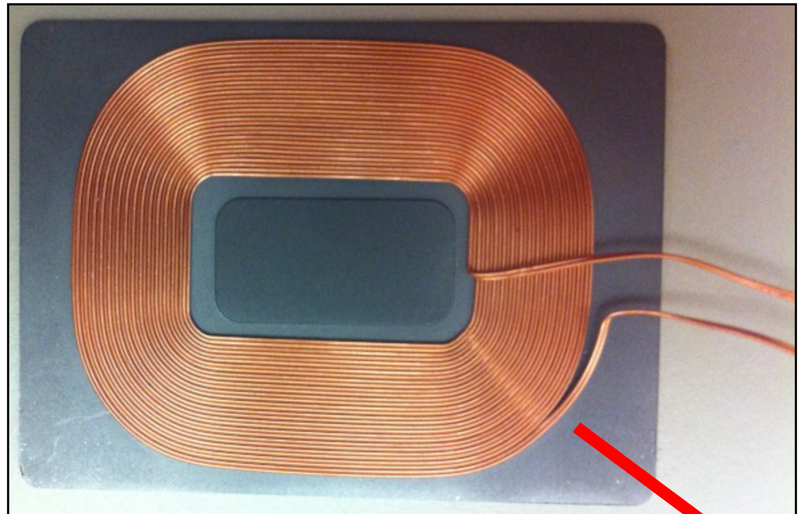


Typical TI Evaluation Kits



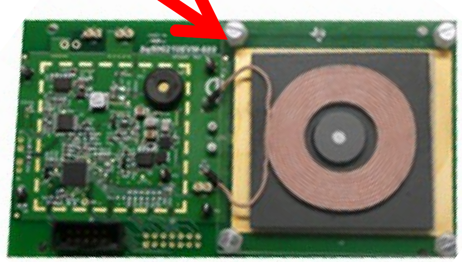
Qi-compliant coil used w/ EVM kit

WPC Compliant Transmitter Coil

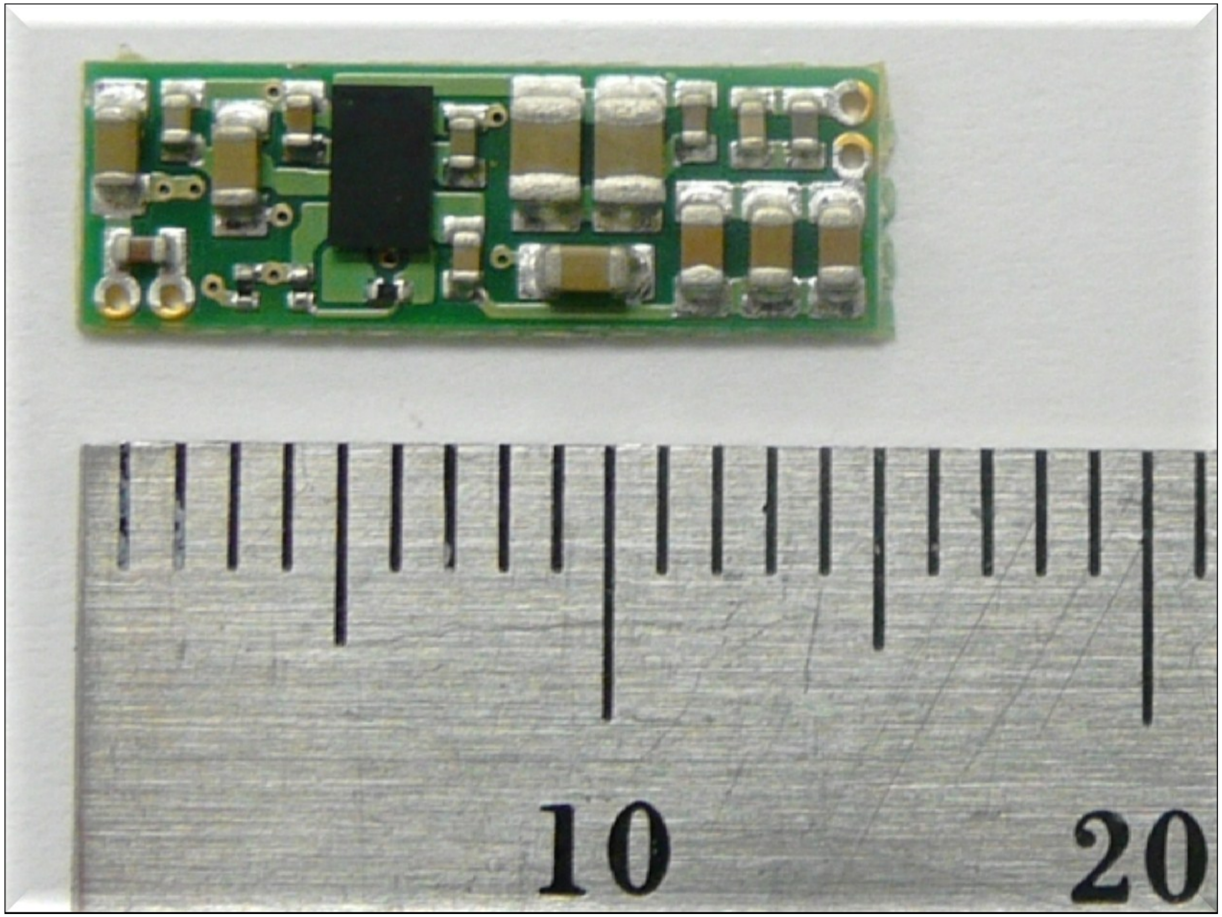


40-mm x 30-mm x 0.75-mm

WPC Compliant Receiver Coil



bq51013 *“form factor”* demo PCB *(PR1041)*

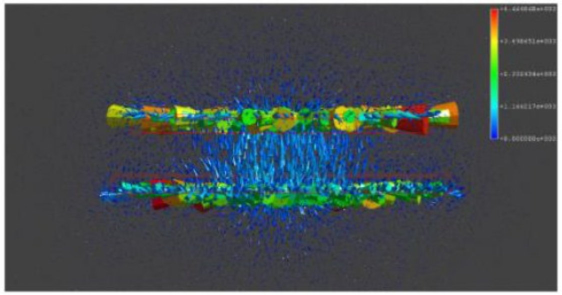


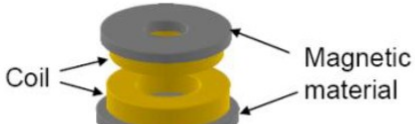
5 x 15 mm footprint for all RX side circuitry

- **Represents what an OEM would design into their actual end-product to enable wireless power from a QI-compliant charging pad.**

WPC1.0 → WPC1.1 Evolution: “FOD”

- **Metal between TX and RX**
  - Bottom of TX and top of RX coils are shielded to create a “closed system”
  - Any metal BETWEEN the RX and TX coils will result in loss / heating due to energy lost in Foreign Metals (Eddy Current)

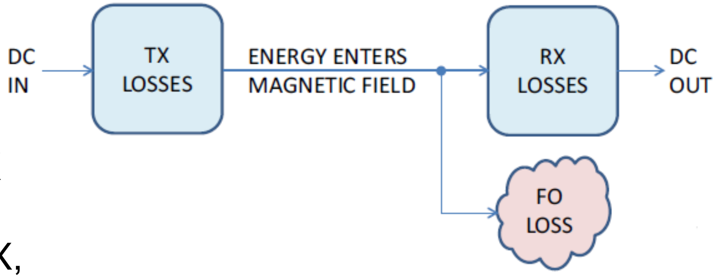




Source: Würth Elektronik

Two methods to detect foreign objects via monitoring power losses:

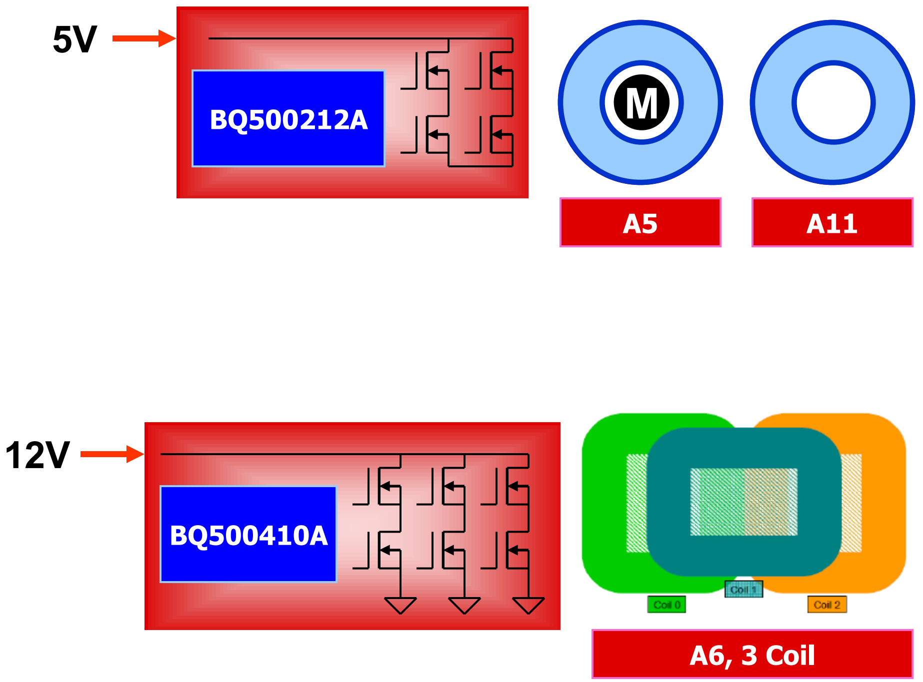
- **PMOD (TI method, Parasitic Metal Object Detection)**
  - An approximation based on the **Rectified Power** reported by RX to calculate losses in the TX-RX system



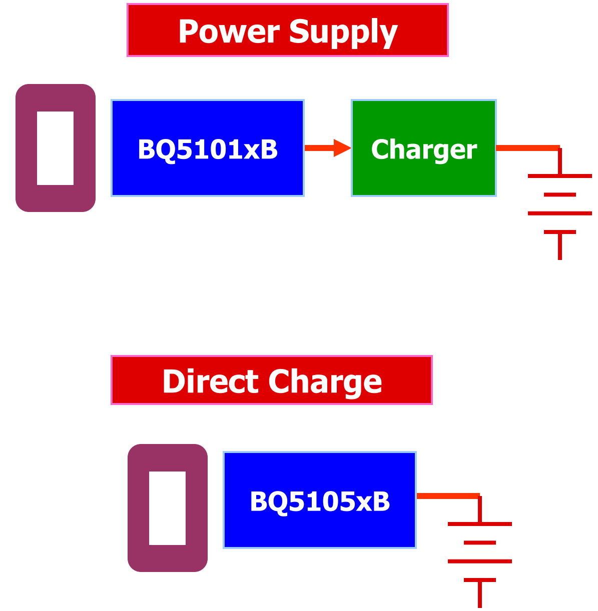
- **WPC1.1: Foreign Object Detection**
  - This uses specific information from characterized RX to improve the accuracy of Foreign Object Detection in WPC system (looking at **Received Power** from RX, and power lost in shield, coil, rectifier and control circuit).
  - FOD is finalized in WPC 1.1 spec

Basic Options for WPC1.1 solution

- **TX, A version**
  - BQ500212A
  - BQ500410A



- **RX, B version**
  - Power Supply, BQ5101xB
  - Direct Charge, BQ5105xB



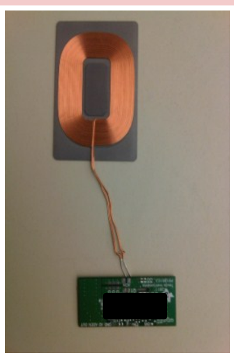
Standard TX Coil Types: A1/A10 vs A6

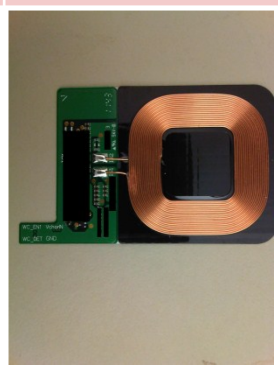
TX Type	A1	A10	A6 Single Coil
Magnet	Yes	No	No
Vin	19V		12V Lower cost adaptor
Ferrite size	53x53mm^2		
Coil Area	Circle		Rectangle, bigger
Power	Half Bridge		
Design	No extension		A6 – 3 coil TX

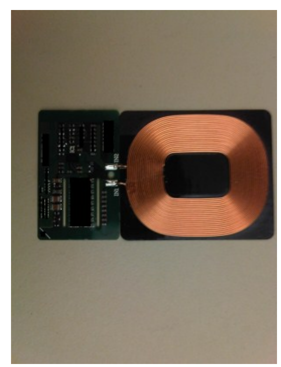
RX Coil Types (examples – many others are possible / in development)

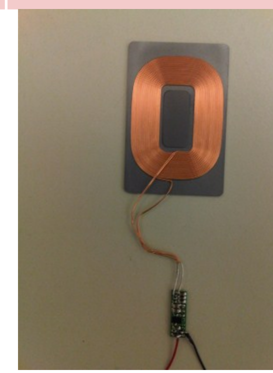
	Example 1	Example 2	Example 3	Example 4	Example 5
Shield z	0.65 mm	0.44 mm	0.40 mm	0.65 mm	0.65 mm
Coil z	0.35 mm	0.35 mm	0.40 mm	0.40 mm	0.35 mm
Coil x,y	29x30 mm²	32x32 mm²	30x34 mm²	13x24 mm²	29x30 mm²
Circuit					
Component z	1.0 mm	0.5 mm	0.60 mm	0.9 mm	1.0 mm
PCB z	0.75 mm	0.4 mm	0.25 mm	0.5 mm	0.5 mm
Area	16x36 mm²	14x37 mm²	20x32 mm²	10x33 mm²	5x15 mm²
Power	5W	4W	3.5W	4W	2.5W
PCB Thermal Performance ^	45C*	50C*	55C*	58C*	62C*

* Temp will depend on many factors. This is just representative of one design. Actual implementation will vary thermal performance

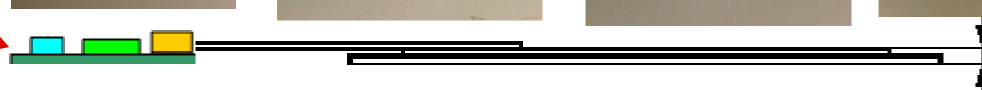








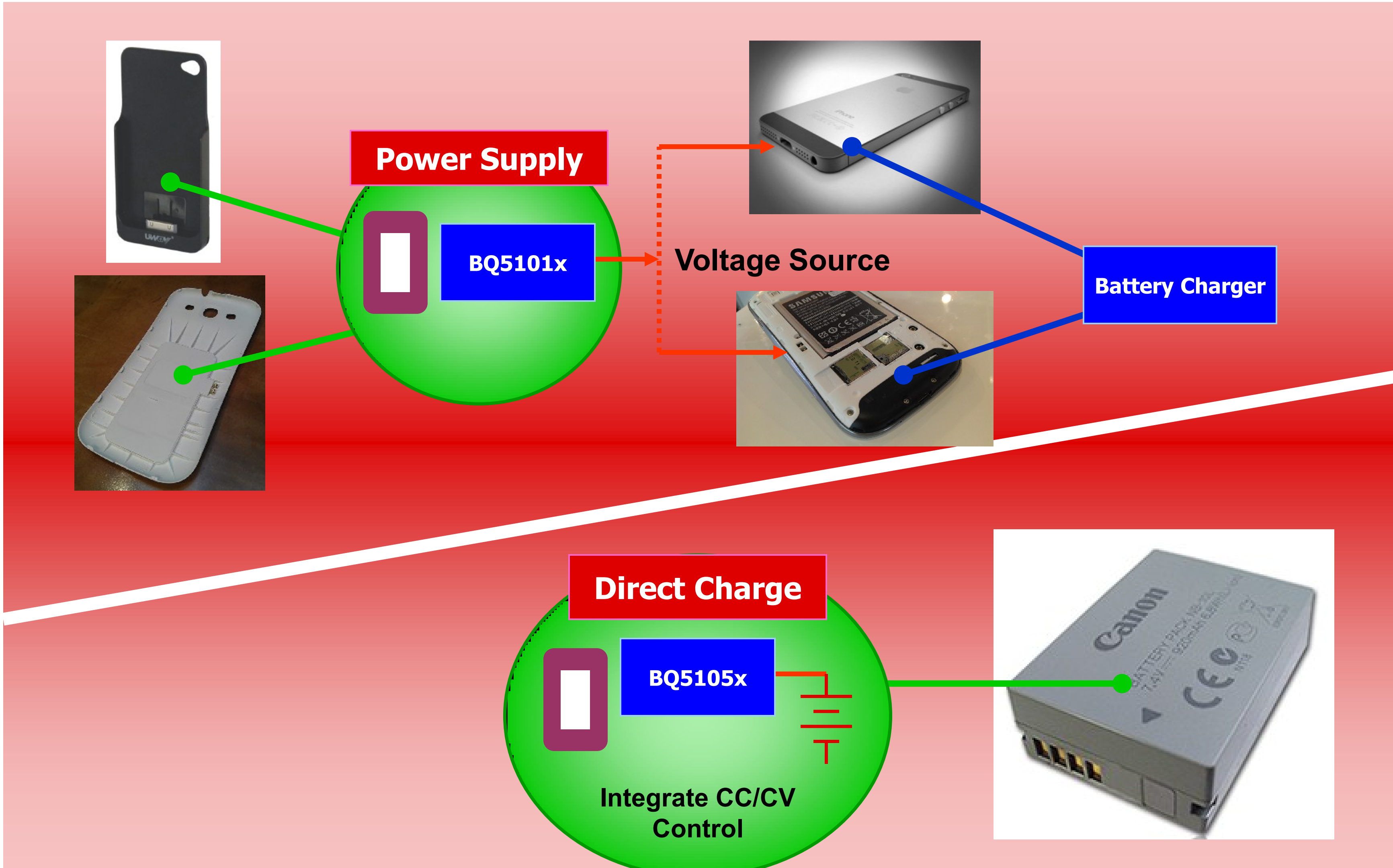
Side View PCB w/ components



Side View Coil w/ shield

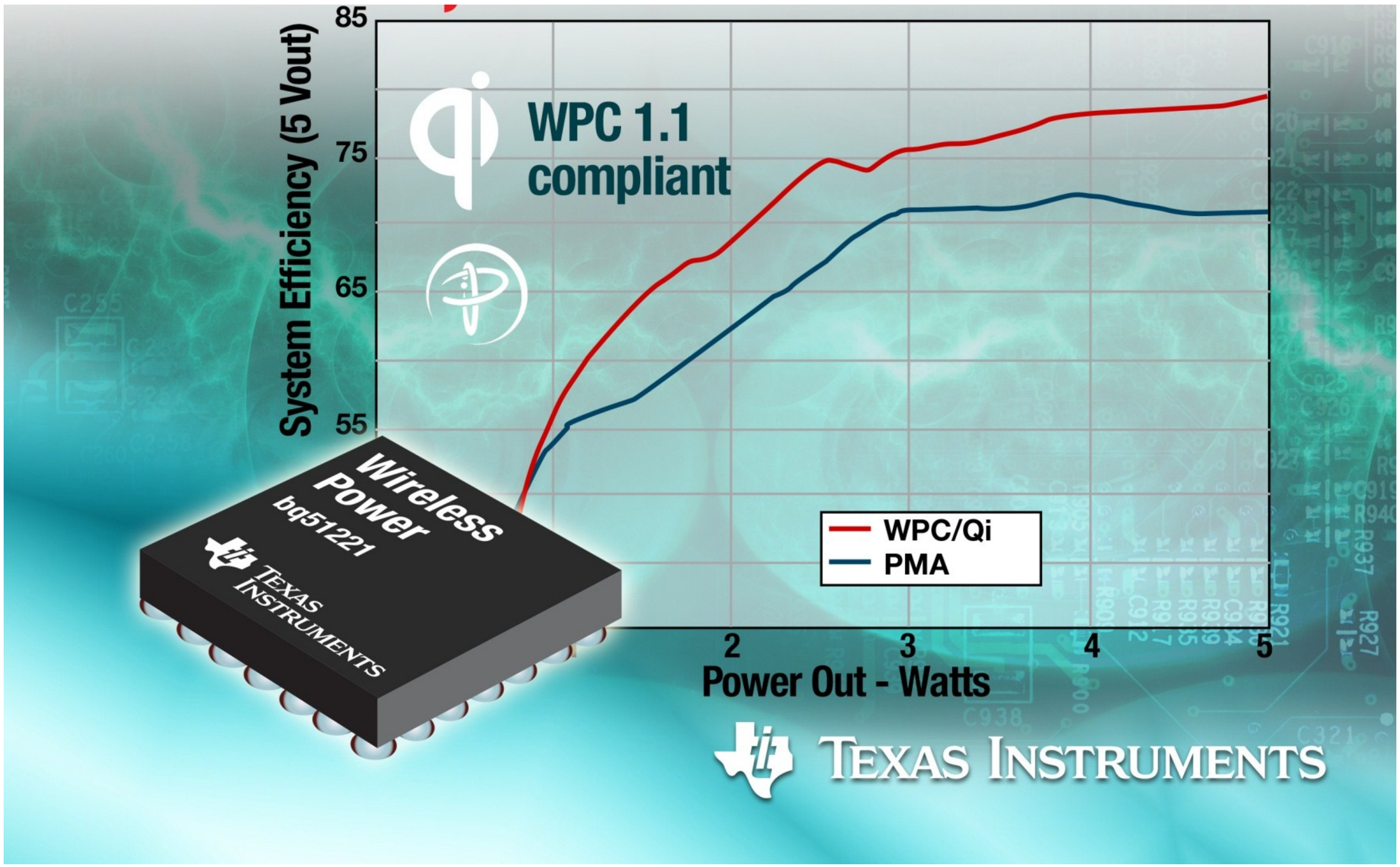
Texas Instruments

RX: bq51k Family options



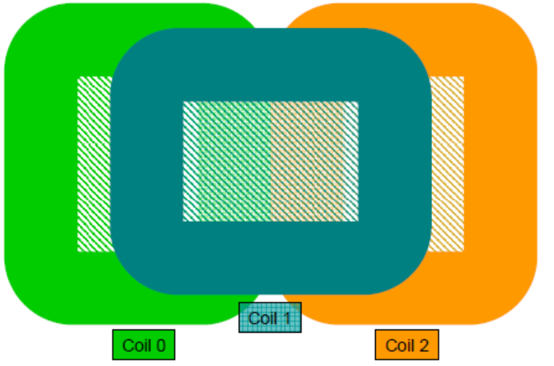
Dual Mode RX: Works on PMA and WPC Pads

- RX device will recognize and respond to detection signals from TX pad
- New silicon core with higher efficiency (lower loss) power FETs
- System-level efficiency now approaching 80% in WPC mode



bq500412 – 3 Coil Transmitter
Enables "Free Positioning" of portable device

- **WPC A6 improves Charging Area for WPC Compliance**
  - From A1 18x18mm to > 70x20mm
  - Extend definition to "At least one Primary Coil"



- **Key Specs**
  - 12V Input Voltage
  - A1 Power Transfer Methodology,
    - Half Bridge
    - 120KHz to 205KHz frequency range
    - 175KHz +/-5KHz Digital Ping to initiate Transfer
    - Same Shielding

- **Drives one coil at a time, Enables Efficiencies > 70%**

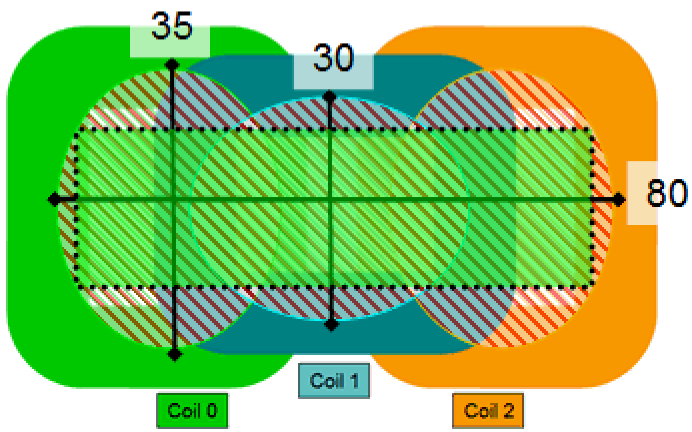
- **Robust Drive methodology addresses potential issues w/ large Transmitter coils (several patents pending)**
  - RX Overvoltage
  - Controlled coupling for WPC1.1
  - Protection from Friendly metal

CE4A Recommendation Wireless Charging:

The CE4A committee has been observing and examining the development of various charging standards since 2010.
The CE4A's observations, discussions, and workshops focused on, among others, the Alliance for Wireless Power (A4WP®), the Power Matters Alliance (PMA®), and the Wireless Power Consortium (WPC®) with its Qi® standard…

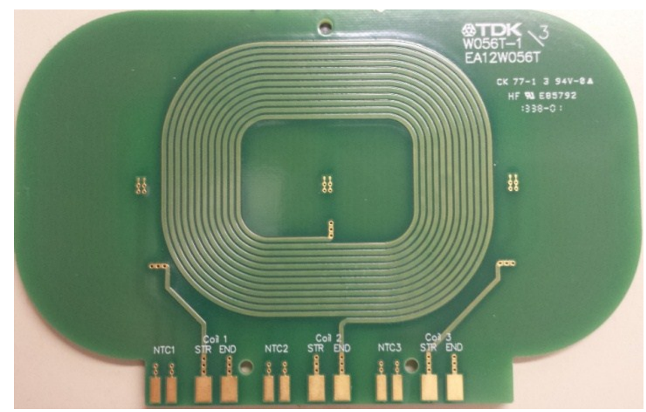
…Based on these considerations, CE4A recommended its members to use the Qi® standard in current and future vehicle models.

Extended Charging Area for "Free Positioning" with Multi-Coil TX – key requirement for automotive built-in TX designs



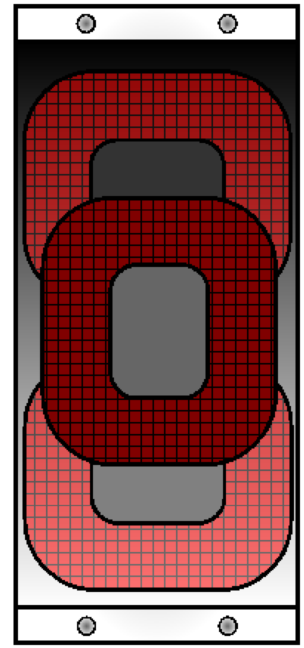
Guaranteed Rectangular Charging Area
For Center of Rx Coil (70x20)

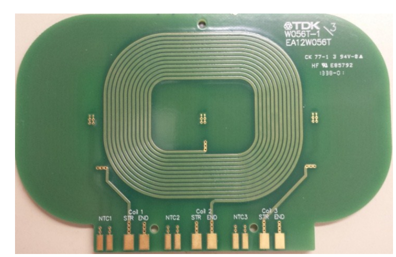
Denotes Active Charging Area
For Center of Rx Coil



bq500414Q – Three Coil Transmitter for Automotive

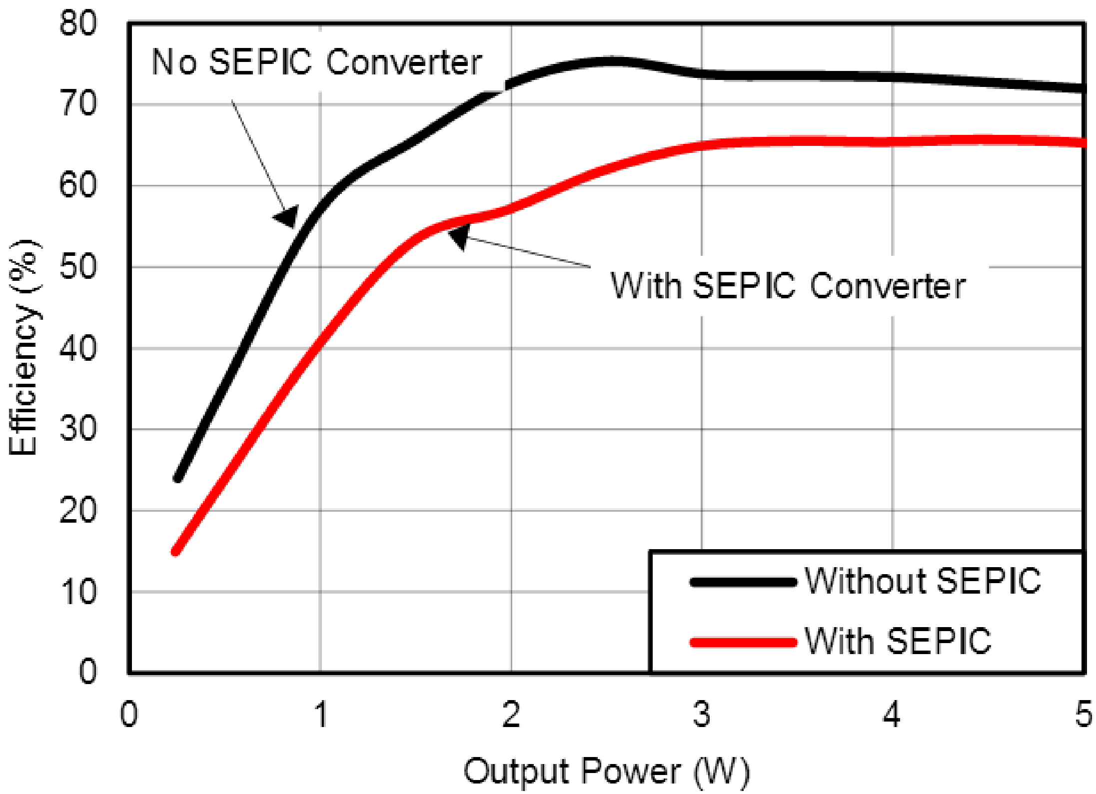
- WPC 3 coil A6 and A21 Transmitter – Liked by CE4A
  - ~70x20mm Guaranteed Charging Area
  - 120kHz to 205kHz frequency range
  - 135kHz Analog Ping to detect RX presence
  - 175kHz Digital Ping to initiate Power
  - Excellent Efficiency ~70%
- Q100 Certification
- WPC 1.1 Compliance (FOD)
- CAN/LIN can access device commands via I2C
- System level EMI improvement (EMI shield)
- Option to move Tx operating frequency when smart key/immobilizer is in use
- **Supports 6V to 16V Input Voltage Range with additional SEPIC**
- Optional Customer Defined Proximity Sensor to turn TX on/off
- Supports A21, PCB coil version of A6



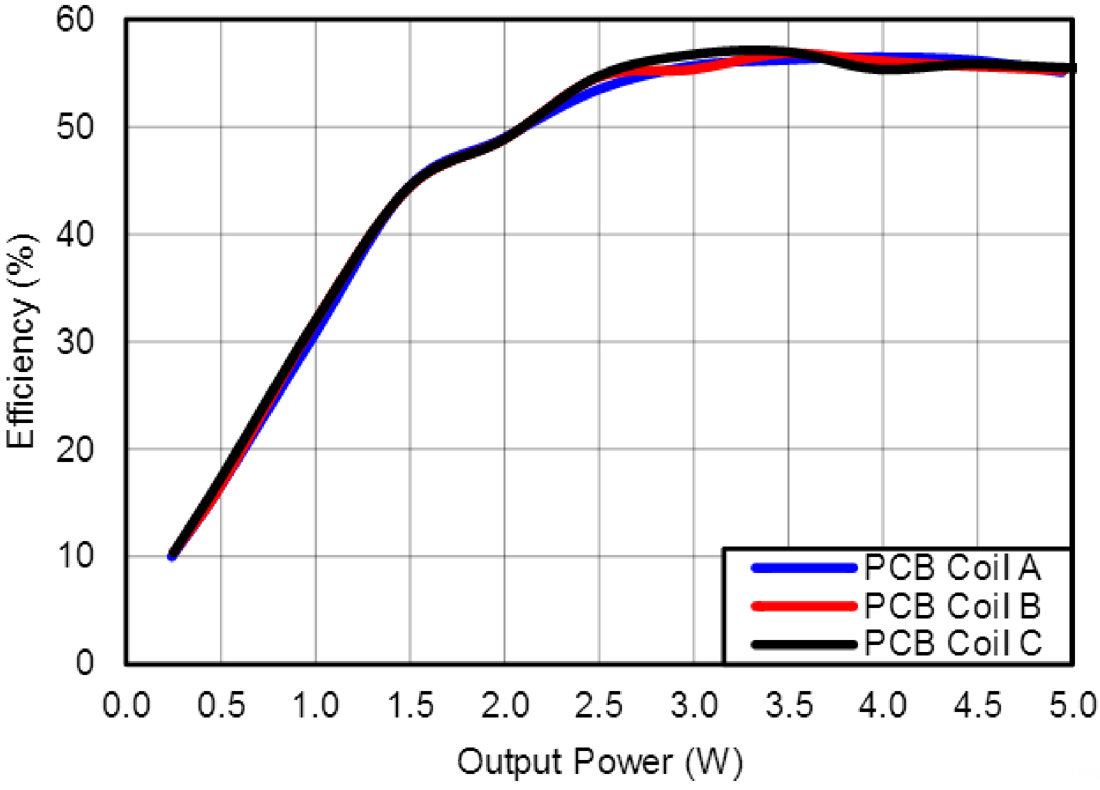


bq500414Q System Level Efficiency

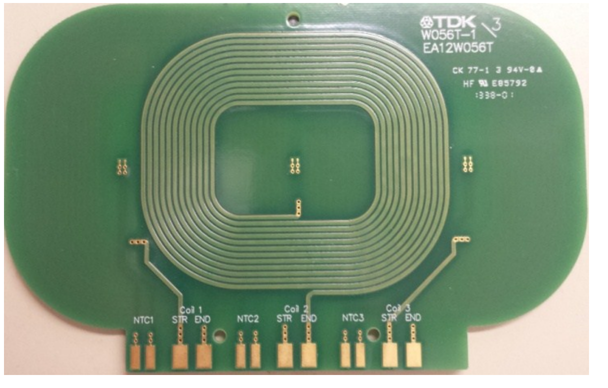
- bq50xxx transmitter controllers use a regulated (5V, 12V, or 19V) power source depending on the specific device
- For an automotive application, vehicle DC power rail is not inherently regulated
- A front-end SEPIC or buck-boost regulator is required to adapt the (typical) 6 – 16V DC source to regulated +12V for input to the bq500414Q
- Net result is that overall system efficiency is about 90% of the standard wireless power system due to additional losses in SEPIC pre-regulator stage



bq500414Q System Level Efficiency with PCB Coil (A21 Type)

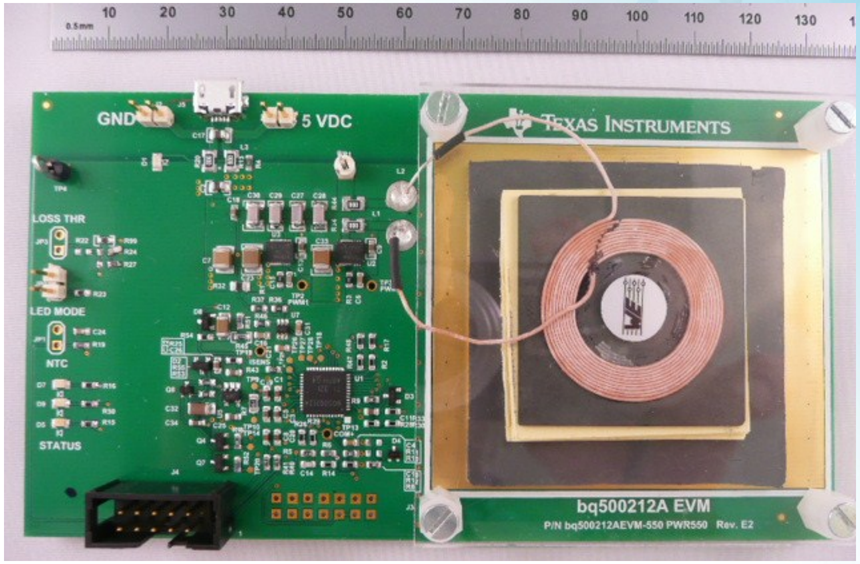


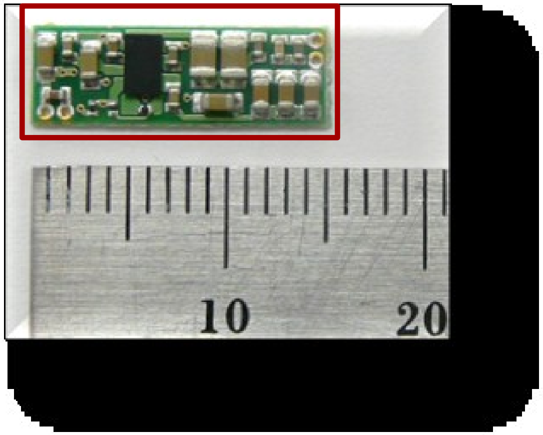
- PCB Coil benefit = resistant to shock & vibration (desired in vehicle environment)
- Drawback = lower efficiency due to limited copper thickness possible in PCB windings

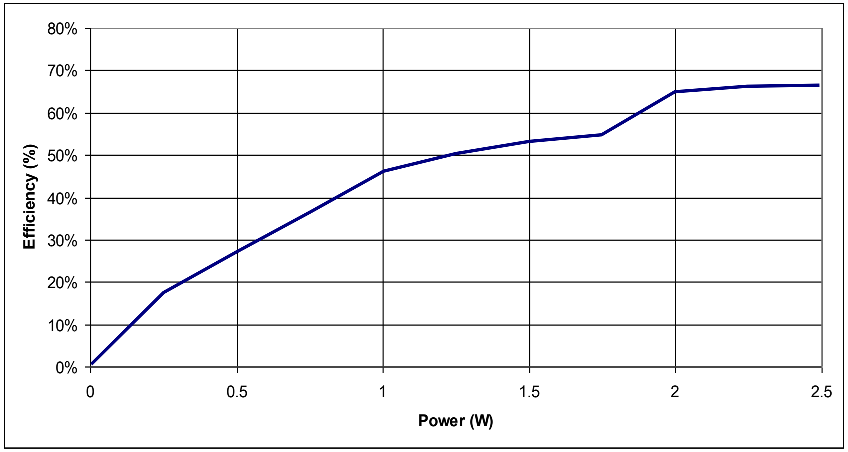


Wireless Power Solutions for Wearable Applications

- Transmitter:
  - bq500212A with modified Coil
- Receiver:
  - bq51003, New 2.5W Receiver with fixed output voltage
  - Total solution size <50mm^2
  - Best in Class Efficiency

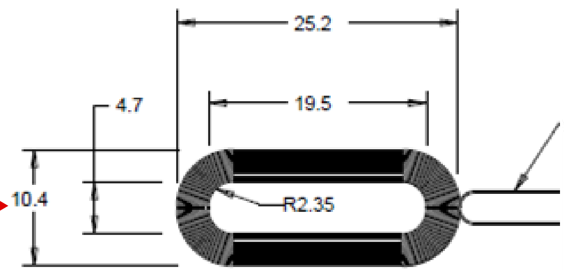




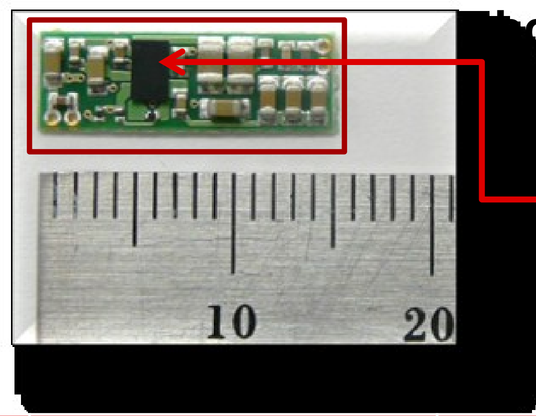


bqTESLA™ RX in Wearable Products

- bqTesla™ wireless power receivers are ideally suited for wearable devices
  - Industry's Smallest solution size – **only 50 mm² true application area**
  - **Best**



Wireless charging Coil for Wearable Devices



q510xxB ireless ceiver chip

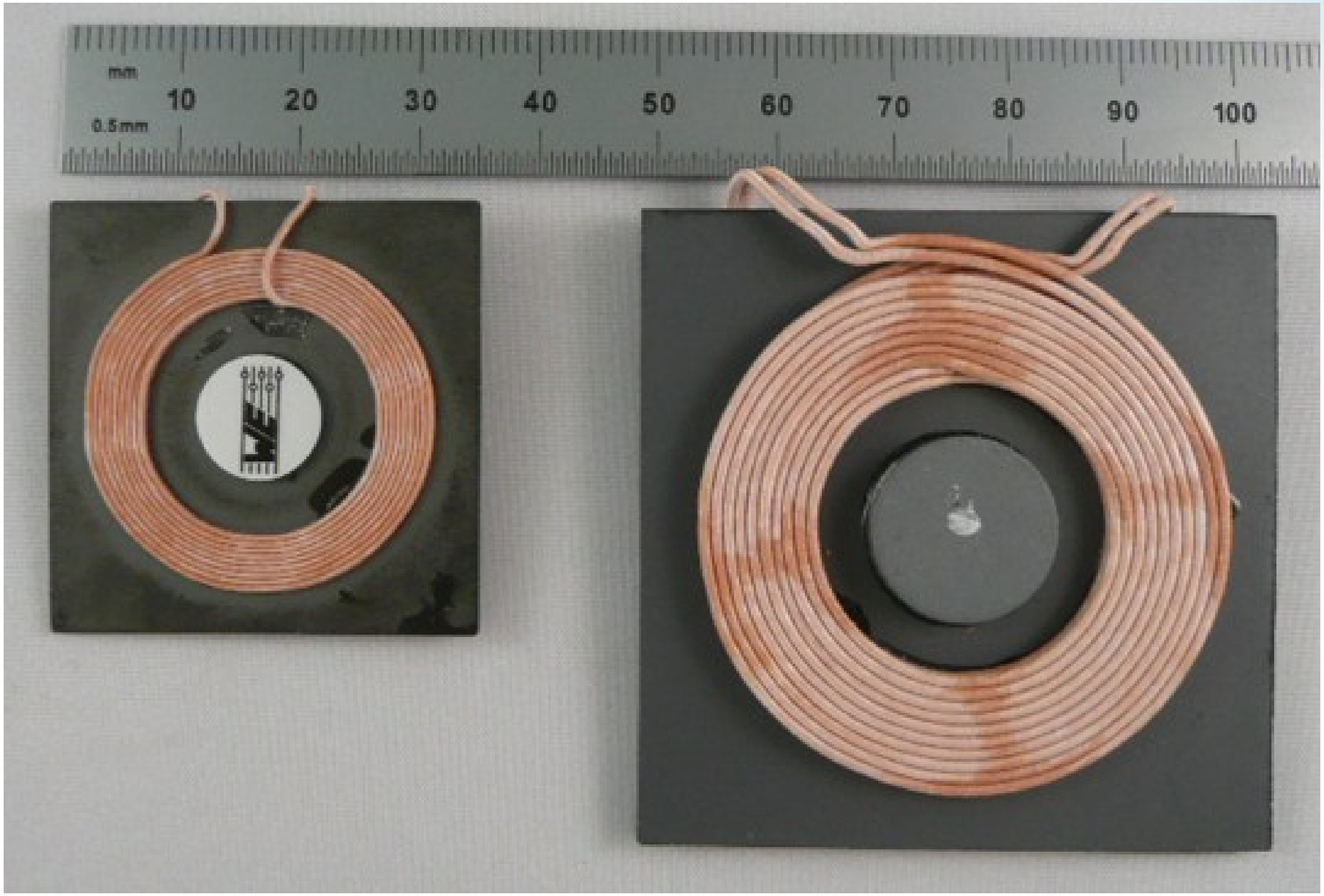
DEVICE	FUNCTION	VOUT	IOUT
bq51003	Power Supply	5V	500mA

Low Power TX

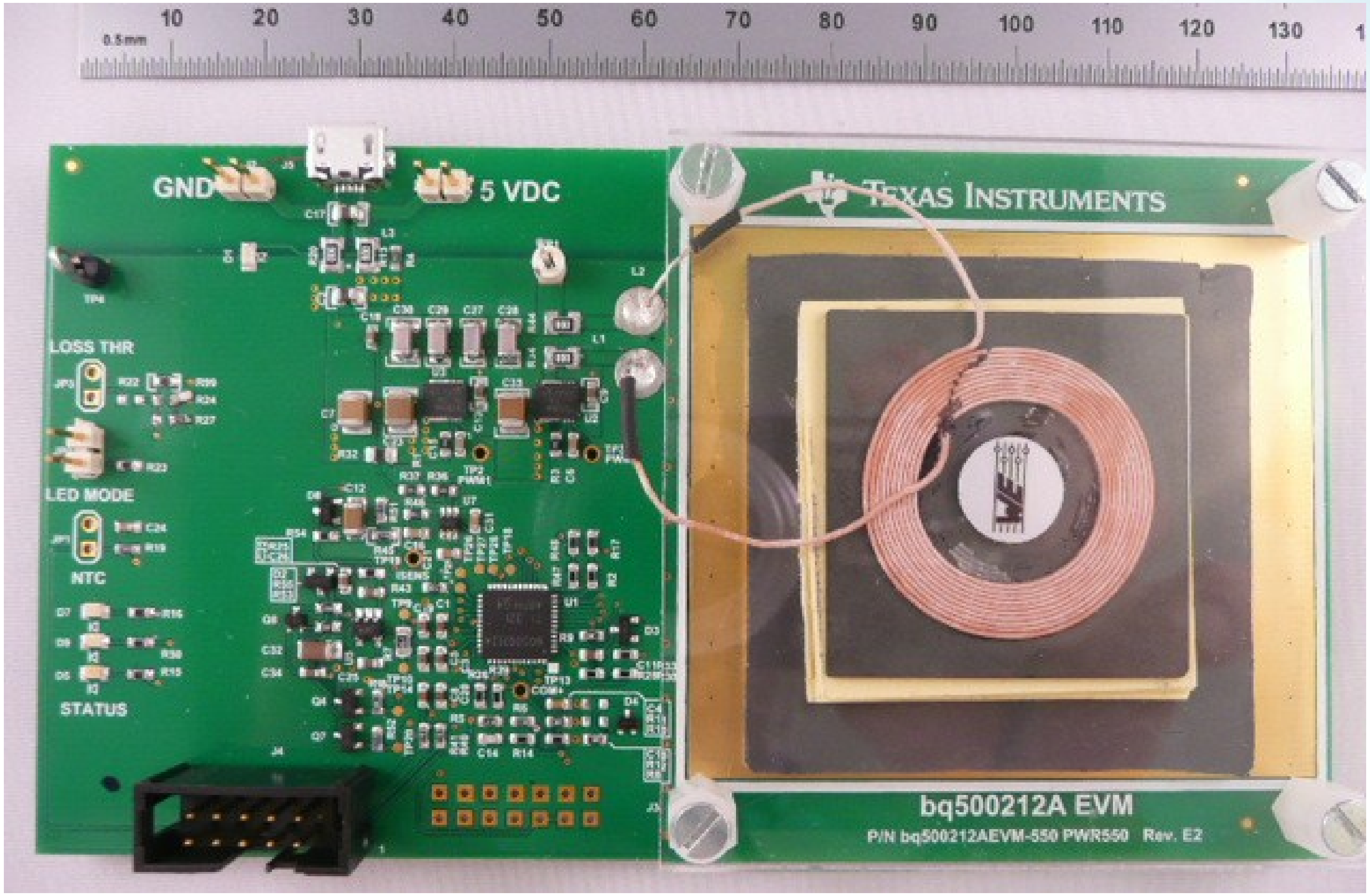
Shaping Innovation

- **Design based on bq500212A**
  - Capacitors changed to low loss COG for test.
  - FOD and PMOD disabled
  - TX to RX coil distance 2.3mm TX and 1.5mm RX
- **Coil based on Würth Elektronik RX coil**
  - Wurth P/N 760308201 WPC RX coil, 10uH 30mm round
  - Reduced number of turns to 10 and inductance of 6.5uH
  - This coil is NOT WPC approved type - solution would be customized for the application
- **Tested with bq51013B RX**
  - System Efficiency will be affected by ILIMIT set point of RX.
  - Dynamic Efficiency Scaling will change set point of RX V_RECT
- **Performance was good with no problems detecting RX and starting power transfer.**
  - Efficiency is ~65%

Test Coil vs Standard A5 coil



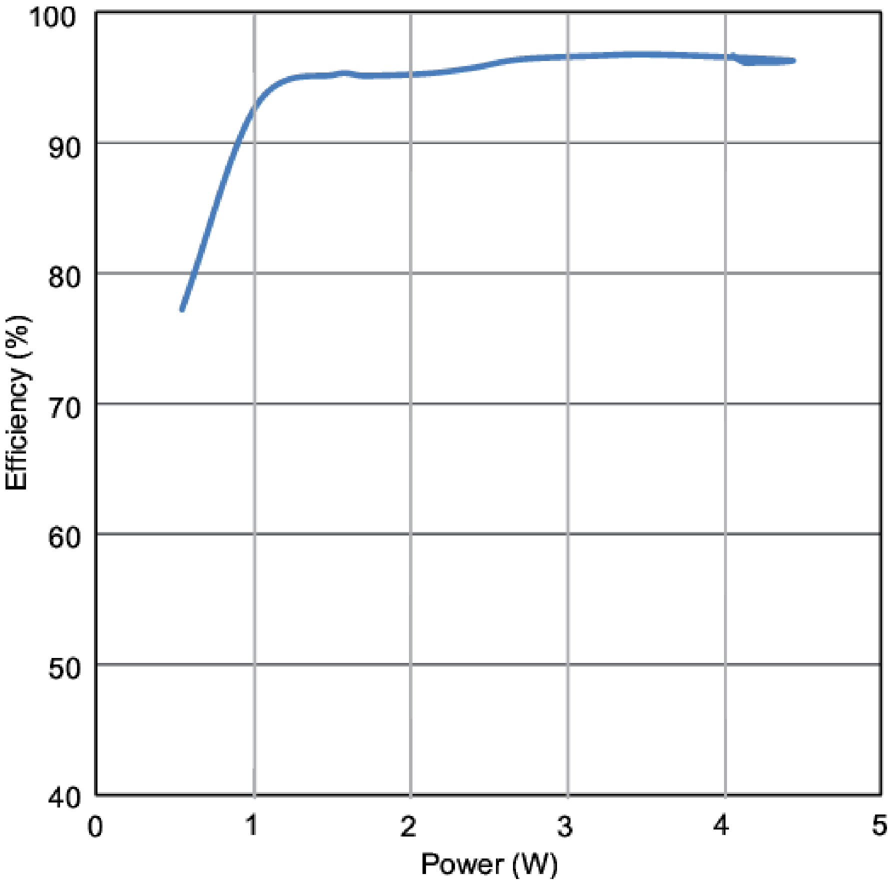
Test TX bq500212A EVM with Coil



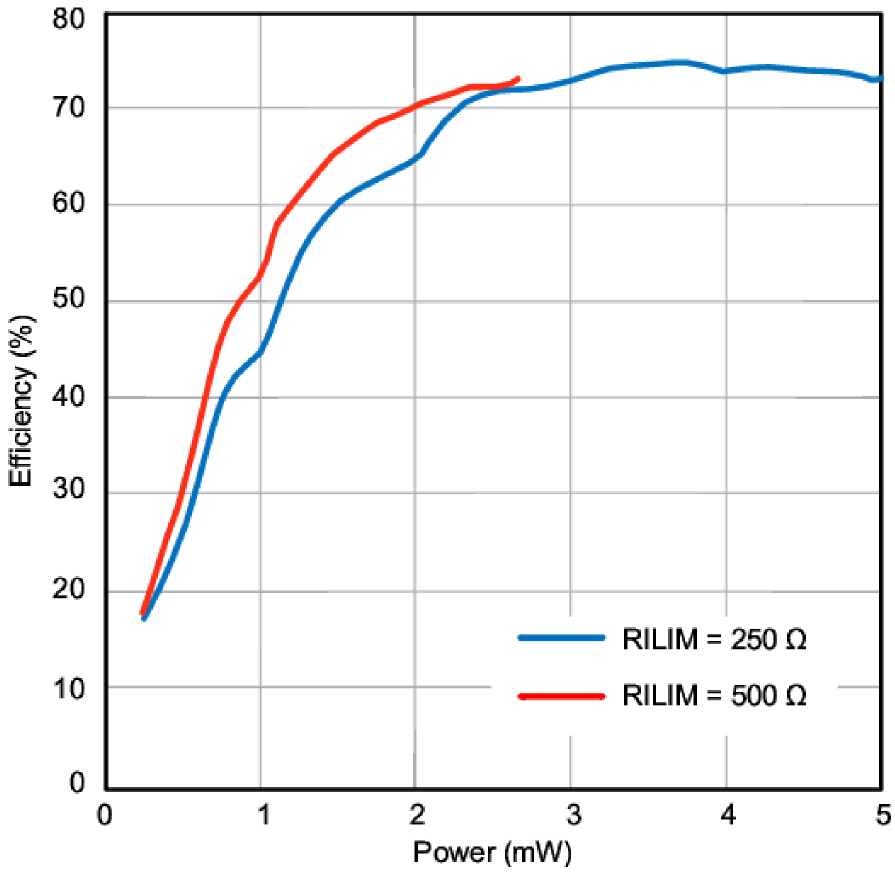
bq51013B 5W Receiver

- Slight optimization for low currents is possible by adjusting receiver current limit

Receiver-side rectifier efficiency

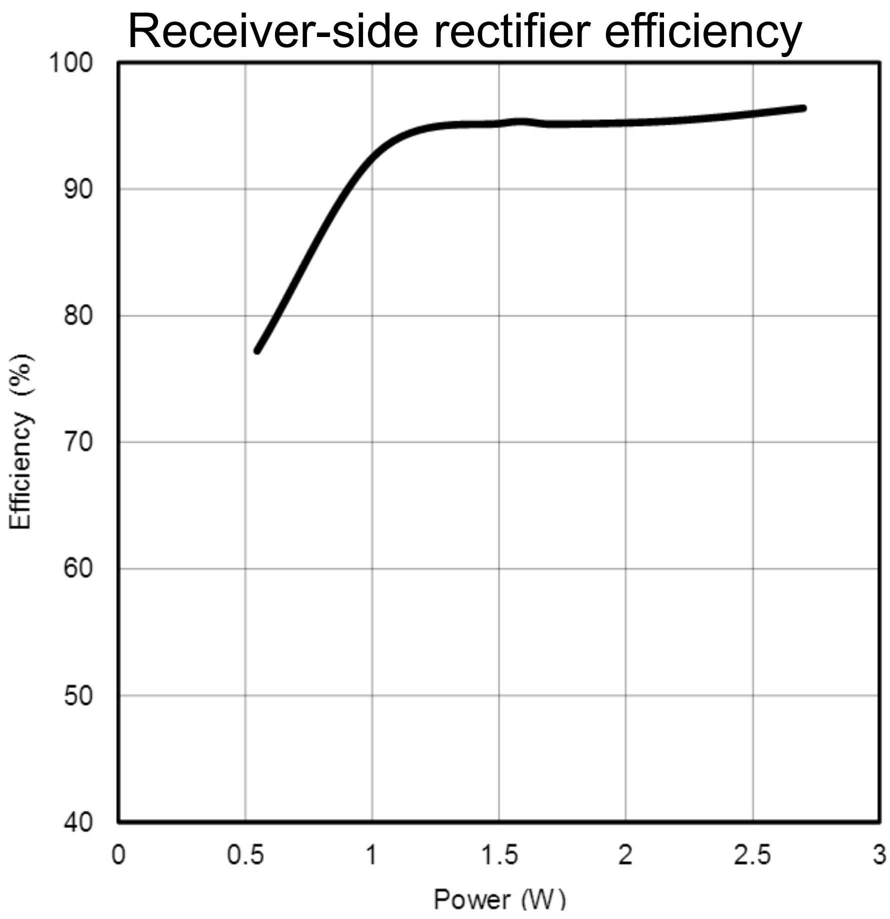


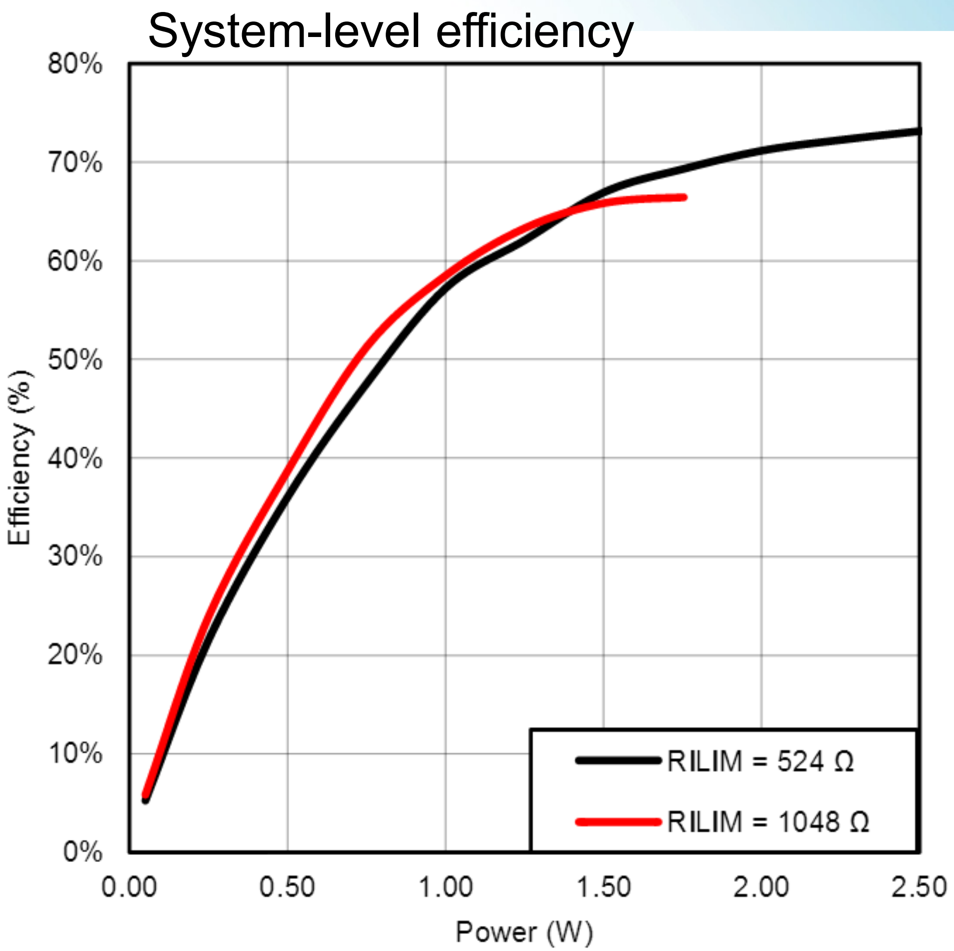
System-level efficiency



bq51003 2.5W Optimized Receiver

- 10 – 15% efficiency improvement at 1W output power vs. standard (5W-rated) receiver





Dynamic Power Limit^{TM} – Key Feature for USB-input powered wireless TX

- **For WPC Compliance, RX can request max 5W, thus, TX need to deliver >7.5W at 75% system efficiency. Typically, 10W TX design is recommended**

- **5V TX is welcome because of the 5V DC source is everywhere, but the TX supply may not provide sufficient power**
  - Typical Laptop USB port is 2.5W only (5Vx500mA)
  - Typical small adaptor is 5W only (5Vx1A)

- **Latest WPC Spec recognizes operation from lower power ports**
  - Need to notify user that “Full 5W Capability” is not available

- **bq500211/A & bq500412 feature “Dynamic Power Limit^{TM}”**
  - Limits output current to ensure Input Supply not pulled down
  - Activates LED to indicate ‘Non WPC/Restricted Power’ operation

- **Not All RX can take advantage of DPL^{TM}**
  - Rx send EPT due to not enough power
  - No ‘Input DPM on Charger’

Summary

- Wireless power is a reality today for millions of end-users
- Vast majority of today's systems use Qi / WPC
- Many use PMA – similar concept; dual-mode receivers are already available
- A4WP – offers benefit of "spatial freedom" but still in development phase
- Challenges to growth need to be overcome
  - Convergence of standards (?)
  - Automotive – additional layer of compliance testing/certification
  - Infrastructure buildout
- Enables new applications in addition to making existing devices more convenient
- We expect wireless power to be a growth market

TI Supporting Tools for Wireless Power

- TI Wireless Power Web Page
  http://www.ti.com/wirelesspower
- bqTESLA™ Evaluation Modules and User Guides
  http://www.ti.com/ww/en/analog/wireless_power_solutions/tools.htm
- TI E2E Community: Wireless Power Forum
  http://e2e.ti.com/support/power_management/wireless_power/default.aspx
- An Introduction to the Wireless Power Consortium Standard and TI's Compliant Solutions
  http://www.ti.com/lit/an/slyt401/slyt401.pdf

Rx Module
bq51013EVM-725

The Leader in Wireless Power Solutions