A Perspective on Far-Field and Near-Field Wireless Power Transfer

Prof. Jenshan Lin

University of Florida

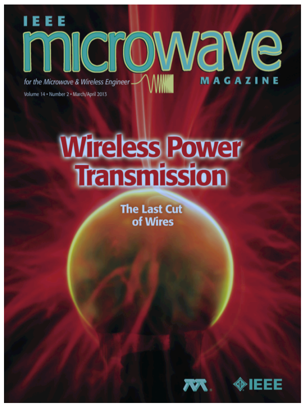
MTT-26 Technical Committee

Wireless Energy Transfer and Conversion

- Established on June 7, 2011.
- Major activities:
  - Wireless Power Transfer Conference (WPTC) – started as a workshop in 2011 (Kyoto, Japan), workshop in Japan again in 2012, and expanded into a conference in 2013 (Perugia, Italy), 2014 (Jeju, Korea), 2015 (Boulder, Colorado, USA), 2016 (Aveiro, Portugal), 2017 (Taipei, Taiwan)
  - Organize workshops and panels in MTT-sponsored conferences
  - Sponsor Wireless Power Student Design Competition during International Microwave Symposium
  - Develop Special Issues in publications – IEEE Microwave Magazine, Proceedings of IEEE, IEEE Transactions on Microwave Theory and Techniques

Special Issues in Publications

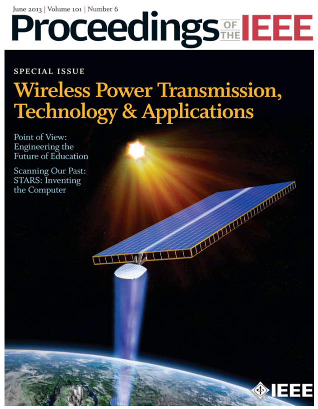
March/April 2013



6 papers

Guest Editors
Z. Chen
S. Kawasaki
N. B. Carvalho

June 2013



18 papers

Guest Editors
K. Wu
D. Choudhury
H. Matsumoto

April 2014
WPT Special Issue

21 papers

Guest Editors
L. Roselli
S. Kawasaki
F. Alimenti

March 2015
WPTC2014
mini-special issue

8 papers

Guest Editors
J. Kim
S. Ahn

Feb 2016
WPTC2015
mini-special issue

7 papers

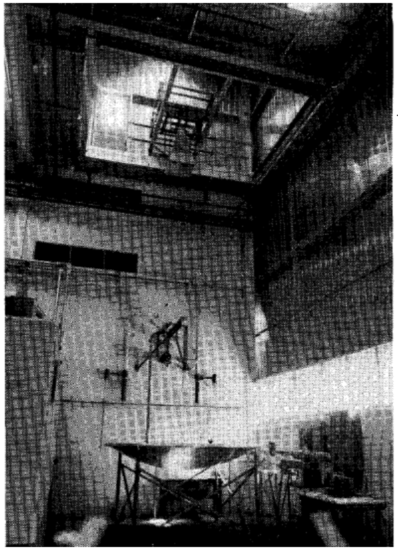
Guest Editors
Z. Popovic
K. Afridi
G. Ponchak

Outline

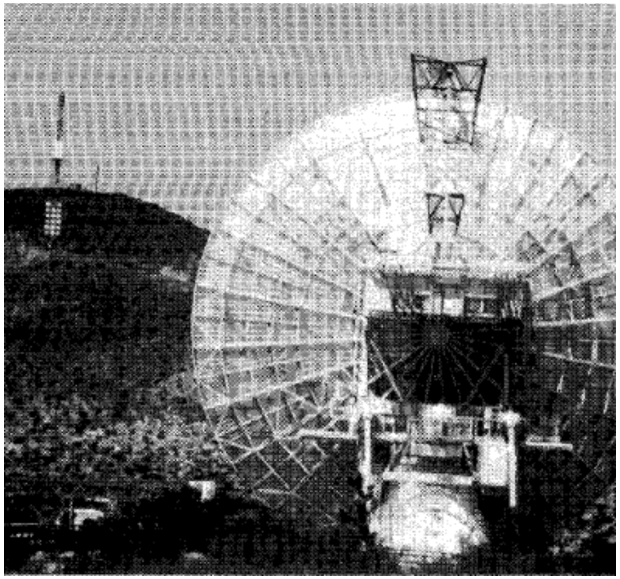
- Far-field WPT
  - An overview of historical developments
  - Challenges of far-field WPT
- Near-field WPT
  - Overview
  - Difference between far-field WPT and near-field WPT
- Magnetic coupling near-field WPT
  - Examples
- Possible future game-changing applications

WPT History - more than one century

- **1899** – Tesla's first experiment to transmit power without wires. **150 kHz**.
- **1958** – 1st period of microwave WPT development. Raytheon, Air Force, NASA.
- **1963** – **Brown** in Raytheon demonstrated the **first microwave WPT system**.
- **1975** – **54% dc-to-dc efficiency** was achieved, receiving **496 W @ 170 cm**.
- **1975** – **30 kW dc received @ 1 mile**
- **1977** – 2nd period of microwave WPT development. NASA/DOE sponsorship. More companies involved. Solar Power Satellite (SPS)
- **1995** – NASA Space Solar Power (SSP) Program



First microwave WPT
100 W dc output, 13% dc-to-dc efficiency

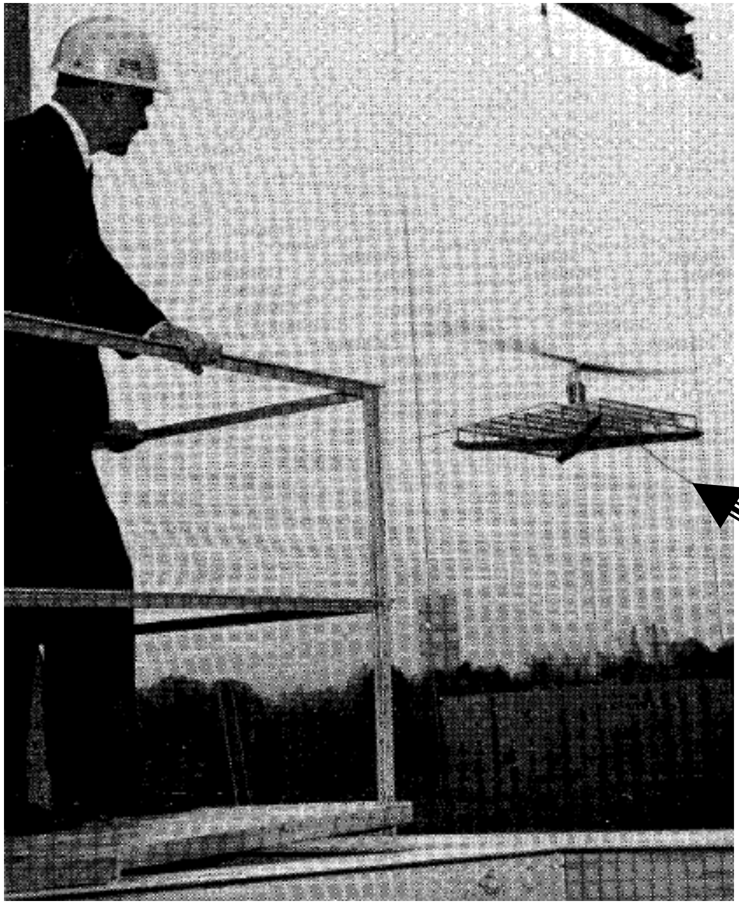


1975 demonstration
30 kW dc output @ 1 mile

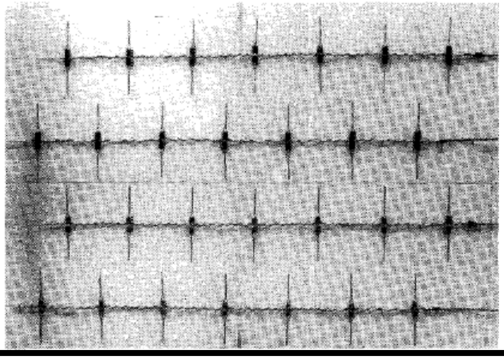
* W. C. Brown, "The History of Power Transmission by Radio Waves," IEEE Trans. Microwave Theory and Techniques, vol. 32, no. 9, pp. 1230-1242, Sept. 1984.

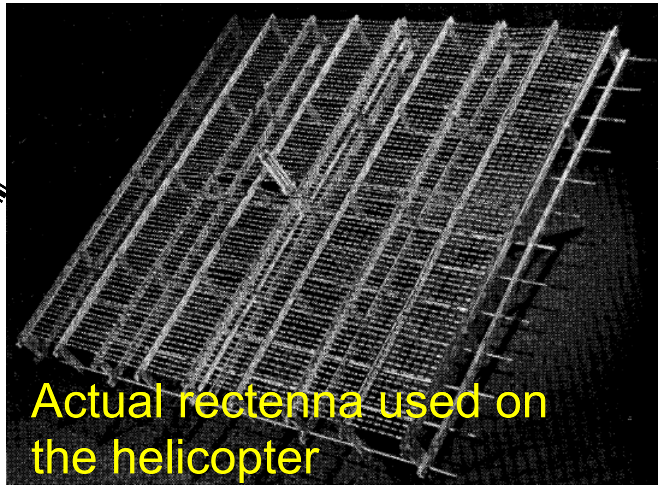
Remote Powering of Helicopter (UAV)

Microwave-powered helicopter flying 60ft above transmitting antenna. 10 hr sustained flight was achieved in 1964.



First "rectenna" – rectifying antenna integrating **solid-state diodes**, 1963. (replacing vacuum tube diodes)





Some ambitious ideas that have not been realized …

Long Distance Wireless Power Grid

- Microwave travels through earth atmosphere twice – overall path ~ 200km
- If using high voltage power line, the path would be several thousands km – more environmental effect
- λ=5000km @ 60Hz – power line becomes good antenna at long distance.

* A. P. Smakhtin, V. V. Rybakov, "Comparative analysis of wireless systems as alternative to high-voltage power lines for global terrestrial power transmission," Proceedings of the 31st Intersociety Energy Conversion Engineering Conference (IECEC 96), vol. 1, pp. 485-488, 11-16 August 1996.

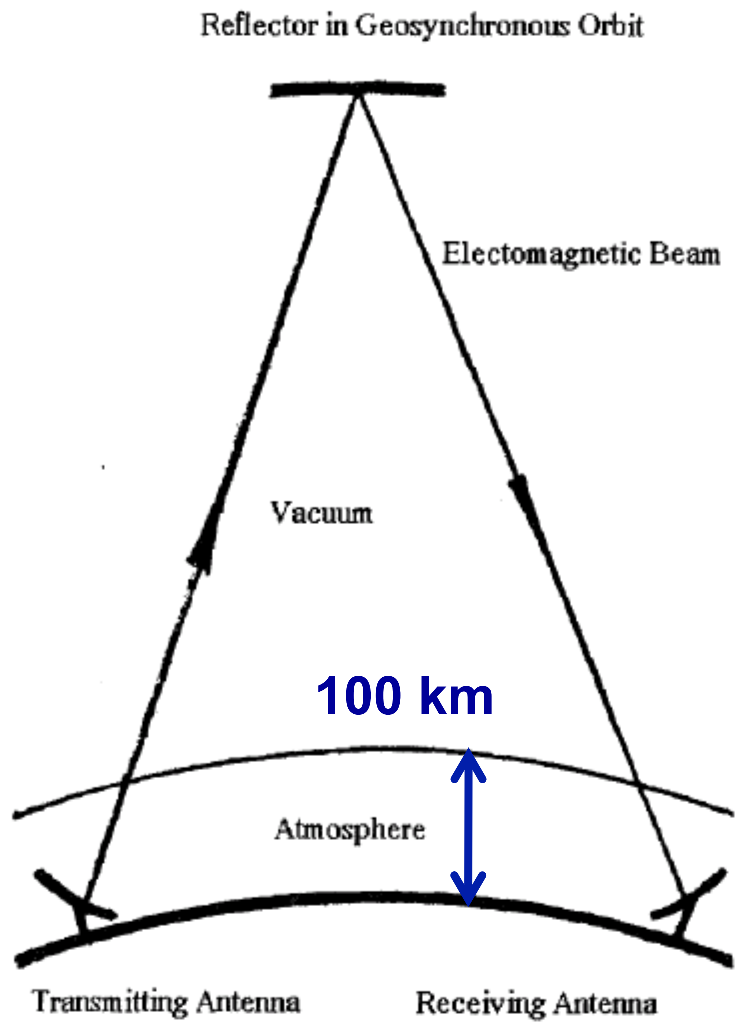
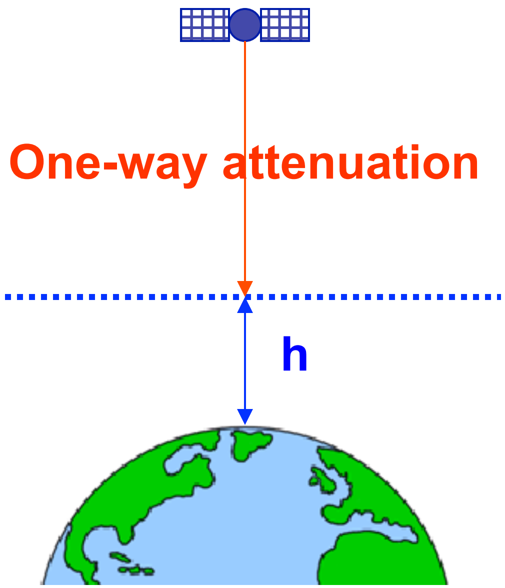
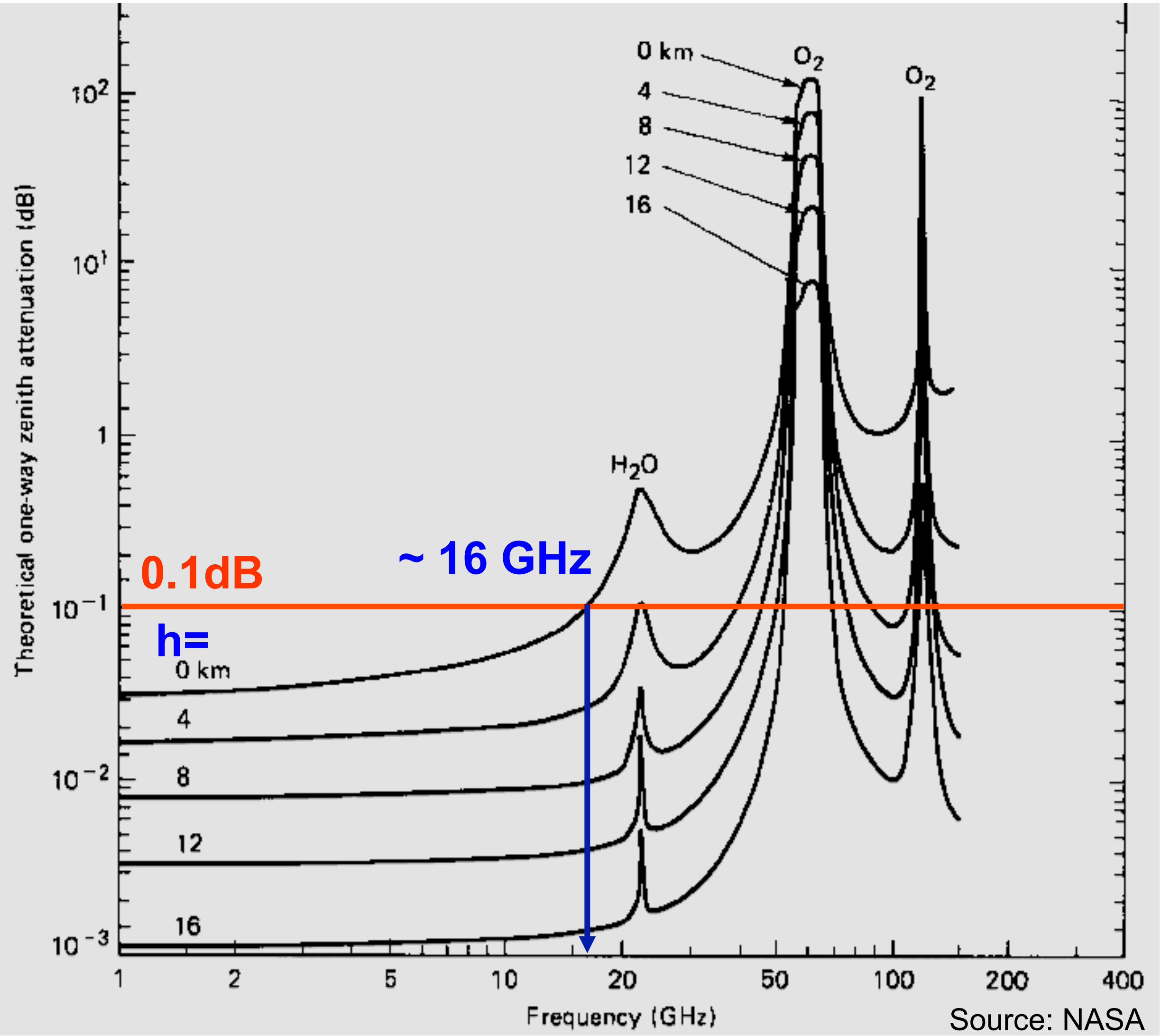


FIGURE 1. CONCEPTUAL SCHEME OF ELECTROMAGNETIC BEAM POWER TRANSMISSION ON EARTH

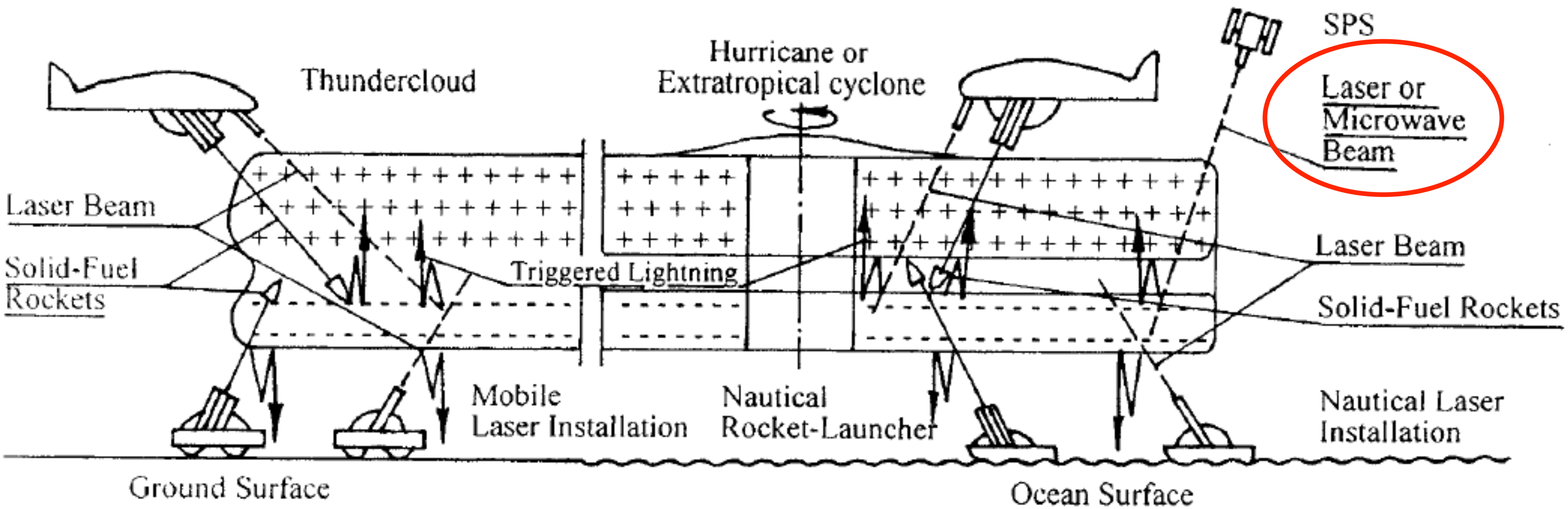
Attenuation Through Atmosphere





- One-way attenuation < 0.1dB for f < 16GHz

Manipulating tropical storms

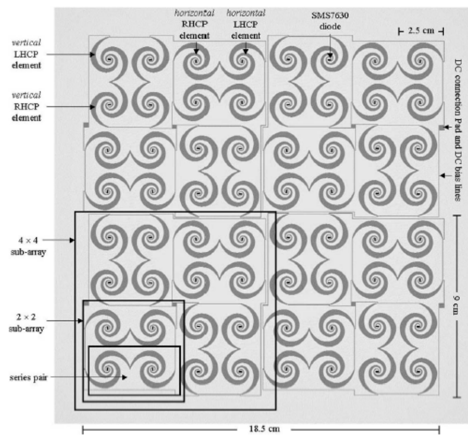


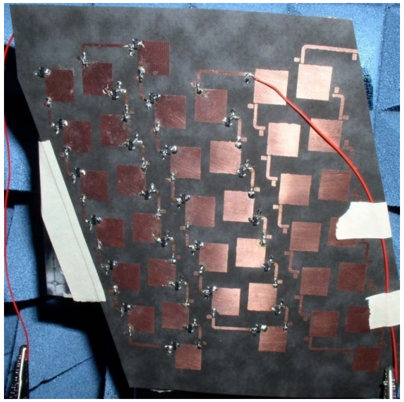
E. Yu. Krasilnikov, “Prevention of destructive tropical and extratropical storms, hurricanes, tornadoes, dangerous thunderstorms, and catastrophic floods,” Nonlinear Processes in Geophysics (2002) 9: 51–59

The most successful application of far-field WPT

RF Energy Harvesting

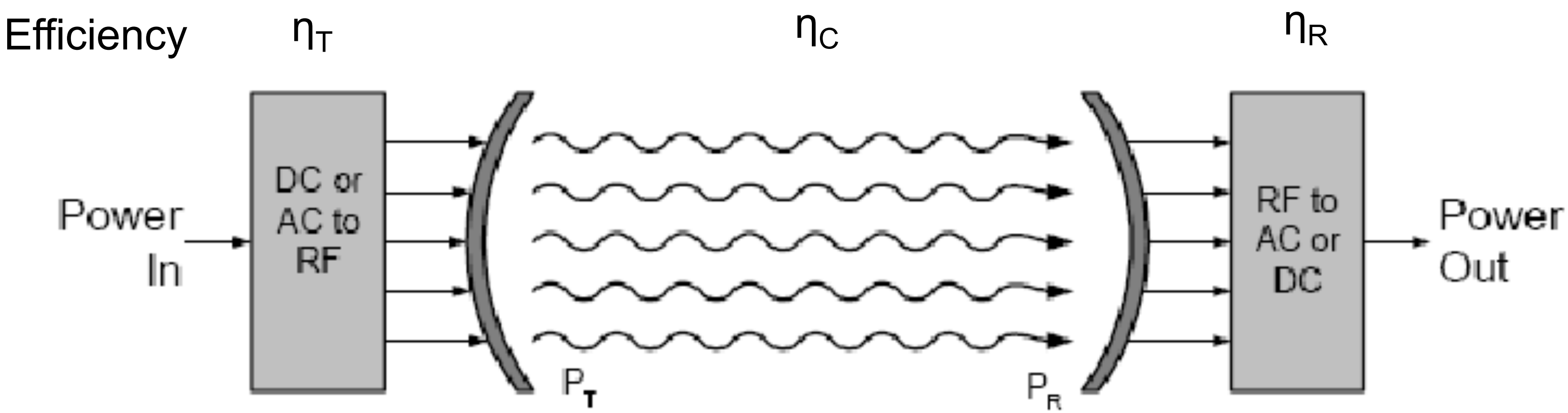
- From ambient RF emissions (broadband) or from a remote RF source (narrow band)
- Suitable for **low power** applications, e.g., **sensor network**
- Recently became a very active research area
- Several new techniques have been proposed (Class-F, harmonics termination, wideband, multi-sine, etc.)





* J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic´, "Recycling Ambient Microwave Energy With Broad-Band Rectenna Arrays," IEEE Trans. Microwave Theory and Tech., vol. 52, no. 3, pp. 1014-1024, March 2004.
* C. Walsh, S. Rondineau, M. Jankovic, G. Zhao, Z. Popovic, "A Conformal 10 GHz Rectenna for Wireless Powering of Piezoelectric Sensor Electronics," IEEE MTT-S International Microwave Symp., pp. 143-146, June 2005.

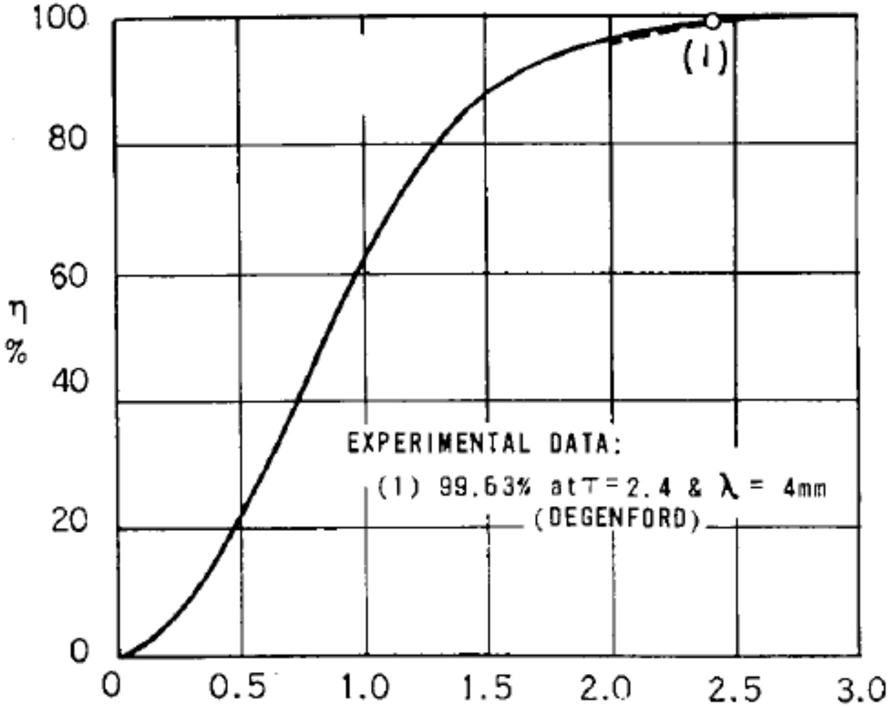
Far-Field WPT System



- DC (or ac) power is first converted to RF power.
- RF power is transmitted by TX antenna to the receiver.
- RF power is received by the RX antenna and rectified to dc power which can further be converted to ac power.
- Total system efficiency = (η_T)x (η_C)x (η_R)

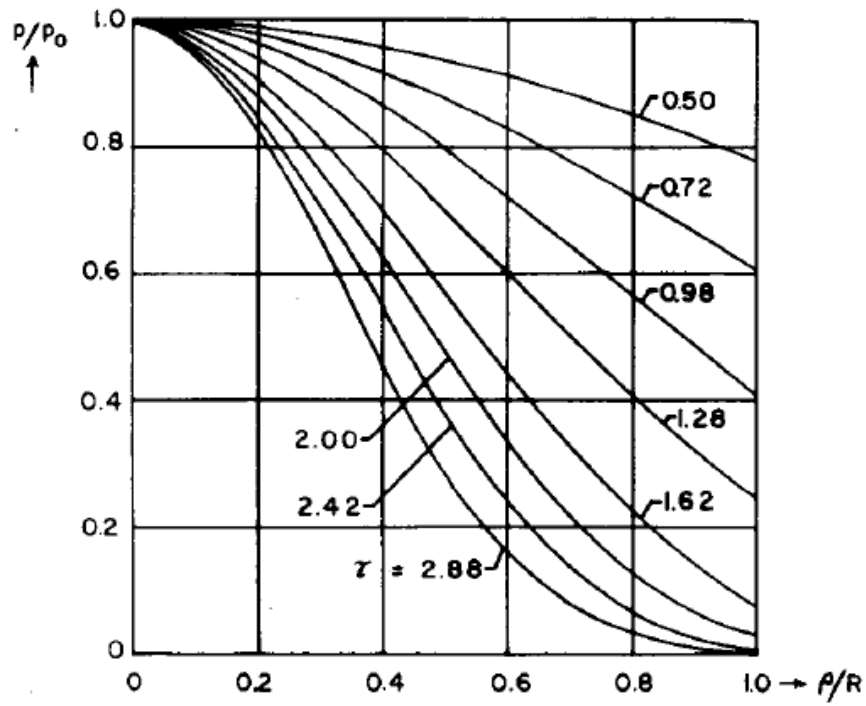
Beam-Forming Antennas

Transmission Efficiency η as a function of τ for optimum power density distribution across the TX antenna aperture as shown on the right.



$$\tau = \frac{\sqrt{A_t A_r}}{\lambda D}$$

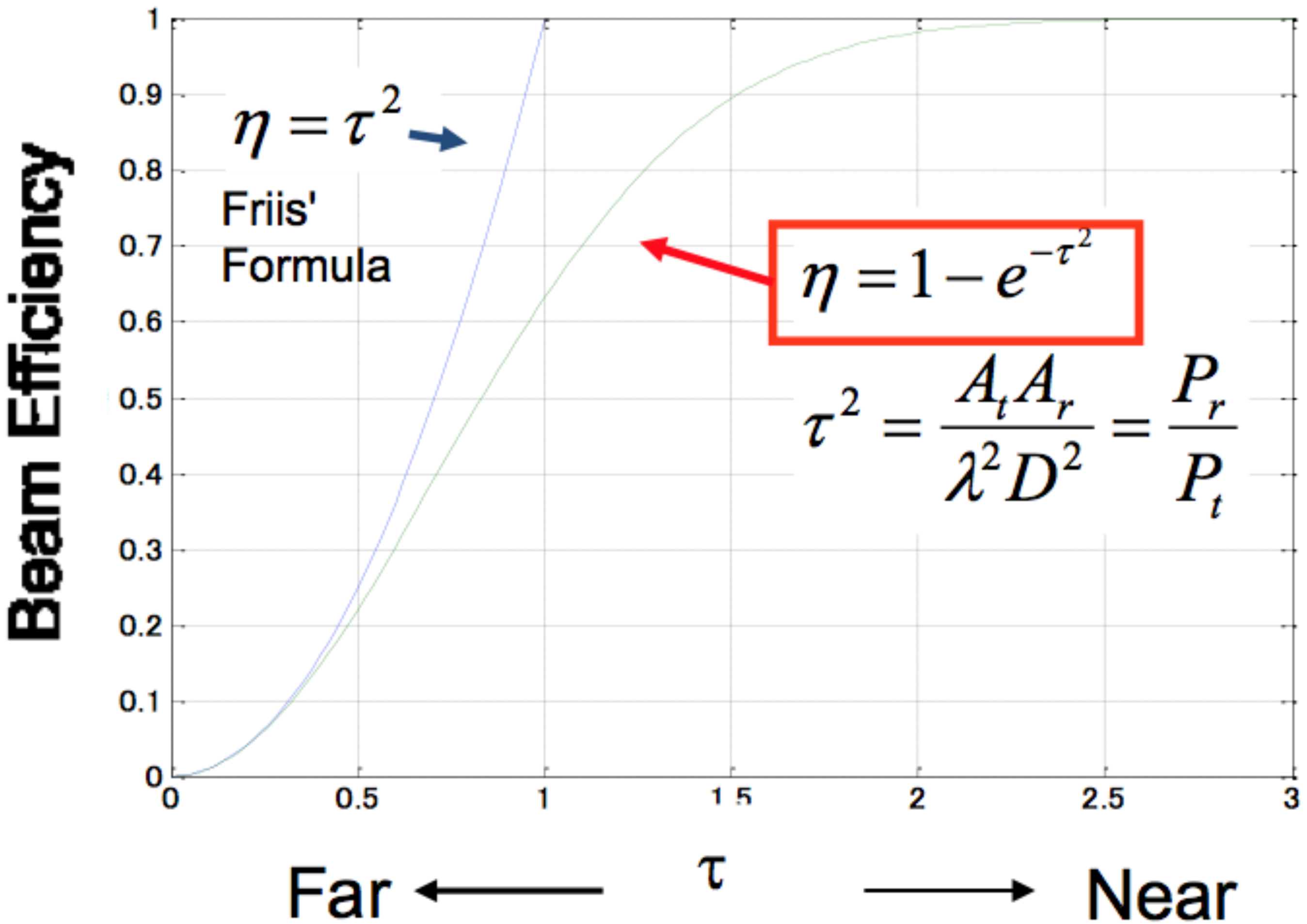
Relative cross-sectional power density distribution across the TX and RX apertures for various values of τ



<u>Need large antenna aperture or higher frequency to achieve high efficiency.</u>

* W. C. Brown, E. E. Eves, "Beamed Microwave Power Transmission and its Application to Space," IEEE Trans. Microwave Theory and Techniques, vol. 40, no. 6, pp. 1239-1250, June 1992, quoting G. Goubau and F. Schwering, "On the guided propagation of electromagnetic wave beams," IRE Trans. Antennas Propagat., vol. 9, pp. 248-256, May 1961.

High Efficiency → Near Field



D:distance, $A_{t,r}$: effective area of Tx, Rx antenna

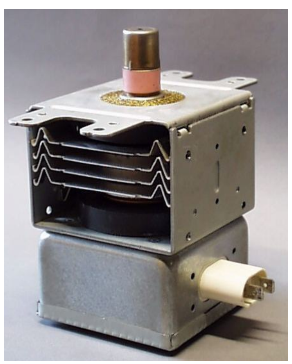
Courtesy of figure from Prof. Naoki Shinohara

High Efficiency Microwave Power Source

- Find devices to generate high power RF.
  - High efficiency
  - Low cost
  - Lightweight
- Efficiency is particularly important at high power level. 90% efficiency of 9 W output means 1 W is lost to heat, whereas 90% efficiency of 90 W output means 10 W is lost to heat.
- If efficiency is not high, heatsink will be needed and that will also increase the cost and weight.
- Cost of microwave power amplifier goes up with power level.
- Where do you find the cheapest high power source at 2.4 GHz that can generate 1000 W?

Microwave Oven

- Microwave tubes have been used to achieve high efficiency and very high output power
  - magnetron, klystron, traveling wave tube (TWT), etc.
  - Magnetron has the highest efficiency and been used in microwave oven. (>80% at several kW demonstrated). Low cost too.
  - However, they are bulky and heavy. For very high power, cooling is still an issue.

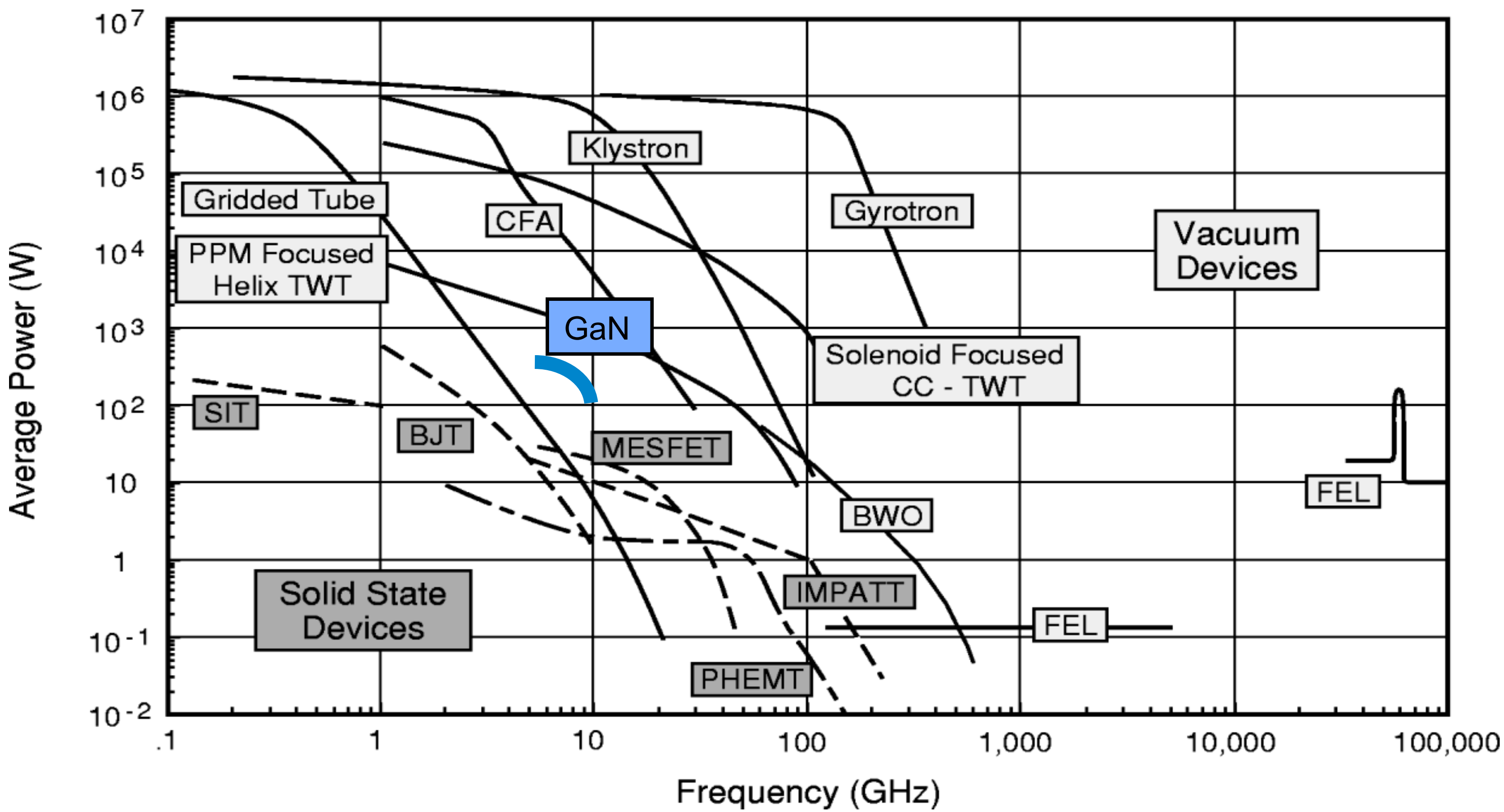


Magnetron inside microwave oven
2.4 GHz, 1 kW, 65% efficiency

Toshiba Klystron
5.7 GHz, 50 MW, 47%, 0.0125% duty cycle

Microwave Power Source

➢ **Solid-state devices still have not displaced microwave tubes yet.**

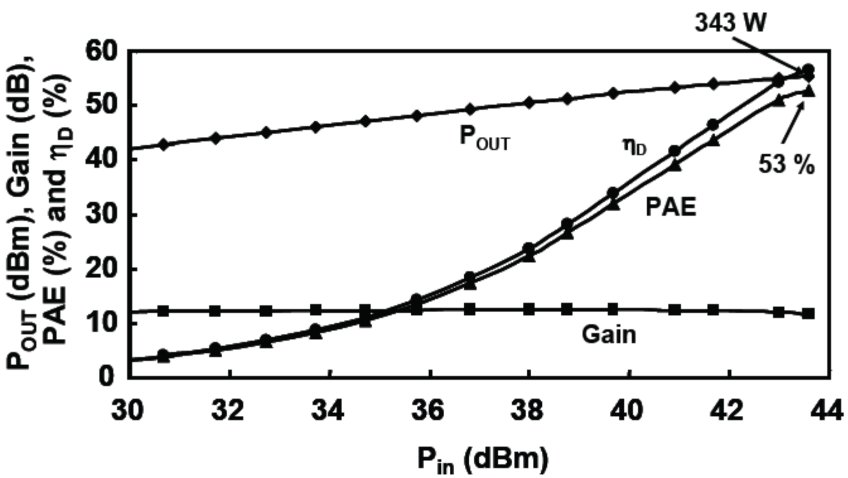


* V. L. GRANATSTEIN, R. K. PARKER, C. M. ARMSTRONG, "Vacuum Electronics at the Dawn of the Twenty-First Century," Proceedings of the IEEE, vol. 87, no. 5, pp. 702-716, May 1999.

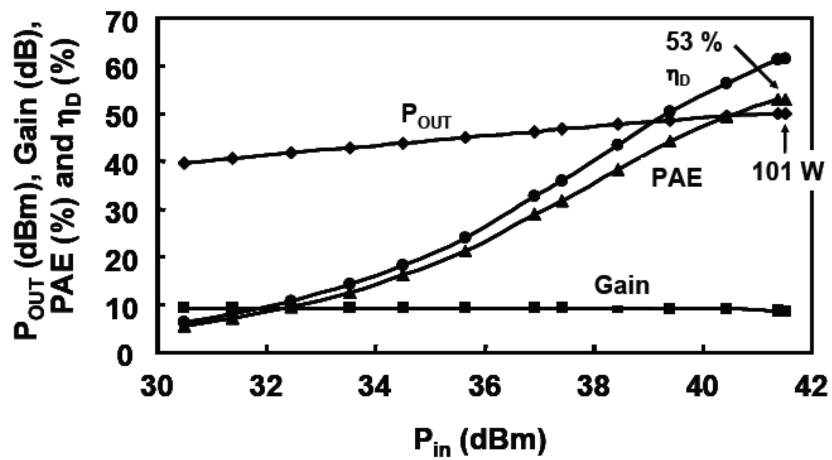
Solid-State Microwave Power Source

- GaN technology is the best candidate at high frequency.
- Spatial power combining of GaN power sources might be a solution.

343 W @ 4.8 GHz (C-Band)



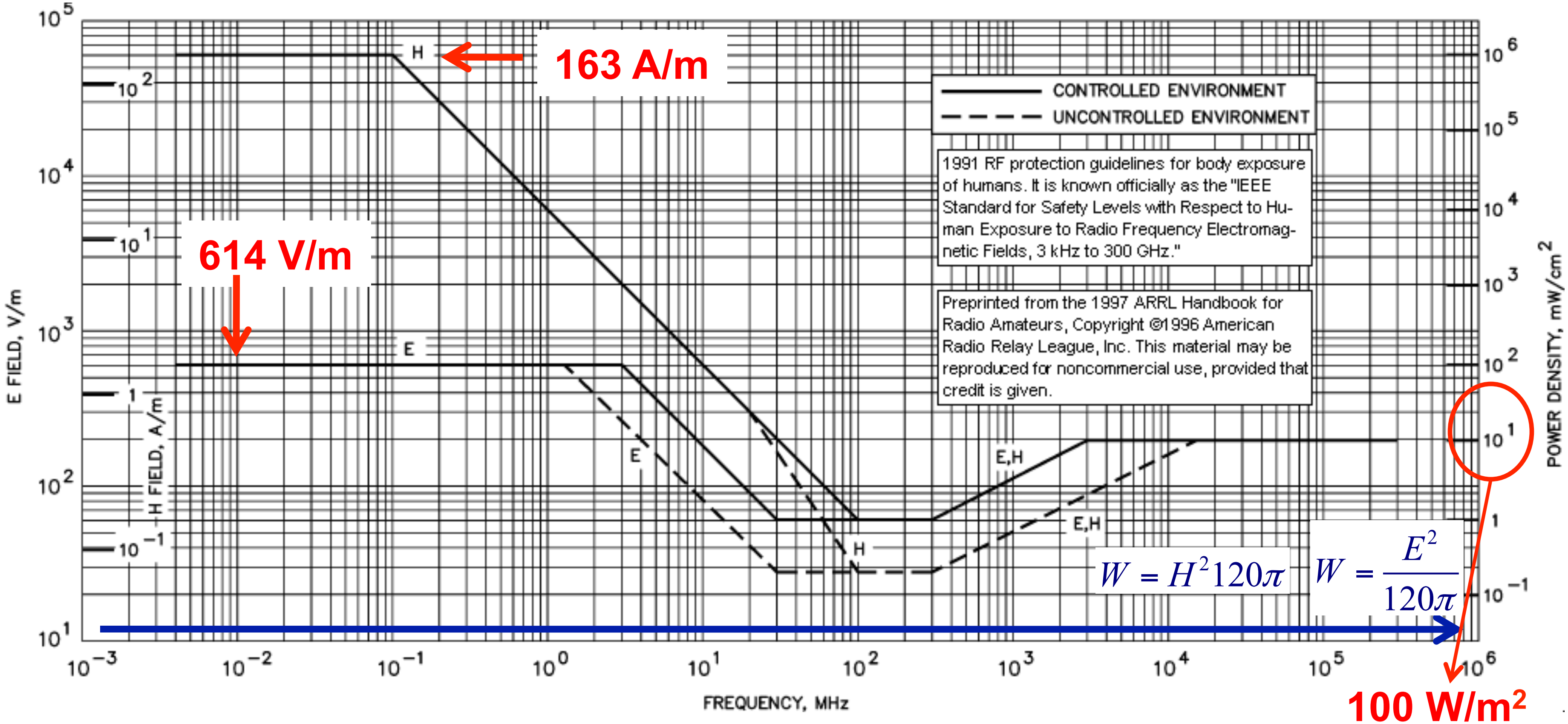
101 W @ 9.8 GHz (X-Band)



- Shigematsu, H.; Inoue, Y.; Akasegawa, A.; Yamada, M.; Masuda, S.; Kamada, Y.; Yamada, A.; Kanamura, M.; Ohki, T.; Makiyama, K.; Okamoto, N.; Imanishi, K.; Kikkawa, T.; Joshin, K.; Hara, N.; , "C-band 340-W and X-band 100-W GaN power amplifiers with over 50-% PAE," *Microwave Symposium Digest, 2009. MTT '09. IEEE MTT-S International* , vol., no., pp.1265-1268, 7-12 June 2009
- 10 μs pulse width and 10% duty cycle.

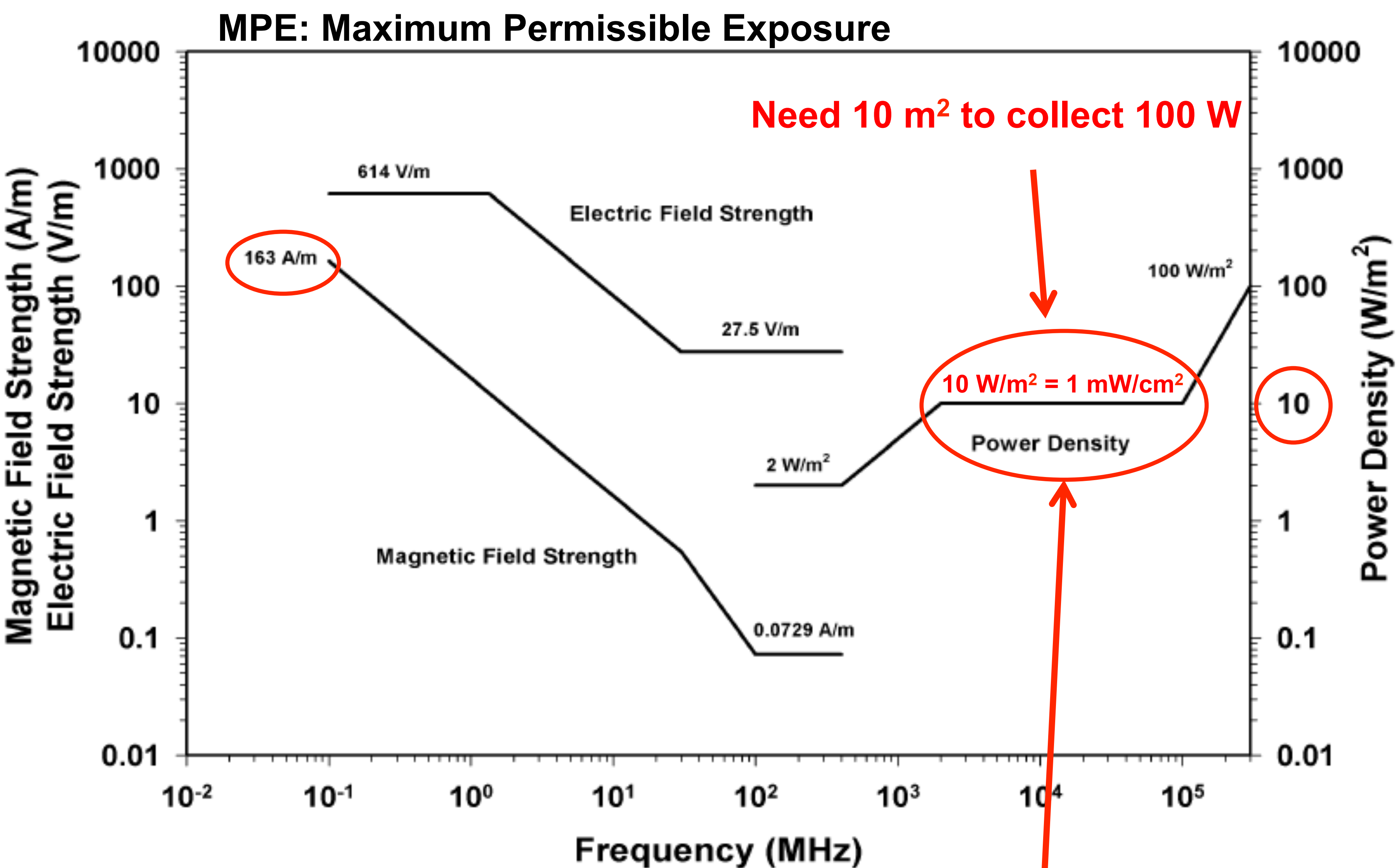
RF Safety – 1999

IEEE Std C95.1 – 1999
IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz



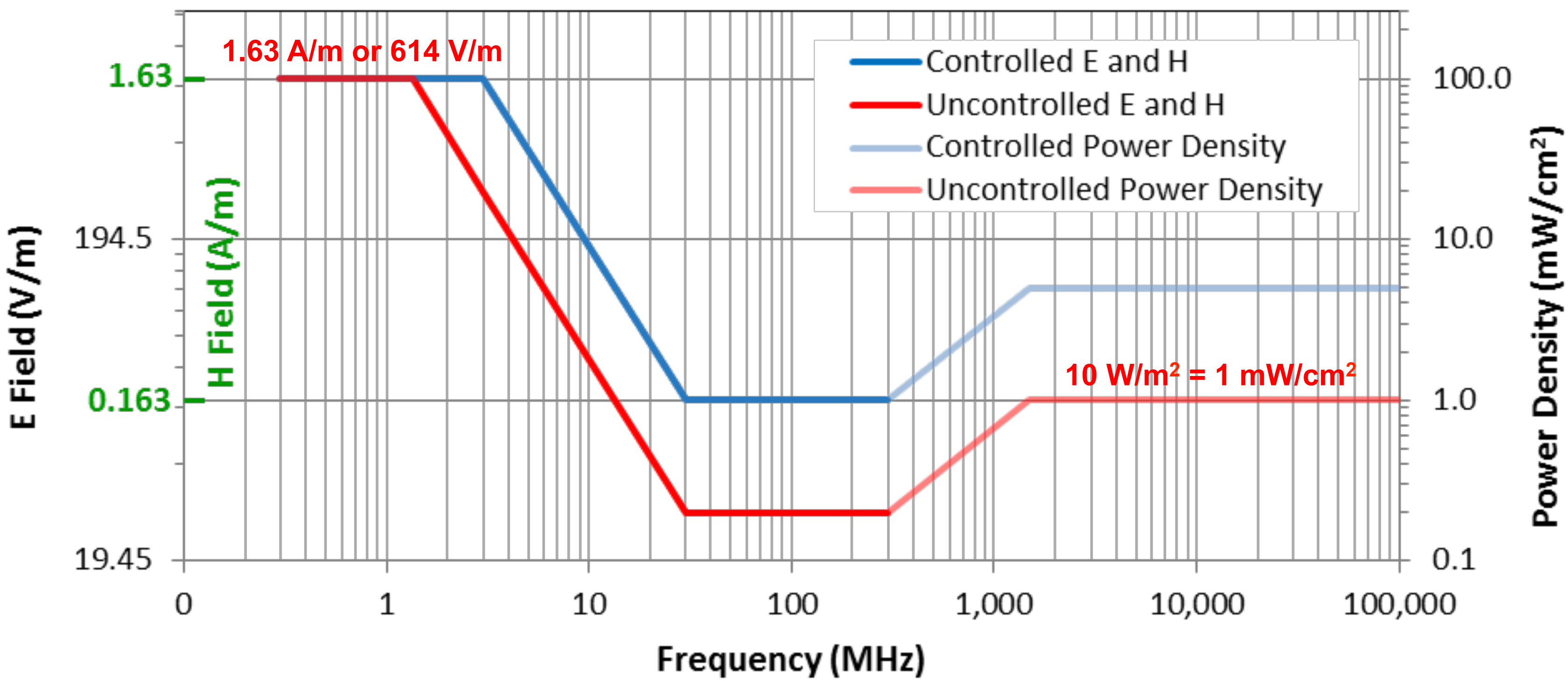
- Transmitted power density is limited by safety standard.
- Magnetic field at low frequency has higher equivalent plane wave power density

RF Safety – 2005, General Public



10x more stringent than 1999 Standard

RF Safety – 2013 (FCC 13-39)



- Key changes from 2005 to 2013:
  - H field limit at low RF is 100 times lower (tougher).
  - In terms of equivalent power density, E and H field MPE limits at low RF become the same.

What's new in the 21st-century WPT?

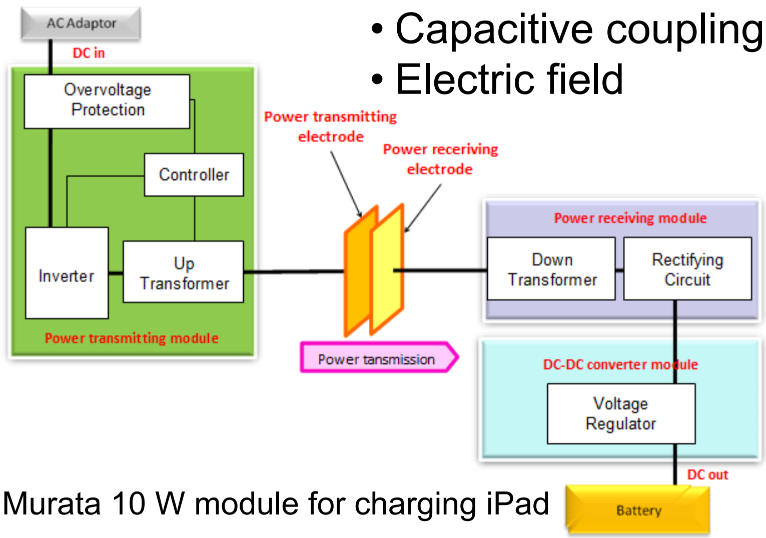
- Lots of personal electronic devices
- More personal electronic devices
  – desktop computers replaced by tablets/pads
  – (almost) everyone has a cellular phone
- More devices need to be charged
  – more electrical wires or go for wireless?
- Electric vehicles
- Wearable devices, medical implants, sensors
- More electromagnetic waves in the air – good for wireless energy harvesting
- Short-range RF propagation channel – no longer far-field

From Far-Field WPT to Near-Field WPT

- Far-field WPT has limitations but has applications
  - Very low power devices or sensor network, where efficiency and safety would not be concerns
  - High power space, military, or industrial applications not sensitive to cost
- However, when it comes to consumer applications such as charging cellular phones, laptops, and other portable electronic devices, or even electric cars, far-field WPT is facing great challenges because of <u>efficiency</u> and <u>safety</u>.
  - Near-field WPT is a better choice.
  - <u>Low-frequency magnetic field</u> can be used to allow higher equivalent plane wave power density.

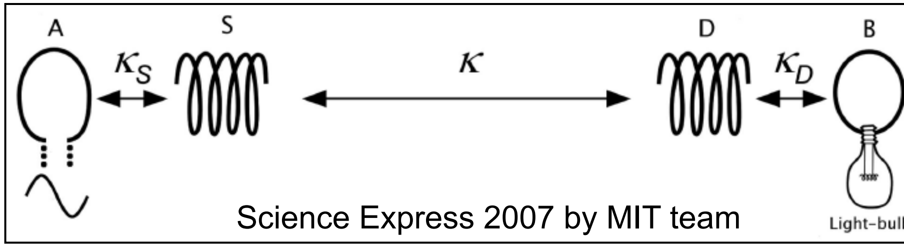
Types of Near-Field Wireless Power

- Capacitive coupling
- Electric field

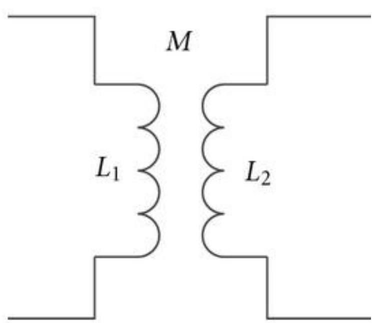


Murata 10 W module for charging iPad

- Magnetic resonance
- Magnetic field
- Four coils



Science Express 2007 by MIT team

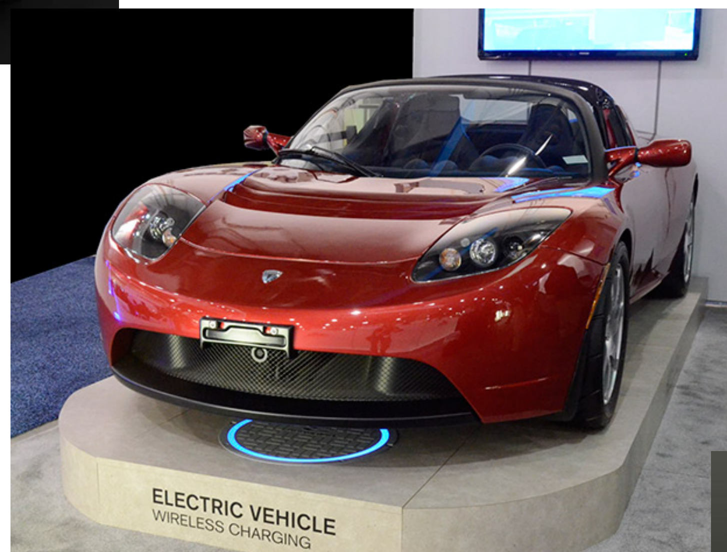


- Inductive coupling, or magnetic coupling
- Magnetic field
- Strong coupling or weak coupling
- Many technologies and many companies

The following discussions will focus on magnetic coupling.

Near-field Wireless Power Charger

- **Magnetic coupling**
- **Higher efficiency than far-field**
- **Low frequency electronics → high efficiency**
- **Less safety concern**

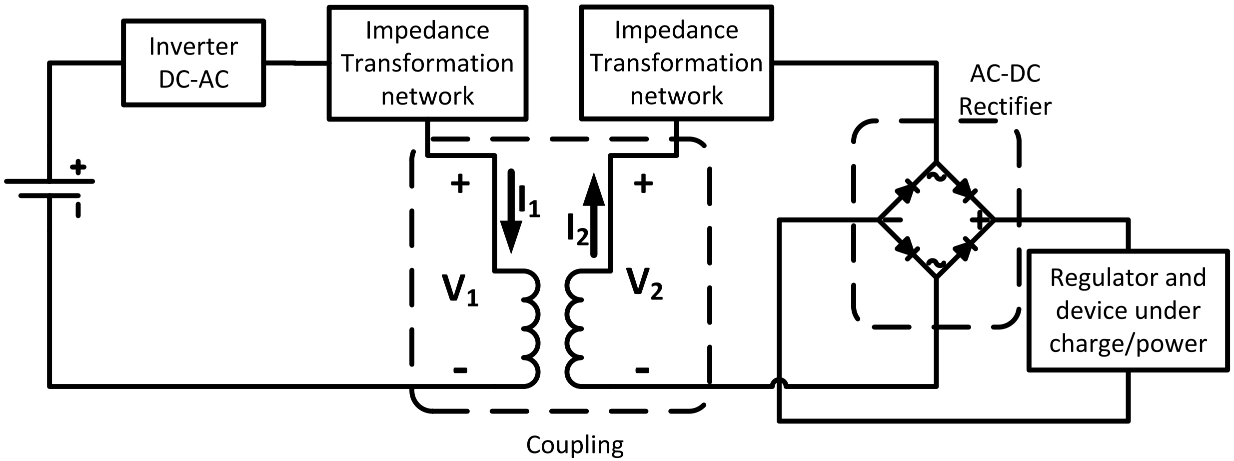


Inductive Coupling

- Magnetic coupling to transfer power has been around for quite many years. Rechargeable electric toothbrush is an example.
- So what’s the challenge?
- It uses spilt ferrite core to achieve strong coupling
- It requires careful alignment
- To have higher power transfer with lateral movement freedom yet keeping high efficiency and without using ferrite core, is a challenge.
- Charging multiple devices is another major challenge.

Electric toothbrush

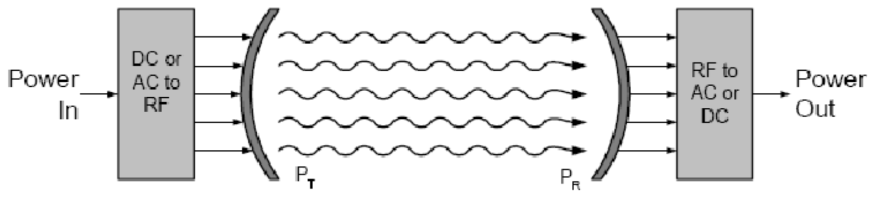
Near-Field WPT System



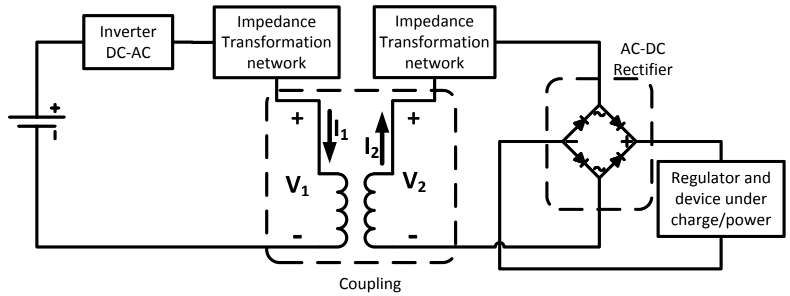
- **<u>Inverter (or transmitter, power amplifier)</u>**
  - Convert dc power to ac power
  - Need to have high efficiency
  - Switch-mode preferred, e.g., Class-D or Class-E
- **<u>Impedance transformation network and loosely-coupled inductive coils</u>**
  - Transform load impedance to a range the inverter (PA) can handle
  - Ensure correct power delivery when load is varying (a major challenge)
- **<u>Receiver</u>**
  - Rectify ac power to dc power
  - Voltage regulator is used to ensure stable dc output

Difference Between Far-Field WPT and Near-Field WPT

Far-Field WPT



Near-Field WPT



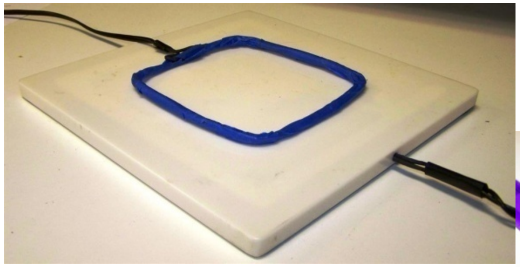
system efficiency = $(\eta_T) \times (\eta_C) \times (\eta_R)$

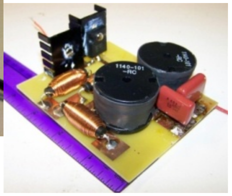
system efficiency = ?

- Because it is near-field coupling, transmitter and receiver are no longer decoupled. Transmitter efficiency depends on the coupling and the load at receiver.
- Because the coupling and the receiver load might change (vs. time or location), the transmitter will see a variable load.
- Essentially, this becomes designing a power amplifier with variable load!
- Need complete system optimization. Optimizing coil-to-coil coupling efficiency alone will not result in an optimized system efficiency.

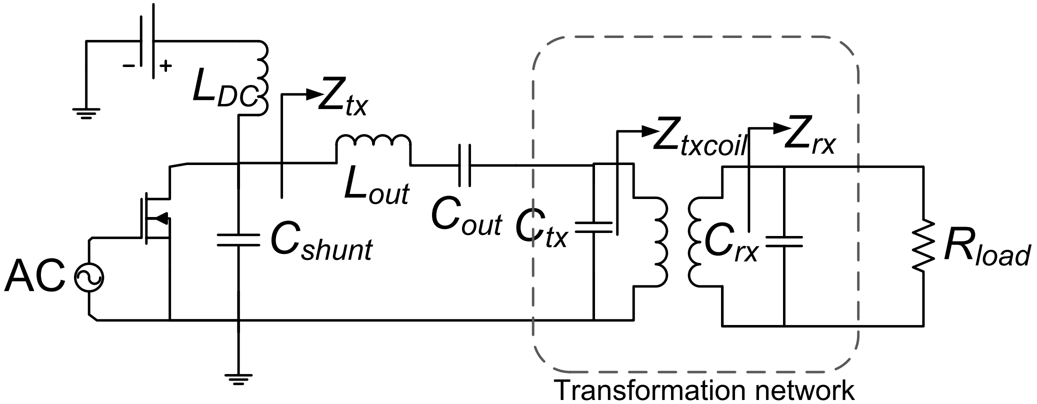
Near-Field WPT – Loosely Coupled

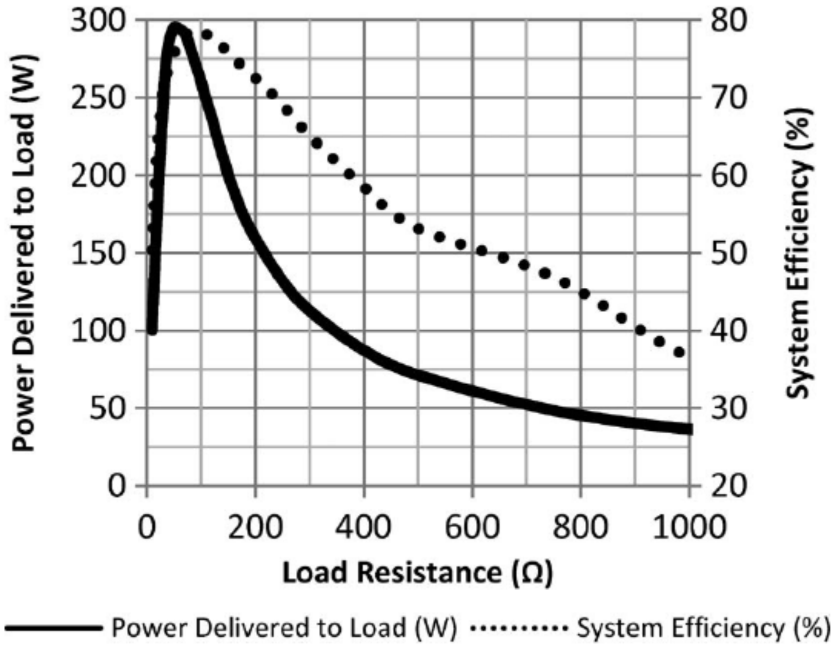
- High power (295 W) delivery with high end-to-end system efficiency (>75%)
- Class-E transmitter operating @ 134 kHz
- Varying location of RX on TX → Power delivery variation 5%
- Coupling coefficient ~ 0.37 (>0.25 to avoid TX heating)





- TX coil 21cmx21cm
- RX coil 13cmx13cm
- Separation 1cm





Z. N. Low, R. A. Chinga, R. Tseng, and J. Lin, "Design and Test of a High-Power High-Efficiency Loosely Coupled Planar Wireless Power Transfer System," *IEEE Transactions on Industrial Electronics*, Vol. 56, No. 5, pp. 1801-1812, May 2009.

Why Class-E?

- Compared to Class-D:
  - Simple single transistor topology
  - Single gate drive instead of out-of-phase gate drive
  - Higher power delivery with same supply voltage
  - Disadvantage: Higher device stress

$$P_{out-ClassE} = \frac{8}{\pi^2+4}\frac{{V_{CC}}^2}{R} = 0.5768\left(\frac{{V_{CC}}^2}{R}\right)$$

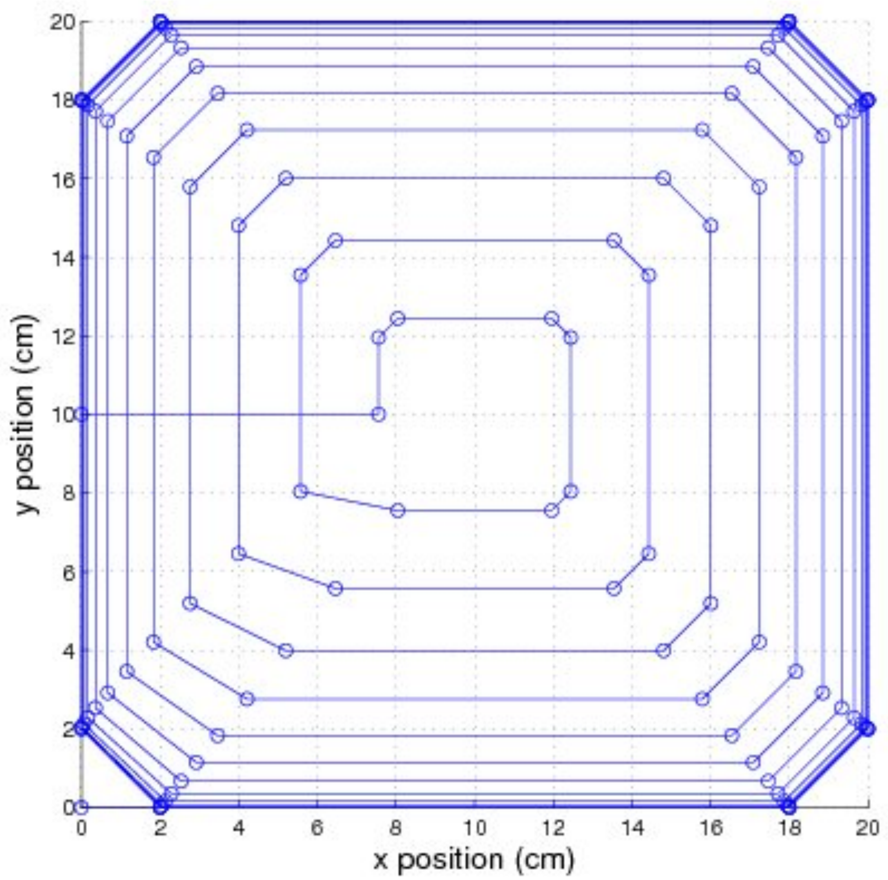
$$P_{out-ClassD} = \frac{2}{\pi^2}\frac{{V_{CC}}^2}{R} = 0.2026\left(\frac{{V_{CC}}^2}{R}\right)$$

For the same …	**Compare …**	**Ratio (Class-E/Class-D)**
Supply voltage	Power delivery	2.847
Power delivery	Supply voltage	0.593
Power delivery	Drain voltage stress	2.112
Supply voltage	Drain voltage stress	3.562

TX Coil Design for Uniform Field

- Rectangular spiral of N turns
- Spacing increases approaching the center.
- Width of turn n to turn n+1 related by ratio f
- Corners blunted by fraction Δ to reduce field peaks
- Coil is fully described by length, width, N, Δ, k.

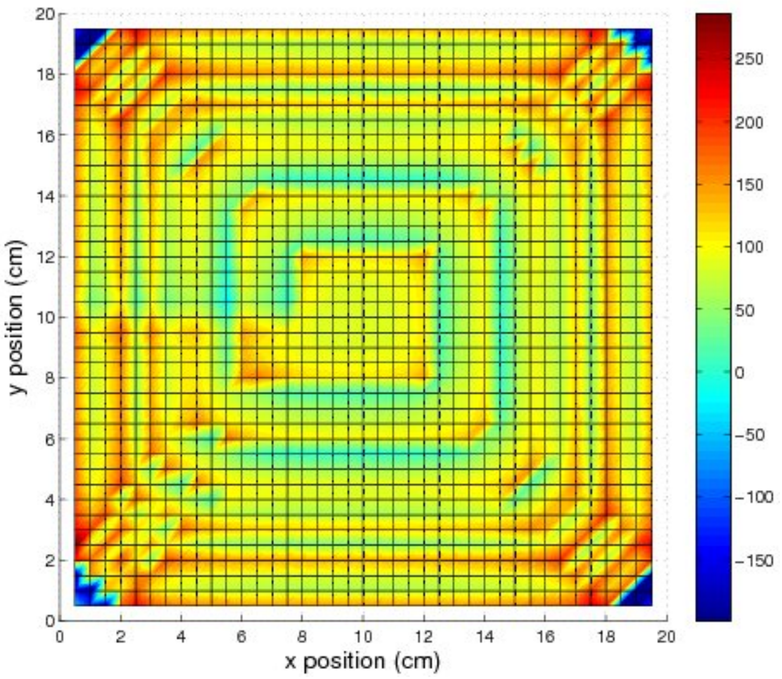
$$f = 1 - (1 - (N - n + 1)/N)^k$$



J. J. Casanova, Z. N. Low, J. Lin, R. Tseng, "Transmitting Coil Achieving Uniform Magnetic Field Distribution for Planar Wireless Power Transfer System," *Proceedings of IEEE Radio and Wireless Symposium*, pp. 530-533, January 2009.

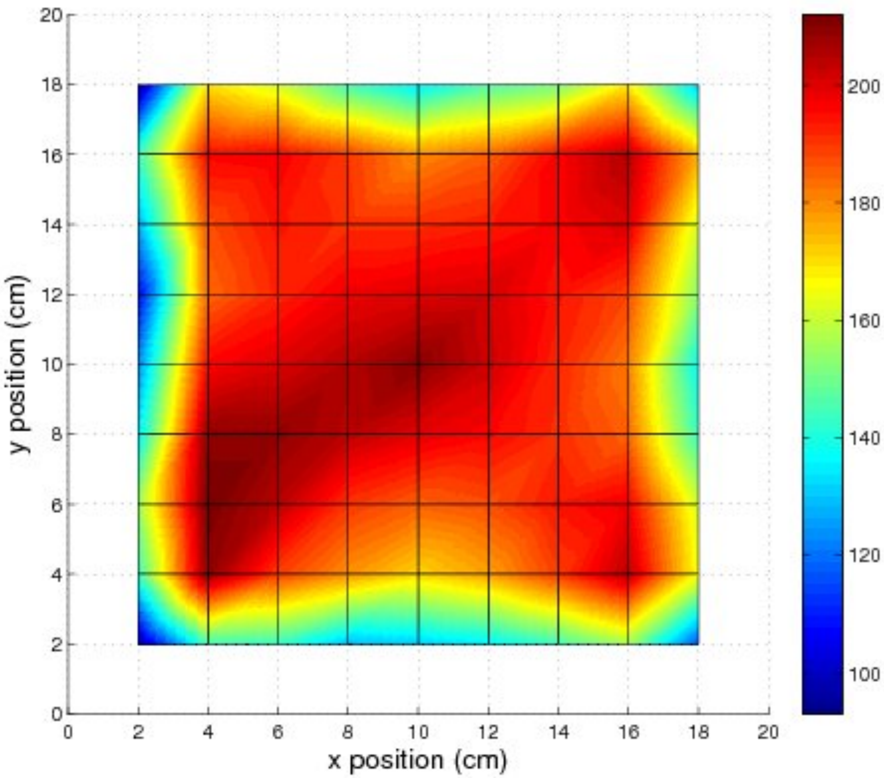
Magnetic Field Distribution

Calculation (Magnetic Quasi-Static)



H (A/m) based on 1 A current on coil

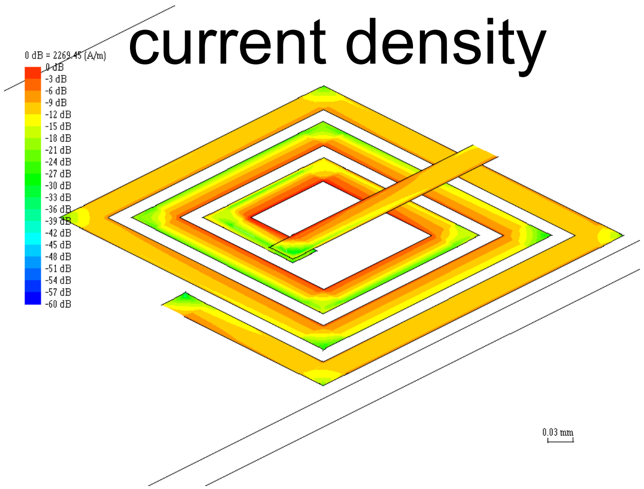
Measurement

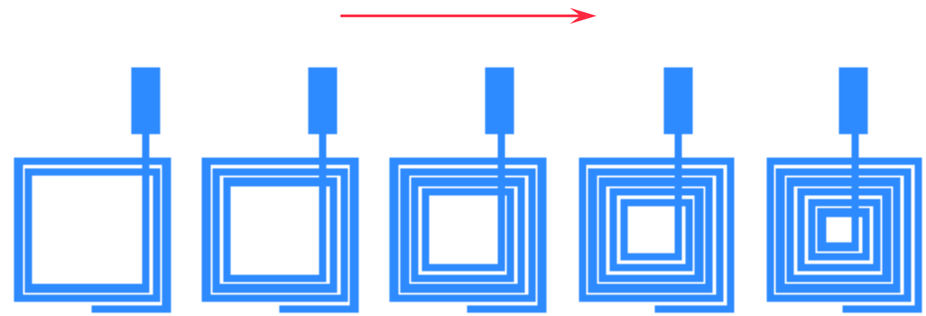


Voltage (mV) on the field probe

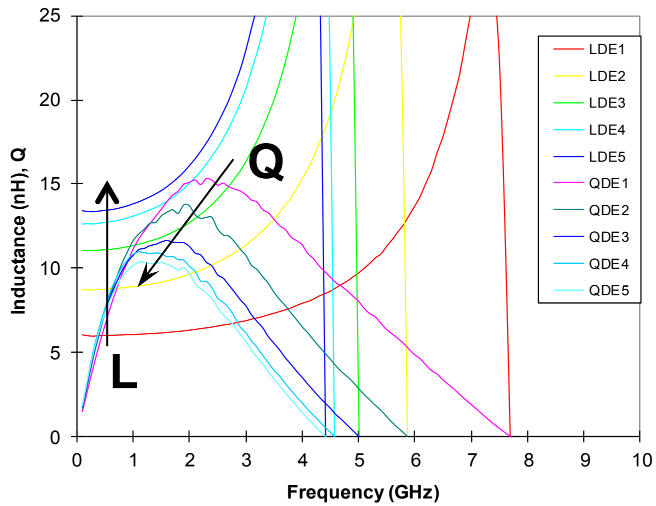
RFIC Inductors – a comparison

current density

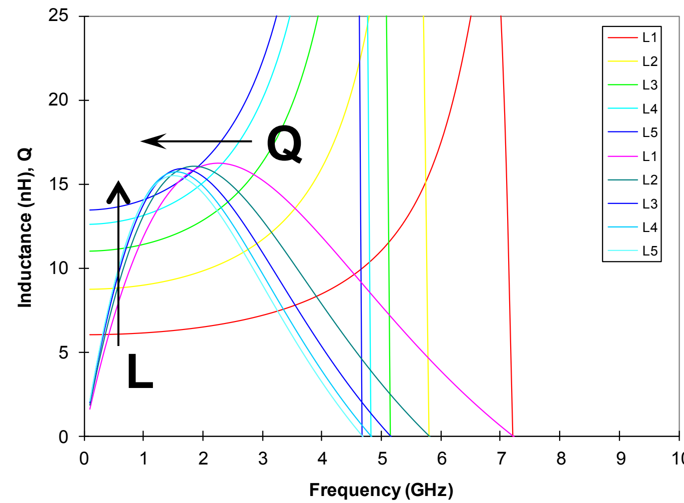




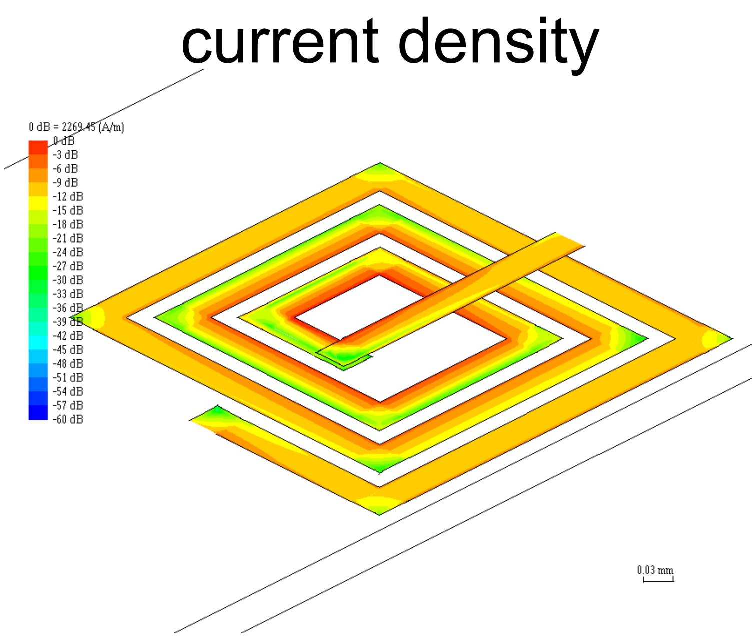
measured

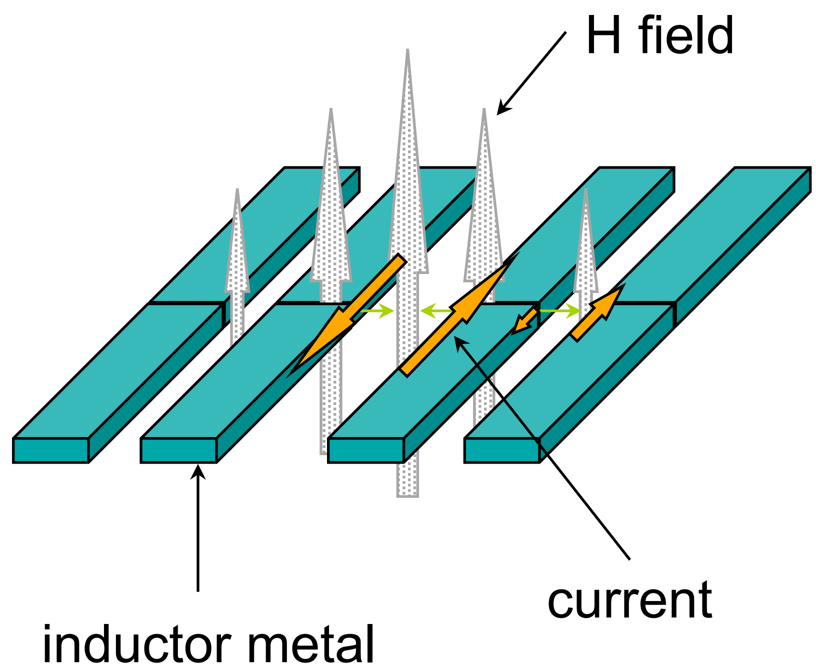


simulation without current crowding effect

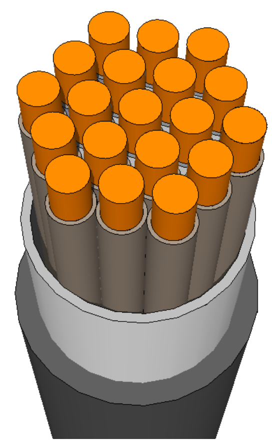


Current Crowding Effect (Proximity Effect)





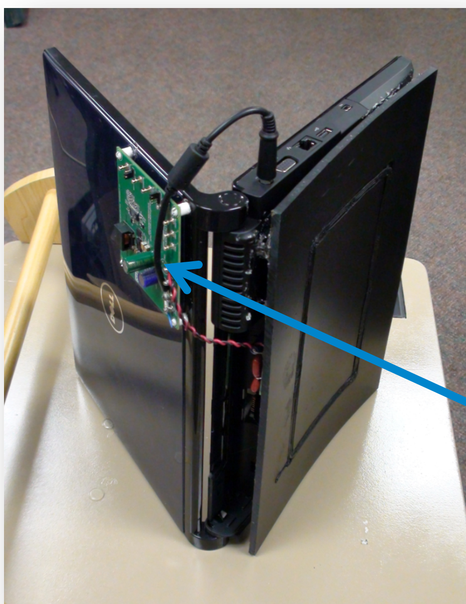
Dense inductor with many turns
→ Building strong magnetic field at center
→ Current concentrating at inner edge near center
→ Lower the Q

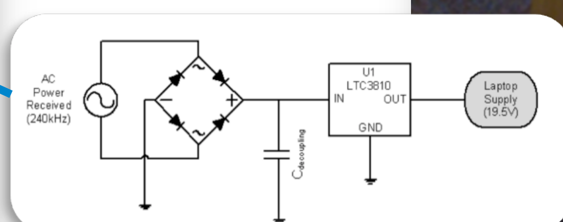


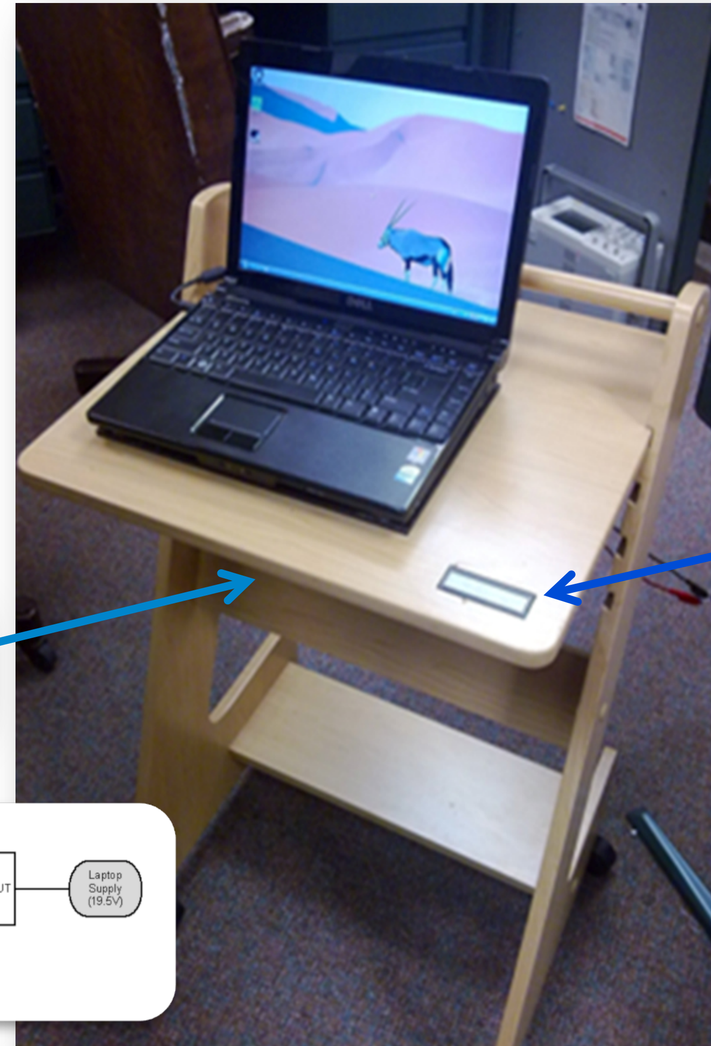
To avoid this, RFIC inductors usually have a hollow center.
In magnetic near-field WPT, Litz wire is used.

Wireless Laptop Charging Station

- Dell Vostro 1310 laptop
- Battery removed from laptop → Power from the wireless power receiver only
- Total power required: 32 W
- TX coil size: 35 cm x 25 cm
- RX coil size: 20 cm x 12 cm





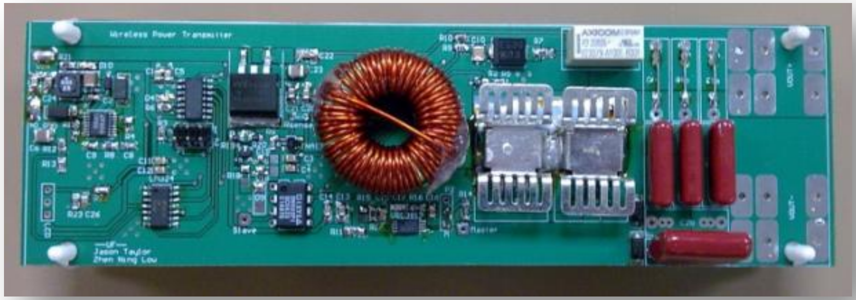


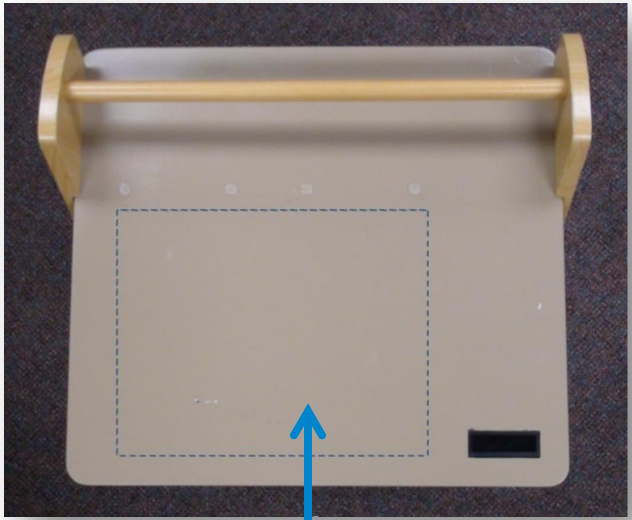
LCD

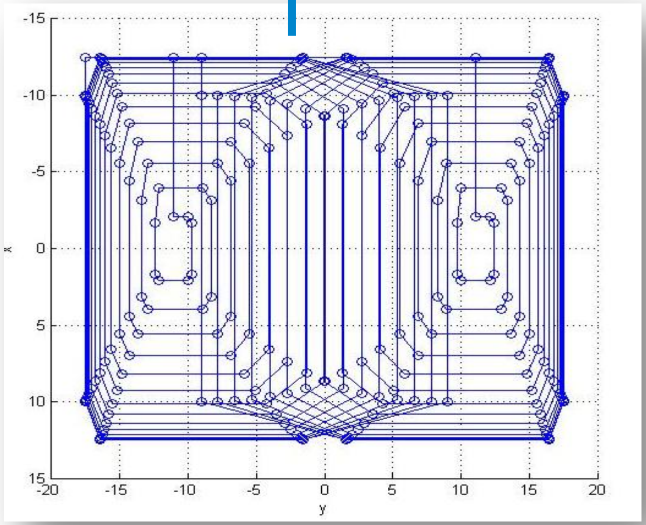
J. A. Taylor, Z. N. Low, J. J. Casanova, J. Lin, "A Wireless Power Station for Laptop Computers," *Proceedings of IEEE Radio and Wireless Symposium*, pp. 625-628, January 2010

Transmitter Design

- TX coil is embedded into the desktop (blue dashed outline).
- Two parallel overlapping coils created uniform magnetic field distribution.
- TX coil size: 35 cm x 25 cm
- TX board size: 5 cm x 17 cm
- Operate at 240 kHz





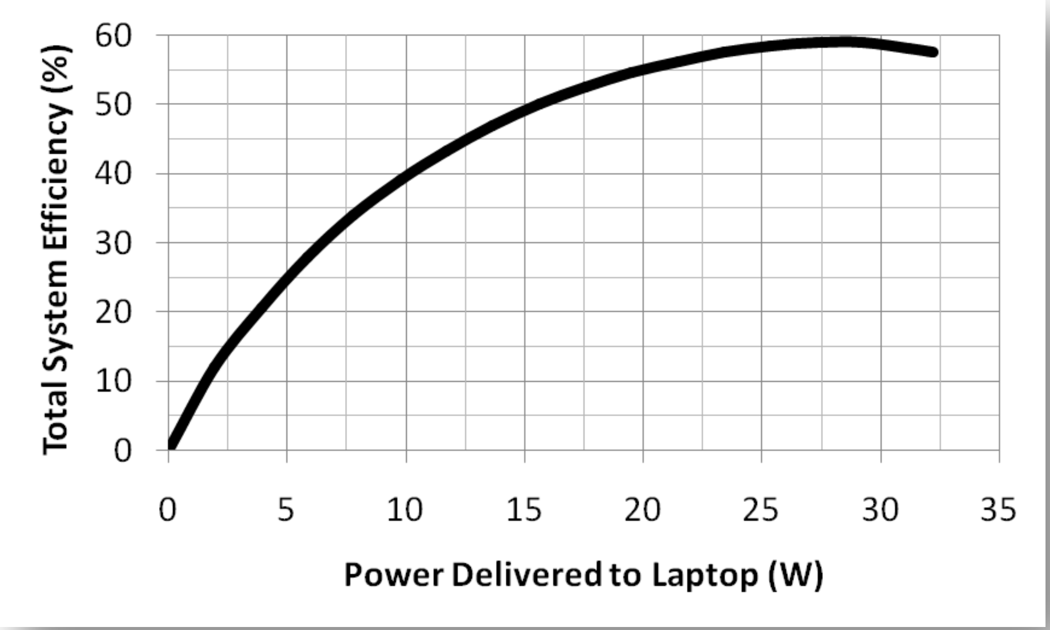


High-power Class-E Inverter

Low-power control circuit

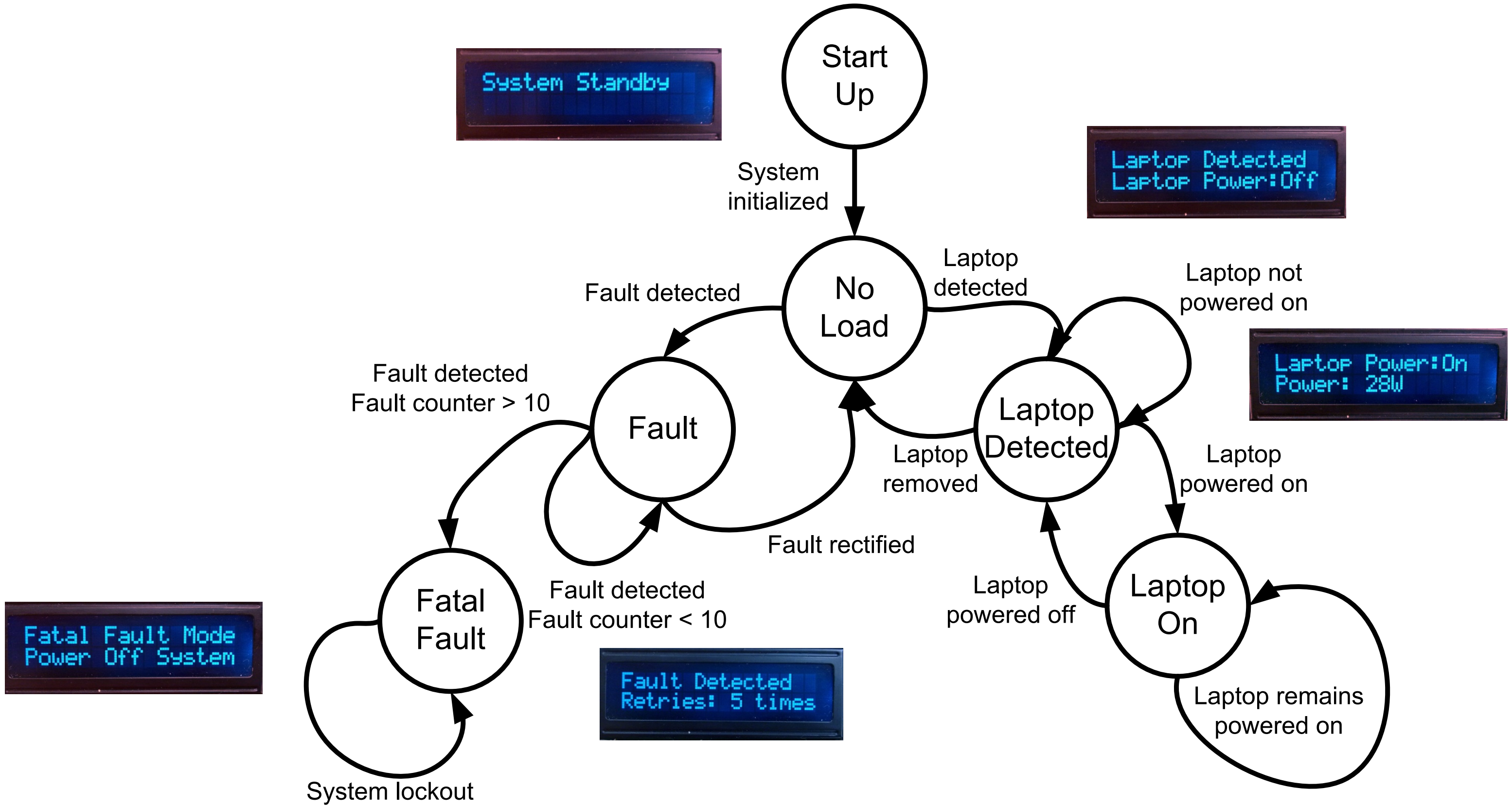
Measurement Result

- Better than 50% for power above 15 W.
- Peak efficiency near 60%.
- Total system efficiency includes the receiver regulator, detection and control circuitry, with respect to the power delivered to the laptop.
- Voltage regulator conversion efficiency: 90%
- Class E amplifier drain efficiency: > 90% for most load conditions



- Since the laptop generates more heat than the wireless power receiver, temperature increase is not observed after high power operation of more than 2 hours.
- Most of the heat is generated at the ferrites and voltage regulator which can be easily dissipated to the environment

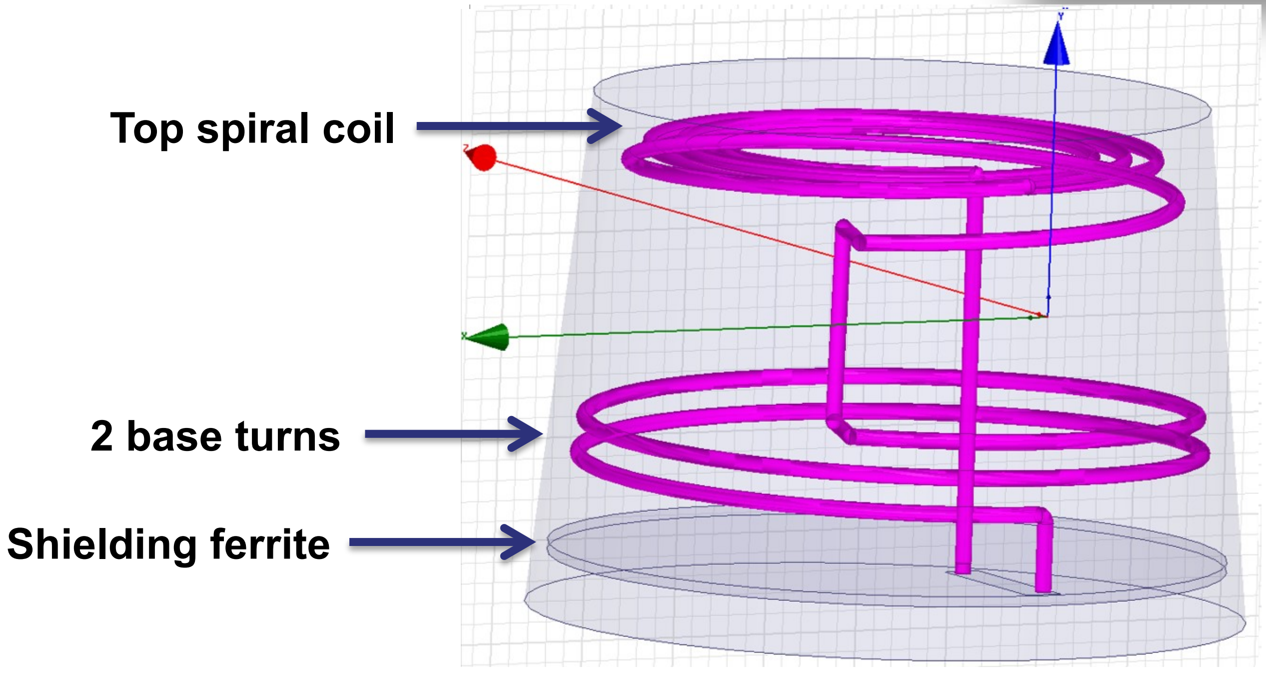
Software Control and Load Detection



- Initial start-up: no load state.
- Supply current and coil voltage sampled by A/D converter
  → determine the system state.
- If no load is detected, the system enters into a low duty cycle state to save power by turning off the system most of the time and only probes the system once every two seconds.
- For simplicity, the fault state (foreign object detection) is only considered if a piece of metallic or magnetic material of significant size is placed in the vicinity of the transmitting coil.

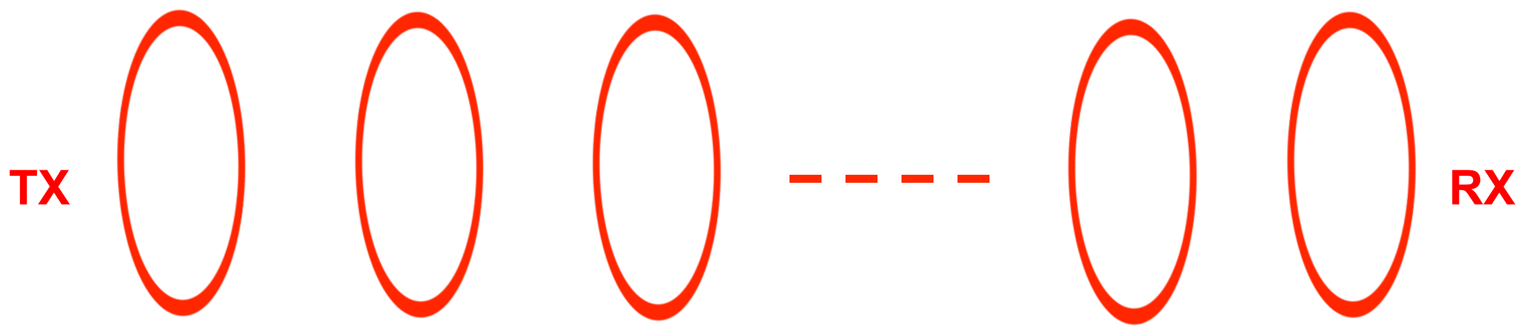
3D Wireless Charging

- 360° uniform charging surface
- Free positioning of the wearable device
- Support up to 10 W to the load
- Coil-to-coil efficiency (1 TX coil vs. 2 RX coils) 79.5%

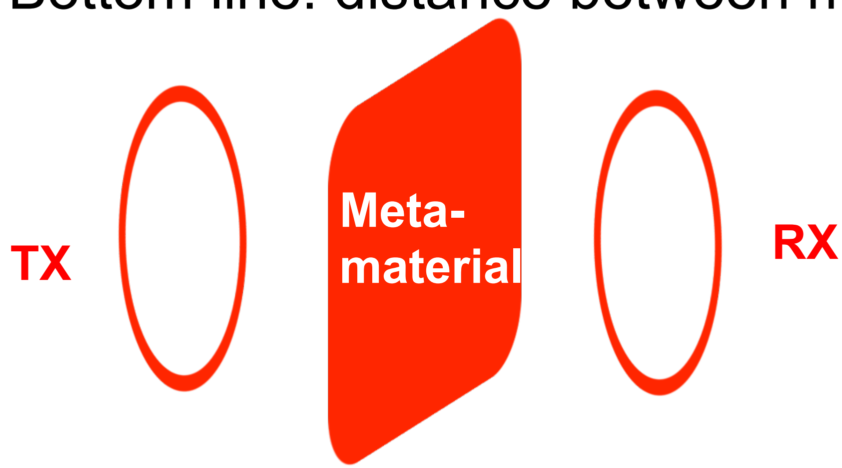


Extending the Near-Field WPT Range

- Resonant coils as relay
  - Bottom line: distance between the last relay coil and RX coils

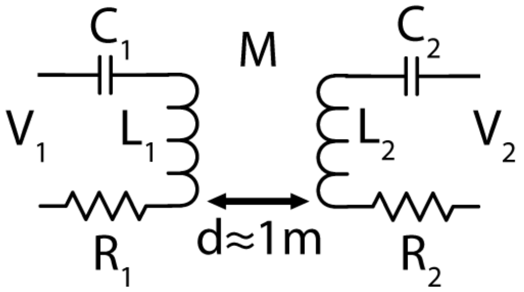


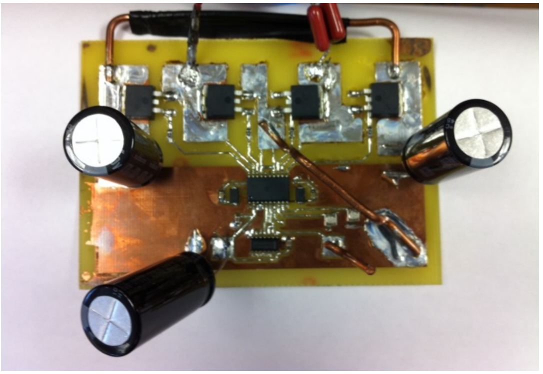
- Metamaterial
  - Bottom line: distance between metamaterial and RX coil

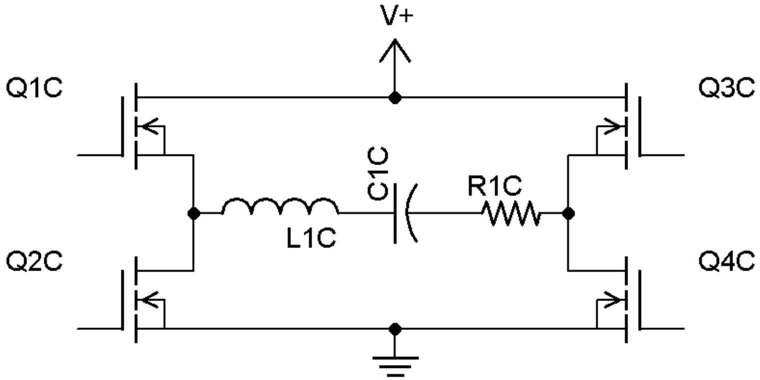


A Mid-range WPT System

- Two **1 m x 1 m** coils separated by **1 m**
- Driven by full-bridge Class-D amplifier
- Frequency: 508.5 kHz
- 75% efficiency across 5-40 W



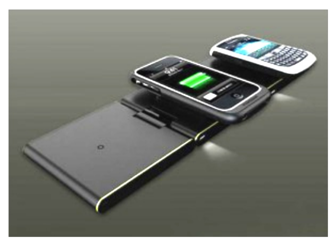




Commercialization and Standardization

- Industry alliances for near-field wireless charging
  - Wireless Power Consortium (Qi):
    est. Dec. 2008, 226 companies (11/2015),
    230 companies (4/30/2016)
  - AirFuel Alliance: 195 companies (11/2015),
    150 companies, (4/30/2016) combining
    - Alliance for Wireless Power (A4WP):
      est. 2012, 140 companies (4/2015)
    - Power Matters Alliance (PMA)
      est. 2012, 68 companies (4/2015)

rezence
Alliance for Wireless Power

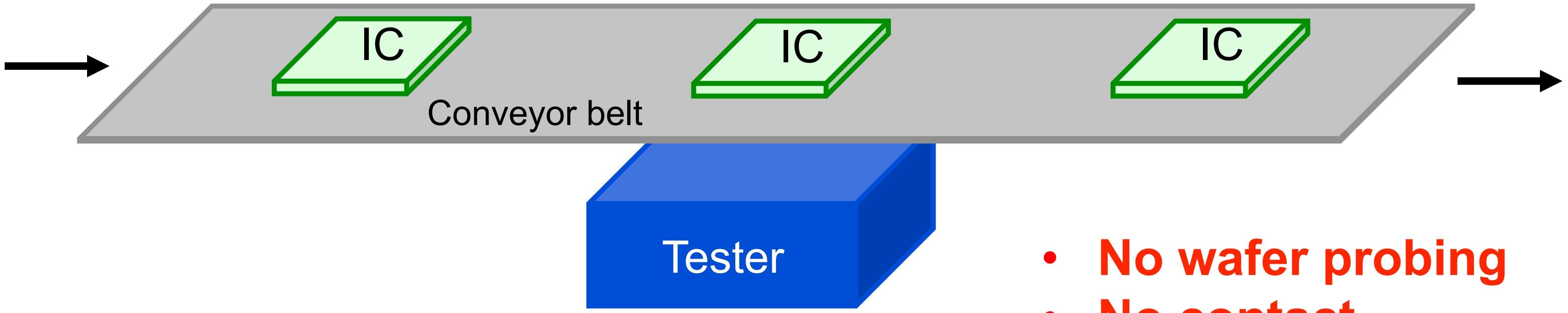


- Trend: saturation or running out of steam? Another merger?
- A unified standard like IEEE 802.11 (WiFi) would be better
  - Compatibility, unlicensed operation

Possible future applications

Wireless-Powered IC Chips

- Signals can be transmitted wirelessly, why not do the same for power? Cut the last wire to the chip!
- A chip mounted on PCB without bond wire or flip-chip bump
- Both operating dc voltage and power consumption of IC chips for mobile devices continue to decrease, making this possible in the future.
- Testing, packaging, and system integration of IC chips in the future will be very different.



- **No wafer probing**
- **No contact**
- **Faster throughput**

Future Chip-Scale Wireless Power

- The development of wireless power and other wireless technologies benefited from semiconductor technology.
- In return, wireless power may revolutionize IC testing and packaging in semiconductor industry.

IoT (Internet of Things) → IoC (Internet of Chips)

UWB radar developed by China's Fourth Military Medical University and manufactured by Xi'an BIKEN Hi-Tech. Development found and saved more than 10 survivors trapped in ruins.

F_{center}: 500 MHz
Range: 15 m
Penetration: 2 m brick wall
Resolution: mm

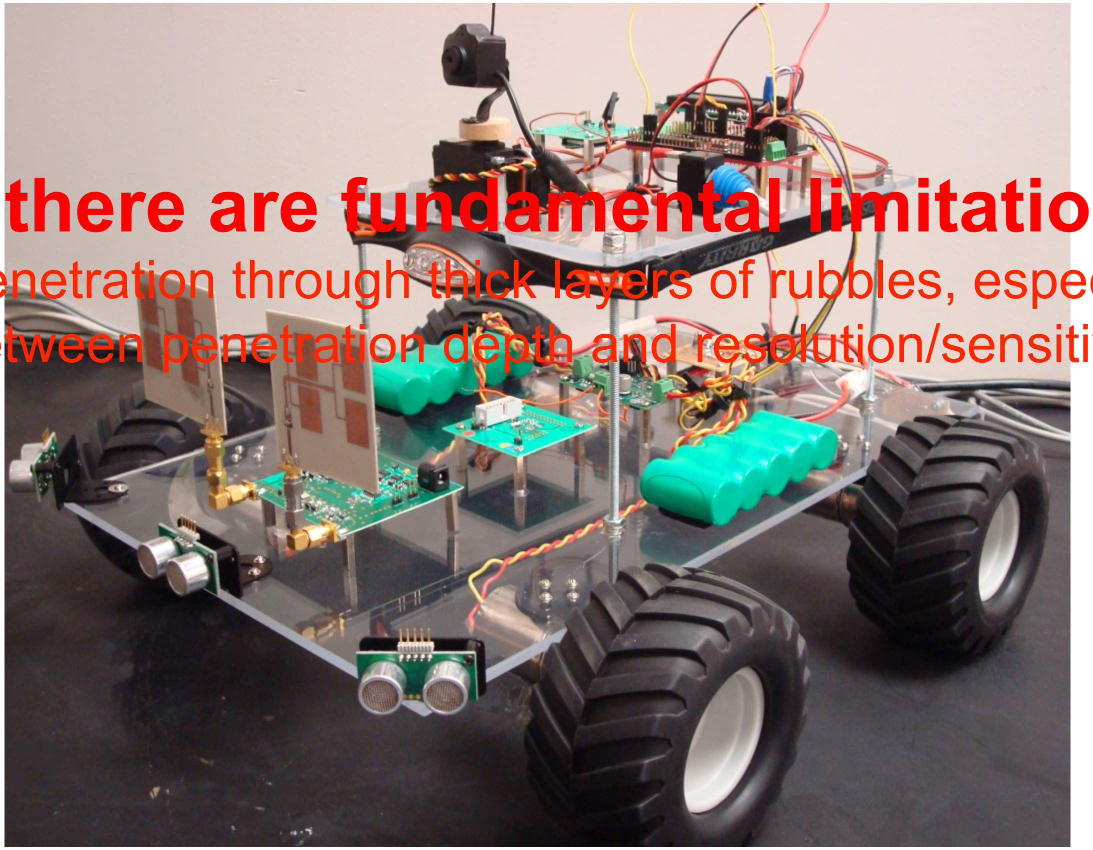
NASA's Radar Found 4 Men Trapped in Rubble in Nepal By Their Heartbeats

Sarah Zhang
Filed to: NEPAL EARTHQUAKE 5/06/15 11:35am

Press Release Issued by the U.S. Department of Homeland Security Science and Technology Directorate

Washington, D.C. - Four men trapped under as much as 10 feet of bricks, mud and other debris have been rescued in Nepal thanks to a new search-and-rescue technology developed in partnership by the Department of Homeland Security's (DHS) Science and Technology Directorate (S&T) and the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL). The device called FINDER (Finding Individuals for Disaster and Emergency Response) uses microwave-radar technology to detect heartbeats of victims trapped in wreckage. Following the April 25

Vital-bot: A vital-sign-searching robot



However, there are fundamental limitations:

- EM wave penetration through thick layers of rubbles, especially when wet
- Trade-off between penetration depth and resolution/sensitivity

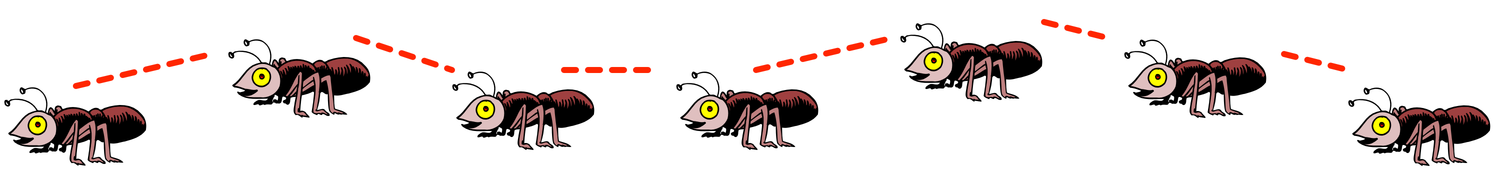
Wireless data link sends detected data to a remote station.

A Solution: Autonomous Small Robots

- Fusion of emerging technologies:
  small radar (IC chip) + wireless power relay + energy harvesting, carried by a small robot
- Wireless ad-hoc communications among robots – wireless swarm network
- More effective to search survivors deep under rubbles.

A swarm of wireless-powered robotic vital-ants

Wireless power and data relayed from/to a station above ground

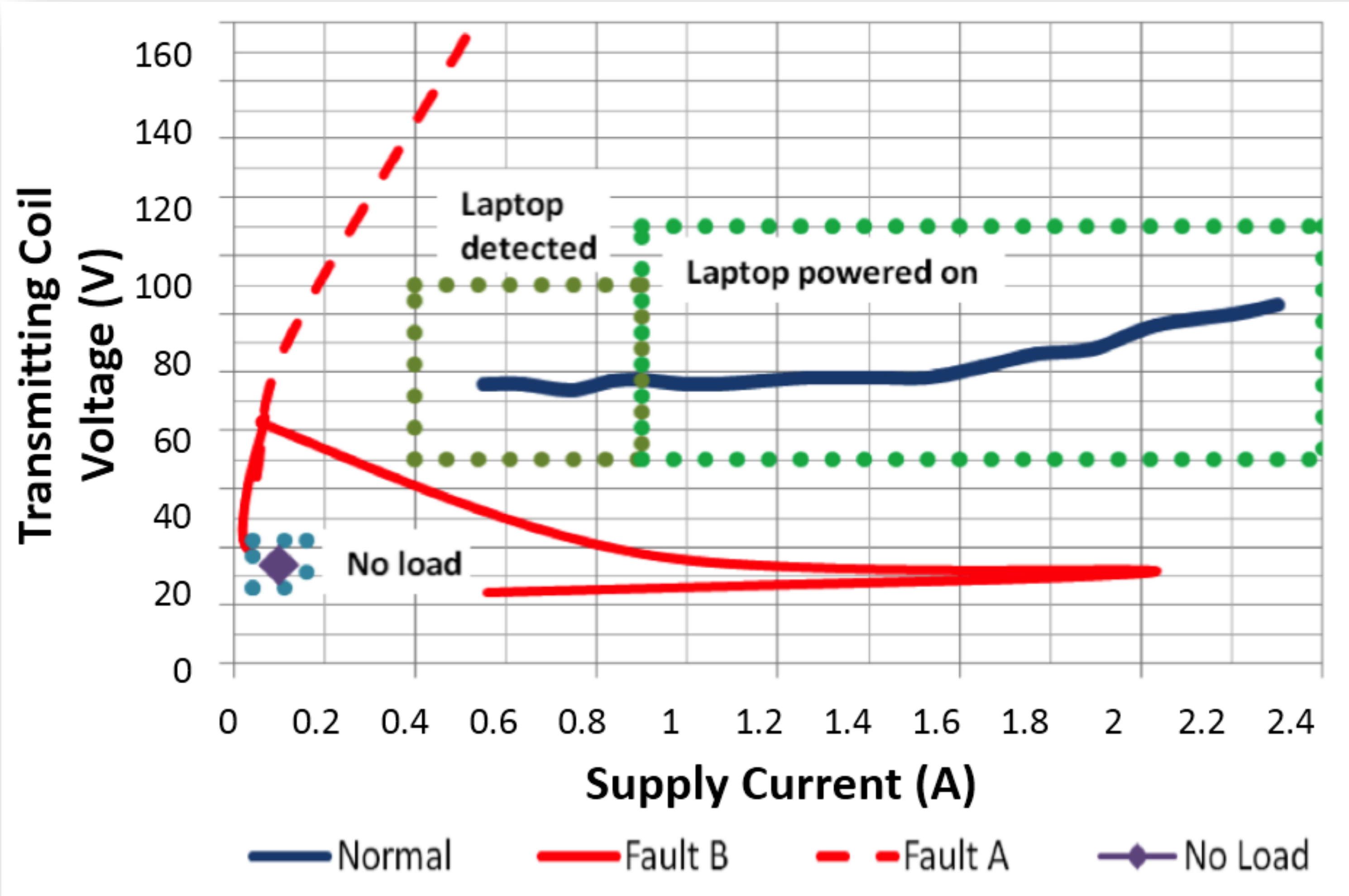


Conclusion

- Wireless Power in the 21st Century: a mix of both long range and short range, both near field and far field
- Far-field wireless power
  - Long range
  - Lower efficiency
  - Space/military, ultra low power devices, sensor network
  - Energy harvesting
- Near-field wireless power
  - Short range – less safety concern
  - Higher efficiency
  - Wireless charging EV, OLEV, personal equipment, IoT
  - Frequency: kHz, MHz, or GHz
- Large scale to small scale
  - OLEV, EV, UAV, laptop, mobile phone, IC chip, …

THANK YOU!

Load Detection



Z. N. Low, J. Casanova, P. Maier, J. Taylor, R. A. Chinga, J. Lin, "Method of Load/Fault Detection for Loosely Coupled Planar Wireless Power Transfer System with Power Delivery Tracking," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1478-1486, April 2010