Electromagnetic Compatibility for Wireless Power Transfer

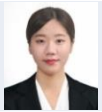
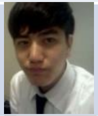
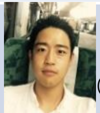
November 20th, 2020

Seungyoung Ahn

EMC Laboratory
CCS Graduate School of Green Transportation
KAIST

Introduction to EMC Lab in KAIST

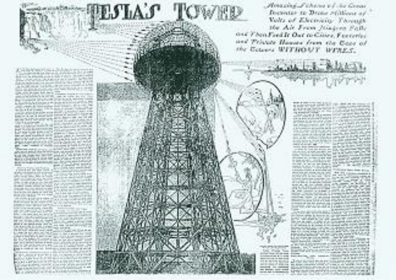
Professor	Education	Experiences	Academic Activity
	1998 B.S. EE, KAIST 2000 M.S. EE, KAIST 2005 Ph.D. EE, KAIST	2001-2002 Visiting Researcher, SIMTech, Singapore 2005-2009 Senior Researcher, Samsung Electronics 2009-2011 Research Professor, KAIST 2011-2015 Assistant Professor, KAIST 2016- Associate Professor, KAIST	Chapter Chair *IEEE EMC Korea Chapter* Distinguished Lecturer *IEEE EMC Society* Assoc. Editor *IEEE T-CPMT* Assoc. Editor *IET Electronics Letters* Topic Editor *MDPI Energies* 80+ Journal & 100+ Conf Publications

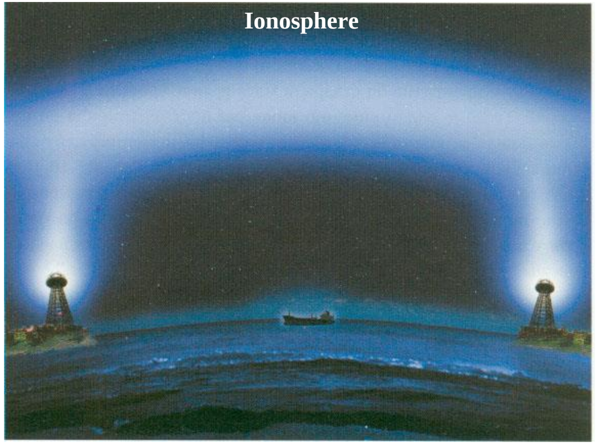
Researcher	Ph. D. Course		Master Course	
 Mr. Yangbae Chun (WPT Standard)	 Jedok Kim (Railway WPT)	 Kyunghwan Song (EMI Shielding)	 Seongho Woo (WPT Protection)	 Sunghee Lee (Package Modeling)
 Dr. Junsung Choi (V2X Communication)	 Jongwook Kim (Underwater WPT)	 Haerim Kim (Biomedical WPT)	 Dong-Ryul Park (AI EMC)	 Seokhyun Son (Vehicular WPT)
 Dr. Jaehyoung Park (WPT EMC)	 Bumjin Park (Mag. Energy Harvesting)	 Hyunwoong Kim (EMP Modeling)	 Dawon Jung (WPT EMI)	 Changmin Lee (Robot WPT)
 Ms. Youngjoo Kim (Staff)	 Jangyong Ahn (EMF on Human)	 Sungryul Huh (Multi-coil WPT)	 Nguyen Minh Nghiem (Vehicular WPT)	 Jaewon Rhee (WPT Circuit)
	 Yujun Shin (WPT Circuit and EMC)	 Andrés Calderón (Hybird ICPT)	 Seunghoon Ryu (Magnetic Sensor)	 Semin Choi (WPT EMC)

Contents

Wireless Power Transfer Technology

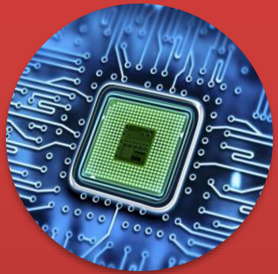
- Nikola Tesla (New York American, May 22, 1904)
  - Tesla's Tower - Amazing scheme of the great inventor to draw millions of volts of electricity through the air from Niagara Falls and then feed it out to cities, factories and private houses from the tops of the towers without wires.


TESLA'S TOWER



http://www.teslasociety.com/tesla_tower.htm

Wireless Power Transfer Applications



IoT / Sensor

μW ~ mW

Biomedical Implants

mW ~ W

Mobile / Home

W

E-Vehicle / Robot

kW ~ MW

Space / Underwater

kW ~ GW

Size & Distance & Power

IoT / Sensor	Biomedical Implants	Mobile / Home	E-Vehicle / Robot	Space / Underwater
μW ~ mW	mW ~ W	W	kW ~ MW	kW ~ GW
mm	mm ~ cm	cm	m	km

Categories of Wireless Power Transfer Technology

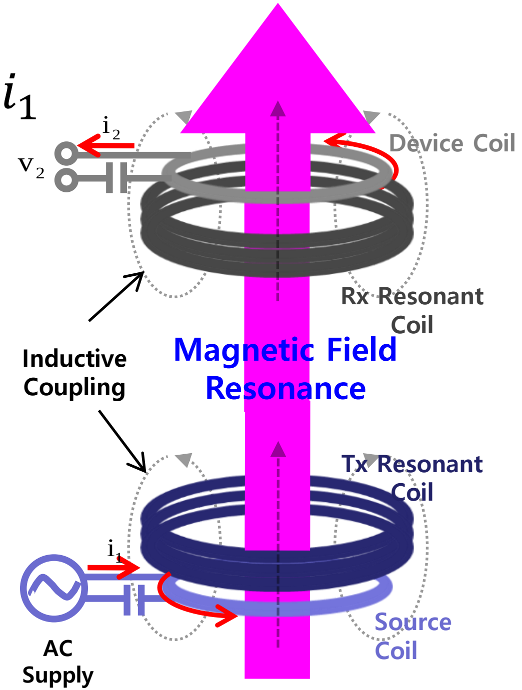
	Magnetic Resonant WPT (Inductive Power Transfer)	Electric Resonant WPT (Capacitive Power Transfer)	Microwave Power Transmission
Frequency	kHz ~ MHz	kHz ~ MHz	GHz
Distance	cm ~ m	cm ~ m	m ~ km
Power	mW ~ MW	mW ~ MW	W ~ GW
Efficiency	30 % ~ 90 %	30 % ~ 90 %	1 % ~ 50 %
Applications	Mobile, EV, Biomedical	Mobile, EV, Drone	Mobile, Sensor, Solar Power Satellite

❑ Resonance is generally used to enhance the distance and efficiency.

Magnetic and Electric Resonant WPT Systems

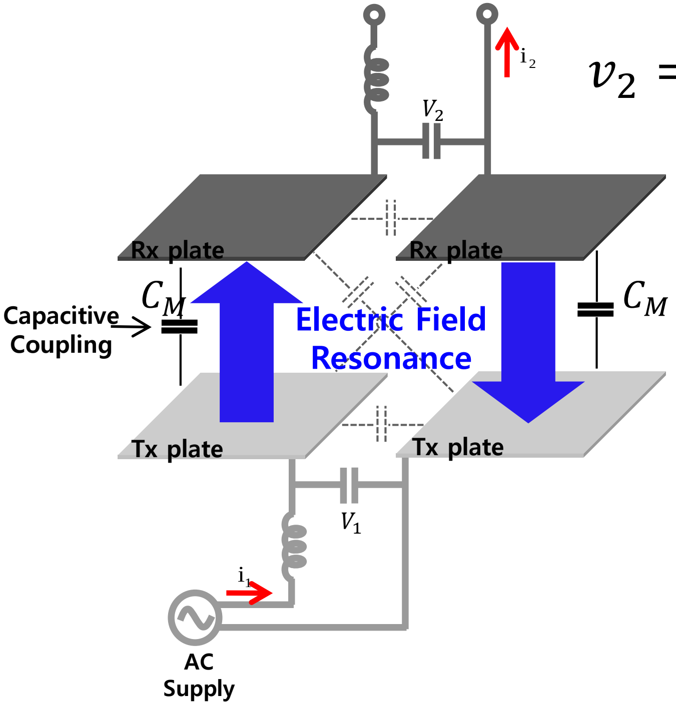
Magnetic Resonance WPT (Inductive Power Transfer)

$$v_2 = j\omega M i_1$$

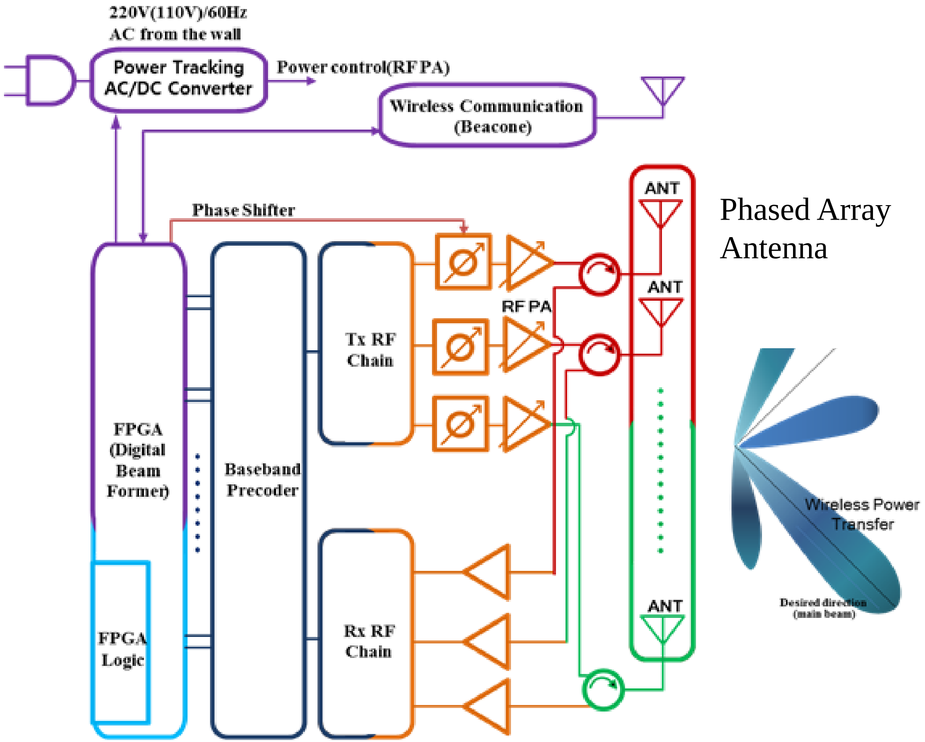


Electric Resonance WPT (Capacitive Power Transfer)

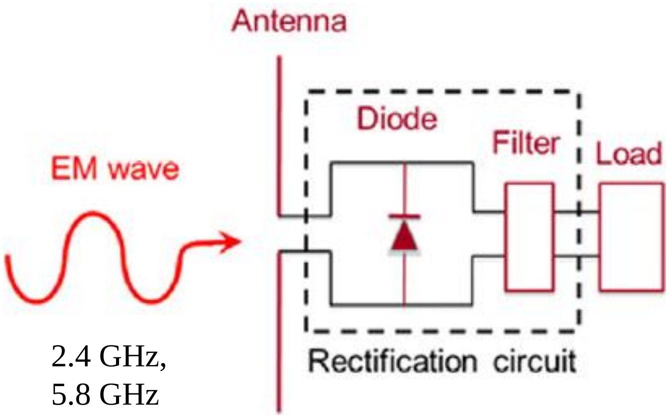
$$v_2 = \frac{i_1}{j\omega C_M}$$



Microwave Power Transmission

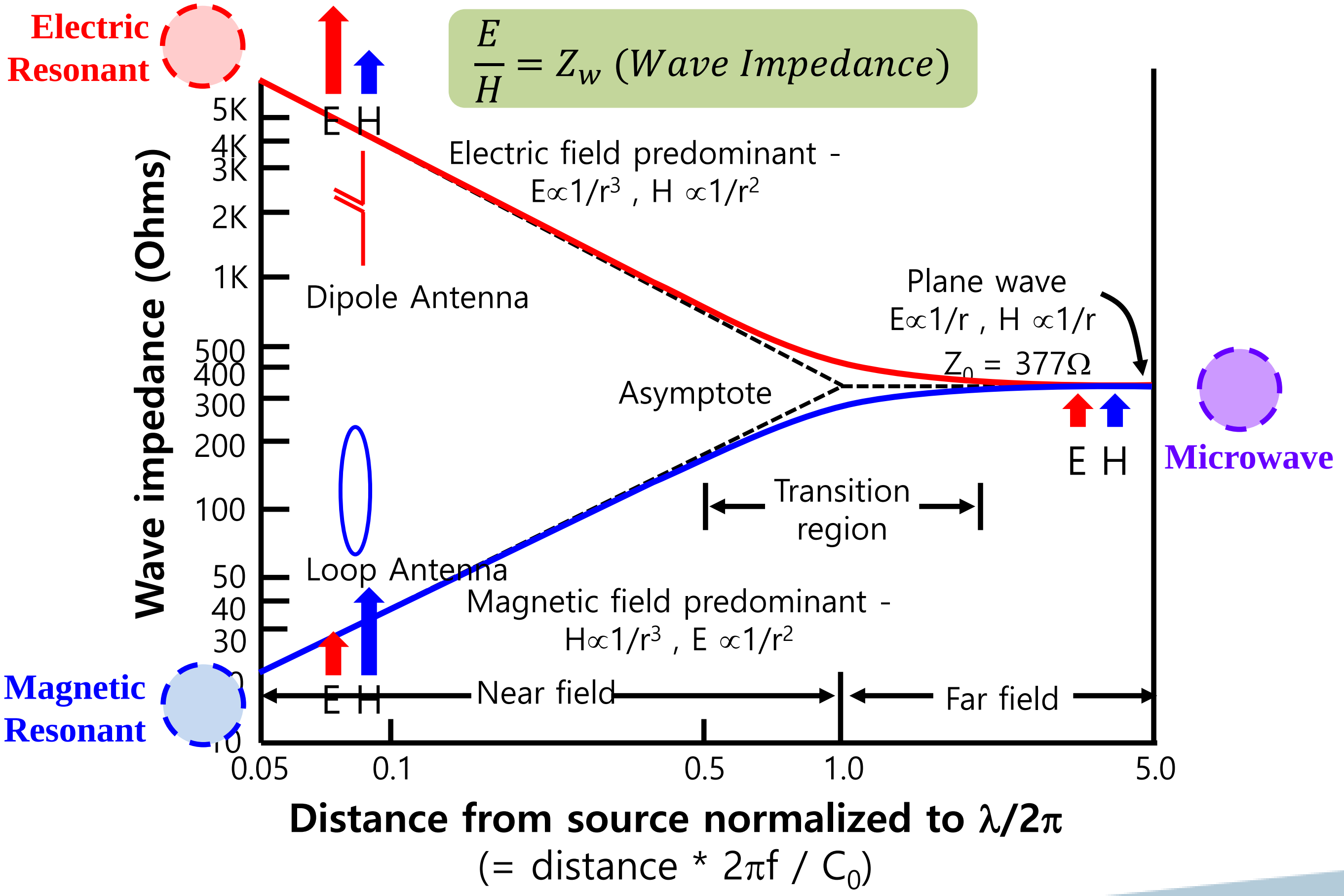


< Transmitter >



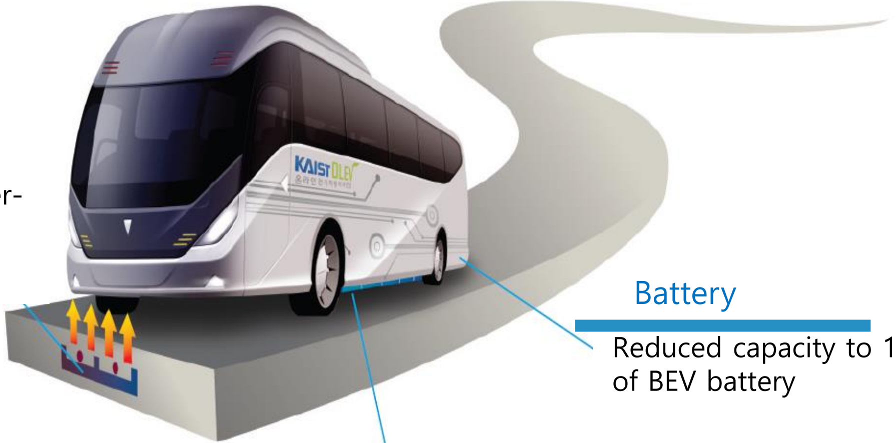
< Receiver >

Wave Impedance of WPT Coils



On-Line Electric Vehicle of KAIST

Solving battery and charging problems by developing OLEV, which enables wireless electric power transmission while vehicle is stopped or running.



Powered Track

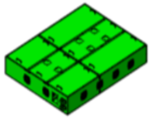
Business-competitive under-road power supply

Power Inverter

3-phase
440V/60Hz

200A
20kHz

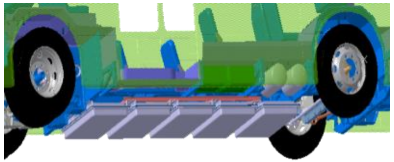
Battery



Reduced capacity to 1/3~1/5 of BEV battery

Pick-up System

Power collection with high efficiency



Wireless Charging EVs in Korea

Seoul Grand Park (Jul. 2011)

Yeosu Expo (May-Aug. 2012)

Shuttle Bus at KAIST (Oct. 2012)

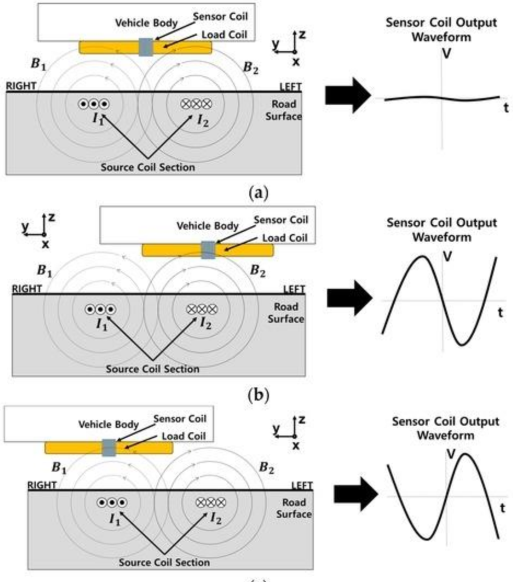
Gumi City (Mar. 2014)

Sejong City (Jun. 2015)

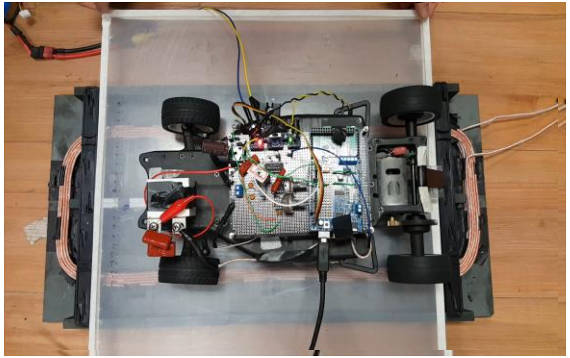
Autonomous Driving and WPT for EV

Autonomous Driving Infrastructure using WPT

- Autonomous Vehicle Alignment System
  - Automatic steering control based on magnetic field



Scale-down experiment for autonomous vehicle alignment

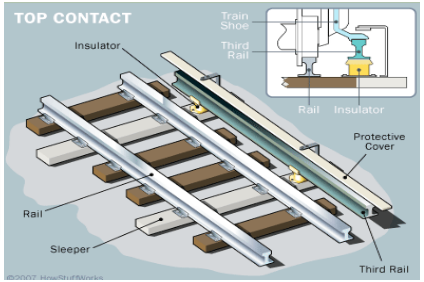


K. Hwang, J. Park, D. Kim, H. H. Park, J. H. Kwon, S. I. Kwak, and S. Ahn, "An Autonomous Coil Alignment System for the Dynamic Wireless Charging of Electric Vehicles to Minimize Lateral Misalignment," *Energies*, vol. 10, no. 3, Mar. 2017.

Limitations of Current Railway System

Catenary & Pantograph Railway System

Third Rail Railway System



Limitations

- High construction cost
- High maintenance cost
- Low reliability & security
- Environmentally unfriendly
- Friction issue for high speed
- Electrical shock

Solution

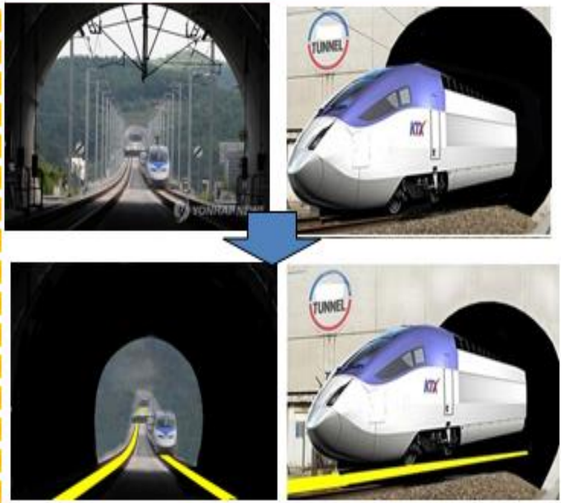
Elimination of contact-based parts

Inductive Wireless Power Transfer application

Benefits of Railway WPT System

Elimination of Power line and Pantograph

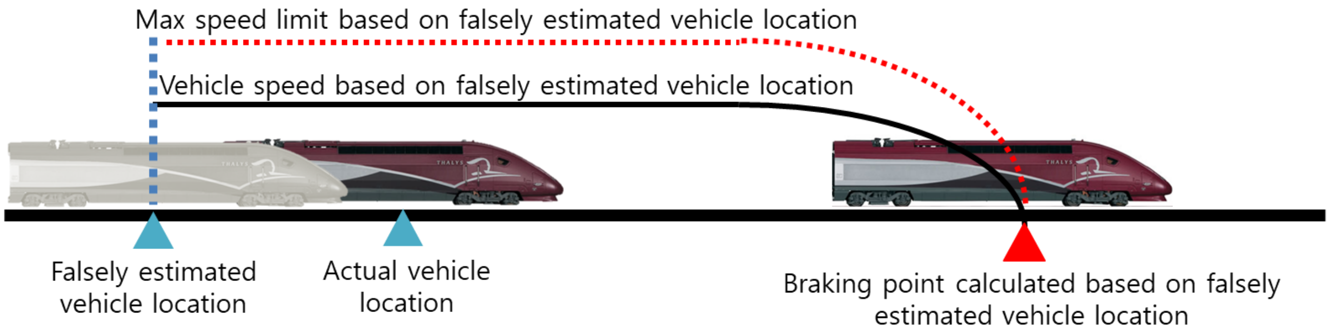
- **Aesthetic feature of city**
- **Friction-less power transmission**
- **Less requirement of Tunnel cross section**



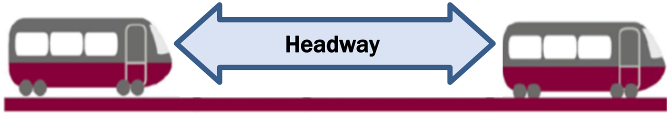
- **No conductive contact is required.**
- **Safe for electrical shock and cost effective railway system operation**

Importance of Vehicle Location Detection

- Precise estimation of vehicle's location can prevent accidents.



- Precise vehicle location can reduce headway between vehicles and increase road capacity

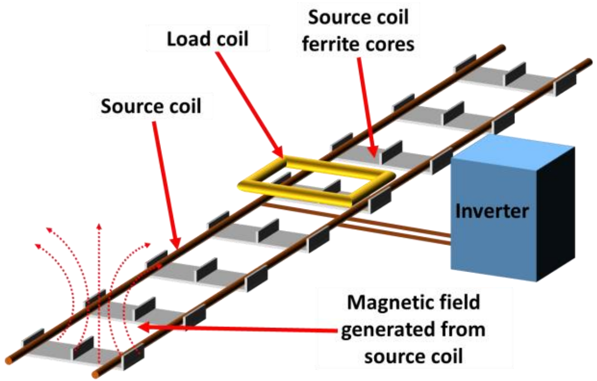


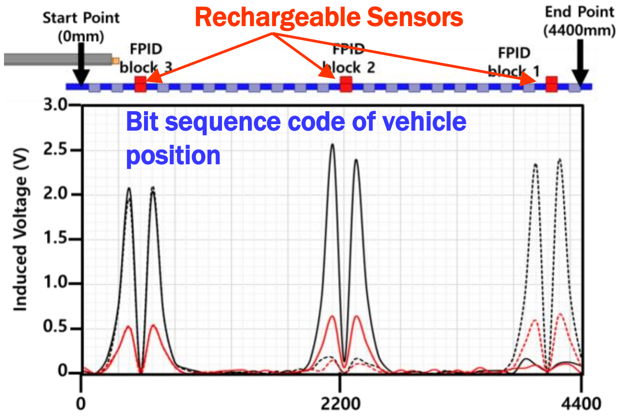
<Minimum safe headway between vehicles>

<Reduced minimum safe headway between vehicles due to precise location detection>

Autonomous Driving Infrastructure

- Accurate global/local positioning of WPT vehicles
  - Code map of vehicle position using magnetic field





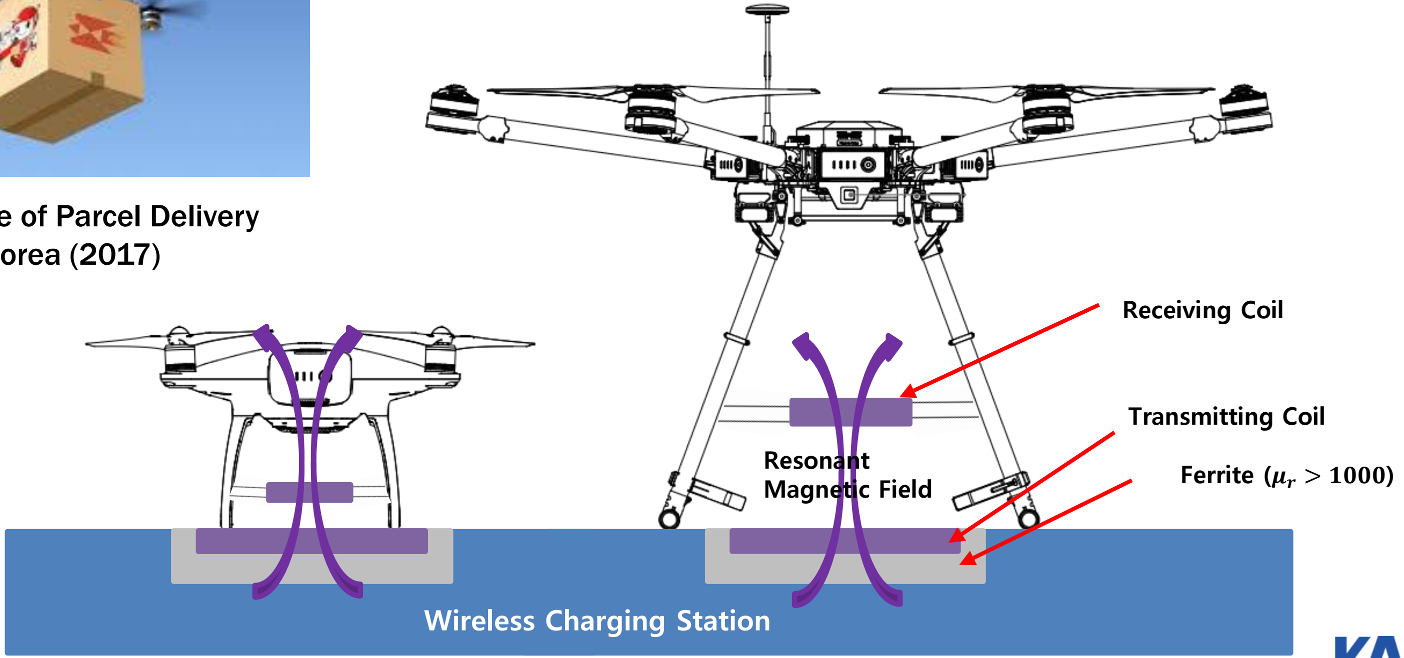
<Experiment Result of Scale-Down System for Vehicle Positioning>

K. Hwang, D. Kim, D. Har, and S. Ahn, “Pickup Coil Counter for Detecting the Presence of Trains Operated by Wireless Power Transfer, *IEEE Sensors Journal*, vol. 17, no. 22, pp. 7526-7532, Nov. 2017.

K. Hwang, J. Cho, J. Park, D. Har, and S. Ahn, “Ferrite Position Identification System Operating with Wireless Power Transfer for Intelligent Train Position Detection,” *IEEE Trans. on Intelligent Transportation Systems*, vol. 20, no. 1, pp. 374-382, Jan. 2019.

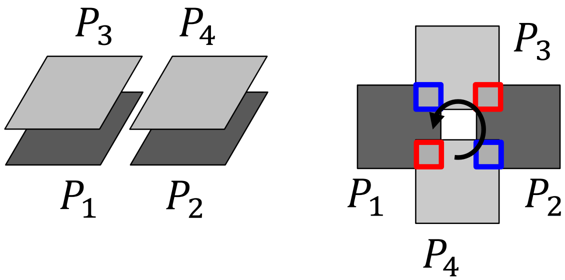
Wireless Charging System for Drone

Test Service of Parcel Delivery
in Korea (2017)



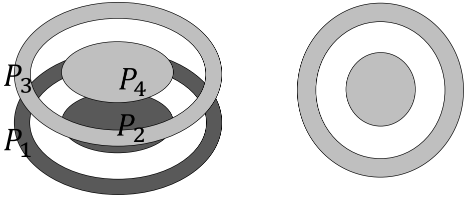
Wireless Charging using Capacitive Power Transfer

Conventional Coupler

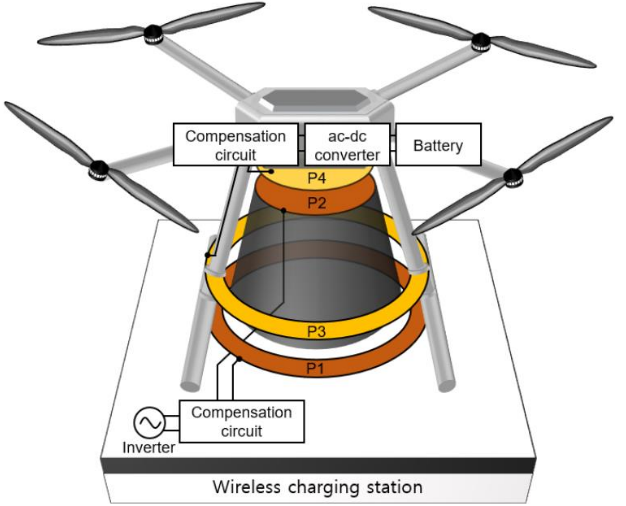


Sensitive to rotational misalignment

Center-aligned Circular coupler



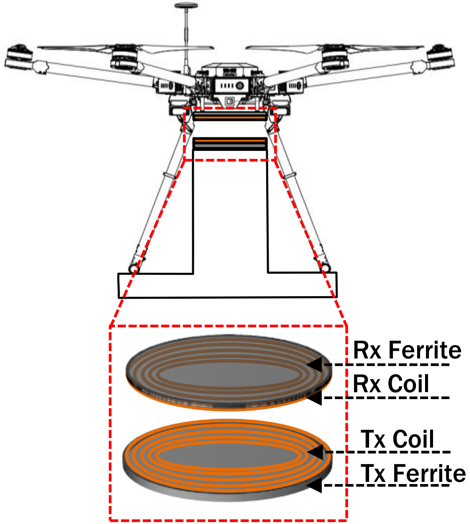
Robust to rotational misalignment.



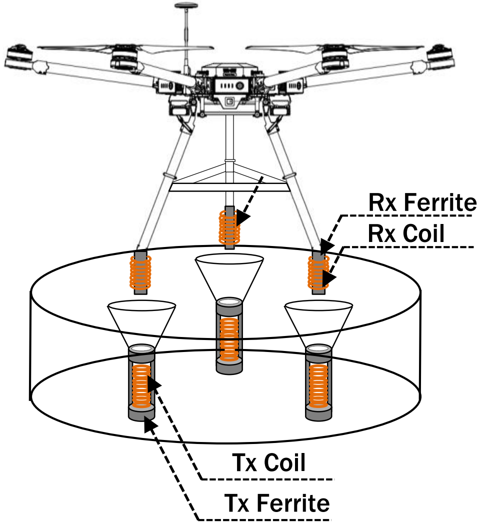
C. Park, J. Park, Y. Shin, J. Kim, S. Huh, D. Kim, and S. Ahn, "Separated Circular Capacitive Coupler for Reducing Cross-Coupling Capacitance in Drone Wireless Power Transfer System," *IEEE Transactions on Microwave Theory and Techniques*, Early Access, May 2020.

Low Weight Capacitive Power Transfer for Drone

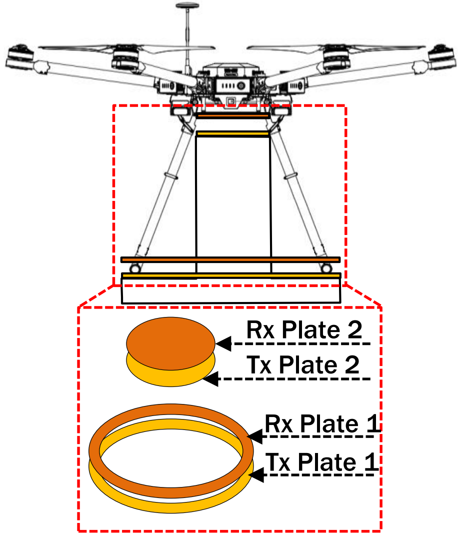
IPT system



IPT system [1]



Proposed CPT system

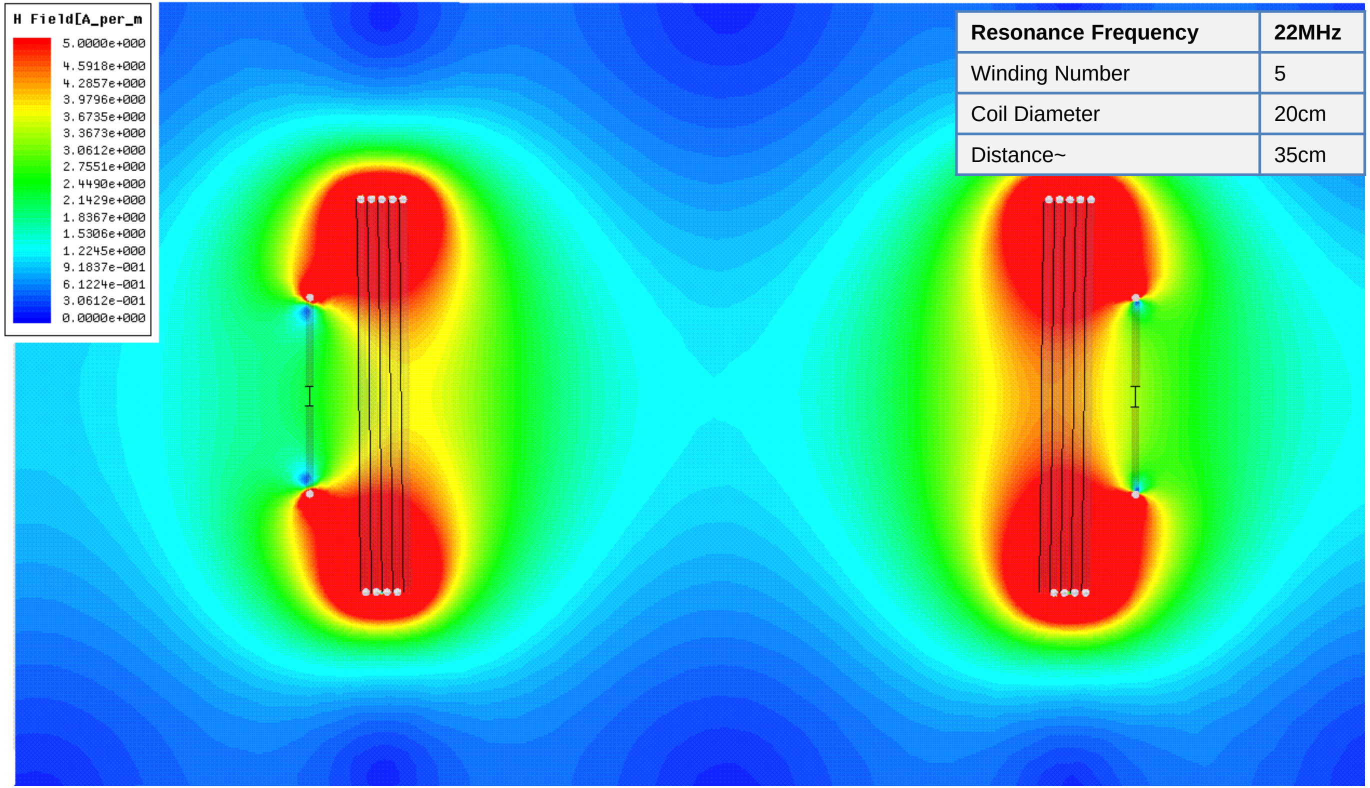


	Transfer Distance	Coil to coil Efficiency	Output power	Tx weight	Rx weight
IPT system	25 mm	93 %	100 W	1443g	911 g
IPT system [1]	< 3 mm	91 %	150 W	908g	504 g
Proposed CPT system	25 mm	89 %	100 W	306g	228 g

[1] C. Song, H. Kim, Y. Kim, D. Kim, S. Jeong, Y. Cho, S. Lee, S. Ahn, and J. Kim, “EMI Reduction Methods in Wireless Power Transfer System for Drone Electrical Charger using Tightly Coupled Three-Phase Resonant Magnetic Field,” *IEEE Trans. on Industrial Electronics*, Vol. 65, No. 9, pp. 6839 – 6849, Sep. 2018.

EMC Issues and Solutions in WPT System

Magnetic Field in Resonance



Resonance Frequency	**22MHz**
Winding Number	5
Coil Diameter	20cm
Distance~	35cm

- Result: S_{11} = -10dB, S_{21} = -4dB

Source: Dr. Youngjin Park (KERI)

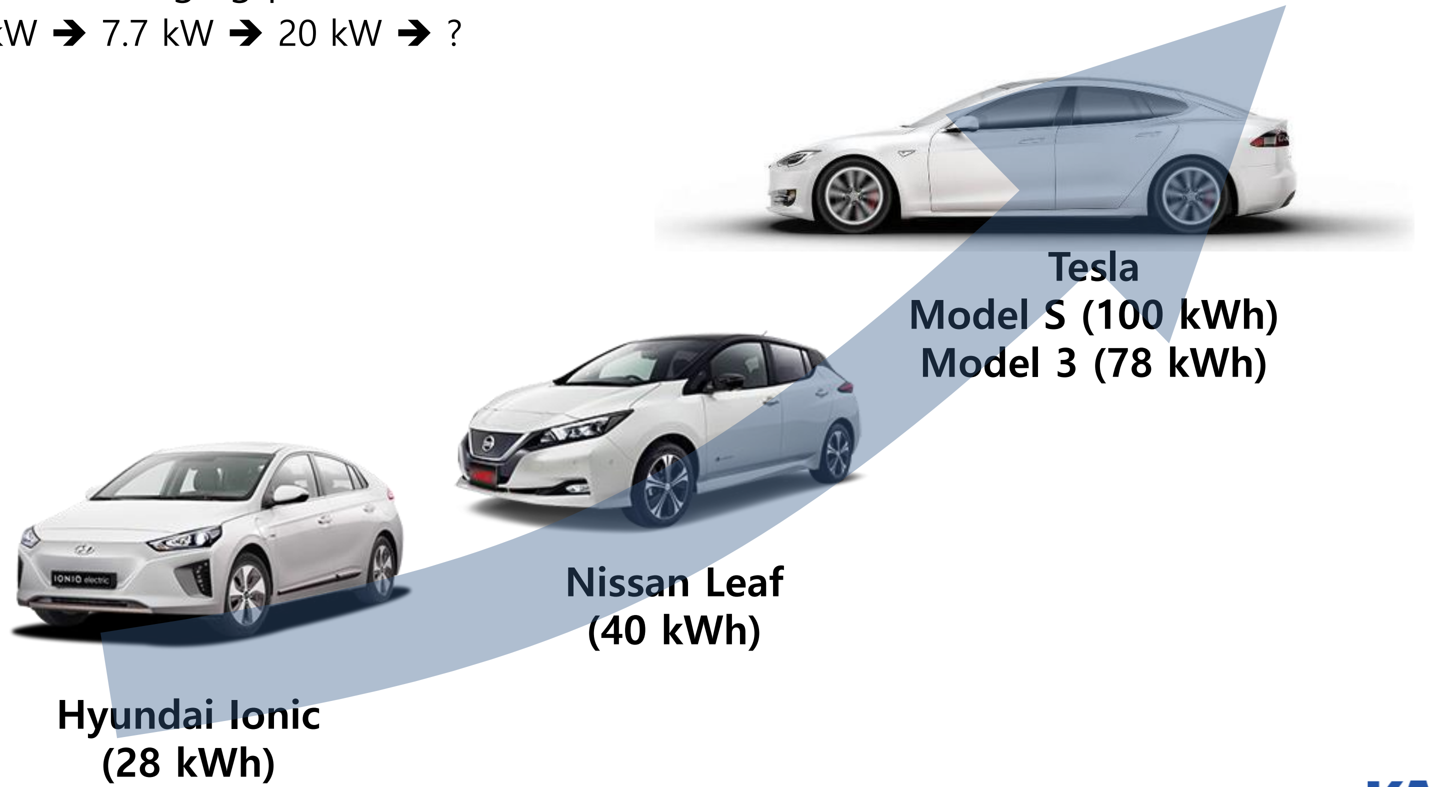
Electric Vehicle Wired Charger

Classification in use here	Level	Current	Power	Type: China	Type: Europe	Type: Japan	Type: North America
	Level 1	AC	≤ 3.7 kW	Devices installed in private households, the primary purpose of which is not recharging electric vehicles			SAE J1772 Type 1
Slow chargers	Level 2	AC	> 3.7 kW and ≤ 22 kW	GB/T 20234 AC	IEC 62196 Type 2	SAE J1772 Type 1	SAE J1772 Type 1
	Level 2	AC	≤ 22 kW	Tesla connector			
Fast chargers	Level 3	AC, triphase	> 22 kW and ≤ 43.5 kW		IEC 62196 Type 2		SAE J3068 (under development)
	Level 3	DC	Currently < 200 kW	GB/T 20234 DC	CCS Combo 2 Connector (IEC 62196 Type 2 & DC)	CHAdeMO	CCS Combo 1 Connector (SAE J1772 Type 1 & DC)
	Level 3	DC	Currently < 150 kW	Tesla and CHAdeMO connectors			

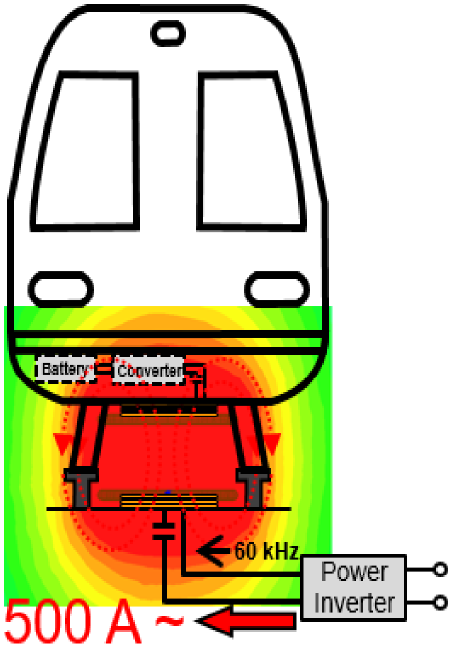
Source: IEA Global EV Outlook 2017

Battery Capacity and Wireless Charging Power

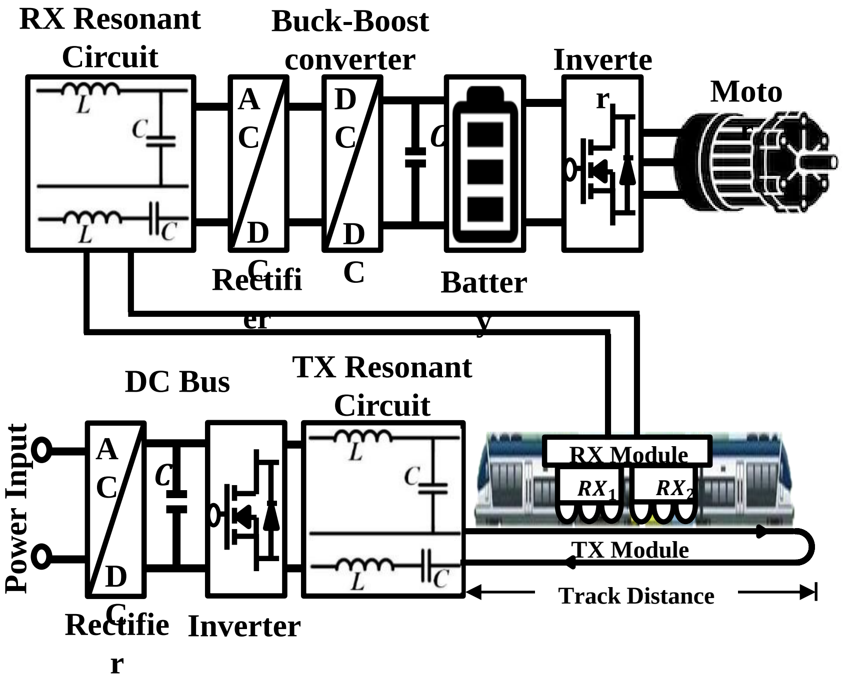
- The wireless charging power should be increased.
  - 3.3 kW ➔ 7.7 kW ➔ 20 kW ➔ ?



Power System Structure for Railway WPT



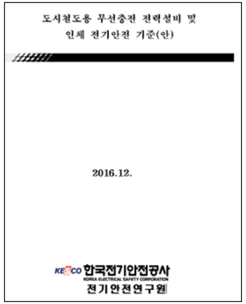
- Urban Railway: 1 MW
- High-Speed Train: 10 MW



< Schematic Diagram of Railway WPT Power System >

Electrical & Electromagnetic Safety

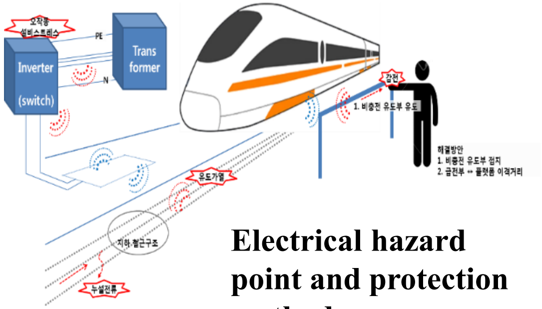
Electrical Safety


도시철도용 무선충전 전력설비 및 인체 전기안전 기준(안)

2016.12.

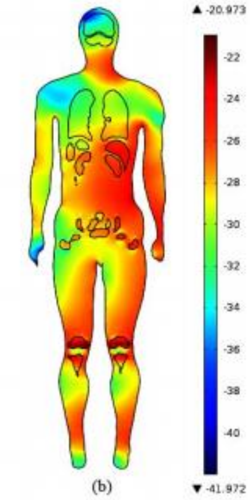
KESCO 한국전기안전공사
전기안전연구원

- Electrical safety regulation
- Parts and observation point
- Measurement method
- On establishing

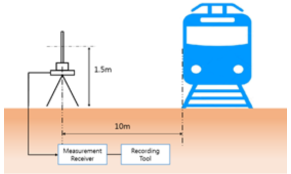


Electrical hazard point and protection methods

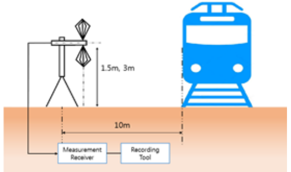
EM Safety



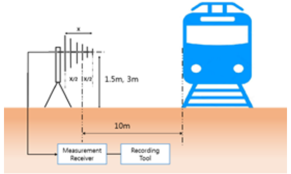
EMF Human Exposure



9kHz – 30MHz



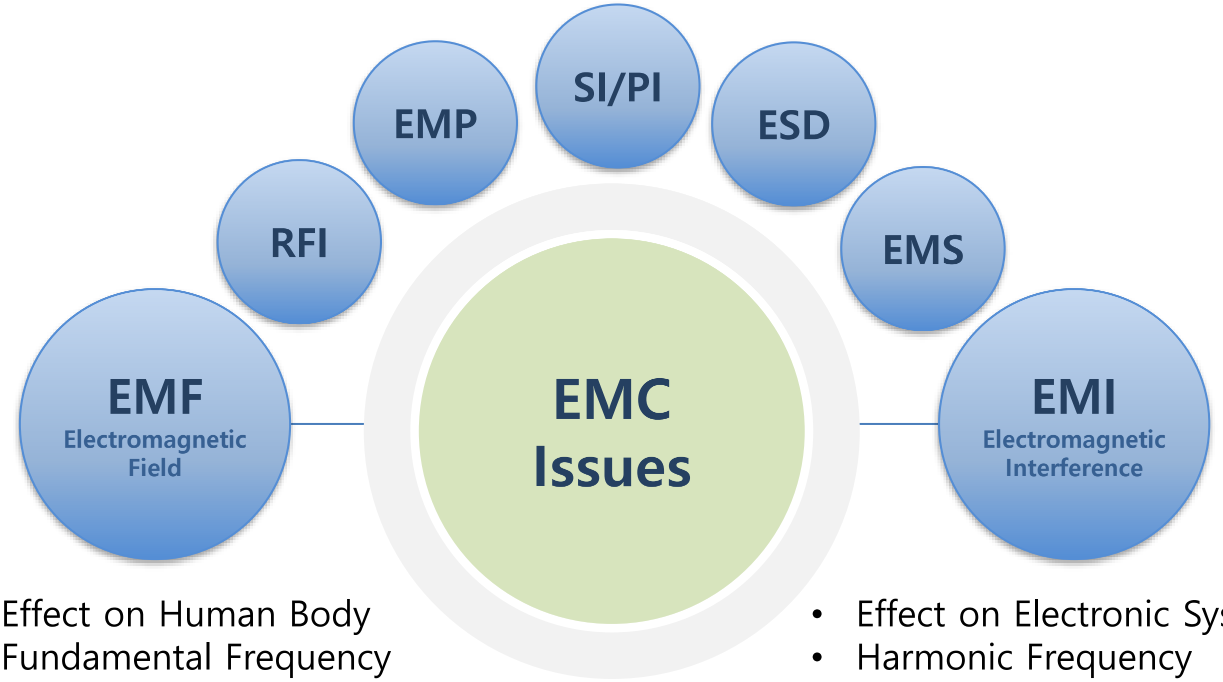
30MHz – 300MHz



300MHz – 1GHz

Electromagnetic Problems in WPT System

❑ EMC Issues due to Wireless Transfer of High Power



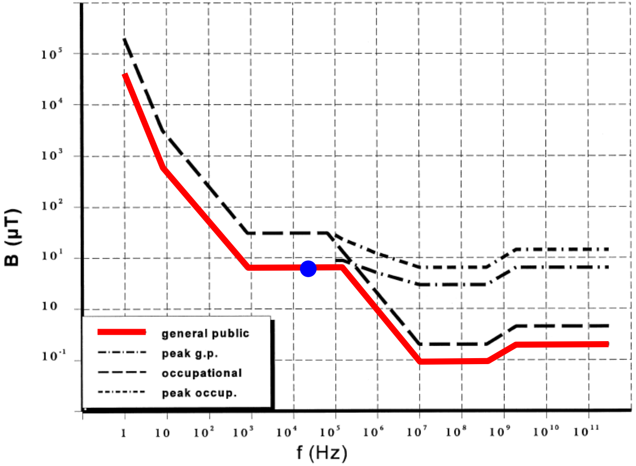
- Effect on Human Body
- Fundamental Frequency
- Near Field
- Shielding, etc.

- Effect on Electronic System
- Harmonic Frequency
- Near and Far Fields
- Filtering, etc.

Electromagnetic Field (EMF) Regulations

[Table] Reference levels for general public exposure to time-varying magnetic fields

Frequency range	B-field (μT)
up to 1 Hz	4×10^4
1–8 Hz	$4 \times 10^4/f^2$
8–25 Hz	$5{,}000/f$
0.025–0.8 kHz	$5/f$
0.8–3 kHz	6.25
3–150 kHz	6.25
0.15–1 MHz	$0.92/f$
1–10 MHz	$0.92/f$
10–400 MHz	0.092
400–2,000 MHz	$0.0046f^{1/2}$
2–300 GHz	0.20

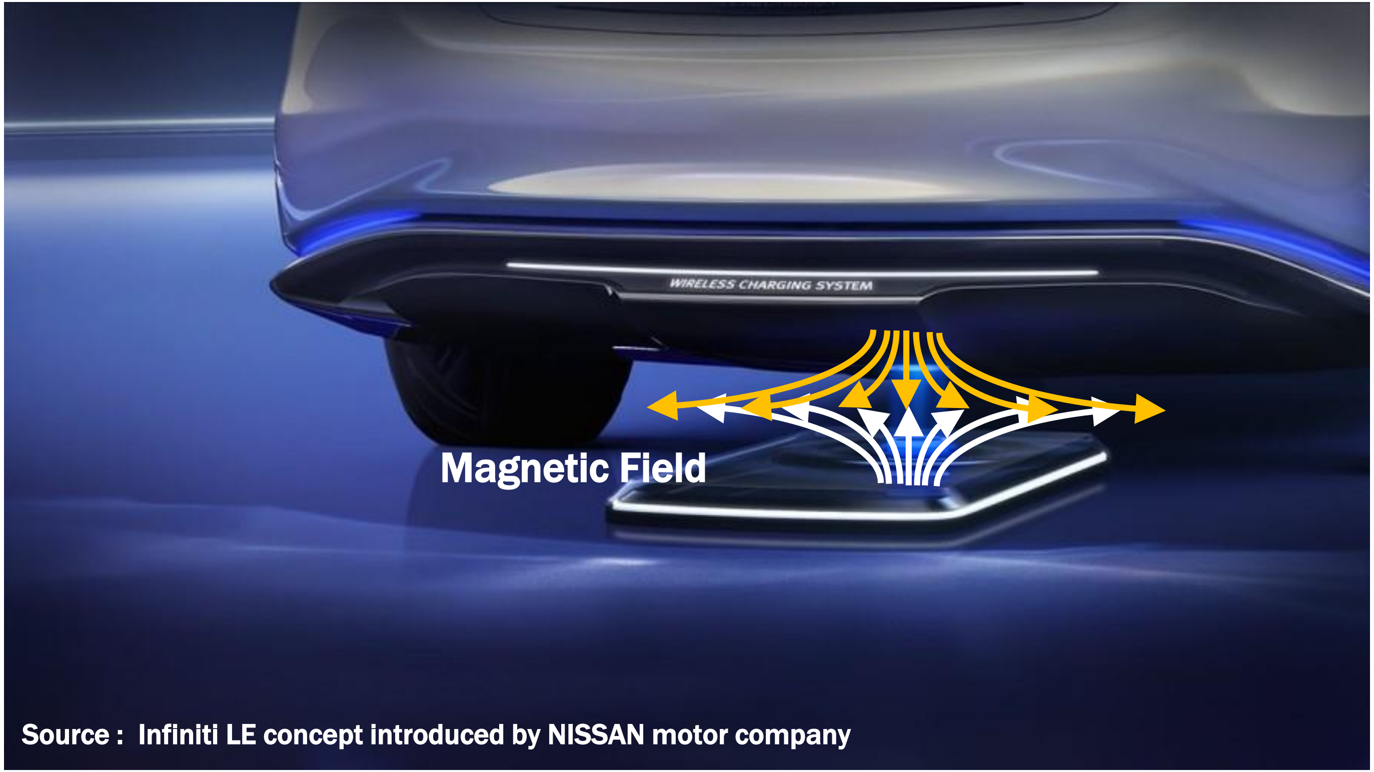


- **EMF limits on whole-body exposure levels of 6.25 µT for the general population.**
- **Earth magnetic field ~ 50 µT**

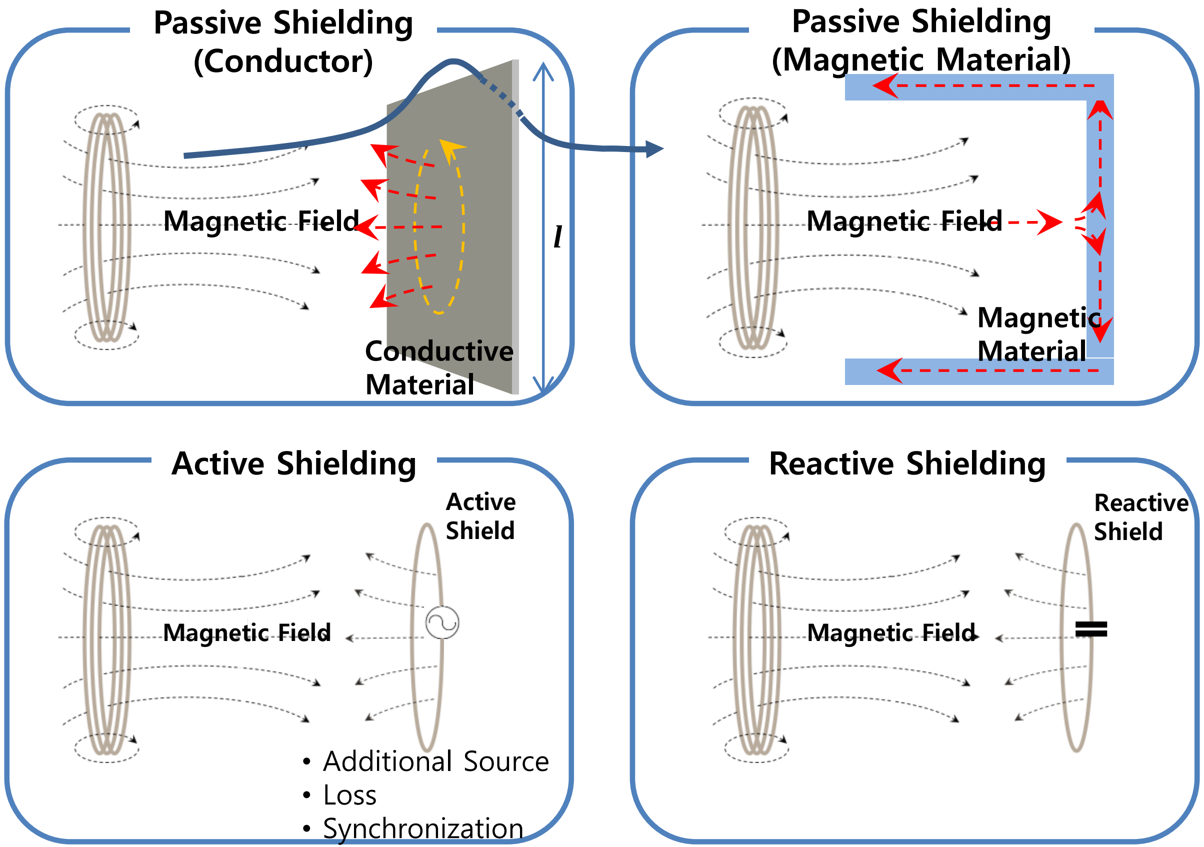
"Guidelines for Limiting Exposure to Time-varying Electric, Magnetic, and Electromagnetic Fields (Up to 300 GHz)," *ICNIRP Guidelines, 1998*

Electromagnetic Field Reduction for WPT EV

- Electromagnetic field from WPT EV is inevitable for high power charging.

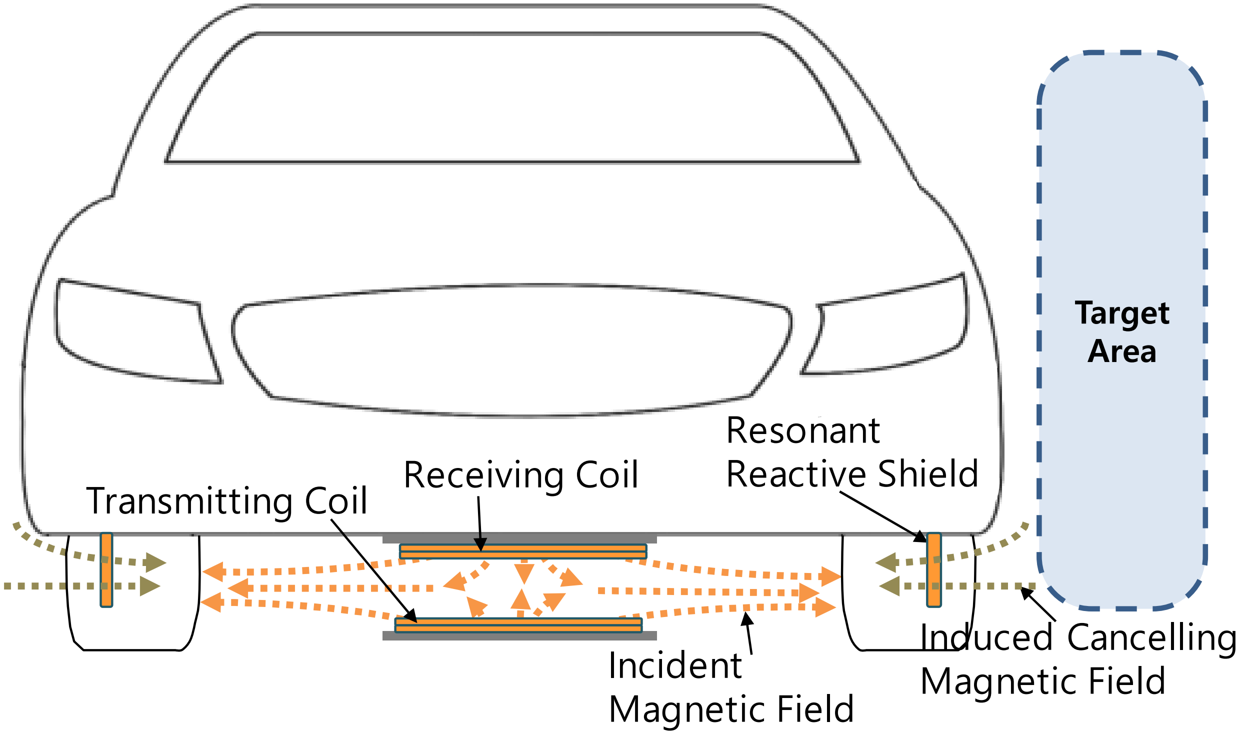


Shielding Methods for Leakage Magnetic Fields



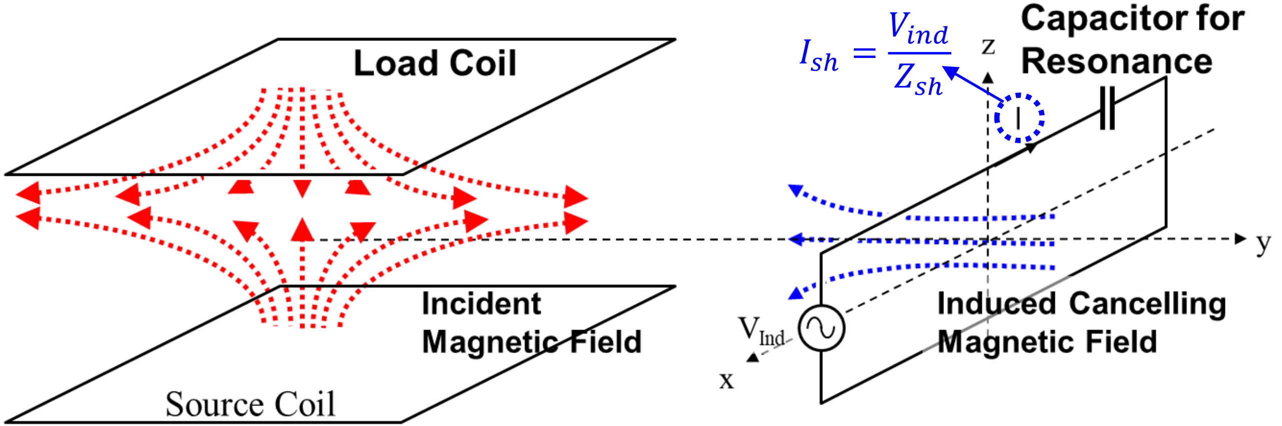
- Additional Source
- Loss
- Synchronization

Leakage Magnetic Field from WPT System in EV



Low EMF Design – Reactive Shielding

- EMF cancellation using reactive shield
  - Impedance of the shield coil determines the cancelling magnetic field

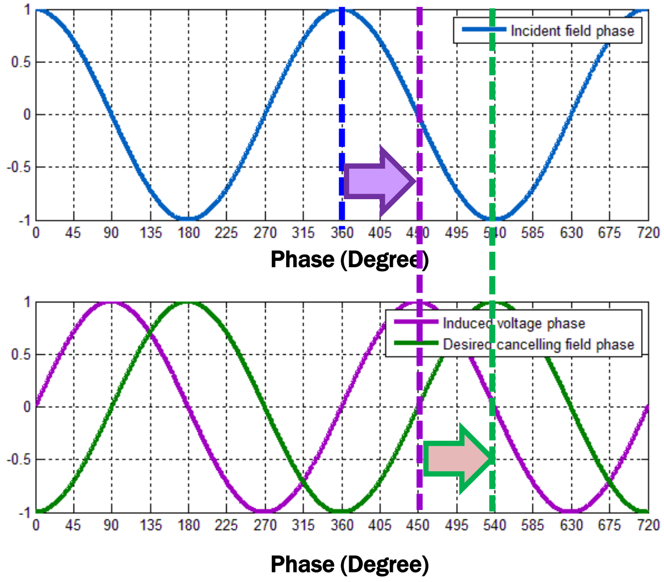


Resonant Reactive Shield Coil

S. Kim, H. H. Park, J. Kim, J. Kim, and S. Ahn, "Design and Analysis of a Resonant Reactive Shield for a Wireless Power Electric Vehicle," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 62, No. 4, pp.1057-1066, Apr. 2014.

Low EMF Design – Reactive Shielding

- Additional 90° phase shift using impedance control
  - ➔ 180° difference between WPT coil current and shield coil current



$V_{ind} = -j\omega M I_S$

+90 degree due to induction

$I_{sh} = \frac{V_{ind}}{Z_{sh}}$

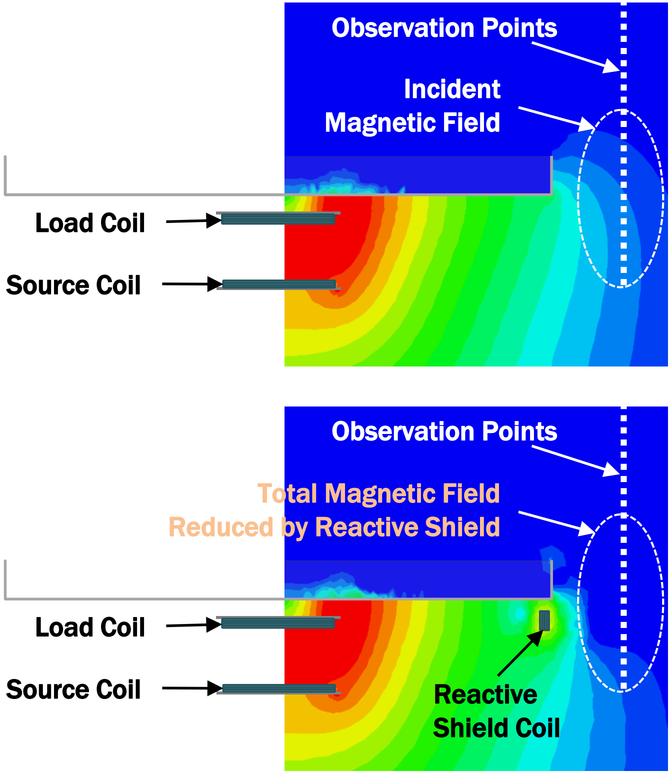
Additional +90 degree due to shield impedance

$$I_{sh} = \frac{V_{ind}}{Z_{sh}} = \frac{V_{ind}}{\left(j\omega L_{sh} + \frac{1}{j\omega C_{sh}}\right) + R_{sh}}$$

Inductive shield impedance $\sim j\omega L_{eq}$

EMF Reduction by Reactive Shield

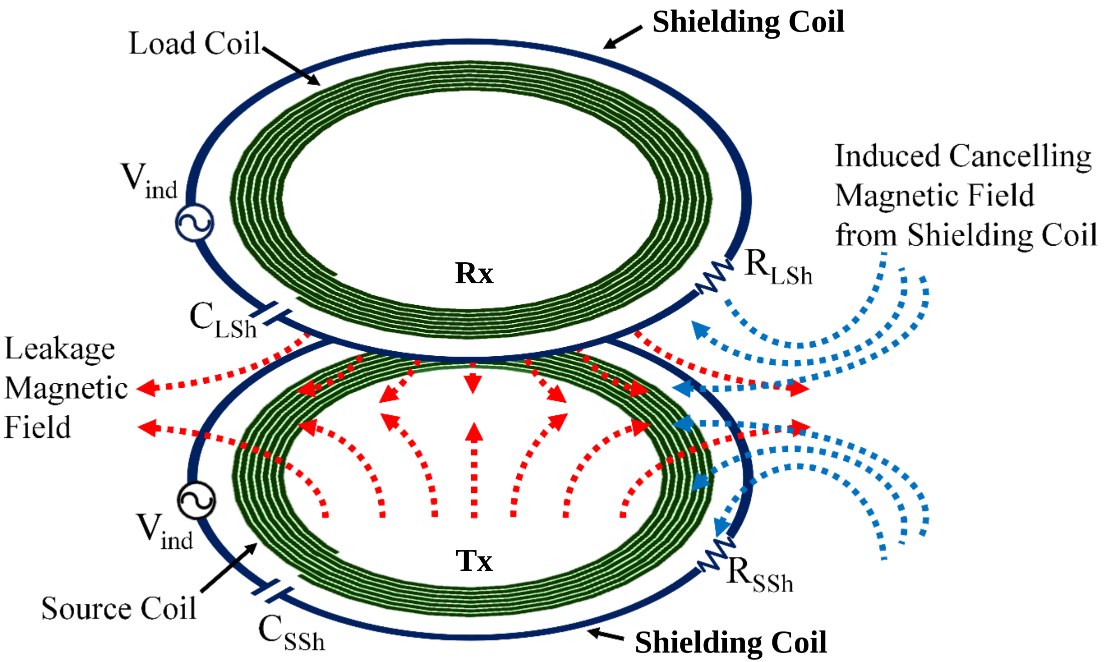
❑ Simulated EMF cancellation



❖ Advantages of Reactive Shield

- Automatic Magnitude Control
- Automatic Phase Control
- Minimal Power Loss
- Compact Size

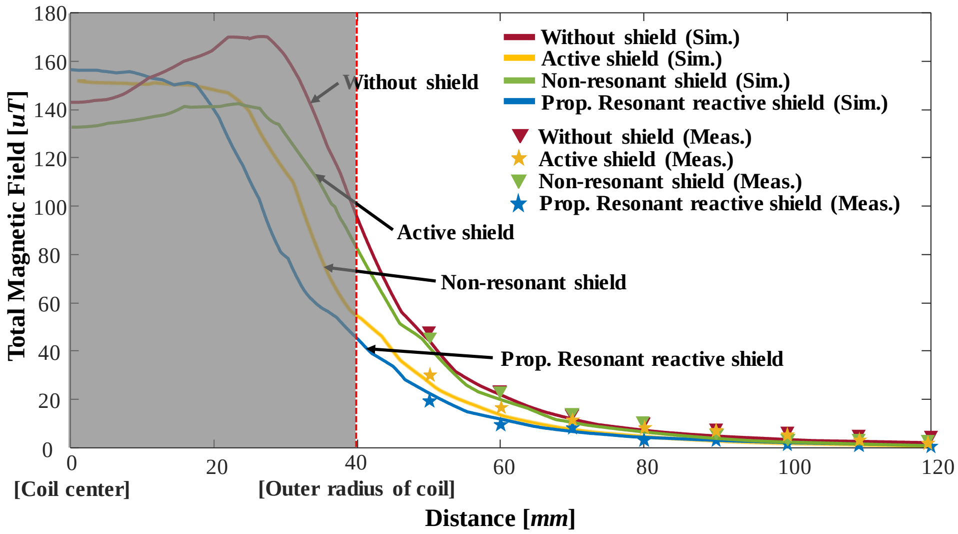
Planar Reactive Shield

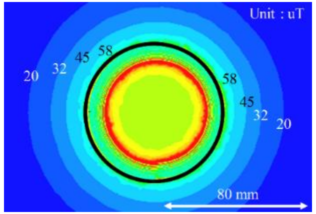


J. Park, D. Kim, H. H. Park, J. H. Kwon, S. I. Kwak, and S. Ahn, "A Resonant Reactive Shielding for Planar Wireless Power Transfer System in Smart Phone Application," *IEEE Trans. on Electromagnetic Compatibility*, vol. 59, no. 2, pp. 695-703, Jan. 2017.

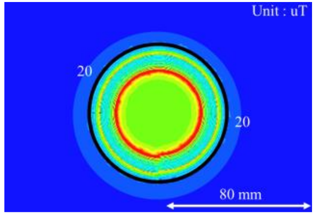
Planar Reactive Shield

	Leakage Field	Efficiency
W/O Shield	Reference	96.2 %
Active Shield	- 47 %	75.1 % (- 21.1%)
Non-resonant Shield	- 3 %	95.0 % (- 1.2 %)
Reactive Shield	-53 %	90.2 % (- 6.0 %)



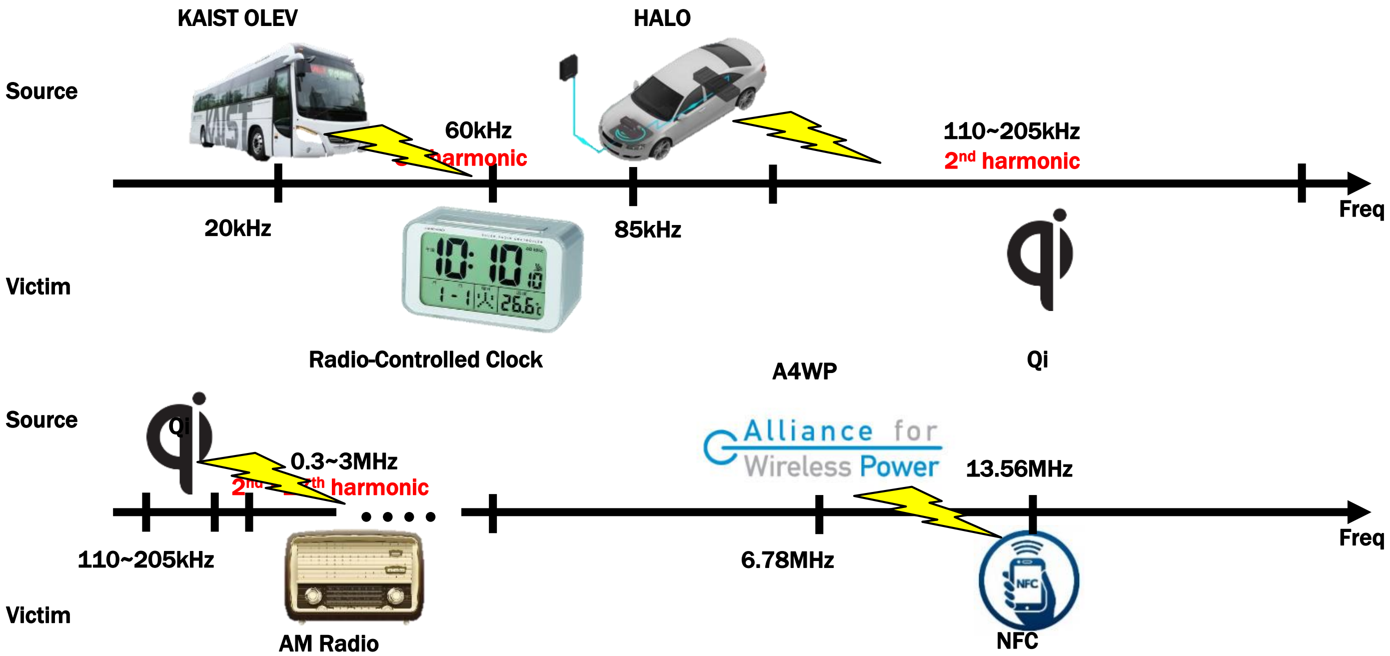


Without Shield



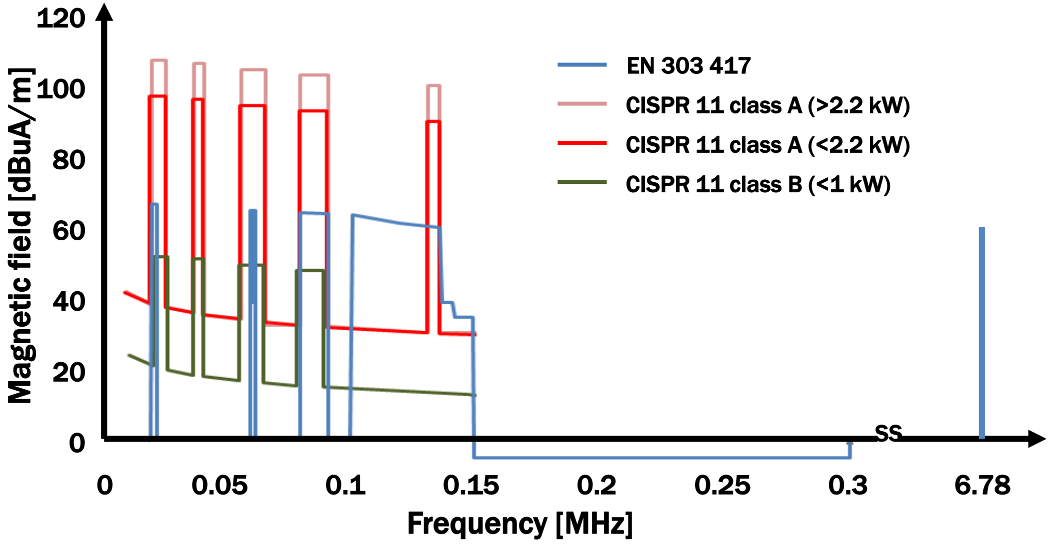
With Reactive Shield

Interference due to Harmonic EMI from WPT System



- Harmonic electromagnetic field generated from WPT systems can affect other electronic application.
- In order to reduce the influence on other peripheral electronic devices, standards and electromagnetic interference regulations are established.

Trends of EMI Regulations in WPT System

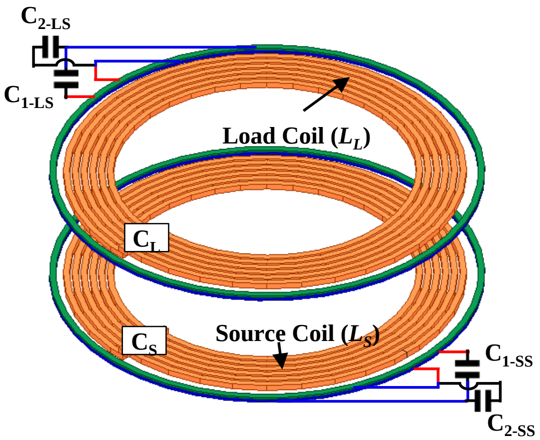


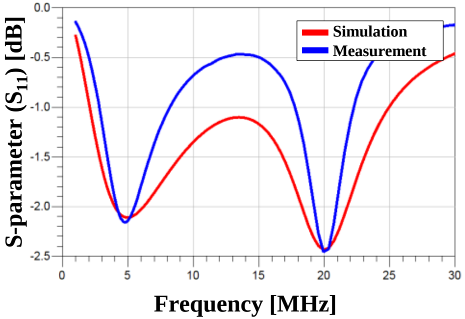
- Regulations and measurement methods are being carried out to suit the characteristics of the products.
- The operating frequency has high regulation level but the harmonic frequency has low regulation level.

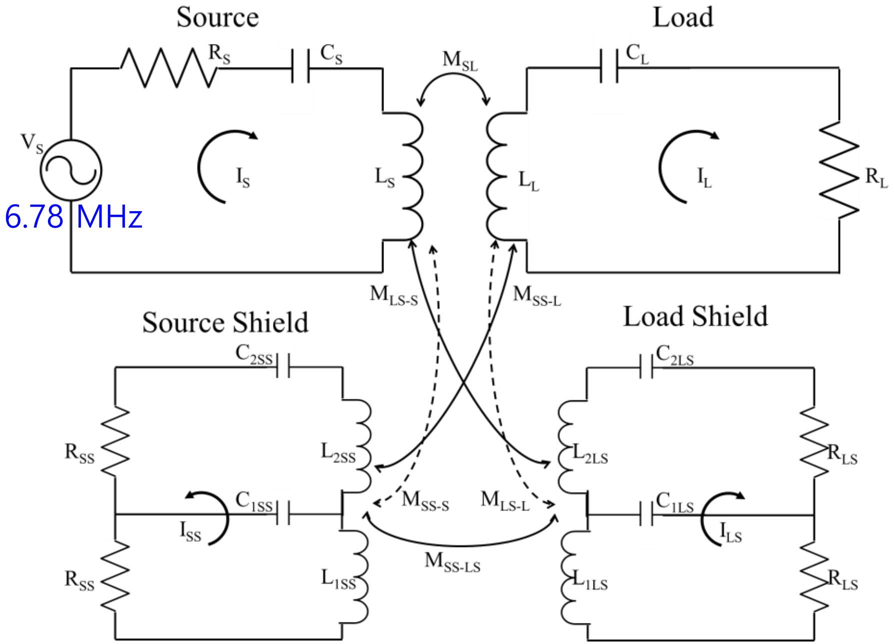
Harmonic frequencies EMI reduction method are needed!

Ref) EN 303 417
Ref) CISPR 11 B/710/CD

Planar Multi-Frequency Reactive Shield

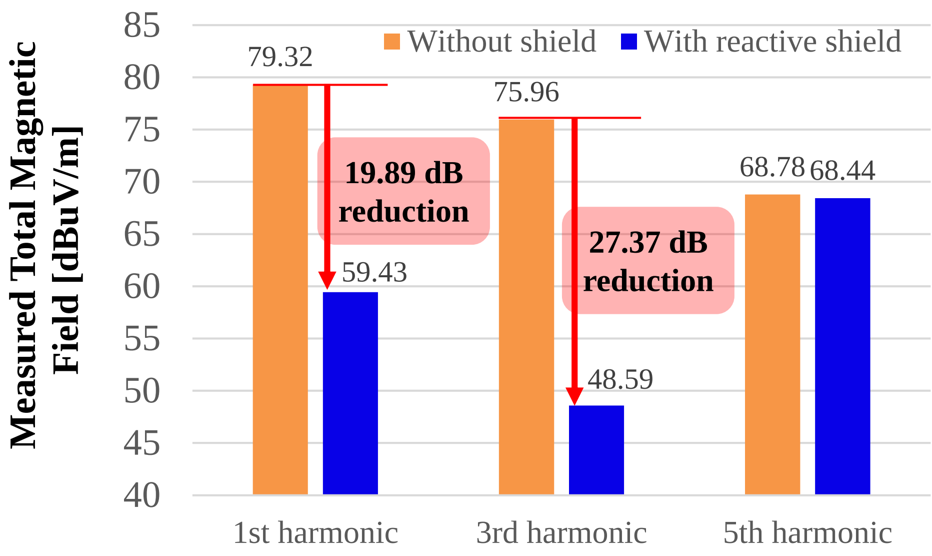






J. Park, C. Park, Y. Shin, D. Kim, B. Park, J. Cho, J. Choi, and S. Ahn, "Planar multi-resonance reactive shield for reducing electromagnetic interference in portable wireless power charging application," *Applied Physics Letters*, 114, 203902, May 2019.

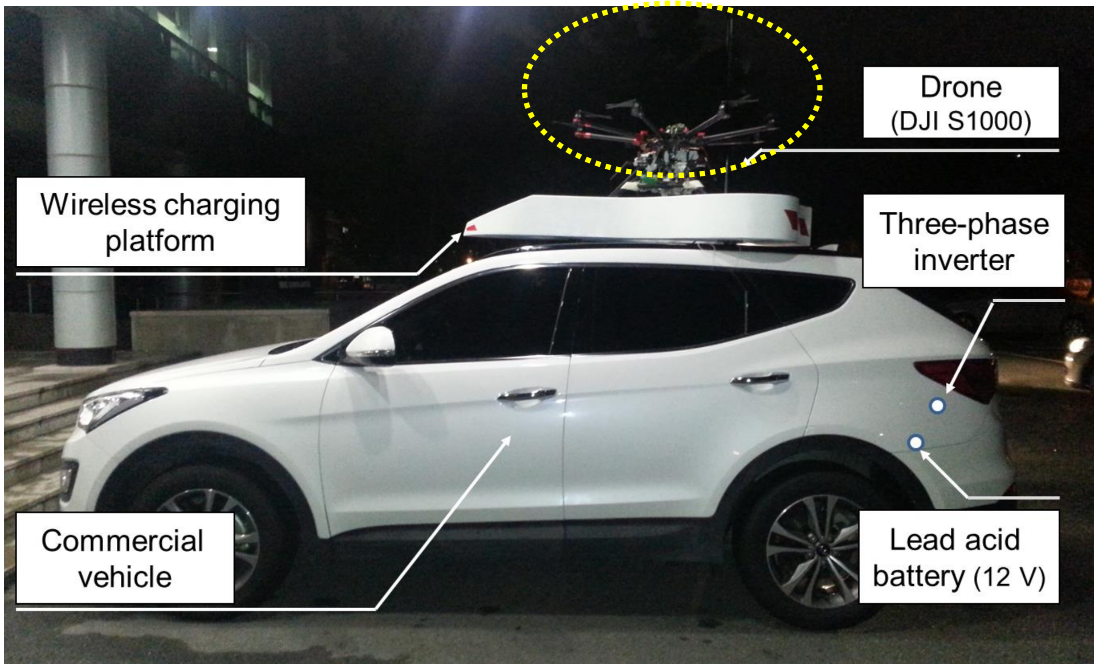
Planar Multi-Frequency Reactive Shield



	Without shield		With reactive shield	
	Simulation	Measurement	Simulation	Measurement
Efficiency (%)	98.3	96.2	93.6 (4.7↓)	90.2 (6.0↓)
SE (dB)				1^{st}: 19.89, 3^{rd}: 27.37

Implementation of Drone on Vehicle

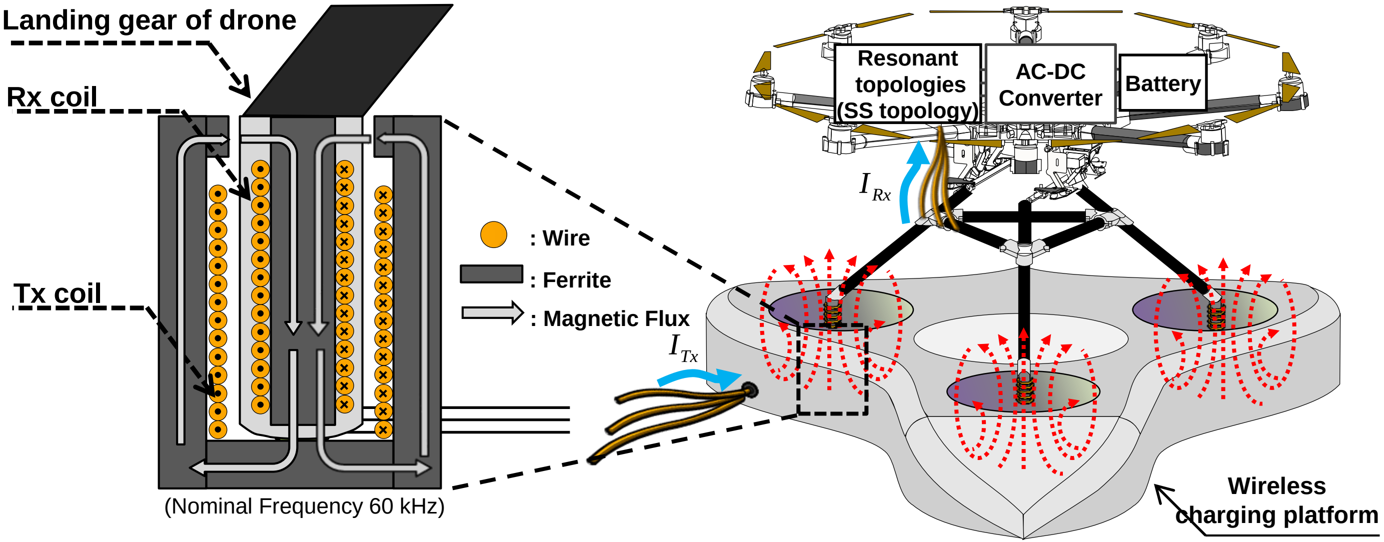
- 150 W-Class Three-phase WPT Charger for Drone



Drone charger system is located on the commercial vehicle with 12V lead acid battery.

C. Song, H. Kim, Y. Kim, D. Kim, S. Jeong, Y. Cho, S. Lee, S. Ahn, and J. Kim, “EMI Reduction Methods in Wireless Power Transfer System for Drone Electrical Charger using Tightly Coupled Three-Phase Resonant Magnetic Field,” *IEEE Trans. on Industrial Electronics*, Vol. 65, No. 9, pp. 6839 – 6849, Sep. 2018.

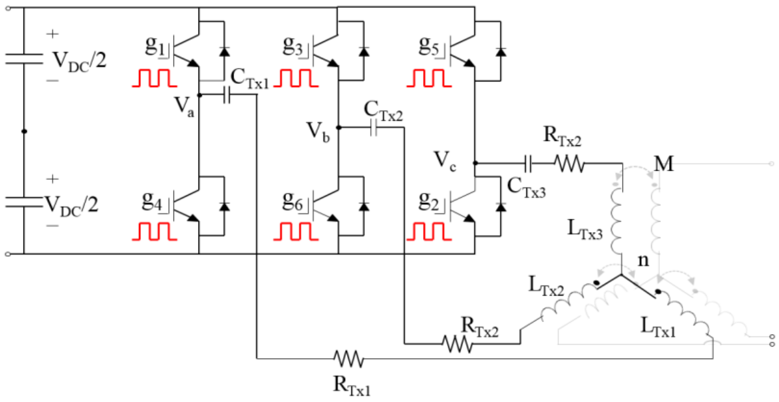
150 W-Class Charger for Low EMF and EMI



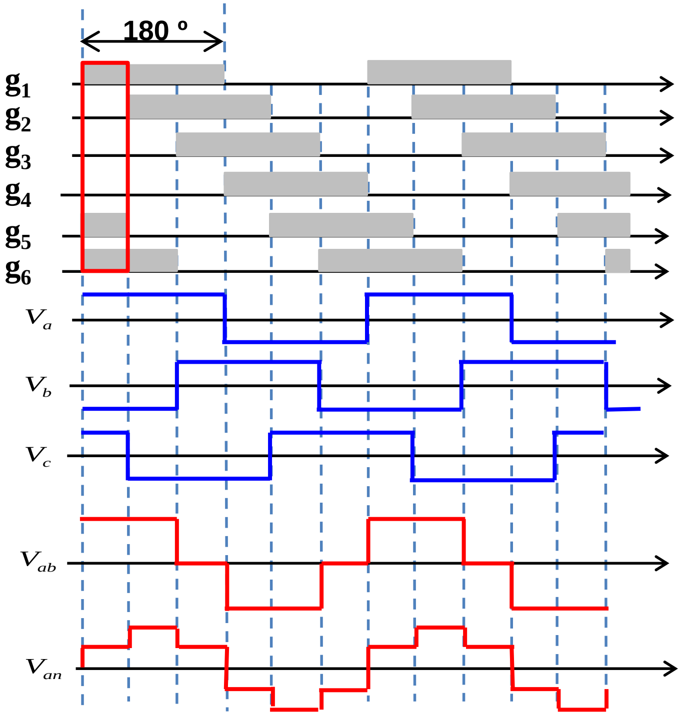
- **Three-phase resonant magnetic field charger with high coupling coefficient can reduce leakage EMFs with closed structure.**

C. Song, H. Kim, Y. Kim, D. Kim, S. Jeong, Y. Cho, S. Lee, S. Ahn, and J. Kim, "EMI Reduction Methods in Wireless Power Transfer System for Drone Electrical Charger using Tightly Coupled Three-Phase Resonant Magnetic Field," *IEEE Trans. on Industrial Electronics*, Vol. 65, No. 9, pp. 6839 – 6849, Sep. 2018.

Switching Time Control for 3-Phase Inverter



< **Three-phase** inverter >



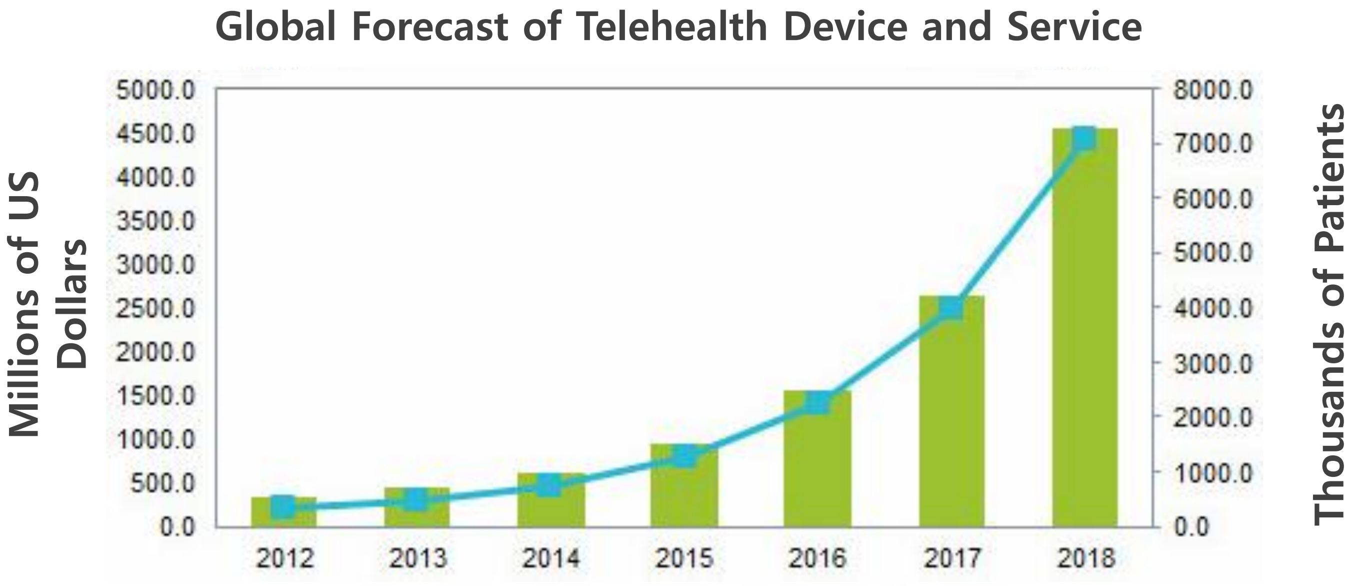
- **THD_v of 3-phase inverter is smaller than the single-phase.**
- **Elimination of 3rd harmonic components is possible.**

$$v_{an} = \frac{2V_{DC}}{\pi}\left[\sin(\omega t) - \frac{1}{5}\sin 5\omega t - \frac{1}{7}\sin 7\omega t + \cdots\right]$$

C. Song, H. Kim, Y. Kim, D. Kim, S. Jeong, Y. Cho, S. Lee, S. Ahn, and J. Kim, "EMI Reduction Methods in Wireless Power Transfer System for Drone Electrical Charger using Tightly Coupled Three-Phase Resonant Magnetic Field," *IEEE Trans. on Industrial Electronics*, Vol. 65, No. 9, pp. 6839 – 6849, Sep. 2018.

Future WPT and EMC Design

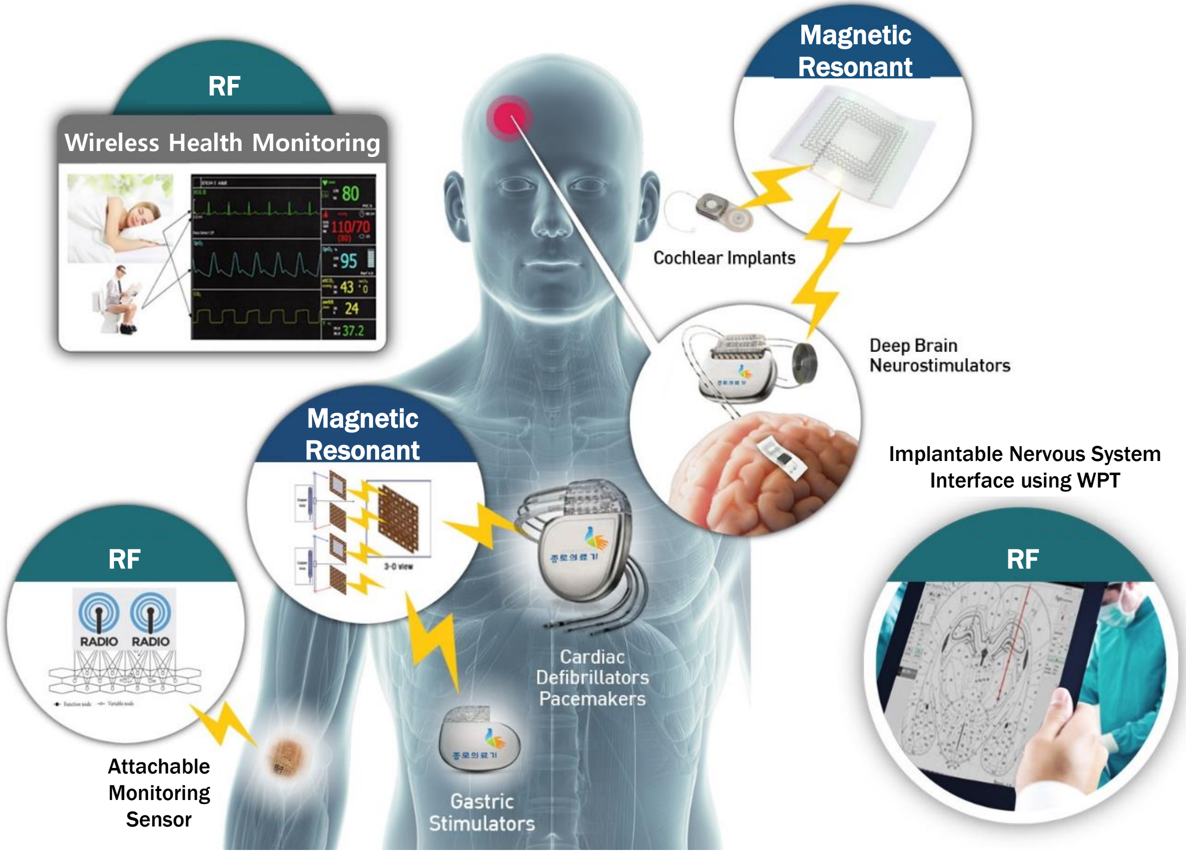
Market Trend of Biomedical Devices



Source: IHS Technology, Jan. 2014.

With increase of telehealth device for higher service quality and low service cost,
Implantable and telehealth devices will increase 10 times by 2025.

WPT for Implantable Medical Devices



Chulhun Seo, "Intelligent Biomedical Wireless Power Transfer Research Center", Korea WPT Workshop, Oct. 2018

Key Technologies in Biomedical WPT Systems

IT

Biomedical WPT Technology

- Implantable Ultra-Small Coil Structure
- High-efficiency WPT using Metamaterial
- Non-interference Wireless Power Transfer

NT

Material and Device for Biomedical WPT

- Bio-Friendly WPT Material
- CNT Material for Implantable Devices
- High Efficiency Flexible Antenna

BT

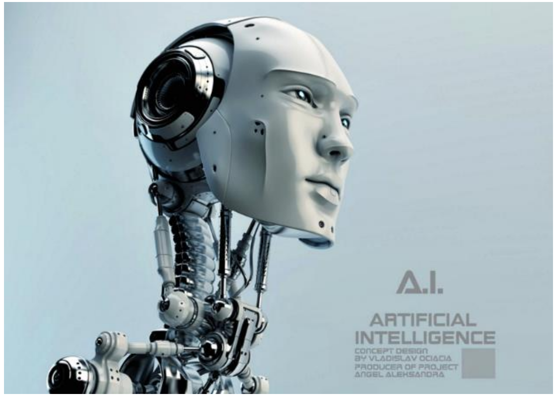
Bio Interface based on WPT

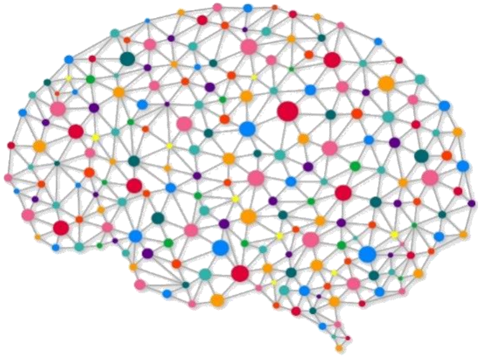
- Wire-Free Patient Monitoring Service
- Nervous System Treatment using WPT Implants
- Wireless Charging Cardiac Sensor

Chulhun Seo, "Intelligent Biomedical Wireless Power Transfer Research Center", Korea WPT Workshop, Oct. 2018

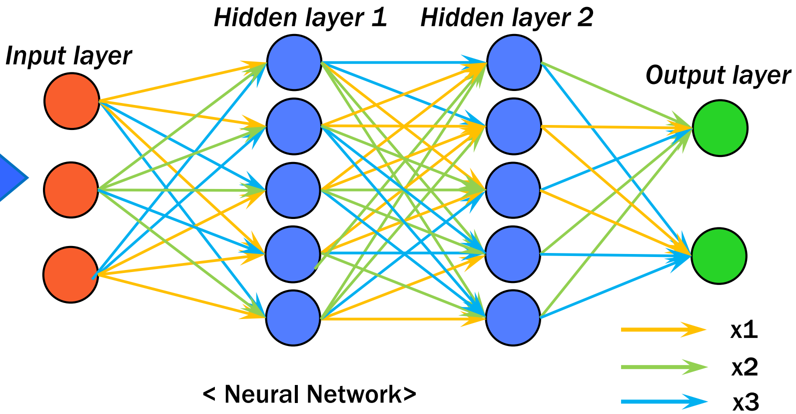
Artificial Intelligence and Deep Learning

- ❑ AI is a model inspired by a biological neural network
- ❑ Values of AI
  - Save time, labor, resources, capital, energy
  - Provide time for human for creative activities
  - Improve life quality
  - Save earth
  - Freedom from labor and nature





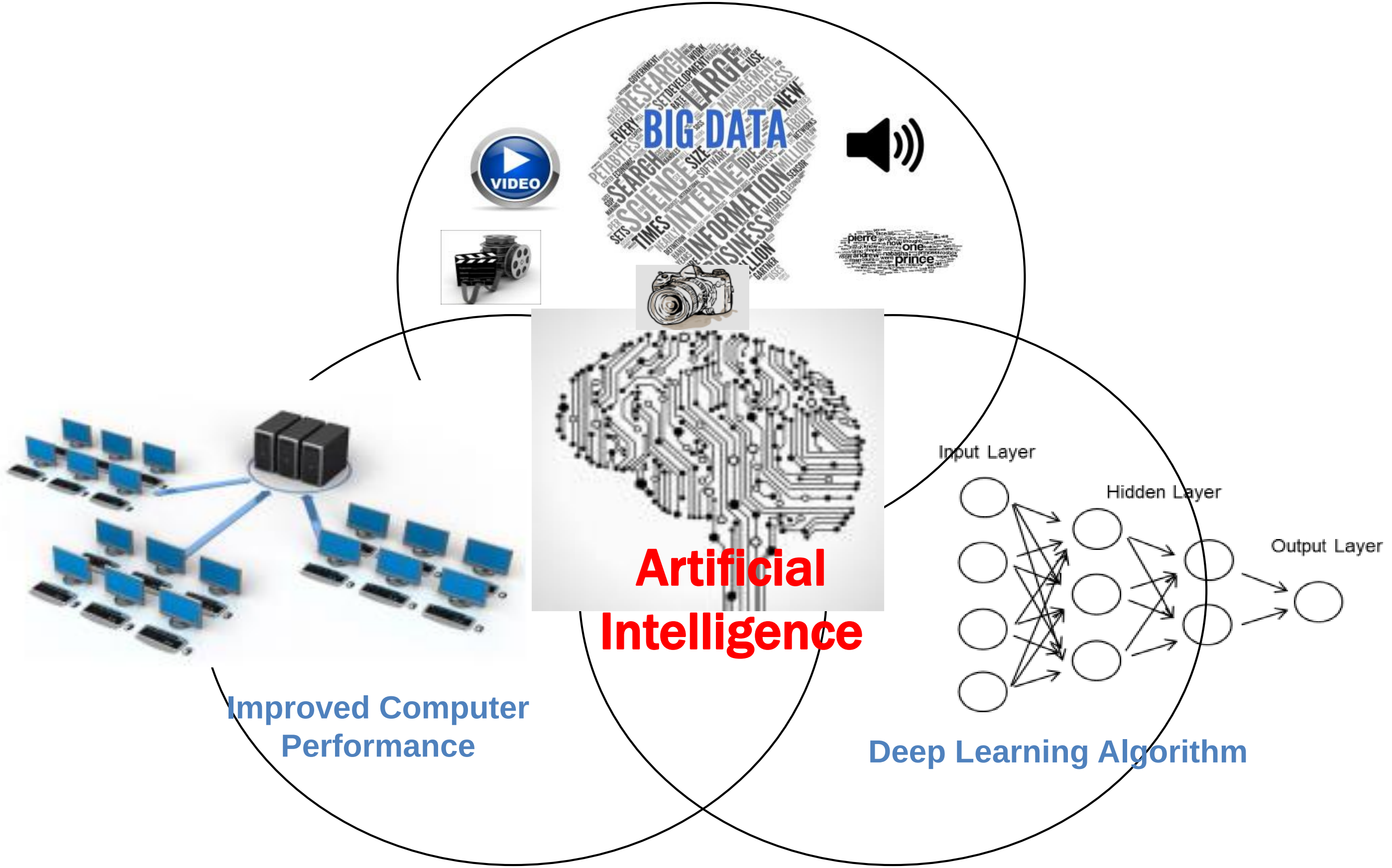
< Human Brain >



< Neural Network>

Ref) *Joungho Kim, "2.5D/3D Terabyte/s Bandwidth HBM Designs for AI Computers," Keynote Speech, EMC Compo 2019.*

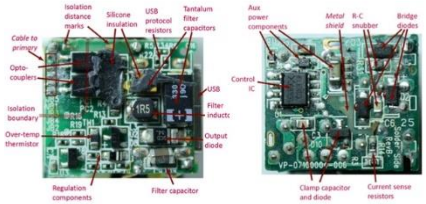
Technology Innovation for Artificial Intelligence



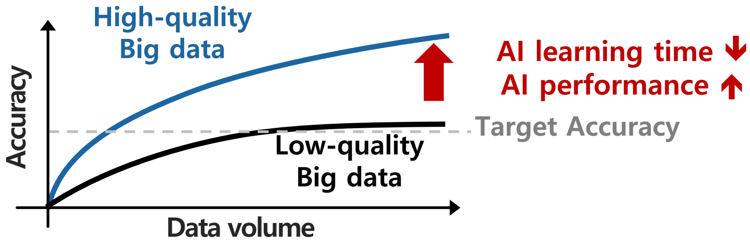
Ref) Joungho Kim, "2.5D/3D Terabyte/s Bandwidth HBM Designs for AI Computers," Keynote Speech, EMC Compo 2019.

Future EMC Design

Conventional EMC Design



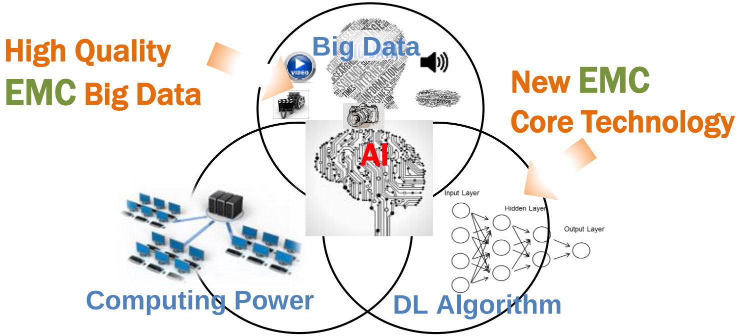
- Complexity in EMC design
  ➔ Long time and huge effort are required.
- AI-based EMC design S/W is needed.



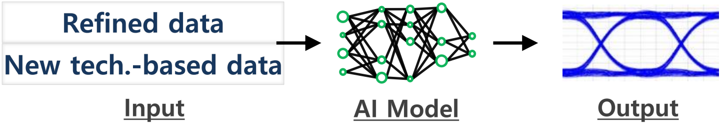
- High-quality big data will enhance the AI EMC.

AI-based EMC Design

- High quality data and optimal AI model



Ref) Joungho Kim, "2.5D/3D Terabyte/s Bandwidth HBM Designs for AI Computers," Keynote Speech, EMC Compo 2019.



- Optimal AI design tool for EMC

Conclusion

- The WPT technology is changing the future electronic system.

- Electromagnetic problems can be critical in WPT technology.

- The solutions for WPT EMC problems should be developed.

- Future design methodologies using AI will enhance the development of WPT and EMC.

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WPTC

IEEE
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pels IEEE POWER ELECTRONICS SOCIETY Powering a Sustainable Future
KIEES Korean Institute of Electromagnetic Engineering and Science
KIEE Wireless Power Transfer Society
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