Personal Introduction

Minfan Fu (Ph.D. candidate)

Homepage: http://www.minfanfu.icoc.cc/

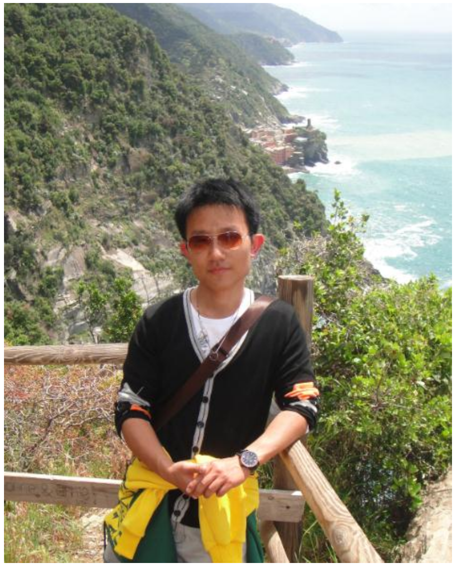
UM-SJTU Joint Institute
Dynamic system control laboratory
http://umji.sjtu.edu.cn/lab/dsc/

JOINT INSTITUTE
交大密西根学院

Outline

- Personal Background
- Introduction of Joint Institute
- Introduction of DSC Lab
- Project Experience
- Research Experience
- Publications
- Selected Honors & Awards

Personal Background



Education

4/2013 -- Present:
Ph.D. in Univ. of Michigan-SJTU Joint Institute, Shanghai Jiao Tong University
Electrical and Computer Engineering GPA: 3.75/4 Rank：4/14

9/2010 – 3/2013:
M.S. in Univ. of Michigan-SJTU Joint Institute, Shanghai Jiao Tong University
Electrical and Computer Engineering GPA: 3.84/4 Rank：4/19

9/2006 – 8/2010:
B.S. in Univ. of Michigan-SJTU Joint Institute, Shanghai Jiao Tong University
Electrical and Computer Engineering GPA: 3.72/4 Rank：3/78

Birthday: Oct.27, 1987 **Hometown:** Nanping, Fujian Province

Research Interests: MHz wireless power transfer，high-frequency resonant converters, control and optimization of energy networks

Laboratory: Dynamic system control laboratory of joint institute (JI)

Joint Institute (2006-Present)

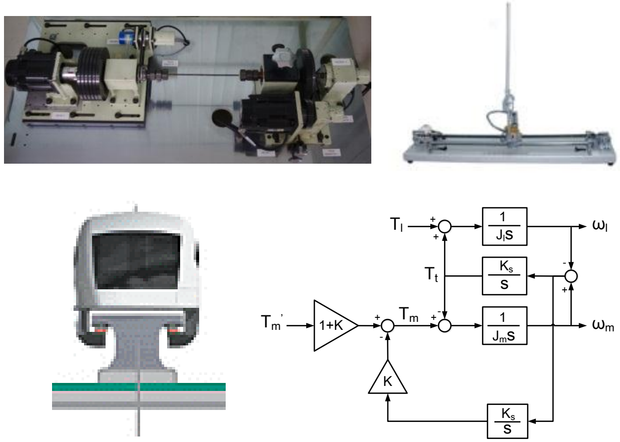
Undergraduate : since 2006 ; Graduate: since 2010

Undergraduate students (2010)

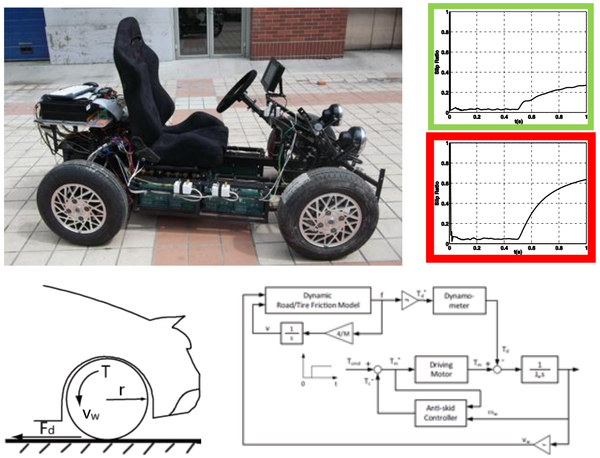
Graduate students (2013)

DSC Lab

DSC Lab

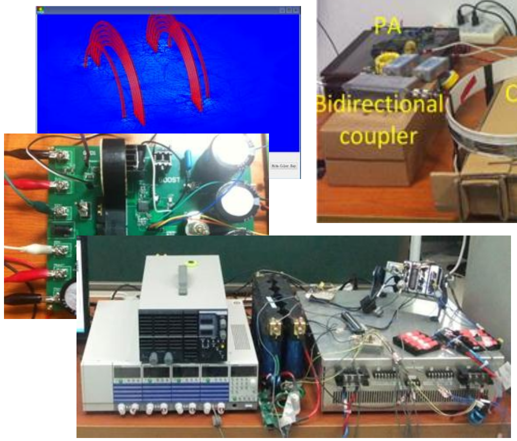


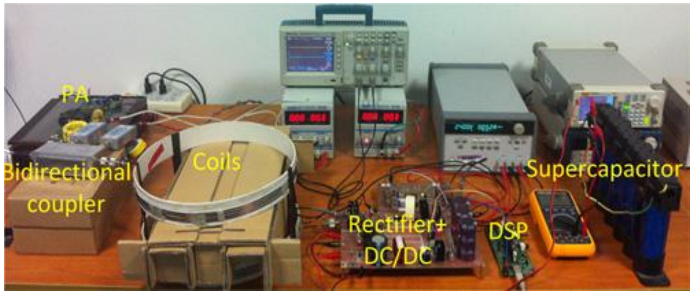
1. Motion control



2. Vehicle dynamics

5 Ph.D., 4 M.S.





Control of Motion and Energy

3. Hybrid energy system

4. MHz wireless power transfer

WPT Group

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Education

Ph.D.	Electrical Engineering, The University of Tokyo (2004)
M.S.	Electrical Engineering, The University of Tokyo (2001)
B.S.	Industrial Automation, East China University of Science and Technology (1997)

Xinen (Alfred) Zhu

Assistant Professor

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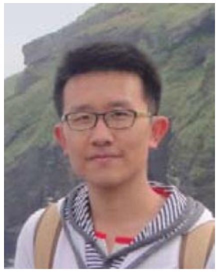
Education

Ph.D.	Electrical Engineering, University of Michigan (2009)
M.Sc.	Electrical Engineering, University of Michigan (2005)
B.Eng.(Honor)	Electronic and Communication Engineering, City University of Hong Kong (2003)

Undergraduates Students (4 Ph.D., 2 M.S.):



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Ming Liu, D2
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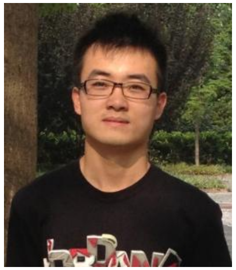

Zefan Tang, M2
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Xinhong Fu, M1
xinhongfu@sjtu.edu.cn

Project Experience

Huawei (China) **Team leader** **9/2015 - present**

Explore and fabricate small and efficient battery management systems by using MHz wireless power transfer techniques.

Intel (USA) **Team member** **9/2015 - present**

Design and implement full-wave Class E rectifiers to achieve low harmonics and high efficiency in a WPT system supporting the A4WP standard.

Intel (USA) **Team leader** **8/2014 - 1/2015**

Develop auto-tuning Class E power amplifiers and high-efficiency Class E rectifiers for WPT systems supporting the A4WP standard. My works include circuit analysis, simulation, optimization, and implementation for the Class E rectifiers.

Intel (China) **Team member** **12/2012 - 6/2013**

Test, analyze, and optimize the WPT prototype system. My work is to provide possible solutions for efficiency improvement based on the measurement.

Bozun Motor (China) **Team member** **12/2011- 10/2012**

Design a controller for a high power (60 kW) disc-type motor. My works include the circuit parameters estimation and the components selection.

Nippon Chemi-Con (Japan) **Team member** **5/2011 - 9/2012**

Design and test the hybrid energy system (batteries + ultracapacitors). I help design the bidirectional DC/DC converter used in the system.

Research Experience

- Research background
- Initial efforts (2010)
- Optimal load control under fixed coupling (2011-2012)
- Optimal load tracking under variable coupling (2013)
- Loading effects analysis for multiple-RX system(2013-2014)
- Cross coupling compensation(2014)
- Class E rectifier for WPT (2014-2015)
- WPT system with energy buffer (2015)
- Multiple-RX system — simultaneous charging (ongoing)
- Multiple-RX system — alternate charging (ongoing)

Research Background

- Power transfer: Compared to chemical and mechanical energy, electrical energy is much easier and more efficient to transform and transfer.
- It calls for ambient power environment, where devices can receive power from the surrounding anytime without any physical connection.

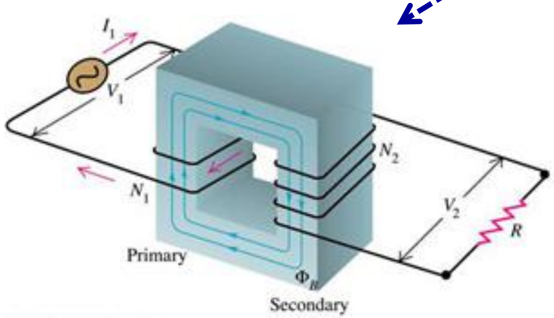
Benefits

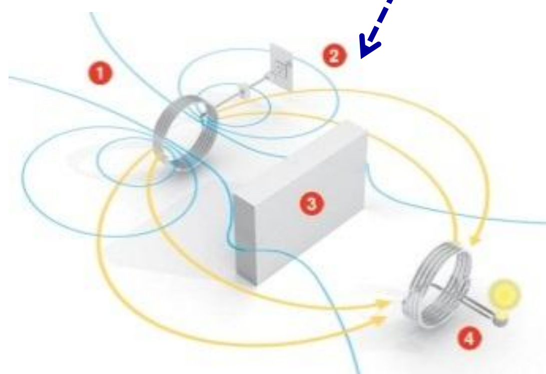
1. Great convenience.
2. Saving cost on direct connectors.
3. Special applications: sterile, rotating, moving.
4. Special environment: wet, dirty.
5. Enclosed design: lower risk of corrosion (oxygen and water).

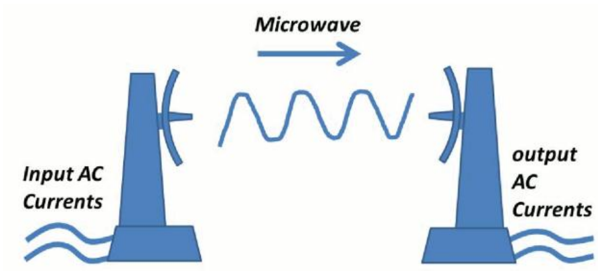



WPT Technologies

	Inductive		Microwave
Types	Closely coupled (non resonant)	Loosely coupled (resonant)	Electromagnetic waves
Typical techniques	Transformer	Inductive power transfer	Wave guides, Parabolic antennas, etc.
Feature	Very small distance, high power and very high efficiency	Medium distance and high efficiency	Small power, large distance and low efficiency



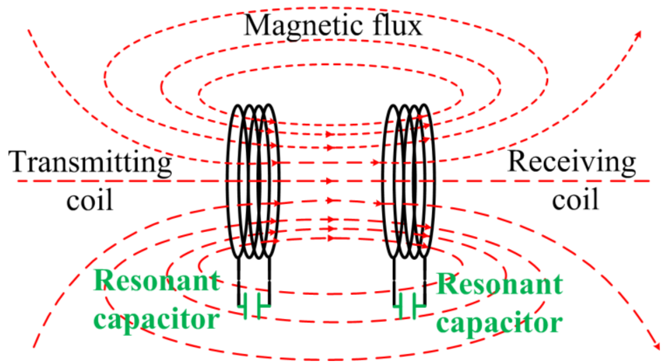




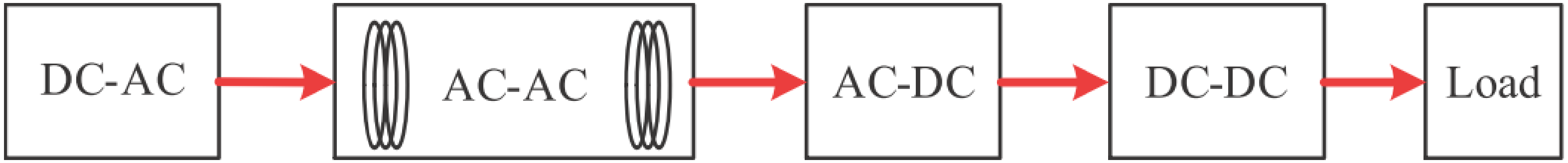
Resonant Inductive Coupling

Power transfer ability between coils (AC-AC):

Frequency(f)	Circuit design difficulty
Coupling (k)	Spatial freedom
Inductance (L)	Coils' size and weight

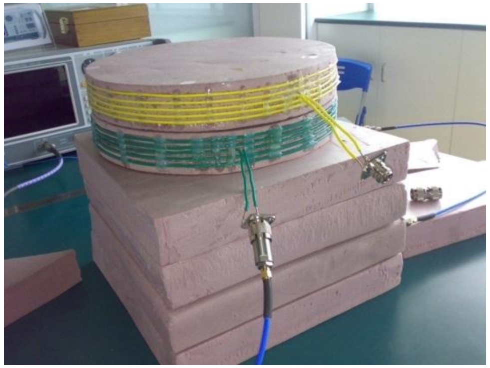


Typical system configuration (kHz ~ MHz)

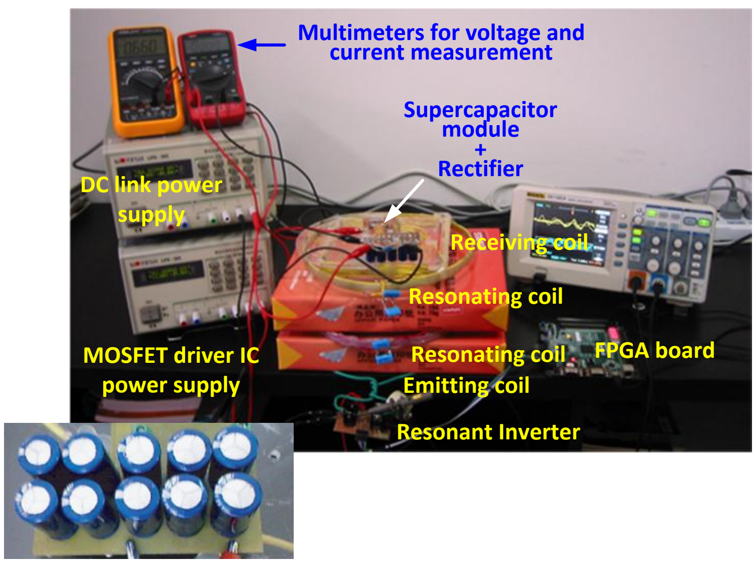


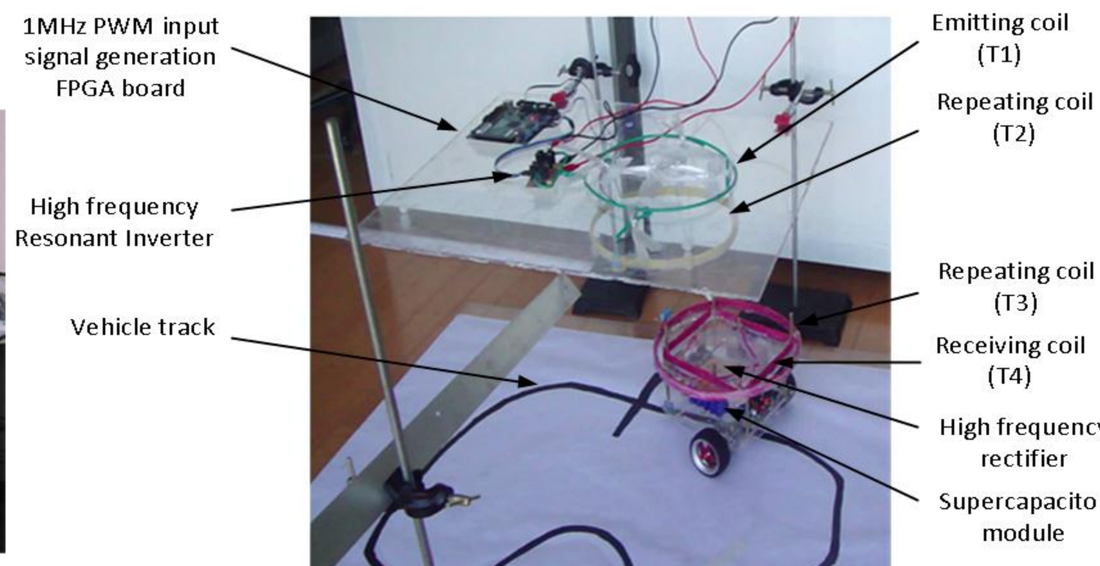
- **MHz system： Smaller, lighter and larger spatial freedom . It is suitable for small or medium power transfer, especially for charging multiple receivers.**
- **Multiple disciplines： Power electronics + Microwave + Control + Optimization**

(1) Initial Efforts Since 2010



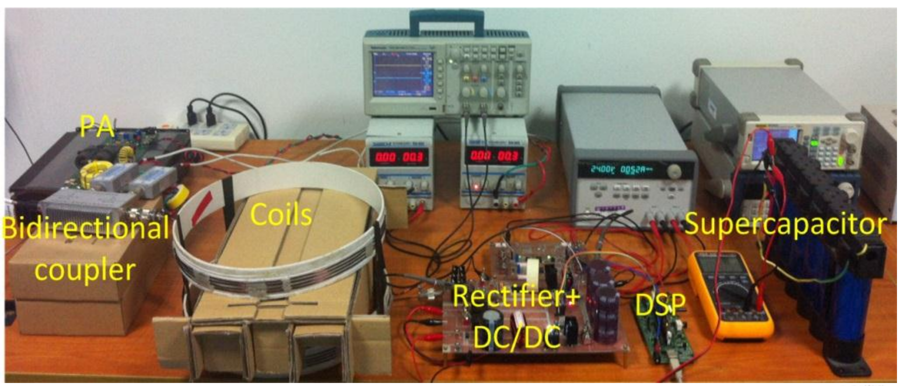
Gap (cm)	5.6	10.1	14.8	19.3	24.1	28
Efficiency (%)	88.84	93.32	**93.69**	92.53	88.07	70.04
F_m (MHz)	13.59	14.74	15.27	15.71	16.11	16.08
F_e (MHz)	19.87	17.85	17.01	16.51	16.11	16.08

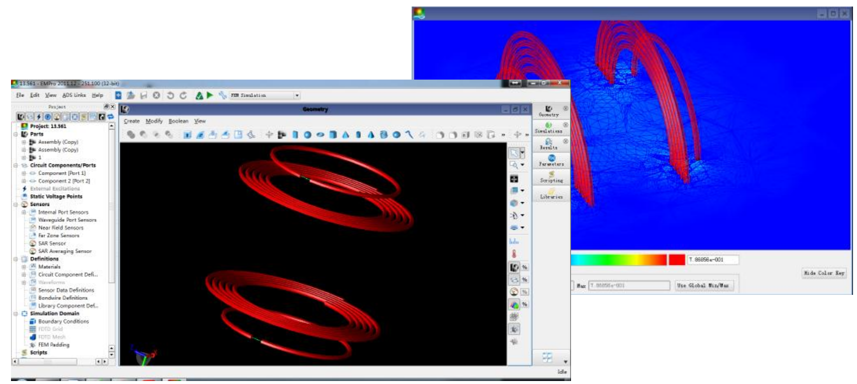


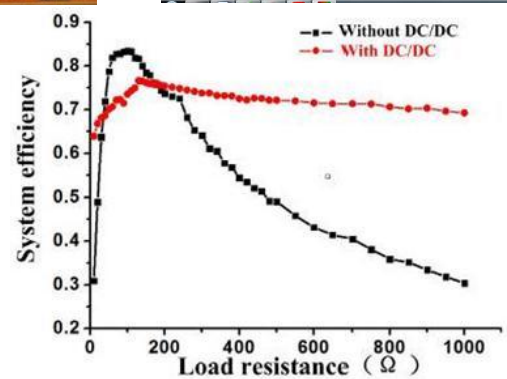


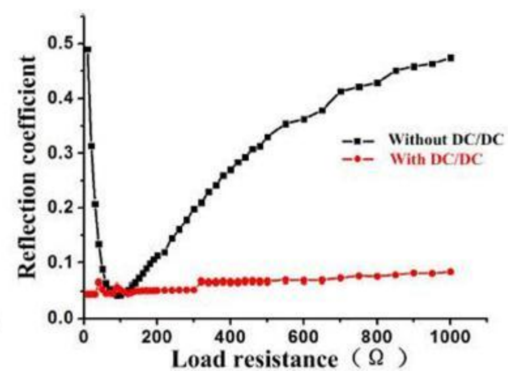
(2.1)13.56 MHz System

- 13.56 MHz WPT System (< 40 watts, 70%)
  - Optimal load analysis and control
  - Circuit design for load control





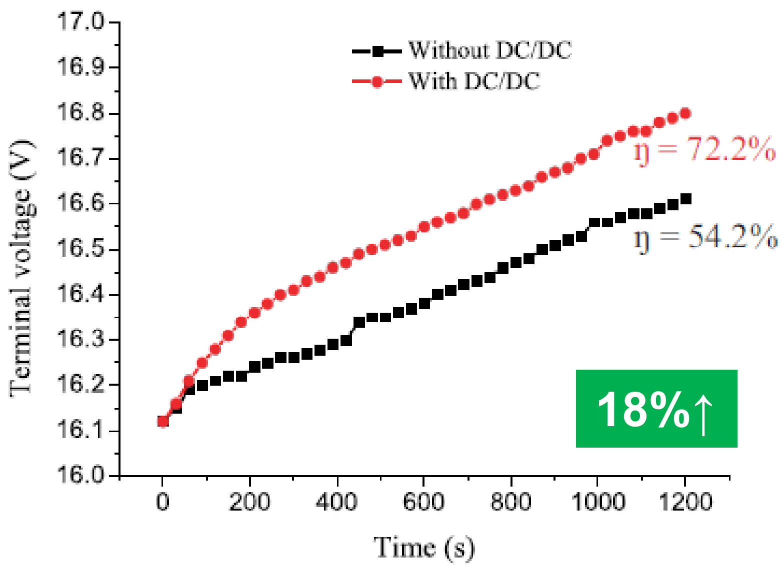




(2.2) Charging for Various Loads

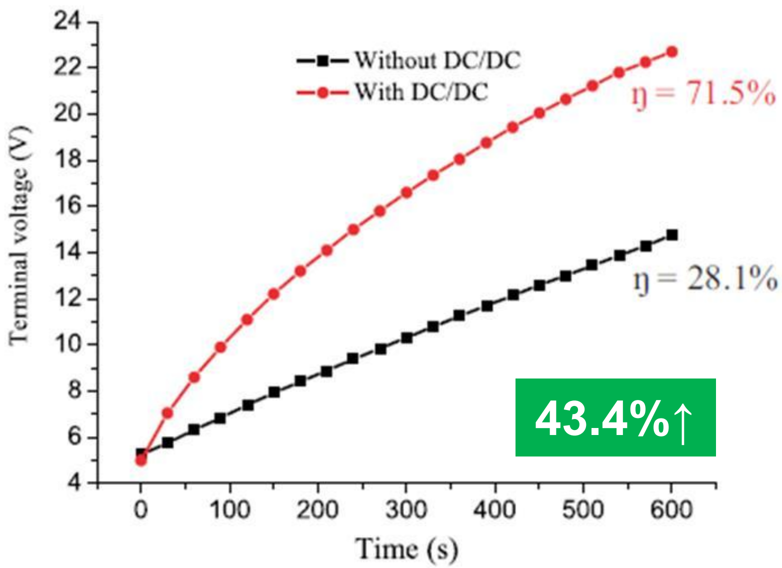
- Efficiency is improved under fixed coil position.

Batteries



Batteries charging improvement using the cascaded boost-buck DC-DC converter.

Ultracapacitors

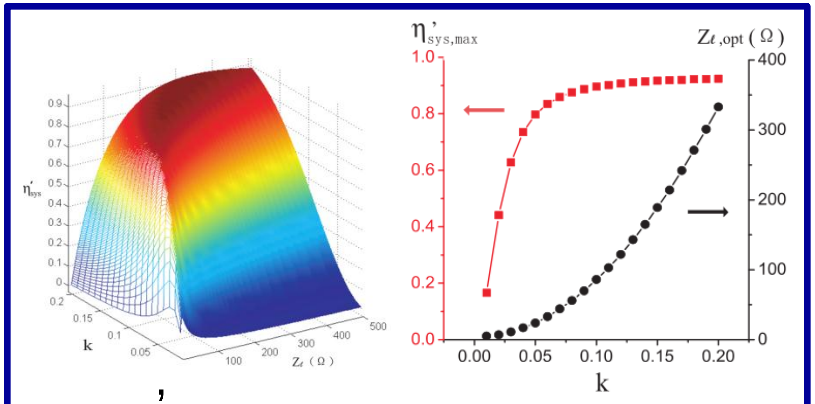


Ultracapacitors charging improvement using the cascaded boost-buck DC-DC converter.

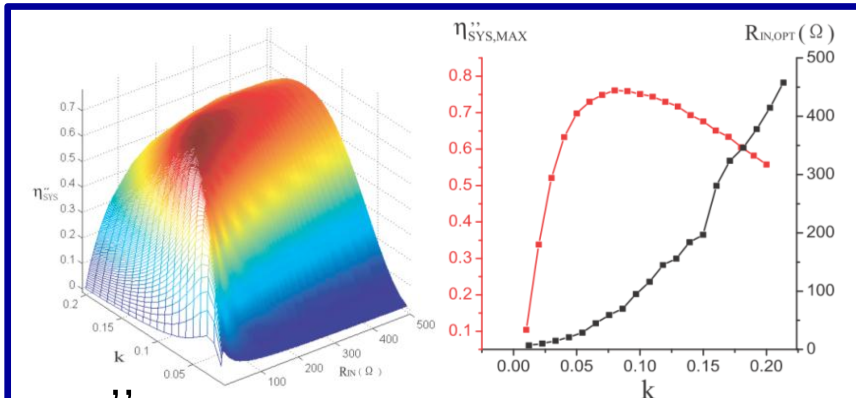
M. Fu, C. Ma, and X. Zhu, "A Cascaded Boost-Buck Converter for High Efficiency Wireless Power Transfer Systems," **IEEE Transactions on Industrial Informatics**, vol. 10, no. 3, pp. 1972–1980, 2014.

(3.1) Coupling Variation

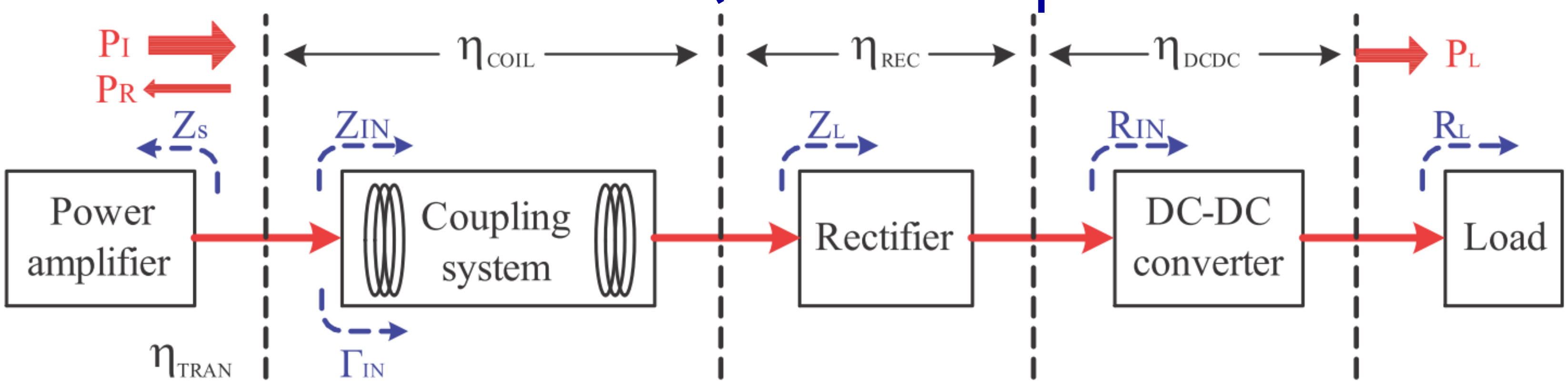
Optimal loads at different ports



$$\eta_{SYS}' = \eta_{TRAN} \cdot \eta_{COIL}$$

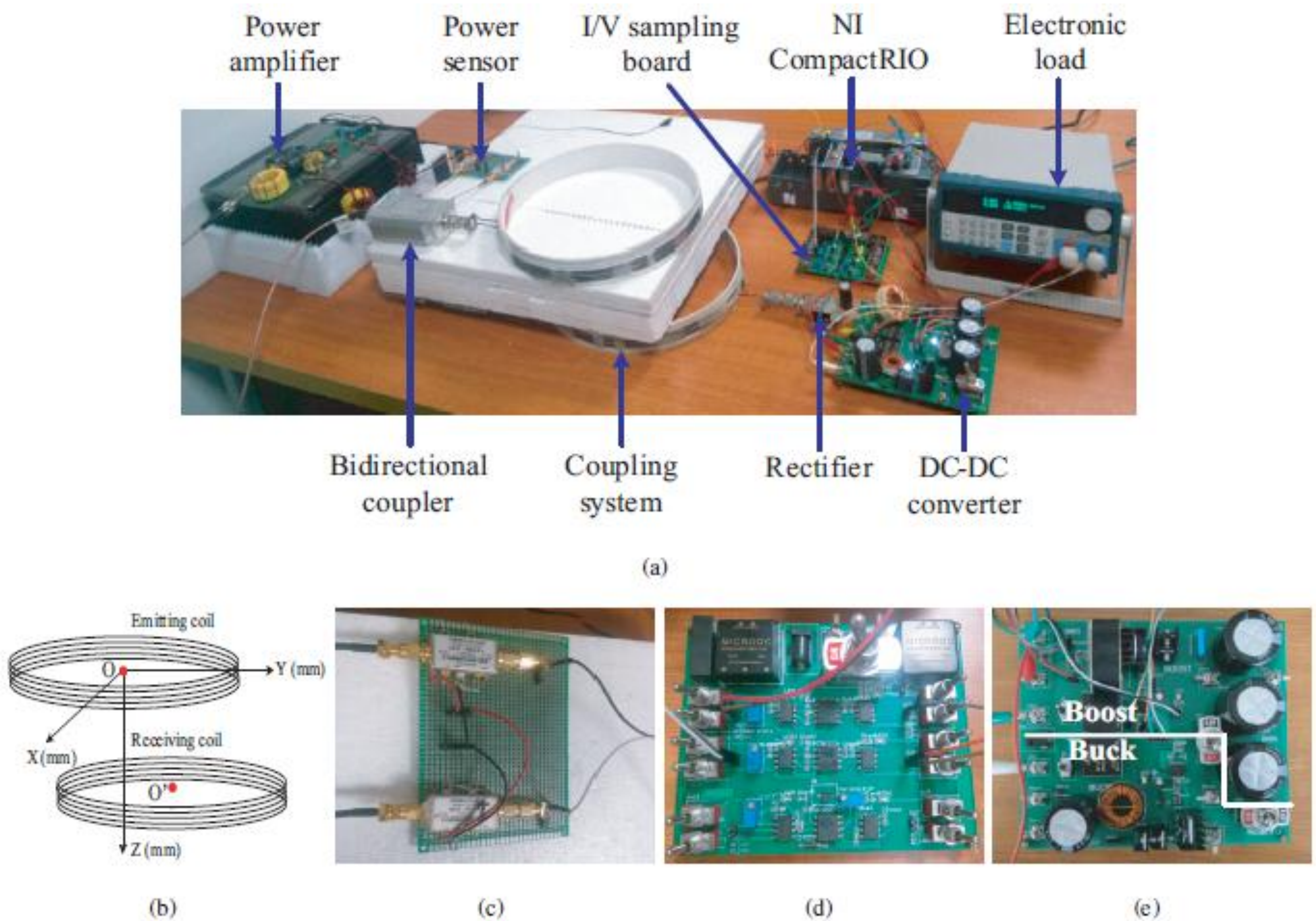


$$\eta_{SYS}'' = \eta_{TRAN} \cdot \eta_{COIL} \cdot \eta_{REC}$$



$$\eta_{SYS} = \eta_{TRAN} \cdot \eta_{COIL} \cdot \eta_{REC} \cdot \eta_{DCDC}$$

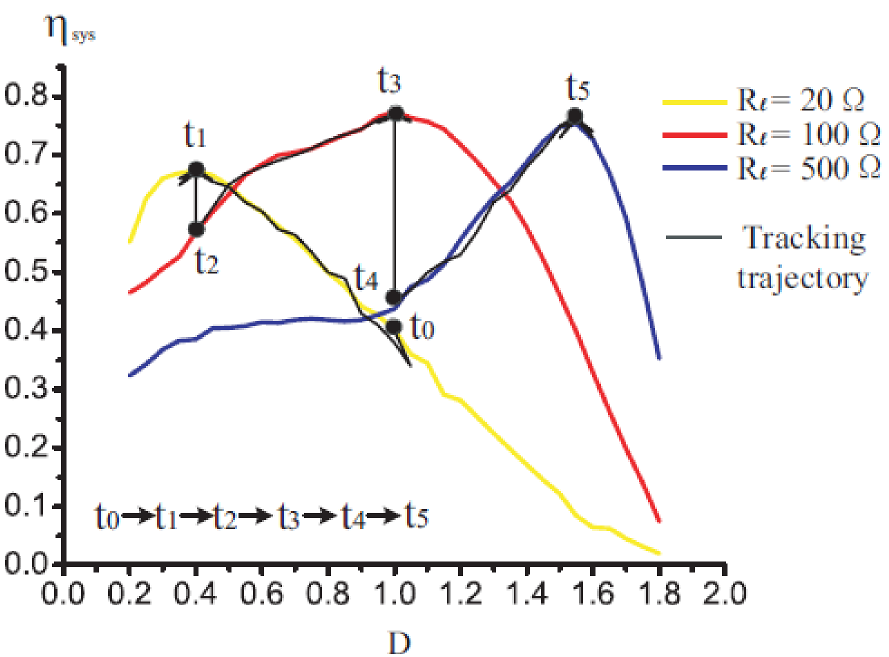
(3.2) System Setup



WPT system configuration. (a) Overall system. (b) Coil relative position. (c) Power sensor. (d) I/V sampling board. (e) DC/DC converter.

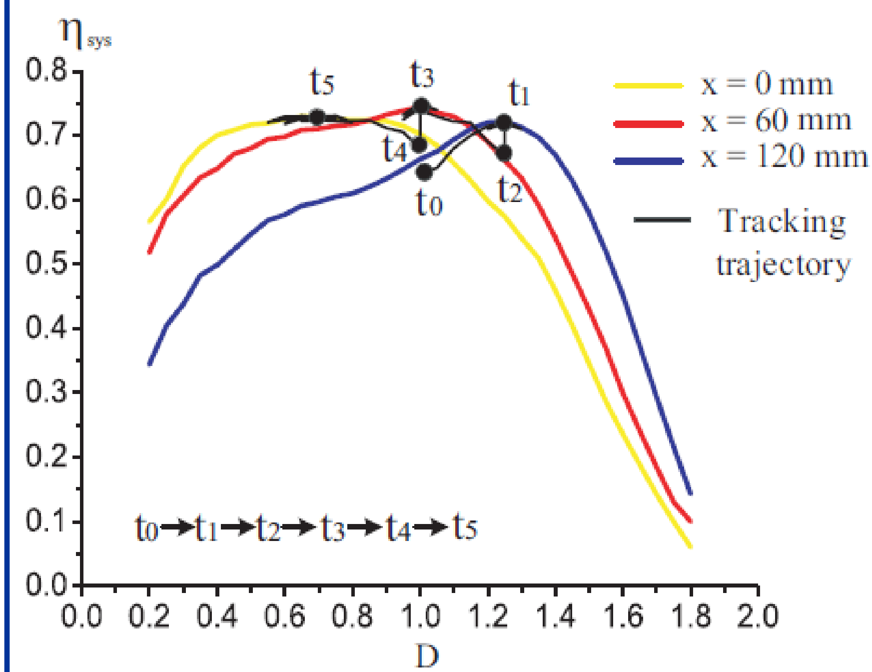
(3.3) Optimal Load Tracking

Load variation



The system can track the maximum efficiency under load variation.

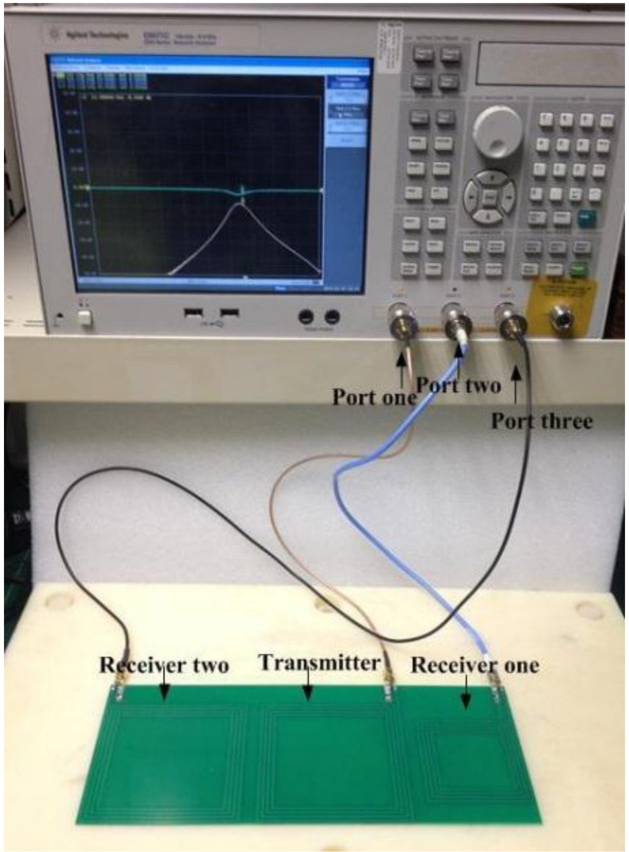
Position variation

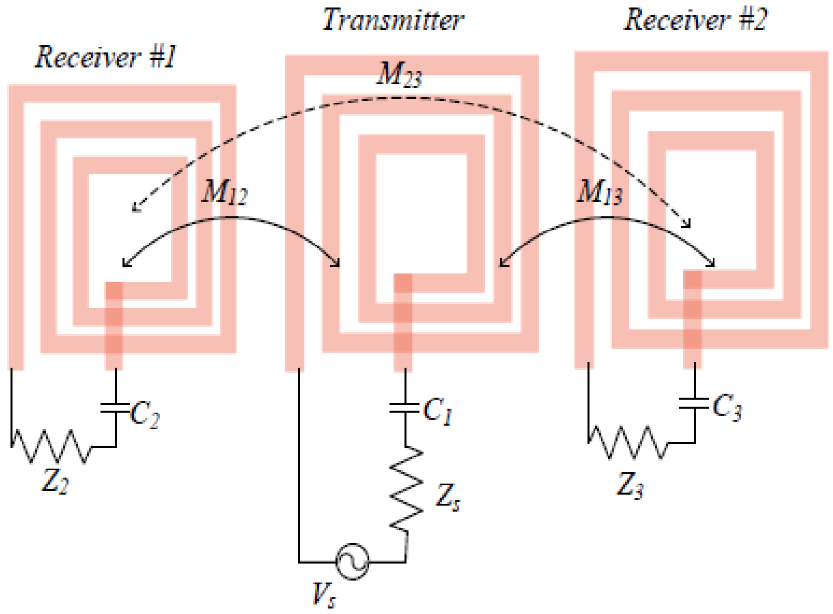


The system can track the maximum efficiency under position variation.

M. Fu, H. Yin, X. Zhu, and C. Ma, "Analysis and Tracking of Optimal Load in Wireless Power Transfer Systems," **IEEE Transactions on Power Electronics**, vol. 30, no. 7, pp. 3952–3963, 2015.

(4.1) One-to-Multiple Coils

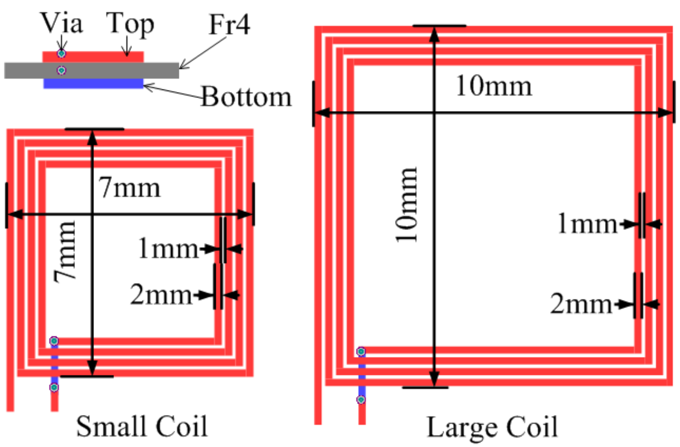




$$Z_{inopt} : Z_{2opt} : Z_{3opt} = R_1 : R_2 : R_3$$

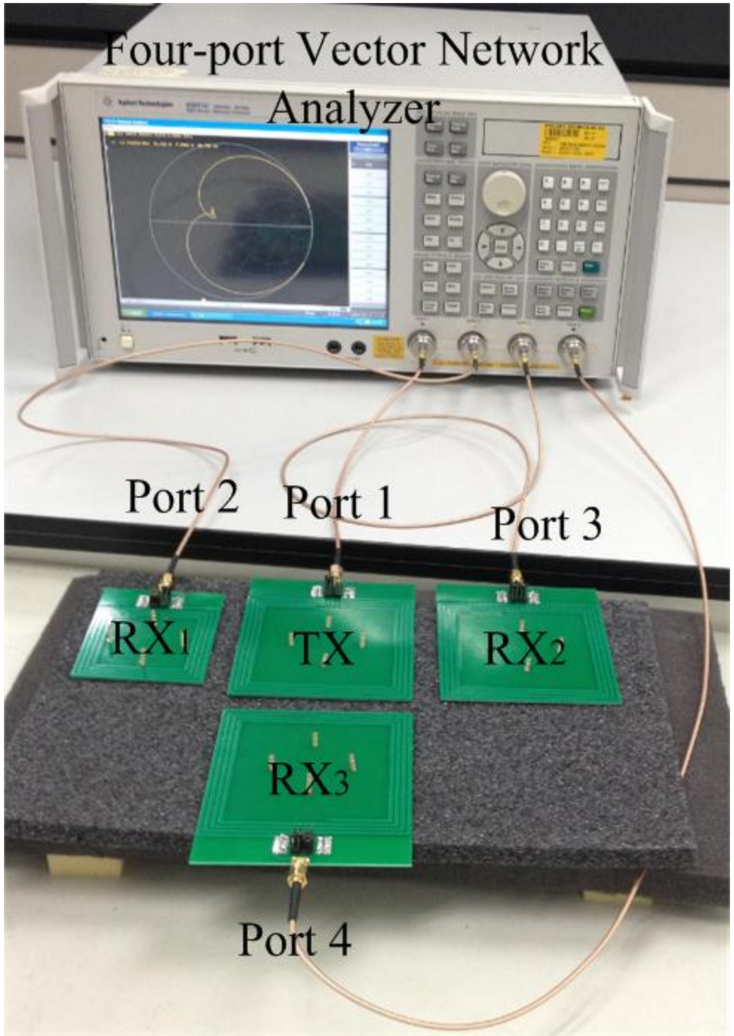
Optimize the power flow? （It is a typical multiple-load energy network）

(4.2) Measurement Platform



Coils' layout

Parameter	Large Coil	Small Coil
R (Ω)	2.05	1.04
L (uH)	3.93	2.01
C (pF)	37.2	72.5



(4.3) Result Comparison

	Cal	PZC	LC
$Z_{L1,OPT}$	13.58	13.4	13
$Z_{L2,OPT}$	27.84	28.4	28
$Z_{L3,OPT}$	25.13	24.8	25
$Z_{S,OPT}$	27.84	26.4-j3.5	26.6-j2
Optimal load ratio ($Z_{S,OPT}$:$Z_{L1,OPT}$:$Z_{L2,OPT}$:$Z_{L3,OPT}$)	**1 : 0.5 : 1 : 0.9**	**1 : 0.51 : 1.08 : 0.94**	**1:0.49:1.05:0.94**
η	0.8629	0.8537	0.8534

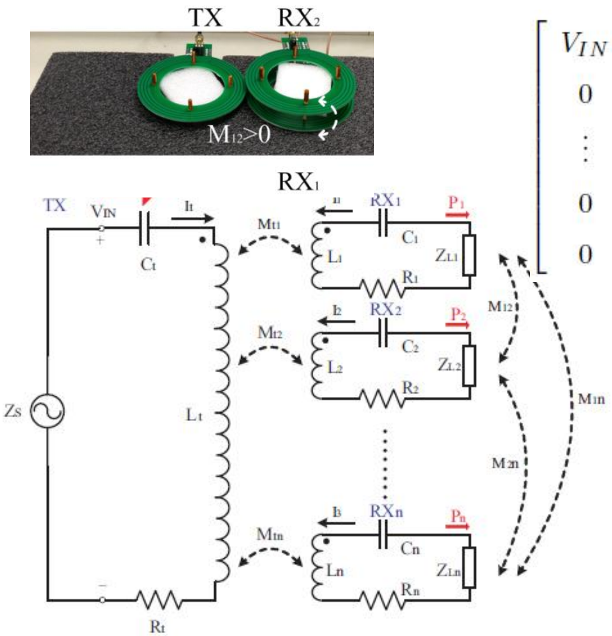
M. Fu, T. Zhang, C. Ma, and X. Zhu, "Efficiency and Optimal Loads Analysis for Multiple-Receiver Wireless Power Transfer Systems," **IEEE Transactions on Microwave Theory and Techniques,** vol. 63, no. 3, pp. 801–812, 2015.

(5.1) Cross Coupling Effects

Evaluate the cross coupling effects between RXs.

- Maximum efficiency is obtained for pure resistive loads under zero cross coupling.
- Load reactance can be used to compensate the cross coupling effects.

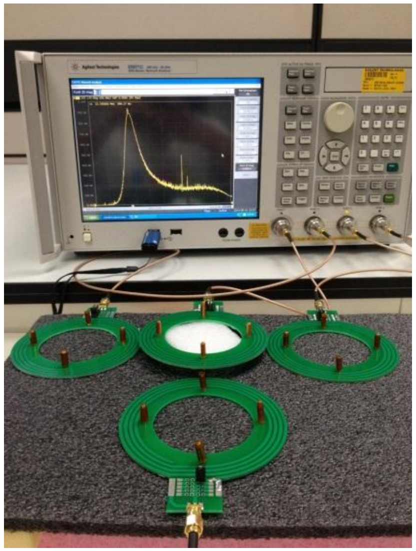
Circuit-model-based optimal reactance derivation

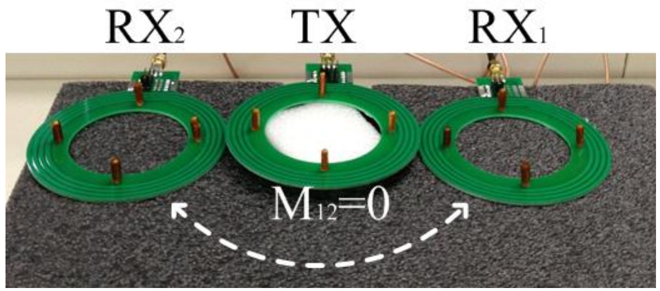


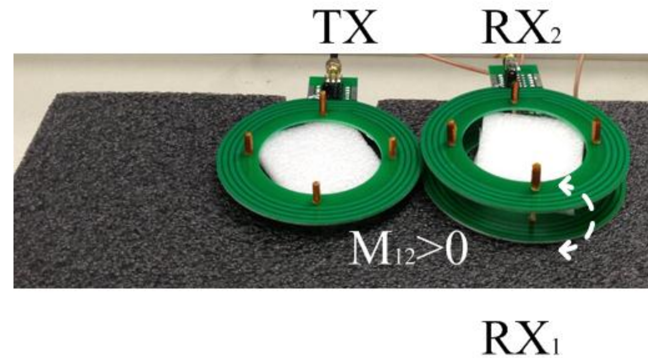
$$\begin{bmatrix} V_{IN} \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_t & j\omega M_{t1} & \cdots & j\omega M_{t(n-1)} & j\omega M_{tn} \\ j\omega M_{t1} & R_1+R_{L1}+jX_{L1} & \cdots & j\omega M_{1(n-1)} & j\omega M_{1n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{t(n-1)} & j\omega M_{1(n-1)} & \cdots & R_{n-1}+R_{L(n-1)}+jX_{L(n-1)} & j\omega M_{(n-1)n} \\ j\omega M_{tn} & j\omega M_{1n} & \cdots & j\omega M_{(n-1)n} & R_n+R_{Ln}+jX_{Ln} \end{bmatrix} \begin{bmatrix} I_t \\ I_1 \\ \vdots \\ I_{n-1} \\ I_n \end{bmatrix}$$

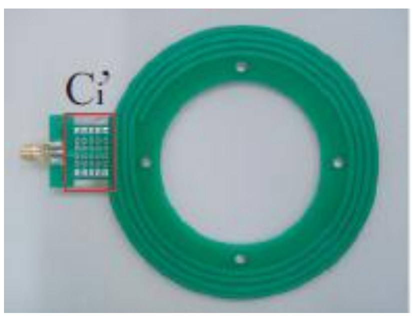
$$X_{Li}^{*} = -\sum_{k=1,k\neq i}^{n} \frac{\omega M_{ik} M_{tk}(R_i + R_{Li})}{M_{ti}(R_k + R_{Lk})}.$$

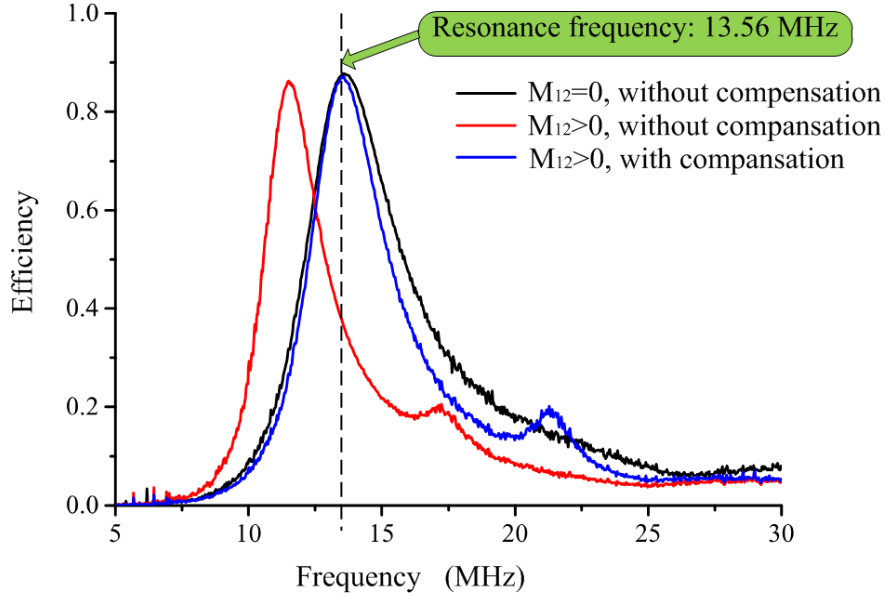
(5.2) Experiment Results











M. Fu, T. Zhang, Patrick Chi Kwong Luk , X. Zhu, and C. Ma, “Compensation of Cross Coupling in Multiple-Receiver Wireless Power Transfer Systems,” **under review**.

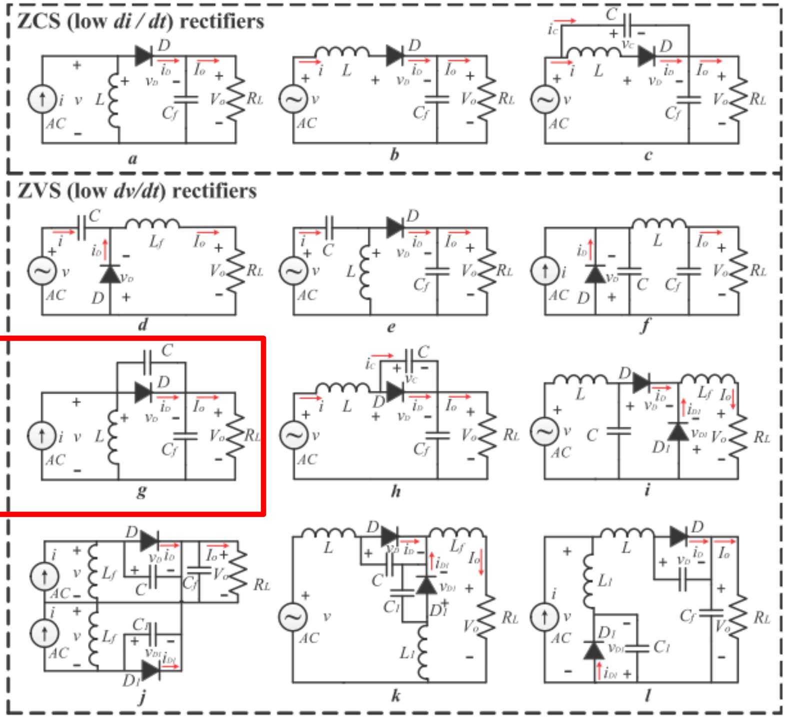
(6.1) Class E Rectifier

MHz systems require high-efficiency rectifiers based on soft switching.

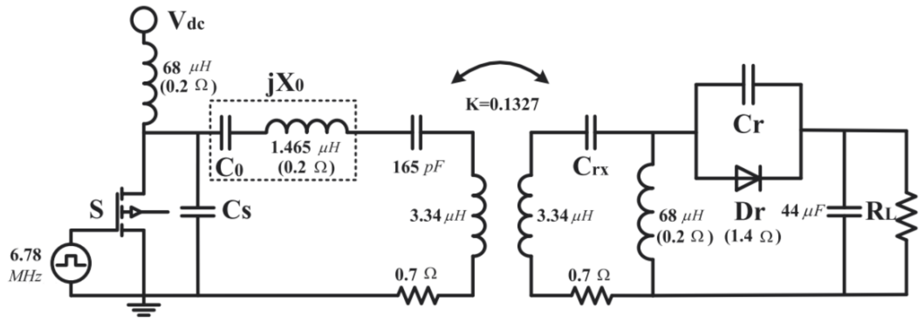
Class E rectifier

- It was first proposed at 1988, as the reverse process of the typical Class E PA.
- It enables soft switching for high-efficiency rectification.
- It was first introduced for WPT at 2014.
- There are various topologies. Our research starts from a current-source driven rectifier.

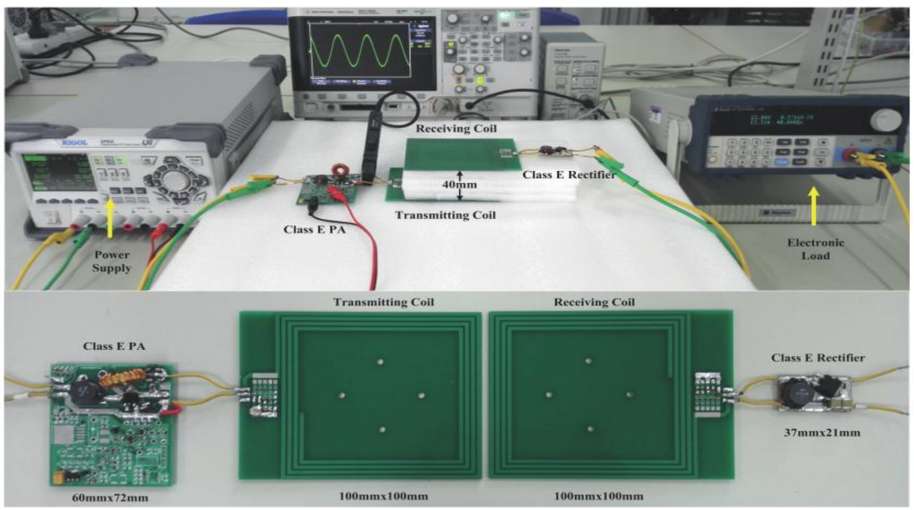
Various topologies



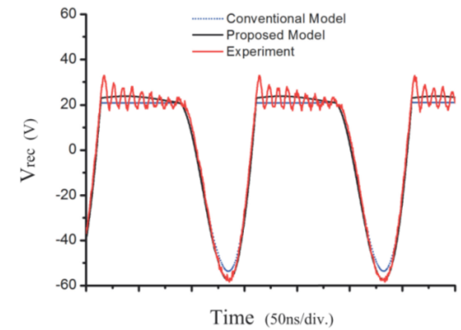
(6.2) Class E^2 WPT System

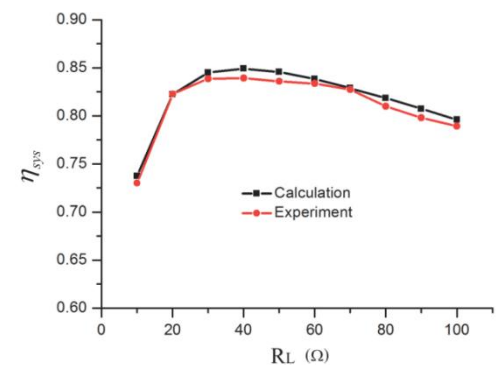


Circuit parameters



Exp. results





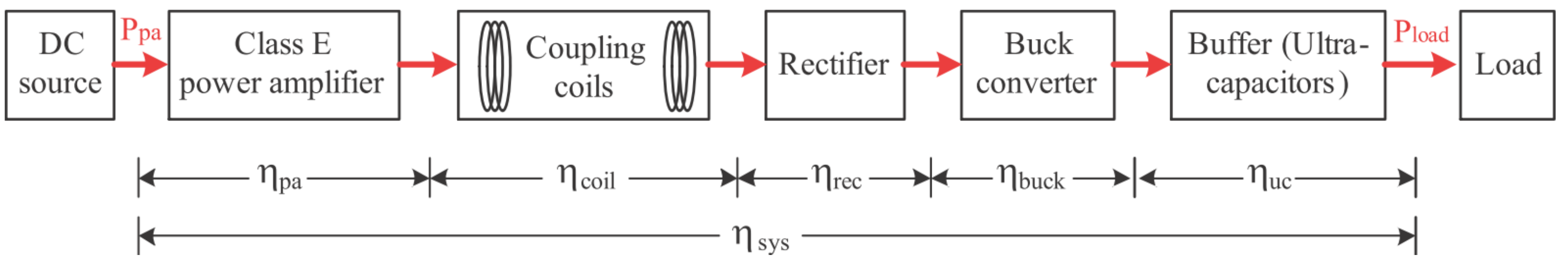
The dc-dc efficiency can reach 85%, which is 5% higher than that using full-bridge rectifiers.

M. Liu, **M. Fu** and C. Ma, “Parameter Design for A 6.78-MHz Wireless Power Transfer System Based on Analytical Derivation of Class E Current-Driven Rectifier”, **accepted by IEEE Transactions on Power Electronics.**

(7.1) System with Buffer

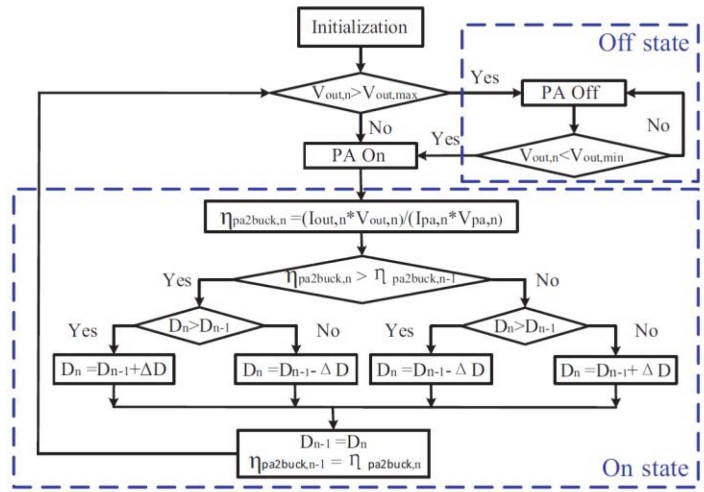
It is desirable to design a WPT system for special applications, which have large power dynamics.

Configuration

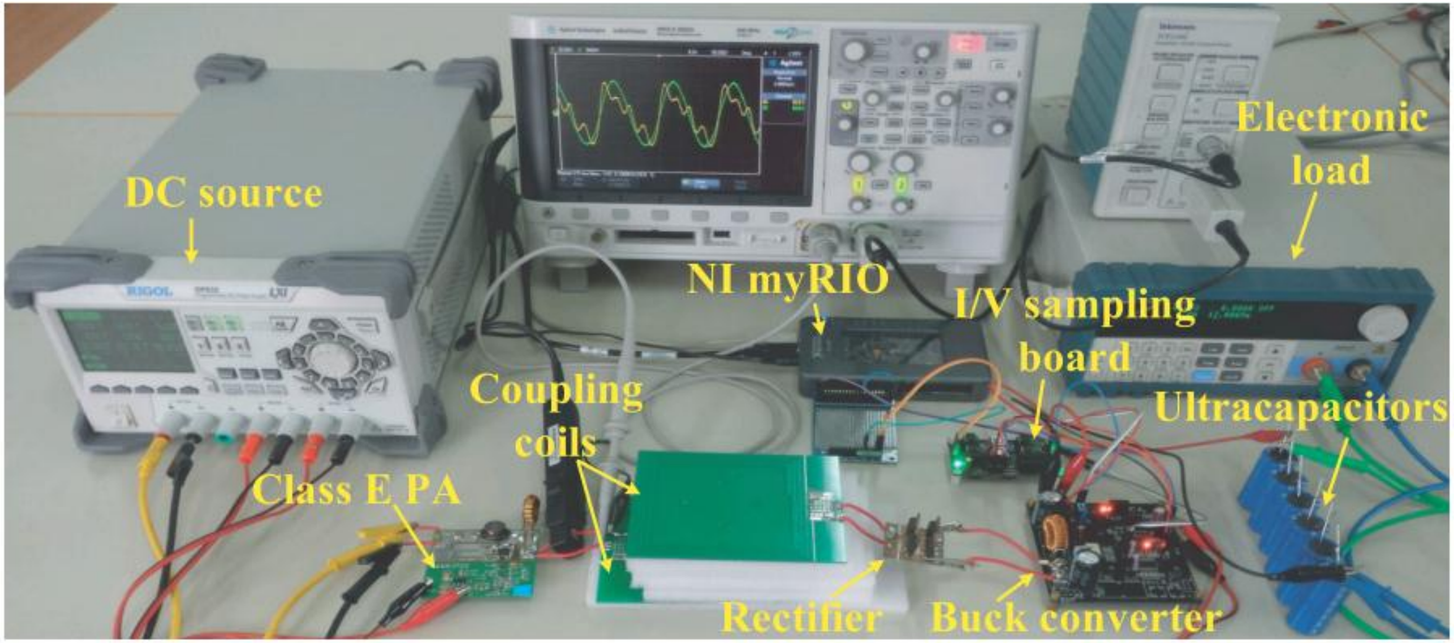


On-Off Control

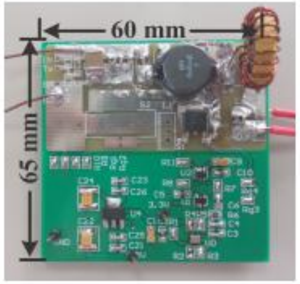
- On state： The system can track the maximum efficiency and supply power for the buffer and the real load.
- Off state： The system is turned off, and the load is charged by the buffer.

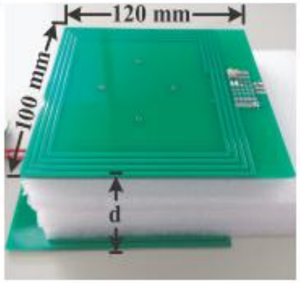


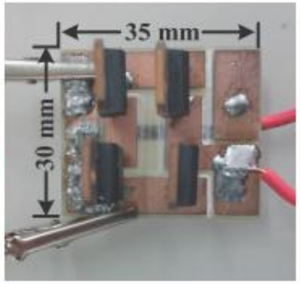
(7.2) Experiment Setup

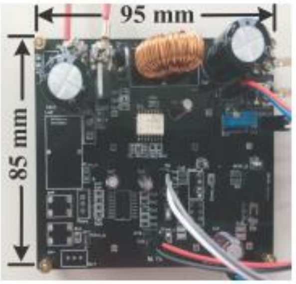


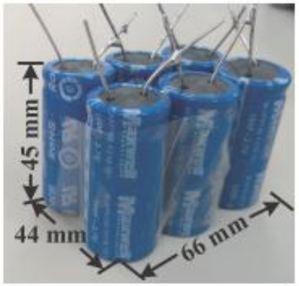
6.78 MHz System







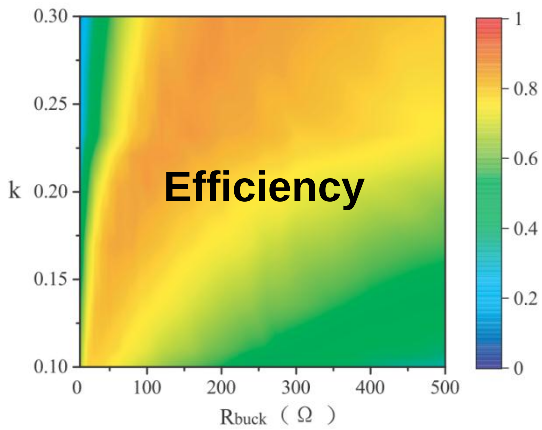


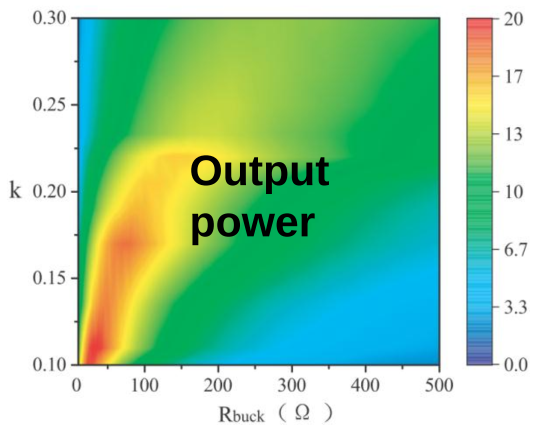


Class E PA Coupling coils Rectifier DC-DC converter UC bank

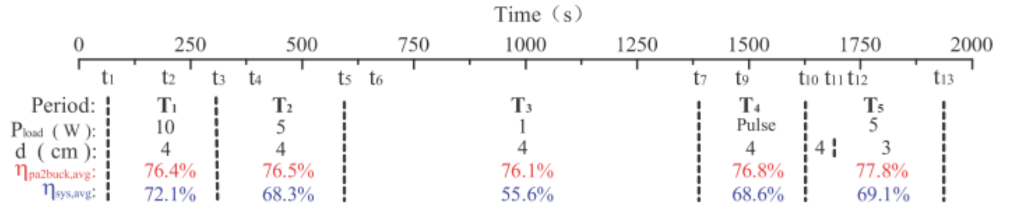
(7.3) Experiment Results

Static characteristics

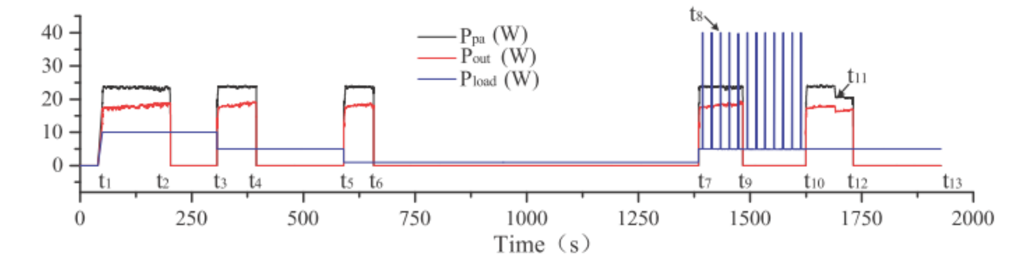




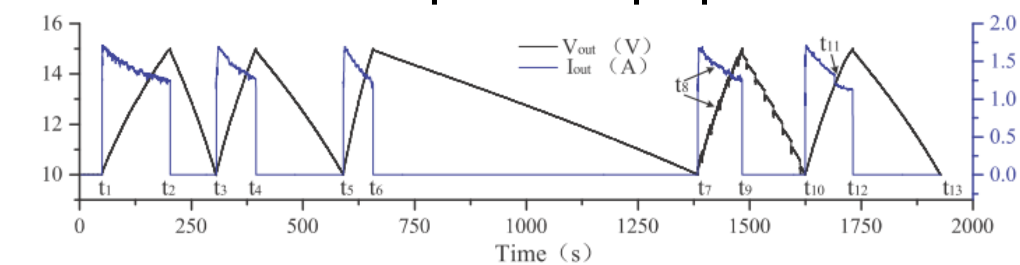
Response under various situations



System characteristics



Input and output power



Output voltage and current

M. Fu, H. Yin, M. Liu, and C. Ma, “A 6.78 MHz Wireless Power Transfer System with High Efficiency over A Wide Load Power Range”, **under review.**

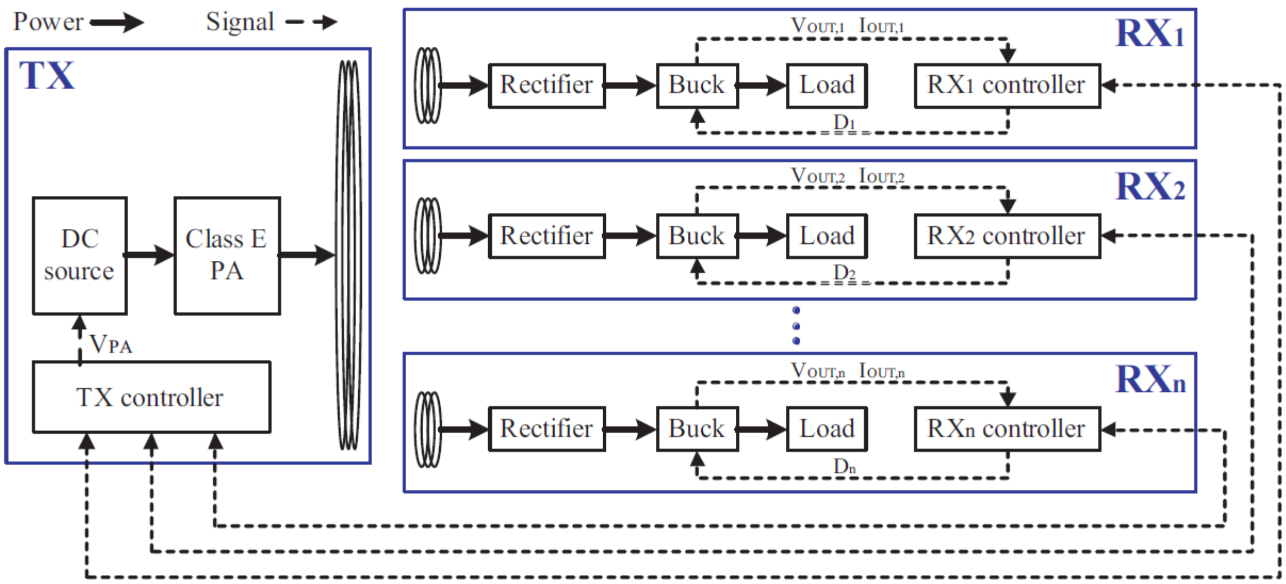
(8.1) Simultaneous Charging

MHz systems improve the spatial freedom, and make it possible to charge multiple devices simultaneously.

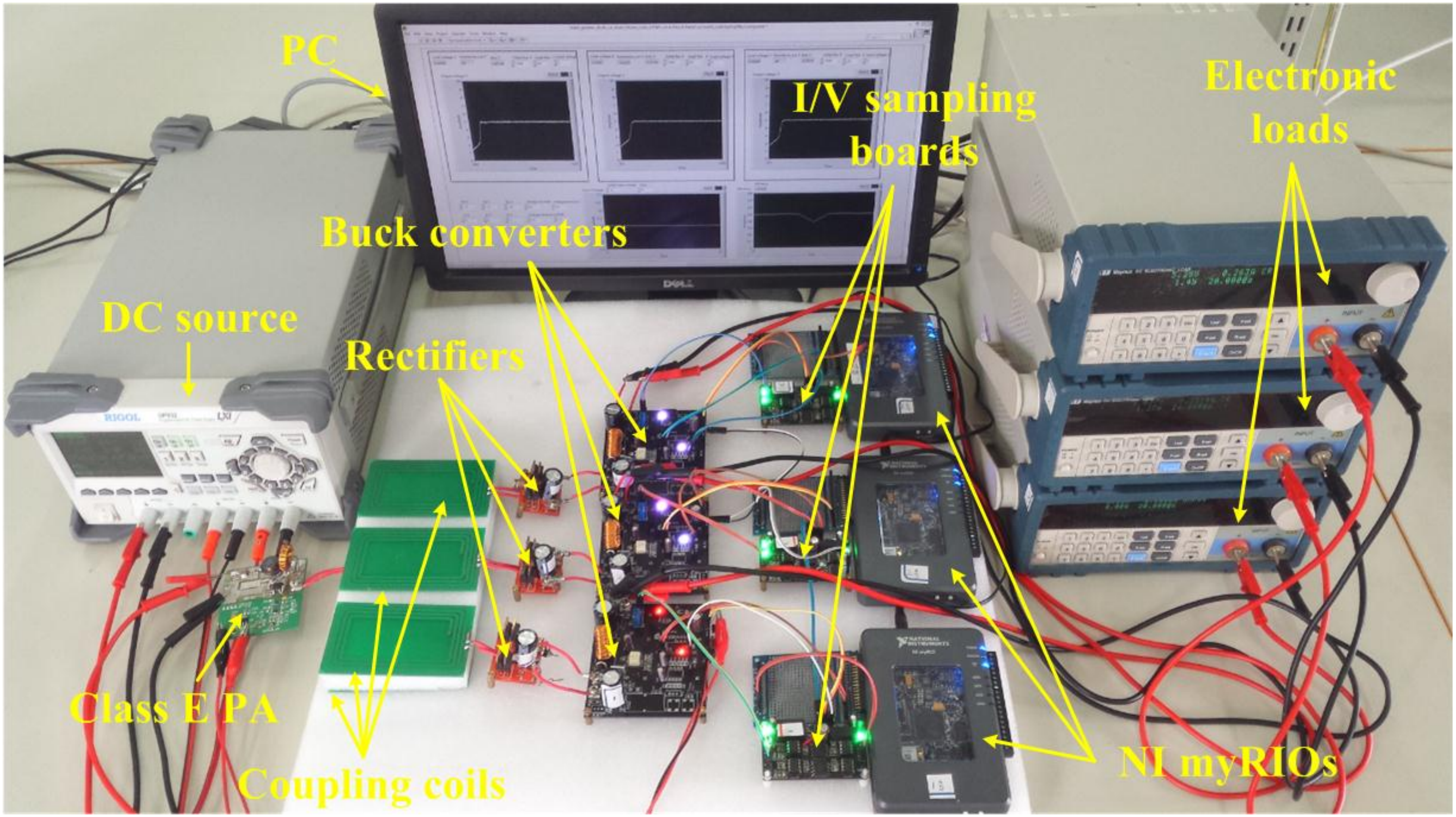
Analysis

A n-RX system can be equivalently represented by a one-RX model. System control approach can be developed accordingly.

System block diagram

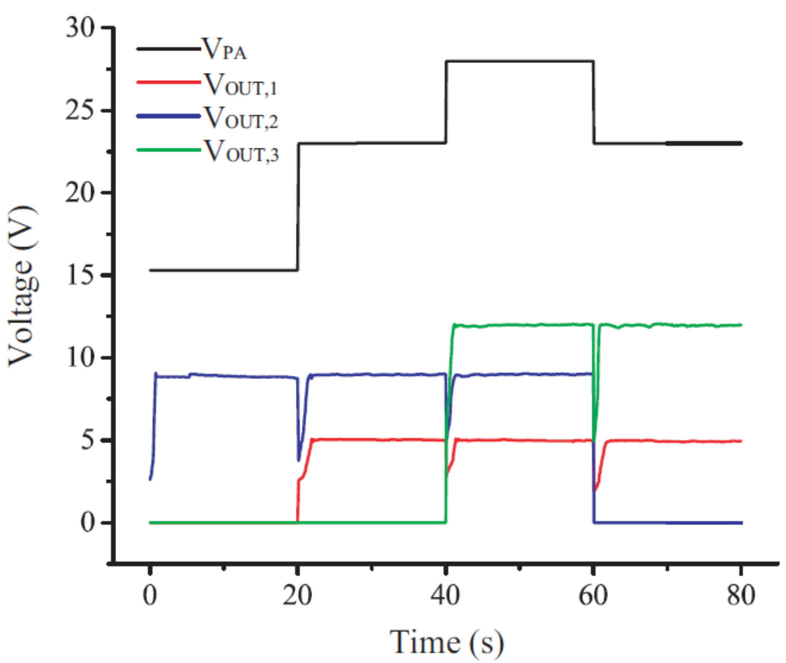


(8.2) Experiment Setup

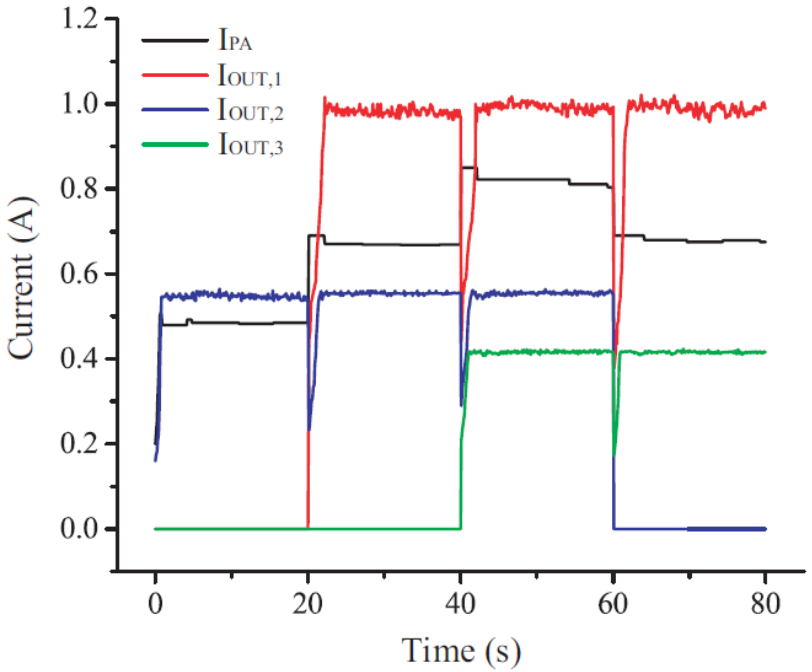


(8.3) Experiment Results

Input and output voltages



Input and output currents

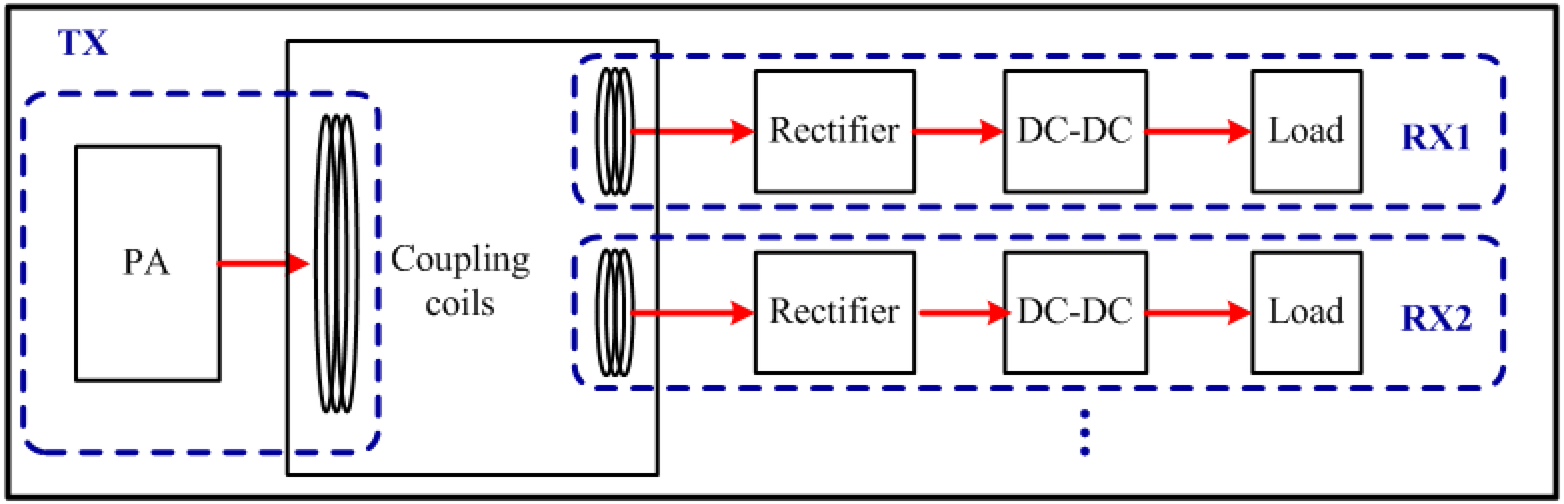


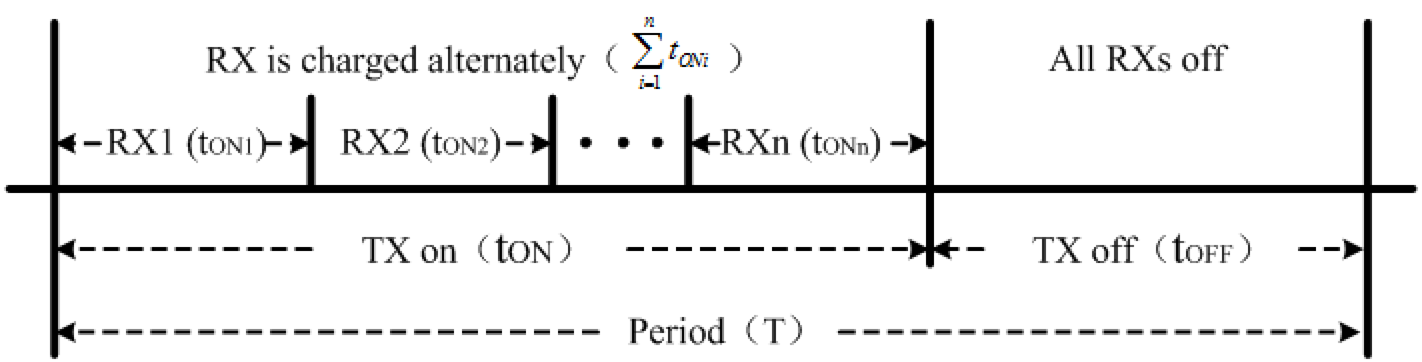
The system can provide a constant output voltage for each receiver with optimized efficiency **(>63%).**

M. Fu, H. Yin, M. Liu, and C. Ma, "Analysis and Control for A 6.78 MHz Multiple-Receiver Wireless Power Transfer System Driven by Class E Power Amplifier", **under review.**

(9) Alternate Charging

Charge each receiver alternately, and the power management can be achieved by time division.





Publications

Journal Papers

1. **M. Fu,** H. Yin, M. Liu, and C. Ma, "Analysis and Control for A 6.78 MHz Multiple-Receiver Wireless Power Transfer System Driven by Class E Power Amplifier", **under review.**
2. **M. Fu,** H. Yin, M. Liu, and C. Ma, "A 6.78 MHz Wireless Power Transfer System with High Efficiency over A Wide Load Power Range", **under review.**
3. **M. Fu,** T. Zhang, Patrick Chi Kwong Luk , X. Zhu, and C. Ma, "Compensation of Cross Coupling in Multiple-Receiver Wireless Power Transfer Systems," **under review**.
4. M. Liu, **M. Fu** and C. Ma, "Parameter Design for A 6.78-MHz Wireless Power Transfer System Based on Analytical Derivation of Class E Current-Driven Rectifier", **accepted by IEEE Transactions on Power Electronics.**
5. M. Fu, T. Zhang, C. Ma, X. Zhu, "Wireless Power Transfer Using Magnetic Resonance Coupling: Basic Considerations and Practices", Transaction of China Electrotechnical Society, vol. 30, sup. 1, pp.6-12, 2015. (Chinese)
6. **M. Fu**, T. Zhang, C. Ma, and X. Zhu, "Efficiency and Optimal Loads Analysis for Multiple-Receiver Wireless Power Transfer Systems," **IEEE Transactions on Microwave Theory and Techniques,** vol. 63, no. 3, pp. 801–812, 2015.
7. **M. Fu**, H. Yin, X. Zhu, and C. Ma, "Analysis and Tracking of Optimal Load in Wireless Power Transfer Systems," **IEEE Transactions on Power Electronics**, vol. 30, no. 7, pp. 3952–3963, 2015.
8. **M. Fu**, C. Ma, and X. Zhu, "A Cascaded Boost-Buck Converter for High Efficiency Wireless Power Transfer Systems," **IEEE Transactions on Industrial Informatics**, vol. 10, no. 3, pp. 1972–1980, 2014.
9. F. Wang，Y. Wang, and M. Fu, "Efficiency Optimization in Low and Medium Power Range of New Energy Grid-connected Three-level Inverter", Automation of Electric Power Systems, vol. 38, sup. 3, pp.101-105, 2014. (Chinese)

Conference Papers

1. **M. Fu**, Z. Tang, M. Liu, S. Liu, X. Zhu and C. Ma, "Output Power Improvement by Impedance Matching Networks for a Class E Power Amplifier Driven Wireless Power Transfer Systems", under review.
2. M. Liu. **M. Fu**, Z. Tang, S. Liu, X. Zhu and C. Ma, "Design Procedure of a Class E DC/DC Converter for Megahertz Wireless Power Transfer", under review.

Publications

3. Z. Tang, **M. Fu**, M, Liu and C. Ma, “Optimization of the Compensation Capacitors for Megahertz Wireless Power Transfer Systems”, accepted by Annual Conference of the IEEE Industrial Electronics Society (IECON) 2015.
4. H. Yin, **M. Fu**, M, Liu and C. Ma, “Power Distribution of a Multiple-Receiver Wireless Power Transfer System: A Game Theoretic Approach”, accepted by Annual Conference of the IEEE Industrial Electronics Society (IECON) 2015.
5. S. Liu, M. Liu, **M. Fu**, C. Ma，X. Zhu, “A High-Efficiency Class-E Power Amplifier with Wide-Range Load in WPT Systems”, IEEE Wireless Power Transfer Conference, May 13-15, 2015, Boulder, Colorado，USA.
6. **M. Fu**, Z. Tang, M. Liu, X. Zhu and C. Ma, “Full-Bridge Rectifier Input Reactance Compensation in Megahertz Wireless Power Transfer Systems”, IEEE PELS Workshop on Emerging Technologies: Wireless Power (2015 WoW), June 5-6, 2015, Daejeon, Korea.
7. M. Liu, **M. Fu**, Z. Tang, and C. Ma, “A Compact Class E Rectifier for Megahertz Wireless Power Transfer”, IEEE PELS Workshop on Emerging Technologies: Wireless Power (2015 WoW), June 5-6, 2015, Daejeon, Korea.
8. C. Zhao, H. Yin, **M. Fu**, C. Ma, “Analysis, control, and wireless charging of energy systems using ultracapacitors”, 2014 IEEE International Electric Vehicle Conference, Dec. 17-19, 2014, Florence, Italy.
9. **M. Fu**, T. Zhang, C.Ma, and X. Zhu, "A Review of Megahertz Wireless Power Transfer Systems Based on Magnetic Resonance Coupling", 2014 Internation Conference of Wireless Power Transmission Technology and Application, Nov. 16, 2014, Nanjing, China.
10. **M. Fu**, T. Zhang, X. Zhu, and C. Ma, “Subsystem-Level Efficiency Analysis of a Wireless Power Transfer System”, IEEE Wireless Power Transfer Conference, May 8-9, 2014, Jeju Island, Korea.
11. T. Zhang, **M. Fu**, X. Zhu, and C. Ma, “Optimal Load Analysis for a Two-Receiver Wireless Power Transfer System”, IEEE Wireless Power Transfer Conference, May 8-9, 2014, Jeju Island, Korea.
12. **M. Fu**, T. Zhang, C. Ma, and X. Zhu, “Wireless Charging of A Supercapacitor Model Vehicle Using Magnetic Resonance Coupling”, ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, August 4-7, 2013, Portland, OR, USA.
13. **M. Fu**, T. Zhang, X. Zhu, and C. Ma: “A 13.56 MHz Wireless Power Transfer System without Impedance Matching Networks”, IEEE Wireless Power Transfer Conference, May 15-16, 2013, Perugia, Italy.
14. C. Ma, X. Zhu, and **M. Fu,** “Wireless Charging of Electric Vehicles: A Review and Experiments", ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Aug. 28–Aug. 31, 2011, Washington D. C., USA.

Selected Honors & Awards

Ph.D.	2015-Preesnt:	The best ten research group of SJTU Excellent party member of SJTU Covidien scholarship (18 kRMB)
	2014-2014:	Excellent graduate student scholarship(5 kRMB) Miyoshi graduate student of SJTU Excellent party member of JI Covidien scholarship (18 kRMB)
	2013-2014:	Scholarship for new Ph.D. student (10 kRMB)
M.S.	2010-2013:	Annual excellent volunteer for blood donation Second price of Infineon cup in the East China Area
B.S.	2006-2010:	Capstone gold prize dean’s list (8 times) yunxia outstanding project scholarship.

Thank you！

Minfan Fu

http://www.minfanfu.icoc.cc/

Dynamic system control laboratory

Univ. of Michigan and Shanghai Jiao Tong Univ. Joint Institute

http://www.umji.sjtu.edu.cn/lab/dsc