Roadmap to a New World with Electricity Like Air

IoT Vertical and Topical Summit at RWW2022

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New World with Electricity Like Air: IoT and IoE Society

IoT: Internet-Of-Things, IoE: Internet-Of-Energy
How do we obtain electricity for IoT Devises?

- **Power Feed Line**
  No time limit of power, but high initial cost, limit of position, no flexibility, etc.

- **Battery**
  Flexibility of position, but time limit of power, high disposal cost, bad for environment etc.

- **Solar Cell**
  Flexibility of position, no time limit of power, but unstable (shadow/night), etc.

- **Energy Harvesting/Scavenging**
  No time limit of power, but low power *(lower ambient power density)*, etc.
<table>
<thead>
<tr>
<th>Category</th>
<th>Market Perspective</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA/IoT Sensor System</td>
<td>3.75 B$</td>
<td>Market will be 2.5 M and 125 B$. Estimated installed WPT will be 30%, Cost in system will be 10%</td>
</tr>
<tr>
<td>Sensor for Nursing and Watching</td>
<td>500 M$</td>
<td>Market will be 5 B$ and WPT will be 10%</td>
</tr>
<tr>
<td>Mobiles</td>
<td>1.27 B$</td>
<td>Smart Phones will be 34 M system. Estimated installed WPT will be 47% and 550 M$. Tablet will be 24 M$ and WPT will be 30% and 230 M$.</td>
</tr>
</tbody>
</table>
Far Field Wireless Power Transfer (WPT)

(a) Wide Beam Type including Energy Harvesting for Multi-Users, Low Power, in Fraunhofer Region

Transmitted Power (Broad) → Electric Power

\[ \eta = \frac{P_r}{P_t} = \frac{G_t A_r}{4\pi d^2} \]

(\(+\) Diffraction)

- Low Power Rectenna is important.

(b) Narrow Beam Type for Single User, High Power, in Fresnel Region

Transmitted Power

\[ \eta = 1 - e^{-\tau^2} \]

\[ \tau^2 = \frac{G_t A_r}{4\pi d^2} = \frac{P_r}{P_t} \]

- Theoretically 100%
- Target detecting and beam forming is important.
- Higher Frequency is better.
Wide Beam Type WPT — Low Power Rectennas -

(a) Wide Beam Type including Energy Harvesting for Multi-Users, Low Power, in Fraunhofer Region

\[ \eta = \frac{P_r}{P_t} = \frac{G_t A_r}{4\pi d^2} \]

\[ (+ \text{Diffraction}) \]

- Low Power Rectenna is important.

Octave Bandwidth RF Harvesting Tee-Shirt by J. A. Estrada et al., Colorado Univ., WPW2019

Broadband and High Impedance Rectenna by C. Song et al. Univ. Of Liverpool, IEEE TIE, 2017

100μW Rectenna by K. Kawai et al., Kyoto Univ., AWPT2021

Rectenna with Tunnel Diode by V. Manev et al., Eindhoven Univ. of Tech., WPW2019

SIW solar cavity-backed slot antenna by S. Lemey et al., Ghent Univ, EuMW2015
Narrow Beam Type WPT — Beam Forming with Higher Frequency

(b) Narrow Beam Type for Single User, High Power, in Fresnel Region

\[ \eta = 1 - e^{-\frac{\tau^2}{4}} \]

\[ \tau^2 = \frac{G_t A_r}{4\pi d^2} = \frac{P_r}{P_t} \]

- Theoretically 100%
- Target detecting and beam forming is important.
- Higher Frequency is better.

"Cota" system by Ossia corp. Retrodirective in Multi Path

EM Simulation in 2.4GHz by T. Sasaki et al., Kyoto Univ., IEEE WPW2019

Rectenna at 95GHz with New Developed GaN Diode, by H. Kazemi, Raytheon, TMTT, 2022

Field Experiment with 91.2kW-TxMW to 1.6kW-RxDC in > 1km in X-Band, by C. Rodenbeck, NRL, J. of Microwaves, 2022
Will far-field WPT become a reality?

We need Novel technologies, Human safety system, and harmonization with conventional wireless applications.

= We need new radio regulation for WPT.

Japan – One of radio applications with License (In-Door, 2.4GHz-band, 5.7GHz-band, and 920MHz-band without license)(2022- )

US – One of ISM applications (governed by Part 18 of the Federal Communications Commission (FCC) rules, while Part 15 contains the rules for unlicensed communication devices, even those that share ISM frequencies) (920MHz-band, 2.4GHz-band and 5.7GHz-band without license)(2017- )

China – One of ISM applications (2016- ) ?? personal information

EU – One of the Short Range Device (917.3–917.7 MHz) (2020.5 in Addendum to ECC Report 200) ?? ECC : Electronic Communications Committee

But European Broadcasting Union (EBU), BBC, and the others are negative in ITU-R
Wireless-Powered ZigBee in Same Frequency Band (TDD-WPT)

- We propose MPT-ZigBee system at same frequency of MPT and ZigBee (at 2.45GHz) with scheduling algorism.
- We can increase a limit power without any interference (5pW/cm² (CW)) -> 1.91mW/cm² (pulse, no scheduling) -> 2.61mW/cm² (pulse, scheduling)

<table>
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<th>Device Type</th>
<th>As join in network</th>
<th>As not join in network</th>
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<tr>
<td>End device</td>
<td>9.46 mW</td>
<td>61.8 mW</td>
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With Novel Technologies and New WPT Regulation

- 2010 R&D period of WPT
- 2010 – 2020 Commercialization of Inductive WPT
- 2020 – Commercialization of Wide-Beam WPT (On-going)
- 2030 - Commercialization of Narrow-Beam WPT (Hopefully)
- 2040 – IoT and IoE Society (Our Dream1)
- 2050 - Power from Space (SPS) (Our Dream2)

“The best way to predict the future is to invent it.”
(by Alan Kay)