Long-range Wireless Power and Information Transmission
limits and proposals

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History

Hertz was a German physicist. He was the first to demonstrate the existence of electromagnetic waves by building an apparatus to produce and detect radio waves.

Tesla demonstrated wireless energy transfer to power electronic devices in 1891 and aspired to intercontinental wireless transmission of industrial power in his unfinished Wardenclyffe Tower project.
• 1890 – First intentional WPT experiment

Nikola Tesla - inductive and capacitive coupling using spark-excited radio frequency resonant transformers, now called Tesla coils.

• 1960 – First Long-Range WPT experiment

William C. Brown pioneered microwave power transmission. Also, he invented the rectenna which could efficiently convert microwaves to DC power.
Historical Introduction and Current Trends

- **1960** – First Long-Range WPT experiment
- Development of the Rectenna 1963
- Flying helicopter 1964
- Solar Power Satellite (SPS) 1968
- JPL Experiments 1975
- Rectenna improvement
- Venus Site Goldstone Facility 1.54 km
- SPS first serious assessment 1980
Historical Introduction and Current Trends

- **1980s**, Canada’s Communications Research Centre created a small airplane that could run off power beamed from the Earth. SHARP

- **1993**, Alaska’21, provide wireless power to small rural communities

- **2001**, Grand Bassin, wireless power to the island canyon

- **2008**, Hawaii demonstration by Managed Energy Tech.. Transmission of energy over 148 km.
Historical Introduction and Current Trends

Nowadays… Internet of Things everywhere…
Historical Introduction and Current Trends

World Population

<table>
<thead>
<tr>
<th>Year</th>
<th>6.3 Billion</th>
<th>6.8 Billion</th>
<th>7.2 Billion</th>
<th>7.6 Billion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Connected Devices

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0.08</td>
</tr>
<tr>
<td>2010</td>
<td>1.84</td>
</tr>
<tr>
<td>2015</td>
<td>3.47</td>
</tr>
<tr>
<td>2020</td>
<td>6.58</td>
</tr>
</tbody>
</table>

Trillion Sensor Visions

Battery Powered IoT Devices

Installed Base (million units)

Year
Internet of Space Probes IoSP
General Concepts

\[ \left( \frac{\lambda}{4\pi r} \right)^2 \]
Design of a WPT Link

Typical WPT chain

\[ \eta_{Total} = \frac{P_{DCout}}{P_{DCin}} = \eta_{DC-RF} \cdot \eta_{Beam} \cdot \eta_{RF-DC} \]

- In Electromagnetic Energy Harvesting we only can control the beaming efficiency and the RF-DC efficiency
Design of a WPT Link

The beaming efficiency: comprises antenna gains, free-space loss and polarization loss due to misalignment between antennas.

- $\theta$ is the polarization angle between the two antennas.
- Dual-polarized antennas alleviate the dependency on the Polarization angle.

\[
\eta_{Beam} = \frac{P_{RF,RX}}{P_{RF,TX}} = G_t G_r \left( \frac{\lambda}{4\pi D} \right)^2 L_{pol}
\]

\[
L_{pol} = \cos^2 \theta
\]
## General Concepts

### Frequency and Wavelength

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength [m]</td>
<td>0.15</td>
<td>0.06</td>
<td>0.03</td>
<td>0.017</td>
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</tbody>
</table>

### DC-RF Conversion

<table>
<thead>
<tr>
<th>DC-RF Efficiency [%]</th>
<th>80</th>
<th>75</th>
<th>65</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Power in Transmitter [W]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Amplifier Gain [dB]</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>RF-RF Efficiency [%]</td>
<td>70</td>
<td>60</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Antenna Feed Power [W]</td>
<td>56</td>
<td>45</td>
<td>26</td>
<td>18</td>
</tr>
</tbody>
</table>

### RF-RF Conversion

<table>
<thead>
<tr>
<th>Antenna gain [dB]</th>
<th>20.0</th>
<th>20.0</th>
<th>20.0</th>
<th>20.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance [m]</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Free Space Attenuation</td>
<td>3.56E-05</td>
<td>5.70E-06</td>
<td>1.42E-06</td>
<td>4.40E-07</td>
</tr>
<tr>
<td>Receive Antenna [dB]</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Beam Efficiency [%]</td>
<td>0.36</td>
<td>0.06</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Received RF power [W]</td>
<td>19.95</td>
<td>2.56</td>
<td>0.37</td>
<td>0.08</td>
</tr>
</tbody>
</table>

### RF-DC Conversion

<table>
<thead>
<tr>
<th>RF-DC Efficiency [%]</th>
<th>80</th>
<th>75</th>
<th>70</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC power [W]</td>
<td>15.96</td>
<td>1.92</td>
<td>0.26</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### DC-DC Efficiency

| DC-DC Efficiency [%] | 15.96% | 1.92% | 0.26% | 0.05% |
General Concepts

- Increase efficiency of Power Amplifiers
- Tx Antenna Gain
- Beam Efficiency
- Rx Antenna Gain
- RF-DC converter

\[ \left( \frac{\lambda}{4\pi r} \right)^2 \]
Transmitter

• Size
• Weight

TWTA – Transmitters
Transmitter based on SPC

GaN
Power Availability at Ka band is limited
Signal Transmitter

Pilot Signal Receiver

Wireless Power Transmitter

Node 1
($x_1, y_1, z_1$)

Node N
($x_2, y_2, z_2$)

Pilot Signal Transmitter

Passive WSN

$d_1$

$d_2$

$f_m$

$\phi$

$\Theta$

$\Theta$

RF to DC conversion efficiency (%)

Breakdown voltage effect

Threshold voltage effect

1-diode

2-diode

4-diode

Higher order harmonics and breakdown effect

input power (dBm)

IEEE WMI

International Microwave Symposium
6 - 11 June 2021, Atlanta, GA
Signal Transmitter

0.7 GHz IF
5.1 GHz LO
5.1 to 5.102 GHz LO

DAC
DAC
DAC
DAC

IQ Mod.
IQ Mod.
IQ Mod.
IQ Mod.

IF
RF
IF
LO

1:16 IF divider
1:16 LO divider

AD5384 Dense DAC

uC

Freq to Voltage Converter
Env. Detector

3.6 GHz

Backscatter Transmit/Receive module
Active Antenna Arrays

Possible Arrangements:
- a. 6-7-2-1-3-4-5
- b. 5-1-3-4-8-9-10
- c. 14-15-16-7-2-1-6
- d. 10-4-8-9-11-12-13
Active Antenna Arrays

Diagram showing the architecture of a multi-antenna system with labeled components such as DC-RF Converter, Antenna TX, Air Interface, Antenna RX, and RF-DC Converter. The diagram also highlights elements like Vgs1, Vgs2, Vds1, and Vds2.
Efficient Transmitter and Constant Power Delivery
Experimental Results
RF-RF Conversion

Design of very high beam efficiency antennas

- Optimize antenna size and beam control in order to guarantee an Fresnel zone operation!!
- Design Gaussian Beam Antenna Arrays
- Optimize reflector based antennas
- Improved Antenna Arrays
Antenna for SWIPT Sensors

Main Goals:

- Capable of transmit energy in all directions with significant gain;
- Minimize gain variation over all directions (EIRP stabilization);
Construction of the Dual-Polarized Antenna and Rectifier

Block diagram of the Dual-polarized Rectenna (Antenna + Rectifier)

Circular shape has been chosen:

- Easy fabrication
- Good radiation characteristics

Microstrip Patch Antenna Topologies
Antenna: Simulations and Measurements

ADS (Advanced Design Systems) EM-Circuit Co-Simulation

Substrate characteristics

Circular patch antenna fed with two orthogonal paths

Matching circuit: quarter wavelength line

Substrate characteristics:

- MSub
  - MSLUB
  - MSRef
  - H=0.767nm
  - ε=2.17
  - μ=1
  - Ord=58.66
  - Hf=39±0.014mil
  - T=0.005mm
  - TanD=0.0009
  - Rough=0mil
State-of-the art - RF-DC converters

Less input power -> less efficiency (need to overcome the threshold barrier)
Increase frequency -> less efficiency (due to the increase of parasitic losses at higher frequencies)

Harvesting circuits for UHF RFID applications are mostly based on CMOS technology and operate at lower power levels (typically below 0 dBm).

Circuits for SPS, MPT and WPT-oriented applications, working at microwave range (2.4 GHz, 5.8 GHz and beyond), are based on discrete Schottky diodes, work at significantly higher input power levels and present increased efficiencies.

The efficiency of ambient EM energy harvesting at very low power levels (below -30 dBm) is reduced.
RF-DC Converters

- Rectifier circuits: envelope detector, charge pump circuits
- Schottky diodes, low / zero barrier diodes

Reported efficiencies for available input power levels in the order of 10 uW are between 10% - 20%, and increase to 30%-60% for available power levels of 100uW.
Desired component

\[ y_{out} = NL[x_{in}(f_0)] = Y(\text{DC}) + Y(f_0) + Y(2f_0) + Y(3f_0) + \ldots + Y(nf_0) \]
RF-DC Conversion

Rectifying devices exhibit a NON-ZERO turn-on voltage $\rightarrow$ a certain amount of energy is needed to overcome the turn-on voltage $\rightarrow$ low power level efficiency is degraded.
Waveform design for improved RF-DC conversion efficiency

Rectifying devices exhibit a NON-ZERO turn-on voltage → a certain amount of energy is needed to overcome the turn-on voltage → low power level efficiency is degraded
Waveform design for improved RF-DC conversion efficiency

Waveform design for improved RF-DC conversion efficiency

Circuits tested under CW and several MS signals with the same average power

![2.4 GHz detector diagram](image1)

Output DC Voltage as a function of Pin

![Output DC Voltage as a function of Pin](image2)

866 MHz Charge pump

Output DC Voltage as a function of Pin

![Output DC Voltage as a function of Pin](image3)
Waveform design for improved RF-DC conversion efficiency

- MS signals can improve the performance of RF-DC converter circuits.

- This answers affirmatively to the first question of this thesis!

- These results suggest that this approach can enhance backscatter systems.

SWIPT – Backscatter with WPT

Combining WPT and Backscatter using dual band sensors

ONE frequency for WPT and OTHER for backscatter

SWIPT – Backscatter with WPT

Backscatter Higher Order Modulation

SWIPT – Backscatter with WPT

Backscatter Higher Order Modulation


5.8GHz
120 Mb/s with 6.7pJ/bit
SWIPT – Backscatter with WPT

Backscatter Higher Order Modulation

- 960 Mbps
- 5.8GHz
- 960 Mb/s with 0.9 pJ/bit
- Average Power Consumption
SWIPT – Backscatter with WPT

Ambient Backscatter

SWIPT – Backscatter with WPT

Millimeterwave Backscatter

Design an MMIC chip for higher frequencies based on high order backscatter modulation.

SiGe BICMOS
SG13S
technology
0.92 mm²
Developing a Deep Space Sensor IoT

Low Orbit Satellite

L Band

S Band

Terminal

IoT Sensor

Mars

Ground station