Energy Harvesting for the Internet-of-Things

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• Motivation and Challenges of IoT
• Energy Harvesting
• Wireless Energy Transfer
• Ambient RF Energy Harvesting
• Hybrid Techniques
• Ways Forward
  ▪ Multiple Antennas
  ▪ Low Power Receivers
• Review
• “Things” have data and the “Cloud” wants data

• Connectivity is essential
  infrequent data chunks or packets

• Enhanced services and performance in healthcare, environment, energy, smart city, security…..

• Big Data needs IoT
• Unique in that there is no one uniform application
• Home, city, bridges, car, people, health, environment ocean etc
• Each application needs unique tradeoffs
  ▪ Sensors, Channel models, Communication systems, Energy harvesting, Low power
**IoT Connectivity Challenges**

- **Low power challenges**
  - Support coin batteries and energy harvesting - 1uA

- **Sensors**
  - Improved sensor technology required - size, accuracy and type

- **Inexpensive**
  - There will be billions of these devices

- **Diversity**
  - Different applications require different solutions and tradeoffs

- **Low latency**
  - Low delay in making connections and sending data chunks
  - Data rate not as critical - streaming not usually required

- **Privacy and Policy**
  - Critical policy and social issues to solve
In this talk we wish to focus on energy harvesting.

If there are to be trillions of IoT devices then it will be impossible to use batteries.

IoT devices will require long lifetimes.

Batteries will need replacement every few years.

Replacing trillions of batteries is time consuming and costly.

Environmentally unsustainable.
• Scavenging techniques
  ▪ Solar
  ▪ Wind
  ▪ Thermal
  ▪ Vibration
  ▪ Ambient RF

• Controllable Techniques
  ▪ Wireless Energy Transfer (WET)
  ▪ RFID
    • Limited communication and range
  ▪ Advances in antenna and RF technology allow enhanced approaches
Wireless Energy Harvesting

- **Wireless Energy Transfer (WET)**
  - RF energy source is controlled

- **Ambient RF Energy Harvesting**
  - Scavenge RF energy from existing RF sources

- Significant common elements between both techniques

Wireless Energy Transfer (WET)

- Under development for 50 years
- Advantages
  - Continuous and stable energy
  - Combine with communication
  - Wide operating range - Far-field
    - Inductive and magnetic resonance coupling
  - Low production cost and size
  - Multicasting
- Many system results developed but hardware implementation limited
- Minimum RF signal required for EH is around -40dBm
- Compare this to less than -100dBm for communication

• EH in DL; Communication in DL

• Channel characteristics very important
  ▪ Interference harms only communication
  ▪ As SNR increases logarithmic increase in rate but linear in EH
  ▪ Use communication when SNR poor but EH when SNR good
**DL EH & DL Communication Systems**

- Rate–Energy Tradeoffs for DL Energy and Communication
- Depends on receiver structure

![Diagram showing energy harvesting and rate-energy tradeoffs](image)

- DL only systems may not be the most important for IoT
EH DL Communication UL Results

- EH in DL; Communication in UL

- Essential for IoT

- Two phase harvest then transmit protocol
  - Multicast DL EH
  - Multiple access UL communication
  - Shorter time required for WET when users close
  - Doubly near-far problem for users far away - very low throughputs
  - User cooperation possible but would need DL communication as well
• Ambient RF signals

• Scavenge Ambient RF Energy to power the “Things”

• Harvesting uW is possible

Ambient RF Energy Harvesting

- 270 London underground stations surveyed
- DTV, GSM 900, 1800 and 3G (1900GHz)
- BS more important ambient sources than MS
- Efficiency and impedance varies with EH power
- 50% of stations suitable for ambient EH
- GSM 900 and 1800 most useful
- 40% efficiency at -25dBm
- Competitive compared to thermal and vibration EH in terms of power per volume of hardware

Hybrid WET and Ambient RF EH

- WET and Ambient RF EH are independent approaches and can be combined together

- Filters necessary in non-hybrid form too in order to support communication
Hybrid WET and Ambient RF EH

- If no communication in DL then receiver structure can be very straightforward- both WET and ambient RF can be harvested together

- Power splitting or power switching are also possible options if DL communication required
Ways Forward

• More Effective Energy Harvesting
  ▪ Use multiple antennas
  ▪ Baseband energy combining

• Low Power receivers
  ▪ Non-coherent Energy Detectors
  ▪ Baseband energy detection combining


• Canonical 40 port planar design

• Antenna densities of 22 antennas per square wavelength

• Greater than 10dB isolation between ports

Antenna Directivity

- In order to collect all the power beamed to it the antenna must be very directive
- For example an array of antennas
- However this is not true for rectennas
- In an array of rectennas the outputs are all combined at baseband so there is no phasing
- Therefore we can get high gain over a broad angle
- Critical for use in many applications
Multi-antenna Energy Harvesting

- Multi-antenna combining

Matching needed to achieve maximum power transfer from multiple antennas into the energy harvesting and receiver circuits

- MCM ($2N^2 + N$)
- Low bandwidth
- High Complexity
- Maximum harvest

- SPM (2N)
- Widely used
- Low complexity
- Good Bandwidth
- Reduced harvest
• $Z_A$: the antenna impedance matrix

• $Z_L$: the load impedance matrix

• $Z_m$: the impedance matrix of the lossless matching network

• $Z_0$: the standard load impedances
• N-element antenna in random RF Field $\overline{E_{inc}}(\Omega, f)$

• $\overline{E_{inc}}(\Omega, f)$ is assumed to be a zero-mean complex Gaussian stochastic process with angular correlation given by

$$E[\overline{E_{inc}}(\Omega, f)\overline{E_{inc}}(\Omega', f)^H] = \overline{S}(\Omega, f)\delta(\Omega - \Omega')$$

$$\overline{S}(\Omega, f) = E[\overline{E_{inc}}(\Omega, f)\overline{E_{inc}}(\Omega, f)^H]$$ is the power angular spectrum (PAS)
Impedance Matching Contributions

- Illustrative 4-port network examples

- MCM \((2N^2 + N)\)
- Simplify to SOM
- SOM \((N^2 + 2N)\)

- New technique
- MLM \((3N)\)
- Solutions

To provide a platform for the comparison of multiple antennas and impedance matching, we select the linear $N$-element antenna array with length $L$ and consider two array configurations.

1) The first is the uniform linear antenna array with adjacent spacings all equal so that $d_{ij} = L/(N - 1)$;

2) The second is the linear antenna array with geometric ratio spacing so that adjacent antenna spacing satisfy $d_{i,i+1} = q d_{i-1,i}$

For fixed length $L$, the larger $N$ may not guarantee increase in total power due to mutual coupling and spatial correlation.
Numerical Experiment Settings

- Total length of linear array: one wavelength $\lambda$
- Ideal half-wavelength dipole array: closed form for mutual impedance
- 2D uniform power angular spectrum: the open-circuit voltage correlation can be found by Jakes Model
- Assuming equal expected power:

$$E[|v_{oc1}|^2] = E[|v_{oc2}|^2] = \cdots = E[|v_{ocN}|^2]$$

- Power Normalization: normalize the total expected received power by the expected power received by a single antenna in isolation with self-conjugate matched load.

$$\tilde{P} = \frac{4R_1E[P]}{E[|v_{oc1}|^2]}$$
• $Z_A$ : the antenna impedance matrix
• $Z_L$ : the load impedance matrix
• $Z_m$ : the impedance matrix of the lossless matching network
• $Z_0$ : the standard load impedances
• SOM has the optimal performance and MLM is next best with sub-optimal performance
• When the number of antennas becomes larger, the performance gap between MLM and SPM becomes larger.
• Non-uniform SPM is slightly better than uniform SPM when the number of antennas is larger.
Numerical Result

- The number of LC components is

<table>
<thead>
<tr>
<th>No. of Antenna</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Port in Matching Network</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
<td>20</td>
<td>2N</td>
</tr>
<tr>
<td>No. of Component for General Matching Network</td>
<td>10</td>
<td>21</td>
<td>36</td>
<td>55</td>
<td>78</td>
<td>105</td>
<td>136</td>
<td>171</td>
<td>210</td>
<td>N (2N + 1)</td>
</tr>
<tr>
<td>No. of Component in Matching Network for SOM</td>
<td>8</td>
<td>15</td>
<td>24</td>
<td>34</td>
<td>43</td>
<td>56</td>
<td>69</td>
<td>79</td>
<td>91</td>
<td>less than or equal to N (N + 2)</td>
</tr>
<tr>
<td>No. of Component in Matching Network for MLM</td>
<td>5</td>
<td>8</td>
<td>11</td>
<td>14</td>
<td>17</td>
<td>20</td>
<td>23</td>
<td>26</td>
<td>29</td>
<td>3N – 1</td>
</tr>
<tr>
<td>No. of Component in Matching Network for SPM</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
<td>20</td>
<td>2N</td>
</tr>
</tbody>
</table>

- Compared to the number of components for general matching, SOM has less than half the components for large N.
- The matching network for MLM has only a few more components than for SPM, but its power performance is better than SPM.
• Previous work suggests the bandwidth performance of MCM is narrow and SPM is large.
• We also investigate the bandwidth performance of SOM and MLM to compare with SPM.
• In the formulation of expected received power, there are three frequency-dependent terms: \( Z_L(f) \), \( Z_A(f) \) and \( C(f) \)

\[
E[P] = Tr(R_L(Z_L + Z_A)^{-1}C(Z_L + Z_A)^{-H})
\]

• We use lumped LC element to build the matching network so \( Z_L(f) \) can be found and the \( Z_A(f) \) can be found by HFSS.
We simulate the harvesting of energy from a WiFi signal with frequency band from 2.4GHz to 2.5GHz for a 6 element dipole array (antennas uniformly placed in one-wavelength).

At the central frequency, SOM has the maximum normalized expected power at 4.636 and those of MLM and non-uniform SPM are 4.123 and 3.166 respectively, amounting to 88.9% and 68.3% of that of SOM.
The average normalized expected power $P_a(\Delta f)$ over the bandwidth $\Delta f$.

For a WiFi frequency band (2.4GHz-2.5GHz), the average power harvested by SOM, MLM and non-uniform SPM is 4.161, 3.866 and 3.156 respectively. This amounts to 92% and 75% for MLM and SPM compared to SOM.

Build MLM impedance for WET but it will perform as good as SPM at all f
• MLM can increase the Ergodic capacity by around 8% compared to SPM over the whole band for different SNR.

• MCM is optimal around 2.45GHz but when the frequency deviates from 2.45GHz MLM can increase the ergodic capacity by up to 5.3% compared with MCM.

• In conclusion, MLM is better than SPM for both narrow and broad bands and better than MCM for broad bands.
Low Power Receiver

• Non-Coherent Energy Detector Receiver
  – Simplified synchronization
  – Simple front end
  – Good rate-energy tradeoff
  – Can use previous ladder matching network
  – High gain broad-beam

• The received energy of each branch is summed to form $r^H r$
• Given the receiver structure is fixed what can we optimize?
• We can optimize the transmit power levels to minimize BER?
• Since we do not know the channel at the receiver side (non-coherent) the optimum ASK signal levels are no longer uniformly distributed for Rayleigh Fading channels
• Turns out they are optimum if distributed in geometric progression with common ratio...
• Assuming N receive branches the received signal can be written as
  \[ r = h s + n \]
  where \( h \) is \( N \times 1 \) random complex fading gain and \( n \) the AWGN vector
• Assume \( s \) is from the constellation
  \[ S = \left\{ \sqrt{E_{s_1}}, \ldots, \sqrt{E_{s_L}} \right\} \]
• Average energy is
  \[ E_{s,av} = \frac{1}{L} \sum_{i=1}^{L} E_{s_i} \]
The channel is Rayleigh fading so \( h \) is complex Gaussian independent of the AWGN noise.

Average SNR per branch of the \( i \)th signal is therefore

\[
\Gamma_i = \frac{E_{s_i} \sigma_h^2}{\sigma_n^2}, \quad i = 1, \ldots, L,
\]

\[
\Gamma_{av} = \frac{E_{s,av} \sigma_h^2}{\sigma_n^2} = \frac{1}{L} \sum_{i=1}^{L} \Gamma_i
\]
System Model

- Overall decision statistic is also zero-mean Gaussian
  \[ r^\top \sim \mathcal{C}\mathcal{N}\left(0_N, \left(|s|^2 \sigma_h^2 + \sigma_n^2\right) I_N\right) \]

- Because we have no channel information the phase of the signal is completely lost in the transmission process

- The magnitude of the received signal is also scaled randomly by a Rayleigh distribution
System Model

• The decision rule is

\[ \hat{s} = \arg \max_{s \in S} \ln \{ f(r|s) \} \]

\[ \hat{s} = \arg \min_{s \in S} \frac{1}{(|s|^2\sigma_h^2 + \sigma_n^2)} r^H r \]

\[ + N \ln \left( |s|^2\sigma_h^2 + \sigma_n^2 \right) \]

• The \( r^H r \) is the key term and in essence represents the energy of the received signal
• The received energy of each branch is summed to form $r^H r$
We can find an analytical expression for $P_e$ when $L=4$ and varying numbers of branches $N$.

- Uniformly spaced symbols
- Saturation at high SNR caused by random magnitude scaling of channel
• Can we overcome the saturation effect by using transmit symbol levels different from uniform?
• Formulate as an optimization problem with constraints on total average power as follows:

\[
\begin{align*}
\text{min} \quad & P_e \\
E_{s_1}, \ldots, E_{s_L} \\
\sum_{i=1}^{L} E_{s_i} &= E_{s, \text{tot}} \\
0 &\leq E_{s_1} < \ldots < E_{s_L}
\end{align*}
\]
Can solve approximately for high average SNR per branch

\[
\sqrt{E_{s_1,\text{asymp}}} = 0, \\
\sqrt{E_{s_i,\text{asymp}}} = \frac{\sigma_n}{\sigma_h} \sqrt{L(i-1)/(L-1) \Gamma_{av}^{(i-1)/(L-1)}} \\
i = 2, \ldots, L,
\]

Implies signal levels follow geometric progression with a common ratio of

\[
\frac{\sigma_n}{\sigma_h} \sqrt{L^{1/(L-1)} \Gamma_{av}^{1/(L-1)}}
\]
We can also determine the diversity easily:

\[ P_e \approx \frac{(L - 1) \left( \frac{N}{L-1} \left( \ln \Gamma_{av} + \ln L \right) \right)^{N-1}}{(N - 1)! L^{1+N/(L-1)} \Gamma_{av}^{N/(L-1)}} \]

\[ - \ln P_e \left|_{\Gamma_{av} \gg 1} \right. \approx \frac{N}{(L - 1)} - (N - 1) \frac{\ln \left( \ln \Gamma_{av} \right)}{\ln \Gamma_{av}} \]

\[ \approx \frac{N}{(L - 1)} \]
Numerical Results

• Baseline comparison is to uniformly spaced ASK

\[
\Gamma_i = \frac{(i - 1)^2 \delta^2 \sigma_h^2}{\sigma_n^2}, \quad i = 1, \ldots, L,
\]

• Relating to average SNR we can find the spacing as

\[
\delta = \frac{\sigma_n}{\sigma_h} \sqrt{\frac{6\Gamma_{av}}{(L - 1)(2L - 1)}}.
\]
Numerical Results

• $L=4$ and varying numbers of branches $N$
Numerical Results

- $L=8$ and varying numbers of branches $N$
Numerical Results

- \( L=4 \) and comparisons with geometric progression approximation
What’s next: Implementation?

- Many results but not many implementations
Summary

- Energy Harvesting is very important in IoT devices
- Provides devices with long life
- Ambient RF EH competitive with other scavenging techniques in terms of power and volume
- WET could be used together with ambient RF EH
- Multiple antennas give useful energy gains
- Noncoherent receivers can be low power and useful
- Need further developments
  - Results required for hybrid systems
  - Exploit multiple antennas at AP
  - UL communication critical for IoT
  - Low power transmitters and receivers
  - Hardware implementations