ICT powered by Energy Harvesting
Research, Trends and Challenges

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General Trends in Powering ICT

• Last century / pre-2000
  – wired & wireless networks with reliable/fault-tolerant power sources
  – wireless networks with portable power sources, e.g. WiFi

• This century / 2000 onwards
  – Low-power device communications
  – Wireless sensor networks
  – Environmentally-friendly “Green” ICT
Mobile Wireless ICT – Limitations

• Battery lifetime
• Wireless NIC is one of the largest energy consumers on a mobile device
• Many wireless communications protocols are not energy-conscious until recently
• Untethered by network, tethered by power supply!
Research Trends – Green MW-ICT

• 2/3 of total energy is consumed in access networks

• Research focuses on:
  – Scheduling to minimize number of sites (base stations) & optimize BS usage
  – Reducing (base) station emissions, e.g. no beaconing
  – Energy efficient coding schemes that carry more information, e.g. network coding
  – More reliance on renewable energy sources
Research Ideas for Green ICT + EH

• Small BSes, each equipped with rechargeable batteries which are recharged by harvesting energy from wind, solar, vibration, etc.

• Daytime – harvest & store enough energy for high user traffic

• Nighttime – draw on energy stored in batteries and function at reduced capacity since user traffic is lower
Research Trends – WSN

Wireless Sensor Networks (WSN)

• Distributed sensors to monitor the environment
  – Replacement of sensor nodes is sometimes impractical or impossible
• Existing research has focused on battery-powered WSNs
• Sustainability of WSN depends on sensor nodes’ lifetime
  – Sensor nodes fail due to battery depletion
• Alternative source of energy needed
Research Trends – Energy Harvesting

• Power remains the key WSN issue
• Energy Harvesting
  – Gather energy that is present in the environment, i.e. ambient energy like solar, wind, vibration, heat, and even radio waves
  – Convert the energy into a form that can be used to power devices

• Energy harvesting vs scavenging
  → Harvesting : regular source, well characterized, and predictable
  → Scavenging : unknown source, highly irregular
Research Trends – WSN-HEAP

• Acronym for **Wireless Sensor Networks Powered by Ambient Energy Harvesting**
  
• Used for denoting WSNs that are solely powered by energy harvesting devices using capacitors/supercapacitors
  
  – Excludes WSNs that use energy harvesters to supplement battery power
  
  – Eliminate the reliance on batteries

• [http://www.energyharvesting.net/](http://www.energyharvesting.net/)
Energy Model of WSN-HEAP node

- Different energy harvesting (charging) rate across time and physical domains
- Average energy charging rate is lower than the rate of energy consumption
- Short duty cycle
# WSN-HEAP vs Battery-powered

<table>
<thead>
<tr>
<th></th>
<th>Battery-operated WSNs</th>
<th>Battery-operated WSNs with energy harvesters</th>
<th>WSN-HEAP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goal</strong></td>
<td>Latency and throughput is usually traded off for longer network lifetime</td>
<td>Longer lifetime is achieved since battery power is supplemented by harvested energy</td>
<td>• Maximize throughput and minimize delay since energy is renewable &amp; the concept of lifetime does not apply</td>
</tr>
<tr>
<td><strong>Protocol Design</strong></td>
<td>Sleep-and-wakeup schedules can be determined precisely</td>
<td>Sleep-and-wakeup schedules can be determined if predictions about future energy availability are correct</td>
<td>• Sleep-and-wakeup schedules cannot be predicted; • Difficult to know exactly which is the awake next-hop neighbor to forward data to</td>
</tr>
<tr>
<td><strong>Energy Model</strong></td>
<td>Energy model is well understood</td>
<td>Energy model can be predicted to high accuracy</td>
<td>• Energy harvesting rate varies across time, space as well as the type of energy harvesters used</td>
</tr>
</tbody>
</table>
Ongoing Research on WSN-HEAP

MAC protocol design
- Maximize throughput given the energy harvesting rates and deployment of WSN-HEAP nodes
- Validate using analysis, simulations, and prototyping & experimentation

Topology & Routing
- Optimal node placement schemes under various energy harvesting scenarios
- Routing algorithm to maximize goodput and reliability

Energy Harvesting Rate Characterization
Energy Harvesting Rate Characterization
Empirical study of Energy Harvesting

• pdf of the charging times for 1000 charge cycles

Empirical study of Energy Harvesting

- Empirical energy characterization of a time-slotted solar EH node

- Used 6 different statistical models to fit the empirical datasets for the number of inactive slots between consecutive active slots

Empirical study of Energy Harvesting

• Results:
  – Transformed Poisson dist. → 3 datasets
  – 2-state Markovian model → 1 dataset
  – Uniform distribution → 2 datasets
  – Geometric distribution
  – Transformed geometric distribution
  – Poisson distribution

• Is there a better model for EH that accounts for all the different factors?

Empirical study of Energy Harvesting

- Solar and Piezoelectric EH

Empirical study of Energy Harvesting

• Markovian models for EH
  – Stationary Markovian model (SM)
  – Generalized Markovian (GM) model, conditioned on scenario parameter, $S_k$, over discrete time $k$

\[ E_1 \rightarrow E_2 \rightarrow \cdots \quad \text{(a) SM model.} \]
\[ S_1 \rightarrow S_2 \rightarrow \cdots \]
\[ E_1 \rightarrow E_2 \rightarrow \cdots \quad \text{(b) GM model.} \]

• Solar – 1\textsuperscript{st} order SM;
• Piezoelectric – GM
Topology Management & Routing
Transmission Power Control

- Forms key aspect of power management in battery-based WSNs to maximize the network lifetime for a given offered load
- In WSN-HEAP, it has been used to maximize throughput, reliability and fairness
- Varying transmission power changes the network topology
Power Control in WSN-HEAP

- Linear (1D) network (monitoring railway tracks) using piezoelectric devices that harvest energy from track deflections with mean rate of 1.5mW
- Analytical study assuming all nodes send directly to any of the sinks without packet relaying

Power Control in WSN-HEAP

Network performance for network with different number of sensors between sinks, $k = 5$ (top) and 10 (bottom)

Power Control in WSN-HEAP

- Grid (2D) network for road monitoring
- Power allocation schemes to maximize throughput, reliability and fairness:
  - Fixed Transmit Power
  - Minimum-Interference Allocation (send only to the nearest sink)
  - Multi-Sink Allocation (send to $j$ of its nearest sinks, $j > 2$)

Power Control in WSN-HEAP

Throughput
- Each scheme has optimal at different node densities, viz. $n=4$ (MS), 5 (MI) and 6 (FP)

Data Delivery Ratio (DDR)
- For all schemes, DDR drops as node density increases due to contention

Fairness
- MI consistently good; fairness of FP and MS drop as node density increases due to near-far problem.
EH Opportunistic Routing

OR Pros and Cons

✔ Unpredictable node operation state and OR schemes give nodes closer to the destination higher relay priority

✘ OR does not account for amount of energy left in the WSN–HEAP node

✘ Nodes are not always on and need to be grouped and prioritized

EH Opportunistic Routing

Goal: Maximize goodput, data delivery ratio, efficiency and fairness.

Divide nodes into forwarding regions; region ID $j$ is computed as follows:

$$j = \begin{cases} 
1, & d_{sender} > d; \\
1 + \left[ \frac{d - d_{sender}}{d} \right] * (k - 1), & d_{sender} \leq d,
\end{cases}$$

where $d_{sender}$ is the distance from the sender to the node, and $d$ is the transmission range.
EH Opportunistic Routing

- Number of regions, $k$

\[
k = f(\text{energy harvesting rate, } \# \text{ neighbors})
= \left\lfloor n_1 p \right\rfloor + 1
\]

where

- $n_1$ – number of nodes within transmission range
- $p$ – probability that a node can (is awake) receive a packet from the sender; depends on energy harvesting rate
- $1$ – region #1 contains all nodes outside the transmission range that may still be able to receive a packet
EH Opportunistic Routing

- Scheduling of transmission – if node is in region $j$, it listens for $j-1$ slots and transmits if no transmission heard.

To illustrate EHOR, let us consider a scenario where a node receives a data packet from a sender at the time illustrated in Fig. 17. In this scenario, the node can only wait for 3 time slots before it has to transmit a data packet or shut down to recharge. If it is in region $R_4$, it has to drop the data packet since it has insufficient energy to wait for the 4th time slot to transmit. If it is in $R_1$, it will transmit the data packet immediately upon receiving the data packet. If it is in $R_3$, it will wait for 2 time slots in order to overhear whether other nodes in $R_1$ and $R_2$ have relayed the data packet. If it overhears that the data packet has already made progress towards the sink, the node will not relay the data packet.

![Diagram]

In EHOR, each node may receive more than one data packet in the receive state but each node can only transmit one data packet in each charging cycle. Although some received packets are being dropped if they cannot be transmitted, nodes in other regions will retransmit the data packet so the impact on data delivery ratio is not adversely affected.

4.4 Energy Considerations in EHOR

By applying regioning, nodes further away from the sender are favored without taking into consideration the energy left in a WSN-HEAP node. This results in suboptimal performance because a node that is scheduled to transmit in a particular slot may be unable to transmit although it has received the data packet. For example, in the scenario as shown in Fig. 16, node $s$ in $R_1$ has...

EH Opportunistic Routing

Observations

- R1 – lowest chance to receiving packet, but highest priority to transmit
- R5 – highest chance of receiving packet but lowest chance of sending it
- Need to also account for energy availability

Redefine transmission slot selection for node:

\[ j = \lceil \beta \times j_d + (1 - \beta) \times j_e \rceil \]

- \( j_d \) – slot selected based on distance criteria
- \( j_e \) – slot selected based on energy criteria
- \( \beta \) – weight factor, \( 0 < \beta < 1 \); depends on EH profile
MAC Protocol Design
MAC Design

• Goal of MAC – control access to the medium with the aim of resolving contention and reducing collisions

• Typical methods include delays, backoffs and retransmissions

• Study generic MAC protocols, like CSMA, slotted CSMA, ID polling, and Probabilistic Polling, to determine if they are suitable for WSN-HEAP
MAC Design – Probabilistic Polling

Sink
1: Send polling packet with contention probability, $p_c$
2: if no sensor responds, then
3: increase $p_c$
4: else if data packet successfully received from one of the sensor nodes OR packet loss due to weak signal strength then
5: maintain $p_c$ at current value
6: else if corrupted packet indicating collision between 2 or more nodes then
7: decrease $p_c$
8: end if
9: Repeat step 1.

Sensor
1: Generate send probability, $p_{send}$
2: Wait for polling packet
3: if $p_{send} < p_c$ then
4: transmit data packet
5: end if
6: Sleep & harvest energy

Sink adjusts $p_c$ according to network conditions
MAC Design – Probabilistic Polling

Comparison of different contention probability ($p_c$) adjustment schemes

MAC Design – Probabilistic Polling

Performance metrics for varying number of WSN-HEAP nodes ($n$) for different MAC schemes ($\lambda = 2$ mW)

MAC Design – Probabilistic Polling

Performance metrics for varying energy harvesting rates for different MAC schemes with 100 nodes (n = 100)

MAC Design – Multi-Tier Prob Polling

MAC Design – Multi-Tier Prob Polling

Simple Cascaded

- Intermediate node listens for polling packet, re-broadcasts it, then listens for data and relays it
- Scalability issue with more tiers
- Intermediate node may not have enough energy to relay data

MAC Design – Multi-Tier Prob Polling

Tier-Independent Polling

- Polling packet gives right to send (data or polling) packet
- If data is available, send data; OR send polling packet
- One transmission per duty cycle
MAC Design – Multi-Tier Prob Polling

Integrated packet
- Exploit broadcast feature of wireless media
- Combine data and polling in 1 packet
  - Decreases energy consumption
  - Increases frequency of data arrival at Access Point
MAC Design – Multi-Tier Prob Polling

Validation process

• 10 – 20 nodes
• Experiments run for 12 hours
  – Functional tests of multihop data delivery
  – Recovery of sensor nodes after night time
  – Duty cycle of sensor nodes under minimum light source
• Light intensity > 200lux
MAC Design – Multi-Tier Prob Polling

Experimental Validation

Sniffed data

16:39:04.750 tier probability
ff ff ff ff 36 94 04 6c 3f 24 6a 00 fc
16:42:09.890
tier hopCount
ff ff ff ff 5e 27 d4 44 3f 24 98 01 fc
16:42:09.947
ff ff ff ff 74 d9 9b c3 3f a3 d5 02 01 00 0a 00
16:42:31.703
ff ff ff ff 74 d9 9b c3 3f a3 d5 02 01 00 0a 00
16:42:31.721
ff ff ff ff 5e 27 d4 44 3f 63 35 01 02 04 cc 02
01 00 0a

MAC Design – Multi-Tier Prob Polling

Challenges

• Under min energy source – 200lux
  – Active : 1.3 secs
  – Harvesting : 23.2 secs
  – Duty Cycle : 0.056

• Synchronisation of sensor nodes in low power devices is difficult due to clock drift

MAC Design – Multi-Tier Prob Polling

Outcome of Experimental Validation

– Successful two tier transmission
– Sensor nodes can survive under conditions with no source of light and recover with the availability of light

Future Work

– Performance evaluation of MTPP using mathematical analysis and simulations
– Probability control at individual sensors
– Extend the energy source
## MAC Design – Current Status

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Validation</th>
<th>Scalability</th>
<th>Fairness</th>
<th>Which EH Technology?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probabilistic Polling</td>
<td>QualNet simulator</td>
<td>One-hop</td>
<td>Availability dependent</td>
<td>any</td>
</tr>
<tr>
<td>ID Polling</td>
<td>QualNet simulator</td>
<td>One-hop</td>
<td>Unfair for inactive nodes</td>
<td>any</td>
</tr>
<tr>
<td>EA-MAC</td>
<td>OPNET simulator</td>
<td>One-hop</td>
<td>Distance dependent</td>
<td>RF</td>
</tr>
<tr>
<td>ODMAC</td>
<td>OPNET simulator</td>
<td>Multi-hop</td>
<td>Duty cycle dependent</td>
<td>any</td>
</tr>
<tr>
<td>Wireless Energy Transfer</td>
<td>ns-2 simulator</td>
<td>Multi-hop</td>
<td>Charging rate dependent</td>
<td>RF</td>
</tr>
<tr>
<td>Dynamic Frame ALOHA</td>
<td>Analytical</td>
<td>Multi-hop</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Multi-Tier Probabilistic Polling</td>
<td><strong>Prototype Experiment</strong></td>
<td>Multi-hop</td>
<td>Availability dependent</td>
<td>any</td>
</tr>
</tbody>
</table>
Applications
Wireless Monitoring of Rail Systems

- Railway track and bridge monitoring
  - Remote (wireless) rail temperature preventive maintenance system in UK’s high speed rail network since 2005
  - Next-generation wireless mesh for predictive maintenance demonstrated for Network Rail (UK) in 2007

- Battery-powered
  - Needs humans to replace battery
  - Poses safety issues and may disrupt rail operations
Self-Powered, Rail-track Monitoring

Benefits of wireless
- Mature and prevalent technology, e.g. GPRS, WiFi, 802.15.4, etc.
- Higher availability & wider coverage
- Online monitoring & remote control
- Reduced costs and wastage

Benefits of self-powering
- Sustainable, economical, environmentally friendly, improved safety

Self-Powered (vibration, solar), Wireless Monitoring Instrument on sleepers on viaduct and at-grade stations

Wind energy from passing trains in tunnels

Vibrational energy from track deflections

Solar energy for outdoor tracks
Self-Powered Building Monitoring

- Self-sustainable Event Reporting

- Only send data when certain events happen, e.g. an earthquake
  - Engineers need to assess structural integrity of buildings after earthquake
  - Power lines may break and batteries need to be replaced regularly → sensors fail at the most needed moment!
Self-Powered Building Monitoring

- Harvest energy from the event to power the sensors
- Vibration energy harvesters must be tuned to the resonance frequency
- Greater vibration $\rightarrow$ more energy $\rightarrow$ take more readings, collect more data and send more packets
- No vibration $\rightarrow$ no power!
  Also, no need to take readings.
Self-Powered Building Monitoring

Not so simple!!!

- All sensors activate at the same time and try to transmit → contention!
- Backoff and try later
  - Waiting also consumes energy
  - May not have enough energy left after backoff!
- Retransmit if collision occurs
  - May not have enough energy to send more than a few packets!
Some concluding remarks

- Energy harvesting has good potential to power many emerging ICT applications, especially wireless sensor networks.
- *Energy neutrality* condition does not always hold in real scenarios.
- Energy sources need to be further studied and modeled.
- New communications and networking schemes are needed → these are likely to be opportunistic in nature.
Open Research Problems

- Correlation in natural phenomena
- Energy sources need to be further studied and modeled
- Bio-inspired and learning approaches
- Context Aware Middleware
- New communications and networking schemes are needed
  - Likely to be opportunistic in nature
  - How to connect to the Internet?
For more information

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