Power Management in Energy Harvesting Sensor Networks

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Outline

• Goals
• Harvesting theory
• Design implication
• Power management algorithm
• Harvesting network
Battery-based & Harvesting-based

• Battery-based tasks:
  – Minimize power consumption
  – Maximize lifetime

• Harvesting-based considerations:
  – Energy-neutral operation (forever).
  – Maximize performance.
Harvesting System

Fig. 1. Harvesting energy from the environment.
Energy sources Classification

• 1. Uncontrollable, predictable:
  • Solar energy (model & predict)

• 2. Uncontrollable, unpredictable
  • Indoor vibration

• 3. Fully controllable
  • Self-power flashlights

• 4. Partially controllable
  • RF energy (source & propagation)
Conditions for ENO

- Nonideal energy buffer situation:

\[
B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{\text{leak}}(t) dt \geq 0
\quad \forall T \in [0, \infty) \tag{3}
\]

\[
B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{\text{leak}}(t) dt \leq B
\quad \forall T \in [0, \infty) \tag{4}
\]
Model Parameter & Definition

• Parameter:
  • Average rate of harvesting and consumption
  • Boundary energy output

• Definition: \((\rho, \sigma_1, \sigma_2)\) Function

\[
\begin{align*}
\int_{\tau}^{\tau+T} P(t) dt & \leq \rho T + \sigma_1 \\
\int_{\tau}^{\tau+T} P(t) dt & \geq \rho T - \sigma_2
\end{align*}
\]
Derivation

• Transform condition (3)(4)

\[
B_0 + \eta \cdot \min \left\{ \int_T P_s(t) dt \right\} - \max \left\{ \int_T P_c(t) dt \right\} - \int_T P_{\text{leak}}(t) dt \geq 0 \tag{7}
\]

\[
B_0 + \eta \cdot \max \left\{ \int_T P_s(t) dt \right\} - \min \left\{ \int_T P_c(t) dt \right\} - \int_T P_{\text{leak}}(t) dt \leq B \tag{11}
\]

• Substitute average rate, boundary output and \((\rho, \sigma_1, \sigma_2)\) Function into

\[
B_0 + \eta(\rho_1 T - \sigma_2) - (\rho_2 T + \sigma_3) - \rho_{\text{leak}} T \geq 0 \tag{8}
\]

\[
B_0 + \eta(\rho_1 T + \sigma_1) - (\rho_2 T - \sigma_4) - \rho_{\text{leak}} T \leq B \tag{12}
\]

• Ensure the energy neutrality and battery limit.
Derivation continues

\[ B_0 + \eta(\rho_1 T - \sigma_2) - (\rho_2 T + \sigma_3) - \rho_{\text{leak}} T \geq 0 \quad (8) \]

- If substitute \( T=0 \) in (8)
- \[ B_0 \geq \eta \sigma_2 + \sigma_3 \] -- Battery I.C. to tolerate bursts

- If take limit \( T \to \infty \)
- \[ \eta \rho_1 - \rho_{\text{leak}} \geq \rho_2 \] --long-term behavior of harvesting

- Do the same things to (12)
- We have the relationship among energy harvesting, consumption and battery.
ENO Theorem

- Energy production: \((\rho_1, \sigma_1, \sigma_2)\) Function
- Load: \((\rho_2, \sigma_3)\) Function

\[
\begin{align*}
\rho_2 &\leq \eta \rho_1 - \rho_{\text{leak}} \\
B_0 &\geq \eta \sigma_2 + \sigma_3 \\
B &\geq B_0
\end{align*}
\]

- \(\eta\) for storage efficiency
- \(\rho_{\text{leak}}\) for leakage
- \(B\) for capacity of battery
- \(B_0\) for initial energy stored
Design implication

• 1. Buffer Size -- the larger the better?
  – Theoretically, larger battery no help for performance.
  – Practical system considerations:
    • Error in learning parameters
    • Storage capacity degrades

• NiMH battery is best choice.
• 2. Achievable performance level
  – Scale down performance:
    • Duty-cycling
    • DVS (dynamic voltage scaling)

• The lower the duty-cycle, the more efficient the harvesting can achieve.

Fig. 3. Increase in battery size if no harvesting used.
• 3. Measurement Support
  – Any power management needs info on energy.
  – Battery-operated devices (cellphone, laptop):
    • Only monitor the residual battery
  – Harvesting-aware devices:
    • Residual battery – not sufficient
    • Energy input from environment
  – What we need to measure:
    • 1. amount of environmental energy extracted
    • 2. variability in the energy supply (used for $\sigma_1, \sigma_2$)
    • 3. know when energy is directly available
      – Avoid energy loss from battery inefficiency
      – Run delay tolerant tasks when supply directly available.
Methods to measure

\[ E_e = \left[ E_b(t_2) - E_b(t_1) + \int_{t_1}^{t_2} P_c(t) \right]^+ \]

• Some problems:
  – 1. Voltage not sensitive to small change (slow)
  – 2. \( t_1, t_2 \) far apart (bad on time)
  – 3. Know \( P_c(t) \) not easy (multi-components & apps)
“Better” Method

• Measure I and V of the harvesting source
  – at any time
  – when available directly
  – At any resolution

– Heliomote  -->

– Price:
  • Additional hardware
Power-Management Algorithms

• For uncontrollable but predictable source

• High-level steps:
  – 1. learn the parameters for using Theorem
  – 2. adapt performance level
  – 3. minimize battery inefficiency and leakage
Performance scaling algorithm

• Use duty-cycling for performance scaling
• Goal: choose duty cycle -> highest $p_2$ for ENO (Best performance & response time)
• Time axis divided into $N_w$ slots
• Calculate energy used from battery in slot i

\[
B(i) - B(i+1) = \Delta TD(i)[P_c - P_s(i)]^+ - \eta \Delta TP_s(i)\{1 - D(i)\}
- \eta \Delta TD(i)[P_s(i) - P_c]^+
\]

Fig. 6. Energy calculation for direct use and with storage.
Optimization Problem

\[
\max \sum_{i=1}^{N_w} D(i) \tag{28}
\]

\[
B(i) - B(i + 1) = \Delta T D(i)[P_c - P_s(i)]^+ - \eta \Delta T P_s(i)[1 - D(i)] - \eta \Delta T D(i)[P_s(i) - P_c]^+ \quad \forall i \in \{1, \ldots, N_w\} \tag{29}
\]

\[
B(1) = B_0
\]

\[
B(N_w + 1) \geq B_0
\]

\[
D(i) \geq D_{\text{min}} \quad \forall i \in \{1, \ldots, N_w\}
\]

\[
D(i) \leq D_{\text{max}} \quad \forall i \in \{1, \ldots, N_w\} \tag{31}
\]

- ENO + max performance within constraint
Power Management Strategy

• Components:
  – 1. instantiation of energy model
    • Track the past & predict the future
  – 2. compute the optimal duty cycle
    • Use the simplified method
  – 3. dynamically adapt duty cycle in real time
    • Minimize the error from real energy availability
Energy Prediction Model

• Use EWMA filter
• Concept: Historical average for each slot

\[ \bar{x}(i) = \alpha \bar{x}(i - 1) + (1 - \alpha)x(i) \]

• Same weighting factor for all days
• Help to adapt to the seasonal variation
• Check the predicted error in diff $\alpha$

Fig. 7. Choice of parameter $\alpha$ through error evaluation.

• In this case 0.5 is the optimal value
Simplify Optimization Problem

• First, initialize the duty cycle as:

\[
D(i) = \begin{cases} 
D_{\text{min}} & \forall \ i \in \mathcal{D} \\
D_{\text{max}} & \forall \ i \in \mathcal{S}
\end{cases}
\]

• Case 1: (underallocated)
  – Allocate \( D_{\text{max}} \) to smallest dark slots

• Case 2: (overallocated)
  – Calculate energy needed
  \[
  L = \sum_{i \in \mathcal{D}} D(i) \left[ \frac{P_c}{\eta} + P_s(i) \left( 1 - \frac{1}{\eta} \right) \right] + \sum_{i \in \mathcal{S}} P_c D(i) < \sum_{i=1}^{N_w} P_s(i)
  \]
  – Reduce duty cycle in sun slot by:
  \[
  \delta = \frac{L}{|S|P_c}
  \]

Same accuracy with general LP problem.
Dynamic Duty Cycle Adaptation

• Target on reduce the effect of clouds or sudden changes
• Basic idea:
  – 1. calculate the excess energy in a slot, denoted by $X$
  – 2. decide future duty cycle should be reduced or increased based on $X$
    case 1: $X<0$, reduce duty cycles in future slots to make up the shortfall
    case 2: $X>0$, increase duty cycles in future to use the excess energy
  This calculation should be performed at the end of every slot.

• Learning error : environment completely diff from its history
  – Larger battery – safeguard

• !: good prediction model > good dynamic adaptation
  – Energy waste could not be eliminated completely
Evaluation of Power management

Fig. 8. Harvested energy measured over several days using Heliomote energy-harvesting sensor node.

Fig. 9. Harvested energy profile on a diurnal scale.
Evaluation of Power management

• First, evaluate the prediction model:

![Graph showing prediction error over time](image)

**Fig. 10. Error performance of the EWMA based prediction method.**

• Max error: 20mw - tolerable for 150mw
Evaluation of Power management

- Duty cycling algorithm evaluation
- Compare with optimal and naïve

Result:
1. close to optimal
2. important to manage for higher duty cycle

Fig. 11. Performance comparison with varying battery efficiency.
Harvesting Networks

• Facts of distributed harvesting networks:
  – The energy availabilities at diff locations are not same
  – Energy distribution in space & time affects network performance significantly
  – Performance of network can be maximized if load distribution is consistent with energy distribution.
  – Performance & flexibility in load allocation are strongly tied to the applications.

• Discuss tow extreme applications
  – Field monitoring & Point event reporting
Field Monitoring

• Task:
  – Monitor distributed field phenomenon
  – Periodic sampling
  – Collect data to base station

• Interest metric: maximum rate

• Method: monitor each data flows in network

• Use the LP optimization to solve the \( R_g \)
• Environment:

Fig. 12. Spatiotemporal variation in solar energy distribution in an outdoor environment. Lighter shades represent higher light intensity.
Deployment & Result

- Max rate under ENO: 75.8 bps
- The optimal routes →

\[
\begin{align*}
Node_2 & \rightarrow \text{Base} : 1.47 \text{bps} \\
& \rightarrow Node_3 : 30.58 \text{bps} \\
& \rightarrow Node_4 : 43.74 \text{bps} \\
Node_3 & \rightarrow \text{Base} : 75.8 \text{bps} \\
& \rightarrow \text{Base} : 30.58 \text{bps} \text{ Relay data from Node}_2 \\
Node_4 & \rightarrow \text{Base} : 75.8 \text{bps} \\
& \rightarrow \text{Base} : 43.74 \text{bps} \text{ Relay data from Node}_2
\end{align*}
\]
Event Monitoring

• Task:
  – Only transmit some special events
  – Network prepare to report an event very fast
• Interest metric: latency of data transfer
• Assumption: most of energy is consumed in idle listening.
• MAC layer behavior:

![Diagram showing MAC layer wake-up protocol](image)

Fig. 14. MAC layer wake-up protocol for communication with sleep mode usage.

• Average hop delay:

\[ D_{hop} = \frac{T_{sleep} + 3T_{cs}}{2} \]

• Route delay:

\[ D_{route} = \sum_{j=1}^{K} \frac{T_{sleep}(j) + 3T_{cs}}{2} \]

• Power consumption:

\[ P_{avg} = \frac{3T_{cs}}{3T_{cs} + T_{sleep}} P_{active} \]
• Benefits of this harvesting-aware approach:
  
  1. MAC delay:
     • Duty cycle based on max $\rho_2$
     • Nodes better harvesting $\rightarrow$ lower $I_{sleep}$
     $\rightarrow$ lower total MAC delay

  2. Route delay:
     • Each node use diff sleep duration ($\leq \rho_2$)
     • Routing protocol can choose neighbor with highest $\rho_2$ as next hop, in order to minimize the whole route delay.
     • ? Is this a reasonable argument?