Energy Efficient Opportunistic Routing in Wireless Sensor Networks

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May 30th, 2013
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Mao, Tang, Xu, Li & Ma, IEEE Transactions on Parallel and Distributed Systems, 2011
Overview

1. Overview

2. Problem Introduction
   ▶ Opportunistic Routing & Forwarder Lists
   ▶ Comparative Techniques

3. Problem Formalisms

4. EEOR
   ▶ Compute expected energy cost
   ▶ Find the optimal forwarder lists

5. Simulation

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Wireless Sensor Network (WSN)

(...) consists of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location. (Wikipedia)
Wireless Sensor Network (WSN)

- **n** nodes
  - Nodes can “hear” or transmit messages
  - Nodes can have different transmit strengths
- Messages or **packets**
- Packets with a source node *s* and target node *t*
- Two models:
  - *Non-adjustable transmission model*
  - *Adjustable transmission model*
Routing in Wireless Sensor Networks

**Find routing protocols that:**
- Minimize energy cost
- Maximize network throughput
- Maximize data delivery reliability
- Minimize date delay
- etc.
Traditional Routing Protocols

- Choose best sequence of nodes between $s$ and $t$
- Forward packet through that sequence
- Does not take advantages of the broadcast nature of wireless communication.
- Transmission could be heard by any node within range
Opportunistic Routing

- Allow any node that overhears the transmission to participate in forwarding the packet
- Routing path selected on the fly
- Path based on the current link quality situations
- **Challenge:** Eliminate unnecessary forwards
Forwarder List

- The list of all nodes that heard or overheard the transmission of a packet.
- A *scheduler* determines which nodes transmit the packet again.
- The scheduler keeps track of the forwarder lists.
Comparative Techniques

- ExOR
- MORE
- Both designed for
  - Large file transferring in wireless static networks
  - Situation where energy saving is not a concern
  - Throughput maximization
ExOR

- Extremely Opportunistic Routing
- Uses forwarder lists
- Scheduler goes in rounds: only one forwarder is allowed to transmit at any time
- Other forwarders listen to the transmissions to learn which packets were overheard by each node
MORE

- MAC independent Opportunistic Routing
  - Randomly mixes packets before forwarding them.
  - Nodes which hear the same transmission do not forward the same packet.
  - No extra scheduler needed.
Problem Formalisms

- Multihop wireless network $G = (V, E)$ with directed links $E$
- Nodes $i \in [1, n]$
- Node $u$ has fixed transmission power $W$
- $w(u, v)$: non-negative minimum transmission power required by by node $u$ to send a packet to node $v$ successfully
- $N_w(u)$: Neighboring nodes of $u$ at transmission power $w$
- $e(u, v)$: error probability for transmission between $u$ and $v$
Problem Formalisms

- $S^*$: S sorted by expected energy cost (low to high)
- $Fwd(u)$: Forwarder list of $u$
  - $Fwd^*(u)$: Sorted forwarder list in order of expected cost
EEOR

- Energy Efficient Opportunistic Routing
- Compute expected energy costs
- Find the optimal forwarder lists
- $C_u(Fwd)$: Expected cost needed by node $u$ to send a packet to $t$ using $Fwd$
- $C^h_u(Fwd^*)$: Expected energy for $u$ to reach at least one node in $Fwd^*$
- $C^f_u(Fwd^*)$: Expected total cost for receiver to get the packet to $t$
- $C^c_u(Fwd^*)$: Communication cost
- $C_u(Fwd^*) = C^h_u(Fwd^*) + C^f_u(Fwd^*) + C^c_u(Fwd^*)$
$C^h_u(Fwd^*)$

Expected energy for $u$ to reach at least one node in $Fwd^*$:

$$\alpha = \prod_{i=1}^{\mid Fwd^*(u) \mid} e(u, v_i)$$

$$\rho = 1 - \alpha$$

$$C^h_u(Fwd^*) = \frac{W}{\rho}$$
Expected total cost for receiver to get the packet to $t$:

$$\beta = (1 - e(u, v1))C_{v1} + \sum_{i=2}^{\left|Fwd^*\right|} \left(\prod_{j=1}^{i-1} e(u, v_j)\right) \cdot (1 - e(u, v_i))C_{v_i}$$

$$C_u^f(Fwd^*) = \frac{\beta}{\rho}$$
$C_u^c(Fwd^*)$ - Communication cost

- Overhead costs
- Adjustment of protocol
- Only forward the packet if all neighbors with higher priority did not forward the packet
- Different computation of $C_u^f(Fwd^*)$
Find the optimal forwarder lists

- \( k \) elements in \( N(u) \): \((2^k) - 1 \) choices (!!!)
- Prefix
- 3 Theorems
- Two scenarios:
3 Theorems

1. The optimum forwarder list of node $u$ must be a prefix of $N^*(u)$

2. If $C_{v_k} < C_u(Fwd^*)$, then $C_{v_k} < C_u(Fwd^* \cup \{v_k\}) < C_u(Fwd^*)$

3. If $C_{v_k} > C_u(Fwd^*)$, then $C_u(Fwd^* \cup \{v_k\}) > C_u(Fwd^*)$
Find the optimal forwarder list

Algorithm 1: ExpectedCostFixedPower($u$, $N(u)$, $C_u$, Fwd)

**Input:** the expected cost of all its neighboring nodes
**Output:** the cost $C_u$ and forwarder list Fwd.

1: Set $C_u = \infty$, Fwd = $\emptyset$.
2: Sort the neighboring nodes $N^*(u) = \{v_1, v_2, \ldots, v_{|N(u)|}\}$ based on its expected cost in increasing order.
3: for ($i = 1; i \leq |N(u)|; i = i + 1$) do
4: if ($C_u > C_{v_i}$) then
5: Set Fwd = Fwd $\cup v_i$ and compute $C_u = C_u$ (Fwd) based on Equation (5).
Find the optimal forwarder list

**Algorithm 3: Expected Cost by Opportunistic Routing**

**Input:** target node $t$, source node $s$, power $w(u, v)$ and link reliability for each link $uv$.

**Output:** the expected cost $C_{u,t}$ from node $u$ to node $t$ using opportunistic routing and the forwarder list of each node $u$.

1: $\forall u \in V$, set $C_{u,t} = \infty$. Let $C_{t,t} = 0$.
2: $\forall u \in N(t)$ run Algorithm 1 or 2 to compute $C_{u,t} \leftarrow C_u$.
3: repeat
4: Let $v$ be the node in $S_1$ that has the minimum cost.
5: Let $S_1 = S_1 - \{v\}$ and $S_2 = S_2 \cup \{v\}$.
6: For each $u \in N(v) \cap S_1$, run Algorithm 1 or 2 to compute $C_{u,t}$, depending on the power model.
7: until no node updated the forwarder list and cost $C_{u,t}$.
Simulation Set-up

- Compare EEOR against ExOR
  - Energy Consumption
  - Packet loss ratio
  - End-to-end delay
  - Packet duplication ratio

- 100 wireless nodes with $W = 50$ in 300x300 $\text{feet}^2$ square region

- Pick 18 random pairs as $(s, t)$, 1 packet per second
Energy Consumption

![Energy Consumption Graph]

- ExOR
- EEOR
- A-EEOR

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Total Transmissions

![Graph showing total transmissions vs. number of packets per source]

- ExOR
- EEOR
- A–EEOR

- Y-axis: \(3 \times 10^4\) to 3
- X-axis: # of Packets per Source

- Graph shows the relationship between the number of packets per source and the total transmissions for different routing protocols.

Conclusions

- Simulation
- Conclusions
- Questions
Thus, MORE needs no special scheduler to coordinate routers hear the same transmission do not forward the same packets.

tic routing protocol. MORE randomly mixes packets before the path is updated after certain routing update period. ExOR from source and destination follow the selected path(s) until the data is delivered correctly. It is interesting to design protocols using opportunistic routing that deliver the data most reliably, or deliver the data with the minimum delay.

Several interesting and challenging problems are left unsolved when multiple nodes could have potentially received the data correctly. It is interesting to design protocols using opportunistic routing that deliver the data most reliably, or deliver the data with the minimum delay.

A challenge is to compute the expected cost accurately when selecting optimum forwarder list for multicast and broadcast. Several interesting and challenging problems are left unsolved when multiple nodes could have potentially received the data correctly. It is interesting to design protocols using opportunistic routing that deliver the data most reliably, or deliver the data with the minimum delay.

Find the optimal forwarder list & Forwarder Lists

Compute expected energy cost

Find the optimal forwarder lists

Simulation

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Duplicated Packets

Fig. 3. Total transmitted packets.

Fig. 4. Total received packets.

Fig. 5. Energy consumption.

Fig. 6. Average delay for each pair.

Fig. 7. Max delay for each pair.

Fig. 8. Average End-to-end delay (ms).

Fig. 9. Max delay for each pair.

<table>
<thead>
<tr>
<th>Source-Destination Pair</th>
<th>ExOR</th>
<th>EEOR</th>
<th>A–EEOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 hops</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3 hops</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>more than 3 hops</td>
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</tbody>
</table>

Questions

- How do ExOR, EEOR, and A–EEOR differ in terms of energy consumption?
- What is the impact of the number of packets per source on the performance of these protocols?
- How do the protocols perform in terms of average delay and maximum delay?

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- Comparative Techniques

Problem Formalisms

EEOR
- Compute expected energy cost
- Find the optimal forwarder lists

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Packet Loss Ratio

![Packet Loss Ratio Chart]

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  - Comparative Techniques

- **Problem**
  - Formalisms

- **EEOR**
  - Compute expected energy cost
  - Find the optimal forwarder lists

- **Simulation**

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- **Questions**
Average Delay

![Average Delay Diagram](image-url)

Summary of Opportunistic Routing

- **Opportunistic Routing**
- Deliver data most reliably or with minimum delay.

**MORE**

- Randomly mixes packets before routing.
- No special scheduler required for routers.
- Randomness ensures unique forwarding.

**EOR and ExOR**

- EOR: Energy-efficient opportunistic routing.
- ExOR: Exponential opportunistic routing.

**ExOR**

- Randomly selects forwarders.
- Dynamic forwarder list.

**MORE**

- Mixes packets randomly.
- No special scheduler.
- Randomness ensures unique forwarding.

**Simulations**

- Experimental results show MORE's median unicast throughput is 45% higher than ExOR.
- MORE's median unicast throughput can run directly on 802.11.

**Conclusion**

- MORE is a viable solution for opportunistic routing.
- Improves reliability and energy efficiency in wireless networks.

**Questions**

- What are the key differences between EOR and ExOR?
- How does MORE compare to traditional routing protocols?
- What are the benefits of using MORE in wireless networks?
Thus, MORE needs no special scheduler to coordinate routers hear the same transmission do not forward the same packets. This randomness ensures that routers that forward them. This randomness ensures that routers that:

- Select the best path(s) using opportunistic routing that deliver the data most reliably, or deliver the data with the minimum delay.
- Use a number of energy efficient routing protocols. MORE randomly mixes packets before the path is updated after certain routing update period. ExOR between a source and destination is calculated, all data flows in network layer of wired networks: after the best path(s) is/are found.

Recent work has focused on single path routing. Banerjee and Misra or lossy wireless link layers in multi-hop wireless networks. Reliable wireless communication in the presence of unreliable wireless links are reliable and then tried to theoretically provide performance guarantees. Most existing power aware protocols did not consider the additional overhead by sensor nodes selecting optimum forwarder list for multicast and broadcast. An interesting question is to design efficient protocols for agreeing a unique node in the forwarder list to forward the data when multiple nodes could have potentially received the data correctly. It is interesting to design protocols using opportunistic routing that deliver the data most reliably, or deliver the data with the minimum delay.
Conclusions

- EEOR outcompetes ExOR in terms of energy consumption, duplication, packet loss and both average and maximum delay
- Network throughput is not analysed
- Many unsolved challenges
Future Work

- Design efficient protocols for selecting optimum forwarder list for multicast and broadcast
- Compute expected cost *accurately* including the overhead
- Design protocols for data delivery reliability or minimum delay
Questions?