Sprinkler: A Reliable and Energy Efficient Data Dissemination Service for Extreme Scale Wireless Networks of Embedded Devices

IEEE TRANSACTIONS ON MOBILE COMPUTING, JULY 2007

Presented by Chia-Yi Lien
September 27, 2007
Outline

- Introduction
- Sprinkler
  - System Model
  - Preliminaries
  - Algorithms to Compute CDS and D-2 Vertex Coloring
  - Data Dissemination Protocol
- Performance
- Conclusion
- Discussion
Introduction

- The objective is to minimize the number of packet transmission and the latency, in that order.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Current Draw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mote</td>
</tr>
<tr>
<td>Microprocessor and Idle radio</td>
<td>8mA</td>
</tr>
<tr>
<td>Packet Reception</td>
<td>16mA</td>
</tr>
<tr>
<td>Packet Transmission</td>
<td>24mA</td>
</tr>
</tbody>
</table>
Outline

- Introduction
- Sprinkler
  - System Model
  - Preliminaries
  - Algorithms to Compute CDS and D-2 Vertex Coloring
  - Data Dissemination Protocol
- Performance
- Conclusion
- Discussion
System Model

- $R$ is the reliable communication radius of the device

- Density assumption
  - If $R$ is the reliable communication radius of the device, then every square of length $\frac{R}{\sqrt{5}}$ contains at least one device
Preliminaries (1/2)

- Dominating set (DS)
  - A DS of a graph $G=(V,E)$ is a subset $V'$ of $V$ such that every vertex $v \in V$ is either in $V'$ or adjacent to some member of $V'$
Preliminaries (2/2)

A bidimensional grid $B(1)$ of size $r \times c$ has $r$ rows and $c$ columns, indexed, respectively, from 0 to $r-1$ (from top to bottom) and from 0 to $c-1$ (from left to right), with $r \geq 1$ and $c \geq 1$.
Outline

- Introduction
- Sprinkler
  - System Model
  - Preliminaries
  - Algorithms to Compute CDS and D-2 Vertex Coloring
  - Data Dissemination Protocol
- Performance
- Conclusion
- Discussion
Algorithms to Compute CDS and D-2 Vertex Coloring (1/9)

- **Assumption**
  - Let $G = (V, E)$ be enclosed in the smallest rectangular area of length $r(R'/\sqrt{5})$ and breadth $c(R'/\sqrt{5})$, where $r, c$ are positive integers, $3 \leq r \leq c$, and $R' = R$.
  - Rectangle is divided into square-shaped clusters of length $R'/\sqrt{5}$
  - One node is selected from each cluster as a clusterhead
  - Only the clusterhead nodes are used to construct a CDS $M$
  - Note that both rectangle and the grid of squares are virtual
Algorithms to Compute CDS and D-2 Vertex Coloring (2/9)

- **CDS Computation**

  - A node $u(i, j) \in M$, where $0 \leq i \leq r - 1$ and $0 \leq j \leq c - 1$, if

    - $r \mod 3 \equiv 0$: $[i \mod 3 \equiv 1] \lor [(i \mod 3 \not\equiv 1) \land (0 < i < r - 1) \land (j = 0)]$.
    - $r \mod 3 \equiv 1$: $[i \mod 3 \equiv 0] \lor [(i \mod 3 \not\equiv 0) \land (j = 0)]$.
    - $r \mod 3 \equiv 2$: $[i \mod 3 \equiv 1] \lor [(i \mod 3 \not\equiv 1) \land (i \not\equiv 0) \land (j = 0)]$. 

Algorithms to Compute CDS and D-2 Vertex Coloring (3/9)

- **CDS** of bidimensional grid $B(1)$

![Diagram of CDS](image)

- $r \mod 3 = 0$
- $r \mod 3 = 1$
- $r \mod 3 = 2$
Algorithms to Compute CDS and D-2 Vertex Coloring (4/9)

- CDS computation for random deployment
Algorithms to Compute CDS and D-2 Vertex Coloring (5/9)

- **D-2 Coloring**
  - Only nodes in $M$ will transmit packets
  - Let $C(i, j)$ be the D-2 color of a node $u(i, j) \in M$ where $0 \leq i \leq r - 1$ and $0 \leq j \leq c - 1$
  - $C(i, j)$ is computed using the following formula:
    - $(i \mod 3 \equiv 0) \land (i \mod 6 \equiv 0)$: $j \mod 11$.
    - $(i \mod 3 \equiv 0) \land (i \mod 6 \not\equiv 0)$: $(j + 6) \mod 11$.
    - $(i \mod 3 \equiv 1) \land (i \mod 6 \equiv 1) \land (j = 0)$: 12.
    - $(i \mod 3 \equiv 1) \land (i \mod 6 \not\equiv 1) \land (j = 0)$: 14.
    - $(i \mod 3 \equiv 2) \land (j = 0)$: $C(i - 1, 0) + 1$. 
Algorithms to Compute CDS and D-2 Vertex Coloring (6/9)

- A D-2 coloring for $M$
  - Time complexity of D-2 coloring algorithm is O(1)
  - D-2 coloring of $M$ requires at least 9 colors [dotted region]; Sprinkler uses 16 colors
Algorithms to Compute CDS and D-2 Vertex Coloring (7/9)

- Cluster Formation
  - Let $b$ be the base station node that originates broadcast data
  - We assume
    - $b$ knows locations of the four corners of the smallest rectangle of length $r \left( \frac{R'}{\sqrt{5}} \right)$ and breadth $c \left( \frac{R'}{\sqrt{5}} \right)$
    - Each node knows the nodes in its one-hop neighborhood – it knows the ID and the location of its one-hop neighbors
Algorithms to Compute CDS and D-2 Vertex Coloring (8/9)

- **Cluster Formation Algorithm**

```
if (ID = b ∨ rcv {locations of four corners})
∧¬sent → then
  if j = 0 then
    select a node u from square (i + 1, 0);
    send {locations of four corners} to u;
  end if
  select a node v from square (i, j + 1);
  send {locations of four corners} to v;
  sent := TRUE;
end if
```

The initial value of the variable sent is FALSE.
Algorithms to Compute CDS and D-2 Vertex Coloring (9/9)

- **Distributed Cluster Formation**
  - Each node in M sends at most two messages
  - Time complexity is $O(1)$. The total number of message is $O(n)$. The message size is $O(1)$. 

![Graph depicting distributed cluster formation](image)
Outline

- Introduction
- Sprinkler
  - System Model
  - Preliminaries
  - Algorithms to Compute CDS and D-2 Vertex Coloring
  - Data Dissemination Protocol
- Performance
- Conclusion
- Discussion
In reality, the link reliability has more than two values.

Here divides data dissemination into two phases, viz., streaming phase and recovery phase.
Data Dissemination Protocol (2/4)

- **Streaming Phase**
  - Only the nodes in the CDS transmit packets
  - Transmission is scheduled
  - When hearing a packet, a node in the CDS synchronizes its time with that of the sender by broadcasting. [global TDMA]
  - Given a node \( u \), let \( P_u \) be the set of CDS nodes, which are closer to the base station than \( u \). The parent of \( u \) is the closest neighbor of \( u \) in the set \( P_u \).
  - A node in the CDS forwards each newly heard packet.
  - Piggybacked negative acknowledgements
  - At the end of this phase, all the nodes in CDS receive the data completely
Data Dissemination Protocol (3/4)

- Recovery Phase
  - Only the non-CDS nodes will enter this phase
  - Recovery request/data messages are sent periodically at certain intervals
  - Since it is few number of transmissions during this phase than that of the streaming phase, recovery request/data message is sent via a RTS-CTS-DATA-ACK mechanism.
  - Separate negative acknowledgement messages
  - At the end of this phase, all the non-CDS nodes receive the data completely
Power management

- It takes 14mA to turn the XSM radio on or off, which is about the same as that to receive a packet.
- During the streaming phase, $u$ keeps its radio off except during time slots when its parent is scheduled to transmit. The periodic switching of radio by a non-CDS node is called power save mode.
- If recovery is required, $u$ switches on its radio and keeps it on until it has received all the packets. After recovery all the packets, $u$ again enters power save mode.
Outline

- Introduction
- Sprinkler
  - System Model
  - Preliminaries
  - Algorithms to Compute CDS and D-2 Vertex Coloring
  - Data Dissemination Protocol
- Performance
- Conclusion
- Discussion
Performance in Practice (1/3)

- Performance in an outdoor environment
Performance in Practice (2/3)

- Constant density
Performance in Practice (3/3)

- Increasing density

![Graph showing the relationship between number of nodes and transmissions/latency](image-url)
Simulation (1/3)

Deluge

Sprinkler
Simulation (2/3)

Deluge

Sprinkler
Simulation (3/3)

TABLE 4
Comparison Regarding Packet Transmission and Latency

<table>
<thead>
<tr>
<th></th>
<th>Deluge</th>
<th>Sprinkler</th>
</tr>
</thead>
<tbody>
<tr>
<td># Data Packet Senders</td>
<td>47</td>
<td>10</td>
</tr>
<tr>
<td># Packet Transmissions</td>
<td>38450</td>
<td>2400</td>
</tr>
<tr>
<td>Latency</td>
<td>514.31</td>
<td>32.56</td>
</tr>
</tbody>
</table>
Conclusion

- Sprinkler uses CDS and TDMA algorithm to minimize the number of packet transmission and the latency
Discussion

- How do we choose a proper value for $R'$?
- The selected CDS nodes may run out of energy quickly