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

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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 1
Energy Required by Common Operations

Operation	Current Draw	
	Mote	Stargate
Microprocessor and Idle radio	8mA	330 mA
Packet Reception	16mA	610 mA
Packet Transmission	**24mA**	**980 mA**

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System Model

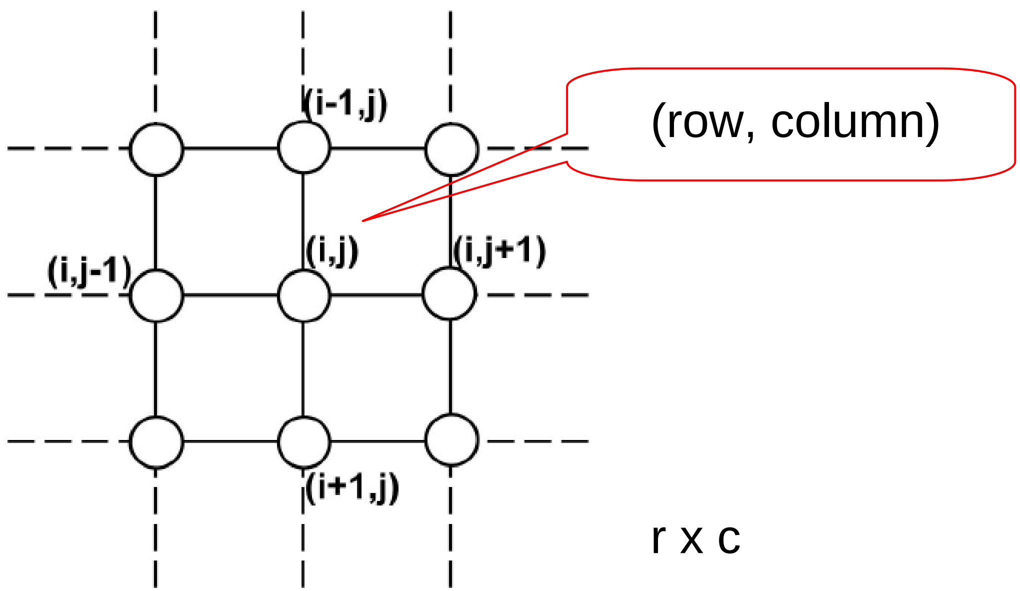
- *R* is the reliable communication radius of the device
- Density assumption
  - If *R* is the reliable communication radius of the device, then every square of length $R/\sqrt{5}$ contains at least one device

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 x 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 $c \geq 1$



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Algorithms to Compute CDS and D-2 Vertex Coloring (1/9)

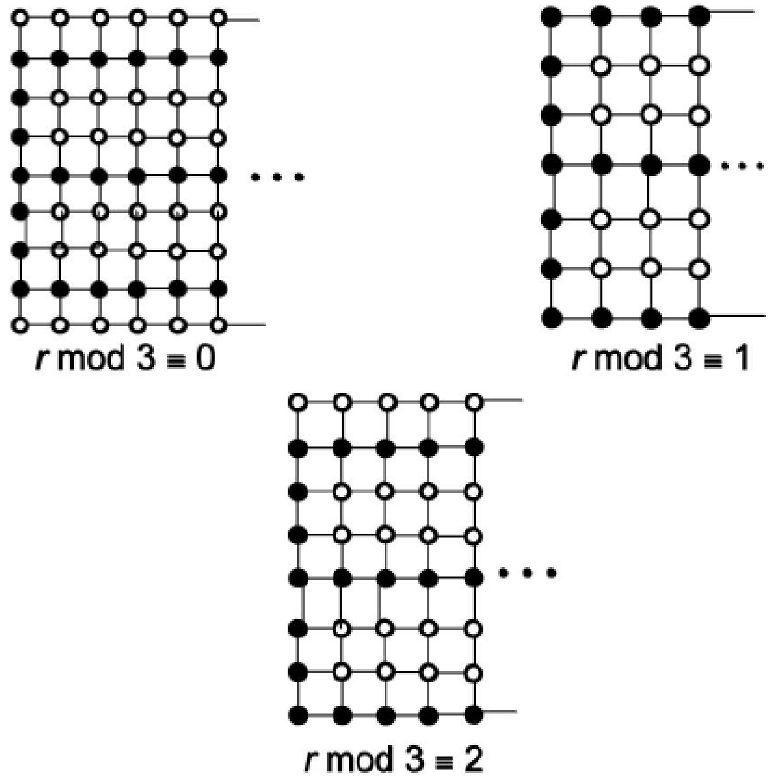
- Assumption
  - Let *G = (V, E)* be enclosed in the smallest rectangular area of length r($R'/\sqrt{5}$) and breadth c($R'/\sqrt{5}$), where r, c are positive integers, $3 \le r \le c$, and R' = R.
  - Rectangle is divided into square-shaped clusters of length $R'/\sqrt{5}$
  - One node is selected 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 $0 \le i \le r-1$ and $0 \le j \le c-1$, if
    - $r \bmod 3 \equiv 0$: $[i \bmod 3 \equiv 1] \vee [(i \bmod 3 \not\equiv 1) \wedge (0 < i < r-1) \wedge (j = 0)]$.
    - $r \bmod 3 \equiv 1$: $[i \bmod 3 \equiv 0] \vee [(i \bmod 3 \not\equiv 0) \wedge (j = 0)]$.
    - $r \bmod 3 \equiv 2$: $[i \bmod 3 \equiv 1] \vee [(i \bmod 3 \not\equiv 1) \wedge (i \not\equiv 0) \wedge (j = 0)]$.

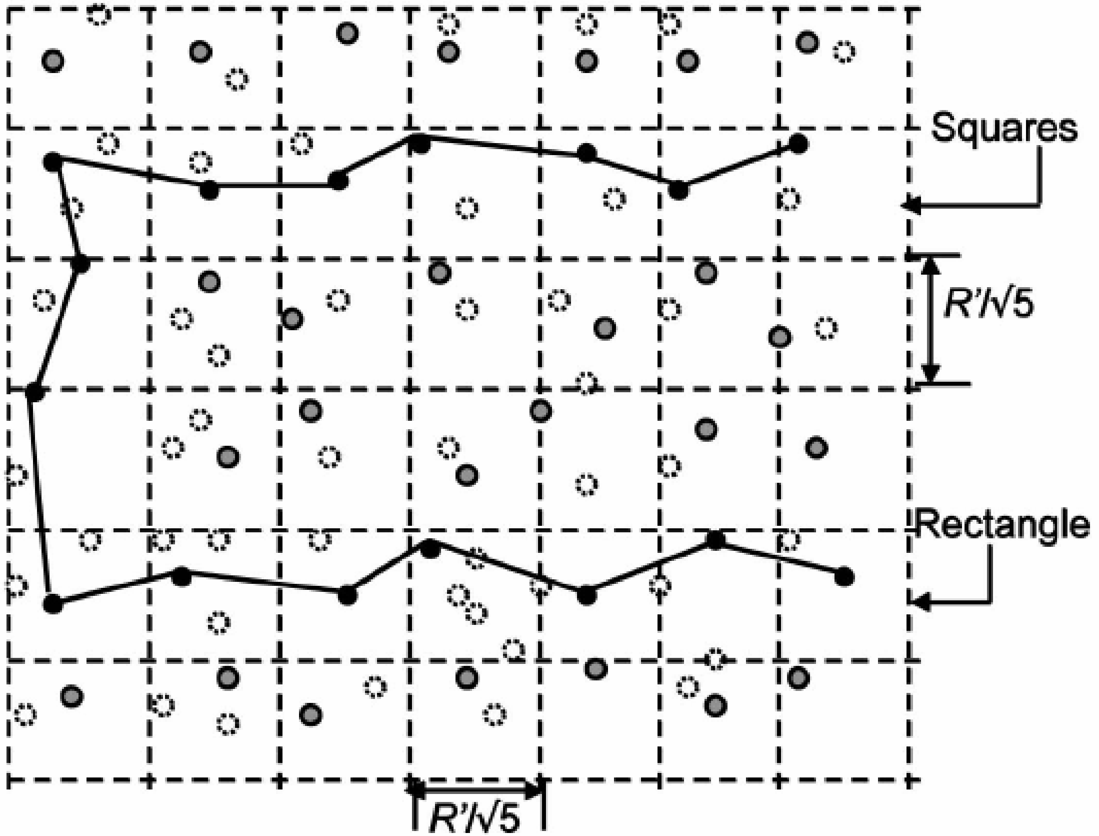
Algorithms to Compute CDS and D-2 Vertex Coloring (3/9)

- CDS of bidimensional grid *B(1)*



Algorithms to Compute CDS and D-2 Vertex Coloring (4/9)

- CDS computation for random deployment

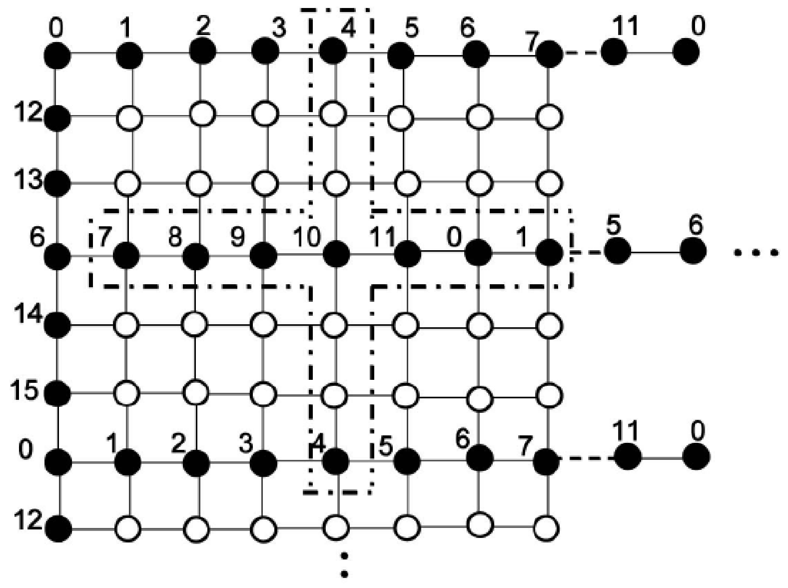


Algorithms to Compute CDS and D-2 Vertex Coloring (5/9)

- 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:
    - $(i \bmod 3 \equiv 0) \wedge (i \bmod 6 \equiv 0)$: $j \bmod 11$.
    - $(i \bmod 3 \equiv 0) \wedge (i \bmod 6 \not\equiv 0)$: $(j+6) \bmod 11$.
    - $(i \bmod 3 \equiv 1) \wedge (i \bmod 6 \equiv 1) \wedge (j = 0)$: 12.
    - $(i \bmod 3 \equiv 1) \wedge (i \bmod 6 \not\equiv 1) \wedge (j = 0)$: 14.
    - $(i \bmod 3 \equiv 2) \wedge (j = 0)$: $C(i-1, 0) + 1$.

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* ($R'/\sqrt{5}$) and breadth *c* ($R'/\sqrt{5}$)
    - 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)

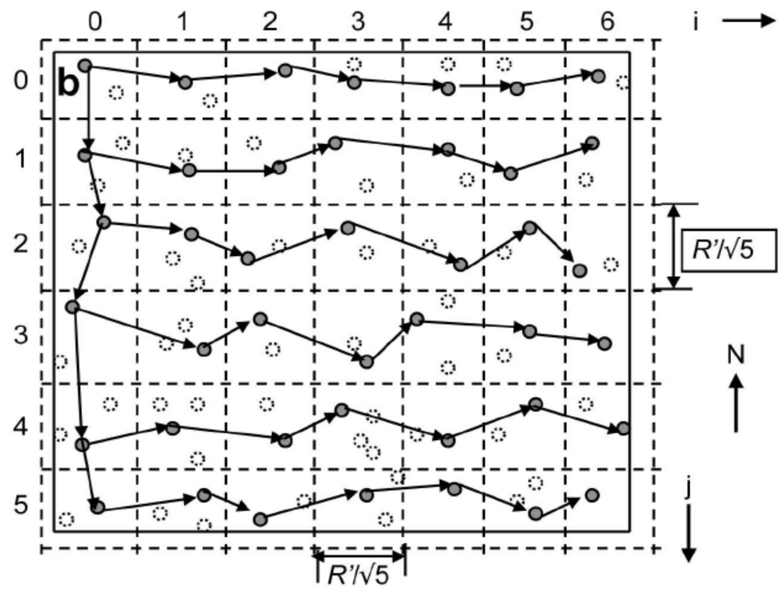
- Cluster Formation Algorithm
  - **if** $(ID = b \vee rcv \langle locations\ of\ four\ corners \rangle)$
    $\wedge \neg sent \rightarrow$ **then**
    if $j = 0$ **then**
    select a node u from square $(i + 1, 0)$; – (A)
    send $\langle locations\ of\ four\ corners \rangle$ *to u*;
    end if
    select a node v from square $(i, j + 1)$; – (B)
    send $\langle locations\ of\ four\ corners \rangle$ *to v*;
    sent := *TRUE*;
    end if
    The initial value of the variable sent is FALSE.

Row = 0, 1,…, i-1

Column = 0, 1, …, j - 1

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).



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Data Dissemination Protocol (1/4)

- 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

Data Dissemination Protocol (4/4)

- 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

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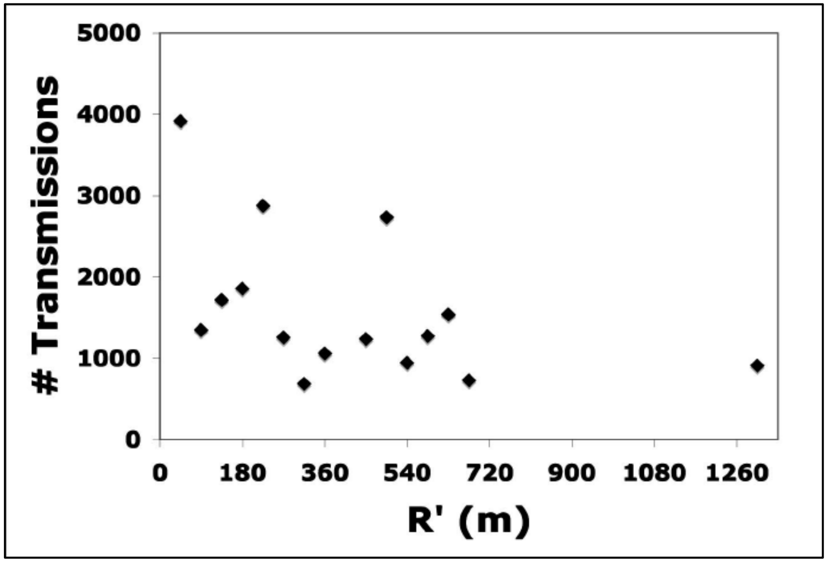
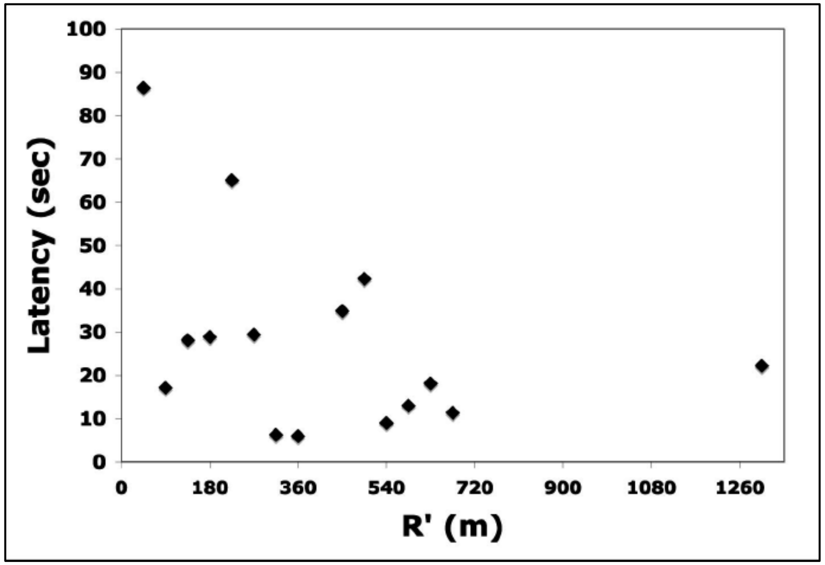
Performance in Practice (1/3)

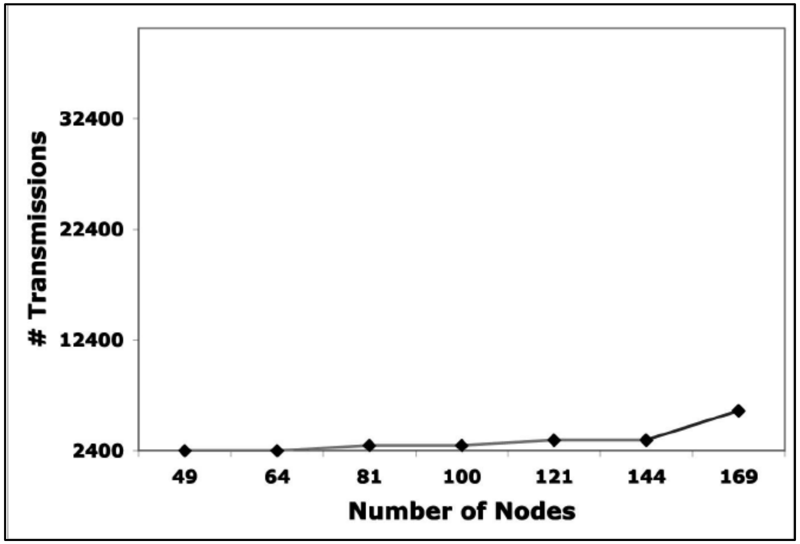
- Performance in an outdoor environment

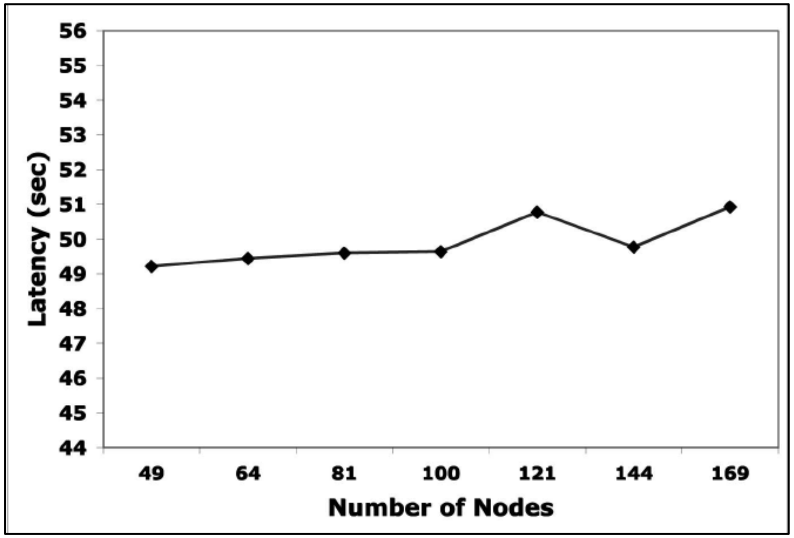




Performance in Practice (2/3)

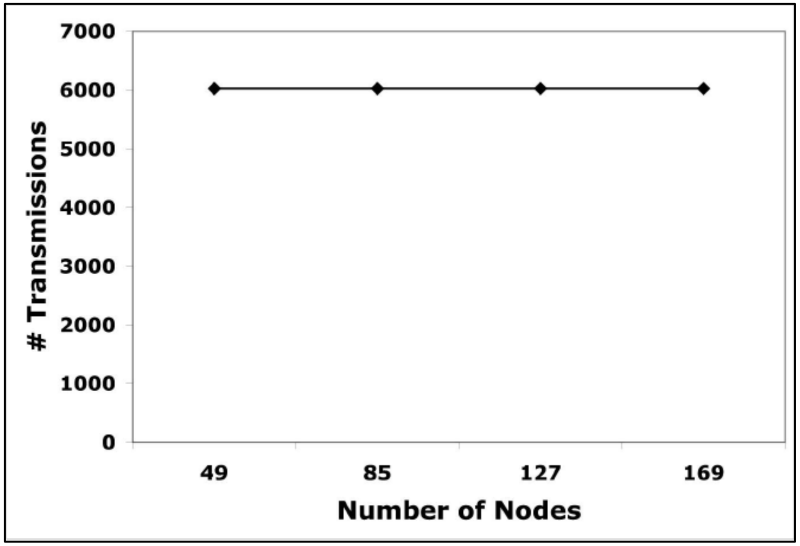
- Constant density

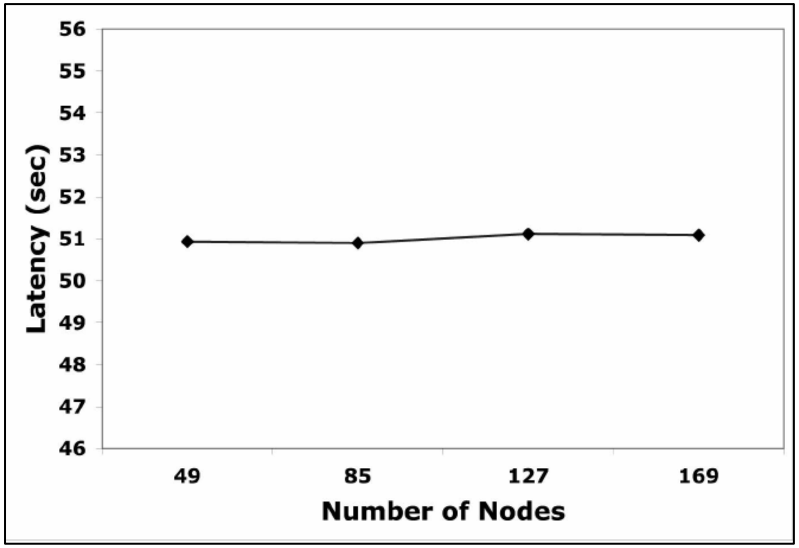




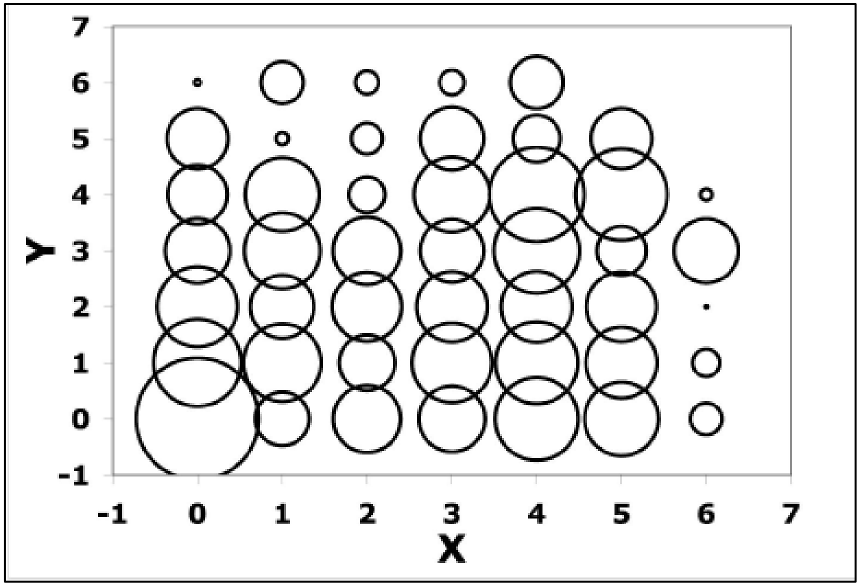
Performance in Practice (3/3)

- Increasing density

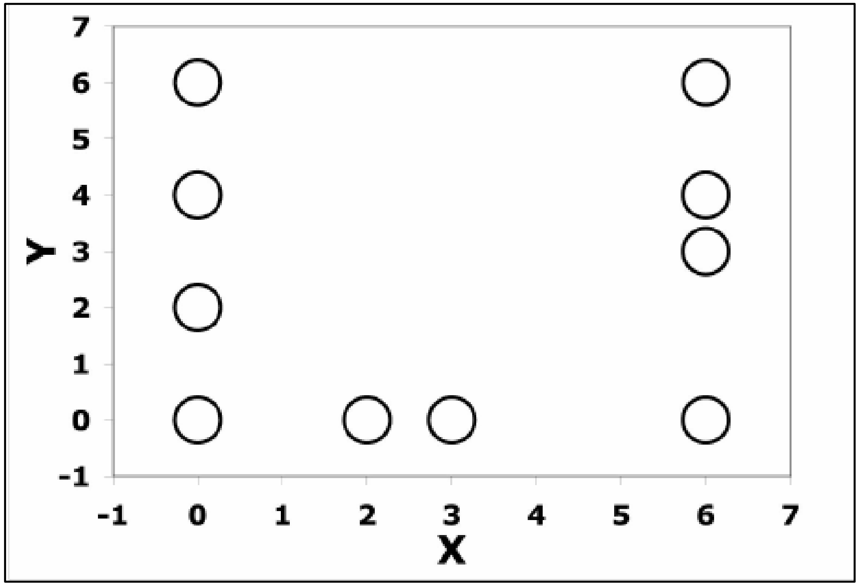




Simulation (1/3)

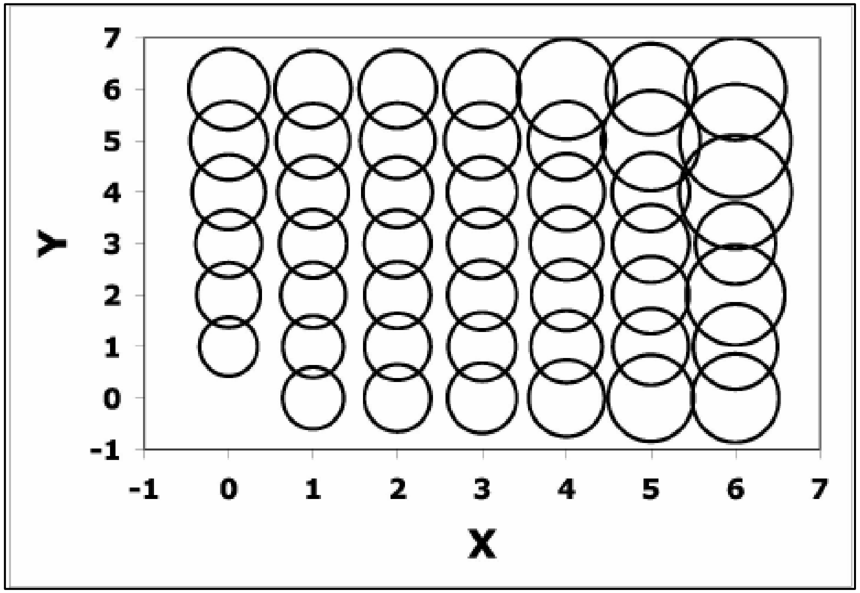


Deluge

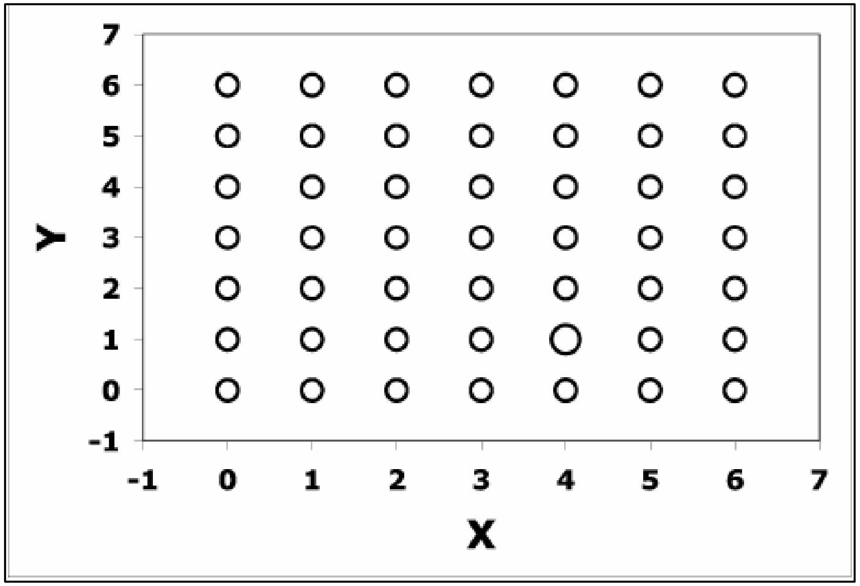


Sprinkler

Simulation (2/3)



Deluge



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Simulation (3/3)

TABLE 4
Comparison Regarding Packet Transmission and Latency

	Deluge	Sprinkler
# Data Packet Senders	47	10
# Packet Transmissions	38450	2400
Latency	514.31	32.56

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