Ad-hoc Wireless Sensor Networks with Application to Fire Detection in Buildings

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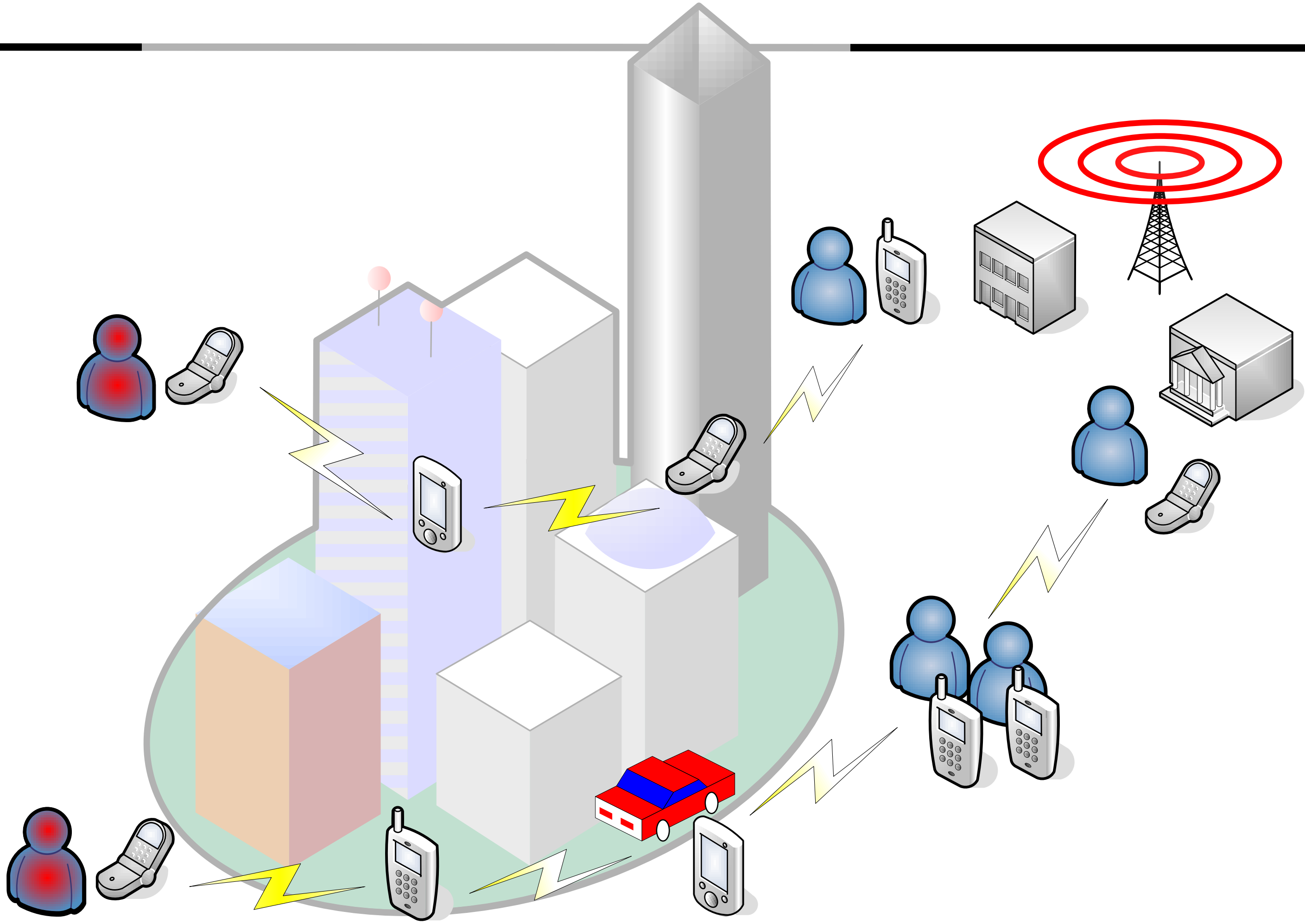
Wireless Networks

- A. Introduction to ad-hoc networks
- B. Network capabilities discussion
- C. Fire scenarios, monitoring
- D. Correlations in sensor data
- E. Sensor clustering based on fire spread
- F. Network reconfiguration after fire damage
- G. Conclusions



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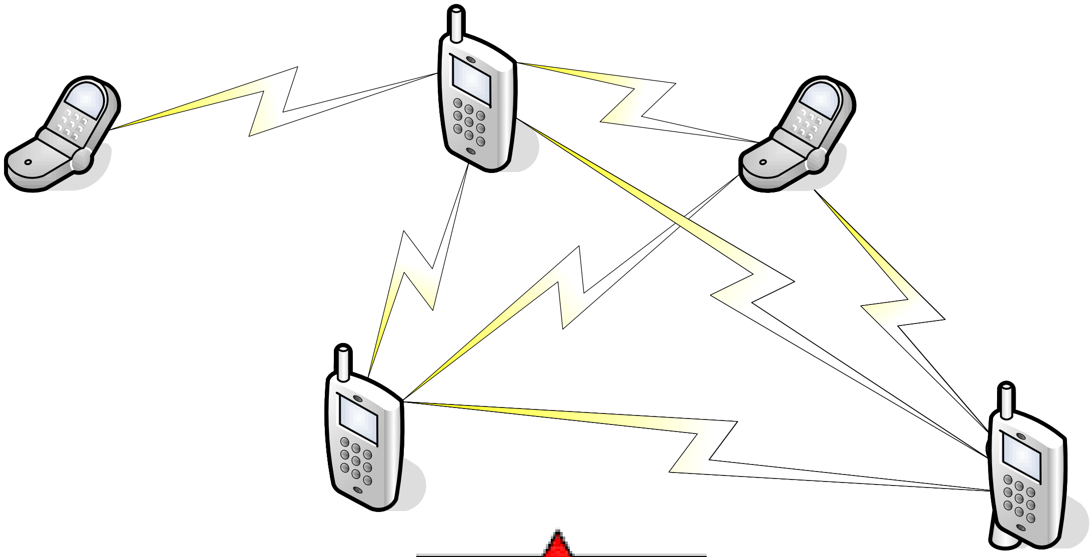
A. Ad-Hoc Networks

- **Flexible structure**
- **Users or nodes move and self reconfigure**
- **Dual use of nodes as:**
  - Sources of information and
  - Transmission relays
- **Extend network reach to destination, sink node or base station**
- **Shorter links reduce overall power required for data transmissions**

Network design

- **Can be point-to-point**
  - Connection set up manually
- **Can be formed as a cluster of nodes with a cluster head**
- **Can be meshed**
- **Can be used to extend the reach of a network**

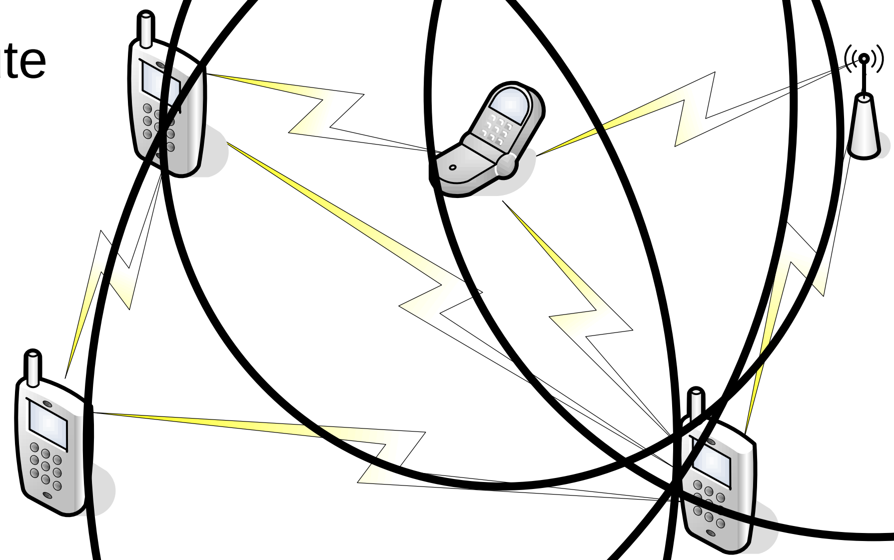


B: Network capabilities

- **To operate as a mesh or extend a network routing is required**
- **Unlike wired networks relying on hierarchical TCP/IP naming, routing information created dynamically**
  - Proactive routing defines routes in advance of required use
  - On-demand routing finds routes for traffic if a route is not already known
- **Routing information must be able to be updated**
  - Loss of node (loss of power, node damage)
  - Loss of link (movement of nodes, obstructions)
  - Optimisation (new improved route available, equalising power drain)

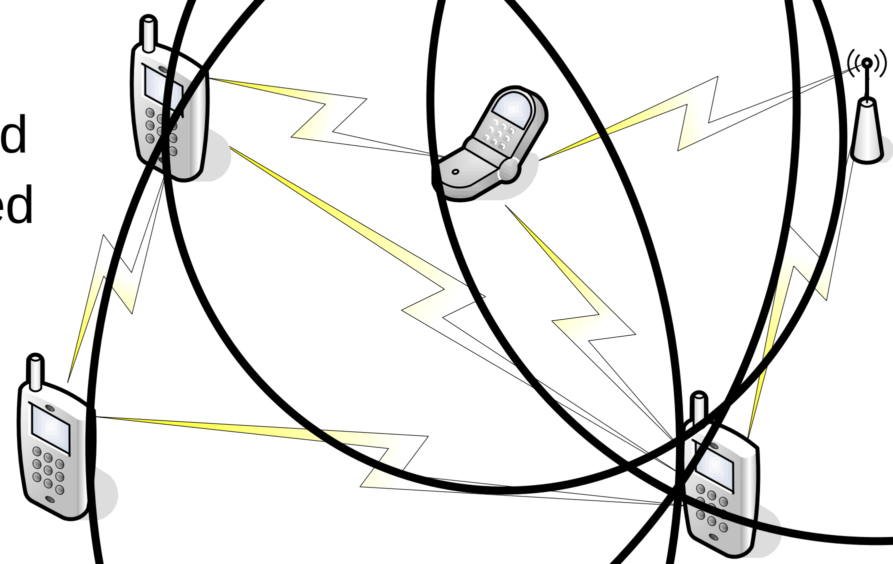
Network capabilities

- **Pro-active routing (e.g. DSDV)**
  - Beacon transmitted
  - Receiving nodes add route
  - Beacon forwarded
  - Again, routes are added
  - Process repeats



Network capabilities

- **On-Demand routing (e.g. DSR)**
  - Node wishes to transmit
  - Sends a Route Request
  - Route requests forwarded
  - When destination reached if return route is known, response is returned
  - If not, destination uses same process to find route
  - Nodes on return route update routing information



Network capabilities

- Hybrids between pro-active and on-demand exist
- Alternative use geographical positioning
- Multicast routing exploits broadcast nature of radio
- Choice of routing depends on trade-off between overhead of route maintenance and demand for routes
- Ad-Hoc relaying incorporated in WiMAX: IEEE 802.16j
- For FireGrid, a hybrid between hierarchical routing and on-demand routing is used

Mobile Ad-Hoc Networks (MANETS)

- **MANET is flexible structure**
- **Users or nodes move and self reconfigure**
- **No Comprehensive Network Information Theory (IT)**
- **Issues:**
  - Multi-link ad-hoc connection system
  - Link IT does not map to network performance
  - Highly dynamical system
  - Large operational overhead
- **No theory to define MANET performance**
- **Simulate to assess: Throughput-Delay-Reliability**

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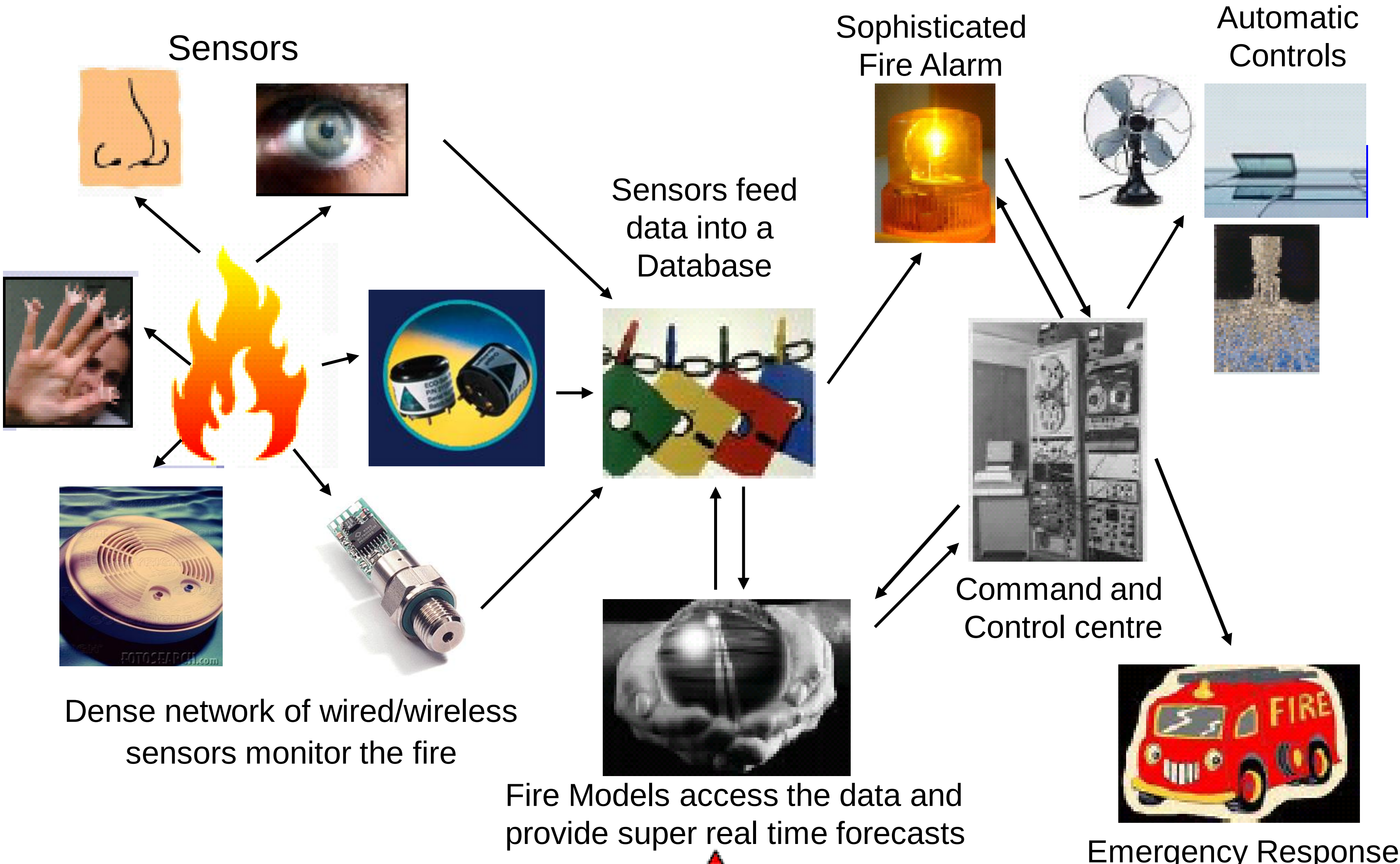
Why model fires?

- Buildings are of high value
- Need to know fire characteristics to fight effectively and combat fire spread
- Mount Blanc tunnel fire was enhanced rather than controlled due to inadequate knowledge!
- Fires usually spread with unpredictable behaviour
- Need dense monitoring sensor arrays

C. The FireGrid Project



FireGrid

Courtesy: Adam Cowlard

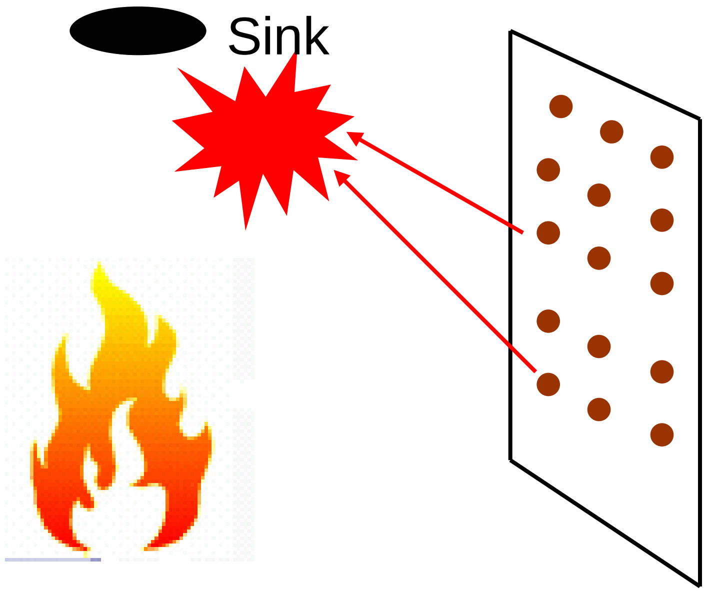
Wired vis Wireless infrastructure?

- Future large buildings will require a network with 1000s of sensors
- In a wired infrastructure, data is transmitted reliably (no congestion or multi-path fading) but …
- Wiring is vulnerable to loss of communications in a fire
- Wiring cost is not predicted to reduce
- Wired sensors are not easily reconfigurable
- Challenge: Extend and complement the existing wired infrastructure with **Wireless Sensors**

Why Wireless Sensor Networks?

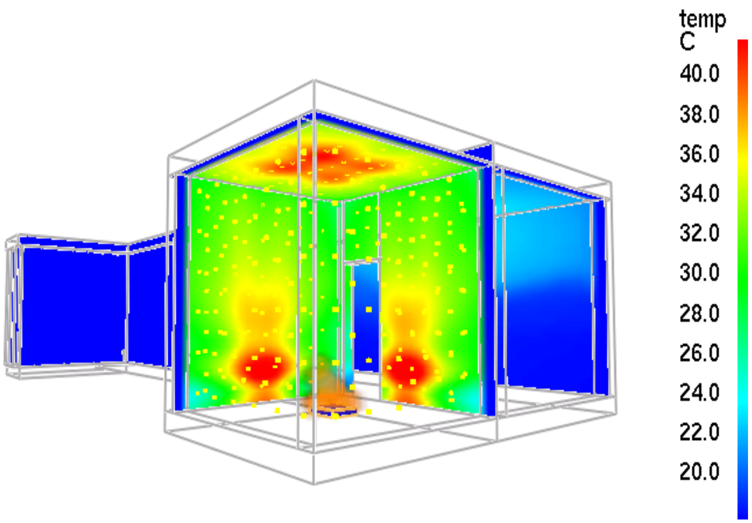
- Enabled by the convergence of:
  - micro-electro-mechanical systems (MEMS) technology
  - wireless communications
  - digital electronics
- Extend range of sensing
- Incorporate redundancy
- Improve accuracy
- Cost expected to reduce with time

Research Challenges and Approach



Research Issues

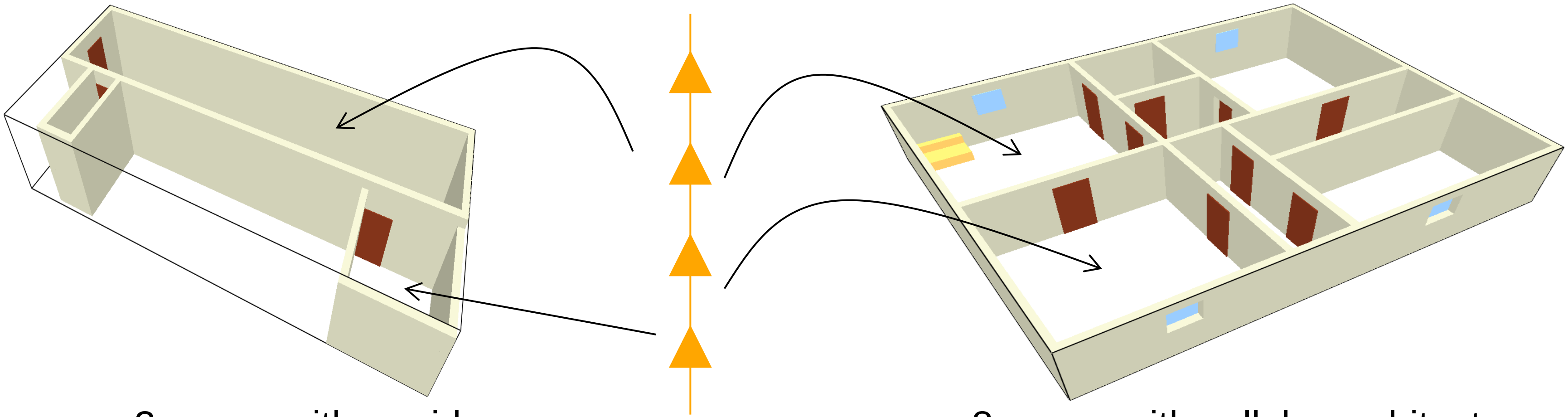
- Need dense sampling to accurately assess fire spread
- Dense sampling and frequent transmitting causes packet losses due to collisions
- In critical events such as in a fire packet losses / latency cannot be tolerated



Approach

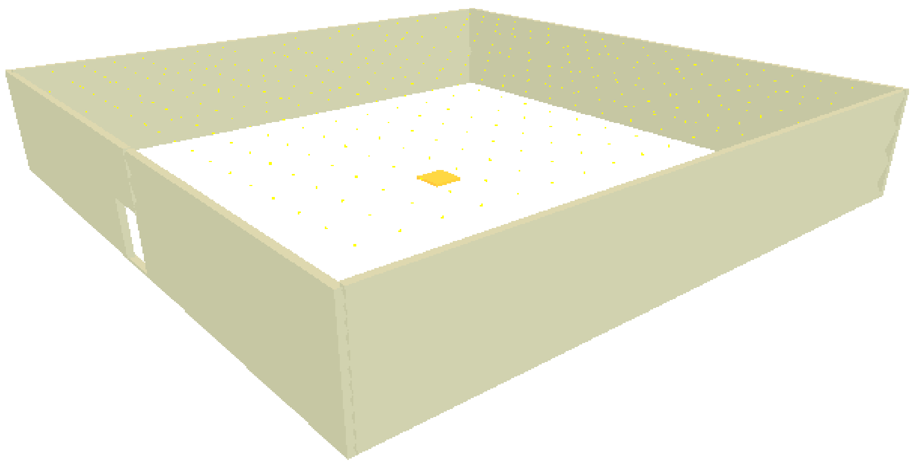
- Use spatial and temporal correlations in the sensed data to reduce overloading data transmission requirements

Three Simple Fire Simulation Scenarios



3 rooms with corridor
(Rack with 4 thermocouples in each room)

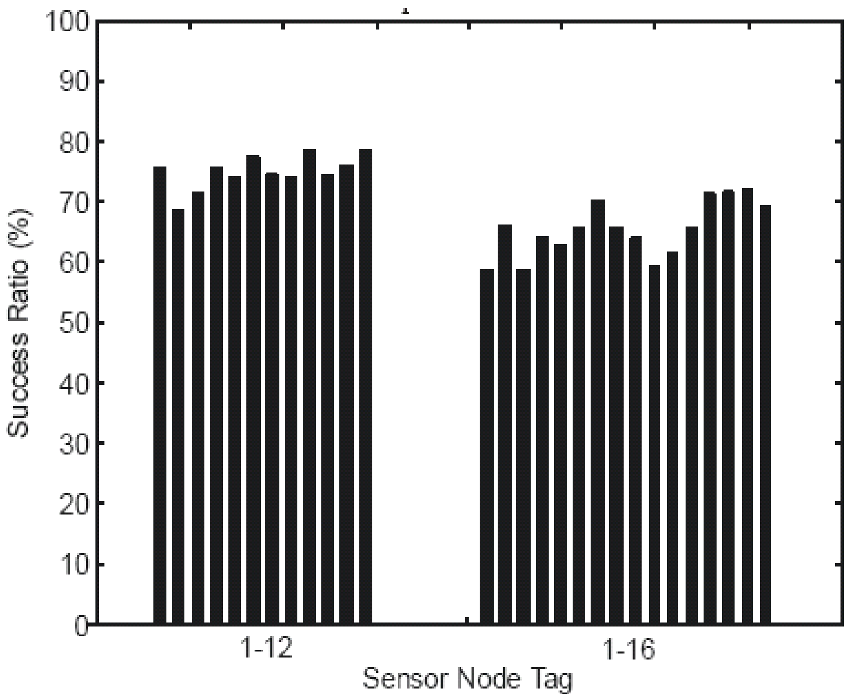
8 rooms with cellular architecture
(4-thermocouple rack in each room)



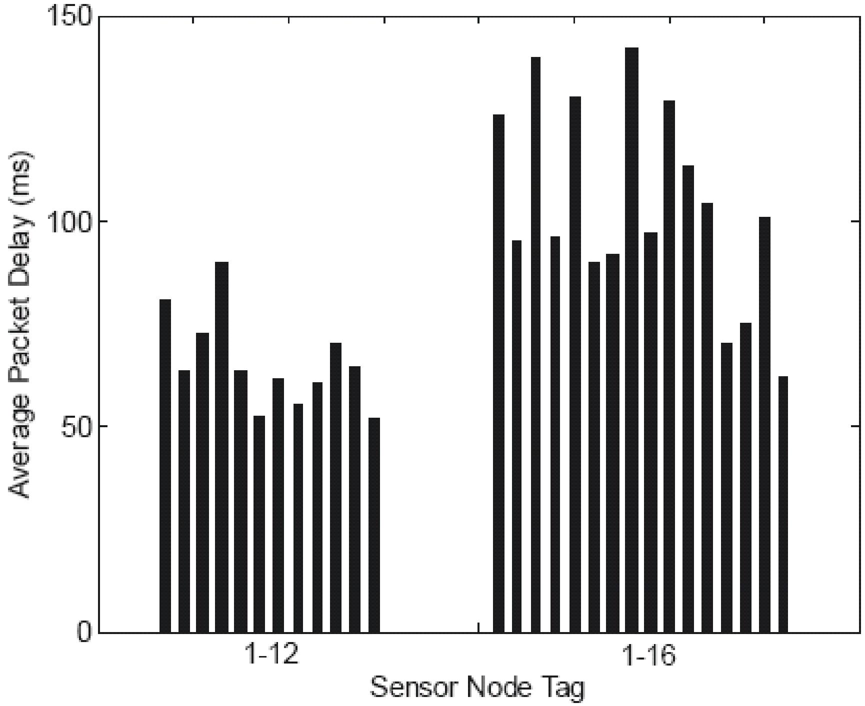
Large 20m x 20m x 4m hall
(587 heat flux sensors on the walls)

IEEE 802.11 Network Simulations

Percentage of packets delivered successfully



Average delay for packet delivery



- 3 room (1-12) and 4 room (1-16) scenarios with 4 sensors per room
- Flat architecture with all sensors communicating to a sink/destination node
- Constant transmission rate of 1 packet/s per sensor
- Collision packet loss and delay already evident with only 16 sensors!

FireGrid

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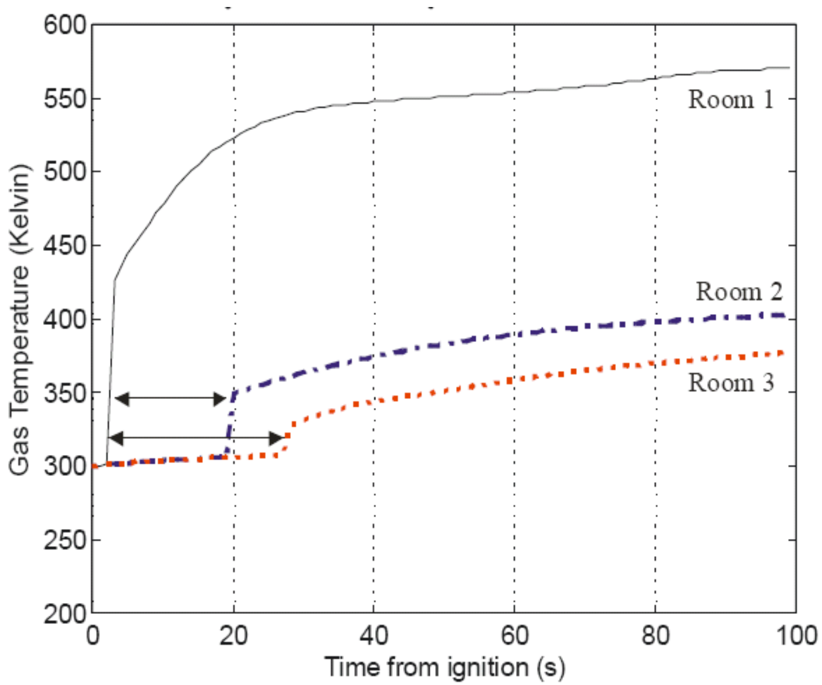
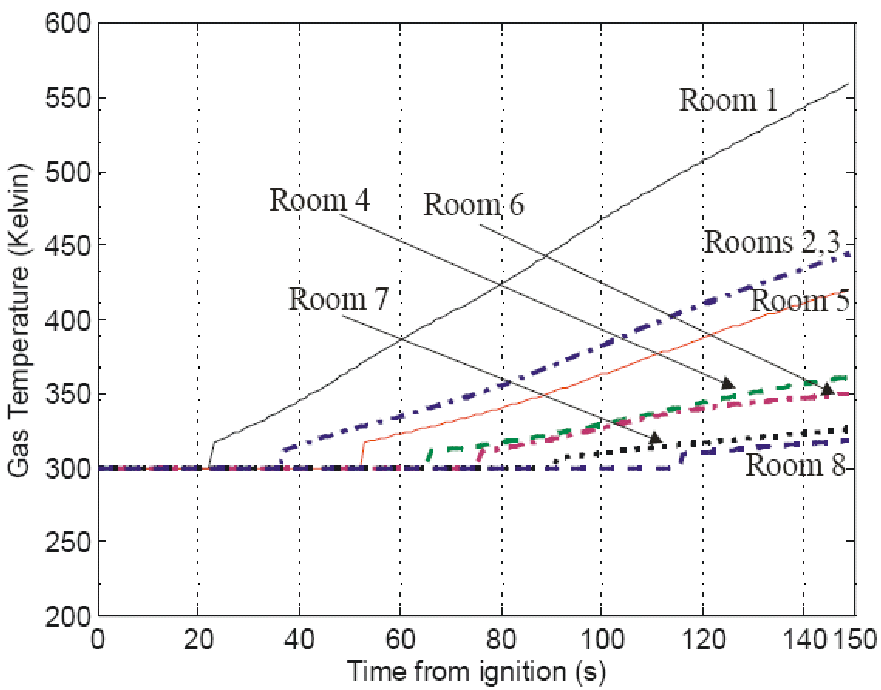
D. Fire Data Characteristics

Temperature reading of uppermost thermocouple in 3 room scenario, with fire starting in room 1



Repeat for 8 room scenario



- See similar air temperature profiles in each room but with lag in time
- Thus sensors in other rooms don't always need transmit, avoiding collisions
- The time lag effect can thus be exploited to reduce transmissions

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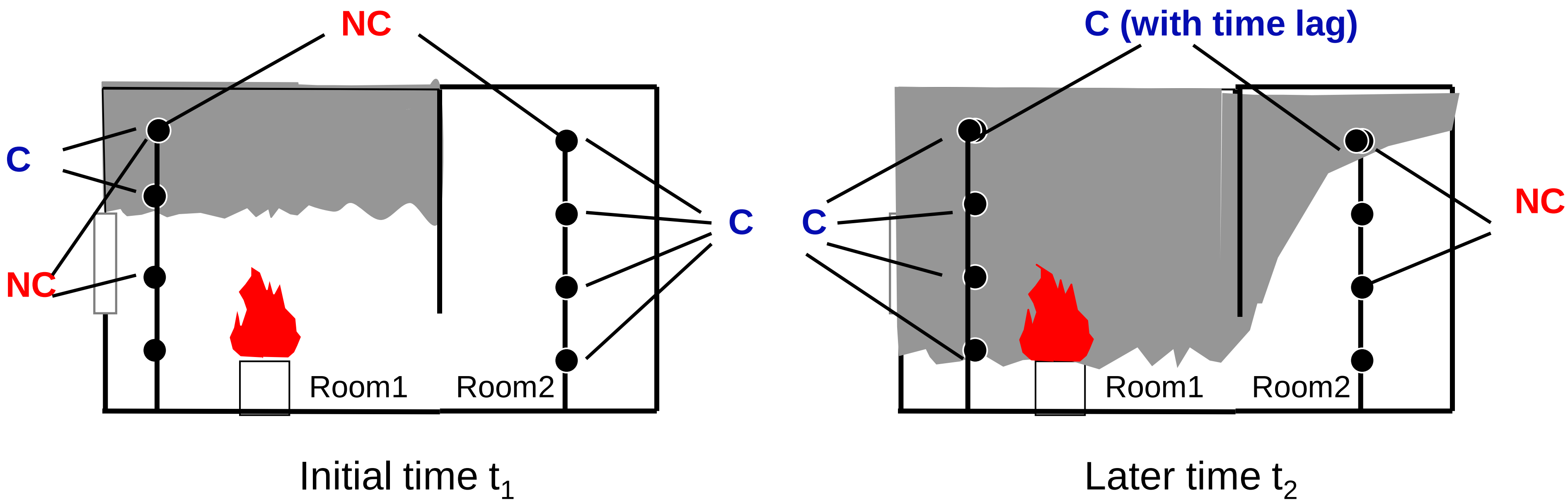
Correlation between Sensor Data in a Fire

Dynamic nature of correlations



C : Correlated

NC: NOT Correlated

- Sensors that are correlated can be clustered to reduce data transmission
- But correlations among sensors change with time
- Experience similar sensor responses in different rooms after a time lag

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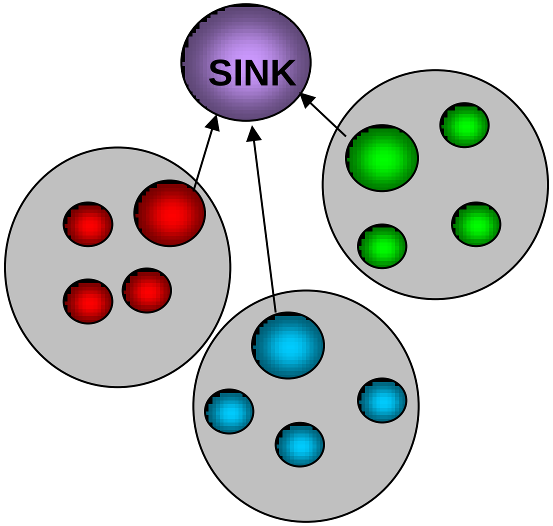
E. Clustered Network Architecture

Partition of sensor network into clusters



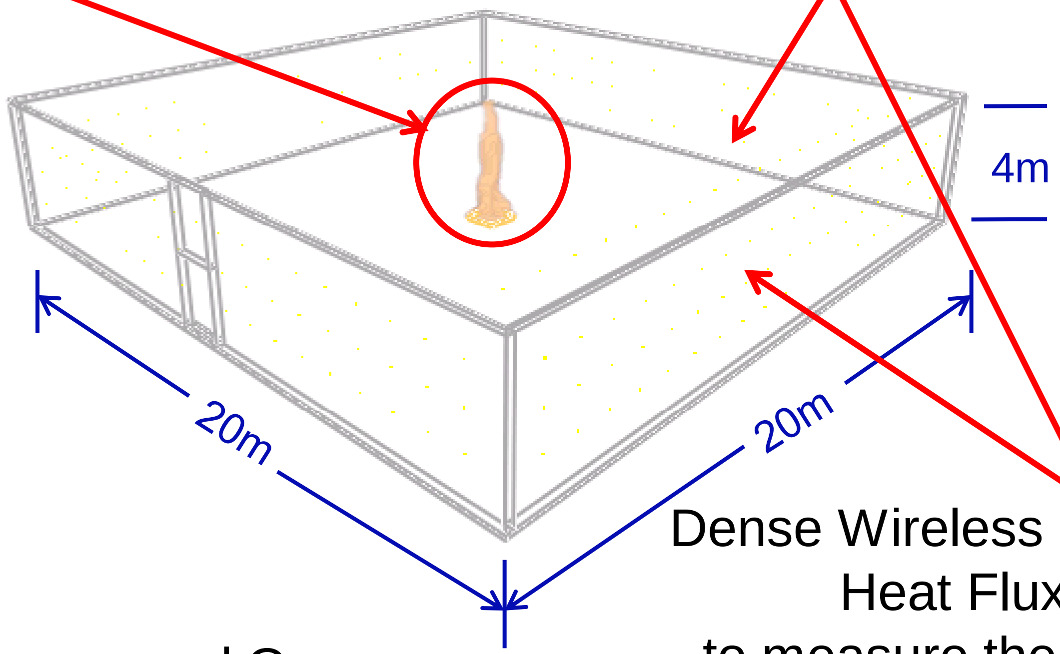
Comparison of power consumption of IEEE 802.11 for flat and clustered networks

IEEE 802.11		Power Consumption for 2000s (in Joules)	Network Lifetime (in days)
Flat	3-room	1854	0.38
	4-room	1854	0.38
	8-room	1854	0.38
Clustered $\alpha=1/4$	3-room	467	1.53
	4-room	467	1.53
	8-room	467	1.53

- How de we group the sensors into clusters?
- What is the error in sensor field representation at the sink or destination node?
- **EXPLOIT THE CORRELATIONS IN THE FIRE DATA WITH CLUSTERING !**
- **Clustering extends by 4X the network battery lifetime**

Description of a Typical Application

Fire Heat Release Rate, H:
Key input parameter to fire models



Dense Wireless Network of 587 Heat Flux Meters to measure the Heat Flux Q in the boundaries

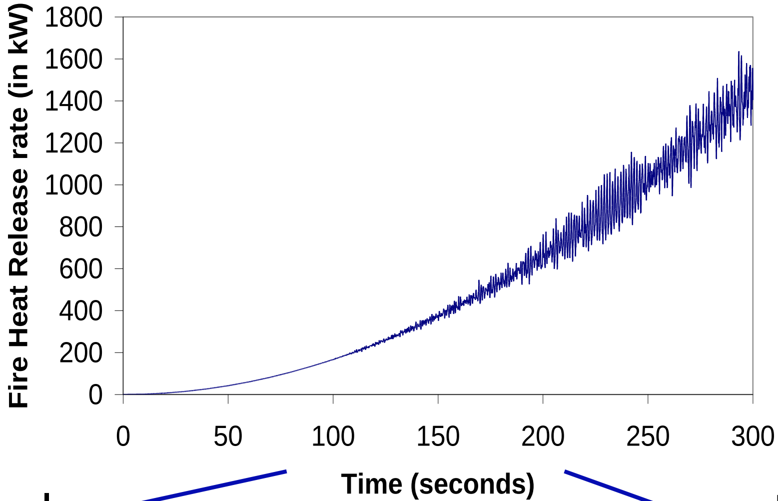
Estimate H using measured Qs:

$$H \approx \frac{A}{M}\sum_{i=1}^{M} Q_i$$

A : Area of sensor coverage; M : Number of sensors;
Q_i : Heat Flux measured by sensor # i;

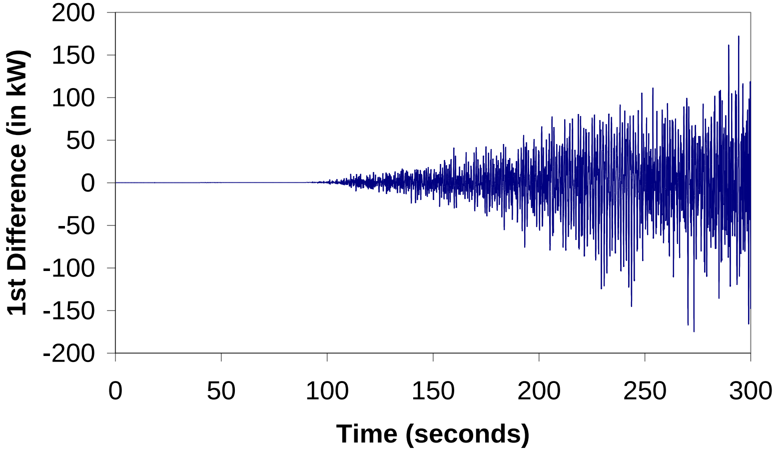
Difficulties in signal processing

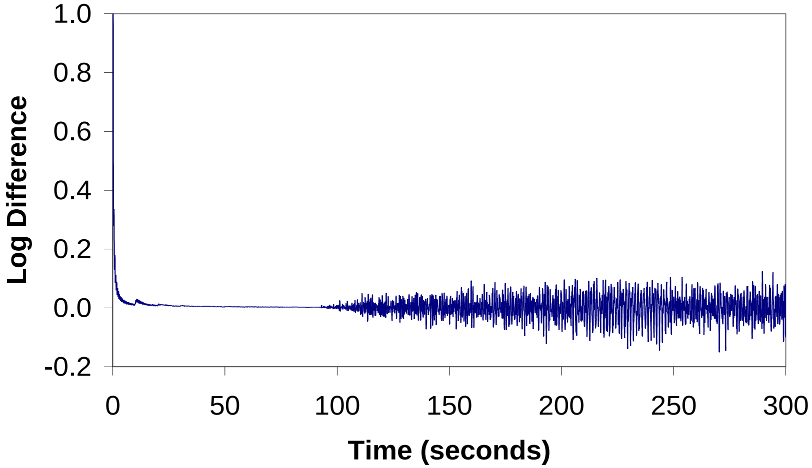
Highly non-stationary signal to be measured:



Differencing between samples

Log-differencing





Neither differencing nor log-differencing achieve stationary data

Exploiting Sensor Correlations

Define a ‘distortion metric’ (D) to quantify the error, with release rate H:

$$D(M) = E\left[\left(H - \frac{A}{M}\sum_{i=1}^{M} Q_i\right)^2\right]$$

$$= E\left[H^2\right] - \frac{2A}{M}\sum_{i=1}^{M} E\left[HQ_i\right] + \left(\frac{A}{M}\right)^2 \sum_{i=1}^{M}\sum_{j=1}^{M} E\left[Q_i Q_j\right]$$

$E[HQ_i]$: Covariance between the Source (H) and Sensor Measurement (Q_i)

$E[Q_iQ_j]$: Covariance between Sensor Measurements at locations i and j

<u>Note:</u>

$D(M)\downarrow$ if $E[HQ_i]\uparrow$

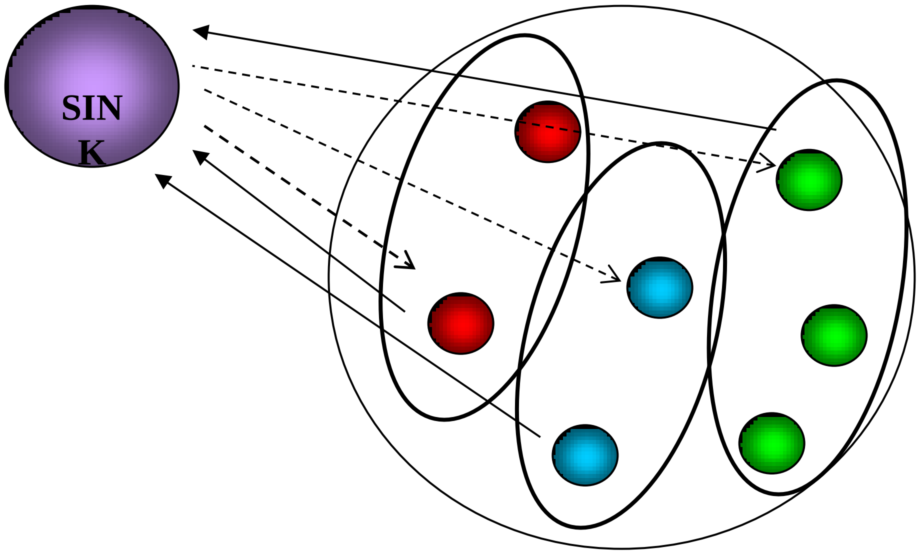
(Place sensors where they are strongly correlated with the source)

$D(M)\downarrow$ if $E[Q_iQ_j]\downarrow$

(Place sensors where they are not correlated with each other)

For each M, optimal sensor placement minimises D(M)

Clustering Algorithm



Centralized Medium Access Control in single-hop star network topology:

- Sink dynamically selects a subset of sensor nodes based on the minimum distortion criterion (Start with sensor clustering by room?)
- Correlations change with time and depend on the number and placement of sensors
- Sink determines when the correlations change and requests nodes to re-cluster to maximise data throughput and minimise delays

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F. Network reconfiguration after sensor loss

- **Review Wireless Mesh Protocols**
- **Simulations of Sensor Losses and Subsequent Wireless Route Recovery**

Existing Wireless Mesh Protocols

Index-Driven (i.e., Hierarchical State Routing (HSR), Internet Protocol version 4 (IPv4), IPv6)

Difficult to configure for networks with large # nodes.

Route may not be optimal for achieving high performance.

Ad-hoc (i.e., Destination Sequence Distance Vector (DSDV), Ad-hoc On-demand Distance Vector (AODV), Dynamic Source Routing (DSR))

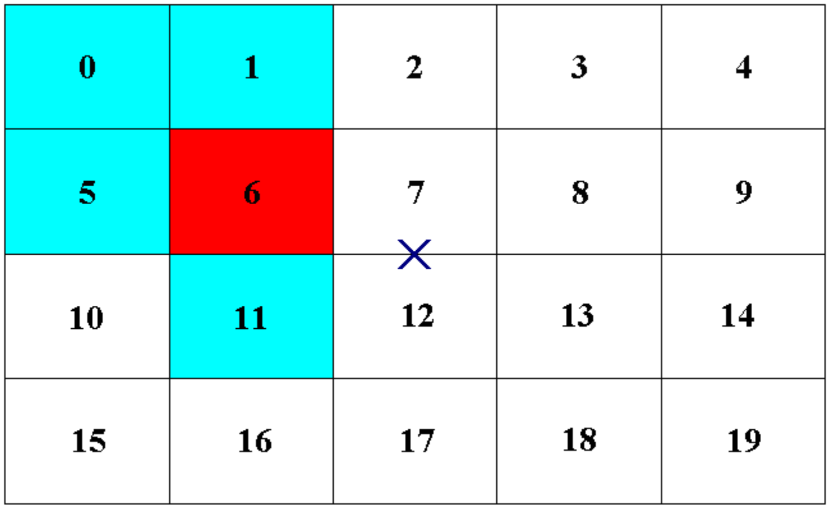
Scalability limits: DSDV supports 100 nodes, DSR/AODV up to 200

Challenge:

- **AODV/DSR extends scalability in single-destination case**
- **But Wireless Fire Networks may need 1k~1M nodes!**

Fire Scenario

Fire Scenario:



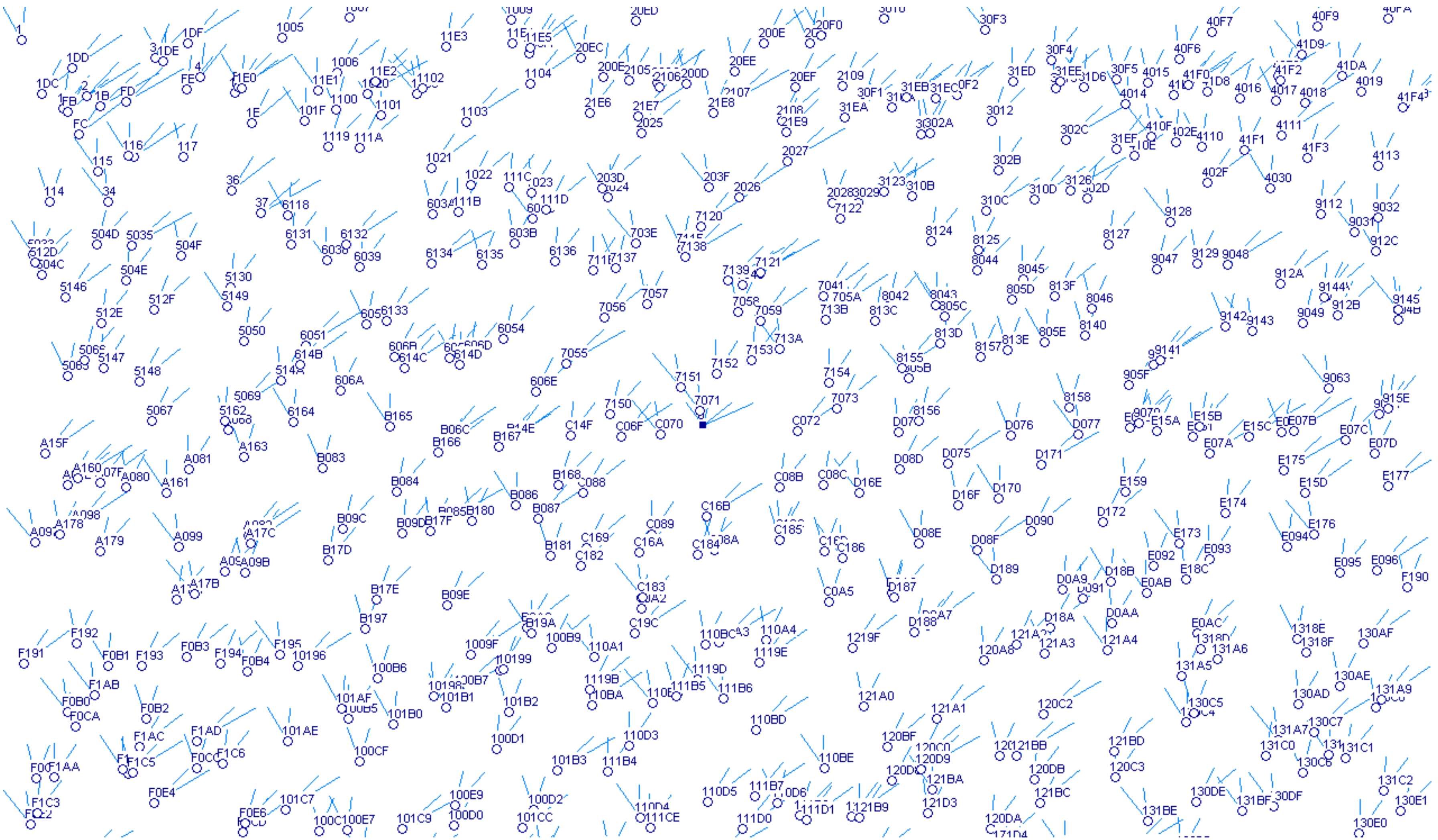
500 sensor nodes in 1250 * 750 (m) area
Single destination sink at centre (x)
IEEE 802.11 range is 10-50m
Maximum node-sink range is 180 m
Typically 3 or 4 hops from edges to x
Mean 5 pkt/s tx from each sensor
AODV routing

Steps:

1. **Generate nodes as designed**
2. **Nodes discover neighbours and routes to destination**
3. **Run 30 minutes to get route-establishment-time-distribution and packet-delay-distribution in zone 0, 1, 5, 11**
4. **Fire quenches all nodes in zone 6 and need to assess route-recovery-time (distribution)**
5. **Run next 30 minutes for new packet-delay-distribution in zone 0, 1, 5, 11**
6. **Repeat 1 – 5 for 30 rounds to acquire mean values**

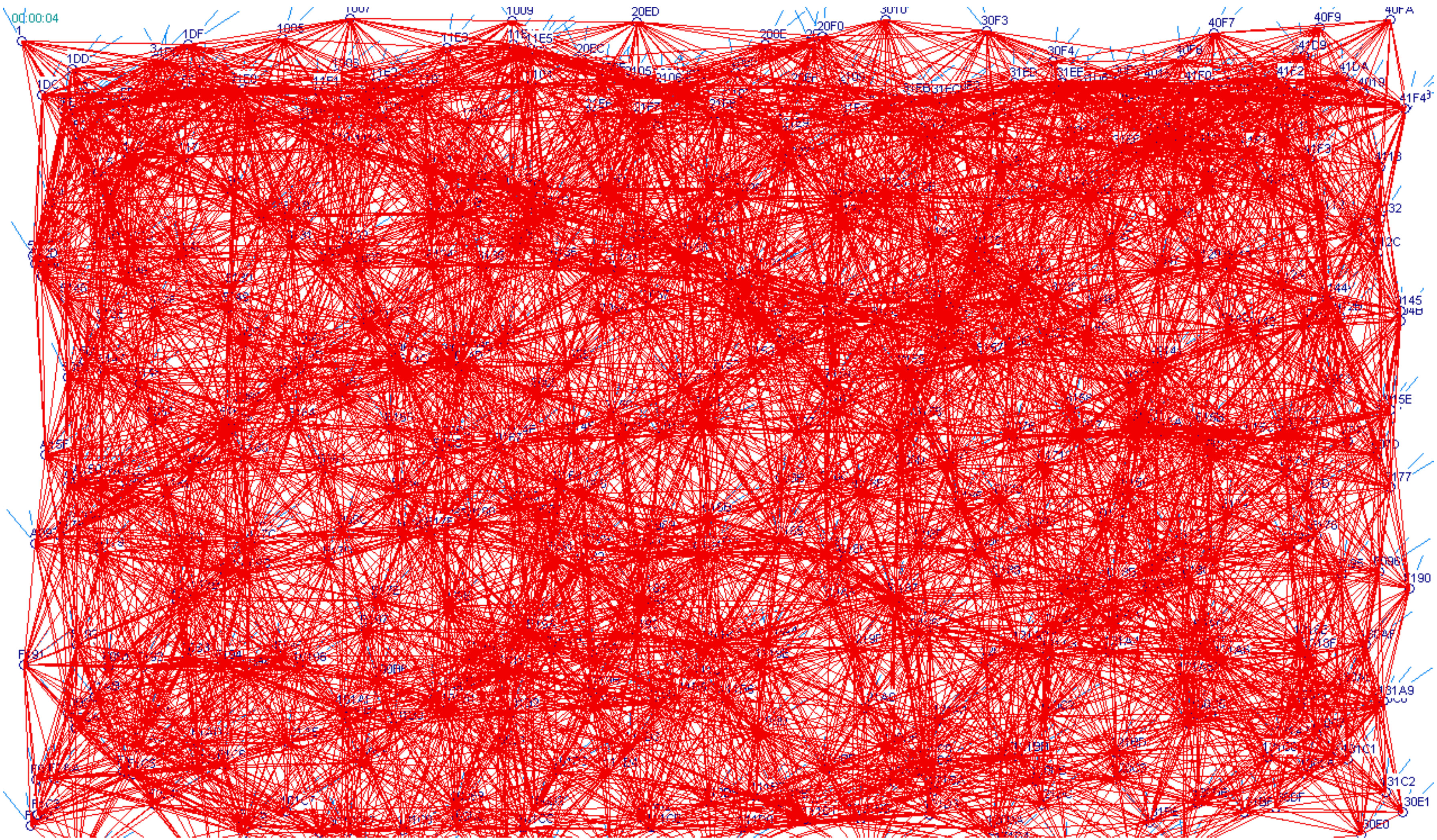
FireGrid

Simulation initial state



Initial state

Ad-hoc On Demand Distance Vector (AODV) Routes



First 30 minutes

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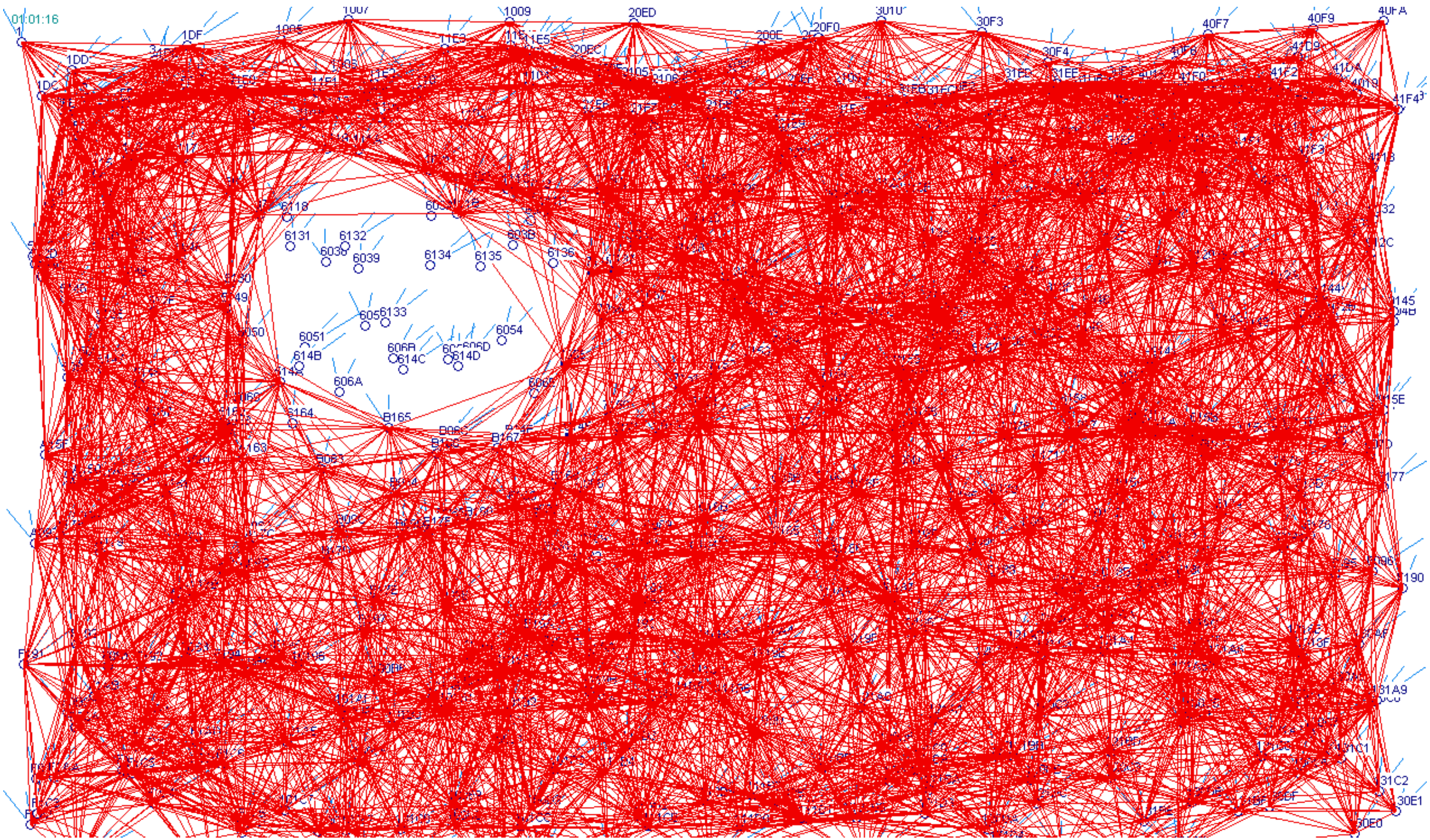
AODV Route Simulation - 2



Second 30 minutes

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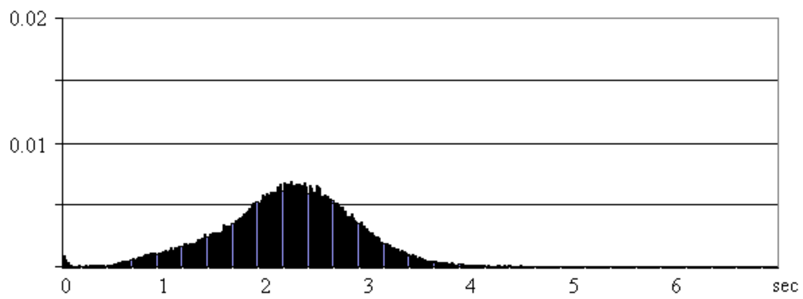
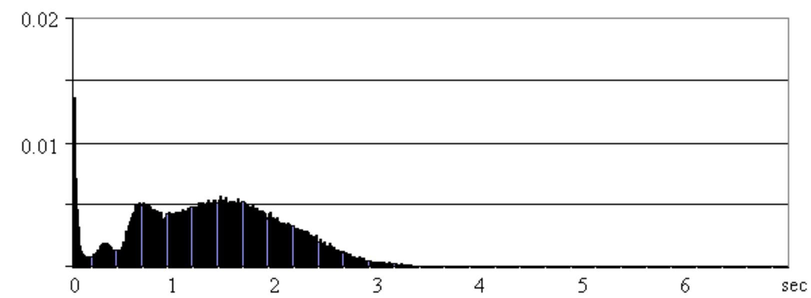
Collision delay PDF Simulation

Delay PDF: sensor from rooms 0, 1, 5 & 11 to sink over 1st 30 min

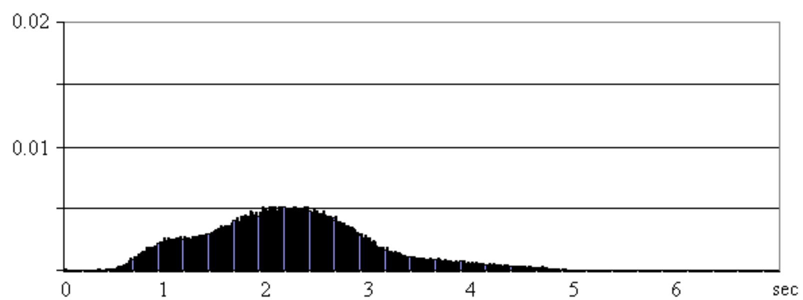
Zone_00(mean delay=2200 ms, rate=3.66 pkts/s)



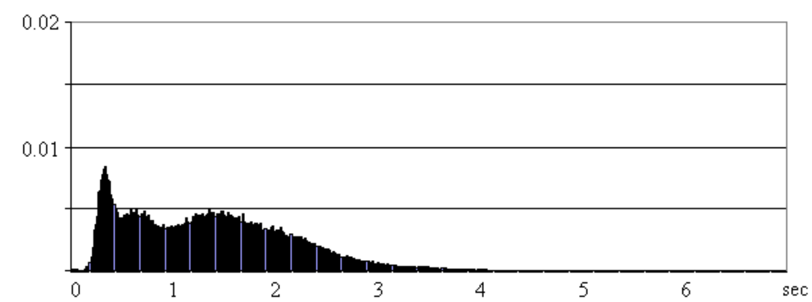
Zone_01(mean delay=1350 ms, rate=3.03 pkts/s)



Zone_05(mean delay=2200 ms, rate=3.38 pkts/s)

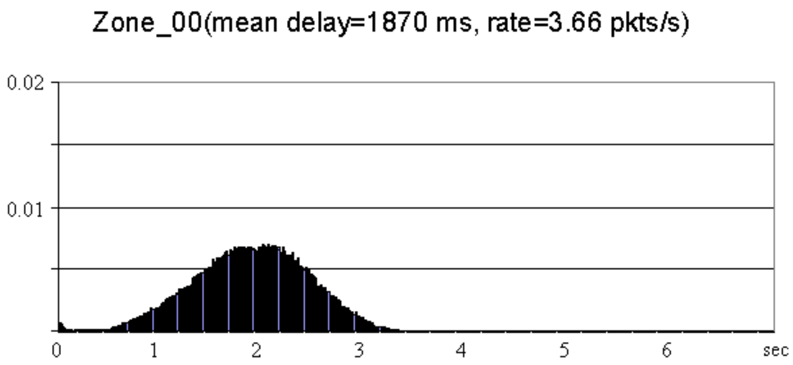


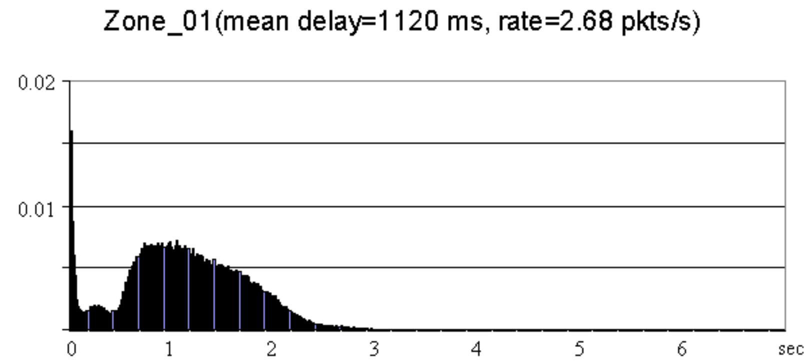
Zone_11(mean delay=1350 ms, rate=2.96 pkts/s)

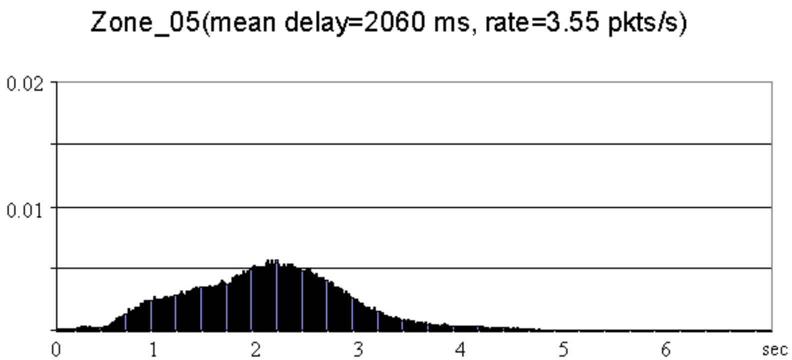


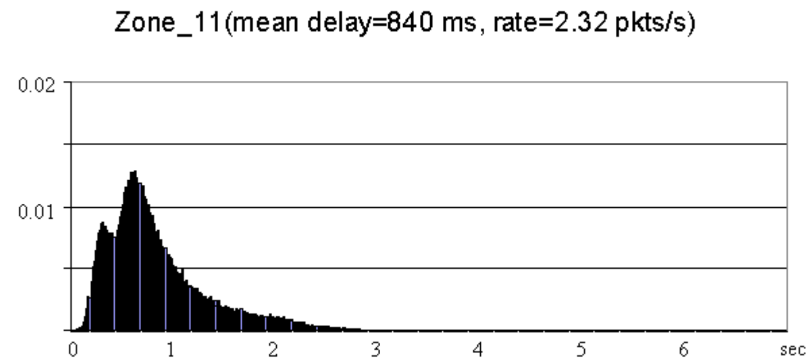
Collision Delay PDF Simulation

Delay PDF: sensor from rooms 0, 1, 5 & 11 to sink over 2nd 30 min



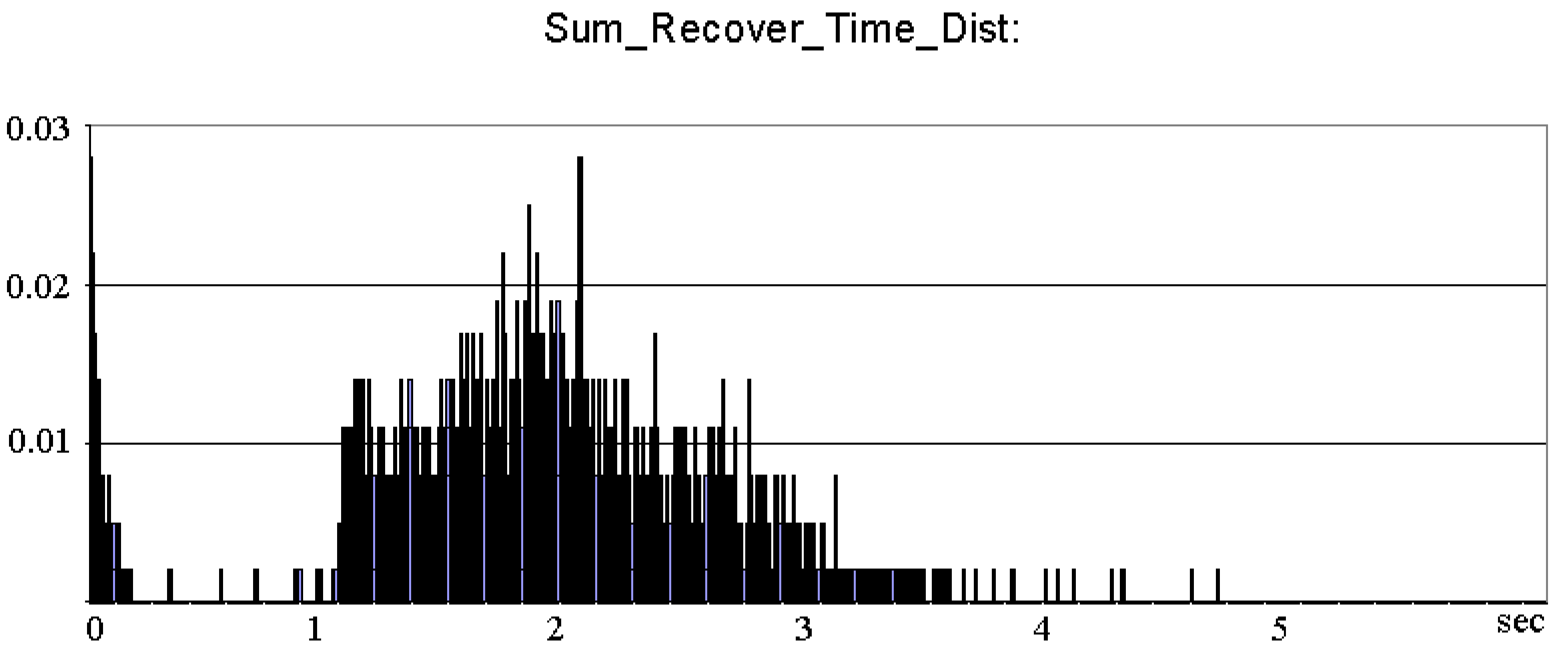






Simulation Histogram over 30 runs

Shows Route Recovery Time is typically 2 s



G. Conclusions

- Ad-hoc is a flexible wireless network concept
- Fire monitoring requires a highly dense network of sensors and wireless transmission is an attraction
- Dense sampling + high transmission rates cause degradation of performance with communications protocols
- Use correlations in sensor fire data to reduce data
- Clustering is a method of exploiting these correlations
- Ad-hoc protocols auto reroute to avoid sensor loss

Technology Strategy Board

bre

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Thank you

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ARUP

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FireGrid

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- **FireGrid results:**

Tsertou *et al*., in: http://www.see.ed.ac.uk/~firegrid/FireGrid/ProjectPapers/WP4