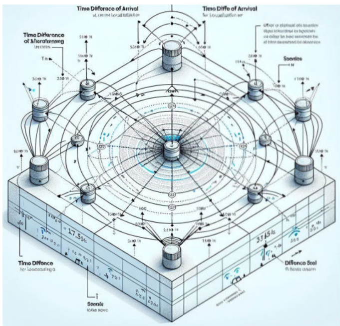
TDoA-Based Localization Case Study



Scenario Context:

- A forest fire detection system uses WSN to locate a sensor triggered by smoke. Three synchronized anchor nodes record the Time Difference of Arrival (TDoA) of the sensor's signal.

Input Values:

- Anchor A1: (0, 0), t1 = 0 (reference)
- Anchor A2: (20, 0), t2 = 0.03 micro seconds
- Anchor A3: (10, 15), t3 = 0.015 micro seconds
- Speed of signal: 300 m/micro seconds (radio waves)

Step by step calculations

- Convert Time to Seconds
- - 1 μs = 10^-6 s
- - t2 = 0.03 μs = 3 × 10^-8 s
- - t3 = 0.015 μs = 1.5 × 10^-8 s
- - Differences from A1:
- - Δt21 = t2 - t1 = 3 × 10^-8 s
- - Δt31 = t3 - t1 = 1.5 × 10^-8 s

Compute Range Differences

- Formula: Range = Speed × Time

- d21 = (3 × 10^8) × (3 × 10^-8) = 9 m (A2 - A1)

- d31 = (3 × 10^8) × (1.5 × 10^-8) = 4.5 m (A3 - A1)

- Meaning: Distance differences from sensor to anchors.

Define TDoA equations

- Sensor position: (x, y)
- Distances:
- d1 = √(x^2 + y^2) (to A1)
- d2 = √((x - 20)^2 + y^2) (to A2)
- d3 = √((x - 10)^2 + (y - 15)^2) (to A3)
- Equations:
- d2 - d1 = 9
- d3 - d1 = 4.5

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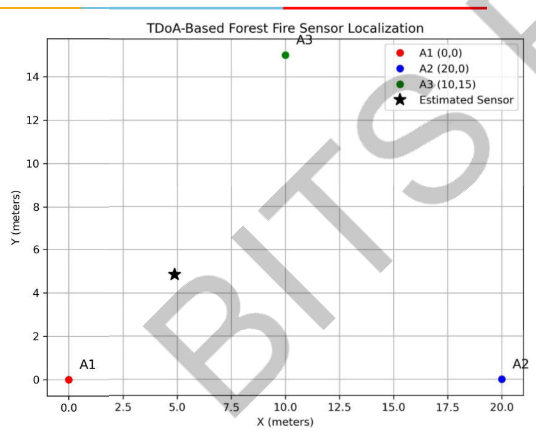
Solve for x and y

- Simplified Equations:
- √((x - 20)^2 + y^2) = √(x^2 + y^2) + 9
- √((x - 10)^2 + (y - 15)^2) = √(x^2 + y^2) + 4.5
- After squaring and solving:
- y ≈ 4.84 m
- Quadratic for x: 1276x^2 - 25520x + 94172.68 = 0
- Solutions: x ≈ 4.88 m or 15.12 m

Verify and conclude

- Test (4.88, 4.84):
  - d2 - d1 ≈ 9 m (matches)
  - d3 - d1 ≈ 4.5 m (matches)
- Test (15.12, 4.84): Doesn't match.
- Final Answer: Sensor at (4.88 m, 4.84 m)



Received Signal Strength (RSSI)

$\frac{P_{RX}}{P_{TX}} =$

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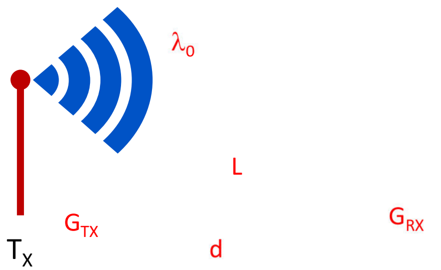
Received Signal Strength (RSSI)



$$\frac{P_{RX}}{P_{TX}} =$$

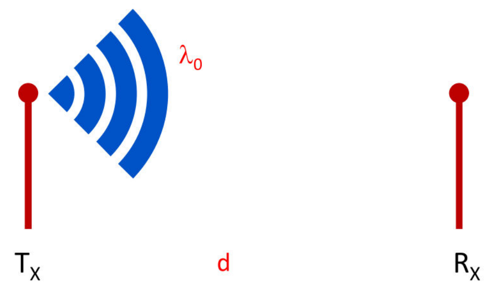
Received Signal Strength (RSSI)

$$\frac{P_{RX}}{P_{TX}} = G_{TX}$$

Received Signal Strength (RSSI)

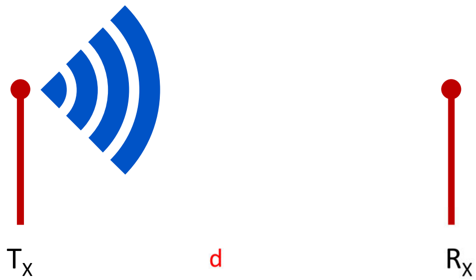
$$\frac{P_{RX}}{P_{TX}} = G_{TX}\ G_{RX}$$

Received Signal Strength (RSSI)



$$\frac{P_{RX}}{P_{TX}} = \frac{G_{TX}\ G_{RX}}{L}$$

Received Signal Strength (RSSI)



$$\frac{P_{RX}}{P_{TX}} = \frac{G_{TX}\ G_{RX}}{L} \quad \lambda_0$$

Received Signal Strength (RSSI)

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$$\frac{P_{RX}}{P_{TX}} = \frac{G_{TX}\ G_{RX}}{L} \quad \frac{\lambda_0}{d}$$

Received Signal Strength (RSSI)

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$$\frac{P_{RX}}{P_{TX}} = \frac{G_{TX}\ G_{RX}}{L} \left\{\frac{\lambda_0}{4\pi d}\right\}^2$$

Received Signal Strength (RSSI)

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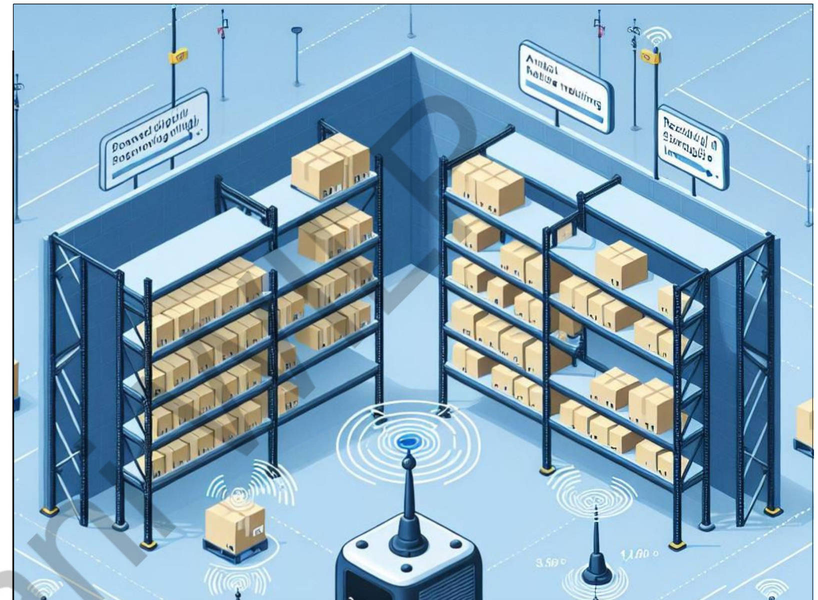
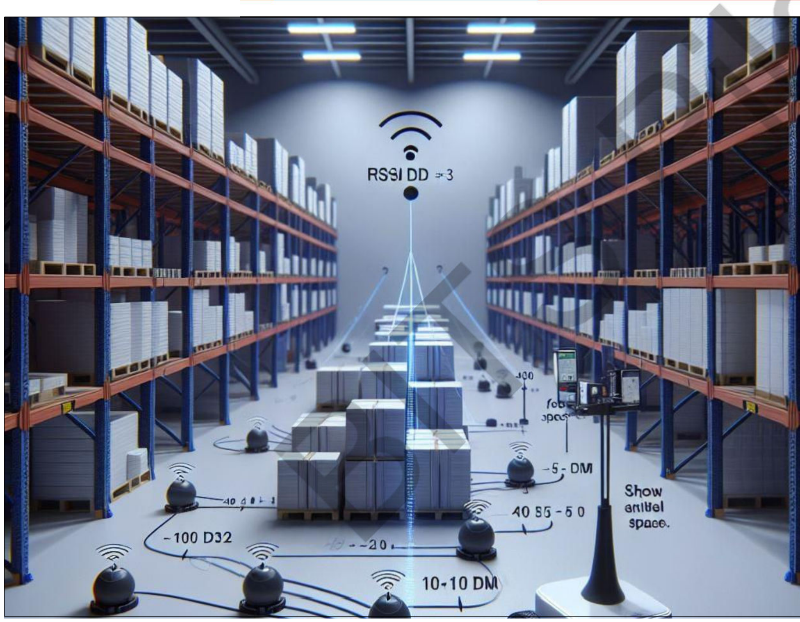
$$\frac{P_{RX}}{P_{TX}} = \frac{G_{TX}\ G_{RX}}{L} \left\{\frac{\lambda_0}{4\pi d}\right\}^2$$ FRIIS Equation

$$PL = 10 \log \frac{G_{TX}\ G_{RX}}{L} \left\{\frac{\lambda_0}{4\pi d}\right\}^2$$

$$d_{max} = \frac{\lambda_0}{4\pi 10^{-PLmax/20}}$$

CASE STUDY - 2





Case Study

RSSI-Based Localization

- **Scenario Context:**
- A warehouse uses WSN to track a mobile robot navigating between storage racks. Three anchor nodes with known positions transmit signals to the robot, and the Received Signal Strength Indicator (RSSI) is measured to estimate its location.

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Input Values:

•Anchor A1: (0, 0), RSSI = -50 dBm
•Anchor A2: (10, 0), RSSI = -60 dBm
•Anchor A3: (5, 10), RSSI = -55 dBm
•Path loss model: RSSI = -40 - 10 * n * log10(d), where n = 2 (free space), d = distance in meters

Step-by-Step Calculations:

1.Convert RSSI to Distance:

1. For A1: -50 = -40 - 20 * log10(d1) → -10 = -20 * log10(d1) → log10(d1) = 0.5 → d1 = 10^0.5 = 3.16 m
2. For A2: -60 = -40 - 20 * log10(d2) → -20 = -20 * log10(d2) → log10(d2) = 1 → d2 = 10^1 = 10 m
3. For A3: -55 = -40 - 20 * log10(d3) → -15 = -20 * log10(d3) → log10(d3) = 0.75 → d3 = 10^0.75 ≈ 5.62 m

Set Up Distance Equations: $(x - 0)^2 + (y - 0)^2 = 3.16^2 \approx 10$
•$(x - 10)^2 + (y - 0)^2 = 10^2 = 100$
•$(x - 5)^2 + (y - 10)^2 = 5.62^2 \approx 31.58$

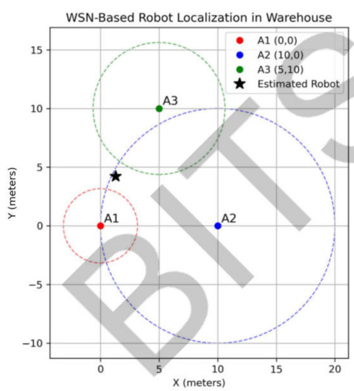
•**Solve Using Trilateration (Subtract Equations):**
•Eq2 - Eq1: $(x^2 - 20x + 100 + y^2) - (x^2 + y^2) = 100 - 10$ → $-20x + 100 = 90$ → $-20x = -10$ → $x = 0.5$

•Substitute x = 0.5 into Eq1: $0.5^2 + y^2 = 10$ → $0.25 + y^2 = 10$ → $y^2 = 9.75$ → $y \approx 3.12$

Verify with A3: $(0.5 - 5)^2 + (3.12 - 10)^2 = (-4.5)^2 + (-6.88)^2 \approx 20.25 + 47.33 \approx 67.58$

Final Result: Robot position ≈ (0.5, 3.12) meters.

RSSI-based localization is simple and cost-effective but sensitive to environmental noise (e.g., walls, interference), leading to errors as seen in A3's verification. Calibration can improve accuracy.



Reference

Theodore S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd Edition, Prentice Hall, 2002.

- Chapter 3: The Wireless Channel
- Section: Large-Scale Path Loss Models

Patwari, N., Ash, J.N., Kyperountas, S., Hero III, A.O., Moses, R.L., & Correal, N.S. (2005). *Locating the nodes: cooperative localization in wireless sensor networks*. IEEE Signal Processing Magazine, 22(4), 54–69.

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Resource Aware Localisation

- An estimated position must have a high precision, and a small localization error.
- Position information must be provided as soon as possible, immediately after network initialization, because many other protocols are based on this data.
- Financial costs for establishing a localization infrastructure must be minimal. This implies cost-efficient beacon hardware as well as minimal number of used beacons.
- The limited resources require minimal effort in computation, communication, and memory consumption.
- Localization must be processed fully distributed to achieve robustness and reliability.
- Algorithms must be adaptive to changing environmental conditions, e.g., fluctuations in the quality of the signal strength indicator.
- Mobility of nodes must be considered.

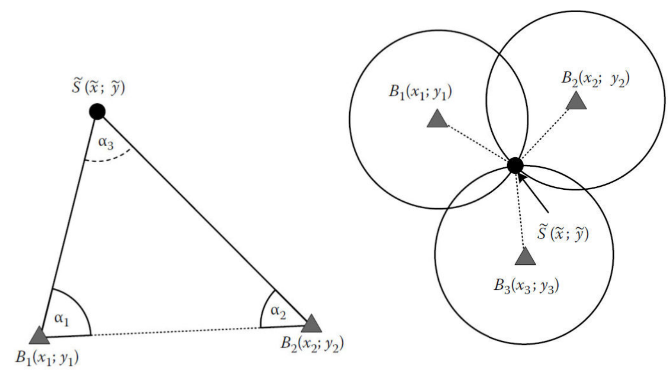
Localisation Algorithm Classification

Approximative versus exact precision → Central versus distributed calculation → Range-based versus distance-free (or angle) → Relative versus absolute localization regarding point of reference → Indoor versus outdoor usage → Beacon-free versus beacon-based

Classification of localisation algorithms

- Localization algorithms
  - Classical methods
    - Trilateration
    - Triangulation
  - Proximity based
    - Nearest beacon
    - Centroid localization
    - Weighted centroid localization
    - Range free
    - Bounding box
  - Optimization methods
    - Fine-grained localization
    - Distributed least squares
    - Convex position estimation
  - Iterative methods
    - Sweeps
    - APS
    - ABC
  - Pattern matching
    - Fingerprinting
    - Pattern Recognition

Triangulation and Trilateration



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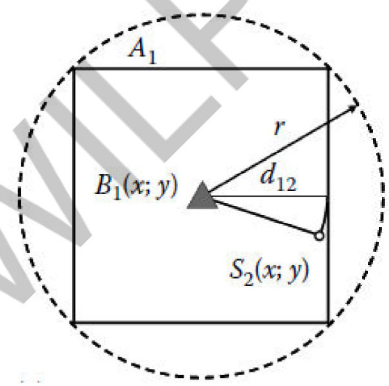
Localisation – Bounding box

- Based upon beacons
  - At Beacon
    - Beacons transmit signals with specific power
    - The range is also well defined
  - At Sensors
    - Determine distance to beacons

Bounding box - Beacon



Bounding box

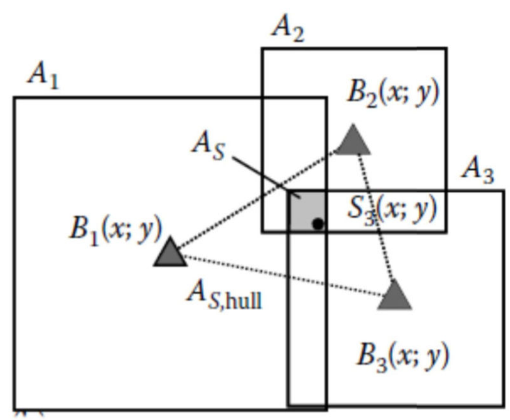
At sensor node

- Quadratic area calculated as d_{ij}^2
- This includes every B_i (x_i, y_i) B_i is the center of the square
- Calculate minimal and maximum coordinates of all resulting squares

$$x_{\min} = \max(x_i - d_{ij}) \le x_j \le \min(x_i - d_{ij}) = x_{\max}$$
$$y_{\min} = \max(y_i - d_{ij}) \le y_j \le \min(y_i - d_{ij}) = y_{\max}$$

- Comparing minimal and maximum coordinates of squares, sensor narrows down the surface on which they are placed

Bounding box



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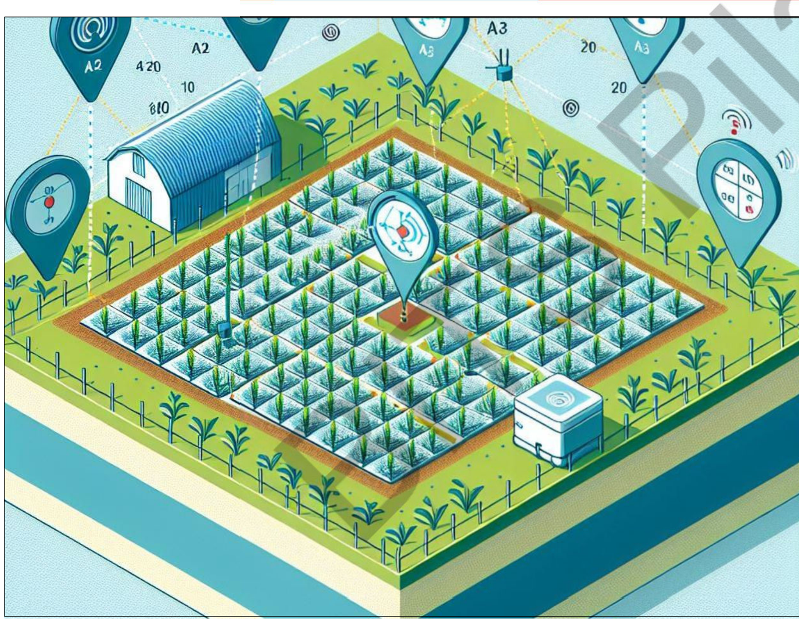
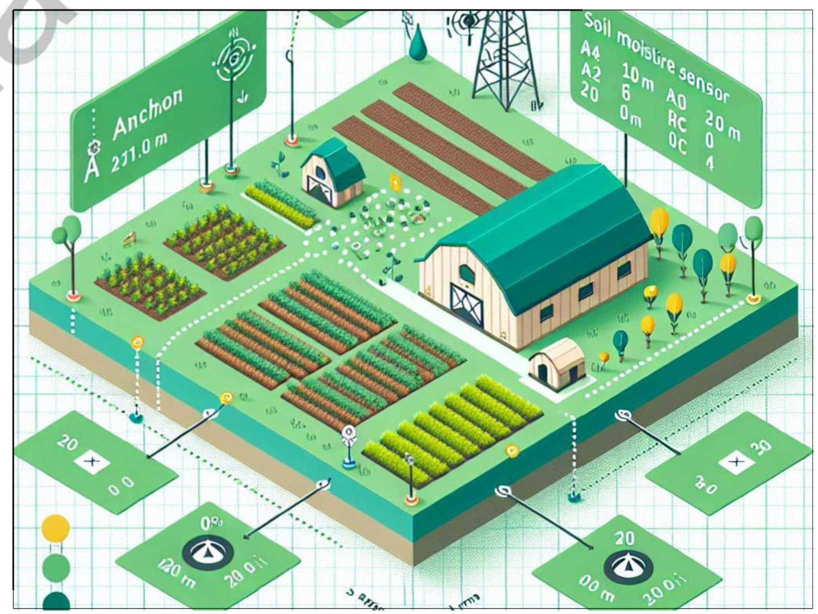
CASE STUDY - 3





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Bounding Box Localization

- **Scenario Context:**

- A smart farm uses WSN to locate a soil moisture sensor. Four anchor nodes detect the sensor within their communication range, forming a bounding box.

Bounding Box Localization Case Study

Input Values:
•Anchor A1: (0, 0), range = 10 m
•Anchor A2: (20, 0), range = 15 m
•Anchor A3: (20, 20), range = 10 m
•Anchor A4: (0, 20), range = 15 m

Step-by-Step Calculations:

1.Define Bounding Boxes:

1. A1: x ∈ [0, 10], y ∈ [0, 10]
2. A2: x ∈ [5, 20], y ∈ [0, 15]
3. A3: x ∈ [10, 20], y ∈ [10, 20]
4. A4: x ∈ [0, 15], y ∈ [5, 20]

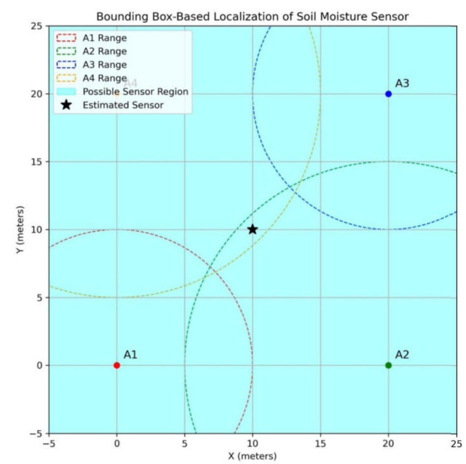
2.Find Intersection:

1. x-range: max(0, 5, 10, 0) to min(10, 20, 20, 15) → [10, 10]
2. y-range: max(0, 0, 10, 5) to min(10, 15, 20, 20) → [10, 10]

3.Centroid of Intersection: Single point (10, 10).

Final Result: Sensor position = (10, 10) meters.

Bounding Box is computationally lightweight and works well with binary (in-range/out-of-range) data, but precision depends on anchor density and range overlap.



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Distributed Least Squares (DLS)

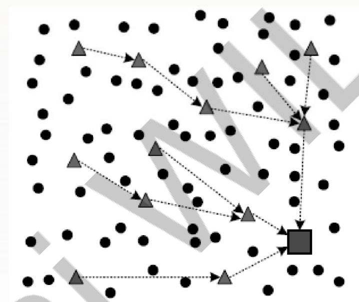
Creates a system of non linear Euclidean distances

Distances are of the form:

- $r_i^2 = (x'-x_i)^2+(y'-y_i)^2$
- i=1,2,3,...m; m – number of beacons
- S'(x',y'): required position
- $B_i(x_i,y_i)$:position of the beacon
- r_i: Distance between them

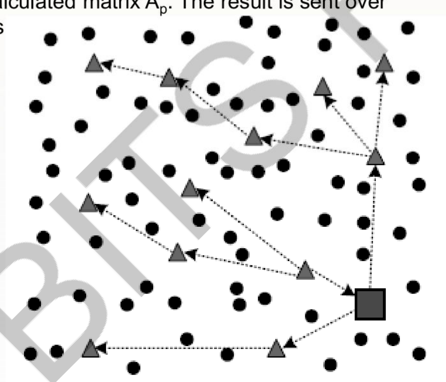
DLS Process Phase 1

All beacons send their position B_i, hop by hop over their beacon neighbours to the base station



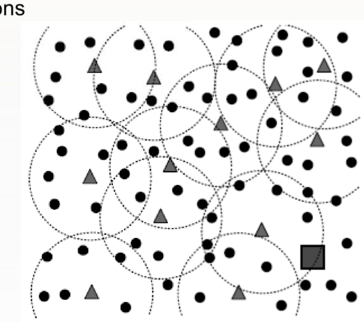
Phase II

Base station generates a precalculated matrix A_p. The result is sent over beacons to all sensor nodes



Phase III

Sensors estimate their position with respect to all beacons based on Ap. The distance is calculated using post calculation Ap.b; where b is the distance vector from the sensor to the beacons



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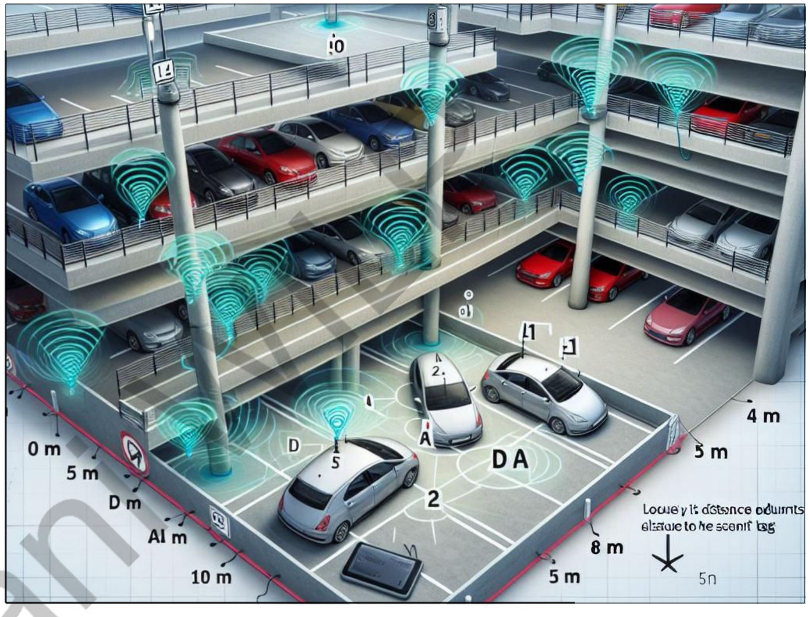
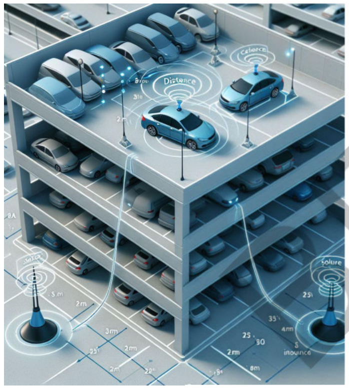
CASE STUDY - 4



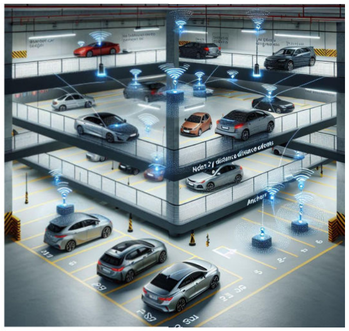
Distributed Least Squares



- **Scenario Context:**
- A WSN in a multi-story parking garage locates a car's sensor tag. Three anchors provide noisy distance estimates, solved iteratively across nodes.

Case Study-4

Distributed Least Squares (DLS)



- **Scenario Context:**
- A WSN in a multi-story parking garage locates a car's sensor tag. Three anchors provide noisy distance estimates, solved iteratively across nodes.
- **Input Values:**
- Anchor A1: (0, 0), d1 = 5 m
- Anchor A2: (10, 0), d2 = 8 m
- Anchor A3: (5, 10), d3 = 6 m

Step-by-Step Calculations:

1.Initial Guess: $(x, y) = (5, 5)$

2.Distance Errors:

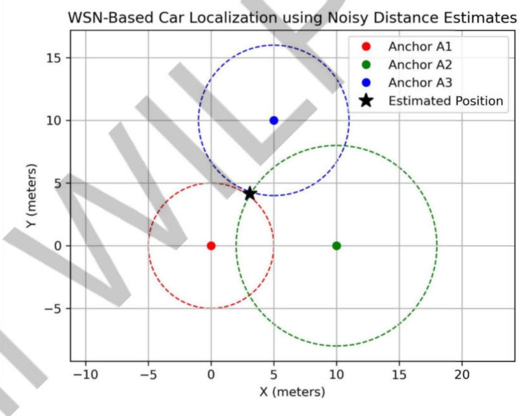
1. A1: $\sqrt{5^2 + 5^2} = 7.07$ m, error = 7.07 - 5 = 2.07
2. A2: $\sqrt{(5 - 10)^2 + 5^2} = 7.07$ m, error = 7.07 - 8 = -0.93
3. A3: $\sqrt{(5 - 5)^2 + (5 - 10)^2} = 5$ m, error = 5 - 6 = -1

3.Minimize Error (Gradient Descent):

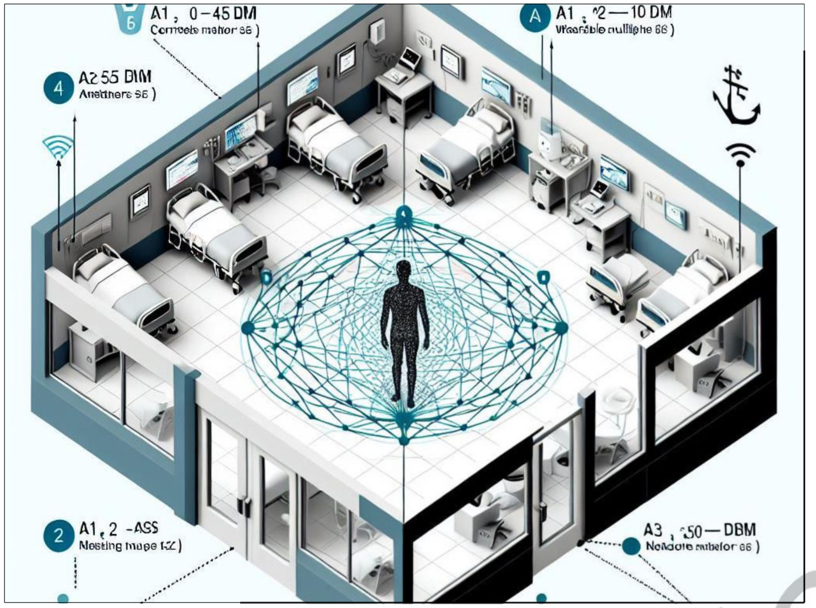
1. Adjust x -= 0.1 * (2.07 - 0.93) ≈ 4.9, y -= 0.1 * (-1) ≈ 5.1
2. Recalculate, iterate until convergence (e.g., $x \approx 3$, $y \approx 4$).

Final Result: Car position ≈ (3, 4) meters.

DLS distributes computation, reducing anchor load, but convergence speed depends on initial guess and noise levels.



CASE STUDY - 5



Hybrid/AI-Enhanced Localization

Scenario Context:

A hospital WSN tracks a patient's wearable device using RSSI and a neural network to correct for indoor multipath effects.

Hybrid/AI-Enhanced Localization

Scenario Context:
A hospital WSN tracks a patient's wearable device using RSSI and a neural network to correct for indoor multipath effects.

Input Values:
- Anchor A1: (0, 0), RSSI = -45 dBm
- Anchor A2: (10, 0), RSSI = -55 dBm
- Anchor A3: (5, 10), RSSI = -50 dBm
- NN trained on: RSSI → distance, accounting for walls

Step-by-Step Calculations:

1.Raw RSSI Distances (n = 2):
1. A1: $d1 \approx 2.24$ m
2. A2: $d2 \approx 5.62$ m
3. A3: $d3 \approx 3.16$ m

2.NN Correction: Adjusts for multipath → $d1 = 2.5$ m, $d2 = 6$ m, $d3 = 3.5$ m

1.Trilateration:
1. $(x^2 + y^2) = 2.5^2 = 6.25$
2. $(x - 10)^2 + y^2 = 6^2 = 36$
3. $(x - 5)^2 + (y - 10)^2 = 3.5^2 = 12.25$
4. Solve: $x \approx 4$, $y \approx 3$ (after substitution and verification).

Final Result: Patient position ≈ (4, 3) meters.

Hybrid/AI methods enhance accuracy in complex environments by learning patterns, but require training data and computational resources.

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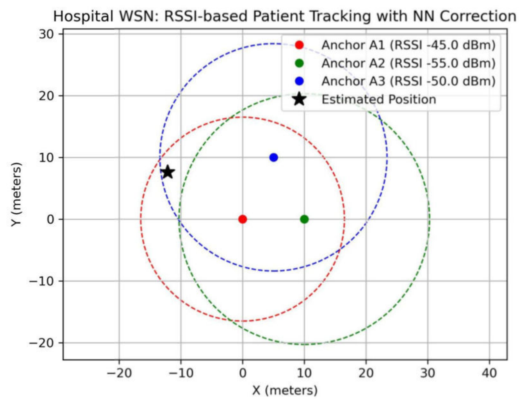

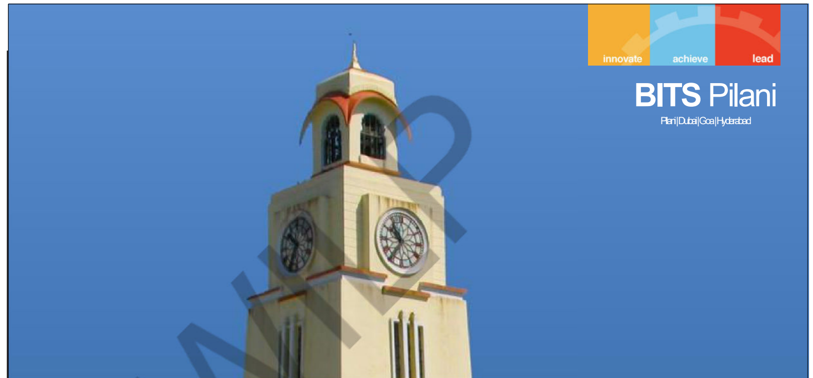

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Questions?

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Network Embedded Applications
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IMP Note to Self

Start Recording

IMP Note to Students

- It is important to know that just login to the session does not guarantee the attendance.
- Once you join the session, continue till the end to consider you as present in the class.
- IMPORTANTLY, you need to make the class more interactive by responding to Professors queries in the session.
- **Whenever Professor calls your number / name ,you need to respond, otherwise it will be considered as ABSENT**

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Routing in WSN

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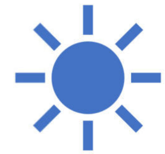
Characteristics of WSN

- Cooperative network
- Operating in unattended environment
- Node
  - Equipped with processor
  - Radio frequency transceiver
  - Sensor and actuator
  - Memory
  - Power source
- Nodes capable of processing and routing

Challenges with existing routing protocols

Computation intensive



Consume large amount of energy

Characteristics of WSN - Routing

Distributed Systems	WSNs
Wired	Wireless
Reliable connections	Error-prone connections (depending on the link quality, signal strength, noise, interference, atmospheric conditions, etc.)
Symmetric links	Asymmetric links
Unlimited power	Scarce power
Generally not real-time	Typically real-time
Each individual node is important	Aggregate behavior counts
Location-independent	Location-dependent
Resources not an issue	Resource-limited

Differences within WSN

Variable Link Properties
Traffic patterns
Routing decisions usually based on geographic coordinates and/or data semantics, instead of node IDs
Unicast, area multicast or anycast semantics
Node sleep/wakeup for power management
Voids on the routing path

Routing in WSN

Flooding
- Advantages?
- Challenges?

Gossiping???
- Forward packet to a random neighbour
- Forwarding done at each hop till destination is reached
- Can have large end to end delay

Data implosion?

Power consumption not accounted for

WSN routing challenges

Battery operated

Communication cost higher than computation cost

Requirement
- Power efficient routing
- Low power MAC protocols
- Reduce power consumption by reduced collisions, idle listening, control packet exchange

Routing: points to be considered

Data delivery model
- Proactive – monitoring data, continuous data delivery
- Reactive- triggered by occurrence of event or query

Direct delivery or multi-hop
- Direct delivery used when sink is close to source
- Multi hop when separation is large
- Multi hop helps conserve battery power

Routing protocols points to be considered

Performance metrics
- Average packet delay
- Delivery ratio
- Energy efficiency
  - Average energy consumed
  - Total energy dissipated
  - Energy*delay metric – energy consumed depends on amount of data exchanged
- Network lifetime
  - First node dies
  - Half node alive (also known as half life)

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Routing protocols – points to be considered

Role of Topology management protocols

- Determine which nodes can turn off their radios
- Coordinate sleep transitions

Energy saving routing protocols

Optimisation based routing protocols

- Also referred to as Energy Aware Routing (EAR)
- Metrics
  - Energy consumed per message
  - Variance in power level of each node
  - Cost/ packet ratio
  - Maximum energy drain
- Challenges
  - Minimisation of energy consumed /packet may lead to poor routing choice. Some nodes may get overloaded
  - Maximise network life

Data centric routing protocols

- Data redundancy leads to energy wastage
- No global identifiers (like IP address)
- Routing done using meta data
- Data negotiation done between nodes
- Data redundancy reduced by data aggregation
  - Data combined from different sources
  - Apply functions such as average, minimum, maximum
  - Avoids overlap

Cluster based routing protocols

- Nodes closer to sink or on optimal path perform more relaying, thus are depleted faster
- Danger – when all nodes close to sink die, sink becomes unreachable
- Cluster or hierarchy formed to avoid this problem
- Cluster heads form the backbone of WSN
  - Collects data from sensors and forwards to sink
  - Equipped with powerful energy reserves
  - Cluster heads could be dynamic – roles keep on changing

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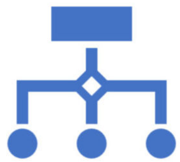
Location based routing

- Use position of source and sink for making routing decisions
- Can also use information on sensed data, data area
- Can be used for targeted delivery
- Has potential to reduce number of transmission

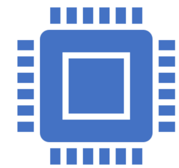


Sensor Protocol for Information via Negotiation (SPIN)

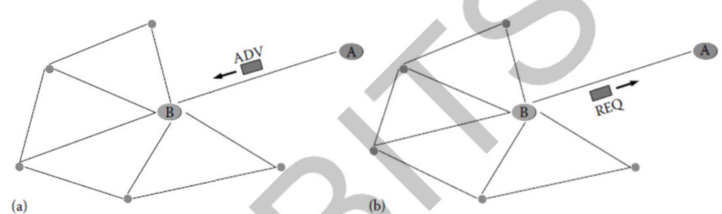
Uses Meta data information for routing

Three types of messages exchanged

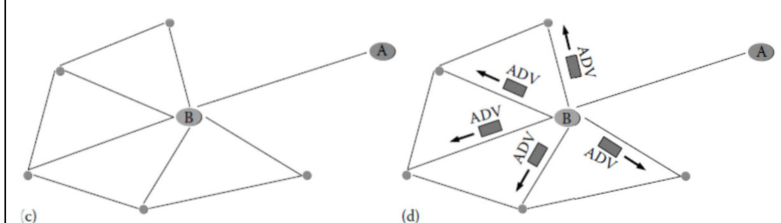
- ADV message – used to advertise node has data to share
- REQ- used by node to request data
- DATA- message that contains actual data



Sensor Protocol for Information via Negotiation (SPIN)



SPIN



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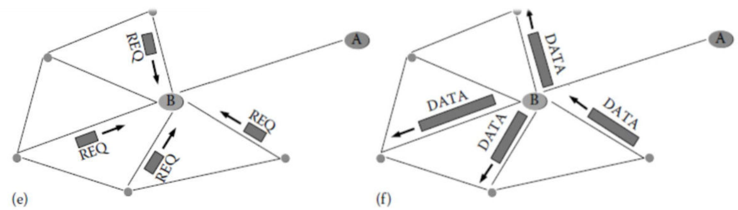
SPIN



SPIN

In a wireless sensor network using the SPIN-PP protocol, a source node generates a data item with a metadata descriptor of 40 bytes. Each node has 8 neighbor nodes on average. The energy costs are:

- Transmitting/receiving an ADV message: 0.12 mJ per byte
- Transmitting/receiving an REQ message: 0.18 mJ per byte
- Transmitting/receiving the DATA message: 0.22 mJ per byte

The DATA message payload is 600 bytes.

SPIN

Questions:

1. Calculate the total energy consumed by the source node to disseminate this data using the SPIN-PP three-phase handshake (ADV → REQ → DATA).
2. Calculate the energy consumed by flooding protocol where the source directly transmits the 600-byte DATA to all 8 neighbors without negotiation.
3. Calculate the percentage energy saved compared to a flooding protocol where the source directly transmits the 600-byte DATA to all 8 neighbors without negotiation.

Also provide your observations and conclusions based on above calculations

SPIN Energy Calculations

ADV Phase:

- Source sends a 40-byte ADV message to 8 neighbors.
  - Transmission energy:
    40 bytes * 0.12 mJ/byte * 8 = 38.4 mJ
  - Reception energy (neighbors):
    40 bytes * 0.12 mJ/byte * 8 = 38.4 mJ
  - Total ADV energy:
    38.4 mJ + 38.4 mJ = 76.8 mJ

SPIN Energy Calculations -II

REQ Phase:

8 neighbors send a 40-byte REQ message back to the source.

Transmission energy (neighbors):
40 bytes * 0.18 mJ/byte * 8 = 57.6 mJ

Reception energy (source):
40 bytes * 0.18 mJ/byte * 8 = 57.6 mJ

Total REQ energy:
57.6 mJ + 57.6 mJ = 115.2 mJ

SPIN energy Calculations - III

DATA Phase:
Source sends a 600-byte DATA message to 8 neighbors.

Transmission energy:
600 bytes * 0.22 mJ/byte * 8 = 1,056 mJ

Reception energy (neighbors):
600 bytes * 0.22 mJ/byte * 8 = 1,056 mJ

Total DATA energy:
1,056 mJ + 1,056 mJ = 2,112 mJ

Total SPIN-PP Energy:
76.8 mJ + 115.2 mJ + 2,112 mJ = 2,304 mJ

2. Flooding Protocol Energy calculations

- Direct DATA transmission of 600 bytes to 8 neighbors (without negotiation):
  - Transmission energy:
    600 bytes * 0.22 mJ/byte * 8 = 1,056 mJ
  - Reception energy (neighbors):
    600 bytes * 0.22 mJ/byte * 8 = 1,056 mJ
  - Total Flooding Energy:
    1,056 mJ + 1,056 mJ = 2,112 mJ

3. Percentage Energy Saved calculations

Calculate using the formula:
Energy Saved (%) = ((Flooding Energy - SPIN-PP Energy) / Flooding Energy) * 100

Substitute the values:
= ((2,112 mJ - 2,304 mJ) / 2,112 mJ) * 100
= (-192 mJ / 2,112 mJ) * 100
≈ -9.09%

A negative value indicates that the SPIN-PP protocol uses approximately 9.09% more energy than the flooding protocol in this scenario

Observations and Conclusions

Conclusion:

- SPIN-PP Energy Consumption: 2,304 mJ
- Flooding Protocol Energy Consumption: 2,112 mJ
- SPIN-PP consumes about 9.09% more energy than the flooding protocol in this specific case.

Observation:

The efficiency of the SPIN-PP protocol depends on the ratio of the metadata (ADV/REQ messages) to the DATA payload. In situations with small metadata and a large DATA payload, the overhead of negotiation may result in higher energy consumption than direct flooding. Optimizations could include reducing the metadata size, increasing the DATA payload, or adjusting the energy cost ratios.

SPIN Protocol Simulation (Simplified)

Nodes are A, B, C, D . One of the nodes A has a data and it makes Metadata A: D1.
a. Employing SPIN how would the data be routed if others had not processed that data before?
b. Employing SPIN how would the data be routed if the node C did get that metadata earlier and others had not processed that data before?

Solution:

a.)

A advertises D1
B requests D1
C requests D1
A sends D1 to B
A sends D1 to C
B advertises D1
C advertises D1
D requests D1
B sends D1 to D

SPIN Protocol Simulation (Simplified)

b.)

A advertises D1
B requests D1
C no response D1
A sends D1 to B
B advertises D1
D requests D1
B sends D1 to D

SPIN advantages

- Shorter dissemination time
- Higher reliability
- Low power consumed during ADV/REQ message than DATA message – overall low power consumed

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EAR – Sequential Assigned Routing Protocol

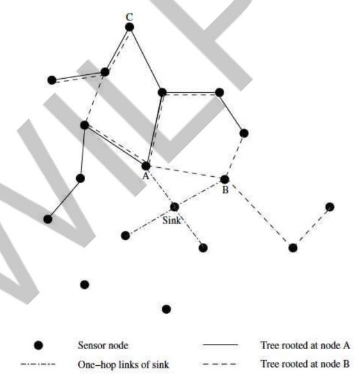
Table driven multi path routing protocol

Aims to improve energy efficiency and fault tolerance

Working

- Multiple paths from each node to sink built using trees
- Each tree is rooted from one hop neighbour of the sink
- A node can belong to multiple trees – leading to multiple disjoint paths

SAR



SAR

Scenario:
A source node (S) wants to send a high-priority packet to the sink node (D).
Three paths are available from source to sink:
Path A: S → N1 → D
Path B: S → N2 → D
Path C: S → N3 → D
Each path has:
QoS metric: Delay (ms)
Residual Energy: Number of packets node can still send
Priority Coefficient (α): Multiplier based on packet priority
Given:

Path	Delay (ms)	Residual Energy	Priority Weight (α)
A	5	40	1.5
B	3	25	1.5
C	4	35	1.5

SAR

Step 1: Compute Weighted QoS Metric
Weighted QoS=QoS Metric×α
Path Weighted QoS Metric
A : 5 × 1.5 = 7.5
B : 3 × 1.5 = 4.5
C : 4 × 1.5 = 6.0

Step 2: Adjust for Energy Resource
Adjusted Path Score=Energy Resource/Weighted QoS Metric
Path Adjusted Score
A : 40 / 7.5 = 5.33
B : 25 / 4.5 = 5.56
C : 35 / 6.0 = 5.83

SAR

Step 3: Path Selection
The highest score corresponds to the most energy-efficient and QoS-compliant path.
Selected Path = Path C (score: 5.83)

Conclusion:
The SAR protocol evaluates multiple paths using a composite metric combining QoS delay, energy resource, and packet priority. In this example, Path C offers the best trade-off between delay and energy, ensuring high-priority delivery with energy balancing.

Energy-Aware Routing Protocol in Cluster based sensor network

- Cluster heads and sensors are fixed and not mobile
- Gateway and senor nodes are different
  - Sensors are battery powered
  - Gateways have unlimited power
- Gateways are centralised network managers
  - Collect sensor data
  - Perform network management
  - Perform data routing

Energy-Aware Routing Protocol in Cluster based sensor network

- Clusters are formed before network starts
- Sensors and gateways are not mobile
- Each cluster head is in range of its node
- Sensor states
  - Sensing
  - Relaying
  - Sensing-relaying
  - Inactive

Energy-Aware Routing Protocol in Cluster based sensor network

Sensor state defined by gateway based on

- Node residual energy
- Performance requirement

MAC is centralised TDMA

Energy-Aware Routing Protocol in Cluster based sensor network

Network functioning

- Data cycle
- Routing cycle

Data cycle

- Sensing and data sent to gateway

Routing cycle

- Routing tables are computed
- Table exchanged with nodes

Path optimisation

Cost of path is sum of cost of links traversed

Metric includes

- Distance
- Residual energy
- Expected lifetime
- Overhead to switch from inactive to active
- Sensing costs
- Maximum connection per relay
- Error rate etc

Energy efficiency

Shutting down nodes not in use

Routing decisions are static for data cycle

New route table calculated only whne a node runs out of power

Low Energy-Adaptive Cluster Hierarchy Protocol (LEACH)

Localized coordination and control for both setup and operational phases

Random rotation of cluster heads

Data aggregation techniques to reduce communication costs

LEACH

Transmission

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$
$$E_{Tx}(k,d) = E_{elec} * k + \varepsilon_{amp} * k * d^2$$

Receiving

$$E_{Rx}(k) = E_{Rx-elec}(k)$$
$$E_{Rx}(k) = E_{elec} * k$$

LEACH

Based on Cluster heads
- Direct transmission
- Long distance, high power transmission

Elected cluster heads

Nodes do low energy transmission to cluster heads

Random rotation prevents energy drain on a single node

LEACH - rounds

Time between election of cluster heads

Performed at predetermined time intervals

Cluster heads change and clusters are reorganised

4 phases

LEACH - Phases

Advertisement phase
- Each node independently decides whether or not to become a clusterhead for the current round.

Choice depends on two main factors:
- Global percentage of cluster-head nodes, which is a predefined parameter for the network,
- The number of rounds in which the node has already been a cluster head.

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LEACH - Phases

Cluster set-up phase:
- After a node has chosen the cluster to join, it has to communicate its choice to the relative cluster head.
- This communication can also use a simple CSMA MAC protocol.

Schedule creation:
- Cluster heads create a TDMA schedule for transmissions inside the cluster and broadcast it to all the cluster nodes.
- In order to avoid interferences with adjacent clusters, each cluster head also selects and communicates a CDMA code to be used during the transmission phase for the whole round.

LEACH - Phases

Data transmission:
- The transmission schedule broadcast to the cluster nodes specifies the time slot in which each node has to transmit.
- During the data phase, non-cluster-head nodes that have data to transmit wait for their time slot and then send data during the allocated transmission time.
- As the radio channel is assumed to be symmetric, the transmitting power can be selected according to the signal strength of cluster-head packets.
- Nodes closer to the cluster head will transmit with lower power.
- Furthermore, as nodes can only transmit during their assigned time slot, they can shut down their radios during the time slots of other nodes.
- Cluster heads, on the other hand have to be active during the whole round, so they cannot shut down their radios.

LEACH data transmission

Cluster heads aggregate data from each node and transmits a single packet to the sink

Election is done using CSMA

Data transmission uses TDMA and CDMA
- TDMA used within the cluster
- CDMA used to reduce interference between nodes of different clusters

Minimum Energy Communication network

Distributed routing protocol	Equipped with low power GPS	Nodes are location aware
Communication is synchronised	Nodes sleep between communication	Self configuration

Minimum Energy Communication network

Premise

- Received power $1/d^n$ d- distance, n – path loss
- Transmission power required is not proportional to covering range
- Use of relays is energy efficient
- A relay range is defined – beyond transmission is not energy efficient
- Perform a localised search for path from source to sink

MECN

Constituent of the protocol

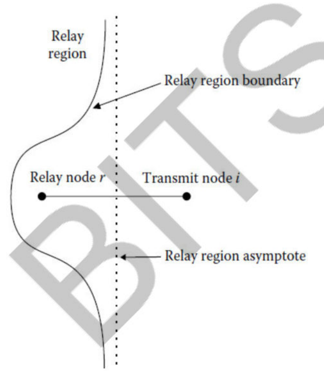
- Enclosure graph
- Minimum path construction

Enclosure graph

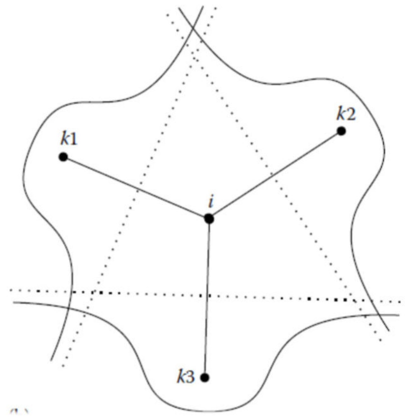
- Beacon transmitted to neighbours
- Listen to beacons from neighbours
- Compute relay region
- Does not account for nodes lying in relay region of other neighbours

Minimum path construction – shortest path algorithm – Bellman -Ford

Minimum Energy Communication network



Minimum Energy Communication network



Sparse Topology Energy Management(STEM)

Designed for nodes spending time on sensing

Energy is optimised during monitoring phase

- Network capacity is reduced during monitoring
- Energy can be saved

Working

- Radios are off for majority of time
- Periodically turned on to listen to neighbours
- Node wanting to communicate switches on the radio and starts transmitting
- Target node on receipt of beacon responds to initiator node
- Dual radio used for wakeup and data plane

STEM

- Suitable for reactive WSN
- Not suitable for proactive WSN
- Delay increases with decreasing duty cycle

Questions?

IMP Note to Self

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Network Embedded Applications (CSIW ZG656)

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Prof.CR Sarma+Prof.Dr.Sandeep Patil
http://taxila-aws.bits-pilani.ac.in/

IMP Note to Self

Start Recording

IMP Note to Students

- It is important to know that just login to the session does not guarantee the attendance.
- Once you join the session, continue till the end to consider you as present in the class.
- IMPORTANTLY, you need to make the class more interactive by responding to Professors queries in the session.
- **Whenever Professor calls your number / name ,you need to respond, otherwise it will be considered as ABSENT**

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Routing in WSN – Part II

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LEACH Example 1

A WSN with 100 nodes exists and it is desired to determine the optimal number of clusters (k) for the LEACH protocol.Assume the energy consumption for transmitting data is proportional to the distance between nodes. There are total nodes (n) = 100 and Probability of a node becoming a CH (p) = 0.05. The energy consumption for transmitting data (E_tx) = 50 nJoule /bit and energy consumption for receiving data (E_rx) = 50 nJoule /bit.

Determine the optimal number of clusters (k) that minimizes the total energy consumption.

LEACH Example 1

Answer:

The optimal number of clusters (k) can be calculated using this formula:

$k = \sqrt{(n * E\_tx / (2 * \pi * E\_rx))}$

Substituting the given values

$k = \sqrt{(100 * 50 / (2 * \pi * 50))}$

$k \approx 5.64$

Conclusion:

The value of k must be an integer and round it to the nearest integer value is k = 6.

LEACH Example 2

If there is a wireless sensor network with 100 nodes ,determine the optimal number of clusters (k) and the cluster heads (CHs) for a given round. The Probability of a node becoming a Cluster Head (p) = 0.05 and Energy consumption for transmitting data (E_tx) = 50 nJoule /bit and for receiving data it is (E_rx) = 50 nJ/bit. Given that Initial energy of each node (E_init) = 1 J.

Determine the optimal number of clusters (k) and the CHs for a given round.

LEACH Example 2

i. Calculate the optimal number of clusters (k) using the formula:

$k = \sqrt{(n * E\_tx / (2 * \pi * E\_rx))}$

Substituting the given values:

$k = \sqrt{(100 * 50 / (2 * \pi * 50))}$

$k \approx 5.64$

Since k must be an integer, we can round it to the nearest integer value. Let's assume k = 6.

LEACH Example 2

ii. Determine the Cluster Heads for the current round:

Each node generates a random number between 0 and 1. If the number is less than the threshold T(n), the node becomes a CH.

T(n) = p / (1 - p * (r mod 1/p)) ; where r is the current round number.

Assuming the current round number is 1and evaluating threshold T(n) Then:

T(n) = 0.05 / (1 - 0.05 * (1 mod 20))

T(n) = 0.05 / (1 - 0.05)

T(n) = 0.0526

Conclusion:

Nodes with a random number less than 0.0526 become Cluster Head.

MECN Example 1

There is a WSN with 5 nodes and need to determine the minimum energy path between node A and node E. Let's assume the energy consumption for transmitting data between nodes is given by the following matrix:

	A	B	C	D	E
A	0	2	3	5	10
B	2	0	1	3	6
C	3	1	0	2	4
D	5	3	2	0	1
E	10	6	4	1	0

Evaluate the minimum energy path from node A to node E.

MECN Example 1

Answer:

Finding the minimum energy path using Dijkstra's algorithm:

A → B → C → D → E

The total energy consumption for this path is:

2 (A → B) + 1 (B → C) + 2 (C → D) + 1 (D → E) = 6

This path has the minimum energy consumption compared to other possible paths.

MECN Example 2

Given a wireless sensor network with 7 nodes and it is desired to determine the minimum energy path between node A and node G. The energy consumption for transmitting data between nodes is given by the following matrix:

	A	B	C	D	E	F	G
A	0	2	5	∞	∞	∞	∞
B	2	0	1	3	∞	∞	∞
C	5	1	0	2	4	∞	∞
D	∞	3	2	0	1	5	∞
E	∞	∞	4	1	0	2	3
F	∞	∞	∞	5	2	0	1
G	∞	∞	∞	∞	3	1	0

The ∞ symbol implies there is no direct connection between the nodes.

Determine the minimum energy path from node A to node G.?

MECN Example 2

Using Dijkstra's algorithm the minimum energy path is evaluated as shown below:

1. Initialize distance array with infinity for all nodes except node A which is set to 0.
2. Realise the edges repeatedly:
   - A → B (distance = 2)
   - B → C (distance = 2 + 1 = 3)
   - C → D (distance = 3 + 2 = 5)
   - D → E (distance = 5 + 1 = 6)
   - E → G (distance = 6 + 3 = 9) or E → F → G (distance = 6 + 2 + 1 = 9)
3. The minimum energy path from node A to node G is:
   total energy consumption for A-B-C- D-E-G =9 & A-B-C-D-E-F-G = 9

Conclusion:

Both paths with same minimum energy taken so either of these paths could be used.

STEM Example

Consider a wireless sensor network (WSN) consisting of 10 sensor nodes uniformly distributed in a 100m × 100m area. Each node can operate in one of two states:

Listen mode, which consumes 50 milliwatts (mW) of power.

Sleep mode, which consumes 5 milliwatts (mW) of power.

The STEM protocol is used to manage energy efficiently by scheduling nodes to alternate between sleep and listen modes. Each node listens for 1 second and sleeps for the remaining 9 seconds in a 10-second duty cycle.

Additionally, a message generated at Node 1 is required to reach Node 10, with the message passing through 3 intermediate nodes (i.e., 3 hops).

STEM Example

Questions:

What is the energy consumed by a single node in one 10-second cycle?

What is the total energy consumed by all 10 nodes in one cycle under the STEM protocol?

If each node were instead in the always-on listen mode, what would the total energy consumption be for one 10-second cycle?

How much energy is saved by using the STEM protocol, both in absolute terms and as a percentage?

STEM Example

1. Energy consumed by a single node per cycle (10 seconds):

Time in listen mode = 1 second → Energy = 50 mW × 1 s = 50 millijoules (mJ)

Time in sleep mode = 9 seconds → Energy = 5 mW × 9 s = 45 mJ

Total energy per node per cycle = 50 mJ + 45 mJ = 95 mJ

2. Total energy consumed by all 10 nodes per cycle:

Energy per node = 95 mJ

Number of nodes = 10

Total energy = 10 × 95 mJ = 950 mJ

STEM Example

3. Energy consumption if all nodes are always in listen mode:
Power consumption = 50 mW for 10 seconds = 500 mJ per node
Total energy = 10 × 500 mJ = 5000 mJ

4. Energy saved using STEM:
Energy saved = 5000 mJ – 950 mJ = 4050 mJ
Percentage saved = (4050 / 5000) × 100 = 81%

Conclusion:
The STEM protocol results in significant energy savings in wireless sensor networks. In this example, it reduces energy consumption by 4050 mJ per cycle, achieving an 81% reduction compared to continuous listening.

Energy Aware Routing Protocol Example

Consider a wireless sensor network (WSN) with **100 sensor nodes** uniformly distributed over an area of **100m × 100m**. The network uses a **cluster-based protocol** where:

- Each cluster has one **Cluster Head (CH)**.
- Energy consumption model:
  - **E_tx = E_elec × k + E_amp × k × d²**
  - **E_rx = E_elec × k**
- Assume:
  - **E_elec = 50 nJ/bit**
  - **E_amp = 100 pJ/bit/m²**
  - **Data packet size (k) = 4000 bits**
  - **Distance between node and CH (d1) = 25 m**
  - **Distance between CH and Base Station (d2) = 75 m**

Questions:
What is the **energy consumed** by a normal node to transmit data to its CH?
What is the **energy consumed** by the CH to receive the data from one node and forward it to the base station?
Calculate the **total energy** used for one communication round if one CH receives data from 10 nodes.

Energy Aware Routing Protocol Example

1. Energy used by a node to transmit to CH:

$$E_{tx\_node} = E_{elec} \times k + E_{amp} \times k \times d1^2$$
$$= (50 \times 10^{-9}) \times 4000 + (100 \times 10^{-12}) \times 4000 \times (25)^2$$
$$= 200 \times 10^{-6} + 250 \times 10^{-6} = 450\mu J$$

2. Energy used by CH to receive from 1 node and send to BS:

- Receiving:

$$E_{rx\_CH} = E_{elec} \times k = 50 \times 10^{-9} \times 4000 = 200\mu J$$

- Transmitting to BS:

$$E_{tx\_CH} = 50 \times 10^{-9} \times 4000 + 100 \times 10^{-12} \times 4000 \times (75)^2$$
$$= 200\mu J + 2.25 \times 10^{-3} J = 200\mu J + 2250\mu J = 2450\mu J$$

- Total per node handled by CH:

$$E_{CH\_total\_1node} = 200\mu J + 2450\mu J = 2650\mu J$$

3. Total energy for 10 nodes in a cluster:

- Total nodes:

$$E_{total\_nodes} = 10 \times 450\mu J = 4500\mu J$$

- CH receives from 10 nodes and sends aggregated data once:

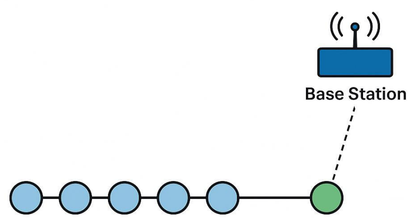
$$E_{total\_CH} = 10 \times 200\mu J + 2450\mu J = 2000 + 2450 = 4450\mu J$$

Total Energy for Cluster = 4500 + 4450 = 8950 µJ (8.95 mJ)

Power-Efficient Gathering in Sensor Information Systems
PEGASIS

- Chain-based routing protocol.
- Each node communicates with its closest neighbor.
- One node (chain leader) sends data to the base station.
- Aims to reduce energy consumption by minimizing the number of transmissions.

PEGASIS Architecture



PEGASIS - Working

- Nodes form a chain using a greedy algorithm.
- Each node receives and sends data to/from a neighbor.
- A different node is selected as leader in each round.
- Leader sends fused data to the base station.

Advantages of PEGASIS

- Significantly reduces energy consumption.
- Minimizes redundant data transmission.
- Increases network lifetime.
- Balances load among nodes.

PEGASIS Limitations

- Delay due to multi-hop transmission.
- Assumes global knowledge of the network.
- Not ideal for dynamic or mobile nodes.

Pegasis

Feature	LEACH	PEGASIS
Cluster Based	Yes	No
Leader	Random per round	Round Robin
Energy consumption	Higher	Lower
Scalability	Moderate	Higher

PEGASIS Example

There is a WSN with 10 nodes, and the need is to determine the total energy consumption for transmitting data from each node to the base station using PEGASIS.
The Energy consumption for transmitting data (E_tx) = 50 nJ/bit and for receiving data (E_rx) = 50 nJ/bit and the Distance between nodes is 10 meters.
Determine the total energy consumption for transmitting 100 bits of data from each node to the base station.

PEGASIS Example

Let's assume the chain is formed in the order: Node 1 → Node 2 → ... → Node 10.

1. Node 1 transmits data to Node 2: E_tx = 50 nJ/bit * 100 bits = 5 µJ
2. Node 2 receives data from Node 1: E_rx = 50 nJ/bit * 100 bits = 5 µJ
3. Node 2 transmits data to Node 3: E_tx = 50 nJ/bit * 100 bits = 5 µJ
4.....
5.....
6......
7.....
8......
9.....
10. Node 10 transmits data to the base station: E_tx = 50 nJ/bit * 100 bits = 5 µJ

Total energy consumption = 5 µJ * 10 (transmissions) + 5 µJ * 9 (receptions) = 50 µ J +45 µ J
= 95 µ J

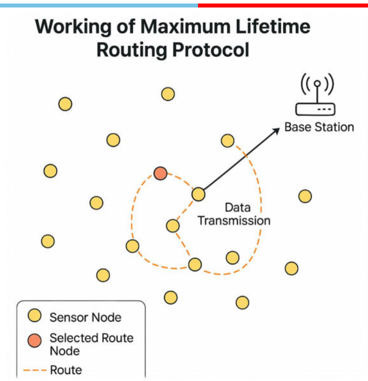
Maximum Lifetime Routing Protocol (MLRP)

- Focuses on maximizing the time until the first node depletes its energy.
- Uses energy-aware routing to balance load among nodes.
- Calculates paths that minimize the maximum energy consumption of any node.
- Selects routes based on remaining energy and energy consumption rate.
- Dynamically adjusts paths to balance node usage over time.

MLRP Features

- Energy-aware routing decisions.
- Balances energy consumption across nodes.
- Extends network lifespan.
- Reacts to changing network conditions.

MLRP Architecture



Advantages of MLRP

- Increases time before first node failure.
- Improves reliability and performance.
- Reduces need for maintenance or node replacement.

Limitations of MLRP

- Requires knowledge of network topology and energy levels.
- May be computationally intensive for large-scale WSNs.
- Sensitive to dynamic changes in the network.

MLRP - Example

Suppose there is a WSN with 5 nodes, and it is desire to determine the maximum lifetime of the network. This network has Initial energy of each node = 1 Joule.
The Transmitting of data energy consumption is 50 nJ/bit and for receiving data = 50 nJ/bit

Determine the maximum lifetime of the network in days if each node transmits 100 bits of data per second.

MLRP - Example

Solution:

Let's assume the network lifetime is determined by the node with the highest energy consumption.

Energy consumption per second = 50 nJ/bit * 100 bits/s = 5 µJ/s

Network lifetime = Initial energy / Energy consumption per second = 1 J / 5 µJ/s
=10^6 micro Joules/5 micro Joules
= 200,000 seconds
So the Maximum lifetime of the network is =200000/60*60*24
=200000/86400
Maximum lifetime of the network =2 Days 7 hrs 33 sec

Real-time Power-Aware Routing (RPAR) Protocol

- Many wireless sensor network applications must resolve the inherent conflict between energy efficient communication and the need to achieve desired quality of service such as end-to-end communication delay.
- This challenge is addressed by Real-time Power-Aware Routing (RPAR) protocol, which achieves application-specified communication delays at low energy cost by dynamically adapting transmission power and routing decisions.

RPAR Design

- RPAR has four components: a dynamic velocity assignment policy, a delay estimator, a forwarding policy, and a neighborhood manager.
- RPAR uses the velocity assignment policy to map a packet's deadline to a required velocity.
- The delay estimator evaluates the one-hop delay of each forwarding choice (N, p) in the neighbor table, i.e. the time it takes a node to deliver a packet to neighbor N at power level p.

RPAR Design

- Based on the velocity requirement and the information provided by the delay estimator, RPAR forwards the packet using the most energy efficient forwarding choice in its neighborhood table that meets the required velocity.
- When the forwarding policy cannot find a forwarding choice that meets the required velocity in the neighbor table, the neighborhood manager attempts to find a new forwarding choice that meets the required velocity through power adaptation and neighbor discovery

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RPAR Conclusion

- RPAR features a power-aware forwarding policy and an efficient neighborhood manager that are optimized for resource-constrained wireless sensors.
- Moreover, RPAR addresses important practical issues in wireless sensor networks, including lossy links, scalability, and severe memory and bandwidth constraints.
- Simulations based on a realistic radio model of MICA2 motes show that RPAR significantly reduces the number of deadlines missed and energy consumption compared to existing real-time and energy-efficient routing protocols.

Constrained anisotropic diffusion routing (CADR)

CADR is a protocol, which strives to be a general form of Directed Diffusion.

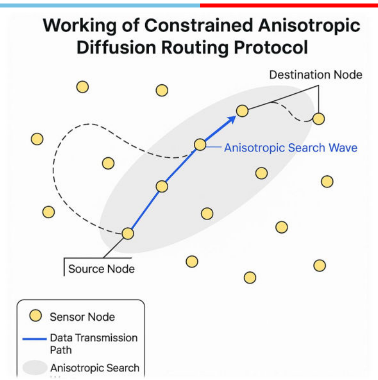
Following Two techniques are proposed

- ➢ Information-driven sensor querying (IDSQ)
- ➢ Constrained anisotropic diffusion routing (CADR)

CADR - Working

- The idea is to query sensors and route data in a network in order to maximize the information gain, while minimizing the latency and bandwidth.
- This is achieved by activating only the sensors that are close to a particular event and dynamically adjusting data routes.
- The major difference from Directed Diffusion is the consideration of information gain in addition to the communication cost.

CADR



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