Role-based Middleware for Wireless Sensor Networks

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Outline

1. Research Statement
2. Wireless Ad hoc Sensor Networks (WSNs)
   - Applications: Civil, Medical, Industrial, Military
   - Network Model
   - System Overview: Hardware/Software
   - Constraints and Challenges
3. Research Contributions
   - Role-based Hierarchical Self Organization Protocol
   - Unified Role Abstraction Framework
   - Role-based Middleware
4. Summary

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Research Goals

- Identify common sensing and networking characteristics among competing application-specific protocol solutions.
- Quantify desired application-oriented context and contingencies in terms of QoS and service requirements.
- Integrate aggregation, hierarchy, and approximation to promote scalability and portability.
- Design a flexible and generic communication abstraction that allow the same set of protocols to be used across applications and platforms with little or no modification.

Outline

Application Objectives

- Reliable monitoring of a variety of environments.
- Enables information gathering and processing.
- Integrates physical sensing and controlling capability with a communication oriented infrastructure, say Internet.
- Useful for various applications including civil and military.

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Sensor Network Applications

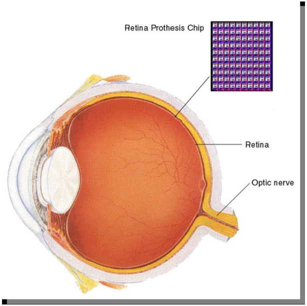
Smart Homes and Offices

Typical Uses

- Sensors controlling appliances and electrical devices in the house.
- Better lighting and heating in office buildings.
- The Pentagon building has used sensors extensively.

Sensor Network Applications

Biomedical/Medical



Typical Uses

- Health Monitors: Glucose, Heart rate, Cancer detection.
- Chronic Diseases: Artificial retina, Cochlear implants.
- Hospital Sensors: Monitor vital signs, Record anomalies.

Sensor Network Applications

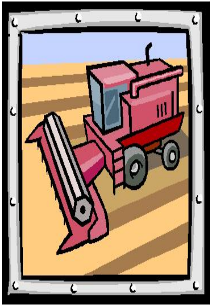
Military/Tactical

Typical Uses

- Remote deployment of sensors for tactical monitoring of enemy troop movements.
- Provides situational awareness.
- Supports troop collaboration, status, and coordination.

Sensor Network Applications

Commercial



Typical Uses

- Agricultural Crop Conditions.
- Inventory and in-Process Parts Tracking.
- Automated Problem Reporting.
- RFID: Theft Deterrent and Customer Tracing
- Plant Equipment Maintenance Monitoring

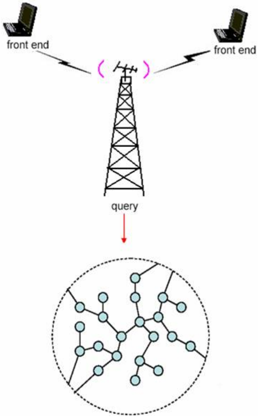
Outline

Ad hoc Communication Paradigm

Proposed Layers for WSNs

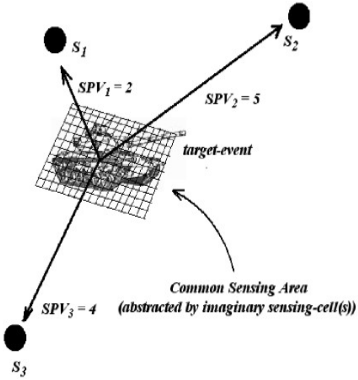
User Queries, External Database
IN–NETWORK Application Processing, Data Aggregation, Query Processing
Data dissemination, Storage and Caching
Adaptive Topology, Geographic Routing
Media Access Control, Location and Time Synchronization
PHYSICAL Communication, Sensing, Actuation, Signal Processing

Typical WSN Infrastructure

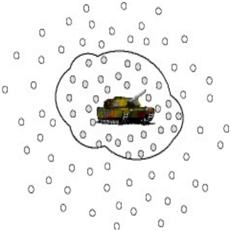


Collaborative Sensing Paradigm

Sensing Proximity/Range

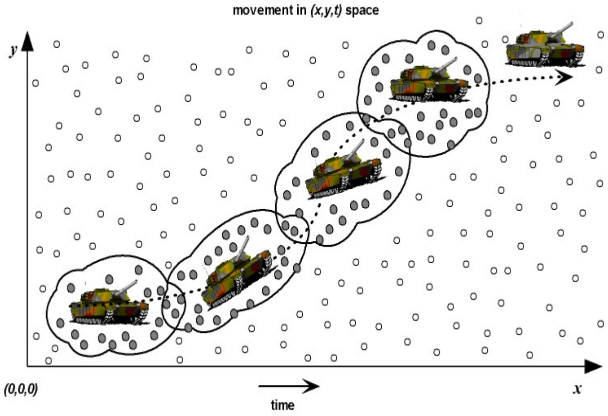


Spatial Sensing



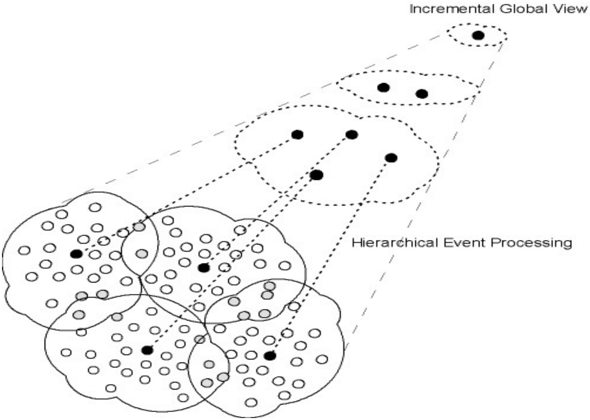
Collaborative Sensing Paradigm

Spatio-Temporal Sensing



Collaborative Sensing Paradigm

Comprehensive Sensing: Incremental and Hierarchical



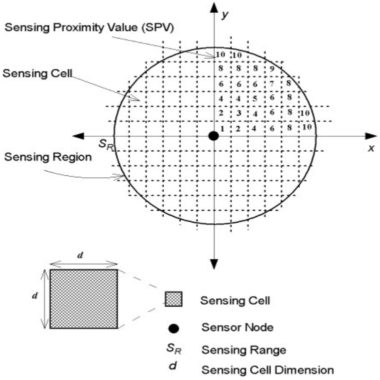
Collaborative Sensing Paradigm

Proposed Sensing Attributes (Metrics)

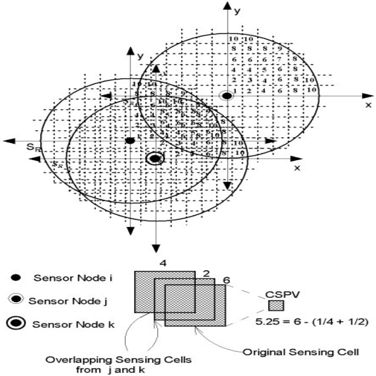
- Sensing Proximity Value (SPV).
- Cumulative Sensing Proximity Value (CSPV).
- Cumulative Sensing Degree (CSD).

Collaborative Sensing Paradigm

Sensing Proximity Value

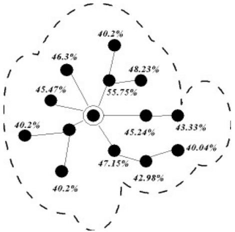


Cumulative Sensing Proximity Value



Collaborative Sensing Paradigm

Group Sensing



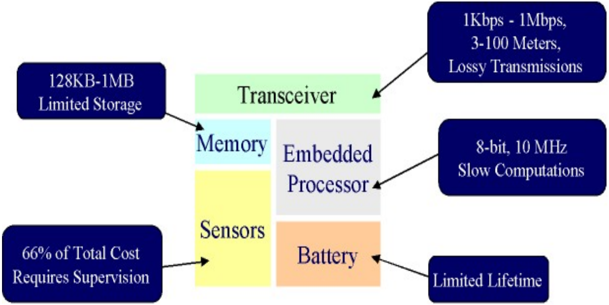
Cumulative Sensing Degree (sQoS)

- Degree of fault tolerant sensing by neighbors.
- Average of CSPVs of all sensing cells.
- CSD: Percentage coverage of ideal and solitary coverages.

Outline

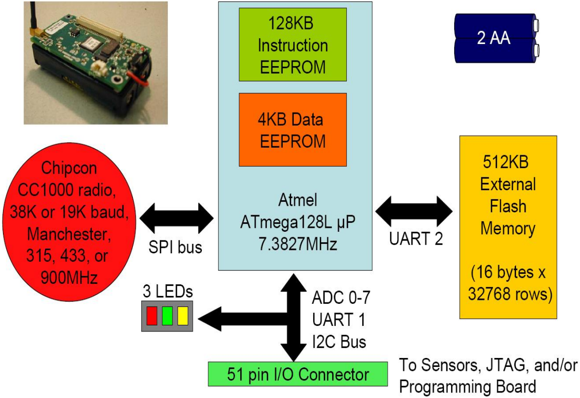
Hardware: System on Chip

Node Hardware Limitations



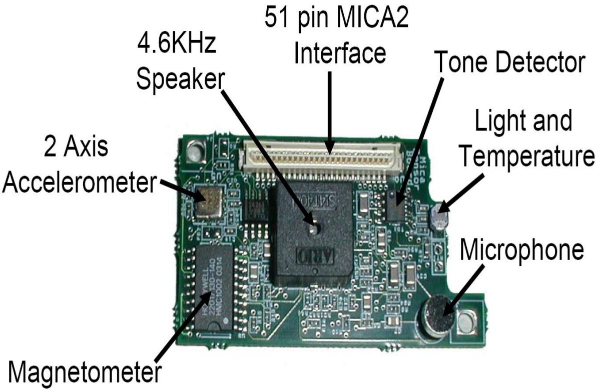
Hardware: Typical Mote

MICA2 Mote (MPR 400CB)



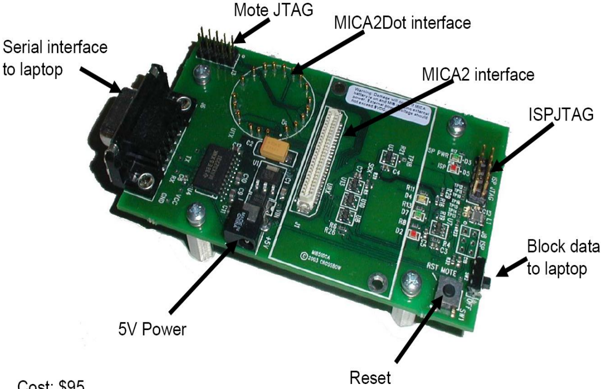
Hardware: Typical Sensor

MTS300CA Sensor Board



Hardware: Programming Board

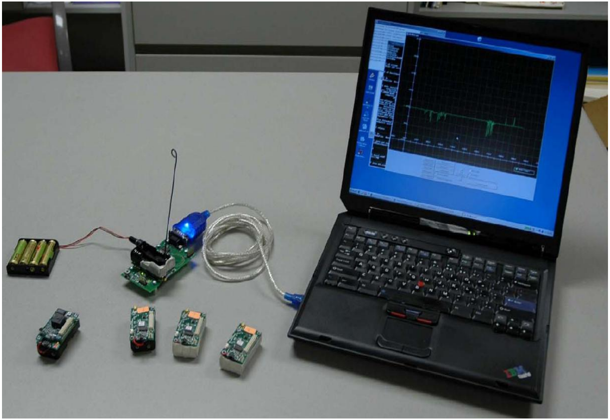
MIB 510



Cost: $95

Typical Hardware Setup

Ad hoc Network With Base Station



TinyOS: Micro Operating System

- Single threaded.
- An open source development environment.
- Component-oriented programming language (NesC).
- Main Ideology: Sleep as often as possible to save power.
- High Concurrency, interrupt driven (no polling).
- Static memory allocation. No heap (malloc) and no function pointers.

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Characteristics

- Large scale deployment.
- High unpredictability.
- Redundancy.
- Constrained resources.
- Real time constraints.
- In-network processing.
- Data-centric processing.
- Security.

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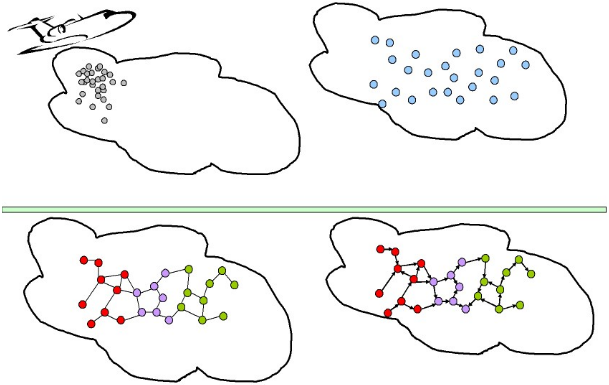
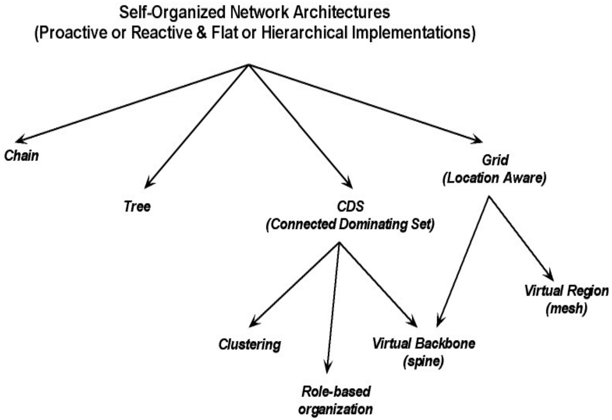
Visualizing Sensor Self Organization

Deploy, Discover, Self-Organize, and Route



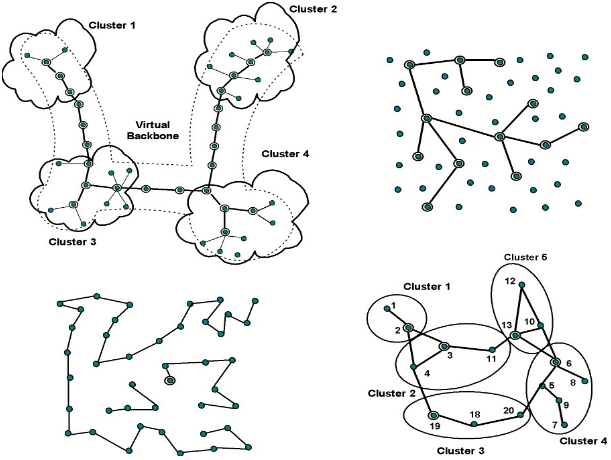
Related Work: Proposed Architectures

Classes of Network Architectures



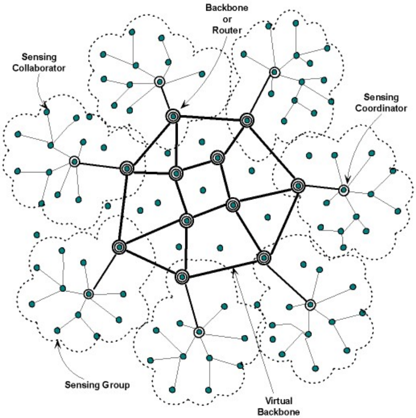
Clockwise: Spine, Tree, Chain, and Cluster (CDS)

Ad hoc Network Architectures

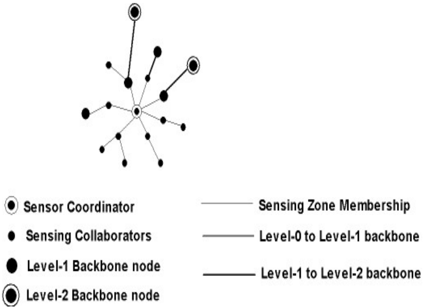


High Level RBHSO Architecture

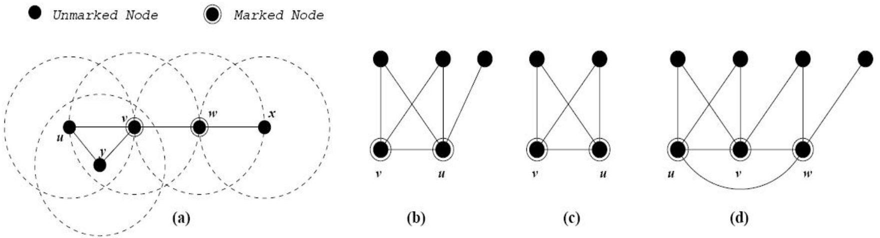
Hierarchical Role Organization



In-network Roles



Recursive Role Domination



Initial marking process

3 examples of dominating set reduction

RBHSO: Algorithm Details

Construct CDS Hierarchy

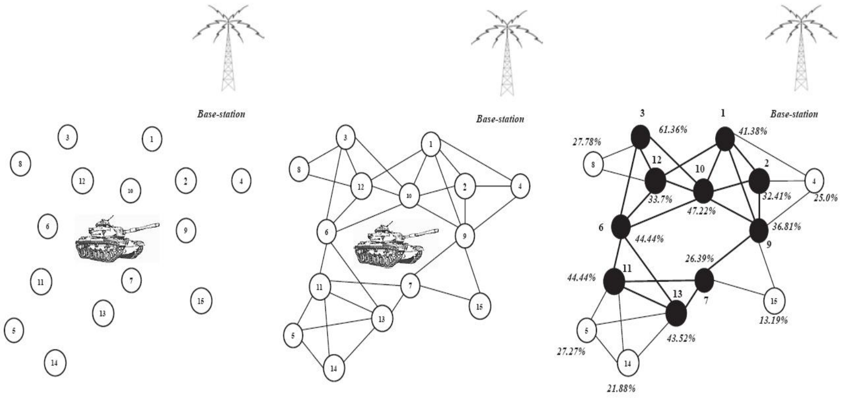
- Neighbor Discovery.
- Initial Marking Process (Level 0 marked nodes).
- Dominating Set Reduction (Level 1+ marked nodes).

Metrics used in order

- Energy Level (EL),
- CSD (or Cumulative Sensing Degree),
- Connectivity based metric or node degree (ND), and
- ID of the sensor node.

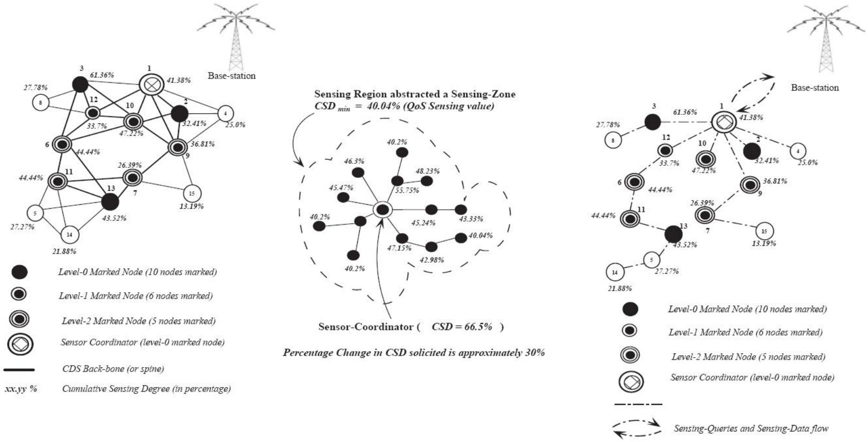
- Sensor Coordinator Selection.
- Sensing Zone Formation Algorithm.

Example Self Organization Scenario



Example 15 sensor nodes deployment $NEIGHBOR_{DISCOVERY}$ stage   marking stage

Example Self Organization Scenario



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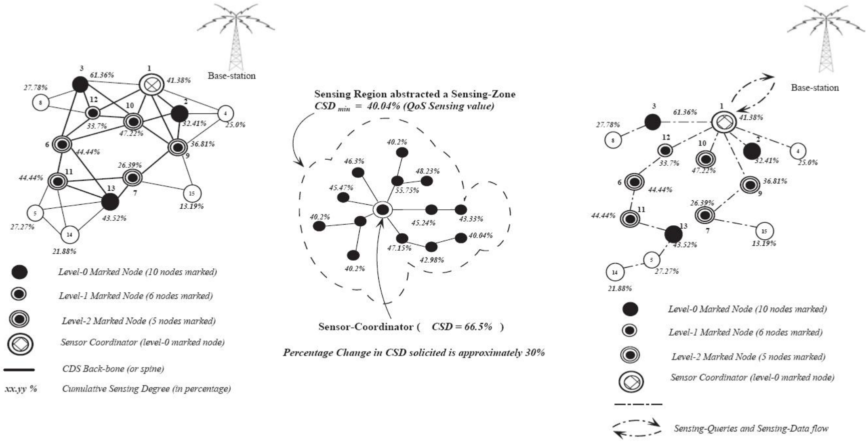
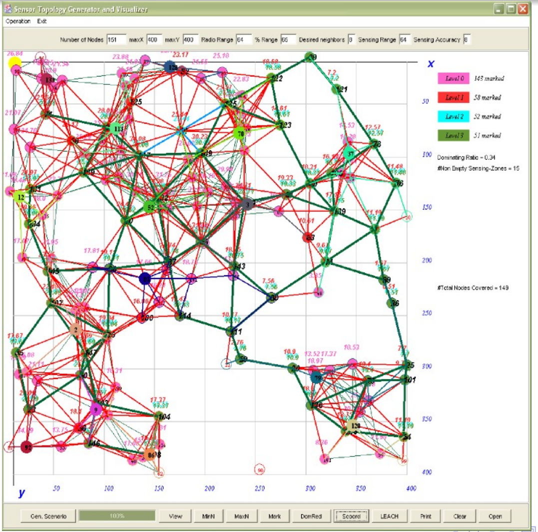
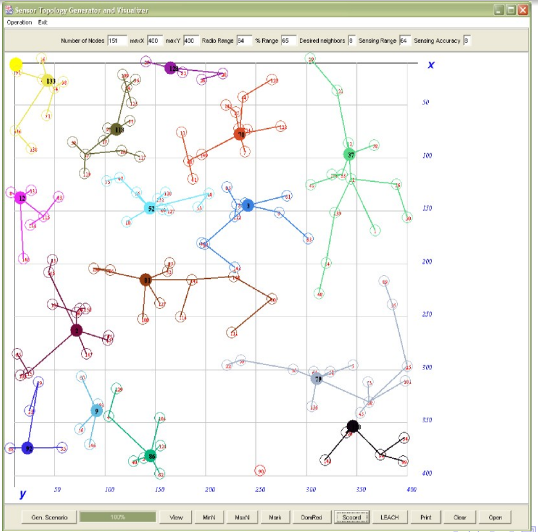


Simulation: Role Hierarchy



Simulation: Sensing Zones



Conclusions

Abstraction: Hierarchy, Approximation, and Aggregation

- Experimented with roles.
- Used several networking and sensing metrics as rules.
- Recursive dominating set reduction results in role-hierarchies.
- Mapped application-specified sQoS such as CSD.

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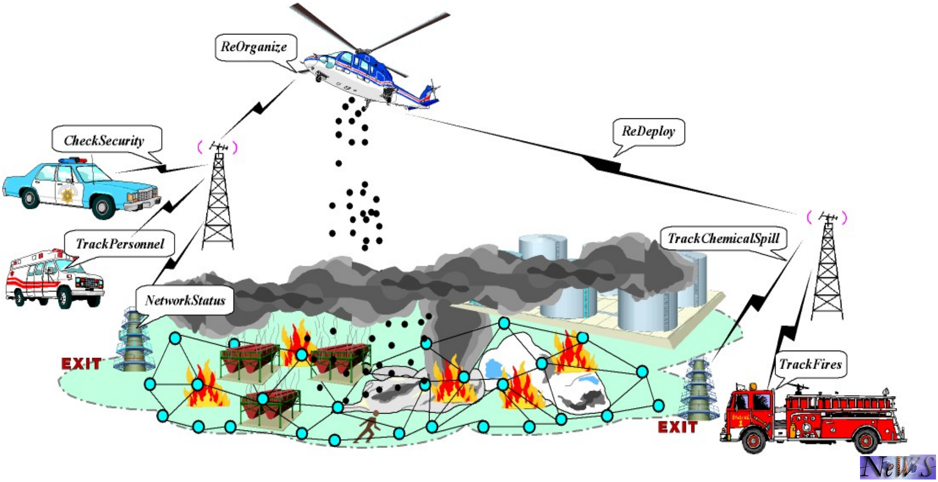
Rescue Mission: Uncertainty and Chaos



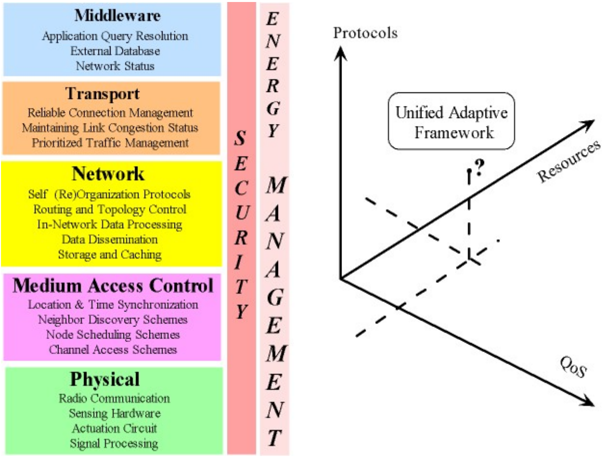
Rescue Mission: Uncertainty and Chaos

Application, Protocols, and Layering Issues

- Protocol optimization(s) are at odds with each other.
- Warrants tradeoff decisions among competing goals.
- Appropriate real-time response to application demands and environmental situations.
- Context-awareness requires *k*-hop sharing of cross-layer information.
- Efficient coordination for fair resource-allocation becomes necessary.

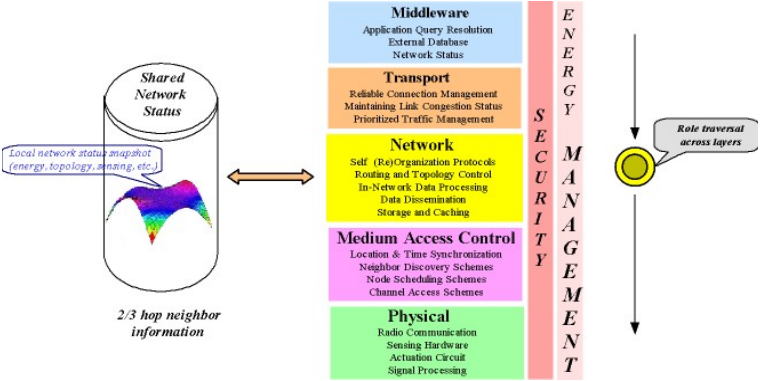
Case for a Unified Role-Abstraction Framework

{Resource, *QoS*, Protocols} optimization dilemma



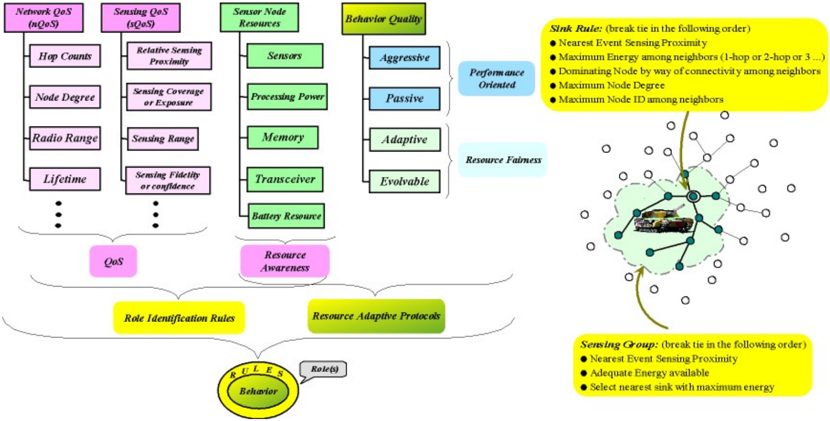
Case for a Unified Role-Abstraction Framework

Role Context-Awareness



Generic Role and Rule based Abstraction

Abstraction: QoS, Resources, Tasks, Roles, and Rules



Elementary Sensor Network Tasks

Fundamental Actions Executed by a Node

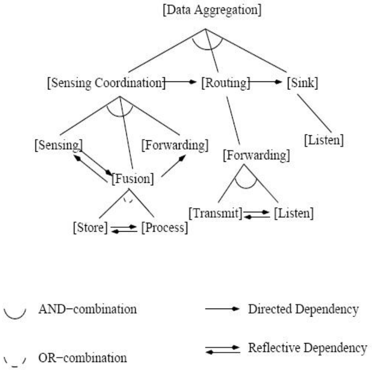
- ON: Node turned *ON* and is idle
- OFF: Node completely turned *OFF* to save energy
- Sense: Sensing task, S
- Process: Processing role, P
- Store: Node storing data in its memory, M
- Transmit: Transmitter, T
- Listen: Role for listening to packets, L

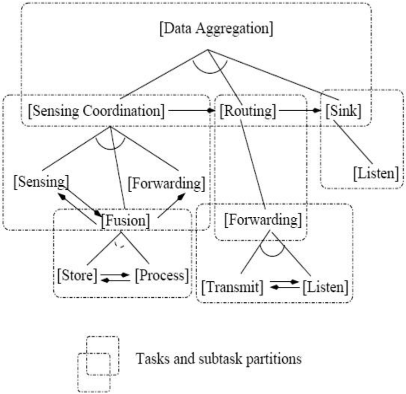
Complex Role Formulations

Role Compositions

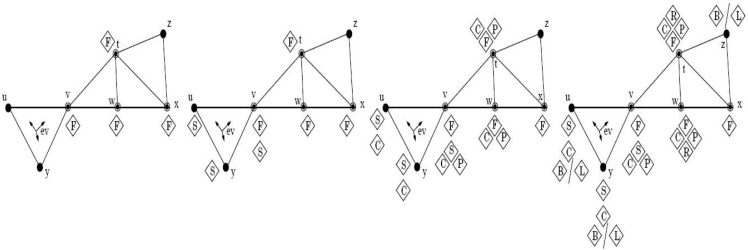
- Forwarder: $F \Leftrightarrow T \bigwedge L$
- Router: Series of forwarders, $R \Leftrightarrow \bigvee_{i=1}^{n} F^i$
- Aggregator: Storage and processing tasks, $A \Leftrightarrow M \bigwedge P$
- Sensing Collaborator: Transmits sensor readings and listens for coordination, S_m i.e. $S_m \Leftrightarrow (S \bigwedge P) \bigwedge (T \rightarrow L)$.
- Sensor Coordinator: Coordinates sensing zone and forwards data to sink, $S_h \Leftrightarrow (\bigvee_{i=1}^{n} S_m^i) \bigvee_{j=1}^{m} F^j$
- Sensing Zone: $S_r \Leftrightarrow ((\bigvee_{i=1}^{n} S_m^i) \bigwedge S_h) \bigvee_{j=1}^{m} F^j$.
- Target Tracking: Track manager, sector manager, and sector.

Hierarchical Task Decomposition and Grouping

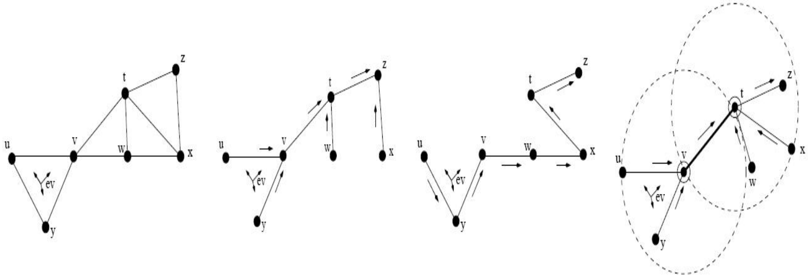




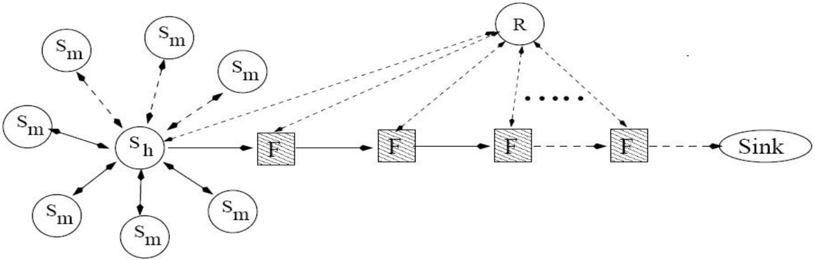
Redundant Role Assignment (RA) Technique



Role Assignment Leads to Topology Differentiation

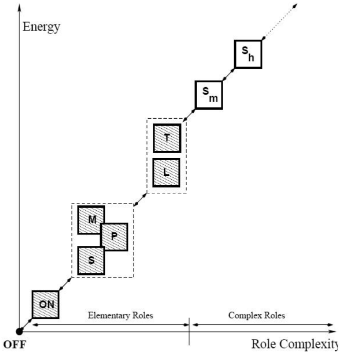


Role Coordination Graph

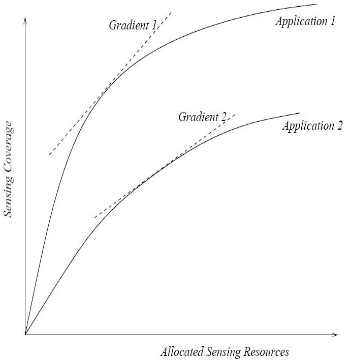


Domain Specific Models

Role Energy Model

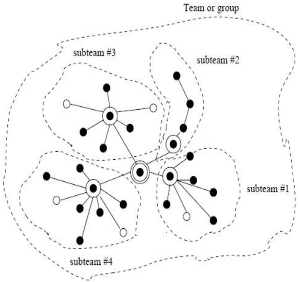


Concave Resource Utility Model

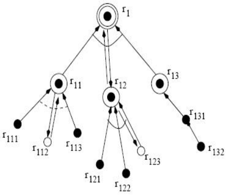


Role Failures

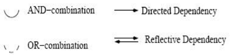
Proactive and Reactive Monitoring



Hierarchical Role-network organization



Dominating monitors for roles at lower level



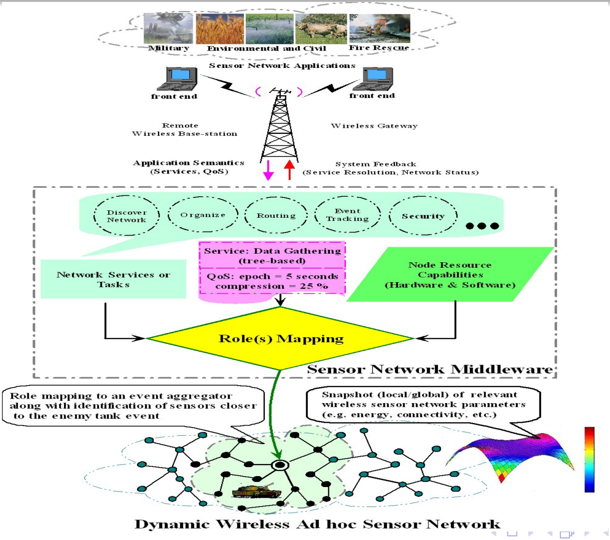
Other Role Properties

Execution Scheduling, State Machine, and Load Balancing

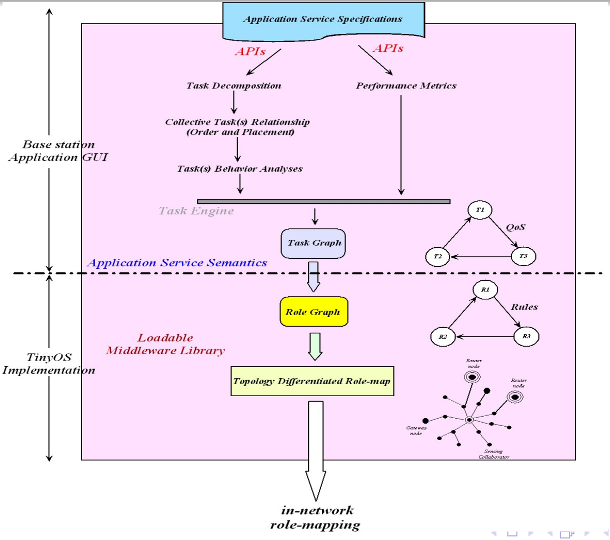
- Execution Scheduling: TDMA time slots coordinated by dominator for role control and execution.
- Role State Machine: Predefined for roles for message arrival, sensing events, and context changes.
- Load Balancing: Pairwise neighborhood role-exchange, role-mergers, and role-redirection protocols.

Outline

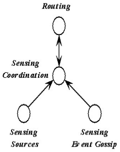
Higher Level Overview



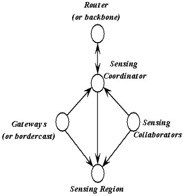
System Control Flow



Generic Code for specifying Executable Roles

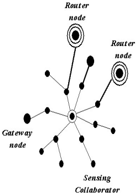


(a)

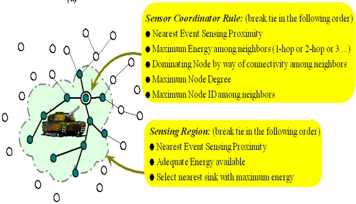


(b)

```
map_roles() {
  geographic_location;
  rules_reduction(geographic_location);
}
protocol_task() {
  while (event) {
    sense();
    query();
    report();
    aggregate();
    compute();
    if (network_status != normal) {
      load_balance();
      remap_roles();
    }
  }
  passive();
}
load_balance() {
  load;
  if (load == low) aggressive();
  if (load == high) evolve();
  if (load == full) adaptive();
  if (load == unbearable) passive();
}
network_status();
remap_roles();
```
(c)



(d)



(e)

Generic Specification Language for Application

- Simple requirement expressed as points in QoS space.
- Weighted sum of points in QoS space.
- Utility based QoS specification.
- Weighted utility based QoS specification.

Multi-Service Minimum Energy Role Assignment (MSMERA)

NP-Complete Problem

- Minimizing the number of roles for a service.
- Minimizing network flows among roles necessary to reduce communication overhead.
- Shortest path communication among roles.
- Solving the above distributedly with partial and local network information is NP-Complete.

Minimum Total Energy RA (MTERA)

Depends on following factors

- Number of messages exchanged during every RA round.
- Number of such RA rounds per service mapping.
- Number of roles per service mapping.
- Number of nodes/role.
- State dependency among distributed roles.
- Hop-count or path-distance among roles.

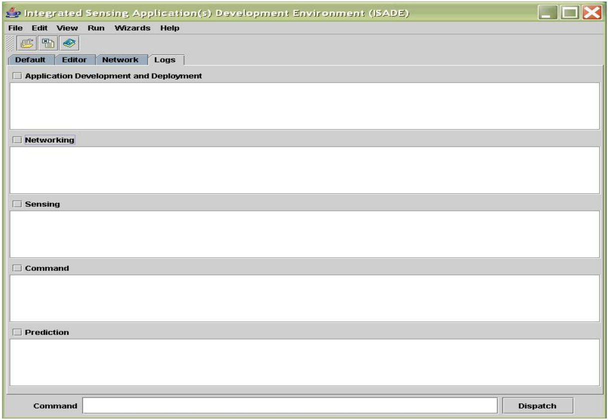
Multi-Service Minimum Energy Role Assignment (MSMERA) Techniques

Our Proposals

- Redundant role assignment technique (naive).
- Greedy recursive domination set based reduction technique.
- Utility based role-assignment technique by way of ranking.
- Hybrid: Cooperative redundant coalitional role-assignment with iterative pruning.

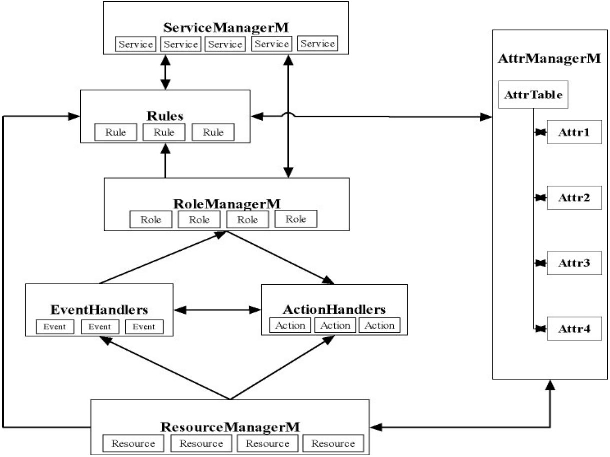
Software Development: User Front End GUI

Integrated Sensing Applications Development Environment



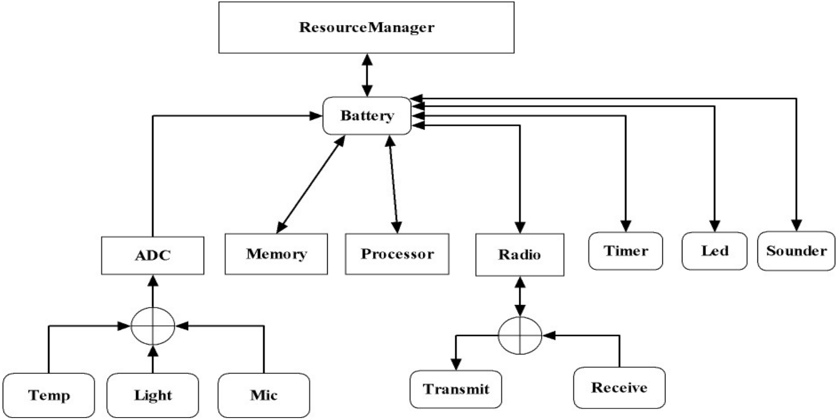
Software Development: Design in TinyOS

RBMW Components in TinyOS



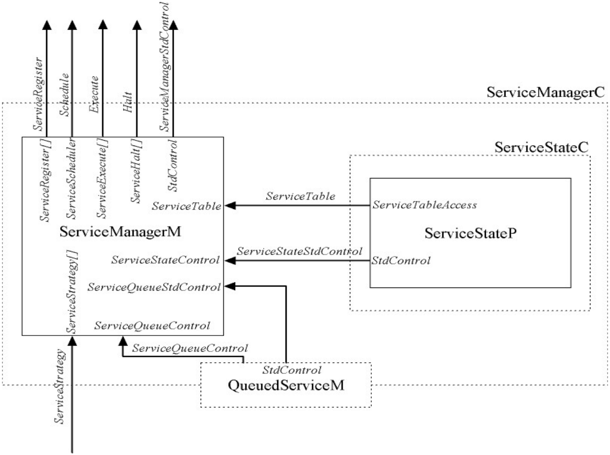
Software Development: Design in TinyOS

Resource Usage Accounting Model



Software Development: Design in TinyOS

Multi-Service Load Balanced Role-Execution



Performance Analysis: Simulation and Implementation

Performance Parameters

- RA algorithm efficiency: Load per node, number of nodes per role, and RA frequency.
- QoS mapping efficiency: Accuracy of mapping and its degradation with time.
- Effects of complex role formulations or task/subtask partitioing and/or grouping.

Conclusions

- Proposed a role-based service paradigm for sensor networks.
- Generalized and unified role-abstraction mechanism across layers, services, and applications.
- Supports rules formulation in terms of cross-layer network attributes for selecting roles.
- Supports service specification in terms of single or weighted set of QoS metrics and utilities.
- Developed emphirical models to quantify service composition quality in terms of energy and resource allocation utility.

Future Work

- Role formulation for other services, e.g. security.
- Export the programming language for roles and application specification over a generic Virtual Machine.
- How about interaction among generic role-societies that employ any role-composition.
- Economical Issues: Provider of a service should benefit monetarily.
- Utility based decision making, Game Theory, and Mechanism Design can provide better RA solutions.
- Standardization efforts needed in the WSN arena for universal adoption of roles.

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Collaborators

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- Dr. Sandeep K. S. Gupta (Co-advisor), Arizona State University.
- Discussion with colleagues: Dr. Daniel Grosu and Fernando Martincic.