Wireless World

Wireless Sensor Networks

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Definition

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations.

Characteristics

- Limited Power
- Unreliable Communication
- Need for Self-Configuration
- Need for Scalability (order of 1000s)
- Mostly Immobile
- Harsh Environmental Conditions
- Small Size
- Cooperative network behavior
- Data-centric rather than address-centric (data expected to be aggregated, compressed, prioritized, dropped)
- Very short packets (overhead important)
- Many-to-one traffic common topology (hot-spot problem)
- Unattended operation

Applications

- Environmental monitoring
- Health monitoring
- Terror threat detection
- Habitat monitoring
- Military surveillance
- Seismic detection
- Inventory tracking
- Process monitoring
- Acoustic detection
- Localization

Performance parameters

- Energy-efficiency
- Lifetime
- Quality of Service (QoS)
- Fidelity
- Scalability

WSN Protocols

- Medium Access Control (MAC) Protocols
- Network Protocols
- QoS Management Protocols
- Time Synchronization Protocols
- Sensor Localization Protocols

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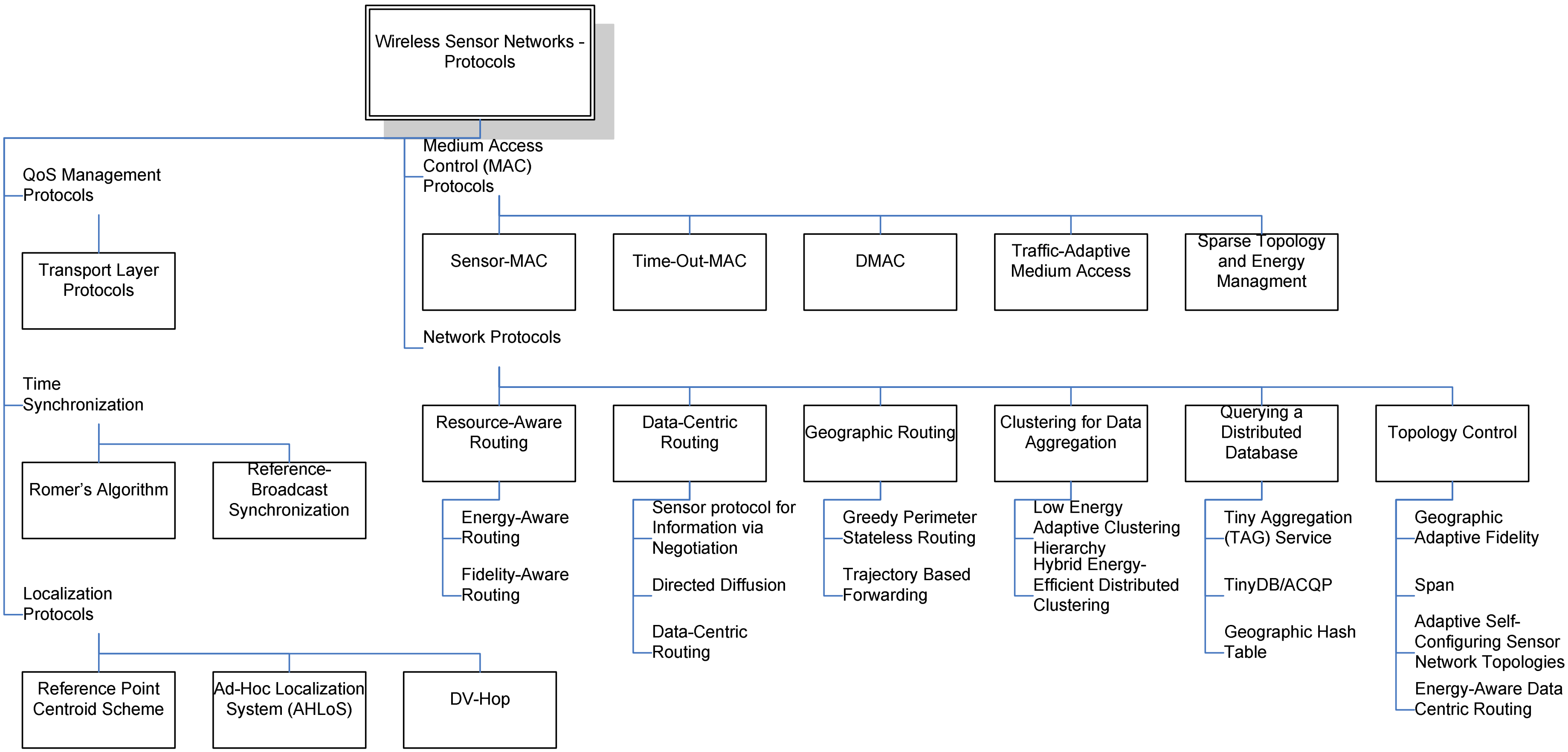

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Medium Access Control (MAC) Protocols

- Energy conservation more important than latency, bandwidth, or fairness
- Focused on reducing idle power consumption (the biggest energy consuming factor) by setting radios into sleep mode as often as possible

Medium Access Control (MAC) Protocols

- Sensor-MAC [2]
- Time-Out-MAC [3]
- DMAC [4]
- Traffic-Adaptive Medium Access [5]
- Sparse Topology and Energy Management [6]

Sensor-MAC

- Each node has an active (~1%-10%) mode (wakeup mode) and a sleep mode
- Nodes required to synchronize their sleep schedules via SYNC packets
- Source node send a packet during destination's wakeup period
- Fragmented data packets allowed
- Energy inefficiencies due to predetermined wakeup period (overhearing)

Time-Out-MAC (TMAC)

- Improvement compared to S-MAC due to adaptive length on the active period
- Messages allowed to be sent only during the “activation period” of an active period. If no “activation event” detected receiving nodes go into sleep mode.
- Improved efficiency due to shorter active periods
- Longer delays expected as some nodes might need to wait until the next active period to complete the transfer

DMAC

- Improved efficiency compared to S-MAC and T-MAC due to staggering of the wakeup times for nodes based on their distance from the data sink
- Assumes a predictable tree based network environment with a single data sink
- Each node calculates its wakeup time period based on the distance from the root's sink (μ *d where μ is wakeup period to accommodate a single send/receive period and d is the tree depth)

Traffic-Adaptive Medium Access

- Different approach compared to S-MAC, T-MAC, and DMAC (all trying to shorten active send/receive period)
- Traffic-Adaptive Medium Access protocol tries to reduce the wasted energy consumption caused by packet collisions.
- Number of packet collisions is reduced by nodes acquiring additional information about their 2-node neighbors (via neighbor protocol (NP) and schedule exchange protocol (SEP)) and using those information to precisely schedule 1 node to send and 1 node to receive the packet (all other nodes sleep)
- Nodes also keep track of "Alternative Winners" in the case 2 neighbor nodes are hidden from each other

Sparse Topology and Energy Management

- Applies to sensor network topologies that continuously sense the environment but actual data transmission only "event based"
- In STEM all nodes in sleep until an event is triggered
- Two STEM network versions: STEM-T and STEM-B
- STEM-T uses separate channel to awake neighbor nodes ("turn on" time instantaneous but need 2 channels)
- STEM-B uses a beacon on a paging channel to awake neighbors

Network Protocols

- Routing decision guided by awareness of the energy resources in the network
- Sink nodes more interested in overall description of environment (data-centric) rather than explicit readings from the individual sensor devices (address-centric)
- Often use sensors' own location knowledge for routing purposes

Network Protocols

- Resource-Aware Routing [7] [8] [9] [10]
- Data-Centric Routing [11] [12] [13]
- Geographic Routing [14] [15] [16] [17]
- Clustering for Data Aggregation [18] [19] [20] [21]
- Querying a Distributed Database [22] [23]
- Topology Control [24] [25] [26] [27]

Resource-Aware Routing (p.1)

- Energy-Aware and Fidelity-Aware Routing
- Energy-Aware Routing
  - Tries to extend the life of the network by using controlled flooding (saves energy)
  - Routing based on nodes' energy cost information as well as they reluctance to forward messages

Resource-Aware Routing (p.2)

– Energy-Aware forwarding based on

$$Cost(Nj) = \sum_{i \in FTj} P_{Nj,\,Ni} C_{Nj,\,Ni}, \text{ where}$$

$$P_{Nj,Ni} \text{(forwarding probability)} = \frac{1/C_{Nj,Ni}}{\sum_{k \in FTj} 1/C_{Nj,Nk}}$$

$$C_{Nj,\,Ni} \text{(link cost)} = Cost(Ni) + e_{ij}^{\alpha} R_{i}^{\beta}$$

$Cost(Ni)$ - cost indicating reluctance of Ni to forward messages

e_{ij} - energy nessesary to transmit from node i to node j

R_i - normalized residual energy

α, β - are tunable parameters

FT_j - forwarding table with cost weighted averages

Resource-Aware Routing (p.3)

- Fidelity-Aware Routing
  - Designed specifically to maintain high-level QoS requirements over long period of time
  - Does not assign cost based on nodes' residual energies but rather based on energy needed to redundantly cover a poorly covered region
  - It extends the life of the network, but it requires additional information from neighboring nodes

Data-Centric Routing (p.1)

- Sensor Protocol for Information via Negotiation
  - Avoids blind broadcasting through short advertisement messages
  - Implosion (each sensor receives many redundant data copies) avoided
  - Overlap (two or more sensors send same data) avoided
  - Resource blindness (Decision not made upon the current resource status) avoided

Data-Centric Routing (p.2)

- Directed Diffusion
  - Creation of an interest query for a region of interest
  - Data acquisition through gradient establishment
  - Supports reinforced paths (paths with higher rate of reliability, reduced latency, and data quality.

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Data-Centric Routing (p.3)

- Rumor Routing
  - Optimal for single short-lived one-shot queries
  - Event detecting sensor creates an “agent” in form of data packet. Packet forwarded in random direction. All packet receiving nodes store the event information as well as direction and distance
  - Query requesting node forwards the request in a random fashion through the network.
  - Expectation is that the random nature of request packet forwarding and the random nature of event packet forwarding will cross at some node consequently giving the path from the requesting node to the event sensing node

Geographic Routing (p. 1)

- Greedy Perimeter Stateless Routing (GPSR)
  - Greedy based forwarding toward the destination (packet forwarded to the node that enables the maximum progress toward the destination node)
  - Perimeter based routing as the maximum progress is calculated using circular distance regions with predefined parameter
  - Due to greedy nature not an optimal path causing inefficiencies when packets reach holes (no nodes to cover the particular region)

Geographic Routing (p. 2)

- Trajectory Based Forwarding (TBF)
  - Path looks like a trajectory rather than a straight line like in GPSR case
  - Trajectory allows multiple paths toward the destination node increasing the flexibility of an overall forwarding strategy
  - Trajectory also enables redundant paths toward the destination node increasing the reliability of the network

Clustering for Data Aggregation

- Clustering of sensor nodes solves the problem of scalability for large networks
- Clusters usually within the geographic neighborhoods
- Two major implementations:
  - Low Energy Adaptive Clustering Hierarchy (LEACH)
  - Hybrid Energy-Efficient Distributed Clustering (HEEDC)

Querying a Distributed Database

- Problem: Interfacing an application to the massively distributed sensor network through an SQL-like querying language
- Three major architectures
  - Tiny Aggregation (TAG) Service
  - TinyDB/ACQP
  - Geographic Hash Table

Querying Distributed Database

- Tiny Aggregation (TAG) Service
  - Minimizes the number of messages transmitted by allowing distributed query execution
- TinyDB/ACQP
  - Execution optimized at several network layers
  - Allows “storage points” containing windows of sensor data for easier query execution
  - Optimizes data acquisition routes even at the network layer as well as semantic routing trees (SRTs) for higher energy efficiency
- Geographic Hash Table
  - Data related to an event is stored at location found by hashing its key to a location within the network (finding data home nodes)
  - Data sent from the home node to the query requesting node via GPSR

Topology Control (p. 1)

- Dominant aspect of power consumption is “idle listening” rather than transmitting
- Topology Control protocols achieve energy efficiency by assigning the role of router to only enough nodes to keep the network well connected (all other nodes “sleep)
- Four major architectures:
  - Geographic Adaptive Fidelity
  - Span
  - Adaptive Self-Configuring Sensor Networks Topologies
  - Energy-Aware Data Centric Routing

Topology Control (p. 2)

- Geographic Adaptive Fidelity (GAF)
  - Divides area into a virtual grid and assigns to each grid cell a designated node – router node (all other nodes put in sleep mode)
  - Network life time proportional to the network's density
- Span
  - Routing relies on backbone nodes
  - All other nodes allowed to sleep for extended period of time until needed in retaining the backbone connectivity in which case nodes become "coordinator" nodes.

Topology Control (p. 3)

- Adaptive Self-Configuring Sensor Networks Topologies (ASCENT)
  - Similar to Span
  - Activation based not only on connectivity but also data loss rates providing the ability to trade energy for communication reliability
- Energy-Aware Data Centric Routing (EAD)
  - EAD algorithm constructs a minimum connected dominating set with the goal of prioritizing nodes with higher residual energy (non-leaf nodes)

QoS Management Protocols

- QoS measured by the content as well as the amount of data being delivered
- Few pieces of important, unique data more valuable than large volumes of less important redundant data
- Transport Layer Protocols [28] [29]
- Application: Environmental Coverage [30] [31] [32] [33]

QoS Management Protocols

- Transport Layer Protocols
  - Pump Slowly Fetch Quickly (PSFQ)
    - Enables reliable re-tasking and reprogramming of nodes
  - Event-to-Sink Reliable Transport (ESRT)
    - Goal to send just enough packets to meet application's reliability requirements
    - Contains mechanism to detect congestions

QoS Management Protocols

- Providing Coverage of an Environment
  - Probing Environment and Adaptive Sleeping
    - Provides balance between energy saving and robustness by nodes becoming active only if the surrounding area is not well covered. Otherwise, stay in sleep mode.
  - Node Self-Scheduling Scheme
    - Self-scheduled node power-off if adequate coverage in the node's "sponsored" sector detected
  - Coverage Configuration Protocol (CCP)
    - Follows CCP rule to maintain K-coverage and to assign nodes eligible for deactivation
  - Connected Sensor Cover
    - Sensors added using Greedy algorithm (starting point randomly chosen)
    - Sensor additions based on which sensor will add most of the unique sections of the desired region

Time Synchronization

- Romer's Algorithm [34]
  - Based on delay estimations between consecutive packets (event based synchronization)
  - Problem: Makes use of two consecutive packets => the estimation uncertainty increases with inter-packet delay
- Reference-Broadcast Synchronization [35]
  - Synchronization based on packet's time of arrival
  - Individual delays between two nodes calculated by exchanging time delay messages of reference broadcast arrival times

Sensor Localization

- Goal to discover relative positioning among neighboring nodes in order to calculate the local topology
- Different methods:
  - Received signal strength indicator (RSSI) (problem: susceptible to errors due to multipaths and shadowing effect)
  - Time of arrival (ToA) (problem: sensor's clocks not precise enough to accurately resolve propagation delays needed for distance calculation)

Sensor Localization Mechanisms

- Reference Point Centroid Scheme [36]
  - Listen to beacons sent by reference points
  - Location computed as the centroid of the locations of the reference points they can hear
- Ad-Hoc Localization System (AHLoS) [37]
  - Allows all nodes to be localized even if they do not have access to three or more reference beacons needed for distance calculation
  - First node with the access to needed beacons estimate their position. Then, they automatically become beacons for other nodes. Process continues until all nodes localized
- DV-Hop [38]
  - Take advantage of “Landmark” nodes (usually GPS equipped nodes with precise coordinates)
  - Estimate based on triangulation techniques using correction factors and the distance (in hopes) to few landmarks

Open Issues

- Appropriate QoS Model selection challenge
- Cross-layer Architecture
- Reliability
- Heterogeneous Applications
- Heterogeneous Sensors
- Security
- Actuation
- Distributed and collaborative data processing
- Integration with other networks
- Sensor Deployment

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