

Chapter 10: Introduction to Wireless Sensor Networks

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Advanced Techniques of Mobile Ad Hoc and Wireless Sensor Networks

Outline



- Infrastructure for wireless?
- (Mobile) ad hoc networks
- Wireless sensor networks
- Comparison



Infrastructure-based wireless networks



- Typical wireless network: Based on infrastructure
 - E.g., GSM, UMTS, ...
 - Base stations connected to a wired backbone network
 - Mobile entities communicate wirelessly to these base stations
 - Traffic between different mobile entities is relayed by base stations and wired backbone
 - Mobility is supported by switching from one base station to another
 - Backbone infrastructure required for administrative tasks





Infrastructure-based wireless networks – Limits?

- What if ...
 - No infrastructure is available? E.g., in disaster areas
 - It is too expensive/inconvenient to set up? E.g., in remote, large construction sites
 - There is no time to set it up? E.g., in military operations



Possible applications for infrastructure-free networks



- Military networking: Tanks, soldiers, ...
- Finding out empty parking lots in a city, without asking a server
- Search-and-rescue in an avalanche
- Personal area networking (watch, glasses, PDA, medical appliance, ...)
- ...



Factory floor automation





Disaster recovery





Car-to-car communication







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Solution: (Wireless) ad hoc networks

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- Try to construct a network without infrastructure, using networking abilities of the participants
 - This is an *ad hoc network* a network constructed "for a special purpose"
- Simplest example: Laptops in a conference room a single-hop ad hoc network



Problems/challenges for ad hoc networks



- Without a central infrastructure, things become much more difficult
- Problems are due to
 - Lack of central entity for organization available
 - Limited range of wireless communication
 - Mobility of participants
 - Battery-operated entities



No central entity ! self-organization



- Without a central entity (like a base station), participants must organize themselves into a network (*selforganization*)
- Pertains to (among others):
 - **Medium access control** no base station can assign transmission resources, must be decided in a distributed fashion
 - Finding a route from one participant to another



Limited range ! multi-hopping



- For many scenarios, communication with peers outside immediate communication range is required
 - Direct communication limited because of distance, obstacles, ...
 - Solution: *multi-hop network*





Mobility ! Suitable, adaptive protocols



- In many (not all!) ad hoc network applications, participants move around
 - In cellular network: simply hand over to another base station
- In mobile ad hoc networks (MANET):
 - Mobility changes neighborhood relationship
 - Must be compensated for
 - E.g., routes in the network have to be changed
- Complicated by scale
 - Large number of such nodes difficult to support





Battery-operated devices ! energy-efficient operation

- Often (not always!), participants in an ad hoc network draw energy from batteries
- Desirable: long run time for
 - Individual devices
 - Network as a whole
- ! Energy-efficient networking protocols
 - E.g., use multi-hop routes with low energy consumption (energy/bit)
 - E.g., take available battery capacity of devices into account
 - How to resolve conflicts between different optimizations?



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Wireless sensor networks

- Participants in the previous examples were devices close to a human user, interacting with humans
- Alternative concept:

Instead of focusing interaction on humans, focus on interacting with *environment*

- Network is *embedded* in environment
- Nodes in the network are equipped with sensing and actuation to measure/influence environment
- Nodes process information and communicate it wirelessly
- ! Wireless sensor networks (WSN)
 - Or: Wireless sensor & actuator networks (WSAN)









WSN application examples



- Disaster relief operations
 - Drop sensor nodes from an aircraft over a wildfire
 - Each node measures temperature
 - Derive a "temperature map"
- Biodiversity mapping
 - Use sensor nodes to observe wildlife
- Intelligent buildings (or bridges)
 - Reduce energy wastage by proper humidity, ventilation, air conditioning (HVAC) control
 - Needs measurements about room occupancy, temperature, air flow, ...
 - Monitor mechanical stress after earthquakes









WSN application scenarios



- Facility management
 - Intrusion detection into industrial sites
 - Control of leakages in chemical plants, ...
- Machine surveillance and preventive maintenance
 - Embed sensing/control functions into places no cable has gone before
 - E.g., tire pressure monitoring
- Precision agriculture
 - Bring out fertilizer/pesticides/irrigation only where needed
- Medicine and health care
 - Post-operative or intensive care
 - Long-term surveillance of chronically ill patients or the elderly



WSN application scenarios

- Logistics
 - Equip goods (parcels, containers) with a sensor node
 - Track their whereabouts *total asset management*
 - Note: passive readout might suffice compare RF IDs
- Telematics
 - Provide better traffic control by obtaining finer-grained information about traffic conditions
 - Intelligent roadside
 - Cars as the sensor nodes







Roles of participants in WSN



- Sources of data: Measure data, report them "somewhere"
 - Typically equip with different kinds of actual sensors



- Sinks of data: Interested in receiving data from WSN
 - May be part of the WSN or external entity, PDA, gateway, ...



Actuators: Control some device based on data, usually also a sink





Structuring WSN application types



- Interaction patterns between sources and sinks classify application types
 - **Event detection**: Nodes locally detect events (maybe jointly with nearby neighbors), report these events to interested sinks
 - Event classification additional option
 - Periodic measurement
 - Function approximation: Use sensor network to approximate a function of space and/or time (e.g., temperature map)
 - Edge detection: Find edges (or other structures) in such a function (e.g., where is the zero degree border line?)
 - Tracking: Report (or at least, know) position of an observed intruder ("pink elephant")



Deployment options for WSN



- How are sensor nodes deployed in their environment?
 - Dropped from aircraft ! *Random deployment*
 - Usually uniform random distribution for nodes over finite area is assumed
 - Is that a likely proposition?
 - Well planned, fixed ! *Regular deployment*
 - E.g., in preventive maintenance or similar
 - Not necessarily geometric structure, but that is often a convenient assumption
 - *Mobile* sensor nodes
 - Can move to compensate for deployment shortcomings
 - Can be passively moved around by some external force (wind, water)
 - Can actively seek out "interesting" areas



Maintenance options



- Feasible and/or practical to maintain sensor nodes?
 - E.g., to replace batteries?
 - Or: unattended operation?
 - Impossible but not relevant? Mission lifetime might be very small
- Energy supply?
 - Limited from point of deployment?
 - Some form of recharging, energy scavenging from environment?
 - E.g., solar cells



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Characteristic requirements for WSNs



- Type of service of WSN
 - Not simply moving bits like another network
 - Rather: provide *answers* (not just numbers)
 - Issues like geographic scoping are natural requirements, absent from other networks
- Quality of service
 - Traditional QoS metrics do not apply
 - Still, service of WSN must be "good": Right answers at the right time
- Fault tolerance
 - Be robust against node failure (running out of energy, physical destruction, ...)
- Lifetime
 - The *network* should fulfill its task as long as possible definition depends on application
 - Lifetime of individual nodes relatively unimportant
 - But often treated equivalently



Characteristic requirements for WSNs



- Scalability
 - Support large number of nodes
- Wide range of densities
 - Vast or small number of nodes per unit area, very applicationdependent
- Programmability
 - Re-programming of nodes in the field might be necessary, improve flexibility
- Maintainability
 - WSN has to adapt to changes, self-monitoring, adapt operation
 - Incorporate possible additional resources, e.g., newly deployed nodes



Required mechanisms to meet requirements



- Multi-hop wireless communication
- Energy-efficient operation
 - Both for communication and computation, sensing, actuating
- Auto-configuration
 - Manual configuration just not an option
- Collaboration & in-network processing
 - Nodes in the network collaborate towards a joint goal
 - Pre-processing data in network (as opposed to at the edge) can greatly improve efficiency



Required mechanisms to meet requirements



- Data centric networking
 - Focusing network design on *data*, not on *node identifies* (idcentric networking)
 - To improve efficiency
- Locality
 - Do things locally (on node or among nearby neighbors) as far as possible
- Exploit tradeoffs
 - E.g., between invested energy and accuracy



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MANET vs. WSN



- Many commonalities: Self-organization, energy efficiency, (often) wireless multi-hop
- Many differences
 - **Applications, equipment**: MANETs more powerful (read: expensive) equipment assumed, often "human in the loop"-type applications, higher data rates, more resources
 - Application-specific: WSNs depend much stronger on application specifics; MANETs comparably uniform
 - Environment interaction: core of WSN, absent in MANET
 - Scale: WSN might be much larger (although contestable)
 - Energy: WSN tighter requirements, maintenance issues
 - **Dependability/QoS**: in WSN, individual node may be dispensable (network matters), QoS different because of different applications
 - Data centric vs. id-centric networking
 - Mobility: different mobility patterns like (in WSN, sinks might be mobile, usual nodes static)



Wireless fieldbuses and WSNs



- Fieldbus:
 - Network type invented for real-time communication, e.g., for factory-floor automation
 - Inherent notion of sensing/measuring and controlling
 - Wireless fieldbus: Real-time communication over wireless

! Big similarities

- Differences
 - Scale WSN often intended for larger scale
 - Real-time WSN usually not intended to provide (hard) real-time guarantees as attempted by fieldbuses



Enabling technologies for WSN



- Cost reduction
 - For wireless communication, simple microcontroller, sensing, batteries
- Miniaturization
 - Some applications demand small size
 - "Smart dust" as the most extreme vision
- Energy scavenging
 - Recharge batteries from ambient energy (light, vibration, ...)



Sensor node architecture



- Main components of a WSN node
 - Controller
 - Communication device(s)
 - Sensors/actuators
 - Memory
 - Power supply





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- Network scenarios
- Optimization goals
- Design principles
- Service interface
- Gateway concepts



Basic scenarios: Ad hoc networks



- (Mobile) ad hoc scenarios
 - Nodes talking to each other
 - Nodes talking to "some" node in another network (Web server on the Internet, e.g.)
 - Typically requires some connection to the fixed network
 - Applications: Traditional data (http, ftp, collaborative apps, ...) & multimedia (voice, video) ! humans in the loop





Basic scenarios: sensor networks



- Sensor network scenarios
 - **Sources**: Any entity that provides data/measurements
 - Sinks: Nodes where information is required
 - Belongs to the sensor network as such
 - Is an external entity, e.g., a PDA, but directly connected to the WSN
 - Main difference: comes and goes, often moves around, \ldots
 - Is part of an external network (e.g., internet), somehow connected to the WSN



 Applications: Usually, machine to machine, often limited amounts of data, different notions of importance



Single-hop vs. multi-hop networks



- One common problem: limited range of wireless communication
 - Essentially due to limited transmission power, path loss, obstacles
- Option: multi-hop networks
 - Send packets to an intermediate node
 - Intermediate node forwards packet to its destination
 - Store-and-forward multi-hop network
- Basic technique applies to both WSN and MANET
- Note: Store&forward multihopping NOT the only possible solution
 - E.g., collaborative networking, network coding
 - Do not operate on a perpacket basis





Energy efficiency of multi-hopping?



- Obvious idea: Multi-hopping is more energy-efficient than direct communication
 - Because of path loss α > 2, energy for distance d is reduced from cd^α to 2c(d/2)^α
 - c some constant
- However: This is usually wrong, or at least very oversimplified
 - Need to take constant offsets for powering transmitter, receiver into account
 - Details see exercise, chapter 2

! Multi-hopping for energy savings needs careful choice



WSN: Multiple sinks, multiple sources









Different sources of mobility



• Node mobility

- A node participating as source/sink (or destination) or a relay node might move around
- Deliberately, self-propelled or by external force; targeted or at random
- Happens in both WSN and MANET

Sink mobility

- In WSN, a sink that is not part of the WSN might move
- Mobile requester

Event mobility

- In WSN, event that is to be observed moves around (or extends, shrinks)
- Different WSN nodes become "responsible" for surveillance of such an event



WSN sink mobility









WSN event mobility: Track the pink elephant







Here: Frisbee model as example



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Optimization goal: Quality of Service



- In MANET: Usual QoS interpretation
 - Throughput/delay/jitter
 - High perceived QoS for multimedia applications
- In WSN, more complicated
 - Event detection/reporting probability
 - Event classification error, detection delay
 - Probability of missing a periodic report
 - Approximation accuracy (e.g, when WSN constructs a temperature map)
 - Tracking accuracy (e.g., difference between true and conjectured position of the pink elephant)
- Related goal: robustness
 - Network should withstand failure of some nodes



Optimization goal: Energy efficiency



- Umbrella term!
- Energy per correctly received bit
 - Counting all the overheads, in intermediate nodes, etc.
- Energy per reported (unique) event
 - After all, information is important, not payload bits!
 - Typical for WSN
- Delay/energy tradeoffs
- Network lifetime
 - Time to first node failure
 - Network half-life (how long until 50% of the nodes died?)
 - Time to partition
 - Time to loss of coverage
 - Time to failure of first event notification



Optimization goal: Scalability



- Network should be operational regardless of number of nodes
 - At high efficiency
- Typical node numbers difficult to guess
 - MANETs: 10s to 100s
 - WSNs: 10s to 1000s, maybe more (although few people have seen such a network before...)
- Requiring to scale to large node numbers has serious consequences for network architecture
 - Might not result in the most efficient solutions for small networks!
 - Carefully consider actual application needs before looking for n ! 1 solutions!



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Distributed organization



- Participants in a MANET/WSN should cooperate in organizing the network
 - E.g., with respect to medium access, routing, ...
 - Centralistic approach as alternative usually not feasible hinders scalability, robustness
- Potential shortcomings
 - Not clear whether distributed or centralistic organization achieves better energy efficiency (when taking all overheads into account)
- Option: "limited centralized" solution
 - Elect nodes for local coordination/control
 - Perhaps rotate this function over time



In-network processing



- MANETs are supposed to deliver bits from one end to the other
- WSNs, on the other end, are expected to provide information, not necessarily original bits
 - Gives addition options
 - E.g., *manipulate* or *process* the data in the network
- Main example: aggregation
 - Apply composable aggregation functions to a convergecast tree in a network
 - Typical functions: minimum, maximum, average, sum, ...
 - Not amenable functions: median



In-network processing: Aggregation example



• Reduce number of transmitted bits/packets by applying an aggregation function in the network





In-network processing: signal processing



- Depending on application, more sophisticated processing of data can take place within the network
 - Example edge detection: locally exchange raw data with neighboring nodes, compute edges, only communicate edge description to far away data sinks
 - Example tracking/angle detection of signal source: Conceive of sensor nodes as a distributed microphone array, use it to compute the angle of a single source, only communicate this angle, not all the raw data

• Exploit *temporal* and *spatial correlation*

- Observed signals might vary only slowly in time ! no need to transmit all data at full rate all the time
- Signals of neighboring nodes are often quite similar ! only try to transmit differences (details a bit complicated, see later)



Adaptive fidelity



- Adapt the effort with which data is exchanged to the currently required accuracy/fidelity
- Example event detection
 - When there is no event, only very rarely send short "all is well" messages
 - When event occurs, increase rate of message exchanges
- Example temperature
 - When temperature is in acceptable range, only send temperature values at low resolution
 - When temperature becomes high, increase resolution and thus message length



Data centric networking



- In typical networks (including ad hoc networks), network transactions are addressed to the *identities* of specific nodes
 - A "node-centric" or "address-centric" networking paradigm
- In a redundantly deployed sensor networks, specific source of an event, alarm, etc. might not be important
 - Redundancy: e.g., several nodes can observe the same area
- Thus: focus networking transactions on the data directly instead of their senders and transmitters ! *data-centric networking*
 - Principal design change



Implementation options for data-centric networking

- Overlay networks & distributed hash tables (DHT)
 - Hash table: content-addressable memory
 - Retrieve data from an unknown source, like in peer-to-peer networking with efficient implementation
 - Some disparities remain
 - Static key in DHT, dynamic changes in WSN
 - DHTs typically ignore issues like hop count or distance between nodes when performing a lookup operation
- Publish/subscribe
 - Different interaction paradigm
 - Nodes can *publish* data, can *subscribe* to any particular kind of data
 - Once data of a certain type has been published, it is delivered to all subscribes
 - Subscription and publication are decoupled in time; subscriber and published are agnostic of each other (decoupled in identity)
- Databases



Further design principles



- Exploit location information
 - Required anyways for many applications; can considerably increase performance
- Exploit activity patterns
- Exploit heterogeneity
 - By construction: nodes of different types in the network
 - By evolution: some nodes had to perform more tasks and have less energy left; some nodes received more solar energy than others; ...
- Cross-layer optimization of protocol stacks for WSN
 - Goes against grain of standard networking; but promises big performance gains
 - Also applicable to other networks like ad hoc; usually at least worthwhile to consider for most wireless networks



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Interfaces to protocol stacks



- The world's all-purpose network interface: sockets
 - Good for transmitting data from one sender to one receiver
 - Not well matched to WSN needs (ok for ad hoc networks)
- Expressibility requirements
 - Support for simple request/response interactions
 - Support for asynchronous event notification
 - Different ways for identifying addressee of data
 - By location, by observed values, implicitly by some other form of group membership
 - By some semantically meaningful form "room 123"
 - Easy accessibility of in-network processing functions
 - Formulate complex events events defined only by several nodes
 - Allow to specify accuracy & timeliness requirements
 - Access node/network status information (e.g., battery level)
 - Security, management functionality, ...
- No clear standard has emerged yet many competing, unclear proposals



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Gateway concepts for WSN/MANET



- Gateways are necessary to the Internet for remote access to/from the WSN
 - Same is true for ad hoc networks; additional complications due to mobility (change route to the gateway; use different gateways)
 - WSN: Additionally bridge the gap between different interaction semantics (data vs. address-centric networking) in the gateway
- Gateway needs support for different radios/protocols, ...





WSN to Internet communication



- Example: Deliver an alarm message to an Internet host
- Issues
 - Need to find a gateway (integrates routing & service discovery)
 - Choose "best" gateway if several are available
 - How to find Alice or Alice's IP?



Internet to WSN communication



- How to find the right WSN to answer a need?
- How to translate from IP protocols to WSN protocols, semantics?



Remote requester





WSN tunneling

 Use the Internet to "tunnel" WSN packets between two remote WSNs





Summary



- Network architectures for ad hoc networks are in principle – relatively straightforward and similar to standard networks
 - Mobility is compensated for by appropriate protocols, but interaction paradigms don't change too much
- WSNs, on the other hand, look quite different on many levels
 - Data-centric paradigm, the need and the possibility to manipulate data as it travels through the network opens new possibilities for protocol design
- The following chapters will look at how these ideas are realized by actual protocols



Homework #10:



- 1. Describe what's the difference and mobile ad hoc network (MANET) and wireless sensor network (WSN) ?
- 2. What's the sensor node architecture ?
- 3. What's difference of node mobility, sink mobility, and event mobility in WSN ?
- 4. What's in-network processing in WSN?

