Outline

- Wireless ad hoc networking focused on 802.11
- RAP (Real-time locAtion-aware Protocol)
Wireless Ad hoc Networking

Adapted a tutorial by Nitin Vaidya and other materials
Overview

- Wireless Propagation/Communication Basics
- Wireless Networks Overview
- MAC design
Wireless Propagation Basics
Ideal Wireless Propagation

- Signal attenuates logarithmically with the distance

\[ P_{\text{recv}} \propto P_{\text{send}} \times (1/r)^n \]

- R is the distance between sender and receiver
- N is the path loss exponent which is characteristic of the environment. Usually, between 2 in free space, to up to 6 indoors

- To receive correctly, the received power should be higher than the receiver radio sensitivity (also, any interference should be really weak – capture threshold)

- Path loss (attenuation) is critical for frequency reuse!
Propagation “Vagaries”

- **Reflection**
  - Propagating wave impinges on an object which is large compared to wavelength
  - E.g., surface of the earth, buildings, walls, …

- **Diffraction**
  - Radio path between transmitter and receiver obstructed by surface with sharp irregular edges
  - Waves bend around obstacles, even when LOS does not exist

- **Scattering**
  - Objects smaller than the wavelength such as foliage, street signs, and lampposts
Wireless Channel

- Channel varies with location and time
- Radio propagation is very complex
  - Attenuation
  - Shadows: signals blocked by large objects
  - Multipath scattering from nearby objects
    - Radar multipath echoes from an actual target cause ghosts to appear.
  - Result: Rapid fluctuation of received power
Wireless Channel

- Many bad effects: high errors, discovering low quality paths, failing to discover good quality paths, etc.
- Most research ignores these effects
  - Not realistic
- Mobility (including that of surrounding objects)
Short Term and Long Term Fading

Less variation the slower you move

For cellular telephony:
-30 dB, 3 $\mu$sec delay spread
Basic channel allocation strategies include TDMA, FDMA, and combinations.

CDMA/Spread spectrum:
- Spread the transmitted data across the full available spectrum
- Pseudo random sequence
- Resilient to jamming
Spread Spectrum/CD MA

- Frequency Hopping or Direct Sequence
- Provides immunity to short-term fading (but not long term fading)
Wireless Networking
Two types of WLANs

Infrastructure:
One master, several slaves

Ad-hoc:
All potential masters and slaves at the same time

IBSS (Independent Basic Service Set)
Last Hop Networks

- "peer-to-server" architecture
- Nodes connect through an Access Point (AP) which is connected to the Internet (wired)
- Traffic is always to/from the AP
- AP can arbitrate communication schedule (making MAC easier)
- Solution is centralized and scalable
- Often used solution today
Ad Hoc Networks

- Wireless networks with all nodes wireless
  - Do not need a static infrastructure
  - Self Organizing or peer-to-peer networks
  - Multi-hop wireless: nodes route packets for others
  - Mobility causes dynamic topology
Why Ad Hoc Networks?

- Ease of deployment
- Speed of deployment
- Decreased dependence on infrastructure
Many Applications

- Sensor Networks!
- Personal area networking
  - cell phone, laptop, ear phone, wrist watch
- Military environments
  - soldiers, tanks, planes
- Civilian environments
  - taxi cab network
  - meeting rooms
  - boats, small aircraft
- Emergency operations
  - search-and-rescue
  - policing and fire fighting
Some Challenges

- Limited wireless transmission range
- Broadcast nature of the wireless medium
- Packet losses due to transmission errors
- Host mobility
- Battery constraints
- Ease of snooping on wireless transmissions (security hazard)
Wireless MAC
Medium Access Control

- Wireless channel is a shared medium
- Need access control mechanism to avoid interference
- MAC protocol design has been an active area of research for many years
MAC: A Simple Classification

- Wireless MAC
  - Centralized
    - Guaranteed or controlled access
  - Distributed
    - Random access

Focus today
Hidden Terminal Problem [Tobagi75]

- Node B can communicate with A and C both
- A and C cannot hear each other
- When A transmits to B, C cannot detect the transmission using the *carrier sense* mechanism
- If C transmits, collision will occur at node B
Busy Tone [Tobagi75, Haas98]

- A receiver transmits busy tone when receiving data
- All nodes hearing busy tone keep silent
- Avoids interference from hidden terminals
- Requires a separate channel for busy tone
MACA (Multiple Access Collision Avoidance) Solution for Hidden Terminal Problem [Karn90]

- When node A wants to send a packet to node B, node A first sends a *Request-to-Send (RTS)* to B.

- On receiving *RTS*, node B responds by sending *Clear-to-Send (CTS)*, provided node B is able to receive the packet.

- When a node (such as C) overhears a *CTS*, it keeps quiet for the duration of the transfer.
  - Transfer duration is included in RTS and CTS both.
Reliability

- Wireless links are prone to errors. High packet loss rate detrimental to transport-layer performance.

- Mechanisms needed to reduce packet loss rate experienced by upper layers
A Simple Solution to Improve Reliability

- When node B receives a data packet from node A, node B sends an Acknowledgement (Ack). This approach adopted in many protocols [Bharghavan94,IEEE 802.11]

- If node A fails to receive an Ack, it will retransmit the packet
IEEE 802.11 Wireless MAC

- Distributed and centralized MAC components
  - Distributed Coordination Function (DCF)
  - Point Coordination Function (PCF)

- DCF suitable for multi-hop ad hoc networking

- DCF is a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol
IEEE 802.11 DCF

- Uses RTS-CTS exchange to avoid hidden terminal problem
  - Any node overhearing a CTS cannot transmit for the duration of the transfer

- Uses ACK to achieve reliability

- Any node receiving the RTS cannot transmit for the duration of the transfer
  - To prevent collision with CTS when it arrives at the sender
  - When B is sending data to C, node A will keep quite

A ─────────── B ─── C
IEEE 802.11

RTS = Request-to-Send

A → B → C → D → E → F
IEEE 802.11

RTS = Request-to-Send
IEEE 802.11

CTS = Clear-to-Send
IEEE 802.11

CTS = Clear-to-Send
IEEE 802.11
IEEE 802.11
CSMA/CA

- **Carrier sense in 802.11**
  - Physical carrier sense (pretty aggressive)
  - Virtual carrier sense using Network Allocation Vector (NAV)
  - NAV is updated based on overheard RTS/CTS/DATA/ACK packets, each of which specified duration of a pending transmission

- **Collision avoidance**
  - Nodes stay silent when carrier sensed (physical/virtual)
  - Backoff intervals used to reduce collision probability
Backoff Interval

- When transmitting a packet, choose a backoff interval in the range $[0, cw]$
  - $cw$ is contention window

- Count down the backoff interval when medium is idle
  - Count-down is suspended if medium becomes busy

- When backoff interval reaches 0, transmit RTS
DCF Example

B1 = 25
B1 = 5
B2 = 20
B2 = 15
B2 = 10

$\text{cw} = 31$

B1 and B2 are backoff intervals at nodes 1 and 2
Backoff Interval

- The time spent counting down backoff intervals is a part of MAC overhead

- Choosing a *large* $cw$ leads to large backoff intervals and can result in larger overhead

- Choosing a *small* $cw$ leads to a larger number of collisions (when two nodes count down to 0 simultaneously)

- Since the number of nodes attempting to transmit simultaneously may change with time, some mechanism to manage contention is needed

- IEEE 802.11 DCF: contention window $cw$ is chosen dynamically depending on collision occurrence
Binary Exponential Backoff in DCF

- When a node fails to receive CTS in response to its RTS, it increases the contention window
  - $cw$ is doubled (up to an upper bound)

- When a node successfully completes a data transfer, it restores $cw$ to $CW_{min}$

- $cw$ follows a sawtooth curve
When a node successfully completes a transfer, reduces \( cw \) by 1

- In 802.11, \( cw \) is restored to \( cw_{\text{min}} \)
- In 802.11, \( cw \) reduces much faster than it increases
- MACAW: \( cw \) reduces slower than it increases
  Exponential Increase Linear Decrease

MACAW can avoid wild oscillations of \( cw \) when large number of nodes contend for the channel
EDCF (Enhanced DCF) in 802.11e for QoS support

- Limitations of DCF in 802.11
  - No notion of priority: Priority inversion when a high priority traffic cannot use the medium due to low priority transmissions
  - A low bit rate node may occupy the medium; Other nodes have to simply wait for a long time!
  - No QoS support

- 802.11e
  - Prioritize traffic categories: audio (highest priority), video, and data (lowest priority)
  - Assign the smallest contention window to the highest priority traffic class
  - Supports burst transmission too
    - Higher priority traffic receives a longer time interval for burst transmission called TXOP (Transmission Opportunity)
Related Standards Activities

- IEEE 802.11
  - http://grouper.ieee.org/groups/802/11/

- Hiperlan/2
  - http://www.etsi.org/technicalactiv/hiperlan2.htm

- BlueTooth
  - http://www.bluetooth.com

- IETF manet *(Mobile Ad-hoc Networks)* working group
RAP: A Real-Time Communication Architecture for Large-Scale Wireless Sensor Networks

C. Lu, B.M. Blum, T.F. Abdelzaher, J.A. Stankovic, and T. He

Adapted Chenyang Lu’s RTAS 2002 slides
Design Requirements

- Minimize end-to-end deadline miss ratio
- Support distributed micro-sensing
  - High-level service API
- Large scale, high density
  - Scalability is key
- Extreme resource constraints
  - Minimal overheads
Location-based Communication

**ID-based**
- From ID to ID
- What is the reading of sensor 125.111.1.5?
- Rely on (unreliable) individual sensors

**Location-based**
- From location to location
- What is the virus density in south terminal of airport?
- Individual sensors NOT important
- **Local coordination**: Sensors in interested area aggregate data
- **Sensor-base comm.**: Send aggregated result to base station
RAP: Real-time location-based Protocols

Sensing/Control Application

Query/Event Service APIs

Query/Event Service

Coordination Service

Location-Addressed Protocol

Geographic Routing

Velocity Monotonic Scheduling

Prioritized MAC
Query/Event API

- RAP provides the following query/event service APIs.
  
  - `query { attribute_list, area, timing_constraints, quierer_loc }
  
  - `register_event { event, area, query }
  
  - Assume that the locations of the base stations are fixed.
The following API call registers a `virus_count` query for a `virus_found` event. If any viruses are found in a rectangular area with coordinates (0,0,100,100), returns the average density of the viruses of the 2⋅2 square area centered at the event location \((X_{event}, Y_{event})\) every 1.5 sec. Every reading should reach the base station within an end-to-end deadline of 5 sec.
Location-Addressed Protocol

- LAP is a connectionless transport layer in the network stack. LAP is similar to UDP except that all messages are addressed by location instead of IP address. Three types of communication are supported by LAP: unicast, area multicast, and area anycast.

  - **Unicast** delivers a message to a node that is closest to the destination location. Unicast can be used by sensors to send query results to base stations.

  - **Area multicast** delivers a message to every node in a specified area. Area multicast can be used to register for an event or send a query to an area, for coordination among nodes in a local group.
Geographic Routing

- Local state $\rightarrow$ Scalability – Routing decisions are local
- Dense network $\rightarrow$ Efficient greedy forwarding works well
- Dense network $\rightarrow$ #hop proportional to distance
- Location based comm. $\rightarrow$ No location directory service
Background – GF

- GF always chooses the node that is closest to the destination in FS.
Limitation of GF - Void

No node in x’s radio communication range is closer to the sink than x itself is.
Deadline & Distance Aware

- Existing ad hoc networks, packets are typically forwarded in FCFS order. FCFS scheduling does not work well in real-time networks where packets have different end-to-end deadlines and distance constraints.

- **Deadline-aware** means that a packet’s priority should relate to its deadline. The shorter the deadline, the higher the packet priority.

- **Distance-aware** means that a packet’s priority should relate to its distance from the
Velocity

- Timing constraint: deadline
- Location constraint: distance to destination
- **Requested Velocity**
  - Embody *both* constraints
  - Reflect local urgency

**Velocity Monotonic Scheduling (VMS):**

*Priority = Requested Velocity*
Example

- **LOW Priority**
  - dis = 60 m; D = 2 s
  - V = 30 m/s

- **HIGH Priority**
  - dis = 90 m; D = 2 s
  - V = 45 m/s

Diagram showing the positions and movements of A, B, C, and D.
Velocity Monotonic Scheduling

**Static VMS**
- **Fixed** velocity on each hop
- \[ V = \frac{\text{dis}(x_0,y_0,x_d,y_d)}{D} \]
  - Source location: \((x_0,y_0)\)
  - Destination location: \((x_d,y_d)\)
  - End-to-end deadline: \(D\)

**Dynamic VMS**
- **Adapt** velocity at intermediate node based on progress
- \[ V_i = \frac{\text{dis}(x_i,y_i,x_d,y_d)}{S_i} \]
  - Velocity at node: \(V_i\)
  - Location of node \(i\): \((x_i,y_i)\)
  - Slack: \(S_i = D - \text{elapseTime}\)
Priority Queue

- Single Queue:
  - Ordered by priority
  - Queue is full, higher priority incoming packets overwrite lower priority.
  - Implementing a data structure whose insertion time, in the worst case, grows logarithmically in the number of packets.

- Multiple Queue:
  - Priority corresponds to a range of requested velocities. A packet is first mapped to a priority, and then inserted into the FIFO queue.
Prioritized MAC

- Collision Avoidance (CA)
  - Channel idle $\rightarrow$ wait for $\text{DIFS} = \text{BASE\_DIFS} \times \text{PRI}$
  - Packets with a higher priority (corresponding to a smaller PRIORIT Y value) on average choose a smaller waiting period.

- Contention
  - Collision (No CTS or No ACK) $\rightarrow$ $\text{CW} = \text{CW} \times (2 + (\text{PRI} - 1)/\text{MAXPRI})$
  - MAXPRI is the maximum value of priority (corresponding to the lowest priority).
  - The backoff counter of a node with a pending lower priority packet increases faster than a node with a pending packet with a higher priority.

- Similar to 802.11’s EDCF
Simulation: Biometric Sensing

- 100 nodes on 136X136 m²
- Periodic query **count** on 31 nodes, **detail** on 15 nodes

![Diagram showing 100 nodes on 136X136 m², with periodic query count on 31 nodes and detail on 15 nodes. The diagram highlights hot regions (sources) and a far-off point.](image-url)
Workload

- Limitations of the GloMoSim simulator, we had to send data flows on top of the UDP/IP stack that contribute to 28 B overhead. In a real implementation we expect to eliminate the UDP/IP headers.
- Network (roughly approximate MICA mote)
  - Communication range: 30.5 m
  - Packet size: 32B (count), 160 B (detail)
  - Bandwidth: 200 kbps (> MICA)
- Protocols
  - Routing: DSR (Dynamic Source Routing), GF (Geographic Forwarding)
  - Scheduling: FIFO, DS (Deadline-based), SVM, DVM
  - MAC: 802.11, extended 802.11 w. prioritization
Flow of Packets

GF – Flow of Packets

DSR – Flow of Packets

Base station
Deadline Miss Ratio
Overall

GlomoSim simulation (deadline: detail: 5 s, count: 10 s)
Conclusion

- **Velocity Monotonic Scheduling**
  - Reduce end-to-end deadline miss ratio
  - Fair service to remote sensors

- **Event/query service API’s**
  - High-level abstraction for distributed microsensing

- **Location-based protocol stack**
  - Scalable
  - Small protocol overhead
Open issues

- VMS
  - How to measure the distance? #hops? Euclidean distance?
  - How to assign appropriate E2E deadlines? Is a deadline good QoS metric?
  - Neither routing nor congestion control is supported