Mobile Wireless Networking
The University of Kansas EECS 882
Medium Access Control

James P.G. Sterbenz
Department of Electrical Engineering & Computer Science
Information Technology & Telecommunications Research Center
The University of Kansas

jgsp@eecs.ku.edu

http://www.ittc.ku.edu/~jgsp/courses/mwnets

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ML.1 MAC and link layer functions and services
ML.2 Contention-free MAC algorithms
ML.3 Contention-based MAC algorithms
ML.4 MAC algorithms for directional antennae
ML.5 Wireless link protocols
### Medium Access and Link Layers

#### Layer/Plane Cube Model

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### MAC Definition

- *Medium access control* arbitrates a *channel* in shared medium (free space, guided wire, or fiber) among *nodes* (or *terminals* or *stations*)
Medium Access and Link Layers

**Link Definition**

- **Link** is the interconnection between *nodes*
  - *intermediate systems* (IS – switches or routers)
  - *end systems* (ES – or terminals, stations, hosts)
  - uses MAC to access channel

  *note: in ad hoc wireless networks nodes are both IS and ES*

---

Medium Access and Link Layers

**MAC and Link Protocol**

- **Link protocol**
  - is responsible for per hop transfer of data *frame*
  - using a **MAC algorithm** to arbitrate channel access
Wireless Networks
Network Elements: Base Station

• **Base station** (BS) or **Access point** (AP)
  - fixed wireless node
    • one or more antennae
    • may be small (e.g. home hub)
    • may have huge tower
  - range is frequently called a cell
  - typically connected to Internet via wired link
    • in which case it is an intermediate system

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KU EECS 882 – Mobile Wireless Nets – MAC & Link
MWN-ML-7

Wireless Networks
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    • in which case it is an intermediate system
    • may wireless multihop through other BSs

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Wireless Networks
Network Elements: Wireless Node

- Base station (BS)
- *Wireless node* (WN) or *Mobile terminal* (MT) or *Access terminal* (AT)
  - *untethered* with no wired connectivity
  - fixed or stationary node doesn’t move
    - wireless does *not* imply mobility
    - typical example: laptop computer
  - *mobile node* (MN) if
    - typical example: mobile phone or PDA

Lecture LM

Wireless Networks
Network Elements: Wireless Link

- *Base station* (BS)
- *Wireless node* (WN)
- *Wireless link*
  - MAC needed to arbitrate
Wireless Networks
Network Elements: Wireless Link

• **Base station** (BS)
• **Wireless node** (WN)
• **Wireless link**
  – MAC needed to arbitrate
  – interconnects BSs

Wireless Networks
Network Elements: Wireless Link

• **Base station** (BS)
• **Wireless node** (WN)
• **Wireless link**
  – MAC needed to arbitrate
  – interconnects BSs
  – interconnects WNs to BSs
Wireless Networks
Network Elements: Wireless Link

- Base station (BS)
- Wireless node (WN)
- Wireless link
  - MAC needed to arbitrate
  - interconnects BSs
  - interconnects WNs to BSs
  - interconnects WNs peer-to-peer
    - multihop WNs are both ES and IS

Mobile Wireless Networking
ML.1 MAC and Link Layer Functions & Services

ML.1 MAC and link layer functions and services
ML.2 Contention-free MAC algorithms
ML.3 Contention-based MAC algorithms
ML.4 MAC algorithms for directional antennae
ML.5 Wireless link protocols
MAC Layer
Service and Interfaces

- MAC is in-between physical layer 1 and link layer 2
  - lower link sublayer in IEEE 802 model
- MAC layer is mostly in control plane
  - control over when to transmit a L2 frame
  - but may have its own encapsulation (e.g. IEEE 802 legacy)
MAC Layer
Service and Interfaces

- MAC is in-between physical layer 1 and link layer 2
  - lower link sublayer in IEEE 802 model
- MAC layer is mostly in control plane
  - control over when to transmit a L2 frame
  - but may have its own encapsulation
    - node address to determine receiver
- MAC layer service to link layer (L2)
  - MAC layer encapsulate/decapsulate if appropriate
  - initiate transfer of frame into the medium

MAC layer frame may encapsulate link layer frame
- done for link layer / MAC protocol independence
  - IEEE 802: 802.2 LLC (logical link control) over 802.N MAC
Medium Access Control

Taxonomy

- Distributed or centralised
- Duplexing in time or frequency
- Contention-based or contention-free
- Random access or reservation-based
- Sender- or receiver-driven
- In-band or out-of-band
  - explicit or implicit signalling

notes: not all combinations practical or possible
no standard taxonomy
e.g. [GL2000] vs. [KRD2006]

Medium Access Control

Distributed

- Distributed MAC
  - each node operates on its own: *ad hoc mode*
  - nodes transmit when they have data
  - subject to MAC
    - mechanisms limit when a node may transmit
  - generally implies random access
- Centralised MAC
Medium Access Control
Centralised

- Distributed MAC
- Centralised MAC
  - arbitration handled by central controller: infrastructure mode
    - infrastructure mode
  - typically base station or cell tower

Medium Access Control
Duplexing

- Duplexing to determine sharing of bidirectional data
- TDD: time division duplexing
- FDD: frequency division duplexing
Medium Access Control
Duplexing: TDD

- Duplexing to determine sharing of bidirectional data
- TDD: time division duplexing
  - forward and reverse transmissions are multiplexed in time
    - within same frequency (and code)
  - generally necessary for distributed (random) MAC
    - otherwise partitioning is needed by central controller
  - adds complexity to MAC
- FDD: frequency division duplexing

Medium Access Control
Duplexing: FDD

- Duplexing to determine sharing of bidirectional data
- TDD: time division duplexing
- FDD: frequency division duplexing
  - forward and reverse transmissions partitioned in frequency
  - generally requires centralised controller
    - unless well-known or standard frequencies used
  - eliminates timer duplexing complexity within transmit band
Medium Access Control

Contestion Based

• Contention-based MAC
  – nodes transmit when they have data
  – subject to MAC
    • per frame decision
    • analogue to connectionless service
    *implications?*

• Contention-free MAC

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Medium Access Control
Contention Free

• Contention-based MAC
• Contention-free MAC
  – reserves or schedules part of the channel
    • partitions or coördinates access
    • per link or flow decision
    • analogue to connection-oriented service
  – collisions not possible
    implications?

Medium Access Control
Contention

• Contention-based MAC
• Contention-free MAC
  – reserves or schedules part of the channel
    • partitions or coördinates access
    • per link or flow decision
    • analogue to connection-oriented service
  – collisions not possible
  – inefficient channel use for non-CBR traffic
  – resource allocation for QoS possible

Note: [Manoj & Murthy] call this
"contention based with reservations or scheduling"
Medium Access Control

Random Access

- **Random-access MAC**
  - nodes transmit when they have data
  - subject to MAC to resolve contention
    - per frame decision
    - pure random vs. carrier sense
- **Reservation-based MAC**

Medium Access Control

Reservation Based

- Random-access MAC
- Reservation-based MAC
  - nodes transmit when they have data
  - subject to MAC reservation
    - typically based on control mechanism
      - RTS/CTS
      - floor acquisition
Medium Access Control

Sender Driven

- Sender-driven MAC
  - sender initiates MAC and transmission when frame to send
  - most MAC algorithms are sender driven
- Receiver-driven MAC

Medium Access Control

Receiver Driven

- Sender-driven MAC
- Receiver-driven
  - receiver initiates MAC when it is ready to receive
    
    \textit{example later}
Medium Access Control
In-Band vs. Out-of-Band Control

- In-band MAC
  - control is in same frequency band as data
  - explicit signalling messages (e.g. RTS/CTS)
Medium Access Control

In-Band Control

- In-band MAC
  - control is in same frequency band as data
  - explicit signalling messages (e.g. RTS/CTS) or
  - implicit signalling (e.g. CSMA/CD): no signalling messages
- Out-of-band MAC

Medium Access Control

Out-of-Band Control

- In-band MAC
- Out-of-band MAC
  - control in dedicated signalling channel
• Link layer is HBH analog of E2E transport layer
  – transport layer (L4) transfers packets E2E

• Link layer (L2) service to network layer (L3)
  – transfer frame HBH (hop-by-hop)
    • sender: encapsulate packet into frame and transmit
    • receiver: receive frame and decapsulate into packet
Link Layer
Service and Interfaces

- Link layer is HBH analog of E2E transport layer
  - transport layer (L4) transfers packets E2E
- Link layer (L2) service to network layer (L3)
  - transfer frame HBH (hop-by-hop)
    - sender: encapsulate packet into frame and transmit
    - receiver: receive frame and decapsulate into packet
  - error checking / optional correction or retransmission
    - recall end-to-end arguments:
      E2E reliability with HBH error control only for performance
  - flow control possible but not generally needed at link layer
    - parameter negotiation typical (e.g. data rate)
Link Layer
Service and Interfaces

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    - flow control possible but not generally needed at link layer
      - parameter negotiation typical (e.g. data rate)
- Link layer multiplexing and switching

Link Layer
Service and Interfaces

- Link layer frame encapsulates network layer packet
  - packet (NPDU – network layer protocol data unit)
  - frame (LPDU link layer protocol data unit)
    - frame = header + packet + (trailer)
MAC and Link Layer Comparison

- Link layer transfers frame hop-by-hop
  *function?*

- encapsulates in frame
- node address not needed for point-to-point link
MAC and Link Layer Comparison

- Link layer transfers frame hop-by-hop
  - encapsulates in frame
  - node address not needed for point-to-point link
- MAC layer arbitrates access to channel
  \textit{function}?
MAC and Link Layer Comparison

- Link layer transfers frame hop-by-hop
  - encapsulates in frame
  - station address not needed for point-to-point link
- MAC layer arbitrates access to channel
  - control-plane function
  - header fields may be necessary: node address
  - link and MAC
- Physical layer transfers bits through medium
  - coded as electromagnetic wave, photons, or electrons

- Link, MAC, and physical layers frequently blurred
MAC and Link Protocols
IEEE 802 Protocol Stack

- IEEE 802 LAN/MAN standards [IEEE 802.1]
  - www.ieee802.org
- Definition of LAN/MAN protocols for L1–L2
  - 802.2: logical link control
  - 802.\( n \): MAC and physical media dependent

<table>
<thead>
<tr>
<th>802.2</th>
<th>802.( n )</th>
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<tr>
<td>LLC sublayer logical link control</td>
<td>MAC sublayer medium access control</td>
</tr>
<tr>
<td>MAC sublayer</td>
<td>MI sublayer media independent</td>
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<tr>
<td>MI sublayer</td>
<td>PMD sublayer physical media dependent</td>
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<tr>
<td>PMD(_1)</td>
<td>PMD(_2)</td>
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</table>

Link Protocol and MAC
Multiplexing vs. Multiple Access

- Multiplexing vs. multiple access
- Link multiplexing
  - single transmitter
  - dedicated point-to-point link
Link Protocol and MAC
Multiplexing vs. Multiple Access

- Multiplexing vs. multiple access
- Link multiplexing
  - single transmitter
  - dedicated point-to-point link
- Multiple access
  - multiple transmitters
  - shared medium
  - essentially physical layer multiplexing
  - MAC algorithm needed to arbitrate

Functional Placement

- MAC and Link layer functionality per line interface
  - end system: network interface (NIC)
  - switch/router: line card
Wireless MAC Algorithms
Design Goals

- Scalable to large networks
- Efficient bandwidth utilisation
  - low control traffic overhead
- Fair among users
  - subject to QoS differentiation
- Resilience
  - minimise impact of hidden and exposed nodes
  - robust against lost control messages, fading, jamming
- Power/energy awareness
  - optimised for energy constrained nodes

Mobile Wireless Networking
ML.2  Contention-Free MAC Algorithms

ML.1  MAC and link layer functions and services
ML.2  Contention-free MAC algorithms
  ML.2.1  Channel partitioning MAC
  ML.2.2  Coördinated access MAC
  ML.2.3  Spread spectrum MAC
ML.3  Contention-based MAC algorithms
ML.4  MAC algorithms for directional antennae
ML.5  Wireless link protocols
Medium Access Control
Contention-Free MAC

- Contention-free MAC
  - ensures that channel is divided in time or frequency
    - reserved or scheduled
    - per link or flow decision
    - analogue to connection-oriented service
    - generally centralised control from base station
  - collisions not possible
  - inefficient channel use for non-CBR traffic
  - resource allocation for QoS possible

Medium Access Control
Contention-Free MAC

- Contention-free MAC taxonomy
  - following EECS 780, [Kurose and Ross], [KRD2006]
- Channel partitioning
  - reserve chunk of channel
  - e.g. TDMA
- Coördinated access
  - take turns
  - e.g. polling using tokens
- Spread spectrum
  - share same spectrum among users without collisions
Mobile Wireless Networking
ML.2.1 Channel Partitioning MAC Algorithms

ML.1 MAC and link layer functions and services
ML.2 Contention-free MAC algorithms
ML.2.1 Channel partitioning MAC
ML.2.2 Coordinated access MAC
ML.2.3 Spread spectrum MAC
ML.3 Contention-based MAC algorithms
ML.4 MAC algorithms for directional antennae
ML.5 Wireless link protocols

Contention-Free MAC Algorithms
Types

- Channel partitioning
  - TDMA, FDMA, WDMA (optical)
  - best under high deterministic load
- Coordinated access (taking turns)
  - polling, token passing
  - performs well in wired networks
    - combines benefits of both partitioning and random access
  - difficult to implement in wireless networks
- Spread spectrum
  - CDMA
  - resistant to interference and jamming
Channel Partitioning MAC
Introduction and Assumptions

- Channel has sufficient capacity
  - individual inter-node date rates less than channel capacity
- Multiple nodes share a channel
- Channel *partitioned* into pieces
  - pieces assigned to individual inter-node communication
  - MAC arbitrates

Channel Partitioning MAC
Alternatives

- TDMA: time division multiple access
- FDMA: frequency division multiple access
  - typically refers to RF
  - WDMA: wavelength division multiple access (light)
- CDMA: code division multiple access
  - spread spectrum (later)
- Note similarity to multiplexing schemes
  - TDMA ~ TDM, FDMA ~ FDM
  - essentially *distributed physical layer* versions of link muxing
Channel Partitioning MAC

TDMA

- TDMA: time division multiple access
- Channel divided into $n$ time slots
  - served cyclically
  - generally equal size
  - within a frequency band
- MAC arbitrates how nodes assigned to slots
  - static TDMA: slots reserved for particular links
  - dynamic TDMA: slots scheduled based on traffic demand
Channel Partitioning MAC
FDMA

- FDMA: frequency division multiple access
- Channel divided into $n$ frequency bands
  - generally of equal bandwidth
  - over period of time

MAC arbitrates how nodes assigned to frequencies
- static TDMA: slots reserved for particular links
- dynamic TDMA: slots scheduled based on traffic demand
Channel Partitioning MAC
Link Duplexing

- Link types
  - half duplex: unidirectional hop-by-hop transfer
  - full duplex: bidirectional hop-by-hop transfer
- Most communication requires full duplex link
  - even unidirectional data transfer
  - *why?*

Channel Partitioning MAC
Link Duplexing

- Link types
  - half duplex: unidirectional hop-by-hop transfer
  - full duplex: bidirectional hop-by-hop transfer
- Most communication requires full duplex link
  - even unidirectional data transfer
  - control messages such as ACKs for ARQ
    - may be highly asymmetric
Channel Partitioning MAC
Link Duplexing

• Link types
  – half duplex: unidirectional hop-by-hop transfer
  – full duplex: bidirectional hop-by-hop transfer

• Most communication requires full duplex link
  – even unidirectional data transfer
  – control messages such as ACKs for ARQ
    – may be highly asymmetric
  – Alternative strategies for \textit{duplexing}
    – separate end-to-end paths

\textit{Problem?}
Channel Partitioning MAC
Link Duplexing

- Link types
  - half duplex: unidirectional hop-by-hop transfer
  - full duplex: bidirectional hop-by-hop transfer
- Most communication requires full duplex link
  - even unidirectional data transfer
  - control messages such as ACKs for ARQ
    - may be highly asymmetric
  - Alternative strategies for duplexing
    - separate distinct end-to-end paths through network
    - paired unidirectional links in same guided media
      - e.g. 2×twisted-pair, 2×fiber
Channel Partitioning MAC
Frequency Division Duplexing

• Duplexing: bidirectional transmission sharing media
• FDD: frequency division duplexing
  – forward and reverse traffic assigned to different freq. bands

advantages and disadvantages?
Channel Partitioning MAC
Time Division Duplexing

- Multiplexing in time and space for full duplex
  - bidirectional data transmission
- FDD: frequency division duplexing
- TDD: *time division duplexing*
  - forward and reverse traffic assigned to *same* freq. bands
  
  advantages and disadvantages?

- forward and reverse traffic assigned to same freq. bands
  - slots divided between upstream and downstream traffic
  - dynamic bandwidth adjustment needed for assymetric traffic
  - operates in conjunction with various channel multiplexing
    - eg. TDD within FDMA

examples in Lecture WN
Channel Partitioning MAC
Advantages and Disadvantages

- Channel partitioning
  - TDMA, FDMA, WDMA (optical)
  - best under high deterministic load
- Coordinated access (taking turns)
  - polling, token passing
  - performs well in wired networks
    - combines benefits of both partitioning and random access
  - difficult to implement in wireless networks
- Spread spectrum
  - CDMA
  - resistant to interference and jamming

Channel Partitioning MAC
Characteristics

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<th>Random Access</th>
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Mobile Wireless Networking
ML.2.2 Coördinated Access MAC

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  ML.2.3 Spread spectrum MAC
ML.3 Contention-based MAC algorithms
ML.4 MAC algorithms for directional antennæ
ML.5 Wireless link protocols

Coördinated Access MAC
Introduction and Assumptions

- Channel has sufficient capacity
  - individual inter-node date rates less than channel capacity
- Multiple nodes share a channel
- Nodes use channel for a period of time
  - in a fully highly coordinated manner
    - central controller (e.g. polling)
    - algorithmic turn taking (e.g. token passing)
  - MAC arbitrates
Coördinated Access MAC

Polling

- Controller grants channel access to node
  - each node polled to determine if it needs to transmit

Coördinated Access MAC

Token Passing

- Token grants channel access to station
  - token passed between nodes
  - generally round robin
Coördinated Access MAC

Token Passing

- Token grants channel access to station
  - token passed between nodes
  - generally round robin

- Topologies
  - wired bus
    - IEEE 802.4 never successful
  - wired ring interconnection
    - IEEE 802.5

*Problem for wireless?*
Coördinated Access MAC
Advantages and Disadvantages

- Channel partitioning
  - TDMA, FDMA, WDMA (optical)
  - best under high deterministic load
- Coördinated access (taking turns)
  - polling, token passing
  - performs well in wired networks
    - combines benefits of both partitioning and random access
  - difficult to implement in wireless networks
- Spread spectrum
  - CDMA
  - resistant to interference and jamming

Coördinated Access MAC
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Mobile Wireless Networking
ML.2.3 Spread Spectrum MAC

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ML.4 MAC algorithms for directional antennae
ML.5 Wireless link protocols

Spread Spectrum MAC
Introduction and Assumptions

• Channel has sufficient capacity
  – individual inter-node data rates less than channel capacity
• Multiple nodes share a channel
• Nodes use channel for a period of time
• Transmission spread in frequency spectrum
  – coding techniques avoid interference
• CDMA: code division multiple access
  – DSSS: direct sequence spread spectrum
  – FHSS: frequency hopping spread spectrum
Spread Spectrum MAC
CDMA

- CDMA: code division multiple access
- Channel use different codes
  - in a given frequency band
  - over period of time
- Analogy: speaking
  - English, German, Chinese, Hindi
  - in the same room at the same time
  - easier to converse in a given language (code)
    if interference is in different languages (codes)

Spread Spectrum MAC
CDMA Types

- Direct sequence (DS)
  - symbols multiplied by higher frequency chipping sequence
- Frequency hopping (FH)
  - transmissions rapidly hop among different frequency carriers
    - pseudorandom sequence negotiated between transceivers
Spread Spectrum MAC
DS CDMA Concepts

- All stations share same frequency band
  - unique code assigned to each station
- Each station has its own *chipping* sequence
  - unique code at chipping rate
  - encoded signal = (original data) × (chipping sequence)
  - decoding: inner-product of encoded signal and chipping seq.
- Multiple stations transmit simultaneously
  - minimal interference if codes are *orthogonal*

*analogy:* [suggested by D. Broyles]
*conversations at the same time in different languages*

---

Spread Spectrum MAC
CDMA Encode/Decode Example

---

sender

receiver

channel output $Z_{lm}$

channel output $Z_{lm}$

received input

$D_l = \sum_{m=1}^{M} Z_{lm} c_m$

$D_l = \sum_{m=1}^{M} Z_{lm} c_m$

$D_l = \sum_{m=1}^{M} Z_{lm} c_m$

sender

receiver

channel output $Z_{lm}$

channel output $Z_{lm}$

received input

$D_l = \sum_{m=1}^{M} Z_{lm} c_m$

$D_l = \sum_{m=1}^{M} Z_{lm} c_m$

$D_l = \sum_{m=1}^{M} Z_{lm} c_m$
Spread Spectrum MAC
FHSS Concepts

- All nodes share set of frequency bands
- Each node has its own channel sequence
  - transmitters and receivers hop through channel sequence
- Multiple nodes transmit simultaneously

Advantages and disadvantages?

Spread Spectrum MAC
FHSS Advantages

- All nodes share set of frequency bands
- Each node has its own channel sequence
  - transmitters and receivers hop through channel sequence
- Multiple nodes transmit simultaneously
- Advantages
  - resistant to interception
    - unless receiver has channel sequence
  - resistant to jamming
    - difficult to jam over wide frequency ranges
Spread Spectrum MAC
FHSS Disadvantages

- All nodes share set of frequency bands
- Each node has its own channel sequence
  - transmitters and receivers hop through channel sequence
- Multiple nodes transmit simultaneously
- Advantages
  - resistant to interception and jamming
- Disadvantages
  - interferes with FDM and DSSS in same frequency bands

Spread Spectrum MAC
Advantages and Disadvantages

- Channel partitioning
  - TDMA, FDMA, WDMA (optical)
  - best under high deterministic load
- Coördinated access (taking turns)
  - polling, token passing
  - performs well in wired networks
    - combines benefits of both partitioning and random access
  - difficult to implement in wireless networks
- Spread spectrum
  - CDMA
  - resistant to interference and jamming
Spread Spectrum MAC
Characteristics

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Mobile Wireless Networking
ML.3  Contention-Based MAC Algorithms

ML.1  MAC and link layer functions and services
ML.2  Contention-free MAC algorithms
ML.3  Contention-based MAC algorithms
   ML.3.1  Random access and slotted time
   ML.3.2  Contention, collisions, and CSMA
   ML.3.3  Hidden and exposed nodes
ML.4  MAC algorithms for directional antennae
ML.5  Wireless link protocols
Contestation-Based MAC
Introduction and Assumptions

- Channel has sufficient capacity
  - individual inter-node date rates less than channel capacity
- Multiple nodes share a channel
- Nodes use channel for a period of time
  - generally entire channel
    - baseband for wired network
    - share a frequency band for wireless (random access in FDMA)
  - in a fully distributed (random) manner
    - similar to statistical TDM
  - MAC arbitrates

Mobile Wireless Networking
ML.3.1 Random Access and Slotted Time

ML.1 MAC and link layer functions and services
ML.2 Contention-free MAC algorithms
ML.3 Contention-based MAC algorithms
  ML.3.1 Random access and slotted time
  ML.3.2 Contention, collisions, and CSMA
  ML.3.3 Hidden and exposed nodes
ML.4 MAC algorithms for directional antennae
ML.5 Wireless link protocols
Random Access MAC

ALOHA

- ALOHA: 1970s radio network among Hawaiian islands
- Senders transmit whenever they have data (no MAC)

Performance metrics
- channel efficiency
  - what fraction of transmission attempts are successful
- channel throughput
  - what is the maximum carried load of the channel?

Problem
- collisions: transmissions interfere with one another
Random Access MAC

ALOHA

- ALOHA: 1970s radio network among Hawaiian islands
- Senders transmit whenever they have data (no MAC)

Problem
- collisions: transmissions interfere with one another
- even if only very small overlap

29 August 2011  KU EECS 882 – Mobile Wireless Nets – MAC & Link  MWN-ML-101
Random Access MAC
Slotted ALOHA

- ALOHA: 1970s radio network among Hawaiian islands
- Senders transmit whenever they have data in slot

Problem
- collisions: transmissions interfere with one another
- improvement: divide time into slots

Random Access MAC
Slotted ALOHA

- ALOHA: 1970s radio network among Hawaiian islands
- Senders transmit whenever they have data in slot

Problem
- collisions: transmissions interfere with one another
- improvement: divide time into slots
- delay transmissions to next slot time
Random Access MAC
Slotted ALOHA

- ALOHA: 1970s radio network among Hawaiian islands
- Senders transmit whenever they have data in slot

Problem
- collisions: transmissions interfere with one another
- improvement: divide time into slots
- delay transmissions to next slot time
- slotted time reduces probability of collisions

![Diagram of ALOHA and slotted ALOHA]

Unslotted vs. Slotted Performance

- Slotting approximately doubles performance
  - slotted: Throughput = $Ge^{-G}$
  - unslotted: Throughput = $Ge^{-2G}$

![Graph showing throughput vs. G for slotted and unslotted]

(adapted from Tannenbaum)
Random Access MAC
Challenges

- Multiple nodes must be able to share channel
- When 2 or more nodes *simultaneously* transmit
  - signals garbled in a *collision*: none of them are successful
- How to arbitrate among them?
  - MAC algorithm

*How can we do better than random transmission?*

---

Mobile Wireless Networking
ML.3.2 Contention, Collisions, and CSMA

ML.1 MAC and link layer functions and services
ML.2 Contention-free MAC algorithms
ML.3 Contention-based MAC algorithms
  - ML.3.1 Random access and slotted time
  - ML.3.2 Contention, collisions, and CSMA
  - ML.3.3 Hidden and exposed nodes
ML.4 MAC algorithms for directional antennae
ML.5 Wireless link protocols
Medium Access Control

Contention

- *Contention-based* or *random-access* MAC
  - nodes transmit when they have data
  - subject to MAC
    - per frame decision
    - analogue to connectionless service
- collisions possible
- efficient channel utilisation
  - in the absence of collisions

Random Access MAC

Contention and Collisions

*What is the simplest way to reduce collisions?*
Random Access MAC
CSMA (1-persistent)

- CSMA – *carrier sense* multiple access
  - nodes can sense if channel is in use by another station
  - wait to transmit to avoid collision
  - human analogy: don’t interrupt others already speaking
- 1-persistent CSMA
  - wait until channel free, then transmit
    (transmit with probability 1)

Problem? How can we do better?

Random Access MAC
CSMA (non- and \( p \)-persistent)

- Problem: synchronisation of collisions
  - waiting nodes will *all* transmit as soon as channel free
- Two options:
- Non-persistent CSMA
  - if carrier sensed wait random period before trying again
    (rather than continuously sensing until channel free)
  - better utilisation, but delayed even when unnecessary
- \( p \)-persistent CSMA (for slotted time)
  - continuously sense carrier until channel is available
  - but with only with probability \( p \) transmit on next slot
Random Access MAC
CSMA Collisions

- Collisions still occur
  - due to propagation delay
  - sender may not know
    channel already in use

- $\Pr[\text{collision}]$ incr. w/ length
  - $B$ & $D$ don’t know other xmit
Random Access MAC
CSMA Collisions

• Collisions still occur
  – due to propagation delay
  – sender may not know channel already in use
• Pr[collision] incr. w/ length
  – B & D don’t know other xmit
  – until signals meet near C
  – and return
• Inefficient
  – channel used by garbage

Can we do better?

Random Access MAC
CSMA/CD

• CSMA/CD: CSMA with collision detection
  – station detecting a collision immediately ceases transmission
  – human analogy: polite conservationist
• Worst case CD takes twice media propagation delay
  – A transmits packet
Random Access MAC
CSMA/CD

- CSMA/CD: CSMA with *collision detection*
  - station detecting a collision immediately ceases transmission
  - human analogy: polite conservationist
- Worst case CD takes *twice* media propagation delay
  - A transmits packet
  - B transmits packet just before A reaches B
Random Access MAC

CSMA/CD

- **CSMA/CD**: CSMA with *collision detection*
  - station detecting a collision immediately ceases transmission
  - human analogy: polite conservationist
- **Worst case CD takes *twice* media propagation delay**
  - A transmits packet
  - B transmits packet just before A reaches B
  - A+B interference travels back to A

Random Access MAC

Collision Detection Efficiency

- CD frees channel earlier
  \[
  \frac{1}{1 + 5 \frac{t_{\text{prop}}}{t_{\text{trans}}}}
  \]
  \(t_{\text{prop}}\): max prop between nodes
  \(t_{\text{trans}}\): time to transmit max frame
- Efficiency
  \(\rightarrow 1 \text{ as } t_{\text{prop}} \rightarrow 0\)
  \(\rightarrow 1 \text{ as } t_{\text{trans}} \rightarrow \infty\)
Random Access MAC
Collision Detection Efficiency

- CD frees channel earlier
  \[ \frac{1}{1 + 5 \frac{t_{\text{prop}}}{t_{\text{trans}}}} \]
  \( t_{\text{prop}} \) max prop between nodes
  \( t_{\text{trans}} \) time to transmit max frame

- Efficiency
  \[ \rightarrow 1 \text{ as } t_{\text{prop}} \rightarrow 0 \]
  \[ \rightarrow 1 \text{ as } t_{\text{trans}} \rightarrow \infty \]

- Much better than CSMA
  - still decentralized,
    simple, and cheap
  problem?

CSMA/CD
Backoff

- If stations all transmit after backoff, same problem
  - need some way of un-synchronising retransmissions

  \[ \text{How?} \]
CSMA/CD
Exponential Backoff

• If stations all transmit after backoff, same problem
  – need some way of un-synchronising transmissions

• Exponential backoff:
  – stations wait a random number of slot times before retrying
  – binary exponential distribution:
    \( n \text{th collision wait randomly among } \{0, \ldots, 2^{n-1}\} \) slots
    1st collision: wait 0 or 1 slots
    2nd collision: wait 0, 1, 2, or 3 slots
    ...
  – low load: minimise delay
  – moderate load: spread retries

CSMA/CD
Problems

Problems?
CSMA/CD

Problems: Collision Detection and Carrier Sense

Problem with collision detection?

- Problems with collision detection
  - station must be able to simultaneously transmit and receive
    - requires full duplex
  - not possible for single wireless tranceiver at given frequency
- **CSMA/CD not appropriate for wireless networks**
  - Ethernet evolution eliminated vast majority of CSMA/CD
Problem with Carrier Sense

- **CSMA/CD not appropriate for wireless networks**

Problem with carrier sense?

- Problem with carrier sense
  - only appropriate when *all* nodes within range
  - typically *not* the case for wireless networks

*problem?
CSMA
Problem with Carrier Sense

- **CSMA/CD not appropriate for wireless networks**
- Problem with carrier sense
  - only appropriate when all nodes within range
  - typically not the case for wireless networks
  - problem: hidden nodes

Mobile Wireless Networking
ML.3.3 Hidden and Exposed Nodes

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  ML.3.3 Hidden and exposed nodes
ML.4 MAC algorithms for directional antennæ
ML.5 Wireless link protocols
Hidden and Exposed Nodes

Hidden Nodes

- *Hidden nodes* (terminals)
  - some nodes are hidden from one another
  - out of transmission range
  - unaware that they are causing collisions with hidden node

Random Access Wireless MAC

Hidden Nodes

- Hidden node problem
Random Access Wireless MAC

Hidden Nodes

- Hidden node problem
  - A can communicate with B
  - C can communicate with B
Random Access Wireless MAC
Hidden Nodes

• Hidden node problem
  – A can communicate with B
  – C can communicate with B
  – A can not communicate with C

unaware of interference
Random Access Wireless MAC

Hidden Nodes

- Hidden node problem
  - A can communicate with B
  - C can communicate with B
  - A can not communicate with C
    - unaware of interference

- Causes of hidden nodes
  - line-of-sight obstructions
Hidden and Exposed Nodes

Exposed Nodes

- Exposed nodes (terminals)
  - some nodes are in range of one another
  - prevent transmission because collision assumed

Example:
- B transmitting to C
Hidden and Exposed Nodes

Exposed Nodes

- Exposed nodes (terminals)
  - some nodes are in range of one another
  - prevent transmission because collision assumed
- Example:
  - B transmitting to C
  - but A hears B: won’t transmit for CA

---

Hidden and Exposed Nodes

Exposed Nodes

- Exposed nodes (terminals)
  - some nodes are in range of one another
  - prevent transmission because collision assumed
- Example:
  - B transmitting to C
  - but A hears B: won’t transmit for CA
  - even though it could to D without jamming B→C
Hidden and Exposed Nodes

Exposed Nodes

- Exposed nodes (terminals)
  - some nodes are in range of one another
  - prevent transmission because collision assumed

Solution?

• Spatial reuse necessary
  - directional antennae one strategy
Random Access Wireless MAC

CSMA

• CSMA/CD not practical for wireless networks
  – full duplex problem
  – hidden terminal problem

*Alternatives that are still better than (pure) CSMA?*

Collision Avoidance

• Collision avoidance (CA)
  – attempt to avoid collision (but don’t detect once occurs)
Random Access Wireless MAC
Collision Avoidance: Floor Acquisition

- Floor acquisition (FAMA: floor access multiple access)
  - efficient negation to determine which node transmits
  - may be in-band or out-of band (e.g. signalling frequency)
  - similar to audio conference floor acquisition protocols

MACA

- MACA: multiple access with collision avoidance
  - in-band floor acquisition

How?
Random Access Wireless MAC
MACA

- MACA: multiple access with collision avoidance
  - in-band floor acquisition
- MACA operation (analogy: teleconference “may I”)
  - sender transmits RTS (request to send) if no carrier sense

```
+-----------------+     +-----------------+
| RTS             |     | RTS             |
+-----------------+     +-----------------+
      A             |     |      B          |
```

- MACA operation
  - sender transmits RTS (request to send)
  - intended receiver replies with CTS (clear to send)
  - all nodes in range of both will detect at least 1 of RTS/CTS

```
+-----------------+     +-----------------+
| CTS             |     | CTS             |
+-----------------+     +-----------------+
      A             |     |      B          |
```
Random Access Wireless MAC
MACA

- MACA: multiple access with collision avoidance
  - in-band floor acquisition
- MACA operation
  - sender transmits RTS (request to send)
  - intended receiver replies with CTS (clear to send)
  - all nodes in range of both will detect at least 1 of RTS/CTS
  - if sender receives clear CTS it can transmit

Random Access Wireless MAC
MACAW

- MACAW: MACA for wireless
  - data frames acknowledged
  - exponential backoff per send/receive pair
  - modified backoff algorithm
    [BDSZ1994] next time
Random Access Wireless MAC
DFWMAC

- DFWMAC: distributed foundation wireless MAC
- MACAW + CSMA/CA = CSMA/CA: collision avoidance
  - RTS/CTS to reduce Pr[collision]
  - used in IEEE 802.11
- Sender
  - sense and wait for DIFS interval

Random Access Wireless MAC
DFWMAC

- CSMA/CA: collision avoidance
  - RTS/CTS to reduce Pr[collision]
- Sender
  - sense and wait for DIFS interval
  - if channel free send RTS
Random Access Wireless MAC  
DFWMAC

- CSMA/CA: collision avoidance  
  - RTS/CTS to reduce Pr[collision]
- Sender  
  - sense and wait for DIFS interval  
  - if channel free send RTS
- Receiver  
  - wait for SIFS interval

Random Access Wireless MAC  
DFWMAC

- CSMA/CA: collision avoidance  
  - RTS/CTS to reduce Pr[collision]
- Sender  
  - sense and wait for DIFS interval  
  - if channel free send RTS
- Receiver  
  - wait for SIFS interval  
  - return CTS if channel idle  
  - receiver hears nodes hidden from sender
Random Access Wireless MAC
DFWMAC

- CSMA/CA: collision avoidance
  - RTS/CTS to reduce Pr[collision]
- Sender
  - sense and wait for DIFS interval
  - if channel free send RTS
- Receiver
  - wait for SIFS interval
  - return CTS if channel idle
- Sender
  - wait for SIFS interval
  - why not DIFS?

DIFS
SIFS
RTS
CTS
sense

5
Random Access Wireless MAC
DFWMAC

- CSMA/CA: collision avoidance
  - RTS/CTS to reduce $Pr[\text{collision}]$
- Sender
  - sense and wait for DIFS interval
  - if channel free send RTS
- Receiver
  - wait for SIFS interval
  - return CTS if channel idle
- Sender
  - wait for SIFS interval
  - transmit frame

![Diagram of DFWMAC protocol](image)
Random Access Wireless MAC
DFWMAC

- CSMA/CA: collision avoidance
  - RTS/CTS to reduce $Pr[collision]$
- Sender
  - sense, wait for DIFS, send RTS
- Receiver
  - wait for SIFS, return CTS
- Sender
  - wait for SIFS, transmit frame
- Receiver
  - wait for SIFS interval and return ACK
- Sender
  - must wait DIFS before next frame

Random Access Wireless MAC
EY-NPMA

- EY-NPMA: Elimination yield – non-preemptive priority multiple access
  - carrier sense
- If no carrier, transmit *immediately* (no DIFS wait)
- If carrier:
  - prioritisation phase
  - contention phase
    - elimination phase
    - yield phase
- Used in ETSI HIPERLAN
  - early competitor for 802.11
Random Access Wireless MAC
Floor Acquisition

- In-band floor acquisition
  - MACA / MACAW / DFWMAC

Alternative?

---

Random Access Wireless MAC
BTMA

- BTMA: busy tone multiple access
  - out-of-band floor acquisition

How?
Random Access Wireless MAC

BTMA

- BTMA: busy tone multiple access
  - out-of-band floor acquisition
- BTMA operation (analogy: raise hand to speak)
  - sender transmits busy tone if no busy tone sense
  - sender transmits data
  - all nodes sensing data carrier tone transmit busy tone

why?

Advantages and disadvantages?
Random Access Wireless MAC

BTMA

- BTMA: busy tone multiple access
  - out-of-band floor acquisition
- BTMA operation (analogy: raise hand to speak)
  - sender transmits busy tone if no carrier sense
  - sender transmits data
  - all nodes sensing data carrier tone retransmit busy tone
    - busy tone propagated 2-hops to avoid hidden-node problem
- Advantages and disadvantages
  + simple and effective
  - inefficient: busy tone channel and exposed terminals

BTMA Variants: DBTMA

- DBTMA: Dual BTMA
  - data channel + out-of-band slotted control channel
  - control channel for RTS/CTS and orthogonal busy tones
    - receiver BT, and transmitter BT,
      why?
Random Access Wireless MAC
BTMA Variants: DBTMA

- DBTMA: Dual BTMA
  - data channel + out-of-band slotted control channel
  - control channel for RTS/CTS and orthogonal busy tones
    - receiver BT, and transmitter BT,
  - directionality of BTs allows spatial reuse

- Operation
  - sender transmits RTS if no BT, active
  - if RTS received, receiver transmits CTS and asserts BT,
  - if CTS received, transmitter asserts BT, and transmits frame
  - receiver turns off BT, when entire frame received
Random Access Wireless MAC
BTMA Variants: RI-BTMA

- RI-BTMA: receiver-initiated BTMA
  - data channel + out-of-band busy tone control channel

Operation
- sender transmits preamble with destination station id
- receiver asserts busy tone (receiver initiation)
- sender transmits data frame if busy tone received
Random Access MAC

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Centralised Random Access MAC

Overview

- Random access MAC exploiting base station
- Examples [GL2000]
  - ISMA: idle sense multiple access
  - RAP: random addressed polling
  - RAMA: resource auction multiple access
Centralised Random Access MAC

**ISMA**

- ISMA: idle sense multiple access
- CSMA/CD performed by BS (base station)
- Base station transmits periodic idle signal (IS) frames
- Stations transmit after IS
- If no collision, BS replies with ISA (IS ACK)

Centralised Random Access MAC

**RAP**

- RAP: Randomly addressed polling
- Each station assigned orthogonal pseudo-random ID
- Contention period
  - stations wishing to transmit CDMA transmit ID
- Data phase
  - BS polls all stations that transmitted
  - stations reply with data frame
Centralised Random Access MAC
RAMA

- RAMA: Resource auction multiple access
- Each station assigned id
  - prioritised
- Contention or auction phase
  - each station transmits ID bit-by-bit
  - BS does logical or and replies
  - stations with mismatch drop out
  - highest ID (priority) stations win
- Inherently unfair

Mobile Wireless Networking
ML.4 MAC Algorithms for Directional Antennae

ML.1 MAC and link layer functions and services
ML.2 Contention-free MAC algorithms
ML.3 Contention-based MAC algorithms
ML.4 MAC algorithms for directional antennae
ML.5 Wireless link protocols
Channel Partitioning MAC
SDMA and Directional Antennæ

• Assumption so far
  – omnidirectional antennæ radiate in all directions
  – radiate even where not needed
  – reduce channel capacity

• Directional antennæ
  – radiate focused beam toward receiver
  – reduce power use
  – reduce interference: spatial reuse

• SDMA: space division multiple access MAC
  – complexity of beam steering and station tracking
Frame Error Detection

Checksum

- Detect errors in PDU
- Binary addition of bytes/words
  - sender: compute checksum and insert in header/trailer
  - receiver: compute checksum and compare to header/trailer

Advantages?

Disadvantages?
Frame Error Detection
Checksum

- Detect errors in PDU
- Binary addition of bytes/words
  - sender: compute checksum and insert in header/trailer
  - receiver: compute checksum and compare to header/trailer
- Advantage:
  - simple to compute
- Disadvantage:
  - weak detection of errors
  - some bit-flip combinations may remain undetected
  - not adequate for error-prone wireless links
Frame Error Detection
CRC

- Cyclic redundancy check
  - stronger error detection for PDU

- View data bits, D, as a binary number
  - choose $r + 1$ bit pattern (generator), $G$

- Goal: choose $r$ CRC bits R such that
  - $<D,R>$ exactly divisible by $G$ (modulo 2)
  - receiver knows $G$, divides $<D,R>$ by $G$
    - if non-zero remainder: error detected
  - can detect all burst errors less than $r + 1$ bits
Frame Error Detection & Correction

FEC

• Forward error correction
  – each PDU has error correcting header
  – combination of header/payload allows significant correction

• Open-loop error control
  – errors corrected at the receiver without retransmissions
  
  *how does this help?*
Frame Error Detection & Correction

**FEC**

- **Forward error correction**
  - each PDU has error correcting header
  - combination of header/payload allows significant correction

- **Open-loop error control**
  - errors corrected at the receiver without retransmissions
  - reduces need over long delay links for:
    - retransmissions
    - sender buffers
  - statistical reliability good enough for some applications
  - e.g. G.975 (255,239) Reed Solomon code in SDH/SONET

**Note:** FEC can also be done end-to-end
- but TCP doesn't support it
Medium Access and Link Layer

Further Reading


Acknowledgements

Some material in these foils is based on the textbook


Significant material in these foils enhanced from EECS 780 foils