The MAC Sublayer

The Medium Access Control (MAC) sublayer is the bottom half of the Datalink layer. The upper half is commonly called the Logical Link Control (LLC) sublayer.

Primary function -
Arbitrate access to a shared transmission medium. The MAC sublayer is NULL for point to point channels.

Motivation for the use of a shared channel:

- Sharing gives better performance than static suballocation using pure TDM or FDM

  Assume interarrival and service time distributions are exponential:

  N = number of stations = 10
  C = capacity of the channel in bits per second = 10,000 bits/sec
  $1 / \mu$ = mean bits / frame = 1,000 bits
  μC = service rate of the channel in frames / second = 10 frames /sec
  λ = total rate at which frames arrive = 5 frames /sec
  T = mean delay = $1 / (\mu C - \lambda) = 1 / (10 - 5) =$ 0.2 secs

  Now suppose we could subdivide channel using FDM or TDM

  $\mu C / N$ = new capacity of each subchannel = 1 frame / sec
  λ / N = arrival rate of each station = 0.5 frames / sec
  T = $1 / (\mu C / N - \lambda / N) = N / (\mu C - \lambda) = 10 / (10 - 5) =$ 2 secs

- Sharing is cheaper than replication (dedicated paths between endpt pairs)

  Nevertheless, replication is becoming common in wired networks

  LANs are now commonly star-wired with a central switch
  The switch supports concurrent transfers between different host pairs
  The switch contains some output buffering for common targets.

- Sharing instead of replication may be the only viable option

  For wireless nets its not possible to replicate space!
  For cable nets replication would defeat the primary advantage of cable -- no need to star wire the world as in the telphone system.

Model parameters for shared medium MAC analysis

Station model:

N independent stations. Each generates frames at rate λ

Channel model

A single channel is used by all stations

No hardware based priority assignment (as there is on a computer system bus)

Two frames whose transmissions overlap cause a collision that destroys both.

Timing model

Continuous time:	frames may be transmitted at any time.
Slotted time:	frames may be transmitted only at distinct clock ticks

Channel sense model

Carrier sense:	stations can determine if channel is busy before sending
No carrier sense:	not possible to determine if channel is in use

Collision model:

Collision detection:	stations can hear a collision and immediately stop
No CD:	station continues to send entire frame

Approaches to controlling channel access

Contention:	Just start transmitting (Collision susceptible)
Token passing:	Can't transmit until you receive token (Collision free)
Reservation:	Make a prior reservation (Collision free)
Hybrid:	Contention based reservation systems.

MAC protocol considerations for contention based approaches

When can I transmit?

Any time / any slot
Only after sensing and detecting idle
Only after sensing idle and waiting a random time

↓ Decreasing Greediness

May be differences in behavior depending upon whether the channel is initially found to be busy or idle.

How do I determine if there was a collision?

Hear it when it happens (Ethernet) (packet time >> RTT)
Hear it later (Aloha) (packet time << RTT)
Don't hear it at all (802.11) and timeout for missing ACK

How long do I wait after a collision before retrying?

States of a shared medium channel

The channel always exists in one of three states (and two of them are bad for throughput):

Idle
Collision in progress
Successful transmission in progress

Often it is assumed that all stations have an infinite backlog of traffic to send. In that case the efficiency of the MAC protocol is

eff = time spent transmitting / elapsed time

where the elapsed time is the sum of the time spent in each of the three states. The efficiency of a protocol may also be expressed as the number of successful transmissions per packet transmission time.

It is typically the case that *reducing greediness*

decreases the time spent colliding but it also
increases the amount of idle time.

Since *idle* is just as costly as *colliding* in terms of loss of efficiency we don't want to be too nice.

Performance analysis of Pure Aloha

Assumptions

- Infinite number of stations
- No carrier sense
- No slotted time
- Random wait until retransmission
- Entire collection of stations generate new traffic at rate ▪▪
- All packets have the same length

Since time is not slotted, window of collision vulnerability = 2 packet times

S = Throughput in packets / packet time = λ if system is stable
G = Total number of transmission attempts / packet time (including collisions)
S < 1 If system is stable
G >= S
P_0 = Probability (or fraction) of successful transmission.
S = P_0G The number of successful transmissions per packet time.

Poisson probability of exactly *k* transmissions in *t* packet times.

$$P(k,t)=(Gt)^k\frac{e^{(-Gt)}}{k!}$$

Window of collision vulnerability in pure aloha is 2 packet times.
Because we have assumed an infinite # of stations, P[my transmission succeeds | I decide to transmit] is:

$$P_0=P(0,2)=(2G)^0\frac{e^{(-2G)}}{0!}=e^{(-2G)}$$

Thus $S=P_0G=Ge^{(-2G)}$

==> max throughput 0.18 packets / packet time at a total offered load of 0.5 packets per packet time.

Slotted ALOHA

All transmissions must start at a slot boundary. Therefore the window of collision vulnerability is now *reduced* to 1 packet time and

$$P_0 = P(0,1) = G^0 \frac{e^{(-G)}}{0!} = e^{-G}$$

and

$$S = P_0 G = Ge^{-G}$$

Maximum value occurs at G = 1

In this case when G = 1

P(0, 1) = Prob[0 attempts in a slot] = e^{-G} = e^{-1} = 0.37 = %wasted
P(1, 1) = Prob[1 attempt in a slot] = Ge^{-G} = e^{-1} = 0.37 = %successes
1 - P(0,1) - P(1, 1) = 0.26 = % collided.

The text shows hat E[number of attempts / transmission] = e^{G}
This result also follows more simply from the fact that

G = S E[number of attempts / transmission]
G = Ge^{-G} E[number of attempts / transmission]
E[number of attempts / transmission] = e^{G}

Carrier Sense Multiple Access (CSMA) protocols:

Assume that unlike Aloha stations can *and must* sense carrier before attempting to transmit. Both the original Ethernet and some modern wireless protocols fall in this class.

Varying types of Persistence have been suggested:

1 - Persistent

- applies to slotted or non slotted time
- transmit any time carrier sensed free
- if carrier sensed busy
    - transmit as soon as carrier sensed free

- Advantage:
    - reduces time in the idle state
- Disadvantage:
    - increases collisions

Non-persistent

- non slotted time
- transmit any time carrier sensed free
- If carrier sensed busy
    - wait a random amount of time and sense again.

- Advantage:
    - Potentially higher throughput
- Disadvantage
    - Worse latency

P- persistent

assumes slotted time

slot = 1 contention interval >= upper bound on signal propagation

```
sense channel
if channel sensed free
    transmit with probability $p$
    delay one slot with probability $1-p$ and return to sense
else (channel busy)
    delay one slot and return to sense
```

P-Q persistent

Act with p persistence when channel detected idle

Act with q persistence when formerly busy channel goes idle

Typically $p > q$

Dealing with collisions

τ = one way signal propagation time

Collisions occur when:

- two or more stations independently transmit within τ units of each other
- two or more stations in a 1 persistent system become ready during the transmission of another

and propagation time in the real world is variable!

CSMA/CD systems can detect collisions

- Minimum time to detect is τ for the station that starts sending first
- Maximum time to detect is 2τ
- When a collision is detected is detected, a sending station
  - Stops
  - Jams for time $2\ \tau$
  - Backs off and waits a random amount of time (possible p, q, r persistence)

The cost of a collision in lost channel time

Pure aloha - minimum of one and a maximum of two packet times

Slotted aloha - exactly one packet time

CSMA/CD Ethernet - Minimum of $3\ \tau$ maximum of $4\ \tau$ (<< packet time).

Performance analysis of CSMA (Simplified version Metcalf and Boggs 1976)

k = number of stations
p = Prob[any station tries to transmit in a given slot]

A = Prob[some station succeeds in acquiring the ether]

$A = kp(1-p)^{k-1}$ = Binomial probability of a exactly one station attempting to transmit in a given slot.

A is maximized at $p = 1/k$
$A \rightarrow 1/e = 0.37$ (same as max S in slotted Aloha) as $k \rightarrow \infty$

$P[\text{CI length} = j] = A(1-A)^{j-1}$ = P[success after j - 1 failures]

E[CI length in contention intervals] = = $1/A$
E[length of contention in time] = $2\tau / A$

Efficiency = Time spent transmitting / (Time spent transmitting + Time Spent Contending)
= $P / (P + 2\tau / A)$
where P = Packet time = the time required to transmit a single frame

$\tau = L / c$ Length of the cable / speed of light

$P = F / B$ F = frame size in bits a
B = channel speed in bits per second

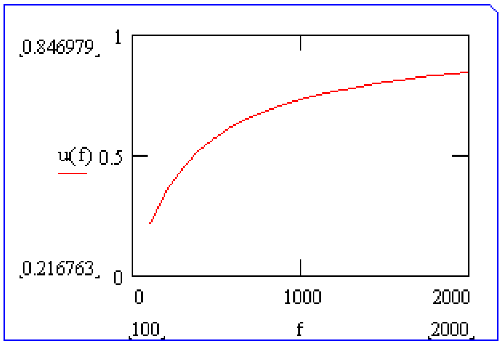
$$\text{Eff} = 1 / (1 + 2\tau / PA) = 1 / (1 + 2BL / FAc)$$

Consequences:

Increasing the bit rate decreases efficiency
Increasing the length of the cable decreases efficiency
Increasing the frame size increases efficiency
Increasing the speed of light increases efficiency

As $P \to 2\tau$ $\quad Eff \to 1/(1+e) \sim 0.26$

which is worse than slotted aloha!!



The graph shown above was computed using the parameters

c = 300000 km/sec
L = 2 km
B = 10,000,000 BPS
A = 1 / e

Efficiency is much higher than possible with Aloha when the length of the contention slot is much less than the length of a packet time.

Real World LAN protocols

Three major approaches have been employed in wired LANs

Early LANs

- Contention (CSMA-CD / Ethernet)
- Token passing (Token ring /Token bus)

LANs of the past 10 years

- Star wired and switched (ATM / Switched Ethernet)
- Wireless (CSMA-CA / 802.11)

Original Ethernet (IEEE 802.3)

1 persistent CSMA
with CD and
binary exponential backoff

slotted time: $2\tau = 51.2$ ▪u-secs

after *i* collisions a station waits between 0 and $2^i - 1$ slots
max wait is 1023
max retries is 16

Frame format (still in use today)

7 bytes	preamble 10101010
1 byte	Start of frame
2 or 6	Destination address (Global vs Local in bit 46)
2 or 6	Source address
2	Length of data
0 - 1500	payload data
0 - 46	pad (Min frame length = 64 bytes= 51.2 usec at 10 Mbps)
4	checksum

Operational constraints (original 10 Base 5)

10	Megabits / second
Base	Baseband signaling
5	Hundred meter segments
2.5 KmMax distance between transceivers	
4 Repeaters	Max along any path

Bridges may be used to
extend further
reduce load on segments

Physical encoding.. Manchester encoded baseband signal

Multiple standards have evolved..

10 Base 5 (Original 500M runs / thick wire / vampire taps)

10 Base 2 (200 M runs / thin wire / BNC connectors)

10 Base T (100~150M runs / Cat 3 and 5 UTP / RJ-45 Connectors)

100 Base T (100M Cat 3 and 5 UTP)

Gigabit over Cat 5 UTP

Gigabit over fiber.

10 Gigabit over fiber (and Cat 6?)

Fiber links can be considerably longer than UTP but the both the medium and the NICs are considerably more expensive.

Packet size issues

Packet time for 1500 bytes on a 1 Gbps links ~ 12 microseconds
This creates excessive CPU load on hosts due to interrupt processing.

Solutions include:
- Large frame sizes
- Interrupt coalescing

Connection mechanisms

Shared bus (10 Base 2/5)

Shared medium hub (10 Base T / 100 Base T)

Receives on one port at a time and transmits input to *all* outputs

Switched hub (raises the effective throughput of the net)

Can receive on multiple ports at a time and transmits only to dest.

Switch can conduct multiple transfers at one time.

Unicast packets are sent by switch *only* to destination host.

Store and forward switch

Can Buffer whole packets like a router before retransmitting

Collision problem is effectively removed.

Cut-through switch

(reduces the latency of the store and forward switch)
Forwards packets as soon as address is recognized.

Thus modern "Ethernets" share little more than frame format with their CSMA-CD precursors

Token passing protocols:

General principles

A single *token* is passed from station to station in a fixed round-robin pattern
A station may not transmit until it holds the token
The length of time a station may transmit is limited
When the time limit is reached or the station has no more data to send, the token is passed.

Operational issues

Initialization - how does the *first* token come to be created
Adding a new system to an operational ring
Removing a system from an operational ring
- Gracefully
- After crash

Loss of token (holder powered off or network error)
Duplicate token (two rings spliced together)

Existing standards

Token Bus:	IEEE 802.4
Token Ring:	IEEE 802.5
FDDI Ring:	Similar to IEEE 802.5

Major differences relate to control of the ring operation

Bus:	Fully distributed control
Ring:	Centralized control

Tradeoff is (theoretically) one of robustness vs. simplicity

Token Bus:

Stations are attached to a shared medium bus as in Ethernet and use a CSMA listen before transmit protocol.

Exercise: Could this protocol be used in a Wireless environment.

Major issues

- Membership management
  - Network initialization
  - Adding new station
  - Orderly withdrawal of a station
- Fault management
  - Lost token
  - Duplicate token
  - Lost successor
- Priority management
  - 4 Priority classes 0, 2, 4, 6

Token passing is in MAC adddress order from high address to low

Frame format

1+ bytes	preamble 10101010
1 byte	Start delimiter
1 byte	Frame control (Packet type) (Type for TOKEN is wrong in handout .. should be 8
2 or 6	Destination address (Global vs Local in bit 46)
2 or 6	Source address
n	Data
4	checksum
1	End delimiter

Each station maintains a zillion timers and must always know

Its own address (this station) (TS)
The next station (NS)
The previous station (PS)

Initialization

CLAIM_TOKEN -

Stations continually listen for valid transmission, and if one is not heard, they time out and issue CLAIM_TOKEN.

```
If a collision occurs
    Contention is resolved using a quartiary countdown
    A CLAIM_TOKEN frame contains up to 4 extra slots whose presence
    usage depends on "current" two address bits
    A station listens after completing its frame.
    If (continuing transmission heard)
        GIVE UP
    else
        Repeat using next two address bits
```

If no collision the transmitting station now owns the token

Adding a new station

- SOLICIT_SUCCESSOR_1(NS) (having a 1 slot response window)
  - May or may not be issued each Token rotation
  - Invites stations between TS and NS to attempt to join bus
  - Station wishing to join responds with SET_SUCCESSOR
  - If collision the token holder
    - Transmits RESOLVE_CONTENTION which has a 4 slot response window
    - Colliders reply in slot # associated with 1st two address bits.
    - If collision repeated
      - Continue using next address bits until resolved.
  - Lowest numbered station in the ring uses a SOLICIT_SUCCESSOR_2
- SOLICIT_SUCCESSOR_2(NS) (has two response windows)
  - Stations with address lower than TS can reply in window 1
  - Stations with address higher than TS can reply in window 2

Orderly exit

Send SET_SUCCESSOR(PS) to PS

Lost successor

Issue WHO-FOLLOWS(NS) specifying current successor
If response received update NS pass token
If no response issue SOLICIT-SUCCESSOR-2
    Any station can respond
If one does a two station ring is created

Lost Token

Time out and CLAIM TOKEN
Rebuild ring

Duplicate token

Generally caused by partitioned bus being rejoined.
Generally detected by a collision occurrence
Action is to drop token
May result in lost token

Priority control (simplified):

Certain proportion of total Token Holding Time can be reserved for each type of traffic Priority 6, 4, 2, and 0.

Problem: If not busy you might has well be able to send data of other classes:

THT = token holding time: the maximum time that a station can hold the token to transmit class 6 data.

TRT4 = token rotation time for class 4: maximum time that a token can take to circulate and still allow class 4 transmissions.
Class 4 time = TRT4 - (Time of last rotation + time of class 6 transmission)

N * THT > TRT4 => Class 4 traffic may be starved.

Example:

N = 10 stations
THT = 20 msec

If all stations have always have class 6 traffic it will take 200 msec for a complete rotation. If TRT4=220 then there will be a total of 20msec per rotation for class 4 traffic.

Token Ring

Basics of operation

No contention at all

Each station has a store and forward buffer

- Tx can be driven from
  - the store and forward buffer (idle)
  - onboard packet buffers (transmitting)

- Rx can be directed to
  - the store and forward buffer (idle)
  - onboard packet buffers (receive)
  - the "bit bucket" (drain)

A station can't transmit until it inverts token bit becoming the token holder

The holder can inject a packet
The holder must drain each packet that it sends.
The holder recreates the token after THT (def 10ms) expires or no more data
The ring must be long enough to hold the token

802.5

4 or 16 Mbits (book says 1 or 4) now available in 100Mbit flavors
Typically hooked up via wire centers (Hubs)
Multiple wire centers may be cabled together

Packet format

Token bit is 4th bit in AC byte
Addressing as in 802.3 and 802.4
FS (frame status) byte at end carries

- A - Address recognized
- C - Frame copied bits

Ring maintenance

- Active monitor election
  - Station transmits CLAIM_TOKEN stream and listens:
    - Sees own address
      - Success
    - Sees higher address desists sending and goes into repeater mode
    - Sees lower address continues sending
    - Highest address station eventually wins:
- Ring maintenance issues
  - Loss of active monitor
  - Orphan frames
  - Loss of token
  - Token priority stuck high
- Active monitor functions
  - Periodically issue ACTIVE_MONITOR_PRESENT
  - Regenerate token
  - Set M=1 on each valid frame or high priority token
  - M=1 on frame or token
    - Eat frame or token
    - Regenerate token
  - Evidence of active monitor
    - Go to standby status
  - Insert delay bits as required

Priority control

- 8 priority levels
- Two fields in each AC byte
    - Priority field
    - Reservation field
- A station with high priority traffic can make a reservation
- Station holding the token on seeing reservation must
    - Remember state
    - Set priority to reservation
    - Immediately release token
- Station issuing a high priority token is responsible for reducing the priority

Comparison of the three technologies

Factor	**802.3**	**802.4**	**802.5**	**Switched-E**
Min latency	Low	Medium	Medium	Low
Max latency	High	Medium	Medium	Medium
Max throughput	Medium	High	High	High
Cost/Complexity	Low	High	Medium	Low

Other collision free protocols:

Polling

One station is identified a “primary”. All others assume secondary status. Primary *polls* secondaries in round robin fasion. Secondaries may not transmit until polled.

Bitmap

Contention slots in which stations make reservations
Followed by frame slots = in number to bits in the bitmap

```
Bit    0  0  0  0  0  1  1   0 ------------ PKT 1--------|--------PKT 2-----0  0
Sta    0  1  2  3  0  1  2   3
```

Disadvantages

Bitmap slots 2 ▪rather than 1 bit time in size
Low numbered stations get worse latency at low loads.
High numbered stations get worse latency at moderate loads.
You must change bit map size to add stations
Bitmap latency at low loads especially if slots are 2 ▪

BRAP = BRAM+MSAP

- Station begin transmission *immediately* after setting bitmap bit.
- Bitmap restarts following transmission with the station *after* the one that just transmitted.
- Disadvantages remaining:
  - Bitmap slots 2τ rather that 1 bit time in size
  - You must change bit map size to add stations
  - Bitmap latency at low loads especially if slots are 2τ

Binary countdown

- Bit map = number of bits in a station address
- If a station has a 1 bit at current slot it writes it into the slot....
- Until it sees a 1 bit written in a slot where it has a zero.
- In that case it gives up.
- Result: Highest numbered ready station wins.
- Obviously this is unfair...
- Solution
  - Use virtual station numbers.
  - After a successful Xmit become virtual station 0.
  - All stations between transmitter and 0 get incremented.
  - ===> Highest priority station is the one that hasn't transmitted in the longest time.

Other MAC protocols

FDDI -

Optical token ring

100 Mbits / second

Sender regenerates token at end of transmission ==> multiple packets possible on Ring

Formerly used to link 802.x LANS in a large enterprise/

Now replaced by GigE

Satellite networks

FDM, STDM ok for phone circuits

Adaptive reservation schemes better for bursty data traffic.

Objective of such schemes:

Heavy <--------------------Load------------------> Light
TDM Aloha

A number of adaptive protocols have been proposed, but in the real world FDM, STDM, ALOHA and CDMA have been used.

Wireless Networks

The Electromagnetic Spectrum

Can be viewed as sinusoidal "waves" passing through space
Includes radio, infrared, visible light, ultra violet light, X-ray, Gamma ray
Frequency, *f* = number of complete cycles of the sine wave / second measured in Hz
Wavelength *l* = length a of complete cycle of the sine wave in meters

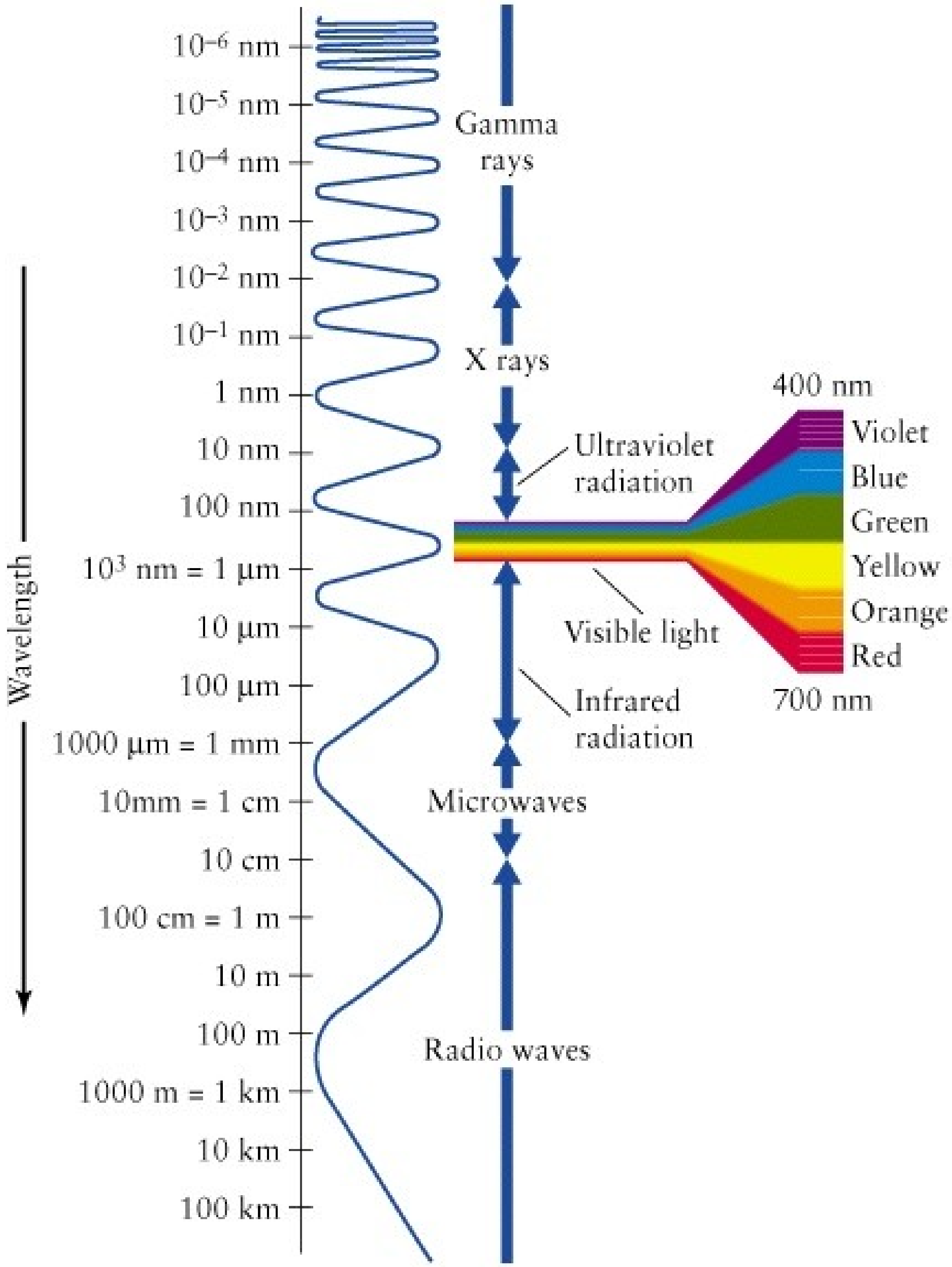
Fundamental relationship is *fl* = *c.*

If *l* is measured in meters and *f* in Mhz *fl = 300.*

A channel is a continuous range of frequencies [*f1, f2*] or equivalently wavelengths [*l2, l1*]

The *bandwidth* of a channel is *f2 - f1.*

The maximum number of bits per Hz *is determined by the SNR* typically in the range of 1 to 16 for wired and wireless channels (c.f. Dial modems)



(Wavelength image from Universe by Freedman and Kaufmann.)

Example: The 1.3 micron band (infrared light) (Channels used in wireless radio communications have significantly lower bandwidth!

$$l2 = 1.21 \text{ microns}$$
$$l1 = 1.38 \text{ microns}$$

The frequency at the center of the band (1.3 micron wave length) is approximately:

$$f = c / l \sim= (3 * 10^{8}) / (1.3 * 10^{-6}) = 2 * 10^{14} Hz$$

The bandwidth is the difference between the min and max frequencies:

$$\begin{aligned} df &= f2 - f1 \\ &= c / l2 - c / l1 \\ &= c\,(l2 - l1) / l1\, l2 \\ &= c\, dl / l2l1 \\ &\sim= c\, dl / l2^{2} = 3 * 10^{8} * 0.17 * 10^{-6} / \ 1.7 * 10^{(-12)} \\ &\sim 30Thz \end{aligned}$$

Spread spectrum techniques

Basic objective - Distribute signal energy across a relatively wide range of frequencies.

Motivations -

- secure communications,
- increased resistance to natural interference and to jamming,
- and to prevent detection of communications

Implementations -

- Frequency hopping (primarily used in military applications)
- OFDM (parallel transmission on multiple subchannels)
- direct sequence spread spectrum (probably the most difficult to understand)

Direct sequence -

- Each bit is transmitted using a sequence of "sub-bits" called chips.
- The specific sequence (e.g. + - - + - - +) that is defined to mean "1" bit
- This sequence doesn't change during operation.
- The complement of the sequence (- + + - + + -) then represents a "0" bit.
- Different transmitters use different chipping sequences
- The chipping sequences are designed to spread the signal power.

CDMA - Code Division Multiple Access

A direct sequence spread spectrum technique in which it is (theoretically) possible for all stations to send simultaneously and non-destructively.

Bit times are divided into *N* Chips (typically 64 or 128)
Each station has a unique chip sequence of 64 or 128 (+1/-1)'s
To send a 1 bit the station sends its chip sequence
To send a 0 bit the station sends the complement of its chip sequence
Chip sequences are *mutually orthogonal* with respect to the standard *dot* product.

$(C_1 \text{ dot } C_2) = 0$
$(C_1 \text{ dot } \sim C_2) = 0$
$(C_1 \text{ dot } C_1) = N$
$(C_1 \text{ dot } \sim C_1) = -N$

Receiver may receive superimposed signals
$C_1 + \sim C_2 + C_3 + \sim C_4$

Receiver *dots* the sum with the *desired* sender's Chip sequence
$(C_1 + \sim C_2 + C_3 + \sim C_4) \text{ dot } C_3 = C_3 \text{ dot } C_3$

Example:

A: -1 -1 -1 +1 +1 -1 +1 +1
B: -1 -1 +1 -1 +1 +1 +1 -1
C: -1 +1 -1 +1 +1 +1 -1 -1
D: -1 +1 -1 -1 -1 -1 +1 -1

If some chips are received in error then the dot product may be somewhere -N and N. If the value is almost N, then its likely a 1 bit was sent. If its nearly -N, then likely a 0 bit was meant. If the dot product ~0 then who knows??

PN sequences

In practice it is common to use PN (pseudo-random) noise sequences instead of dedicated chipping sequences.

- The sequences consist of a mix of -1 and +1's
- To send a 1 bit the sequence itself is sent
- To send a 0 bit the inverse of the sequence is sent
- The receiver performs the dot product of the received sequence with the known PN sequence

A large postitive result -> 1
A large negative result -> 0

Wireless LANs - IEEE 802.11

Original 802.11 physical layer used three basic physical layer technologies:

- Infrared
- Microwave (2.4 Ghz) Industrial, Scientific, Medical (ISM) Band
  - Frequency hopping spread spectrum
  - Direct sequence spread spectrum
- Data rates limited to 1 - 2 Mbps

Newer additions include

802.11a (Orthogonal FDM) (OFDM using 52 subchannels of 1 Mhz bandwidth providing up to 54 Mbps on 5 Ghz UNNI (unlicensed National Information Infrastructure) band

802.11b (HR -DSSS (High rate DSSS)) up to 11 Mbps

802.11g (OFDM) up to 54 Mbps on 2.4 Ghz ISM band.

802.16 -> WiMAX SC/OFDM/OFDMA using 192/256 subchannels

MAC Layer Issues

The wireless environment is far more hostile than the wired one and this affects MAC protocol design. Here are some "classic" problems:

The hidden station problem

A --------------- B --------------C

Suppose C is transmitting to B but A is out of range of C
If station A wishes to send to B, it will sense idle but will cause a collision.

The exposed station problem

D --------------A-------------B-------------C

Suppose A is transmitting to D and B wants to transmit to C.
B may falsely conclude that a successful transmission is impossible when in fact it would succeed.

Operational modes of 802.11 networks

Ad hoc mode

An 802.11 networking framework in which devices or stations communicate directly with each other, without the use of an access point (AP). Ad hoc mode is also referred to as peer-to-peer mode or an Independent Basic Service Set (IBSS). Ad hoc mode is useful for establishing a network where wireless infrastructure does not exist or where services are not required.

Infrastructure mode:

A mode in which devices communicate with each other via an Access Point (AP) which is typically connected to a wired network. When one AP is connected to wired network and a set of wireless stations it is referred to as a Basic Service Set (BSS).

The ESS -

An Extended Service Set (ESS) is a single logical network segment (also known as a subnet), It is identified by its Service Set Identifier (SSID). If the available physical areas of the wireless APs in an ESS overlap, then a wireless client can roam, or move from one location (with a wireless AP) to another (with a different wireless AP) while maintaining Network layer connectivity. For example, *cuairnet* and *tigernet* are SSIDs and the campus wireless networks are ESS's.

Within infrastructure mode one of two types of coordination function is used:

> DCF - Distributed Coordination Function: The MAC procedure is distributed among all the wireless stations.
>
> PCF - Point Coordination Function: A base station also called an Access Point (AP) controls all access to the channel using the polling technique.
>
> DCF is mandatory but PCF is an optional add on. All “real world” wireless LAN's use DCF.

DCF -

802.11 uses a MAC protocol called CSMA/CA (Collision Avoidance)

Two modes of CSMA-CA

Physical Channel Sensing

Sense channel
If idle emit entire frame
If busy defer until contention slot (backoff) counter reaches 0
If collision use binary exponential backoff.

Virtual Channel Sensing

C ----- A ----- B ------- D

Suppose A wishes to send to B
A sends a short RTS to B containing the length of the message
B sends CTS back to A
C hears RTS and notes the network busy in its NAV (network allocation vector)
D hears CTS and notes the network busy in its NAV
A sends the packet
B sends an ACK

Dealing with noisy channels

Frames may be fragmented with each fragment carrying its own checksum
Fragments are numbered and acked individually using an S & W protocol.
The NAV mechanism protects only the first fragment

PCF -

No station may send until polled by the AP
An entry / exit protocol is also run by the AP

Interoperation of DCF and PCF

```
|  Frame        |
                | SIFS |<--ACK---->
                |          PIFS  |<----Poll----->
                |                    DIFS |<------Data----->
                |                              EIFS    |
                |                                      | Bad frame recovery  |
```

SIFS - Short interframe spacing

The SIFS is a *10 usec* delay whose purpose is to give the last transmitter time to switch his radio from Tx to Rx mode.

Only one station is eligible to send when the SIFS expires

The eligible station will send

CTS
ACK
Response to Poll
Next fragment of a burst

PIFS - PCF InterFrame Spacing

If an AP operating in PCF mode wishes to send a poll it must wait SIFS+PIFS and if the channel is still idle it may do so.

The receiver of the poll may respond at the end of the SIFS

DIFS -DCF Interframe Spacing

The standard contention slot is *20 usec*.
The end of the DIFS is 2 contention slot times beyond the end of the SIFS for a total of *50 usec*. (or SIFS + PIFS in a PCF system).

EIFS - Extended InterFrame Spacing
Used by a receiver of a bad or unknown frame to report

The 802.11 contention algorithm

A *dual persistence* approach is employed

- Limits on the size of the *contention window* CW are defined by *CWmin = 31 slots and CWmax = 1023 slots.* The current size of the contention window is called *CW. CW* is reset to *Cwmin* after a successful transmission and is doubled after each collision.

- When a station becomes ready to send, it senses the carrier for DIFS amount of time and if nothing is heard it transmits.

- If it hears a transmission in progress, it waits until the Tx ends and computes a random number of slots *wcount* between 0 and *CW* (Where *CW* is initially *CWmin*).

- It listens through the SIFS and the DIFS and if it hears a transmission commence it defers until the end of that transmission. While no transmission is heard, it decrements *wcount* for each 20 usec slot time that passes.

- When *wcount* reaches 0, the station will transmit.

- If another station starts transmitting before *wcount* reaches 0, the decrementing of *wcount* is suspended until the frame, the following sifs and pifs have passed at which time it resumes where it left off.. In this way the last come first served behavior is avoided.

- A collision is *inferred* from a missing CTS or ACK. CW is doubled when a collision occurs until it reaches *CWmax*. CW is reset to *CWmin* when a transmission succeeds.

802.11e

To provide some manner of DiffServ (but still not the QoS capability of WiMAX) EDCF was invented.

In 802.11e four traffic classes are identified:

TC0 - VOIP
TC1 - Video
TC2 - Best Effort
TC3 - Background

These traffic classes have differentiated values of CWmin and CWmax.

The protocol also employs an variable *Arbitration IFS (AIFS)* which generalizes the DIFS and this makes it possible to give one traffic class ABSOLUTE priority over another in a heavily loaded network. In the table below it can be seen that the AIFS for TC0 and TC1 is the same as the DIFS but TC2 and TC3 have successively higher values.

Values of these parameters are typically configurable and mapping parameter sets to workloads and desired outcomes is a "work of art".

Traffic Type	***CWMin***	***CWMax***	***AIFS***
Background (TC3)	31	1023	7
Best Effort (TC2)	31	1022	3
Video (TC1)	15	31	2
Voice (TC0)	7	15	2

802.11 Frame Structure

Bytes	
2	Frame control
2	Duration - time the frame + ack will occupy channel
6	Address 1- Source host
6	Address 2 - Dest host
6	Address 3- Source AP
2	Seq # (12 bits frame id and 4 bits fragment id)
6	Address 4 - Destination AP
0-2312	Data
4	Checksum

Frame control word

Bits	
2	Protocol Version
2	Frame base type (Control, management, or data)
4	Subtype (RTS, CTS, etc.)
1	To DS (Frame is going to an intercell *distribution system)*
1	From DS (Frame is coming from an intercell distribution system)
1	MF (More fragments follow this one)
1	Retry (Retransmission of previously sent frame)
1	Pwr (Power management bit used to put station to sleep or wake it up)
1	WEP (Frame body has been encrypted using Wired Equivalent Privacy alg)
1	O (Process frames strictly in the order in which they are received)

802.11 Services

Intercell services

Association - ability of a mobile station to connect to a base station. Parameters include SSID, data rate, PCF capabilities, power management needs.

Disassociation - breaking the connection. Can be triggered when either the mobile station or the base station goes down.

Reassociation - changing of base station. Occurs when a mobile station changes cells while up.

Distribution - a routing service provided by the wired distribution system (DS)

Integration - performing required packet reformatting at a base station. (e.g. reassembly of fragments prior to forwarding on an ethernet).

Intracell services

Authentication - A mechanism by which stations must authenticate before being accepted by the base station. Not in the original standard and potentially a nuisance to internet cafe users. Its absence has led to "warchalking"

Deauthentication - Occurs when a station disassociates or reassociates.

Privacy - The flawed WEP algorithm

Data delivery - best effort service like ethernet.

Security issues

The 802.11 physical layer is like an early Ethernet a bus in which all stations hear all transmissions

It is less secure than early Ethernet in that *any* unauthorized person can (almost) unobtrusively monitor net traffic.

See *newarchitect.html* in the class directory for an example of the problem.

A potential solution is to encrypt each packet.

WEP (using a variant of the RC-4 encryption algorithm) was chosen as the standard.

Unfortunately WEP turned out to be a defective implementation.
See *wepweaknesses.pdf* and *crackingwep.pdf* in the class directory.
See the *airsnort* hack kit on the web.

Current solution:
Be sure to use SSL tools (ssh, scp, etc) which use a non-broken implmentation of RC-4

802.11i --> 802.11-2007 defines a new encryptions standard (WPA) WiFi protototected access that is based on the Advanced Encryption Standard (AES) instead of RC4. It is available in current products and has yet to be broken.

The problem of disseminating and maintaining control of the security keys to a large population of users remains challenging.

Other ways of enhancing security include:

Don't broadcast the SSID.
Limit associations to stations having MAC addresses in an access list.

Other wireless technologies

802.16 – (later WiMAX) Designed to provide broadband wireless service to fixed stations (i.e. a MAN)

Later versions support mobility.
MAC layer protocol is a variant of the DOCSIS protocol.

Bluetooth - Designed to connect cell phones to computer modems (a Pico Net or Personal Area Network)

Links are limited to 10 m.
Uses 79 channels of 1 Mhz each in the 2.4 Ghz ISM band.

Data over Cable TV systems

Defined by the Data of Cable Service Interface Specification (DOCSIS).

The physical layer medium is a shared access cable.

MAC functions are controlled by a “head end” device called a *Cable Modem Terminating System* (CMTS).

User attachment points are dual ported devices called Cable Modems (CMs) that run

DOCSIS on the cable side
Ethernet on the user side

Traffic flow is always CM <-> CMTS never CM <-> CM

Typical aggregate bandwidth shared by all users in DOCSIS 1.1 systems

30 Mbps downstream – from the CMTS
5 Mbps upstream – toward the CMTS

ATDM bandwidth sharing is enforced by the CMTS with typical maximum values of

3 Mbps downstream ---> now 6 Mbps or more
256 Kbps upstream ---> now 768 Kbps or more.

Downstream bandwidth sharing is simple because the CMTS is the only Tx'er

The CMTS uses (possibly prioritized and or deficit) round robin service to deliver packets to CMs

Upstream channel access

Upstream bandwidth allocation is not so simple, because all CM's must share the same cable.

The upstream channel is ATDM multiplexed in fixed time units called *mini-slots*.
The mini-slot is a power of two mulitple number of *basic ticks*.
The basic tick is 6.25 usec.

Typical values:

Upstream bit rate	$5.12 * 10^{6}$ bps
Basic ticks per minislot	4
Minislot length	25 usec
Bytes / minislot	16

Since a standard TCP/IP packet requires at least 20 bytes each of IP and TCP header a minislot is not intended to carry an entire packet. It should be instead viewed as somewhat analogous to an ATM cell.

Allocation of mini-slots

Usage of individual mini-slots is dictated by a special control packet called the MAP which is sent on the *downstream* channel every few milliseconds and describes the near future allocation of slots in the *upstream* channel. The set of mini-slots described in a single MAP is called a *frame*.

Frame time is typically in the range 2 – 10 msec.

Upstream uses of mini-slots include:

> Grants to CMs for upstream data transmission
> Contention Slots for new CMs to request to come on-line
> Unsolicited grants for service such as cable telephones (UGS)
> Grants for dedicated slots in which upstream bandwidth can be requested in a contention free way (RTPS = real time polling service).
> Contention Slots in which CMs may request upstream bandwidth

When a cable modem has best effort upstream traffic send it:

Generates a random number backoff based upon its current backoff window size
Starting with the next MAP it waits backoff contention slots (which may be multiple map times) and then makes its request in the next contention slot.
If successful, the request will be acknowledged (but not necessarily granted) in the next MAP.
A collision is inferred by the absence of an acknowledgment. The CM must double its backoff window and start over.

Refinements

The min and max sizes of the backoff window are specified periodically by the CMTS in special control messages and so may be dynamic.

A CM can request upstream grants for a maxium of one packet at a time, but a *piggy backing* facility allows the station to request additional grants at the end of the current packet without having to use the contention mechanism.

Multiple IP frames can be concatenated in a single MAC layer traffic *burst.*

QoS in DOCSIS and WiMAX

Upstream Service categories include:

UGS - a service flow receives unsolicited grants at a fixed rate.

RTPS – a service flow receives dedicated slots in which to request upstream service at a fixed rate (but doesn't have to use it). A RTPS flow cannot make contention requests.

NRTPS - a service flow receives periodic opportunities to request upstream service but can also use the contention mechanism.

BE – only the contention mechanism is used.

Assigning QoS attributes

Classifier rule - Used to associate packets with particular *service flows* based upon source or destination MAC address, IP address, Port address.

Service flow - Has a service category (UGS, RTPS, etc) and a service parameters such as minimum guaranteed throughput, maximum permitted throughput, maximum allowed jitter.

Typically service flows and classifier rules must be manually set up by a system administrator. Sensible defaults for generic categories (VoIP, best effort, etc) can facilitate the problem to a certain degree.

Dynamic Service Activation (DSA)

UGS and RTPS services consume upstream bandwidth whenever they are active.

A telephone service should consume bandwidth *only* when a call is in progress.

Therefore, provisioning must be a two step process. The system administrator must provision a service flow but DSA protocols between the CM and CMTS activate and deactivate the service automatically.

In this way bandwidth is not consumed by inactive but provisioned flows.