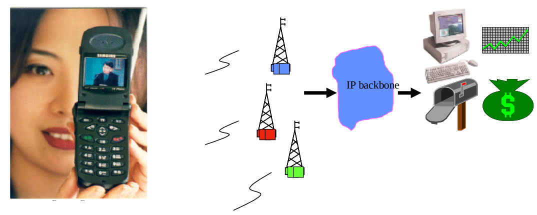
無線網路多媒體系統
Wireless Multimedia System (Topic 3)

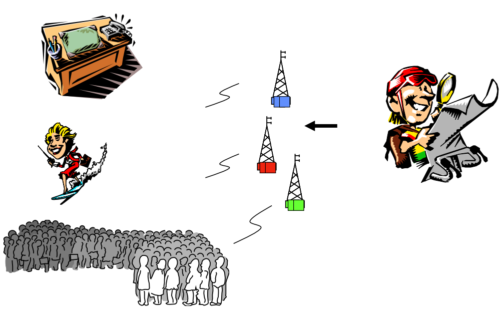
Wireless Link I: Fundamental issues of Multiple Access

吳曉光博士
http://wmlab.csie.ncu.edu.tw/wms

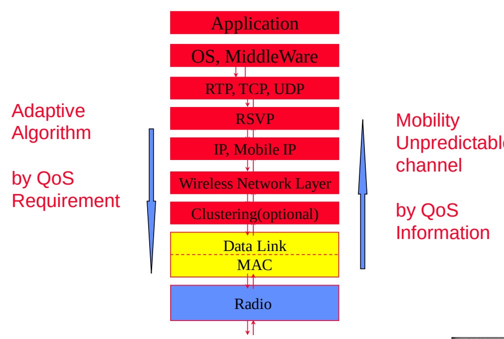
How to deal with Radio Propagation



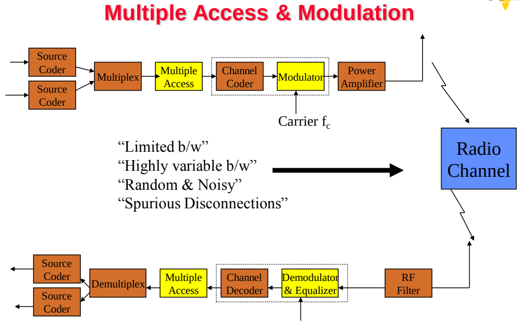
Where are you from?



QoS and Multimedia Traffic Support

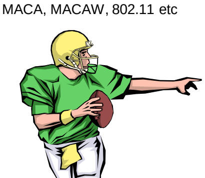


Multiple Access & Modulation

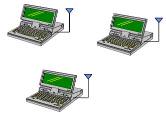


Topic III Agenda

- **Wireless Link**
  - Deployment of "Pervasive Computing" and "Seamless Telecom services"
  - Channel resource sharing in time, frequency, and code dimensions
  - Spread Spectrum-direct sequence, frequency hopping, interference resistance
  - Static techniques: TDMA, FDMA, CDMA
  - Random access techniques: MACA, MACAW, 802.11 etc



What kind of multiple access environments?



Reading list for This Lecture

- **Required Reading:**
  - (Bharghavan94) V. Bharghavan, A. Demers, S. Shenker, L. Zhang,"MACAW: A Medium Access Protocol for Wireless LANs, Proceedings of SIGCOMM'94
  - (J.J.97) L. Fullmer and J.J. Garcia-Luna-Aceves, Solutions to Hidden Terminal Problems in Wireless Networks, Proceedings of SIGCOMM'97
  - (Jing 2006) J. Zhu, B. Metzler, X. Guo, Y. Liu, "Adaptive CSMA for Scalable Network Capacity in High-Density WLAN: A Hardware Prototyping Aprroach", Proceedings of Infocom 2006.

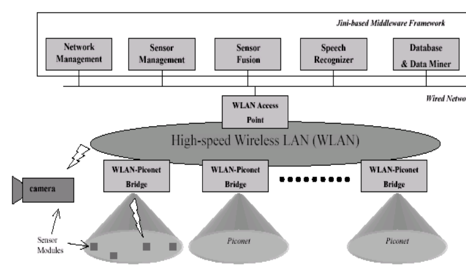
Further Reading

- (David 95) David D. Falconer, F. Adachi, and B. Gudmundson,"Time Division Multiple Access Methods for Wireless Personal Communications",IEEE Communication Magazine January 1995
- (Vadu2000) Vaduvur Bharghavan,"Achieving MAC Layer Fairness in Wireless Packet Networks". IEEE MobileCom2000
- (Songwu Lu2000) Haiyun Luo, Songwu Lu, Vaduvur Bharghavan,"A New Model for Packet Scheduling in Multihop Wireless Networks". IEEE MobileCom2000
- (J.J.2001) L. Bao A New Approach to Channel Access Scheduling for Ad hoc Networks, IEEE MobileCom2001
- (Alex2001) A. Woo, David E. Culler,"A Transmission Control Scheme for Media Access in Sensor Networks", IEEE MobileCom2001
- (Gavin2001) G. Holland, N. Vaidya, P. Bahl,"A Rate-Adaptive MAC Protocol for Multi-Hop Wireless Network, IEEE MobileCom2001

Pervasive Computing Projects

Packet Oriented -> Multimedia Traffic

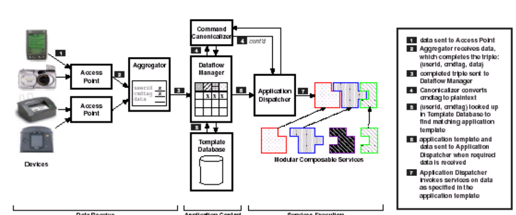
Smart Kindergarten (UCLA)



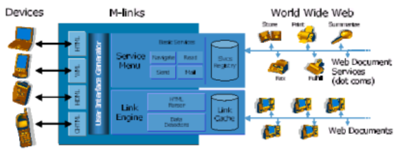
Cricket Location-Support System (MIT)

- Beacon broadcast <-> Listeners
- Cricket Location-support system

Making Computer Disappear (Stanford) ADS (Appliance Data Services)



M-Links (Xerox)



Seamless Telecom Deployments

Circuit Services-> Data Services -> Multimedia

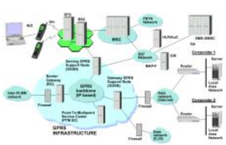
2.5 G & 3 G

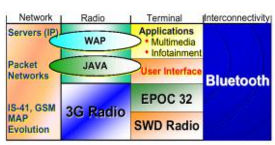
Packet Radio

Packet Backbone

→

System Integration
Multimedia Services
Mobile Computing





Wireless Networking Technology

Telecom & Datacom

Circuit & Packet

MAC Design Issues

- **What kind of Resource we have?**
- **How much you need and how often and how regular you need?**
- **How often you will initial request?**
- **How much traffic you could afford?**
- **How much "Promise" you could provide?**
- **How fair you are going to be?**
- **Control or "Let it be"?**
- **Power Saving Issues?**
- **Complexity?**

Circuit Switch (Static Technique)

- **Cellular System**
  - AMPS
  - GSM
- **Voice System**
  - Continue Traffic
- **Circuit Set up**
  - Reserve A trunk

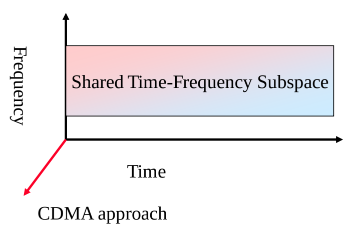
HOW about Data

Packet Radio

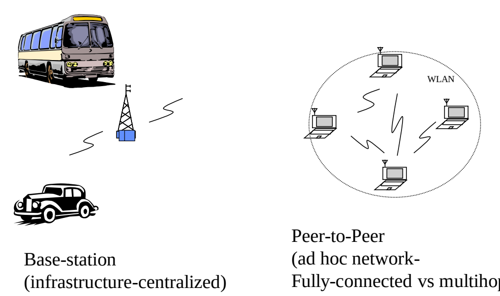
- **Packet Nature**
  - If we could deliver information by packet
  - Bursty Type of Traffic
  - Packet Size

Multiple Access

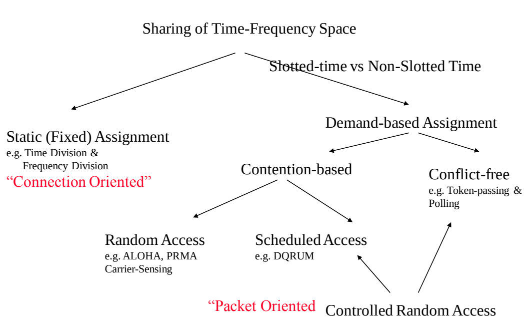
- **Fundamental Problem**
  - How to share the Time-Frequency Space among multiple co-located transmitters?



Cellular versus Ad hoc Models

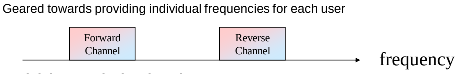


Approaches to Wireless Multiple Access

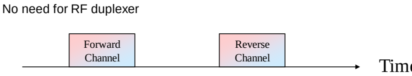


Frequency Division & Time Division Duplexing

- **Frequency Division Duplexing (FDD)**
  - Two distinct frequency at the same time for the two directions
  - Frequency separation must be coordinated to allow cheap RF technology
  - Coodination with out-of-band users between the two bands
  - Geared towards providing individual frequencies for each user

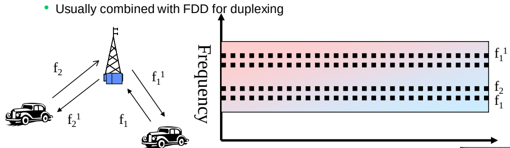


- **Time Division Duplexing (TDD)**
  - Two distinct sets of time slots on the same frequency for the two directions
  - Time latency because only quasi-duplex
  - No need for RF duplexer



Frequency Division Multiple Access (FDMA)

- **Assign different frequency bands to individual users or circuits**
  - Frequency band (“channel”) assigned on demand to users who request service
  - No sharing of the frequency bands: idle if not used
  - Usually available spectrum divided into number of “narrowband” channels
    - Symbol time >> average delay spread, little or no equalization required
  - Continuous transmission implies no framing or synchronization bits needed
  - Tight RF filtering to minimize adjacent band interference
  - Costly bandpass filers at basestation to eliminate spurious radiation
  - Usually combined with FDD for duplexing



Example-AMPS Cellular System

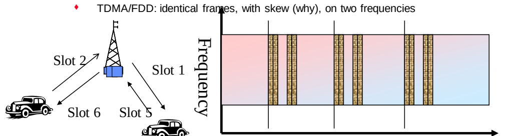
- **User FDMA/FDD**
  - A channel is a pair of frequency duplexed simplex channels
  - Each simple channel is 30 KHz
  - Simple channels are separated by 45 MHz (allow cheap RF duplexers)
  - Forward link 869-894 MHz, reverse link 824-849 MHz
  - Two carriers per market share the channels
- **Number of supported channels in AMPS**

$$N = \frac{B_{total} - 2B_{guard}}{B_{channel}} = \frac{12.5MHz - 2(10kHz)}{30KHz} = 416$$

- **Problem: set of active users is not fixed**
  - How is the FDMA/FDD allocated to a user who becomes active?
    - Static multiple access is not a complete solution .. Need a separate signalling channel with “demand-access”.
    - Pure FDMA is basically “dead” in the digital world

Time Division Multiple Access (TDMA)

- **Multiple user share frequency band via cyclically repeating “time slots”**
  - “channel”==particular time slot reoccurring every frame of N slots
  - Transmission for any user is non-continuous: buffer-and-burst digital data & modulation needed, lower battery consumption
  - Adaptive equalization is usually needed due to high symbol rate
  - Larger overhead-synchronization bits for each data burst, guard bits for variations in propagation delay and delay spread
  - Usually combined with either TDD or FDD for duplexing
    - TDMA/TDD: half the slots in a frame used for uplink, half downlink
    - TDMA/FDD: identical frames, with skew (why), on two frequencies



TDMA

- **More features**
  - Simply mobility & link control.. Snoop for other BSs during idle slots
  - Pulsating power envelop:interference with devices such as hearing aids
- **Possible enhancements to basic TDMA to integrate non-voice services**
  - Different # of slots per frame to different users (variable bit rate)
  - Dynamically reassign time slots for “bandwidth on demand”

Packet Radio

- **Packet Nature**
  - If we could deliver information by packet
  - Bursty Type of Traffic
  - Packet Size

CSMA with Collision Detection/Avoidance

- **CSMA/CD:enhancement to slotted or unslotted CSMA schemes**
- **Node monitors its own transmission**
  - If collision detected, transmission is aborted without waiting for a NACK backoff and re-transmission procedure started
  - A jamming signal may be sent to get everybody else to abort too
- **Problem: does not work with RF wireless**
  - Cannot easily sense the channel while transmitting
    - MH’s signal will dominate, need different receiving and transmitting antenna patterns
- **But, does work well with infrared wireless.. Directional receivers**
- **Wireless networks stick with ACK/NACK approach**
  - Popular called CSMA/CA
  - 802.11

CSMA with Collision Detection/Avoidance

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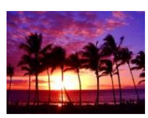
RANDOM Access

- **Give everybody freedom**

Hawaii Story

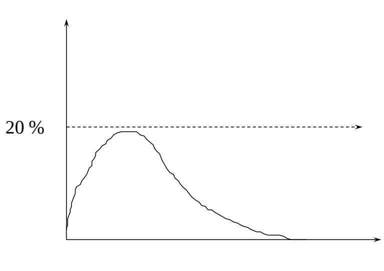
- **University of Hawaii**
- **ALOHA**
  - Hello and Goodbye



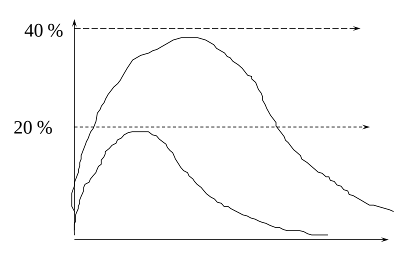

ALOHA System

- **If you want, transmit**
- **If no acks**
  - wait a random time
  - transmit the same packet again
- **Problem ?**
  - Collision ?
  - A lot of Users ?

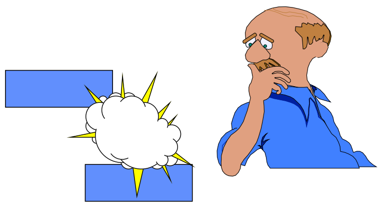

Pure ALOHA Throughput



Slotted ALOHA Throughput



Slotted ALOHA



Maybe We could do some arrangement ?

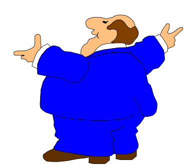
QoS & Delay

Whenever Users are many

- **No one will succeed**
- **Collides all the time**

Reason

- **No one really listen to other people**
- **No one really cares**



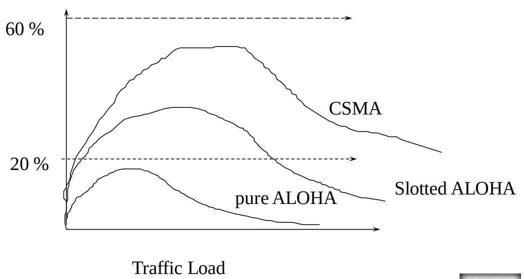
CSMA

- **Most LANs use CSMA**
- **Carrier Sense**
  - CSMA/CA: Collision Avoidance
  - CSMA/CD: Collision Detection

CSMA

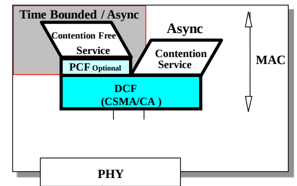
- **Check if carrier is ok**
- **if the channel is free**
  - transmit
- **Otherwise, if the channel is busy**
  - wait a random time and try again
  - Back of a random time

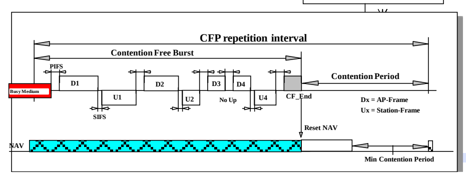
CSMA



Multimedia support? Integrated CSMA/TDMA MAC Protocol

- **Hybrid of reservation and Random Access**
- **A frame is segmented into:**
  - Two reservation intervals for isochronous traffic
  - One interval for random access traffic



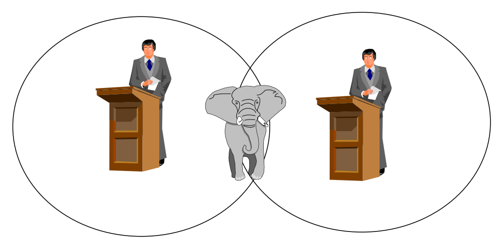


Can Support AP or Ad Hoc

- **AP (Access Point)**
- **Ad HOC**
  - Coordination Function will be distributed among all of the nodes of the ad hoc network

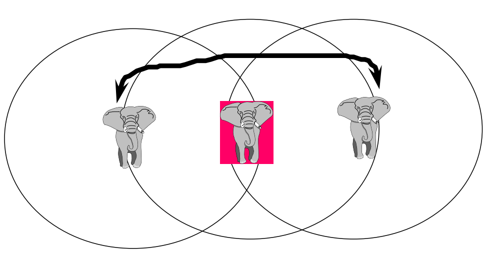
Challenge of Wireless Network

- **Does "listen before you talk " work ?**



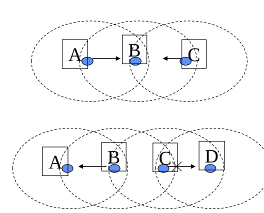
Hidden Terminal

- **Due to transmission range**

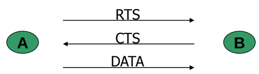


Carrier Sense Multiple Access (CSMA)

- **To avoid collision, sender senses the carrier before transmission. But collision occurs at the receiver not transmitter.**
- **Hidden Terminal -**
- **Exposed Terminal-**



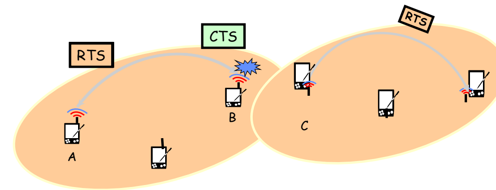
Multiple Access Collision Avoidance (MACA)



- Request-To-Send (RTS) packet: A to B.
- Clear-To-Send (CTS) packet: B to A.
- Node overhearing RTS will defer until A receive CTS.
- Node overhearing CTS will defer until B receive data.
- What do the above two features achieve (Hidden Terminal and Exposed Terminal)?

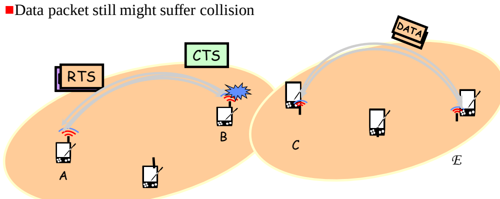
Hidden Terminal Problem Still Exists (1)

- Data packet still might suffer collision



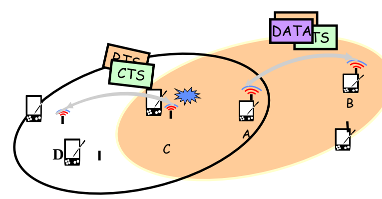
Hidden Terminal Problem Still Exists (2)

- Data packet still might suffer collision



Exposed Terminal Problem Still Exists

- Node C can not receive CTS



MACAW

Features

- Backoff algorithm.
- Multiple Stream model.
- Basic Message Exchange
  - ACK
  - DS
  - RRTS

Backoff Algorithm

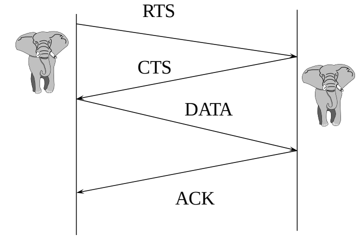
- The algorithm used in MACA: Binary Exponential Backoff (BEB).
  - Maintains a Backoff counter (BO)
  - BO is doubled after every collision
  - Reduced to minimal BO after every successful RTS-CTS exchange.
  - Sender waits for an interval chosen randomly between 1 and BO.
  - $F_{inc}(x) = MIN [2x, BO_{max}]$
  - $F_{dec}(x) = BO_{min}$
- Results in unfair sharing of bandwidth.

Modifications used in MACAW

1. After every successful transmission all pads are made to have the same BO. (What is the problem with this?).

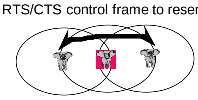
2. Gentler adjustment (MILD):
   - Upon collision $F_{inc}(x)$ = MIN [1.5x, BO_{max}].
   - Upon success $F_{dec}(x)$ = MAX [x-1, BO_{min}].

RTS/CTS/DATA/ACK



Problems in Contention-based Wireless Multiple Access

- **Near-Far effect-characterized by capture ratio of the receiver**
  - Strongest (near by) transmitter can capture the intended receiver
  - Weaker (far away) transmitters get ignored by the receiver
  - Depends on receiver and modulation used
  - Fairness terminal problem
- **Hidden terminal problem**
  - Terminal "hidden" from the transmitter may disrupt the receiver
  - Makes carrier sensing ineffective
  - A cannot detect collisions at B due to transmission from C
  - Solve by using RTS/CTS control frame to reserve medium

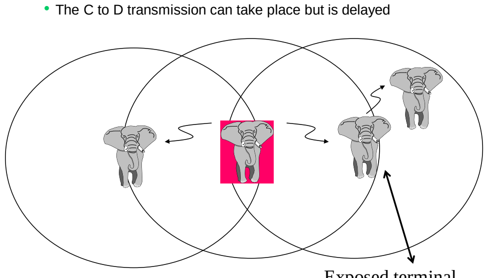


More on RTS/CTS

- **RTS/CTS serve to "reserve" the medium**
  - RTS contains length of proposed transmission
  - CTS also contains length of proposed transmission
  - MHs overhearing RTS defer all transmissions until after CTS would have finished (including receiver turnaround time)
  - MHs overhearing CTS defer for length of data packet transmission
  - Retransmission happen only if no CTS is received in reponse to RTS
- **Binary exponential backoff (BEB) has problems**
  - Does not provide fairness if every MH generate enough traffic to consume the channel
  - After collisions, the less-backed-off mobile wins eventually all but one MD are backed-off to BOmax

Exposed Terminal Problem

- **C will sense channel busy, and defer, but doesn't need to**
  - The C to D transmission can take place but is delayed



CSMA/CD?

- **Collision Detection ?**
- **If a collision is detected, stop transmitting the present packet ?**
- **Is CSMA/CD possible ?**
  - transmit and receive at the same time ?
  - CSMA wireless network, transmit and receive at the same frequency band
  - unlike Cellular System, uplink and downlink

IEEE 802.11 MAC

- **Support for multiple access PHYs; ISM band DSSS and FHSS, IR @ 1 and 2 Mbps**
- **Efficient medium sharing without overlap restrictions**
  - Multiple networks in the same are and channel space
  - Distributed Coordination Function: using CSMA/CA
  - Based on carrier sense mechanism
- **Robust against interference (e.g. co-channel interference)**
  - CSMA/CA+ACK for unicast frame with MAC level retransmission
- **Protection against Hidden terminal problem: Virtual Carrier Sense**
  - Via parameterized use of RTS/CTS with duration information
- **Provision for Time Bounded Services via Point Coordination Points**
- **Configurations: ad hoc & distributed system connecting access points**
- **Mobile-controlled hand-offs with registration at new basestation**

Enhanced MAC Techniques

- **Token Bus and Token Ring**
  - Token are passed among nodes
  - How about wireless network ?
    - Nodes might leave ?
    - Break the Order
    - Take away the token

Basic Scenario

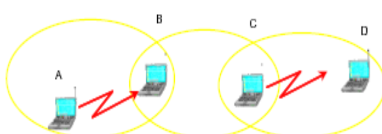


Fig. 1. A is sending a packet to B when C should decide whether to transmit to D.

Hidden and Exposed Stations

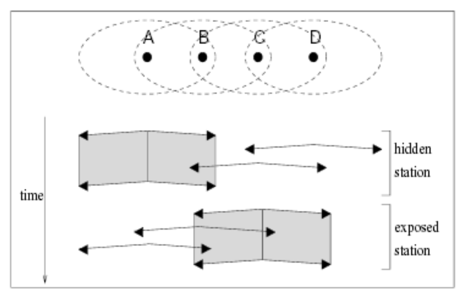


Figure 1: Hidden and Exposed Stations

Capture Effect/Near Far Problem

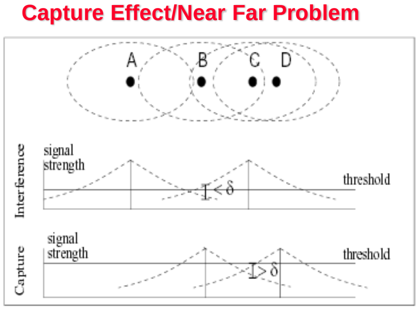
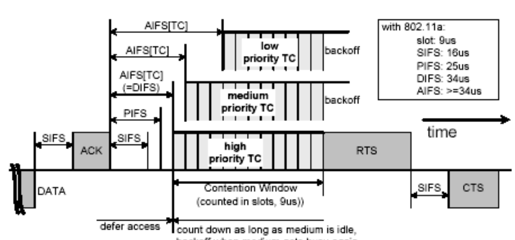
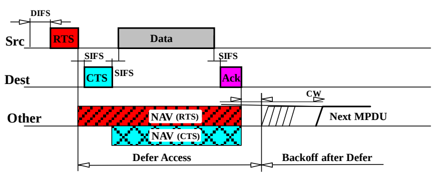


Figure 2: Interference and Capture

802.11 E



802.11



Interference Issue for CSMA/CA

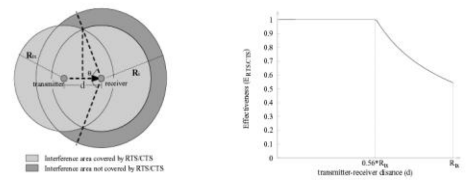
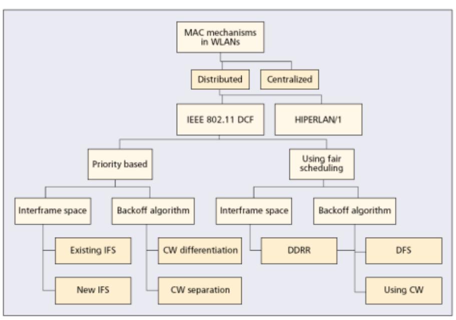


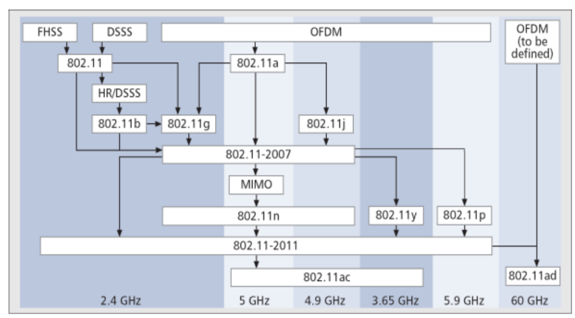
Fig. 1. Effectiveness of RTS/CTS handshake when d is larger than $T^{-1}_{SNR} * R_{tx}$ and smaller than R_{tx}.

Fig. 2. Effectiveness of RTS/CTS handshake for TWO-RAY GROUND model and SNR threshold as 10.

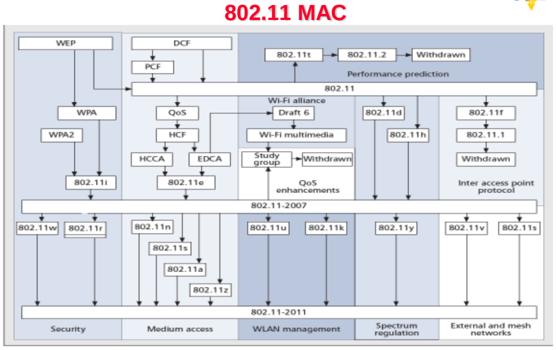
QoS issue for 802.11



802.11 PHY



802.11 MAC



Further Issues

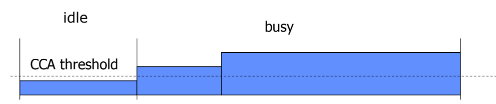
- **QoS (Quality of Services)**
  - Blackburst
  - Backoff
- **Efficiency**
  - Dynamic Carrier Sense
  - RTS/CTS false blocking issue
- **Broadcast Protocol**
- **Collision Detection**

High-Density (HD) WLAN

- In HD-WLAN, its overall capacity can be expressed as $L \times S \times C$
  - L – per link capacity
  - C – number of simultaneous trans. Per channel.
  - S – the number of non-interfering channels
- Hence, the issues of HD-WLAN is
  - How to increase the performance of S.
- Co-Channel Inference (CCI)

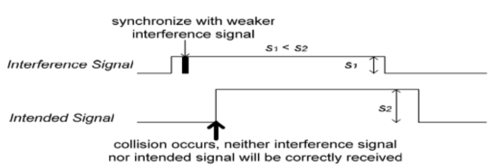
Clear Channel Assessment (CCA)

- A station performs CCA before a data trans. to simple the energy in the channel.
- The station will proceed only if the sampled energy is below a threshold known as the CCA threshold.



Receiving Sensitivity (RS)

- Today's consumer 802.11 radios are often not a le to preempt a receiving process to capture a newly-arrived strong signal.
- This issue called "stronger-last" collision".



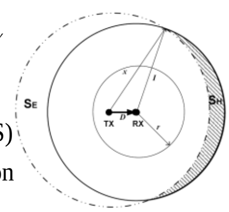
Analytical Model for RS/CCA Adapt.

- In 802.11 WLAN research, the logarithm path loss model is widely used to show average SS at receiver.

$$P_{RX}(d) = P_{RX}(\bar{d})\left(\frac{\bar{d}}{d}\right)^{\gamma}$$

$\gamma = 2$ free-space (LOS)

$\gamma = 4$ ground reflection



Only Strong signals triggers Recv.

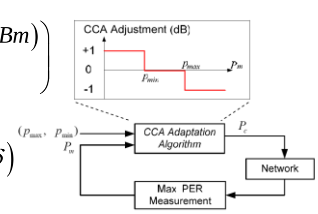
- most of the weak signal that causes strong-last collision will be from device in co-channel cells.
- Hence, let $P_r = RSSI$ be the RS threshold, and RSSI stands for receive signal strength indicator.
- However, signal strength is not constant.

$$P_r = \bar{s} - \sigma$$

CCA adaptation algorithm

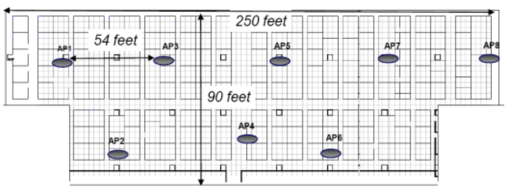
- The maximum of measured PER values is used with a simple linear adaptation algorithm.

$$P_c = \begin{cases} \max\left(P_{c_{\min}}, P_c(dBm) - \delta(dB)\right) \\ P_c \\ \min\left(P_{c_{\max}}, P_c + \delta\right) \end{cases}$$



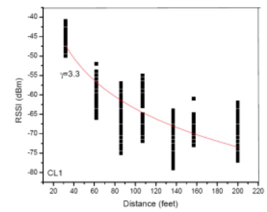
Experimental Topology

- **Testbed Setup**
  - 8APs, (cisco Aironet 1130 802.11ABG)
  - N clients with Centrino 2200 and WAG511(11a)



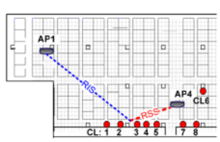
Experimental – Channel Characterization

- **6 clients are deployed, one in each corner of the network.**
- **HD-WLAN is config. in 802.11g channel 1 using 11dbm as trans. power.**
- **CL: 3.3, 3.9, 3.3, 3.6, 3.9, 3.5.**

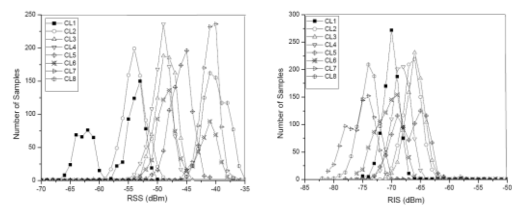


Channel Characterization

- **Next, CL1-8 are deployed to measure the RSSI between AP1 and AP4.**
- **In each run, CL samples RSSI received from AP1 and AP4 with a 10-second interval from 4000seconds.**



Results of Channel Characterization



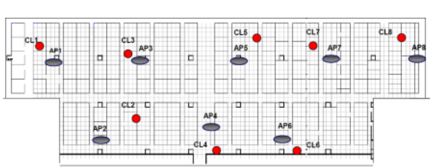
RS Adaptation

- **Downlink, UDP traffic to all active CLs with packet size 1400bytes.**

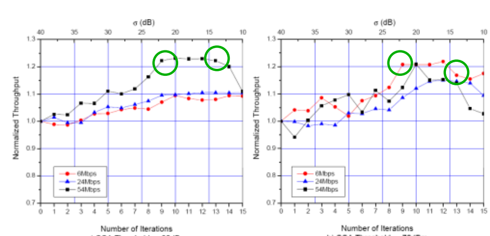
$$P_m = \max(p_i)|_{i=\{1,2,\ldots n\}};$$

$$Th = \frac{1}{n}\sum_i x_i;$$

$$Fi = \frac{(\sum_i x_i)^2}{n\sum_i x_i^2},$$



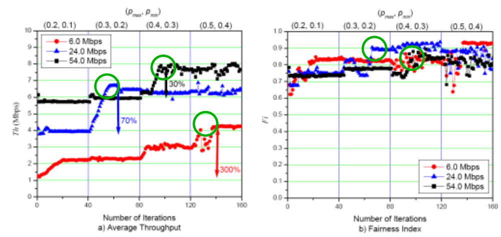
RS Adaptation Results



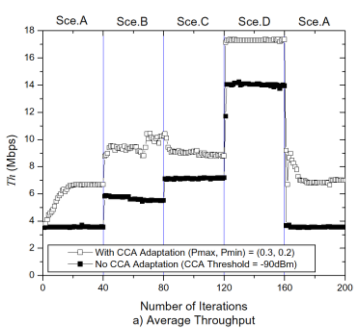
CCA Adaptation

- Next, we investigate the effect of the Pm target with CCA adaptation.
- Four targets
  - (pmax, pmin) = {(0.2, 0.1), (0.3, 0.2), (0.4, 0.3), (0.5, 0.4)} are tested in sequence
  - with total 160 iterations and
  - each one staying 40 iterations.

CCA Adaptation results

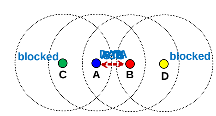


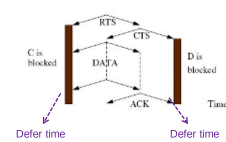
Dynamic CSMA Scheme



RTS-CTS-Based

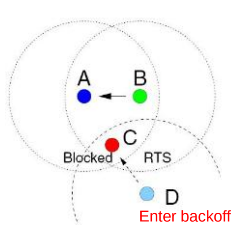
- RTS-CTS-Based means RTS-CTS-DATA-ACK 4 way handshaking mechanism
- RTS (Request-to-Send)
- CTS (Clear-to-Send)
- ACK (acknowledgement)
- NAV (Network Allocation Vector)





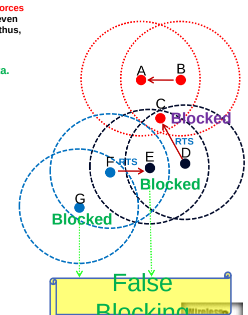
Blocking

- Node C is blocked due to the communication between node A and node B.
- Node D does not get any response to the RTS packets it sends and enters backoff.
- Due to node C neither a hidden node nor an exposed node, so this paper call the problem is blocking problem.



False Blocking(1)

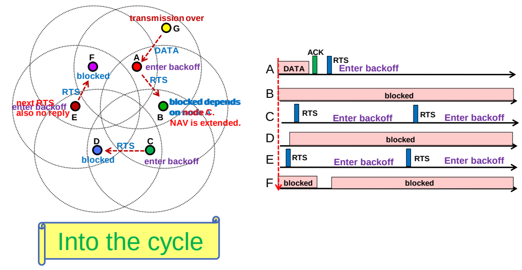
- For short, an RTS packet, destined to a blocked node, forces every other node that receives the RTS to inhibit itself even though the blocked destination does not respond, and thus, no DATA packet transmission takes place. We call this problem the false blocking problem.
- Because D and F are not really transmitting data.



False Blocking(2)

- False blocking, however, may propagate through the network, one node may become false blocked due to a node that itself is false blocked.
- False blocking may affect the network performance seriously due to unnecessary block.
- The worst case of the false blocking will decrease the throughput down to zero. This paper call the worst case "Pseudo Deadlock".

Pseudo Deadlock(1)



Reliable Broadcast

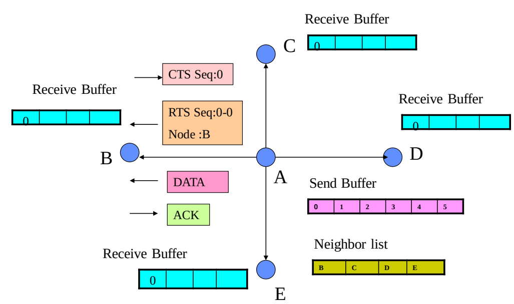
MAC Reliable broadcast in ad-hoc networks, K. Tang and M. Gerla

MILCOM, Oct 2001

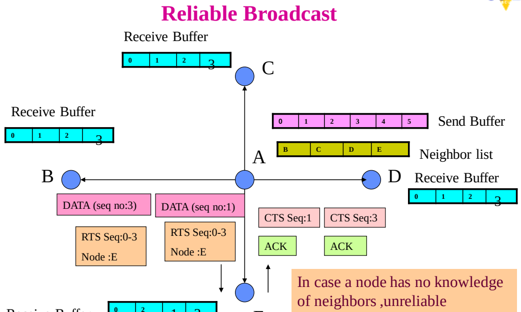
Broadcast Medium Window protocol

- Reliably transmit each packet to each neighbor in a round robin fashion through RTS/CTS exchange
- Neighbor list is updated on reception of any of (RTS/CTS/DATA/ACK/HELLO) frames.
- Each node maintains 3 buffers :
  - Input buffer
  - Send buffer
  - Receive buffer

Reliable Broadcast

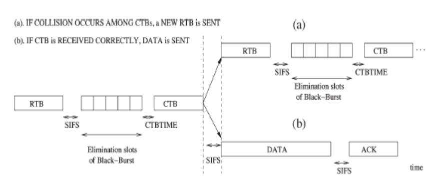


Reliable Broadcast



In case a node has no knowledge of neighbors ,unreliable broadcasting is done using CSMA/CA until neighbors are detected.

Directional Broadcast



Sequence of packets. (a) Second RTB/CTB handshake. (b) DATA/ACK.

Directional Broadcast

➢The **length of black-burst** for ith iteration :

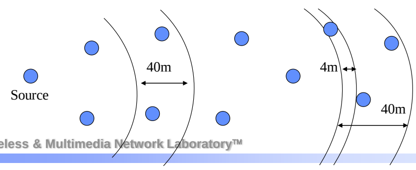
$$L_i = \lfloor (d - L_{i-1}^{longest} . W_{i-1}) . N_{max} / W_{i-1} \rfloor . SlotTime$$

$$i = 2,3,\ldots,d_{max}$$

W_i :segment width in ith iteration

$L_i^{longest}$: length of the longest black burst in ith iteration.

➢Fast decrease in **segment width**: ⇨ **Few nodes** ⇨ **Few iterations**.



Directional Broadcast

Random Collision Resolution Phase

➢Failure of collision resolution phase – start random phase

➢Random black burst lengths are chosen from [0, N_{max}-1] slots.

➢This phase continues

➢**until successful CTB or**

➢**until a maximum no of random iterations**

➢ More probability of success

➢**Because of short stripped segment at the start of random phase**

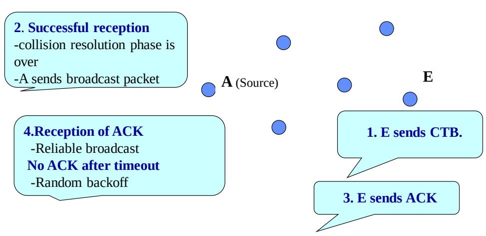
No Black-Burst Response

➢Assumes loss of RTB packet

➢Retransmits RTB after a random amount of time.

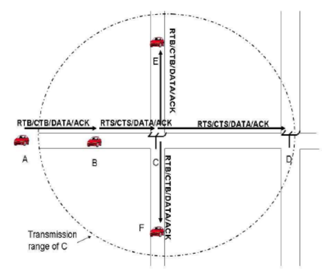
Directional Broadcast

Transmission of DATA and ACK



Intersection Broadcast

UMB Protocol



Intersection Broadcast

Fully Ad-Hoc intersection Handling

(AMB protocol)

➢Define an intersection region of radius R with intersection as the centre.

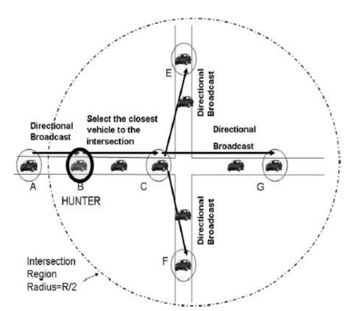
➢Selects a Hunter vehicle inside the intersection region.

➢Select a vehicle for branching the Packet Dissemination

➢Hunter vehicle sends I-RTB (Intersection-RTB)

➢Vehicle closest to the intersection sends the longest black-burst

Intersection Broadcast



Node Contention

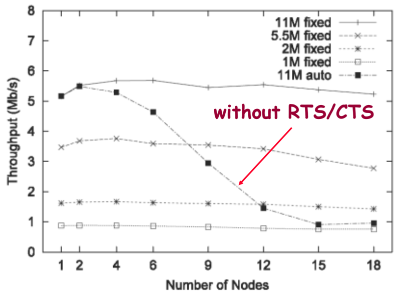


Fig. 7 Throughputs with node contentions.

[Choi, ACM SIGMETRICS'05]

Collision Aware Rate Adaptation (CARA)

- Employs two methods for identifying collisions:
  1. RTS Probing
  2. Clear Channel Assessment (CCA)
- Focuses on when to **decrease** the transmission rate.
  - → Set M_{th} , the consecutive increase threshold, to the same value as ARF: M_{th} = 10.

CARA RTS Probing

- Assumes all RTS transmission failures are due to collisions.
- Transmission failure after RTS/CTS must be due to channel errors.
- RTS probing that enables an RTS/CTS exchange ONLY when a data frame transmission fails.

RTS Probing State Diagram

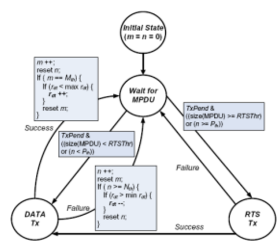


Fig. 3. State transition diagram of RTS Probing

RTS Probing

TABLE I

LIST OF NOTATIONS USED IN THE RTS PROBING PROCEDURE

Notations	Comments
m	consecutive success count
n	consecutive failure count
M_{th}	consecutive success threshold
N_{th}	consecutive failure threshold
$TxPend$	status: a data frame is pending
R_{dt}	array of transmission rates 802.11a = {6, 12, 18, 24, 36, 48, 54 Mbps}* 802.11b = {1, 2, 5.5, 11 Mbps}
r_{dt}	transmission rate: an element of R_{dt}
$++$	increase transmission rate to the next higher one
$--$	decrease transmission rate to the next lower one
P_{th}	probe activation threshold
$RTSThr$	frame size-based RTS Threshold as defined in the standard

* The 9 Mbps rate is excluded as it is shown useless in [19].

RTS Probing

CARA default: [P_{th} = 1, N_{th} = 2]

- Data frame transmitted without RTS/CTS.
- If the transmission fails, RTS/CTS exchange is activated for the next retransmission. If this retransmission fails, then the rate is lowered.
- If retransmission is successful, stay at same rate and send next frame without RTS/CTS.

ARF vs RTS Probing

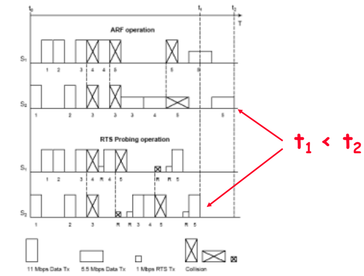


Fig. 4. Illustration of ARF and RTS-Probing timelines for a two-station network, when channel status is good enough to accommodate the highest transmission rate of the 802.11b PHY, i.e., 11 Mbps

CCA Detection

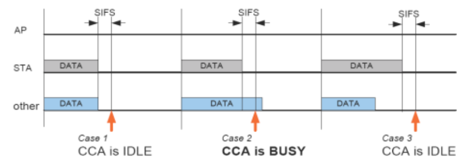


Fig. 5. Three possible cases of collision. In the second case, the collision can be detected via CCA detection.

This assumes no hidden terminals!

*In this case [Case 2], retransmit without increasing the failure count and *without lowering the transmission rate*.

*CCA does not help for Case 1 or Case 3.

CARA-1 (with RTS Probing)

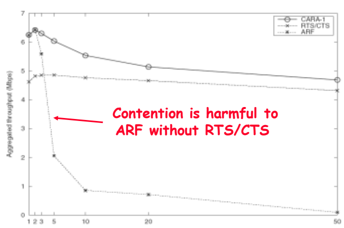


Fig. 7. Throughput comparison of our proposed rate adaptation scheme (CARA-1) against RTS/CTS and ARF for star-topology networks with various number of contending stations