King Fahd University of Petroleum & Minerals Computer Engineering Dept

COE 543 – Mobile and Wireless Networks

Term 082

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Lecture Contents

1.

Fixed Assignment Access for Voice-Oriented Networks

- Voice-Oriented networks ~ cellular telephony or PCS
- Fixed allocation of resource (frequency, time, code, etc)
- Three basic access techniques:
  - Frequency Division Multiple Access (FDMA)
  - Time Division Multiple Access (TDMA)
  - Code Division Multiple Access (CDMA)
- The choice of technology impacts:
  - Capacity
  - QoS

Background and References

- Background:
  - Chapter 8, W. Stallings, "Data and Computer Communications," Sixth Edition, Prentice Hall International Inc.
- References:
  - Chapter 4 [Pahlavan]
  - Chapter 3 [Garg]

Uplink/Down Link Duplexing

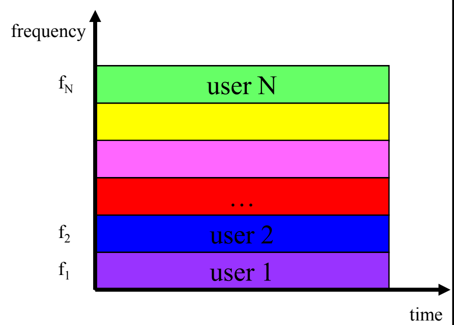
- Mechanism to differentiate between uplink and downlink transmissions
- Two basic techniques are used:
  - Frequency Division Duplexing (FDD)
  - Time Division Duplexing (TDD)
- FDD
  - Usually large coverage areas
- TDD
  - Share one RF circuitry
  - Accurate open-loop power control (refer to IS-95)
  - Usually low-power local communications
- More will be provided later on the pros and cons of each of these technologies

FDMA

- All users may transmit simultaneously – each using a distinct carrier → channel
- Basics: Frequency Division Multiplexing (FDM)
- Design Issues:
  - Adjacent channel interference (refer to backup slides – voiceband signals)
  - RF spectrum mask
  - Near-far problem – a concern especially on reverse link
    - Carriers belonging to one set are not adjacent
    - Guard bands – reduces spectral efficiency

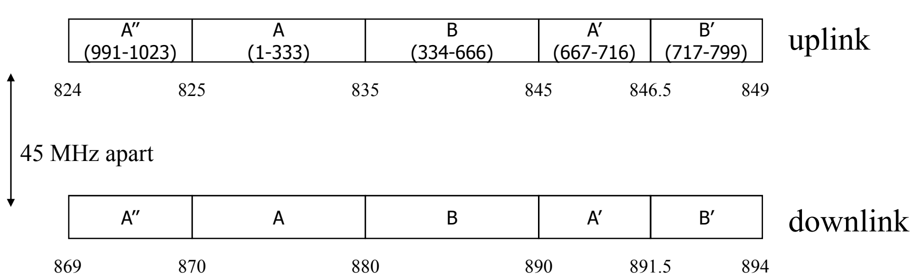
FDMA – cont'd

- A user is assigned a carrier f_i for each direction (uplink and downlink)
- A user may employ continuous transmission
- Data (user's info) is modulated using the assigned carrier
- Analog circuitry (VCO) is required to keep track of frequency shifts



Example: AMPS

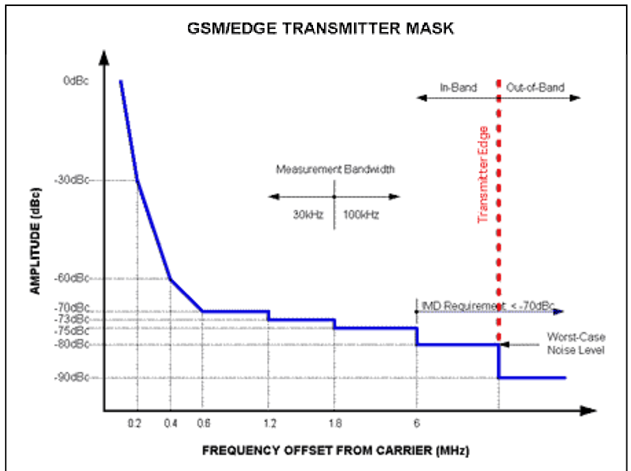
- A user is assigned an uplink and a downlink channels that are 45 MHz apart



Original FCC designation:
A band for independent carriers
B for traditional wireline (regional Bell Operating Companies) carriers
A', B', and A" were added later

Signal Mask – GSM Example

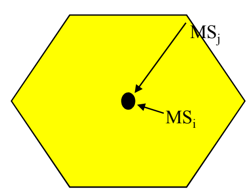
- GSM
  - Carrier spacing = 200 kHz



From: http://www.maxim-ic.com/appnotes.cfm/appnote_number/1886/ln/en

Near-Far Problem

MS_i at distance 10 meters from BS
MSj at distance 1 km from BS
Assume two mobiles transmit same power

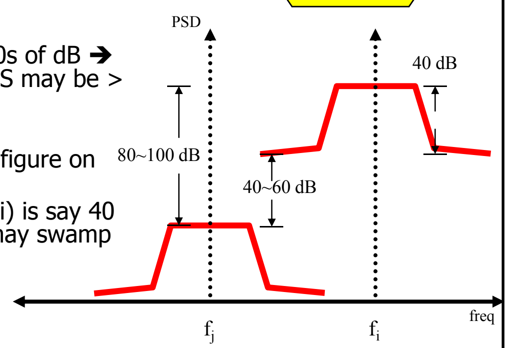


Since received power strength falls 40 dB/decade
→ received power from MS_i is 80 dB higher than that from MS_j

Due multipath – RSS may fluctuate 10s of dB → difference in received power at BS may be > 100 dB

- An extreme case is shown in the figure on the side:

For j: If out-of-band transmission of (i) is say 40 dB below transmitted power, it may swamp jth signal by 60 dB!!

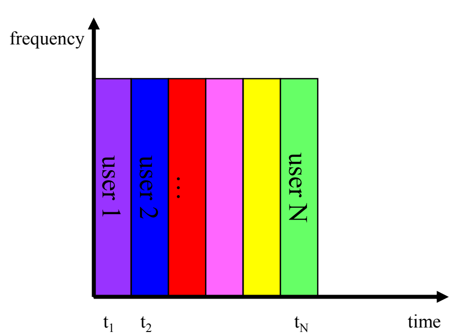


Time-Division Multiple Access

- A number of users share the same frequency band by taking assigned turns in using the channel
- BS controller assigns slots - slot released upon the completion of call
- Advantages:
  - Flexibility – can provide different access rates at no cost
- Disadvantages:
  - Requires accurate synchronization with BS and rest of users
    - Guard times

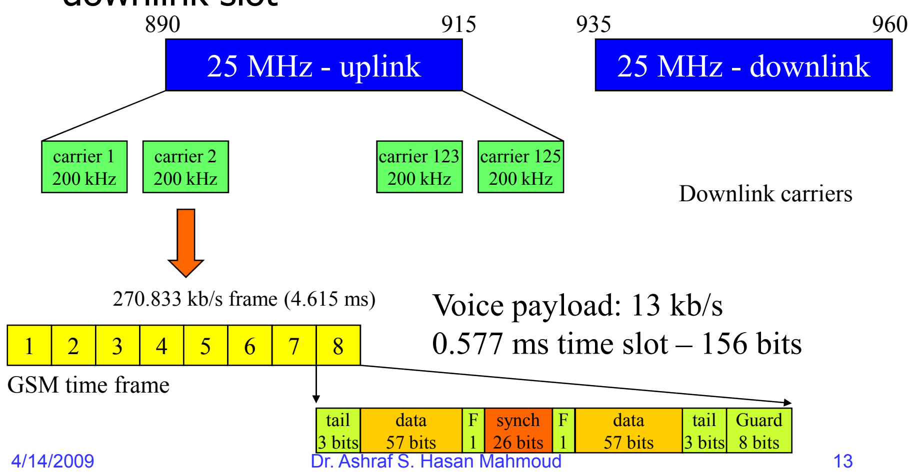
TDMA

- All the band is used by the user during his slot
  - Fixed assignment – predetermined order
  - Slot waster if there is no info for transmission

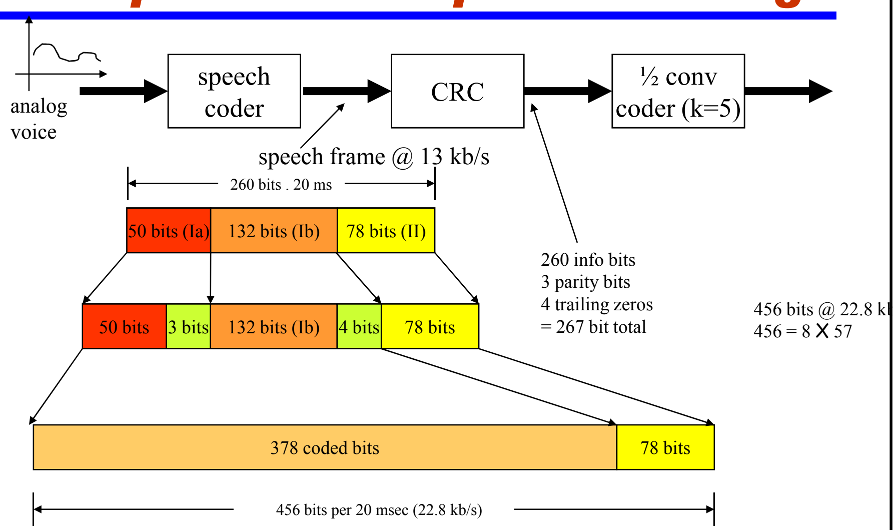


Example: GSM

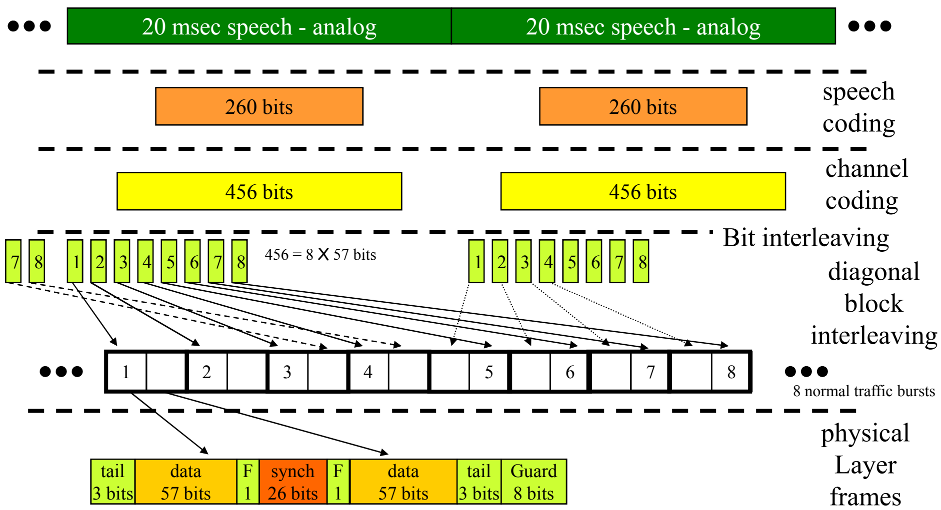
- The user is assigned one uplink slot and one downlink slot



Example: GSM – Speech coding



Example: GSM – Speech coding



Example: GSM - References

- M. Rehnema, "Overview of the GSM System and Protocol," IEEE Communication Magazine, April 1993, pp. 92-100.
- J. Cia and David J. Goodman, "General Packet Radio Service in GSM," IEEE Communication Magazine, October 1997, pp. 122-131
- http://www.it.iitb.ac.in/~it644/lectures/gsm_files/frame.htm

Capacity of FDMA and TDMA

- Review Cellular concepts slides

$$\text{No of channels per cell} = \frac{\text{Total BW / BW per user}}{\text{frequency reuse factor}}$$

But we already know that frequency reuse factor, K, and SIR are related by

$$SIR = S\, q^{\alpha}/6 = (S/6)\,(3K)^{\alpha/2}, \text{ or}$$

$$K = 1/3 \times [6/S \times SIR\,]^{2/\alpha}$$

where S is the number of sectors at the BS

Capacity of FDMA and TDMA - Example

- Consider an FDMA or TDMA with the following parameters:

Total BW = 1.25 MHz,
Path-loss exponent, $\alpha = 4$,
SIR_{min} = 18 dB (or 63),
No of antenna sectors, S = 3
BW per user = 10 kHz (~IS-54)

$$K = 1/3 \times [6/S \times SIR]^{2/\alpha} \approx 4$$

Therefore,

$$\text{No of channels (users) per cell} = \frac{(1.25\times10^{6})/(10\times10^{3})}{4}$$

$$= 31$$

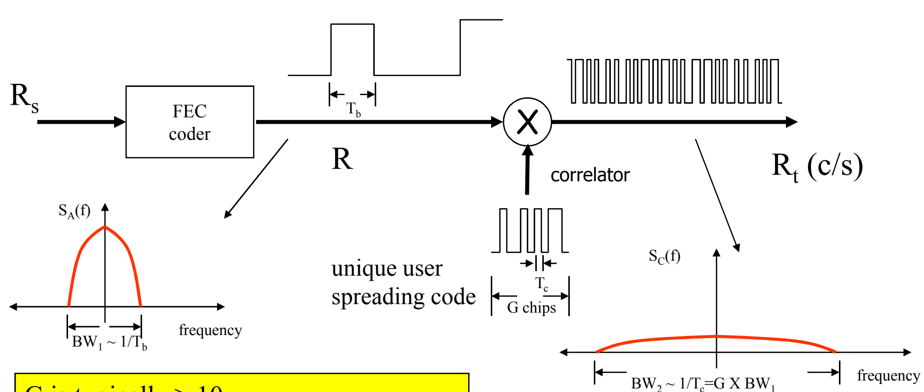
Direct-Spread Code-Division Multiple Access (DS-CDMA)

- Spread Spectrum (SS): a technique in which a signal is of original bandwidth W is transmitted over a bandwidth equal to GXW where G >> 1
  - G is referred to as the spreading gain
- DS-CDMS: A bit stream of rate R b/s (bit duration, T_b = 1/R sec) occupies a bandwidth of W ≈ R Hz
  - The bandwidth is roughly inversely proportional to the duration of the smallest signal element (bit), i.e. W ≈ $1/T_b$ = R
  - If the signal is multiplied by a code: where every bit is multiplied by a sequence of G chips each of duration T_c, then the new signal have a bandwidth ≈ $1/T_c$ = G/T_b = GXW

Frequency hopping (FH) is another form of spread-spectrum technology – review chapter 3 [Pahlavan]

Code-Division Multiple Access (CDMA)

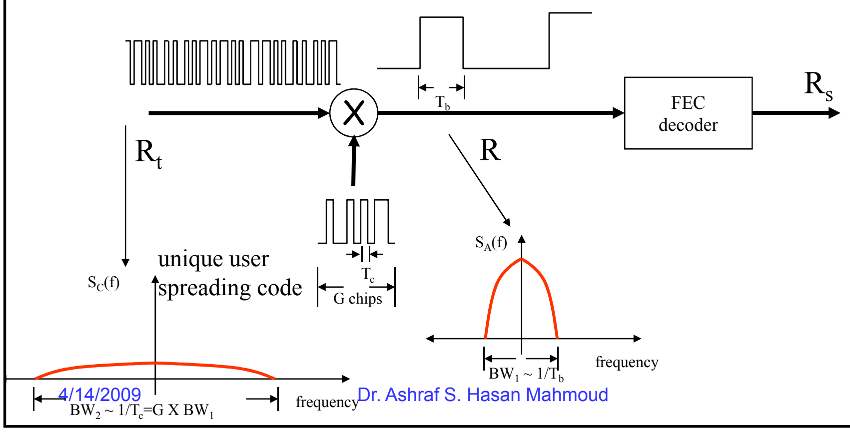
- DS-CDMA Transmitter (simplified)



G is typically > 10
- For IS-95 G = 9.6 kbs/1.25 MHz = 128

Code-Division Multiple Access (CDMA)

- DS-CDMA Receiver (simplified):
  - Typically, the signal is passed through a LPF and then sampled - the samples are then used by the FEC decoder
  - An alternative receiver structure: Replace the correlator by a filter matched to the specific user code



How Does CDMA work?

- Input:
  - Assume we have N users transmitting simultaneously
  - Let the bit stream of the i^{th} user by $R_i(t)$
  - Let the code assigned to the i^{th} user by $C_i(t)$
  - Codes are ORTHOGONAL, i.e.

$$C_i(t) \text{ X } C_j(t) = 1 \text{ if } i = j$$
$$= 0 \text{ if } i <> j$$

- Operation:
  - Each user uses its code to spread its signal – the signal transmitted by the i^{th} user is $S_i(t) = R_i(t)C_i(t)$
  - The signal received (say by the base station) is the sum of all transmitted signals (ignore multi-path copies for the time being),

$$S_r(t) = \sum S_i(t) = \sum R_i(t)C_i(t)$$

How Does CDMA work? – cont'd

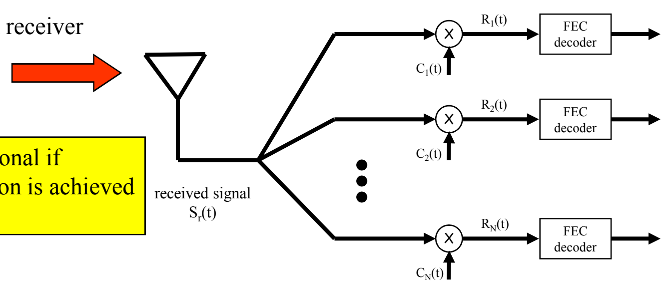
- Demodulation (De-spreading):
  - Receiver dedicates a path structure per user – multiplies the received signal with the k^{th} user code

$$C_k(t) \text{ X } S_r(t) = C_k(t) \text{ X } \sum S_i(t)$$
$$= C_k(t) \text{ X } \sum R_i(t)C_i(t)$$
$$= R_k(t)$$

i.e. only the k^{th} signal is retrieved from the k^{th} receiver path

Simplified basestation receiver

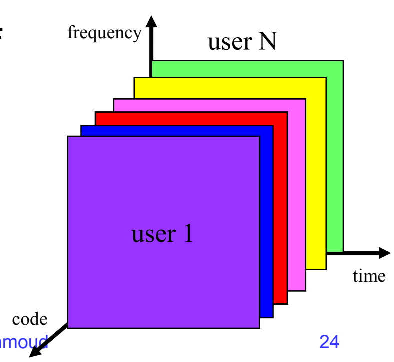
Codes are only orthogonal if
-Perfect synchronization is achieved
-No multipath exists



Code Division Multiple Access

- User transmits all the time (not in a particular slot) and using all the frequency bandwidth
- User is assigned a distinct code

- A frequency reuse factor of one is potentially possible with CDMA



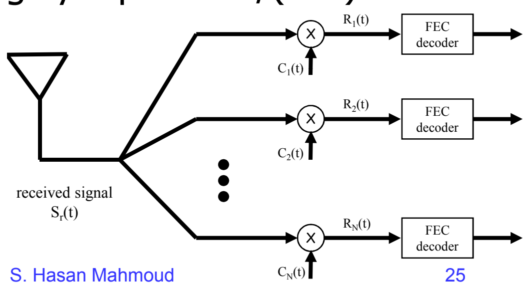
Signal Quality for DS-CDMA

- Let there be N users in the cell
- The SIR at the receiver before the correlator is roughly equal to 1/(N-1) – **assuming each is transmitting P_i Watts such that P_iXChannel_Attenutation$_i$ is equal for all users**
- The SIR at the receiver after the correlator or matched filter is roughly equal to G/(N-1)

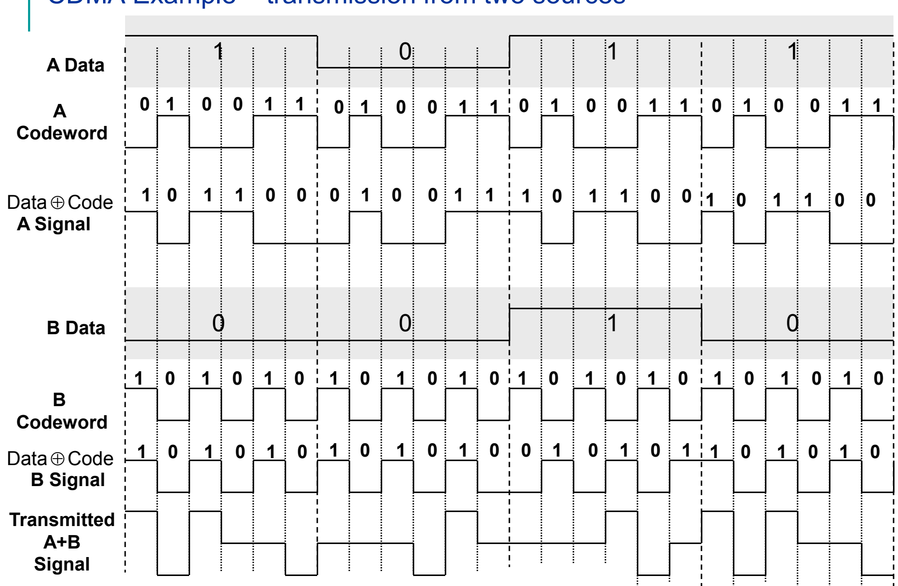
- The de-spreading procedure involves:
1. Concentrating of the desired power in the bandwidth of interest
2. Diluting the power of the interferers – this is referred to as **interference suppression**

➔ SIR after correlator = G/(N-1)

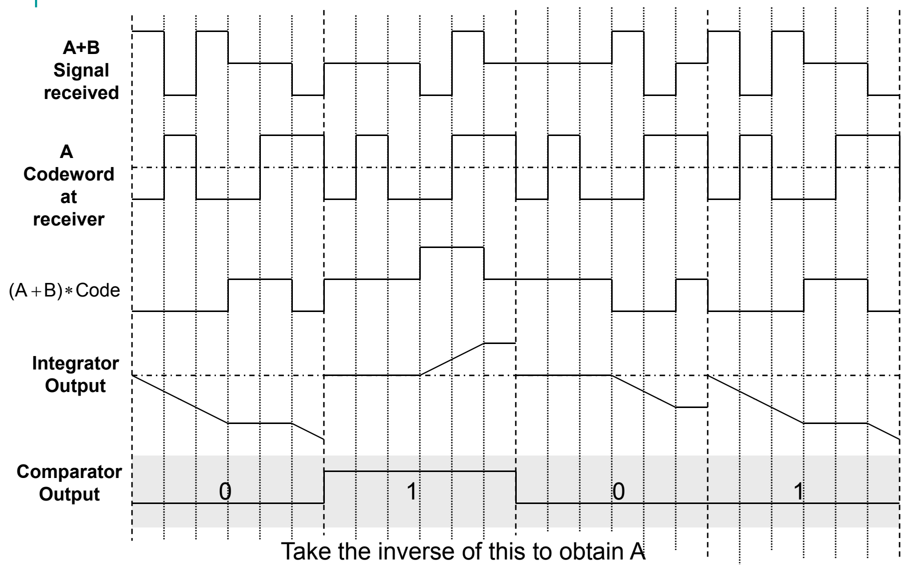
- Because of this property CDMA-based networks can tolerate more (~10-20% G) interference compared to FDMA or TDMA based networks



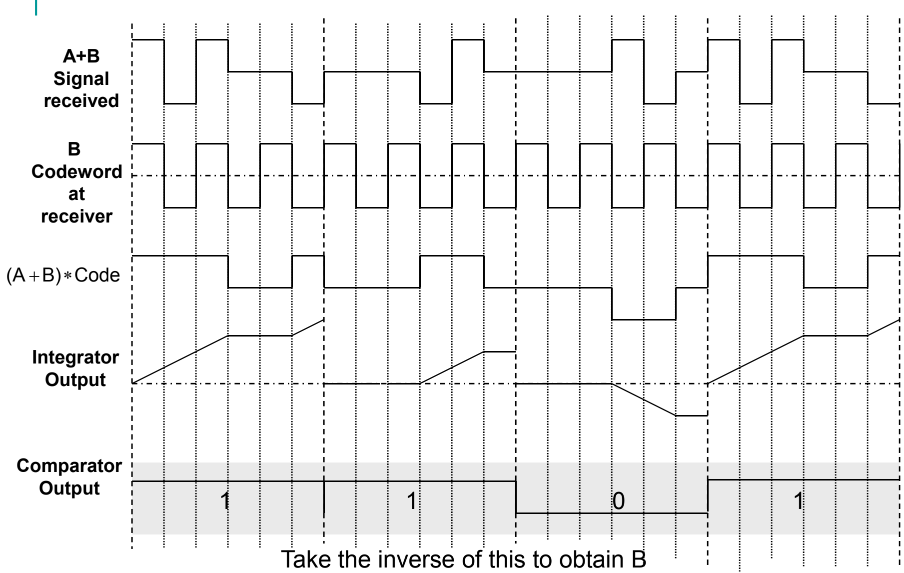
CDMA Example – transmission from two sources



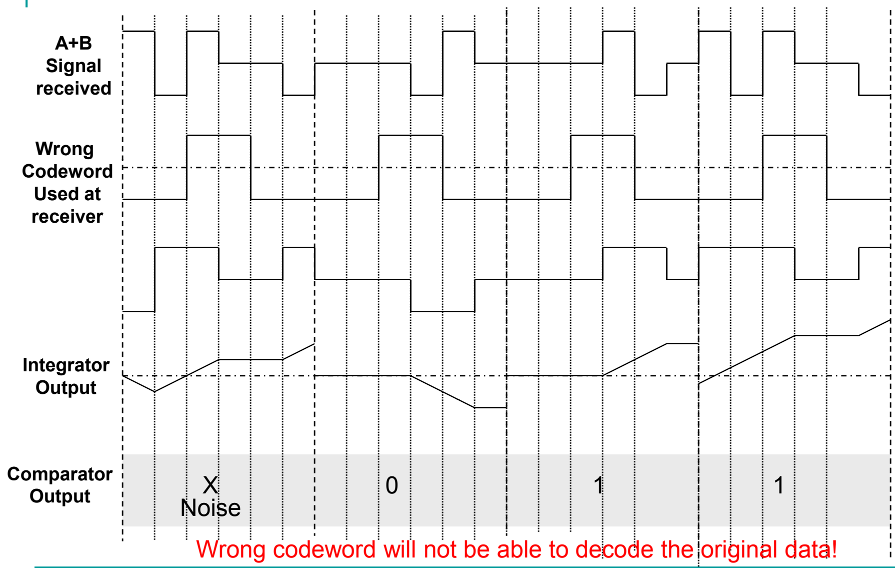
CDMA Example – recovering signal A at the receiver



CDMA Example – recovering signal B at the receiver



CDMA Example – using wrong codeword at the receiver



Signal Quality for DS-CDMA – cont'd

- The analysis and conclusions in previous slide are true only if the underlined assumption is true
  - Therefore CDMA system require a mechanism to ensure that the received signal power from different users at the receiver is not more than what is required for proper modulation and decoding of the signal
  - Near-far problem again!
  - This mechanism is called **power-control**
- CDMA requires an excellent power control mechanism to utilize its interference suppression advantage

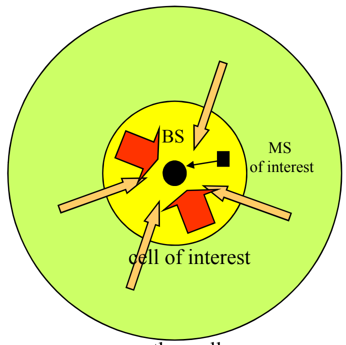
Uplink Interference Calculation

- Consider the link quality of one mobile of interest
- Interference received by the BS at the cell of interest, I_{total},

$$I_{total} = I_{intra} + I_{inter}$$

where I_{intra}: interference power from users within the cell of interest (remember all users are transmitting all the time on the same band),

I_{inter}: interference power from user outside the cell of interest



Uplink Interference Calculation – cont'd

Typically, I_{inter} is a fraction of I_{intra}, therefore I_{total} can be written as

$$I_{total} = I_{intra} (1 + I_{inter}/I_{intra}), \text{ or}$$

$$I_{total} = I_{intra} \text{ X } F$$

Typical values for F range from 1.2 to 1.6 or higher depending on the propagation model, power control, etc.

I_{intra} is assumed to be (N-1) X P where N is the number of users in the cell of interest and P is the received power from each user at BS (note the perfect power control assumption)

Hence,

$$I_{total} = F \text{ X } (N-1) \text{ X } P$$

If the BS is employing sectorized antennas, then the amount of received interference is inversely proportional to the number of sectors, S; This translates to

$$I_{total} = F \text{ X } (N-1) \text{ X } P / S$$

Furthermore, if interfering calls are only active v fraction of the time, then the actual total received interference is given by

$$I_{total} = v \text{ X } F \text{ X } (N-1) \text{ X } P / S$$

For voice users, v ~ 0.4

Signal Quality for DS-CDMA – cont'd

- Consider a cellular CDMA network – N users per cell
- Received SIR for i[th] user is given by (note $Pr_i = P_i X Channel\_Attenuation_i$)

$$SIR_i = \frac{Pr_i}{\text{Total interference}} = \frac{1}{v \times F \times (N - 1)/S}$$

where
N = total number of user per cell
F = ratio of $(Pr_{int}/ \sum Pr_j) + 1$ – typically 1.2~1.6
v = activity factor on the interfering links – about 40% for voice
S = number of antenna sectors at the BS

Writing this in terms of $(Eb/No)_i$,

$$(Eb/No)_i = \frac{\text{System BW}}{R_i} \times \frac{S}{vXFX(N-1)} = G \times \frac{S}{vXFX(N-1)}$$

Or

$$N = 1 + S \times \frac{G}{v \times (Eb/No) \times F}$$

N is the maximum number of user per cell, if Eb/No is the minimum required quality for properly received signal

Example: IS-95 Capacity

- Parameters for IS-95:

System BW = 1.25 MHz

User bit rate = 9.6 kb/s

➔ Spreading gain, G = $(1.25X10^6)/(9.6X10^3)$ = 128

S = number of sectors = 3

V = voice activity factor = 0.4

$(Eb/No)_{min}$ = minimum required signal to interference-plus-noise ratio per bit = 7 dB or $10^{7/10}$ = 5.01

F = ratio of total interference to inter-cell interference = 1.6

Therefore number of users per cell, N,

$$N = 1 + S X G/(vXFX(Eb/No)_{min}) = 120$$

Compare this to about 31 user for an equivalent FDMA or TDMA as in previous example ➔ 120/31 ≈ 4 times

Example – Problem 4.6

A GSM system with sectored antenna s (K = 5) is to replace AMPS (K = 7) with same cell sites.

a) Determine the no of voice channels per cell for the AMPS

b) Determine the no of voice channels per cell site for the GSM

c) Repeat (b) if a W-CDMA system with BW = 12.5 MHz for each direction is to be used. Assume a signal-to-noise requirement of 4 (or 6 dB) and include effects of antenna sectorization (2.75)[1], voice activity, and intercell interference (F = 1.6)

(1) – The effective sectorization is 2.75 considering antenna imperfections – Although S may be equal to 4 or even 6 but interference is reduced to 1/2.75 rather than 1/4 or 1/6

Example – Problem 4.6

Solution:

a) For AMPS (ignoring control channels):

N = 12.5 MHz / (7 X 30 kHz) = 59 channels

b) For GSM

N = 12.5 MHz X 8 slots / (4 X 200 kHz) = 125 channels

c) For W-CDMA

N = 1 + (12.5MHz/9.6kb/s) X 2.6/(0.4 X 1.6 X 4) = 1323 users!!

Qualcomm IS-95 Systems

- Operates in the same frequency band as AMPS
- Uses FDD with 25 MHz for each direction
- User Identification:
  - Forward link: 64 Walsh codes (orthogonal codes) are used
  - Reverse link: long PN code with different time shifts
- Different modulation techniques on downlink and uplink
  - O-QPSK
  - QPSK
- Downlink pilot signals are transmitted to assist mobiles acquire and track the correct frequency and phase
- Strong coding is used (especially on reverse link)
- Required Eb/No for correct operation 5~7 dB
- Power control is essential

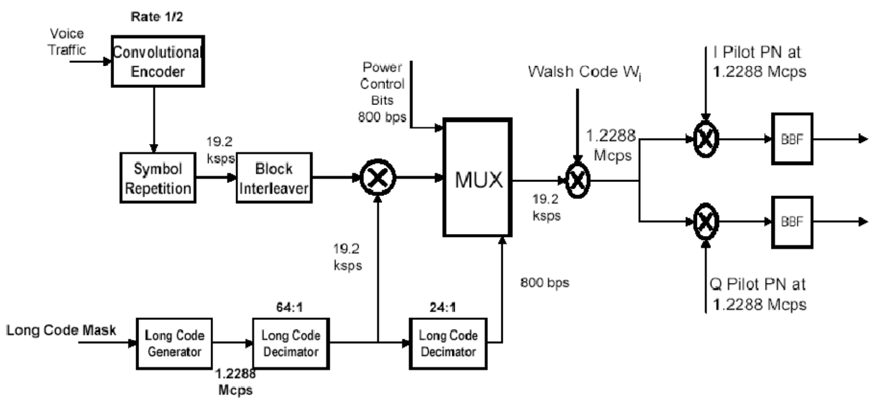
Qualcomm IS-95 Systems

Parameters for IS-95B System

Modulation	QPSK/O-QPSK
Chip rate	1.288 Mc/s
Channel rate	1.2, 2.4, 4.8, 9.6 kb/s (RS-1) 1.8, 3.6, 7.2, 14.4 kb/s (RS-2)
Filtered BW	1.25 MHz
Coding	1/2 (1/3) convolutional code for downlink (uplink) Viterbi decoding for both
Interleaving	With 20 ms spans
Power control	Open-loop, closed-loop (800 b/s) control
Vocoder	Variable rate ~ 1- 8 kb/s
Receiver	RAKE – take advantage of multipath

Qualcomm IS-95 Systems

Forward traffic channel structure (Rate Set 1)



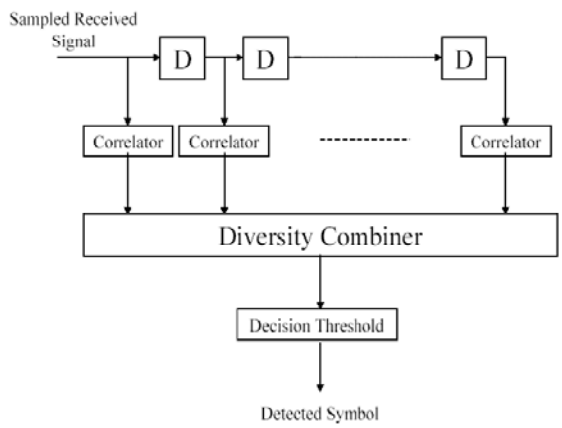
Qualcomm IS-95 Systems – cont'd

- Power Control Functionality:
  - Open loop:
    - upon powering up, MS measures received power from BS and adjusts its transmit power → not optimal – why?
    - The pilot signal is used as a reference
  - Closed loop:
    - A feedback mechanism is implemented between the BS and the MS to control the transmit level at the MS
    - IS-95 uses 800 commands per second to perform this function
- Softhandoff:
  - MS communicates with more than one BS
  - Downlink: Signals arriving from multiple BS (carrying same info) are received by the RAKE receiver and combined as one signal
  - Uplink: MS's signal received by more than one BS – combined by the network (BSC or MSC)

Qualcomm IS-95 System – cont'd

- Original receiver design – tap delays were fixed – nowadays tap delays are variable (tracking functionality)
- Delays short enough to resolve distinct paths (usually one or half chip duration)
- Goal: to capture all major paths
- Multiple signal paths are combined:
  - Selectively,
  - Equal-gain, or
  - Maximal ratio ➔ the optimal method
- IS-95 calls for a 3 moving fingers

General Rake Receiver Structure



Space Division Multiple Access

- Control the radiated energy for each user
- Users are served using "spot beam" antennas
- Spot beams may use same frequency (as in TDMA or CDMA) or different frequencies (as in FDMA)
- Sectorized antenna – is one primitive form of SDMA – review capacity expansion technique slides
- Adaptive antenna array:
  - Steer multiple beams (one for each user)
  - Best suited for TDMA or CDMA systems
- Difficult for reverse link:
  - Requires coordination of power levels
  - Huge power required to form beams - not available

Space Division Multiple Access – cont'd

- More practical, at least to date, at the BS
- The limiting case:
  - Infinitesimal beam width and infinitely fast tracking ability → zero interference
  - All users communicate to BS on one channel
  - Able to combine multipath signals for one user and obtain a better signal
  - Not feasible since it require infinite number of elements
- Gains can be achieved using reasonably sized antenna beams

Comparison Between FDMA, TDMA and CDMA

- Read section 4.2.4 in book - Important

Performance of Fixed-Assignment Access Methods

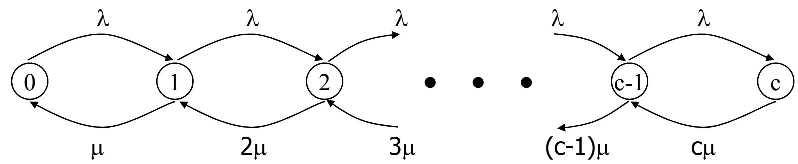
- FDMA/TDMA provide a hard capacity limit (number of channels)
  - FDMA – maximum number of carriers per cell
  - TDMA – maximum number of slots per frame X number of carriers per cell
- CDMA-based also has a hard capacity limit dictated by the number of Walsh codes for example, but usually practical capacity is lower
  - Soft-capacity figure: Near the capacity boundary, the addition of one extra user degrades the link quality for all
  - Call admission control mechanism attempt to limit maximum number of ongoing calls before link quality degrades for all
- If you operate a maximum no of channels, then call blocking and call delay are the two important measures!

This material has been presented in the Cell Concept Module

Erlang-B and Erlang-C Models

- More details to be provided in COE540
- Model designed to predict blocking probability (Erlang-B) and average call delay (Erlang-C) for a given number of channels and traffic intensity
- Valid for voice and traffic models conforming to the basic assumption (usually not applicable to data)
- Assumptions, Terminology and Parameters:
  - Channels ←→ Servers: c servers
  - Users ←→ Calls
  - Calls arrive according to a Poisson process with rate = λ
    - Inter-call arrival is an exponentially distributed r.v. with mean $1/\lambda$
  - Call duration is exponentially distributed r.v. with mean = $1/\mu$
  - Traffic intensity, $\rho = \lambda/\mu$

Erlang-B (M/M/c/c) Model – Call Blocking

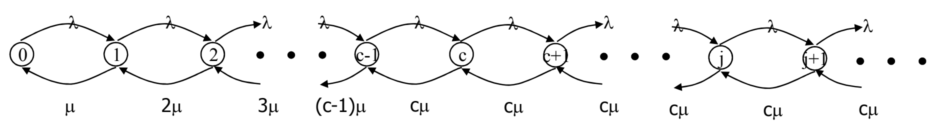


- As was shown earlier – review previous notes, the call blocking probability is given by

$$B(c,\rho) = \frac{\rho^c / c!}{\sum_{i=0}^{c} \rho^i / i!}$$

- ρ – is referred to as the offered load, while ρX[1-B(c,ρ)] is referred to as the carried load
- Note in this model – calls arriving while there are c calls are blocked – no buffering is employed

Erlang-C (M/M/c) Model – Call Delay



- The probability that an arriving call having to wait is given by

$$\Pr(delay > 0) = \frac{\rho^c}{\rho^c + c!\left(1 - \frac{\rho}{c}\right)\sum_{k=0}^{c-1}\frac{\rho^k}{k!}}$$

- The average delay is given by

$$D = \Pr(delay > 0) \times \frac{1}{\mu(c-\rho)}$$

- The probability of the delay exceeding t time units is given by

$$\Pr(delay > t) = \Pr(delay > 0)e^{-(N-\rho)\mu t}$$

Examples

- An IS-136 cellular provider owns 50 cell sites and 19 traffic carriers per carrier per cell each with bandwidth of 30 kHz. Assuming each user makes three calls per hour and the average holding time per call is 5 minutes. Determine the total number of subscribers that the service provider can support with a blocking rate less than 2%
- Solution:

c = 19X3 = 57 per cell

B(57,ρ) = 0.02 ➔ ρ = 45 Erlangs per cell

$(\lambda/\mu)_{sub}$ = 3/60*5 = 0.25 Erlangs per sub

Number of subs = total traffic / traffic per user

= 45 / 0.25

= 180 per cell

Number of subs for all sites = 180 X 50 = 9,000 subs

Note that $\rho_{all\_subs} = (\lambda/\mu)_{all\_subs} = \lambda_{all\_subs}/\mu$

whereas, $\rho_{sub} = (\lambda/\mu)_{sub} = \lambda_{sub}/\mu$

λ_{all_subs} = no of subs X λ_{sub}

CDMA Capacity Revisited - Downlink

- Reverse link capacity was analyzed before – Refer to the "Uplink Interference Calculation" Slides.
  - Assume perfect power control – i.e. all signals received at basestation arrive with the required Eb/No always (not more and not less)
- What about downlink calculations?
- The amount of users/transmissions/channels to be supported on the uplink or downlink is variable – Erlang models can not be applied directly!!

CDMA Capacity Revisited – Downlink – con'td

- Consider a basestation in the cell of interest, cell 0, serving N users
- i^{th} (i=0, 2, …, N-1) user is at distance d_i from basestation ➔ The corresponding pathloss attentuation between the user and our cell is equal to PL_{i0} (computed using the appropriate model – refer to the RF propagation module)
- The i^{th} user is assigned a data rate R_i – Assume the system bandwidth = W Hz
- The downlink transmissions from one basestation are ideally orthogonal – however, in practice, there is loss of orthogonality and therefore, simultaneous downlink transmissions interfere with one another – assume orthogonality factor, ρ, where 0<ρ<1 (i.e. ρ = 1 means perfect orthogonality - ρ = 0 means total loss of orthogonality)

CDMA Capacity Revisited – Downlink – 3

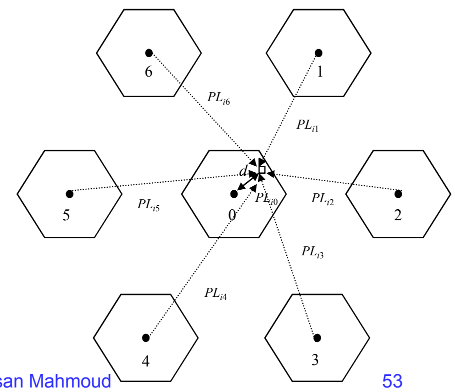
- The basestation can assign any of the follow bit rates ={R_i, $2^i R_0$, i=0, 1, …, 5} where R_0 = 9.6 kb/s - Assume users request the highest rate possible given the available power and interference conditions
- The basestation allocates enough transmit power, P_i, to the i^{th} mobile such that recevied (Eb/No)i is at least equal to a required EbNo threshold.
- The basestation is continuously transmitting overhead channels (pilot, sync and paging) – amount of power allocated to overhead channels is Pov Watts
- The total power budget for basestation is equal to Ptotal Watts – The amount of power that can be used for traffic channels is given by (1-β)Ptotal – where Pov = β Ptotal
- Assume interferers of 1^{st} tier are equally loaded (i.e. if the total transmit power of our basestation is X Watts, then each of the cochannel interferes is transmitting X Watts)
  - Transmissions of one basestation are completely inorthogonal to transmissions of another basestation
- Thermal noise can be neglected

CDMA Capacity Revisited – Downlink – 4

- Let us write the received SIR formula at the mobile:
  - Our cell is transmitting:

$$\sum_{i=0}^{N-1} P_i + Pov$$

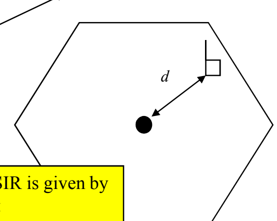
  - Each of the other cochannel interferers is transmitting the same power



CDMA Capacity Revisited – Downlink – 5

- Let us write the received SIR formula at the mobile:

$$SIR_i = \frac{P_i PL_{i0}}{\underbrace{(1-\rho)PL_{i0}\left[\sum_{j=0,j\neq i}^{N-1} P_j + Pov\right]}_{\text{Transmissions from our cell of interest}} + \underbrace{\left[\sum_{j=0}^{N-1} P_j + Pov\right]\sum_{k=1}^{6} PL_{k0}}_{\text{Transmissions from cochannel cells}} + \underbrace{ThermalNoise}_{\text{Thermal noise power – usually ignored}}}$$



But the relation between Eb/No and SIR is given by (review COE342 textbook chapter 3):

$$\left(\frac{E_b}{N_o}\right)_i = \frac{W}{R_i} \times SIR_i$$

CDMA Capacity Revisited – Downlink – 6

- Notes:
  - Thermal noise power is usually negligible compared with interference power
  - Transmissions from our cell of interest interfere as long as there is orthogonality loss (i.e. $\rho < 1$)
  - Transmissions from cochannel cells ALWAYS interfere regardless of the orthogonality factor ρ

CDMA Capacity Revisited – Downlink – 7

- Let us write the Eb/No for the i[th] transmission:

$$\left(\frac{E_b}{N_o}\right)_i = \frac{W}{R_i} \times \frac{P_i PL_{i0}}{(1-\rho)PL_{i0}\left[\sum_{j=0, j\neq i}^{N-1} P_j + Pov\right] + \left[\sum_{j=0}^{N-1} P_j + Pov\right]\sum_{k=1}^{6} PL_{k0}}$$

- Dividing the numerator and denominator by PL_{i0}, results in

$$\left(\frac{E_b}{N_o}\right)_i = \frac{W}{R_i} \times \frac{P_i}{(1-\rho)\left[\sum_{j=0, j\neq i}^{N-1} P_j + Pov\right] + f_i\left[\sum_{j=0}^{N-1} P_j + Pov\right]}$$

where f_i is given by $f_i = \left[\sum_{k=1}^{6} PL_{k0}\right] \Big/ PL_{i0}$

Note that f_i is only a function of the mobile location in the 0[th] cell (cell of interest).

CDMA Capacity Revisited – Downlink – 8

- For every (x,y) location in the 0^{th} cell (cell of interest), and given a Path Loss Model one can calculate:
  - The path loss coefficient between the user and the 0^{th} cell, PL_{i0}
  - The path loss coefficient between the user and each of the 6 co-channel interferers PL_{k0} (k=1,2, …, 6).
  - f_i is obtained by dividing PL_{i0} by the sum of PL_{k0}s
- If we assume a Hata RF propagation model – then f_i can be approximated by a 6^{th} degree polynomial as shown in the following matlab code – d is the mobile distance from the center of 0^{th} cell, i.e. d = √(x^2+y^2)
- The Hata RF model is also shown

CDMA Capacity Revisited – Downlink – 9

```
function f = f_function( d );
P = [-11.9104   31.0419  -25.2090    9.8841   -1.4902    0.0739   -0.0004];
f = polyval(P, d);
if (length(f) > 1)
  I = find(f < 0);
  f(I) = 0;
else
  if (f < 0) f = 0;
  end
end

function L50 = HataModel( d, fc, hb, hm);
%
%
ahm = 3.2*(log10(11.75*hm)).^2 - 4.97;
L50  = 69.55 + 26.16 * log10(fc) - 13.82 * log10(hb) - ...
        ahm + (44.9 - 6.55 * log10(hb))* log10(d);
```

Remember:
The output of the RF model is in dBs
Typical values for inputs:

```
CellR   = 1.0  % cell radius;
fc      = 2000; % carreir freq in MHz
hb      = 50.0; % basestation antenna height - meters
hm      = 3.0; % mobile antenna height - meters
```

CDMA Capacity Revisited – Downlink – 10

- Back to the Eb/No equations (i=0, 1, …, N-1)

$$\left(\frac{E_b}{N_o}\right)_i = \frac{W}{R_i} \times \frac{P_i}{(1-\rho)\left[\sum_{j=0,j\neq i}^{N-1} P_j + Pov\right] + f_i\left[\sum_{j=0}^{N-1} P_j + Pov\right]}$$

- For a given set of N users with known locations, then the assigned Pi's (i=0, 1, …, N-1) is governed by the set of linear equations above
- The conditions of the Pi's (the solution for the above linear system) are:
  - Pi > 0 for all i = 0, 1, …, N-1
  - Sum of all Pi's should be less or equal that what a basestation can allocate for traffic ((1-β) Ptotal)
- Otherwise, the solution for Pi's is not acceptable

CDMA Capacity Revisited – Downlink – 11

- How does the linear system of equations look like?
- To answer this question let us rewrite the Eb/No equation as

$$E_i = G_i \times \frac{P_i}{(1-\rho+f_i)\left[\sum_{j=0,j\neq i}^{N-1} P_j + Pov\right] + f_i P_i}; \quad i = 0,1,\cdots,N-1$$

where Ei = (Eb/N0)i, and Gi = W/Ri

- Or

$$(E_i f_i - G_i)P_i + E_i(1-\rho+f_i)\left[\sum_{j=0,j\neq i}^{N-1} P_j\right] = -E_i(1-\rho+f_i)Pov \qquad i = 0,1,\cdots,N-1$$

CDMA Capacity Revisited – Downlink – 12

- Using the above notations, the linear system is given by

$$\begin{bmatrix} (E_0 f_0 - G_0) & E_0(1-\rho+f_0) & \cdots & E_0(1-\rho+f_0) & \cdots & E_0(1-\rho+f_0) \\ E_1(1-\rho+f_1) & (E_1 f_1 - G_1) & \cdots & E_1(1-\rho+f_1) & \cdots & E_1(1-\rho+f_1) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ E_i(1-\rho+f_i) & E_i(1-\rho+f_i) & & (E_i f_i - G_i) & \cdots & E_i(1-\rho+f_i) \\ \vdots & \vdots & & \vdots & \cdots & \vdots \\ E_{N-1}(1-\rho+f_{N-1}) & E_{N-1}(1-\rho+f_{N-1}) & \cdots & E_{N-1}(1-\rho+f_{N-1}) & \cdots & (E_{N-1} f_{N-1} - G_{N-1}) \end{bmatrix} \times \begin{bmatrix} P_0 \\ P_1 \\ \vdots \\ P_i \\ \vdots \\ P_{N-1} \end{bmatrix} = -Pov \begin{bmatrix} E_0(1-\rho+f_0) \\ E_1(1-\rho+f_1) \\ \vdots \\ E_i(1-\rho+f_i) \\ \vdots \\ E_{N-1}(1-\rho+f_{N-1}) \end{bmatrix}$$

using conventional methods (reduced raw echelon form, LU decomposition, etc) to solve this system requires O(N^3) operations – However, one can exploit the system structure (coefficients in one raw are equal except for the ith entry) to solve the system using Sherman-Morrison-Woodbury method (page 51 of Matrix Computation - Golub and van Loan, 2nd ed.) for O(N^2) operations.

CDMA Capacity Revisited – Downlink – 13

- **Code:**

```
function [Flag, Powers] = GetRequiredPower(BW, Rho, Ptotal, ...
                          Pov, Rates, f_d, Nt, EbNo)
Flag   = 0;
Powers = zeros(1,Nt);
G    = BW./Rates;
% A * P = b
% build the A matrix
A  = zeros(Nt, Nt);
A  = -((EbNo./G) .*(1-Rho+f_d))' * ones(1,Nt);
Ad = 1-(EbNo./G).*f_d;
for i=1:Nt;
   A(i,i)  = Ad(i);
end
%
% for the b vector
b = (EbNo./G).*((1-Rho+f_d) .* Pov);
%
% Solve for the powers
P = A\b';
%
% Test validity of solution
if (~(sum(P<0))) & (sum(P) < (Ptotal - Pov))
   Flag = 1;
   Powers = P;
end
```

The following function in matlab solves the system of equations to determine if the current set of transmissions can be supported or not

Mapping between code variables and variables used in the previous slides:

BW → W (bandwidth of System)
Rho → ρ (orthogonality loss factor)
Ptotal → Ptotal (total basestation power)
Pov → Pov (overhead power allocation)
Rates →[R0, R1, … RN-1] set of rates assigned to the N users
f_d → [f0, f1, …, fN-1] set of f_i coefficients that are calculated using the approximation polynomial
Nt → N (number of users)
EbNo → Eb/No – The signal quality requirement for each transmission at the specified rate

Function output:

Vector P = [P0, P1, …, PN-1] set of powers assigned to users
If the solution vector P is valid, the function sets Flag to TRUE and returns P
else Flag is set to 0

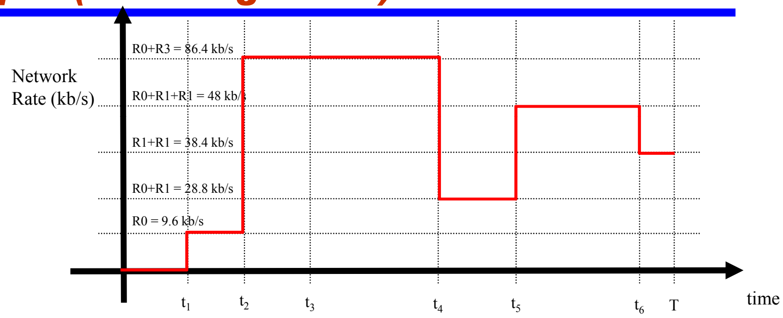
CDMA Capacity Revisited – Downlink – 14 - Procedure

- Assume EbNo = 10^(5/10) for all transmissions – Rho (ρ) = 0.1, BW = 1.25 MHz, Ptotal = 24 Watts, Beta (β) = 0.2 (i.e. Pov = 0.2X24, Ptraffic = 24 – 0.2X24 = 18 Watts)
- Initially the system is empty (i.e. no users are connected to the basestation)
- First connection request arrives - associated with a data block (number of bytes) to transmit
  - Calculate the f_i for this mobile using its location and the RF model
  - Assume we will try to assign it the maximum bit rate possible – so try the following rates in the descending order: [307.2 153.6 76.8 38.4 19.2 9.6]
  - Nt = 1; Let Rates = [307.2e3] and use the function to determine if the rate can be supported or not
    - If flag = true – solution is found – assign rate – calculate when this transmission will be finished (time = Datablock size/Rate)
    - If flag = false – try next lower rate and repeat call for function
    - If no rate is suitable – transmission can not be served – block mobile
- Repeat procedure for additional users
- When a transmission is completed – it is removed from the system variables (i.e. power is released) Nt, Rates and other variables are updated

CDMA Capacity Revisited – Downlink – Problem Statement

- Assume a CDMA system – Burst/Transmission requests are arriving to the basestation according to a Poisson process with rate λ requests per second. Each request coming from a different mobile with a random (x,y) location (and therefore a different f_i value). The request is also associated with a random data block size (B_i Bytes) for transmission. if:
  1. The requests are served in a blocking FCFS order – assume all burst requests that can be served starting with an empty system (you may want to check this based on the path loss model) – bursts that are delayed more than D_max seconds are dropped and not served.
  2. The requests are served in a non-blocking FCFS order. Bursts that can not be served immediately are placed in FCFS queue where the system attempts to serve them every time an ongoing burst is completed. Again, assume that bursts delayed for more than D_max seconds are dropped and not served
- Required output:
  - Throughput – time average of assigned rates (see next slide)
  - Probability of burst request dropping – Ratio of dropped burst requests to total number of number of arriving requests
  - Average access delay for a burst request
  - Etc.

CDMA Capacity Revisited – Downlink – Example (blocking FCFS)



t1: Burst request 1 arrives – assigned R0 (9.6 kb/s) at t1 – zero access delay
t2: burst request 2 arrives – assigned R3 (76.8 kb/s) at t2 – zero access delay - total rates on downlink = R0+R3 = 86.4 kb/s
t3: burst request 3 arrives – could not be served – wait
t4: burst 2 finishes service – power released – request 3 can served (assume it did not expire) – assigned rate R1 (19.2 kb/s) – access delay for request 3 = t4-t3 – total rates on downlink = R0+R1 = 28.8 kb/s
t5: burst 4 arrives – assigned R1 (19.2 kb/s) at t5 – zero access delay – total rates on downlink = R0+R1+R1 = 48 kb/s
t6: burst 1 finishes service – power released – total rates on downlink = R1 + R1 = 38.4 kb/s
T: simulation time completed

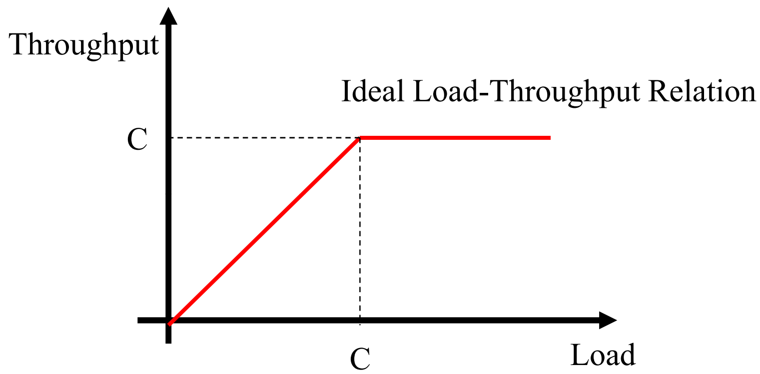
Results:
Average throughput = area under the curve from t = 0 till t = T
Prob of being delayed = ¼
Average access delay = (0 + 0 + (t4-t3) + 0)/4

Random Access for Data Services

- Random access is suitable for bursty (intermittent variable – non constant) data applications
- Contention-based schemes
  - Originally for wireline LANS - CSMA/CD used for IEEE802.3 (Ethernet)
- Non-contention based schemes:
  - Reservation
  - Polling
- Performance measures
  - Throughput
  - Delay (packet)

Performance Measures

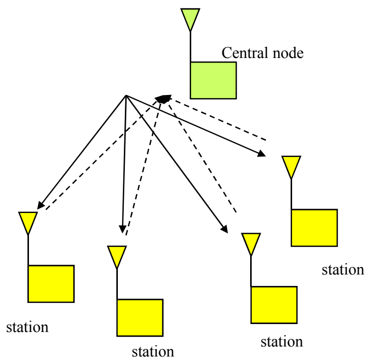
- Throughput
- Delay (packet)

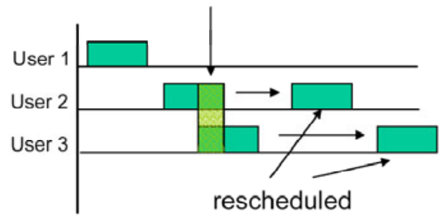


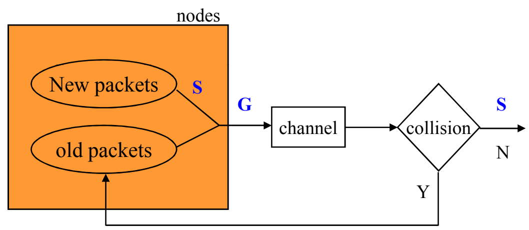
ALOHA-Based Wireless Random Access Techniques

- Pure ALOHA Protocol
  - Developed in 1971 by university of Hawaii
  - Multiple ground stations communicate to a central node
  - A station transmits when the data packet arrives
  - BS receives packet and decodes – if correct an ACK is sent back
  - if ACK is not received, station retransmits it packet after some random delay to avoid repeated collisions
  - Collision: when two packet transmissions overlap – note this model ignore errors due to the wireless link other than interference

Pure ALOHA



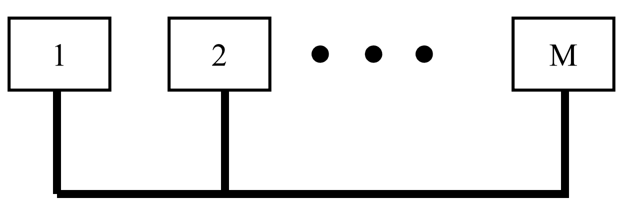




Uplink carrier 413 kHz, 9.6 kb/s
Downlink carrier 407 kHz, 9.6 kb/s

ALOHA Random Access Procedure

- **Assume**
  - **Packet transmission time: P**
  - **Total # of packet arrival (new + retransmission) ~ Poisson with rate λ**



ALOHA - Throughput

- **Poisson arrival (new + retransmitted) of packets:**

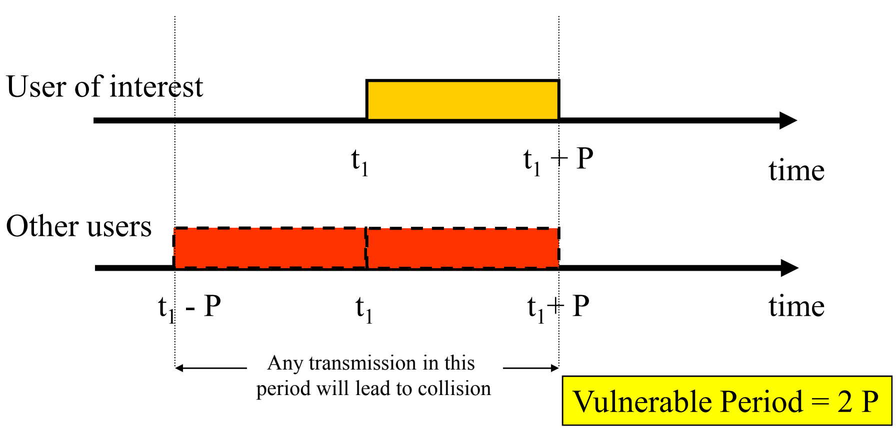
$$\text{Prob[k arrivals in t sec]} = \frac{(\lambda t)^k}{k!} e^{-\lambda t}$$

- **Offered Load (G): Average number of attempted packet transmissions per packet transmission time, P**

- **Throughput (S): Average number of successful transmissions per packet transmission time, P**

Pure ALOHA – Throughput – cont'd

- **Vulnerable Period**



ALOHA Throughput – cont'd

- Throughput = fraction of attempted transmission that are successful (i.e. did not collide)
- Therefore,

$$S = G \times \text{Prob[no collision in 2 P seconds]}$$
$$= G \times \text{Prob[0 packet arrivals in 2 P seconds]}$$

$$= G \times \frac{(2G)^0}{0!} e^{-2G}$$

Or

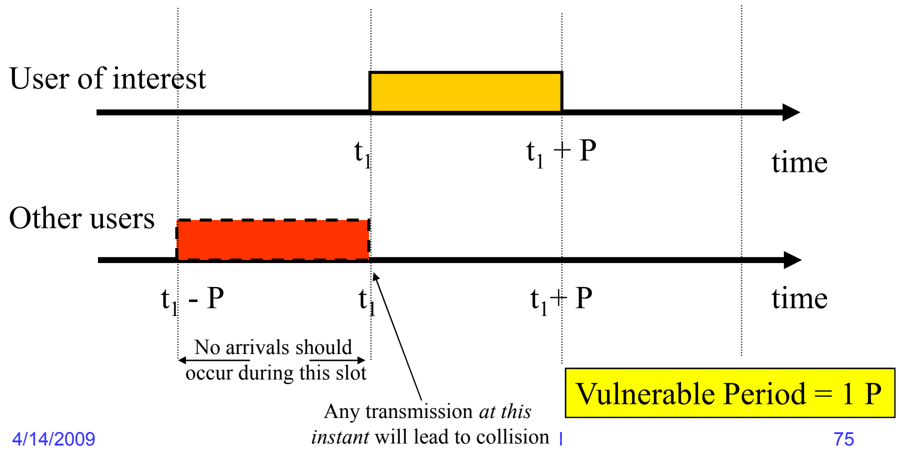
$S = G e^{-2G}$ packets/packet transmission time

Slotted ALOHA

- An improvement over pure ALOHA
- Time axis is slotted
- Transmission occur only at the beginning of a time slot
- A packet arriving to buffer has to wait till the beginning of the time slot for transmission
- Cost: common clock signal!

Slotted ALOHA – Throughput – cont'd

- **Vulnerable Period (note time axis is divided into slots – transmissions can only start at the beginning of a time slot)**



Slotted ALOHA – Throughput

- **Throughput = fraction of attempted transmission that are successful (i.e. did not collide)**

- **Therefore,**

S = G X Prob[no collision in 1 P seconds]
= G X Prob[0 packet arrivals in 1 P seconds]

$$= G \times \frac{(G)^0}{0!} e^{-1G}$$

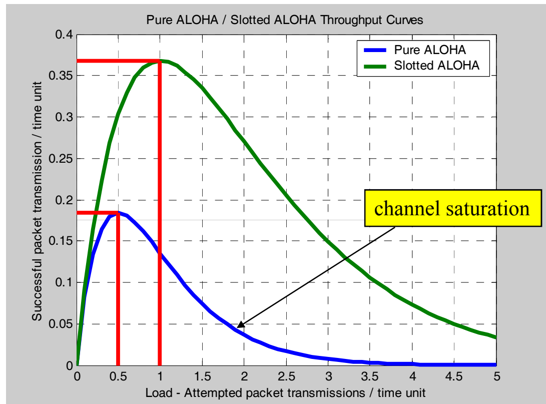
Or

$$S = G e^{-1G} \quad \text{packets/packet transmission time}$$

ALOHA – Throughput – cont'd

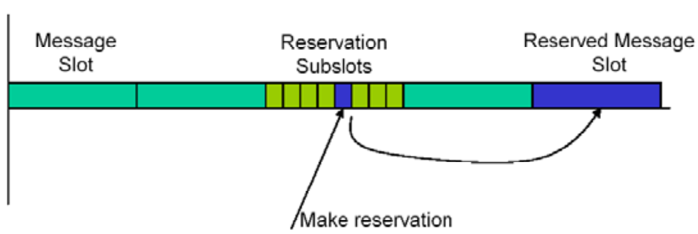
- **Pure ALOHA: Max throughput, S = 0.5 e^{-1} or ~ 18% at G = ½**
- **Slotted ALOHA: Max throughput, S = e^{-1} or ~ 36% at G = 1**

- **For Pure ALOHA:**
  - **Stable operation range: 0 < G < 0.5**
  - **Unstable operation range: G > 0.5**
- **For Slotted ALOHA:**
  - **Stable operation range: 0 < G < 1.0**
  - **Unstable operation range: G > 1.0**



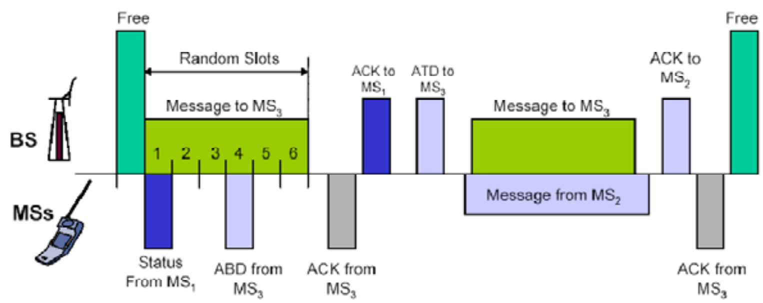
Reservation ALOHA (R-ALOHA)

- R-ALOHA = Slotted ALOHA + TDMA
- Time axis is divided into contention slots + contention-free slots
- MS sends short requests to contend for the upcoming contention-free intervals
- If reservation is successful, MS send its info (usually a much long packet) during the correspond contention-free interval
- Originally: Altair 18-19 GHz – early 1990s



Dynamic Slotted ALOHA - Mobitex

- A version of R-ALOHA
- A mobile can transmit only during certain “free” cycles consisting of equal length slots initiated by the BS after the transmission of “FREE” frame



Packet Reservation Multiple Access (PRMA)

- A scheme to integrate voice (periodic) and low-bit data (non-periodic)
- Once a user acquires a slot it is reserved until it is explicitly released (a NULL packet) – no need for repeated asseveration – efficient for long/continuous bursts
- Protocol can utilize the discontinuous nature of speech – voice activity detector (VAD)
- Details: D. Goodman, S.X. Wei, “Efficiency of Packet Reservation Multiple Access,” IEEE Transaction on Vehicular Technology, Vol. 40, No. 1, February 1991, pp. 170-176.

Reservation in GPRS

- A single 200 kHz carrier – 8 times slots
- Time slot carries
  - 9.6 kb/s (standard),
  - 14.4 kb/s (enhanced), or
  - 21.4 kb/s (for no error coding)
- A maximum bit rate of 8 X 21.4 = 171.4 kb/s
- MAC (Uplink):
  - MS sends reservation request to BS
  - BS sends notification indicating the allocation for an uplink channel
  - MS can transmit data
- MAC (Downlink):
  - BS sends notification to MS indicating allocation on downlink
  - MS monitors that downlink channel for receiving data

CSMA-Based Wireless Random Access Techniques

- Carrier-Sense Multiple Access (CSMA) or Listen Before Talk (LBT) schemes
- Unlike ALOHA-based protocol, users "sense" the channel to determine whether it is free or not
- Reduce chances of collision

Non-persistent CSMA

- Station does not sense channel continuously while it is busy
- If (channel == busy) then wait random time before sensing again
- LABEL: If (channel == idle) {

```
                transmit packet
              }
              else {
                wait random time (backoff)
                when backoff expires Goto LABEL
              }
```


p-persistent CSMA

- Time is divided into slots
- Slot = maximum propagation delay
- If station has info to send

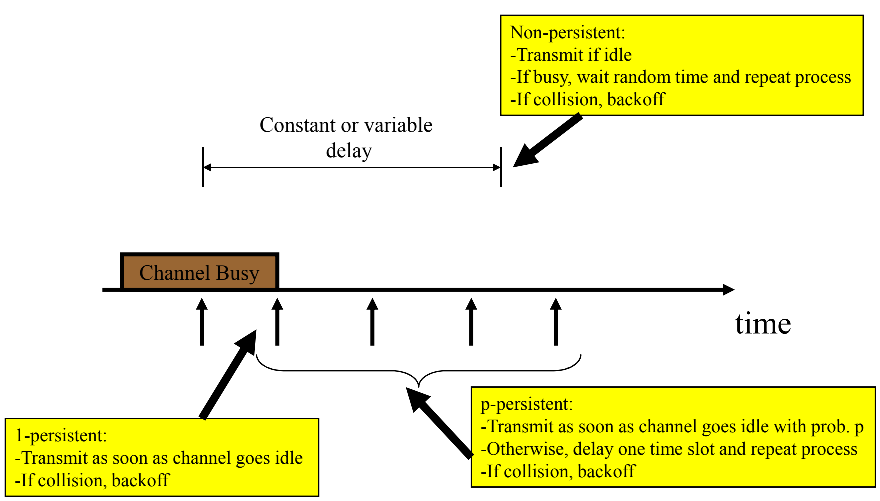
```
 if (channel == idle){
   tx info with probability p
   with probability q = 1-p postpone action till next slot
 }
else{
   continue sensing channel till it becomes free
   start procedure again
}
```

- Algorithm is repeated for next slot

1-persistent CSMA

- A special case of p-persistent
- Info is transmitted as soon as the channel is sensed to be idle
- If an ACK is not received within a specified time:
  - Station waits a random time period
  - Resumes listening to channel to resend info

CSMA Protocols - Summary



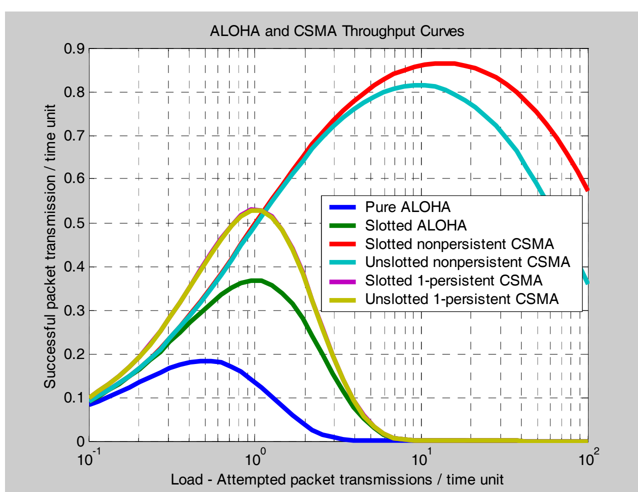
Throughput of CSMA Protocols

- Unslotted Nonpersistent CSMA $$S=\frac{Ge^{-aG}}{G(1+2a)+e^{-aG}}$$
- Slotted Nonpersistent CSMA $$S=\frac{aGe^{-aG}}{1-e^{-aG}+a}$$
- Unslotted 1-Persistent CSMA $$S=\frac{G[1+G+aG(1+G+aG/2)]e^{-G(1+2a)}}{G(1+2a)-\left(1-e^{-aG}\right)+(1+aG)e^{-G(1+a)}}$$
- Slotted 1-Persistent CSMA $$S=\frac{G\left[1+a-e^{-aG}\right]e^{-G(1+a)}}{(1+a)\left(1-e^{-aG}\right)+ae^{-G(1+a)}}$$

a = T_{prop}/T_p
T_{prop} = propagation delay
T_p = packet/frame transmission time

Throughput Figures for CSMA Protocols – cont'd

- For a = 0.01
- How does the performance look like for a ~ 1? What about a >> 1?
- Check the answer in figure 4.19



Delay Analysis for ALOHA

- For a given packet transmission, the overall delay, D, is given by

$$Dp = Tp + Tprop + Tproc + Tack + Tprop, \text{ or}$$
$$Dp \approx Tp + 2Tprop$$

where Tp = time to transmit a packet
Tprop = propagation time
Tack = time to transmit ACK/NACK
Tproc = processing time at the receiver

Let the probability of successful transmission = Ps
Then Probability of needing n successive transmissions to one packet is given by
Prob[n transmission per packet] = $(1\text{-}Ps)^{n-1}Ps$ n=1,2, …
The average number of transmissions needed to deliver one packet, Navg, is given by

Navg = Σ n X Prob [n transmission per packet] for n=1, 2, 3, …
= 1/Ps
Overall average delay per packet is given by

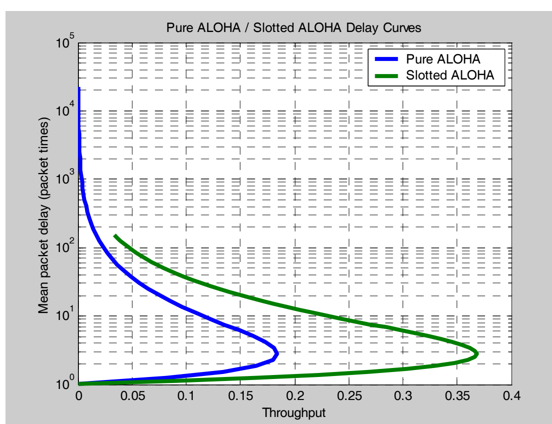
Delay = Navg X Dp = Tp (1+2a)/Ps

Remember (refer to previous ALOHA slides)
For pure ALOHA: Ps = exp(-2G)
For slotted ALOHA: Ps = exp(-G)

Delay Analysis for ALOHA

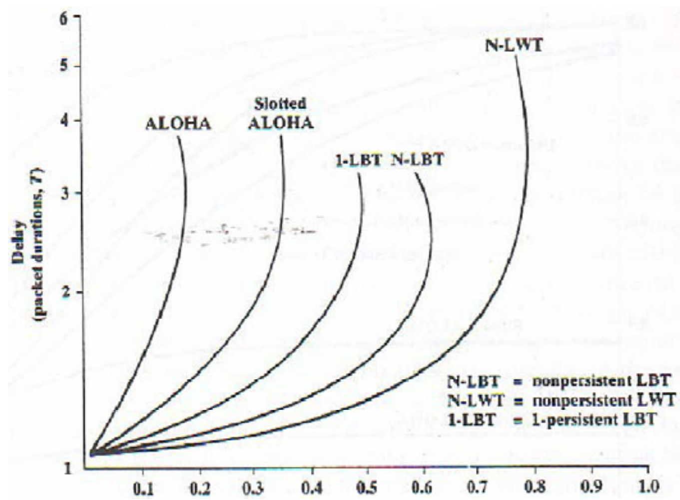
- For pure ALOHA:
- At S = Smax = 18%
- G = 0.5, and
- D = (1+2a) exp(1) = 2.7*(1+2a)

- For slotted ALOHA:
- At S = Smax = 36%
- G = 1, and
- D = (1+2a) exp(1) = 2.7*(1+2a)



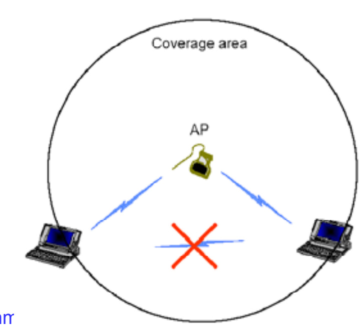
Delay Figure for CSMA Protocols

- Delay Figure



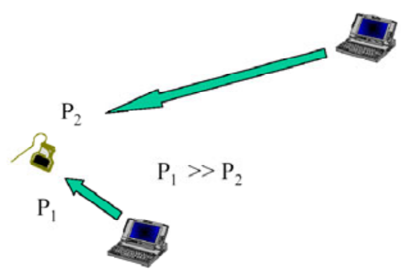
Hidden Terminal Problem

- Two terminals communicating in with one access point (AP)
  - Out of the coverage of each other → can not sense whether the channel is idle or busy
  - Degrades CSMA performance because of increased collisions



Capture Effect

- Collision between packets does not necessarily mean both packets are corrupted – the one arriving at with the highest Eb/No may survive
- The AP detects the packet from the closest station
  - This increases throughput – higher than predicted – why?
- Capture can improve throughput and reduce delay for slotted ALOHA and non-persistent CSMA – See example in book by Pahlavan



Example 1:

- A centralized network providing a maximum of 10 Mbps and services a large set of user terminal with pure ALOHA protocol

a) What is the maximum throughput for network?

b) What is the offered traffic in the medium and how is it composed?

Solution:

a) Smax = 18% ➔ Network throughput = 0.18 X 10 = 1.8 Mbps

b) At S = Smax, G = 0.5,

➔ Offered load = 0.5 X 10 = 5 Mbps

1.8 Mbps of delivered packets

\+ 3.2 Mbps of collided packets

Example 2:

a) Determine the transfer time of a 20 kB file with a mobile data network with a transmission rate of 10 kb/s?

b) Repeat for an 802.11 WLAN operating at 2 Mb/s

c) What is the length of the file that the WLAN of part (b) can carry in the time that mobile data service of (a) carries its 20 kB file?

Example 2: cont'd

a) This file limit is used by ARDIS and Mobitex

Time = 20 (kB) X 8 (b/B) / 10 kb/s = 16.38 seconds

b) An IEEE 802.11 network operating at 2 Mb/s would transfer the file in 20X1024X8/2e6 = 81.9 msec

c) In 16.38 seconds, the IEEE 802.11 WLAN would transfer = 16.38 X 2e6/1024/1024 = 3.9 MB file

CSMA with Collision Detection (CSMA/CD)

- Used for wired LANs
- Adopted in the IEEE802.3 (Ethernet) standard
- Can support up to Giga bits per second
- The MAC protocol
  1) Wait until the channel is idle
  2) Transmit and listen while transmitting
  3) If collision, stop packet, transmit a jam signal, and then wait for a random delay
  4) Goto (1)
- Protocol gives up transmission after 16 attempts

Note: no feedback mechanism for CSMA/CD is required

With 1-persistent

Binary Exponential Back-off

- For a terminal that have collided n (n=1, …,15) successive times:
  - Choose a random number K from set {0, 1, 2, …, 2^m-1}, where m = min(10,n) – uniform distribution
  - Wait for K time slots
  - E.g. after first collision – terminal waits either 0 or 1 time slot – after 2^{nd} collision – terminal waits either 0, 1, 2, or 3 time slots, and so on
- The probability of repeated collisions is reduced significantly
  - **E.g.** What is the probability that two terminals will collide the forth time if they have collided 3 consecutive times?
  - **Soln:** = Prob[both choose the same random number for the 4^{th} time] = 8 X 1/8 X 1/8 = 1/8

CDMA/CD – Performance

- Time slot = 2 X Tprop
- The time which guarantees that all terminals know (receives the jamming signal) of the collision
- By 3 X Tprop – the channel is clear

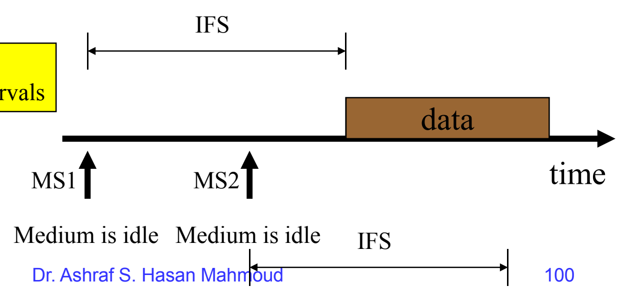
- Efficiency of CSMA/CD ≈ 1/(1+3a) – where a = Tprop/Tframe

Prob[1 terminal transmits] = β = Np(1-p)$^{N-1}$
This probability is maximized if p = 1/N
For large N ➔ Prob[1 terminal transmits] = $\beta \approx$ 0.4
Let A be number of time slots wasted till a successful tx goes through, therefore A = βX0 + (1- β)X(1+A)
➔ A = 1.5
Therefore Efficiency = Tframe/(Tframe + 1.5X2*Tprop), or
= 1/(1+3a)
Actual performance is closer to = 1/(1+5a)

CSMA for Wireless Links

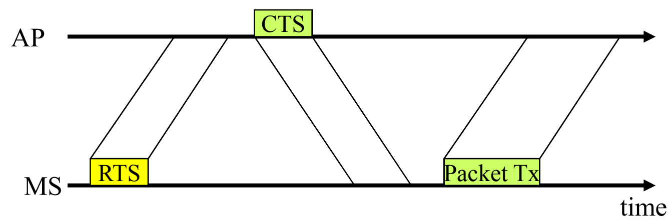
- Collision detection is not possible – Why?
- Collision avoidance is used ➔ CSMA/CA
- Employed by IEEE802.11
  - IFS: Intra-frame spacing – intervals between CWs
  - CW: contention window: contention and tx of packets
  - Backoff counter

Prioritization can be achieved by assigning different IFS intervals



Request-to-Send and Clear-to-Send

- A third alternative for collision avoidance
- Employed by IEEE802.11
- No contention



Integration of Data in Voice Networks

- CDPD: Mobile data over AMPS
  - Overlaid packet data service supporting data rates up to 19.2 kb/s
  - Unused AMPS channels are into random access channels
  - Air-interface and physical layer for CDPD and AMPS are different
- GPRS: Mobile data over GSM
  - Can support up to 170 kb/s
  - Same physical layer as GSM
  - Traffic over GPRS is routed to the packet switched network rather than PSTN

Integration of Data in Voice Networks – Capacity Issues

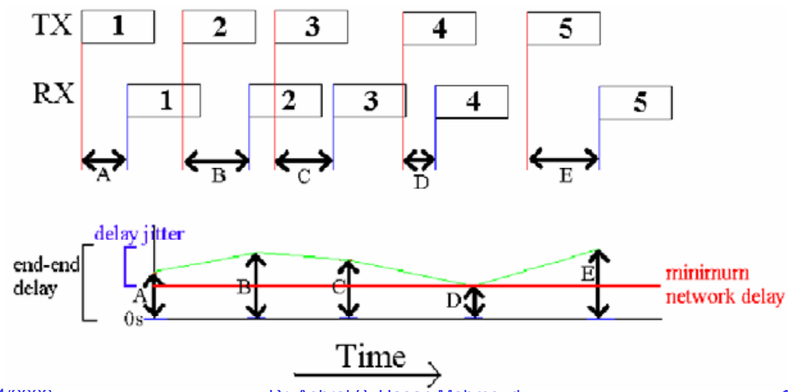
- General approach: dedicate n (n=0, 1, .., c) channels out of c for data use
  - Data traffic can also use the other c-n voice channels when channels are idle
  - Refer to analysis in the book
    - Average active period where a channel is available for data
    - Mean length of blackout period
- For TDMA
  - Movable Boundary TDMA scheme with silence detection

Integration of Voice in Data Networks

- Voice is a synchronous traffic
  - Delay intolerable – voice packets with delay greater than $T_{threshold}$ are useless
  - Delay jitter
    - Receiver my buffer packets to compensate for jitter

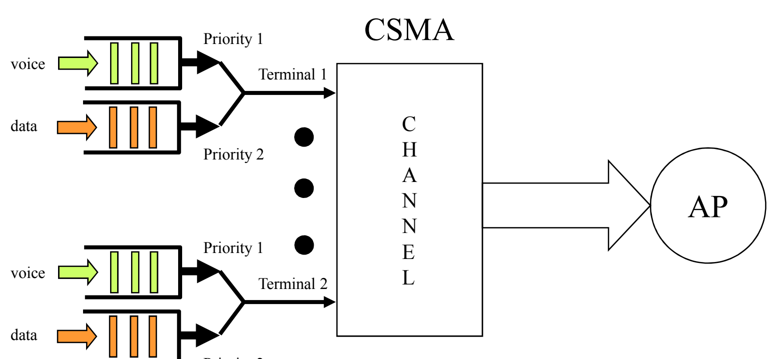
Definition of Delay Jitter

- End-to-End Delay = Minimum Network Delay + Delay Jitter – note packets are transmitted at a constant rate

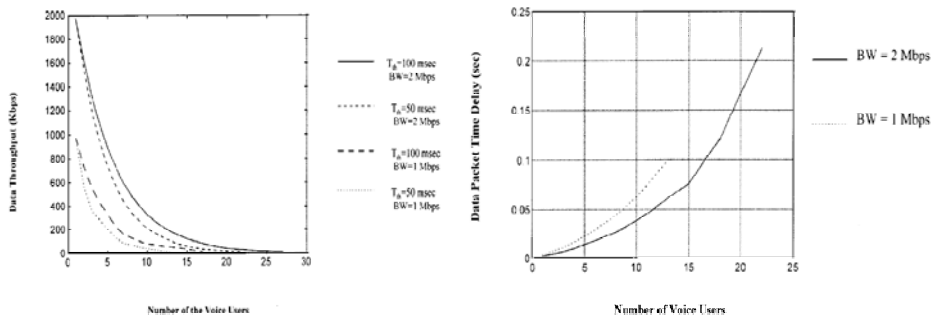


Integration of Voice in Data Networks - Example

- **Source**: A. Zahedi and K. Pahlavan, "Capacity of a wireless LAN with voice and data services," IEEE Transactions of Communications, July 2000, pp.1160-1170.



Integration of Voice in Data Networks



(a) Throughput of data versus number of voice users for variety of thresholds for acceptable delay in voice packets
(b) Data packet time delay versus number of voice users

Source: A. Zahedi and K. Pahlavan, "Capacity of a wireless LAN with voice and data services," IEEE Transactions of Communications, July 2000, pp.1160-1170.

Jitter in VoIP on WLANs

- Objective: to playback the real-time traffic with no jitter (as if CBR)
- Method: use jitter compensation buffer at receiver
- Operations:
  - Packets exceeding delay deadline are dropped
  - Play packet in its slot
  - Reorder packets if needed