Wireless Communications

EEENG 5820

Lecture 9

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Today

- Review of FDMA/TDMA/CDMA
- Packet Radio
- Capacity of Cellular Systems

9.1 Introduction

- **Duplexing**
  - A two-family house
  - To talk and listen simultaneously
  - Simplex, half-duplex, and full duplex

- **FDD**
  - Each user has two distinct bands of frequencies
  - Uplink/Downlink, forward/reverse channel
- **TDD**
  - Each user are allowed to access the channel in assigned *time slots*
  - Each duplex channel has both forward and reverse time slot

9.2 FDMA

- **Each user is allocated a unique frequency band or channel**

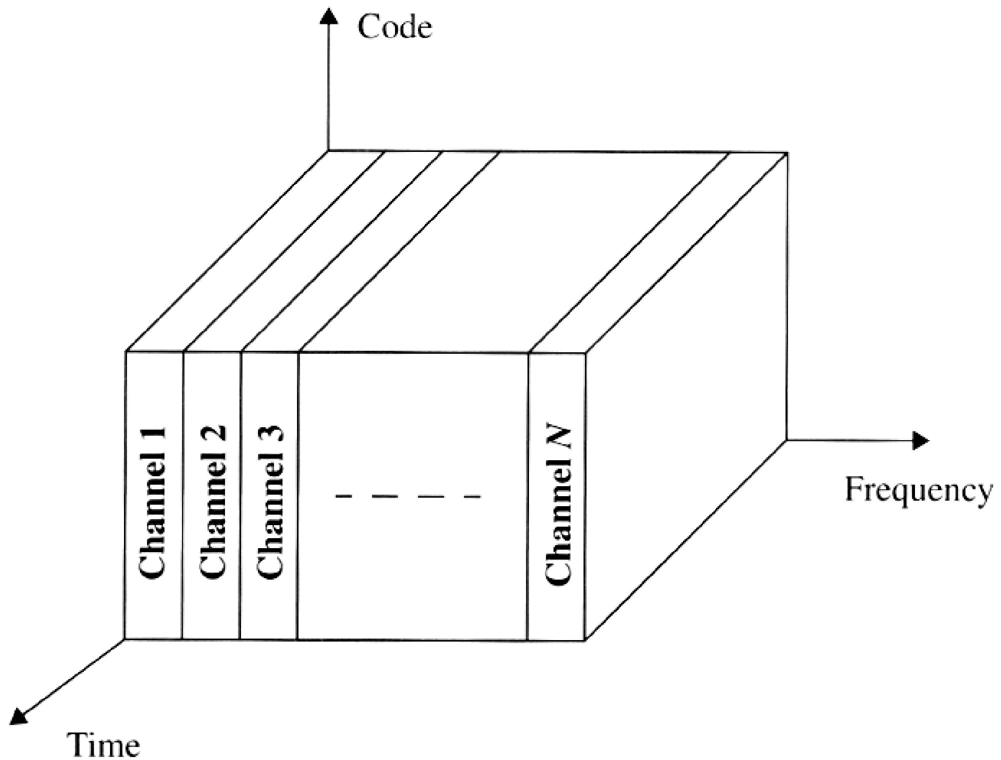


Figure 9.2 FDMA where different channels are assigned different frequency bands.

9.2 FDMA

Features of FDMA

- If an FDMA channel is not in use, then it sits idle and cannot be used by other uses
- Narrow bandwidth (30 kHz in AMPS)
- Complexity of FDMA is lower compared TDMA
- Fewer bits are needed for overhead (synchronization and framing bits)
- Higher cell site system costs, bandpass filters to eliminate spurious radiation at the base station
- Nonlinear effects: signal spreading in frequency domain and generate *inter-modulation* frequencies

9.3 TDMA

- **Divide the radio spectrum into time slots, and in each slot only one user is allowed to either transmit or receive**

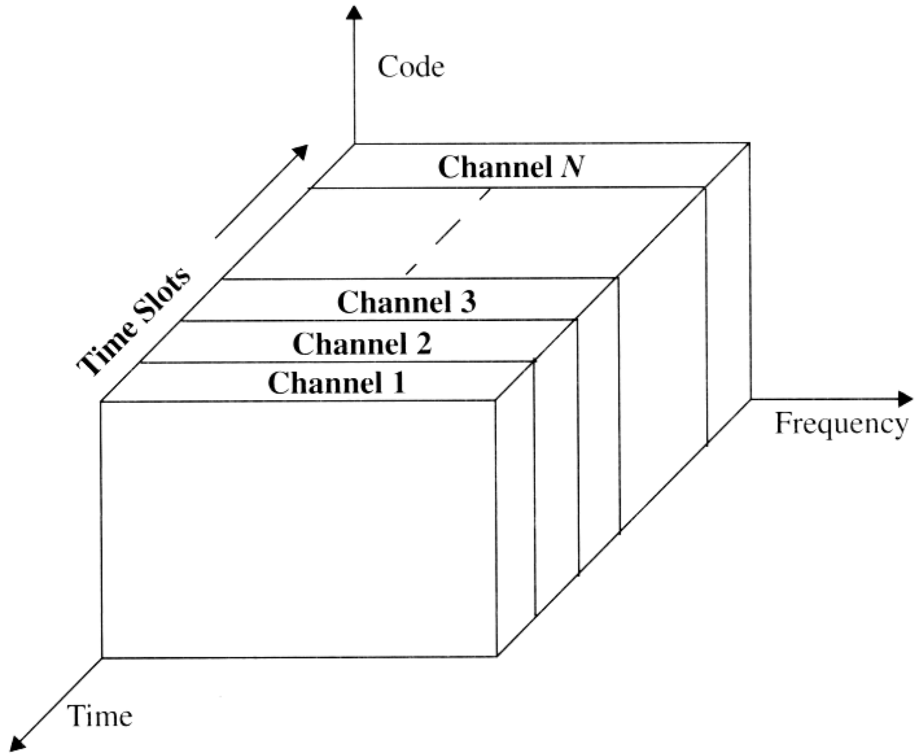


Figure 9.3 TDMA scheme where each channel occupies a cyclically repeating time slot.

9.3 TDMA

- **Features**
  - Data transmission occurs in bursts, not continuous, which results in lower power consumption
  - Simpler handoff since handset can listen on an idle slot (mobile assisted hand off MAHO)
  - Adaptive equalization is needed since the data rate is high
  - High synchronization overhead is required
  - Bandwidth can be a supplied on demand to different users by concatenating or reassigning time slots based on priority

9.4 Spread Spectrum Multiple Access

- SSMA uses signals which have a transmission bandwidth that is several orders of magnitude greater than the minimum required RF bandwidth (IS95, 1.25MHz)
- Frequency Hopped Multiple Access (FH)
- Direct Sequence Multiple Access (DS), also called Coded Division Multiple Access (CDMA)

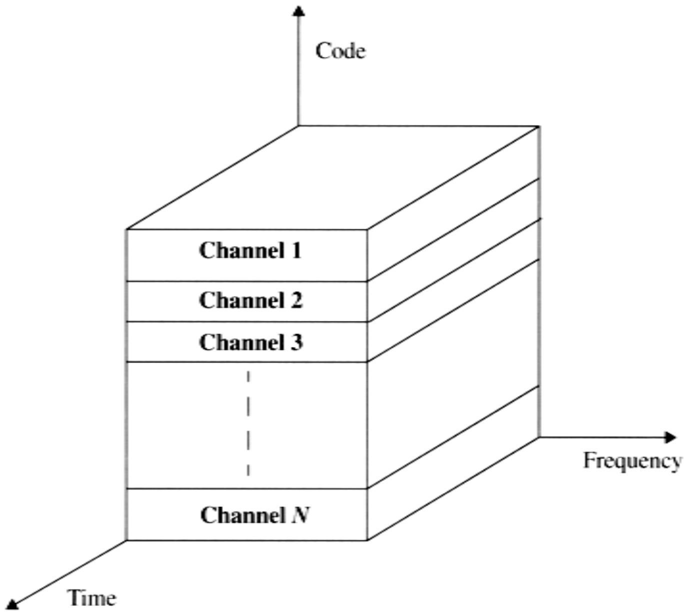


Figure 9.5 Spread spectrum multiple access in which each channel is assigned a unique PN code which is orthogonal or approximately orthogonal to PN codes used by other users.

9.4 Spread Spectrum Multiple Access

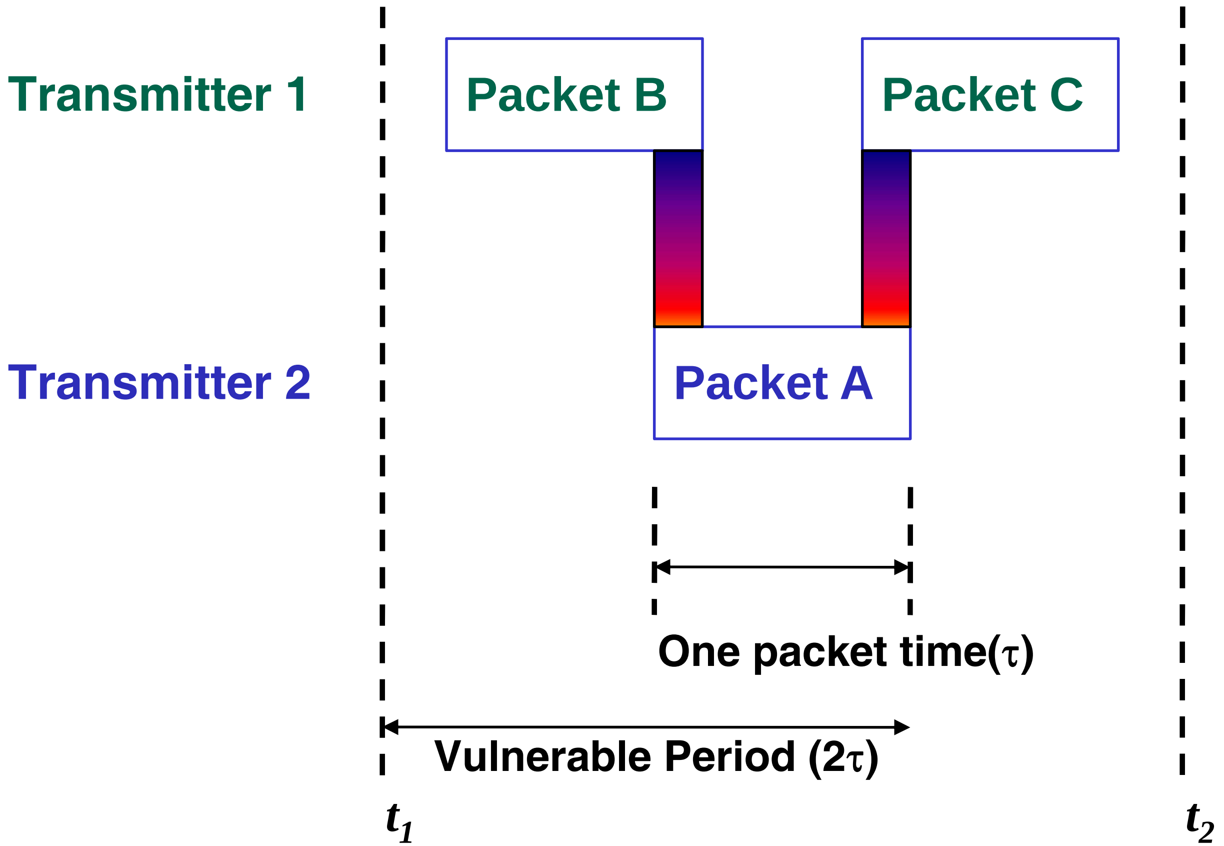
Features

- Soft capacity limit. Increasing the # of users raises the noise floor
- Multipath fading may be substantially reduced because the signal is spread over a large spectrum
- Channel data rates are very high, multipath is delayed by more than a chip (noise), RAKE reciever
- Soft handoff since CDMA uses co-channel cells, MSC choose the best version of the signals
- Near-far problem, power control

9.6 Packet Radio

- **Coordinated v.s. Uncoordinated**
- **ACK/NACK for transmission acknowledgement**
- **Easy to implement**
- **Low spectral efficiency and large delays**
- **ALOHA protocol**
  - Contention techniques
  - To serve a large number of users
  - Evaluated by throughput and delays
- **ALOHA: Hawaiian language – *affection, love, peace*, etc.**
- **Created by *Norman Abramson* et.al. at the University of Hawaii in 1970**

9.6.1 Packet Radio Protocols



If a collision occurs, the user waits a RANDOM amount of time, and then retransmits the packet

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9.6.1 Packet Radio Protocols

Assumption

- All packets have a constant packet length
- Fixed channel data rate
- All users may generate new packets at random time interval
- Packet transmissions occur with a Poison distribution having a mean arrival rate λ of packets per second.

$$P(X = k) = \frac{\lambda^k e^{-\lambda}}{k!} \quad k = 0, 1, 2, \cdots$$

- Packet duration is τ seconds

9.6.1 Packet Radio Protocols

- **Traffic occupancy or throughput**

$$R = \lambda \tau$$

  - R is measured in Erlangs
  - If R>1, then the packets generated by the users exceed the maximum transmission rate of the channel
  - A reasonable throughput: $0 < R < 1$

- **Normalized throughput**

$$T = R \cdot \Pr[\text{no collision}] = \lambda \tau \cdot \Pr[\text{no collision}]$$

- **Probability of *n* packets generated during a *given packet duration***

$$\Pr(n) = \frac{\mathrm{R}^n \mathrm{e}^{-R}}{n!} \qquad \Pr(0) = \mathrm{e}^{-R}$$

9.6.1 Packet Radio Protocols

Contention Techniques

- **Random access:**
  - No coordination among users
  - Messages are transmitted from the users as they arrive at the transmitter
- **Scheduled Access**
  - The users transmit messages within allotted slots or time intervals
- **Hybrid Access**
  - Combination of random access and scheduled access

9.6.1 Packet Radio Protocols

Pure ALOHA

- A user accesses a channel as soon as a message is ready to be transmitted
- In case of collisions (NACK), the terminal waits for a random period of time and retransmits the messages
- Probability of no collision during the interval of 2τ is

$$\Pr(n) = \frac{(2R)^n e^{-2R}}{n!} \quad at \quad n = 0$$

- Throughput

$$T = R \cdot \Pr[\text{no collision}] = \lambda\tau\, e^{-2R} = R\, e^{-2R}$$

9.6.1 Packet Radio Protocols

Slotted ALOHA

- Time is divided into equal time slots of length greater than τ
- Users have synchoronized clocks and transmit a message only at the beginning of a new time slot
- Vulnerable period is only one packet duration

$$\Pr(n) = \frac{(\mathrm{R})^n \, \mathrm{e}^{-R}}{n!} \quad n = 0$$

- Throughput

$$T = R \cdot \Pr[\text{no collision}] = \lambda\tau \, e^{-R} = R\, e^{-R}$$

9.6.1 Packet Radio Protocols

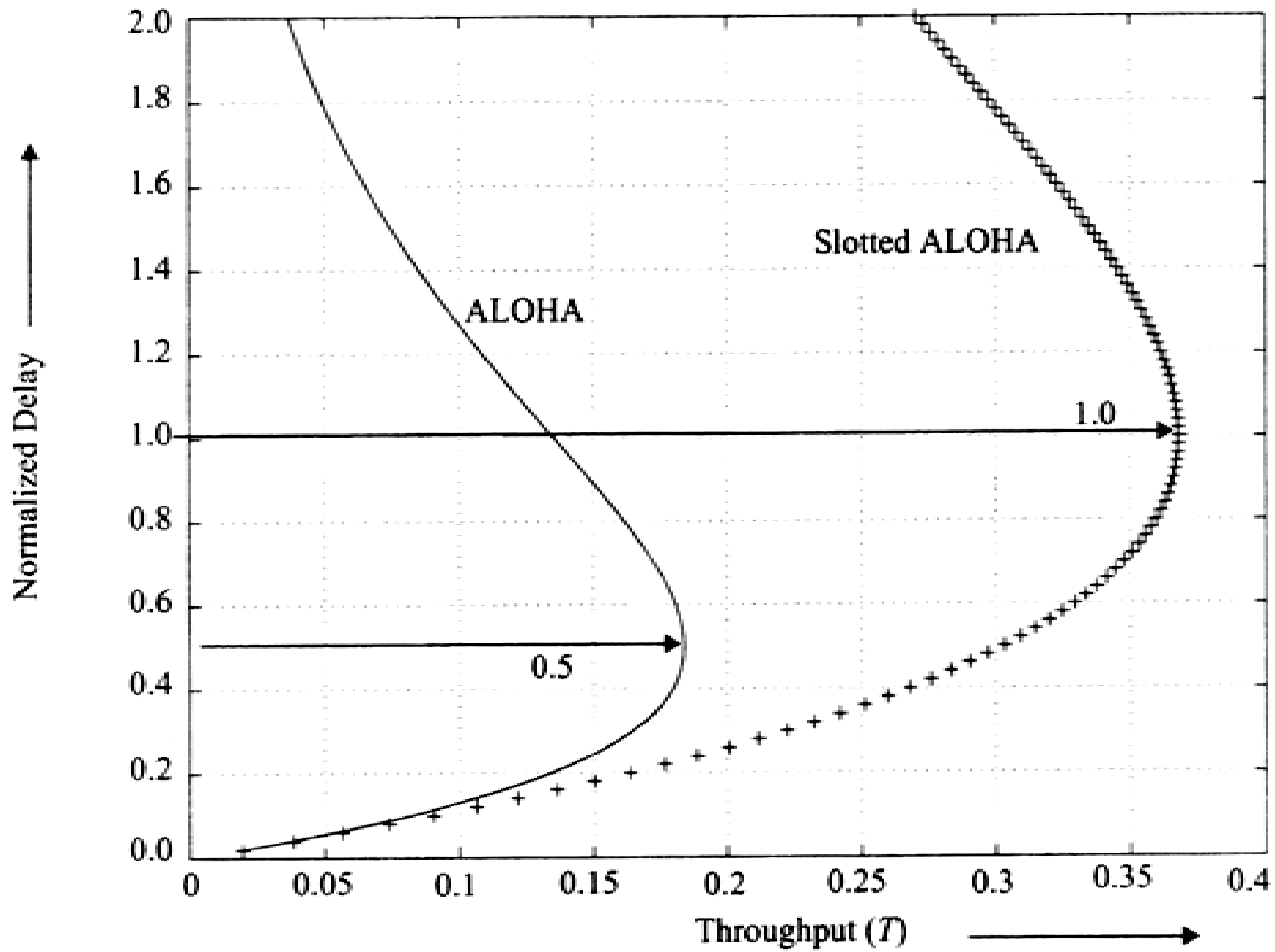

Figure 9.10 Tradeoff between throughput and delay for ALOHA and slotted ALOHA packet radio protocols.

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9.6.1 Packet Radio Protocols

Example: **Determine the maximum throughput for ALOHA and slotted ALOHA**

$$T = \mathrm{R}\mathrm{e}^{-2R} \Rightarrow \frac{dT}{dR} = e^{-2R} - 2\,\mathrm{R}\,e^{-2R} = 0 \Rightarrow R_{\max} = \tfrac{1}{2}$$

$$T_{\max}\Big|_{R_{\max}=1/2} = \frac{1}{2}\mathrm{e}^{-1} = 0.1839$$

$$T = \mathrm{R}\mathrm{e}^{-R} \Rightarrow \frac{dT}{dR} = \mathrm{e}^{-R} - R\mathrm{e}^{-R} = 0 \Rightarrow R = 1$$

$$T_{\max}\Big|_{R_{\max}=1} = \mathrm{e}^{-1} = 0.3679$$

9.6.2 Carrier Sense Multiple Access (CSMA) Protocols

- **ALOHA: no detection of channel before transmission (no exploitation of information of other users)**
- **CSMA: transmission if channel is idle**
  - Detection delay: the time required to sense whether or not the channel is idle
  - Propagation delay: how fast it takes for a packet to travel from base station to mobile terminals (*A → B, when the packet has not reached B, B may send packets*)

9.7 Capacity of Cellular Systems

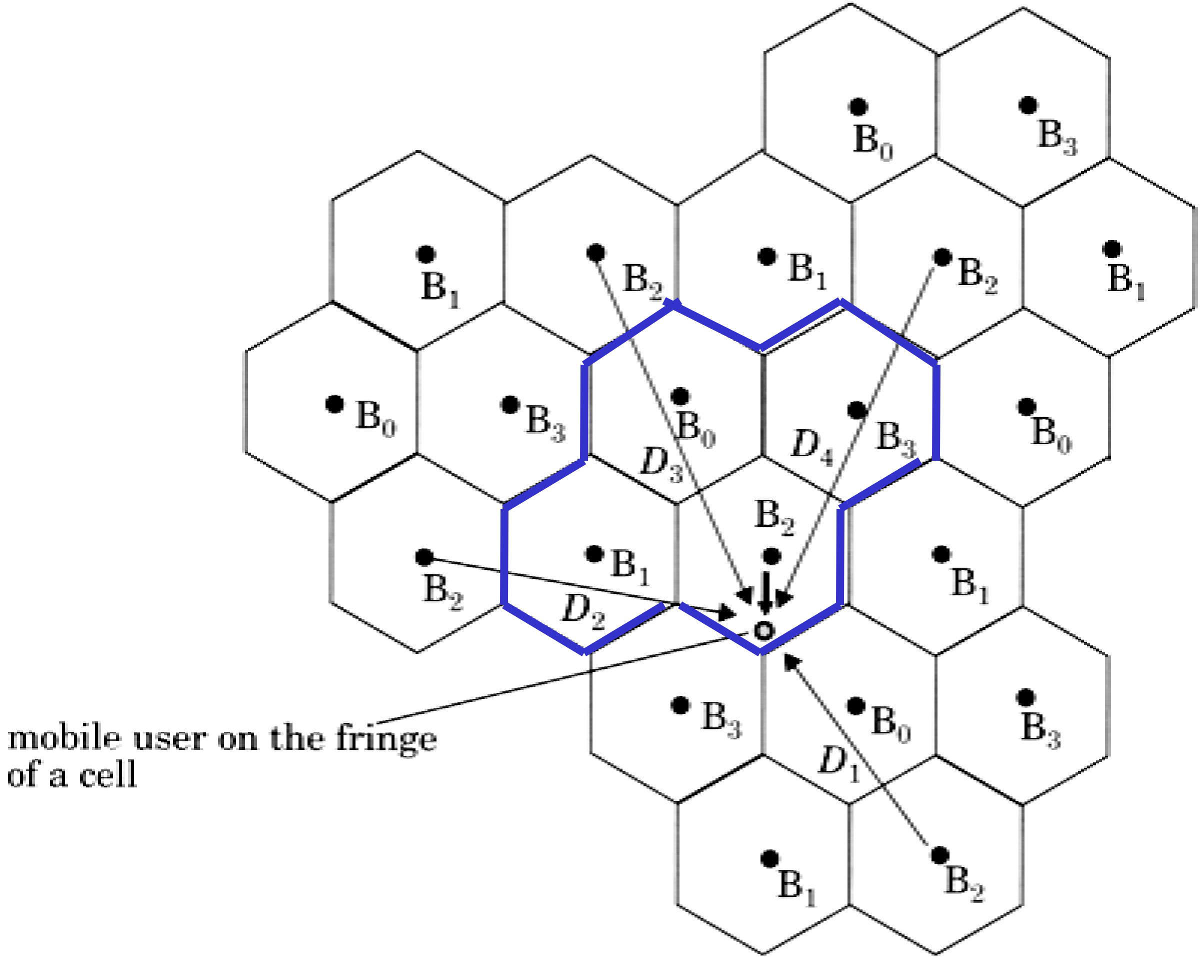

Figure 9.11 Illustration of forward channel interference for a cluster size of $N = 4$. Shown here are four co-channel base stations which interfere with the serving base station. The distance from the serving base station to the user is D_0, and interferers are a distance D_k from the user.

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9.7 Capacity of Cellular Systems

- **Channel capacity: the maximum number of channels or users than can be provided in a fixed frequency band**
  - Required carrier-to-interference ratio (C/I)
  - Channel bandwidth B_c.
- **Carrier-to-interference (C/I)**

$$\frac{C}{I} = \frac{D_0^{-n_0}}{\sum_{k=1}^{M} D_k^{-n_k}}$$

Approximation →

$$\frac{C}{I} = \frac{D_0^{-n_0}}{6D^{-n}}$$

n_k : path loss exponent

9.7 Capacity of Cellular Systems

- **When $D_0=R$, maximum interference, and minimum C/I is $(C/I)_{min}$, then**

$$\frac{1}{6}\left(\frac{R}{D}\right)^{-n} \geq \left(\frac{C}{I}\right)_{min} \xrightarrow{Q = D/R} Q = \left(6\left(\frac{C}{I}\right)_{min}\right)^{-1/n}$$

Radio capacity:

$$m = \frac{B_t}{B_c N} \text{ radio channels/cell} \xrightarrow{Q=\sqrt{3N}} m = \frac{B_t}{B_c \frac{Q^2}{3}} = \frac{B_t}{B_c\left(\frac{6}{3^{n/2}}\left(\frac{C}{I}\right)_{\min}\right)^{2/n}}$$

B_t: total spectrum
B_c: channel bandwidth

9.7 Capacity of Cellular Systems

Note:

- (C/I)min is lower in digital systems than analog system (12 dB for digital system and 18dB for FM)
- To compare different systems, an equivalent $(C/I)_{eq}$ I used. Lower $(C/I)_{min}$ means more capacity

For n = 4

$$m = \frac{B_t}{B_c \sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_{\min}}}$$

$$\left(\frac{C}{I}\right)_{eq} = \left(\frac{C}{I}\right)_{\min} \left(\frac{B_c}{B'_c}\right)^2$$

9.7 Capacity of Cellular Systems

Example: Compare four systems for n=4

- System A: B_c = 30kHz, $(C/I)_{min}$ = 18dB
- System B: B_c = 25kHz, $(C/I)_{min}$ = 14dB
- System C: B_c = 12.5kHz, $(C/I)_{min}$ = 2dB
- System D: B_c = 6.25kHz, $(C/I)_{min}$ = 9dB

Consider: $B_c^{'} = 6.25kHz$

System A: $(C/I)_{eq} = 18 - 20\log(6.25/30) = 31.68dB$

System B: $(C/I)_{eq} = 14 - 20\log(6.25/25) = 26dB$

System C: $(C/I)_{eq} = 2 - 20\log(6.25/12.5) = -4dB$

System D: $(C/I)_{eq} = 9 - 20\log(6.25/6.25) = 9dB$

9.7 Capacity of Cellular Systems

- **Digital cellular systems**

$$\frac{C}{I} = \frac{E_b R_b}{I} = \frac{E_c R_c}{I}$$

R_b: bit rate
R_c: symbol rate

For n = 4

$$\frac{(C/I)}{(C/I)_{eq}} = \frac{(E_c R_c / I)}{(E_c^{'} R_c^{'} / I')} = \left(\frac{B_c^{'}}{B_c}\right)^2$$

R_c and B_c is linear

$$\frac{E_c}{E_c^{'}} = \left(\frac{B_c^{'}}{B_c}\right)^3$$

9.7 Capacity of Cellular Systems

- **For FDMA systems**

$$m = \frac{B_t}{\frac{B_t}{M}\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_{\min}}}$$

$$C = E_b R_b$$

$$I' = I_0 B_c$$

I_0 : Interference per Hertz

- **For TDMA systems**

$$C' = E_b R_b^{'}$$

$$I' = I_0 B_c^{'}$$

I_0 : Interference per Hertz

9.7 Capacity of Cellular Systems

Compare systems.

- FDMA: 3 channels, each is 10kHz, data rate 10kbps
- TDMA: 3 time slots, channel bandwidth 30kHz, data rate 30kpbs

$$C' = E_b R_b' = 3R_b E_b = 3C$$

$$I' = I_0 B_c' = 3I$$

C/I is the same

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9.7.1 Capacity of Cellular CDMA

- **FDMA/TDMA is bandwidth limited**
- **CDMA Is interference limited**
- **Techniques to reduce interference**
  - Multisectorized antenna
  - Discontinuous Transmission Mode (DTX)
    - Voice signals duty: 3/8 in landline networks, ½ for mobile systems

9.7.1 Capacity of Cellular CDMA

- For a single-cell system with power control, all the signals on the reverse channel are received at the same power level at the base station.
- Let the number of users be N, then signal-to-noise ratio is

$$SNR = \frac{S}{(N-1)S} = \frac{1}{N-1}$$

Bit energy-to-noise ratio

$$\frac{E_b}{N_0} = \frac{S/R}{(N-1)(S/W)} = \frac{W/R}{N-1}$$

9.7.1 Capacity of Cellular CDMA

- **Consider the background thermal noise η**

$$\frac{E_b}{N_0}=\frac{W/R}{N-1}\rightarrow\frac{E_b}{N_0}=\frac{W/R}{(N-1)+(\eta/S)}$$

$$N=1+\frac{W/R}{E_b/N_0}-(\eta/S)$$

- **Consider voice activity α or sectorizing**

$$\frac{E_b}{N_0^{'}}=\frac{W/R}{(N_s-1)\alpha+(\eta/S)}$$

Ignoring noise

$$N_s=1+\frac{1}{\alpha}\left[\frac{W/R}{E_b/N_0^{'}}\right]$$

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Homework

- 9.4(a, b), 9.7, 9.10, 9.12, 9.13