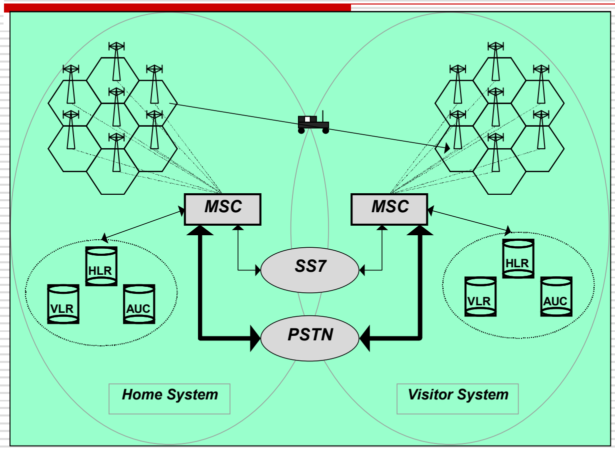
Part #1:
Introduction to Wireless Communication Systems and Networks

Goals:
- Introduce the basic concepts of a Wireless System
- Understand the basic operation of a cellular system
- Present the operation of a simple Wireless System (1G – AMPS)

Disclaimer:

- Engineering is all about tradeoffs
- Every scientific field has its basic assumptions and limitations
- The limitation of Wireless and Mobile System is the Communication Bandwidth …
- … and the tradeoff is between Bandwidth and "Quality of Service"
- What is "Quality of Service"? It depends on the what you communicate.

Wireless Mobility (w/SS7)



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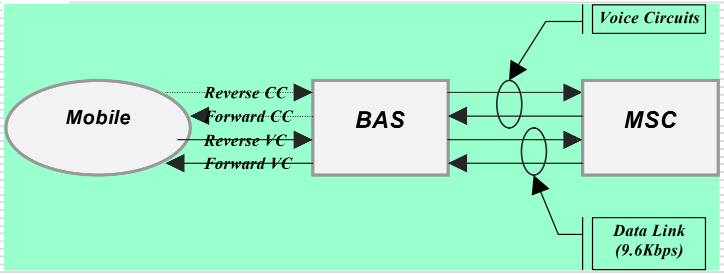
Basic Network Configuration



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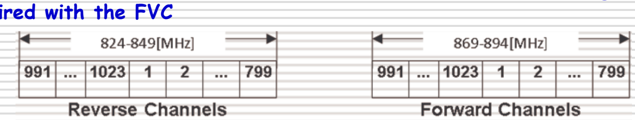
Advanced Mobile Phone System (AMPS)

- Multiple Access: FDMA
- Duplexing Scheme: FDD
- Channel Bandwidth: 30 [kHz]
- Forward Channel Spectrum: 869[Mhz] - 894[MHz]
- Reverse Channel Spectrum: 824[Mhz] - 849[MHz]
- Transmit/Receive frequency spacing: 45[MHz]
- Number of Channels: 666/832
- Channel Reuse: 7
- Base-station coverage radius: 2-25 [km]
- Voice Modulation: FM
- Peak Deviation for VC: +/- 12 [KHz]
- CC Date Rate: 10[Kbps]
- Peak Deviation for CC +/- 8 [KHz]
- Spectral Efficiency: 0.33[bps/Hz]
- Data Coding: BCH (40,28) on FC and BCH (40,36) on RC

AMPS Channelization

- Forward (Downlink) Channels from the Base-Station to the Mobile
- Forward Control Channel (FCC): Broadcast channel. used for subscriber paging and voice channel assignment
- Forward Voice Channel (FVC): Dedicated channel; used for a single call
- Reverse (Uplink) Channels from the Mobile to the Base-Station
- Reverse Control Channel (RCC): Random Access with "sensing" provided by FCC
- Reverse Voice Channel (RVC): Dedicated channel, used for a single call and paired with the FVC



Channel	Channel Number	Center Frequency [MHz]
Reverse Channels	$1 \le N \le 799$	$0.030 \cdot N + 825.0$
	$991 \le N \le 1023$	$0.030 \cdot (N - 1023) + 825.0$
Forward Channels	$1 \le N \le 799$	$0.030 \cdot N + 870.0$
	$991 \le N \le 1023$	$0.030 \cdot (N - 1023) + 870.0$

AMPS Channelization (con't)

- There are two service providers in each market: A band (nonwireline) and B band (wireline).
- The original allocation of 666 channels (A and B bands) included 21 control channels and 312 voice channels for each service provider
- The extended allocation of 832 channels (5 [Mhz] extra allocated by the FCC in 1987) includes 21 control channels and 395 voice channels for each service provider (A, A', A", B, and B' bands).

Reverse Channels

A"	A	B	A'	B'
991-1023	1-333	334-666	667-716	717-799

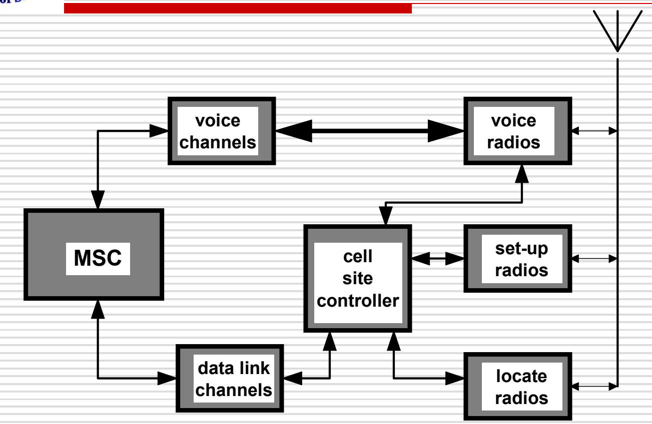
824 825 835 845 846.5 849

Forward Channels

A"	A	B	A'	B'
991-1023	1-333	334-666	667-716	717-799

869 870 880 890 891.5 894

AMPS Base Station Architecture



Basic Call Set-up Procedure: Mobile Initiated Call

MSC	BAS	Mobile
	continuously transmits the setup data on the FCC	
		• scans and locks on FCC • initializes call • seizes RCC • sends service request
	forwards service request	
• selects a VC • sends channel assignment to BAS		
	forwards channel assignment to the mobile (on FCC)	
		• tunes transmitter/receiver to the assigned VC • transmits SAT on the RVC
	• detects SAT • sends confirmation message to MSC	
completes call through the PSTN		

Note: The example follows the (now obsolete) AMPS air-interface.

Basic Call Set-up Procedure: Network Initiated Call

MSC	BAS	Mobile
	continuously transmits setup data on FCC	
		scans and locks on the strongest FCC
• incoming call is received • returns audible ring to the caller • sends paging message to the cells		
	• reformats the paging message • sends the paging message on the FCC	
		• detects the page • seizes RCC • sends service request
	forwards service request to MSC	
• selects VC • sends channel assignment to the BAS		
	forwards channel assignment to the mobile (on FCC)	
		• tunes transmitter/receiver to the assigned VC • transmits SAT on the RVC

con't ...

Note: The example follows the (now obsolete) AMPS air-interface.

Basic Call Set-up Procedure: Network Initiated Call (con't)

MSC	BAS	Mobile
	• detects SAT • sends alert to mobile on FVC	
		• alerts user • sends ST on RVC
	detects ST	
		• user answers • stops ST on RVC
	• detects absence of ST • sends answer message to MSC	
• receives answer message • stops audible ring to the caller • completes connection through the PSTN		

Note: The example follows the (now obsolete) AMPS air-interface.

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Part #2:
Intro to Wireless Communication Systems

Goals:
- Introduce the fundamental concepts of a Wireless System
- Understand the basic operation of a cellular system
- Present the operation of a simple Wireless System (1G - AMPS)
- Discuss the basic terms used in the field of Wireless Systems
- Introduce a number of Enabling Technologies

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- Engineering is all about tradeoffs
- Every scientific field has its basic assumptions and limitations
- The limitation of Wireless and Mobile System is the Communication Bandwidth …
- … and the tradeoff is between Bandwidth and "Quality of Service" (QoS)
- What is "Quality of Service"? It depends on the what you communicate.

Voice	Data
Real time (low delay)	Delays are acceptable
Sensitive to jitter	Insensitive to jitter
Some errors allowable	Errorless communication
Constant bit rate	Variable bit rate ⇒ burstiness

- Are there any other consideration beyond bandwidth and QoS? … of course!
- Many … for example: cost, operational flexibility, design/operation complexity, advanced features, etc
- An additional consideration is the "type" of communication system ...
- Other limitations of Mobile System are:
  - Energy/Power (limited by battery technology)
  - Processing (limited by processing complexity)
  - Size (limits certain physical processing; e.g., frequencies, MIMO, etc)

Elements of a Wireless Cellular System

- Communication Type
  - Simplex
  - Half Duplex
  - (Full) Duplex
- Channels:
  - Type
    - Control Channels
    - Voice/Data/Traffic Channel
  - Direction:
    - Forward (downlink)
    - Reverse (uplink)
- Paging and Registration Operations

Elements of a Wireless Cellular System

- The cellular infrastructure supports mobility management through the SS7 system.
- A mobile maintains air link with a *BAse-Station (BAS)* through a *Common Air Interface (CAI).*
- Base-stations are connected to a *Mobile Switching Center (MSC)* through air or land lines. MSC was also referred to in the past as *Mobile Telephone Switching Office (MTSO).*
- Mobility Management addresses two operations: *handoff* (also known as *handover* and *ALT*) and *roaming.*
- 2G and above systems use the *MAHO (Mobile Assisted Handoff),* in which the network makes the handoff decision based on the measurements of the signal strength of adjacent base stations.
- There are two protocols that support mobility management: EIA/TIA Interim Standard 41 (IS-41 or ANSI-41) and Global Systems for Mobile Communications (GSM) Mobile Application Part (MAP).

Elements of a Wireless Cellular System

- MSC controls the following functions: call setup, call transfer, billing, interaction with PSTN, etc. It uses the SS7 for that purpose.
- In particular, MSC utilizes the SS7 signaling network to validate location and to deliver calls for roamers. To do so, it uses three databases: *Home Location Register (HLR), Visitor Location Register (VLR), and Authentication Center (AUC).*
- HLR, VLR, and AUC may or may not be located in close proximity to the MSC.
- HLR is used to register the current location of a mobile. It is updated through the *Registration Process.*
- VLR is used to record the roamer in a specific system. It is also updated through the *Registration Process.*
- AUC is used authenticate a roamer to the network to ensure that the user is eligible to receive the requested services.
- There are three main functions associated with Mobility Management: *Roaming, Registration,* and *Routing*

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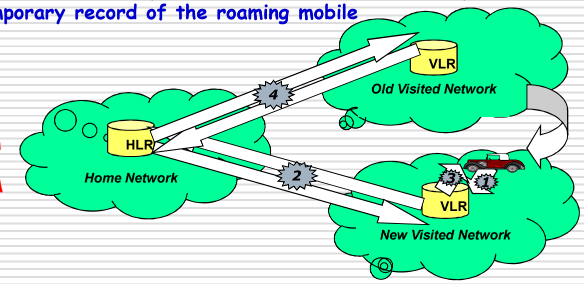
Cellular System Elements: Registration

- Roaming involves registration and mobile location tracking.
- Roaming involves *two-level* strategy in which the mobile registers with its HLR with information such as directory number, profile information, current location, and validation period.
- Upon roaming into a visited system, the VLR of the visited system creates a temporary record of the roaming mobile

The Registration Process (IS-41 and GSM MAP)



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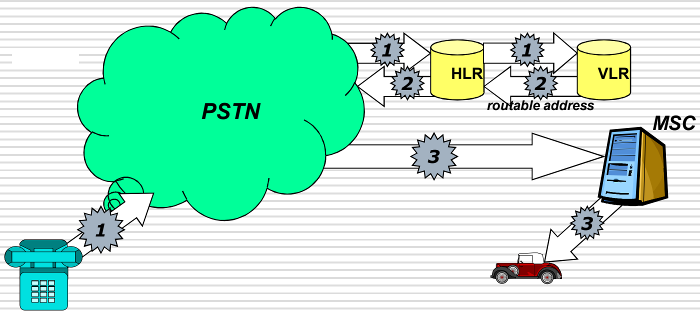
Cellular System Elements: Call Routing



Note: the *PSTN originating switch* can query the HLR or, if not capable of doing so, the call is routed to the home MSC.

Elements of a Wireless Cellular System

- Communication Type
  - Simplex
  - Half Duplex
  - (Full) Duplex
- Channels:
  - Type
    - Control Channels
    - Voice/Data/Traffic Channel
  - Direction:
    - Forward (downlink)
    - Reverse (uplink)
- Paging and Registration Operations

Let's look at the design of one (very) simple cellular system – the 1G AMPS

To update or not to update?

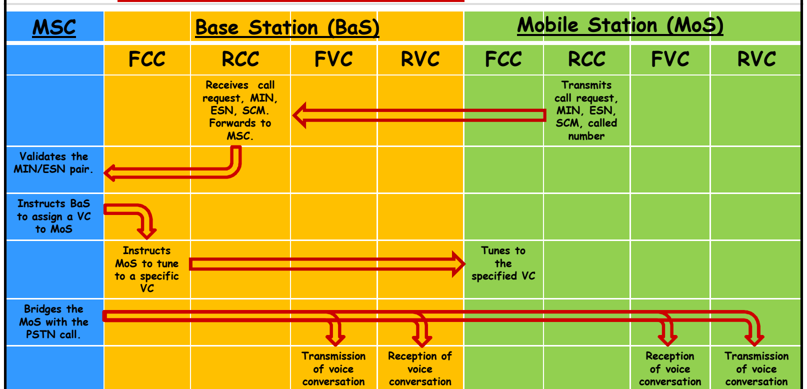
An (old) research question – how often to register?

- If there were no registration, the MSC would not know where the mobile is. So registration is required. But too frequent registration wastes resources.
- If the MSC does not know the particular cell that the mobile currently resides in, then when a call arrives, the MSC pages all the cells. This may be costly in resources if calls arrive frequently.
- So, there is some <u>optimal</u> registration frequency, as to minimize the resources.
- This optimal registration frequency depends on:
  - Frequency of call arrivals
  - Mobility
  - Cost of a page relative to cost of a registration
- We will discuss this in more details later in the course.

Call Set-up Procedure: Network Initiated Call

MSC	Base Station (BaS)				Mobile Station (MoS)			
	FCC	RCC	FVC	RVC	FCC	RCC	FVC	RVC
Receives a call from PSTN. Broadcasts MIN to all BaS-s.								
	Pages for the MIN user				Receives the MIN			
		Receives MIN, ESN, SCM. Forwards to MSC.				Confirms receipt of MIN. Sends ESN + SCM.		
Validates the MIN/ESN pair.								
Instructs BaS to assign a VC to MoS								
	Instructs MoS to tune to a specific VC				Tunes to the specified VC			
Bridges the MoS with the PSTN call.			Transmission of voice conversation	Reception of voice conversation			Reception of voice conversation	Transmission of voice conversation

Call Set-up Procedure: Mobile Initiated Call



SCM = Station Class Mark

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Part #3:

Introduction to Wireless Communication Systems and Networks: Enabling Technologies

Goals:
- Review basic terms used in the field of Wireless Systems
- Introduce a number of Enabling Technologies
- Discuss the evolution of Wireless Systems and Networks

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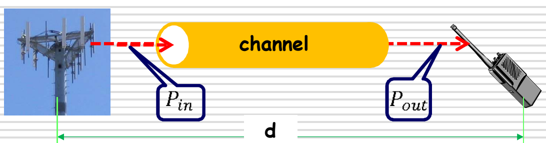
Units … and more units



dB units are also used to express attenuation/amplification

$$dB = 10 \cdot log \frac{P_{in}[W]}{P_{out}[W]} = 10 \cdot log \frac{P_{in}[mW]}{P_{out}[mW]}$$

So, if some signal has X [dBm] power and is transmitted through a channel that attenuates Y [dB], then the received signal is: (X-Y) [dBm]. (If Y<0, then we understand it to be attenuation and we would calculate the received signal as (X+Y) [dBm].)

$$dBW = 10 \cdot log \frac{P[Watt]}{1[Watt]}$$

$$dbm = 10 \cdot log \frac{P[mW]}{1[mW]}$$

Frequency Division Multiplexing

- The total spectrum is divided into separate, non-overlapping frequency channels.
- Channels are assigned to users for the duration of a call; i.e., during the call in progress, a channel is dedicated to that pair of users. When the call terminates, the channel can be reassigned to another pair of users.
- FDMA is used in nearly all first-generation radio systems and many second generation systems as well.
- Example; 1G AMPS system: There are total of 832 full duplex channels. Each full duplex channel consists of two bands of 30 KHz width each, separated by exactly 45 MHz. Out of these channels, 42 are control channels and the rest are voice channels.
- Communication from the base-station to a subscriber is called a forward link and from a subscriber to its base-station a reverse link.

Frequency Division Multiplexing (con't)

- To estimate the required number of channels to support some user population, the design takes into the account: the required *quality of service,* the average call duration, the traffic intensity, and the call activity factor.
- The *quality of service* is usually the percentage of blocked and dropped calls.
- *Erlang-B* formula (blocked calls cleared) is routinely used to perform these calculations:

$$E(\Gamma,N)=\frac{\Gamma^N/N!}{\sum_{i=0}^{N}\Gamma^i/i!},$$

where Γ is the total offered load, N is the number of channels, and is the probability of call being blocked.

- For example, the Public Switched Telephone Network (PSTN) system is designed for 1% blocked calls, while the Cellular Phone System is designed for 2% blocking probability. Advanced wireless systems are expected to provide 1% blocking.

Frequency Division Multiplexing (con't)

- The design of channelized access (such as FDMA) usually relies on the *truncking efficiency*, also called *channel group efficiency.* Due to the *truncking efficiency*, larger pool of available channels can serve larger user population with the same quality of service (and the channel utilization is higher).
- For example, consider two cases: a pool of 15 channels and a pool of 45 channels. When designed for 1% blocking probability, the 15-channel pool can support, on the average, 8 calls (at 53% occupancy), while the 45-channel pool can support, on the average, 33 calls (at 73% occupancy).

Note: The example follows the (now obsolete) AMPS air-interface.

Time Division Multiplexing

- Time Division Multiple Access allows multiple users to share the same frequency band by multiplexing their transmissions in time; i.e., time is divided into non-overlapping-in-time slots. These time slots are assigned to calls.
- Note that the signaling rate is equal to the sum of all the data rates of all the multiplexed transmissions. Thus the bandwidth of the frequency band needs to be wide enough to accommodate this aggregated rate.
- In practice, the total spectrum is divided into frequency channels (FDM) and each frequency channel is further divided in time by TDMA. Thus, the access scheme is often termed FDM/TDMA.
- Practically, to avoid overlapping between transmissions in adjacent slots, some guard time is included in every slot. The overlap can be created by imperfect synchronization or uncompensated differences in delays between different mobiles and the base-station.

Time Division Multiplexing (con't)

- TDMA is used in many second/third generation systems, such as IS-54/136, GSM, etc.
- For example, in IS-136, the original 30 KHz AMPS channels are subdivided into 6 time slots each. Since data rate of each slot is 8 Kbps, the total data rate of a 30 KHz channel is 48 Kbps.
- To accommodate 8 Kbps coded speech and overhead, 16 Kbps per user is required. Thus, each user uses two slots per frame (1 and 4, 2 and 5, 3 and 6). Consequently, the capacity of IS-136 is three times that of AMPS.
- Further improvements in voice coding would require 4 KHz, which with overhead can be accommodated in a single slot per frame. Consequently, IS-136 would improve the capacity of AMPS by six times.

Code Division Multiplexing

- Code Division Multiple Access (CDMA) allows multiple users to share the same frequency band at the same time by multiplexing their transmissions in the code space. In other words, different transmissions are encoded with orthogonal codes and, thus, can coexist at the same time on the same frequency band.
- As the cross-correlation between any two codes is very low (ideally zero), the destinations can retrieve the transmissions by correlating the received signal with the appropriate code.
- CDMA is implemented through the use of *Spread Spectrum* techniques. Developed initially for military applications, Spread Spectrum spread the power of a signal over a bandwidth that is considerably larger than the signal's bandwidth. The spreading is done using one of the orthogonal codes.

Code Division Multiplexing (con't)

- The features of the CDMA technique, useful for military communications are:
  - The resulting spectral density is considerably smaller than the original one ⇨ this can be used to hide the signal
  - After decoding, the power density of a narrow-band interferer (intentional or not) is very small ⇨ this can be used for anti-jamming protection
  - After decoding, because of small cross-correlation between different codes, transmission encoded with different code appears as noise ⇨this can be used to multiplex a number of transmissions on the same channel (i.e., multiple access scheme)
- Spread Spectrum can be done using several schemes; e.g., *Direct Sequence (DS)* or *Frequency Hopping (FH).* We will concentrate here mainly on the DS technique.

Code Division Multiplexing (con't)

- The noise-like interference among the different CDMA transmissions, limit the number of users that can concurrently use the same CDMA "channel." The quality of service determine this number of users.
- Note, in CDMA a "channel" is defined as a spectral bandwidth that is shared among many users.

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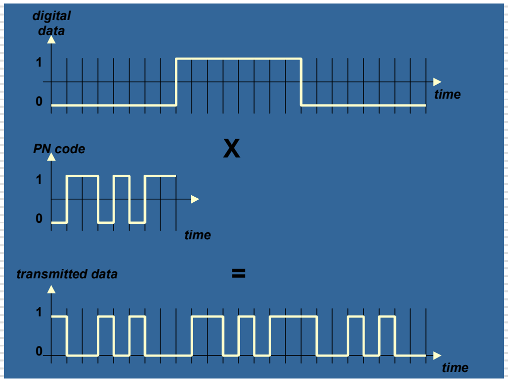
Code Division Multiple Access

Direct Sequence Spread Spectrum (DSSS) – Spreading



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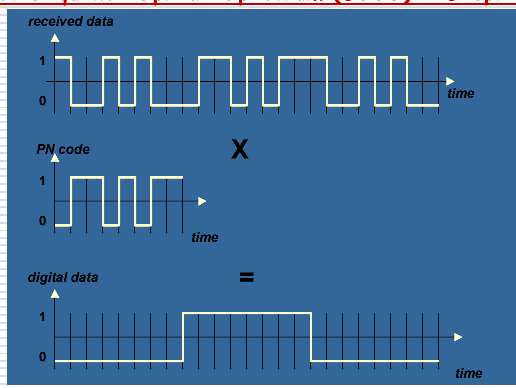
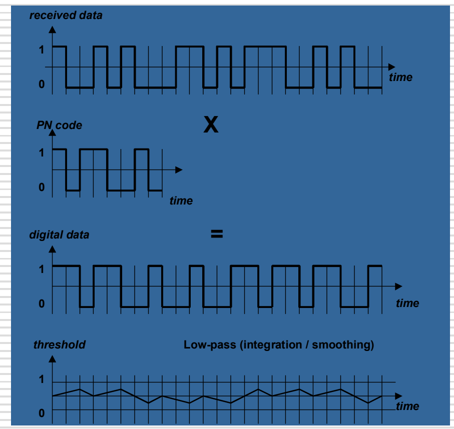
Code Division Multiple Access

Direct Sequence Spread Spectrum (DSSS) - Despreading

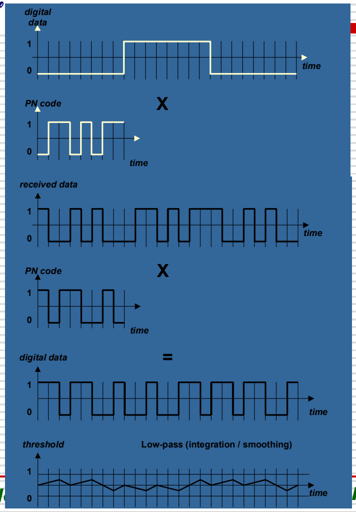


Code Division Multiple Access



DSSS - Rejection of Orthogonal Transmissions

Code Division Multiple Access



DSSS – Rejection of Orthogonal Transmissions

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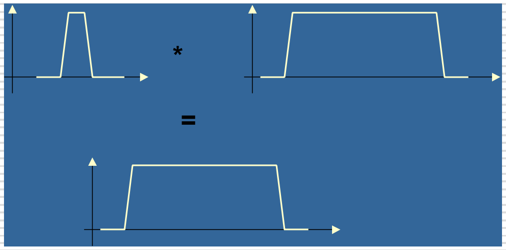
Code Division Multiple Access

Direct Sequence Spread Spectrum (DSSS) – Spectral View



Multiplication in time domain → Convolution in frequency domain

In DS, the narrowband signal is multipled by a wideband pseudonoise (PN code) signal. Multiplication in the time domain translates to convolution in the spectral domain. Thus, the resulting signal is wideband.

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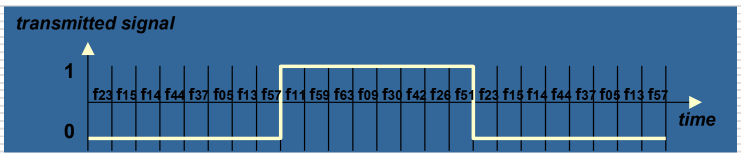
Code Division Multiple Access

CDMA using Frequency Hopping (FH)



In FH, the carrier frequency rapidly hops among a large set of poassible frequencies according to some pseudorandom sequence (the code). The set of frequencies span a large bandwidth. Thus, the bandwidth of the transmitted signal appears as largely spread.

Advantages vs. Disadvantages of CDMA

Advantages

* Flexible system design: can accommodate variable traffic load with temporal quality of service degradation
* Statistical multiplexing: taking advantage of idle connections (such as speed activity factor)
* Interference is based on the average, rather than peak, energy level
* Provides good discrimination from interfering transmissions
* Reuse of 1: no channel assignment (reassignment) required
* Support for *Soft Handoffs*
* Improved performance in a multipath environment (the capture effect and rake-type receivers)
* Coexistance with other wireless technology (such as mocrowave – especially with B-CDMA)
* Some limited degree of security due to the Spread Spectrum technique

Advantages vs. Disadvantages of CDMA

Disadvantages

- Requires code (PN sequence) synchronization and tracking
- Requires (adaptive) power control to eliminate the near-far problem
- Potential interference problems (especially in N-CDMA) due to sharing the broad spectrum of CDMA

Spread Spectrum Multiple Access

- Transmissions from "other users" (with orthogonal codes) are seen as noise.
- A receiver needs to know the code that a transmission was encoded with to be able to decode the message. (Some limited security is provided by the Spread Spectrum technique.)
- To decode the signal, for example, the received signal is slid along a local replica of the PN code.
- Thus, Spread Spectrum allows multiple users to share the same channel.
- Processing Gain (PG) is defined as:

$$\text{Processing Gain} = \frac{\text{Bandwidth of the spread signal}}{\text{Bandwidth of the original signal}}$$

Spread Spectrum Multiple Access

- The PG indicates the amount of improvement in the Signal-to-Interference Ratio (SIR) resulting from spreading the signal bandwidth
- Assume that the original pulse duration is *n* times the chip duration. Thus the PG equals *n*.
- For example, if the chip bit-rate is 1 Gbps and the signal is 10 Mbps, then the PG =100 or 20 dB.

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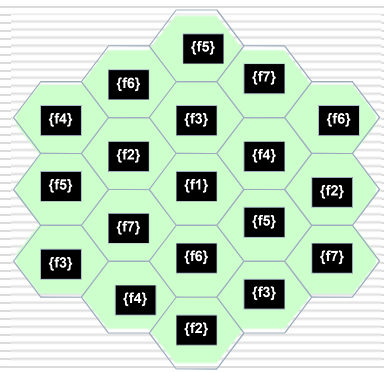
Part #4:
Generations of Wireless Systems
The Cellular Principle

Goals:
- Introduce the Cellular Principle
- Present the basics of Cellular Network design tradeoffs

Intro to the Cellular Principle

Maximum number of simultaneous calls = total number of channels (e.g., 350)

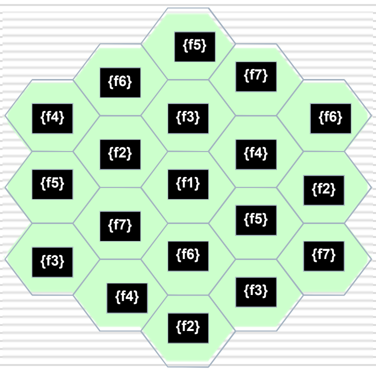
Intro to the Cellular Principle



Divide the area into "zones" and allow to <u>reuse</u> the channels among zones!!! Let's refer to "zones" as "cells."

E.g., divide the 350 channels into 7 sets {fi}, i=1,…,7, and assign one such set to each cell. Reuse the set in "sufficiently distant" cells.

Intro to the Cellular Principle



In our example, if each set is reused 3 times, the overall capacity is increased by the factor of 3 ! … We can now accommodate 3x350=1050 calls.

$$\sum_j n_j \quad (e.g., = 3\cdot 7\cdot 50 = 3\cdot 350)$$

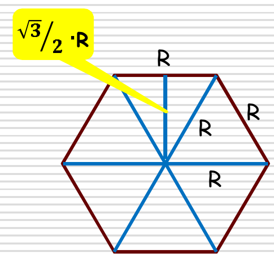
Intro to the Cellular Principle

- **Advantages of Cellular Systems**
  - Increased capacity
  - Lower transmission power
  - Better coverage (more "predictable" propagation environment)
  - Larger reliability (more robust system)
- **Disadvantages of Cellular Systems**
  - Interference from "co-channel" cells
  - Handoffs/Handovers
  - Network of base-stations
  - More "hardware" and larger right-of-way costs
  - Congestion in "hot spots"
- **Design Choices**
  - Cluster formation (reuse pattern, cell sizing, etc)
  - Channel reuse and allocation schemes
  - Handoff schemes
  - Power control schemes

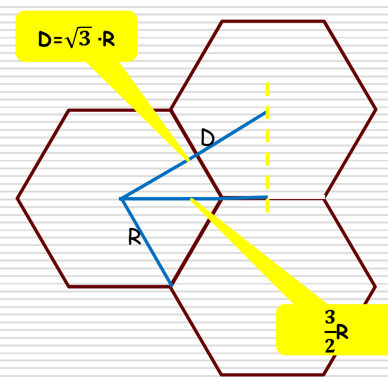
Cellular System Modeling

- The actual coverage of the radiation pattern is highly irregular and is influenced by various effects, such as terrain topology, man-made structure, atmospheric conditions …
- Cells are modeled as hexagons, to describe continuous coverage. (The cells shape should approximate the "radiation pattern" of an omni-directional antenna, which we assume to be a circle. We use hexagons, as the largest polygon that still tessellate a plane.)
- The cell size (the so called, macro-cell) can vary from 0.5 mile in metropolitan areas to 10 miles in rual areas.
- Note that the "hexagonal" pattern is created by the location of base-stations.

Hexagonal Geometry

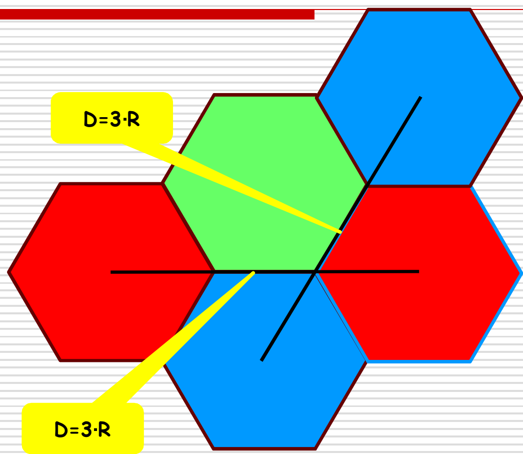


$$Area = 6 \cdot \frac{\sqrt{3}}{2} R \cdot \frac{R}{2} = \frac{3\sqrt{3} \cdot R^2}{2}$$



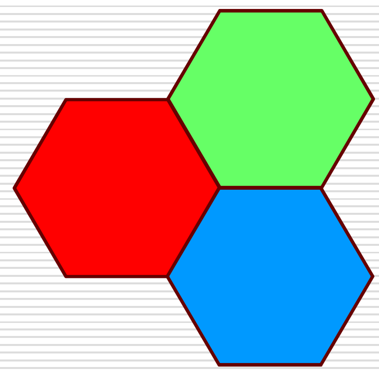
Hexagonal Geometry

$N = 3$



Hexagonal Geometry

$N = 3$



Hexagonal Geometry

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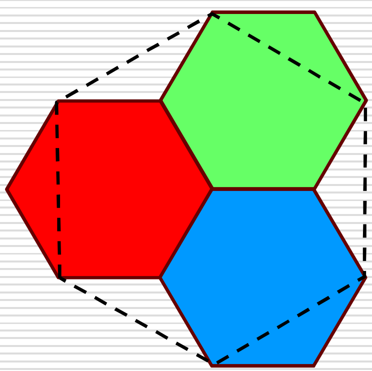

Hexagonal Geometry

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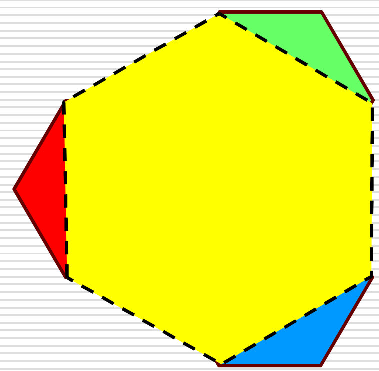

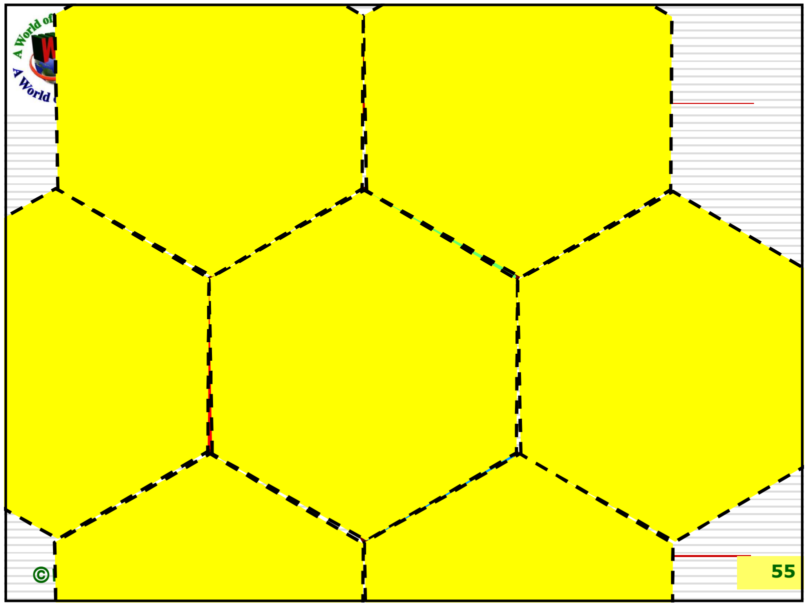
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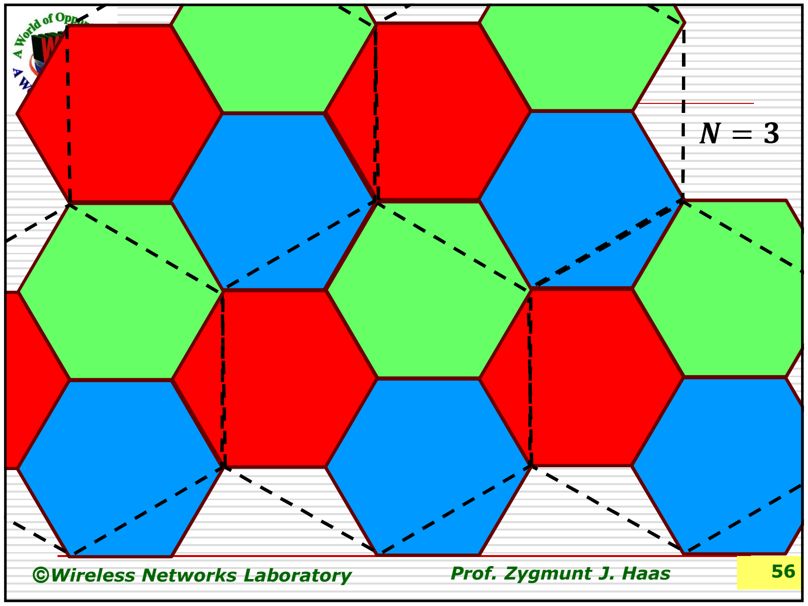
N = 3
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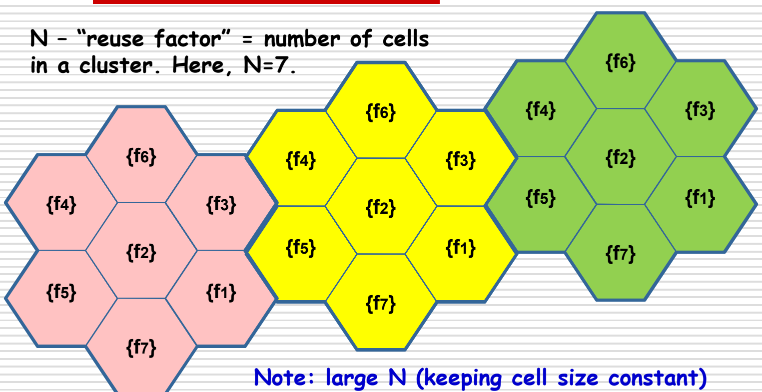
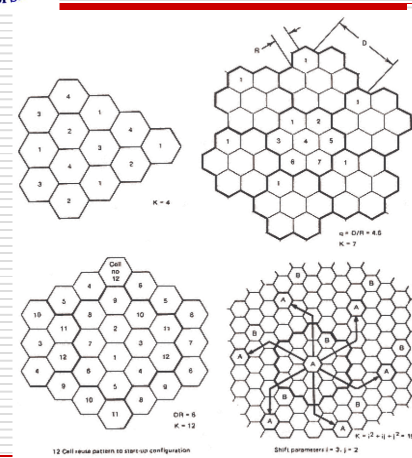
The Cellular Principle – Cluster Formation

N – "reuse factor" = number of cells in a cluster. Here, N=7.



Note: large N (keeping cell size constant)
→ less capacity, but also
→ less interference … Why?

The Cellular Principle – Cluster Formation



I.e., to ensure plane tessellation, clusters are modeled as hexagons too.

To ensure plane tessellation:

$$N = i^2 + ij + j^2$$

where $i, j = 0,\ 1, 2, \cdots$

The Cellular Principle – Cluster Formation

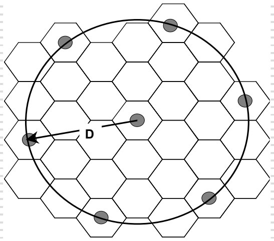
$N = i^2 + ij + j^2$

$Q \equiv \frac{D}{R} = \sqrt{3N}$

i, j	Cluster Size (N)	Co-channel Reuse Ratio (Q)	
i = 1, j = 1	3	3	
i = 1, j = 2	7	4.58	
i = 2, j = 2	12	6	
i = 1, j = 3	13	6.24	

The Cellular Principle – Cluster Formation

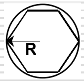
In hexagonal geometry, for any N, each cell has exactly 6 co-channel cells in the first tier.



The co-channel distance, D, depends on N:

$D = R\sqrt{3N}$ or

$Q \equiv \frac{D}{R} = \sqrt{3N}$



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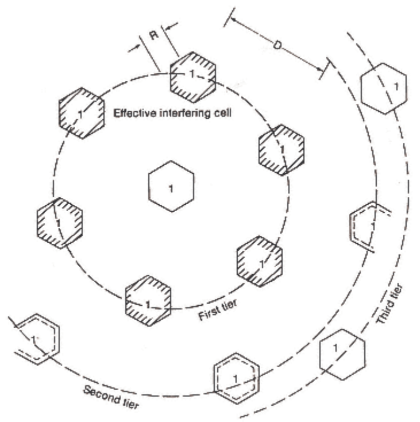

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The Cellular Principle – Cluster Formation

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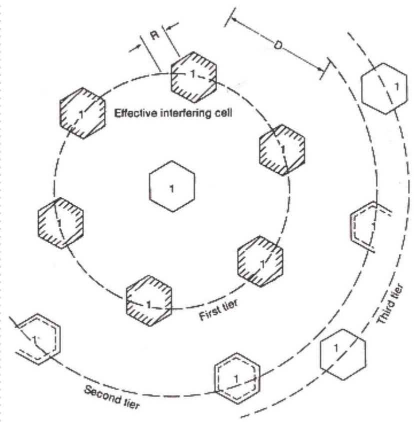

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The Cellular Principle – Co-channel Interference

- $(C/I)_{downlink}$ is the received Carrier-to-Interference ratio at the (desired) mobile receiver
- $(C/I)_{uplink}$ is the received Carrier-to-Interference ratio at the(desired) base station (uplink)
- Note: the two are not (necessarily) the same
- $(C/I)_{downlink} = \frac{Power_{signal}}{\sum_{all\,interferers} I} = \frac{P_{transmit}/R^{\gamma}}{\sum_{all\,interferers} P_{transmit}/d^{\gamma}} = \frac{1}{6}\left(\frac{d}{R}\right)^{\gamma} = \frac{1}{6}Q^{\gamma}$,

  where we assumed that:
  1. The transmit powers of the mobile and all the base stations (desired and interfering) are the same.
  2. All the interfering base stations are at equal distance, d, from the mobile in question.
  3. Neglecting the interference from non-first-tier interferers.
  4. The mobile is at the "worst case" position.
  5. $Q \equiv \frac{d}{R}$, where R is the cell radius

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The Cellular Principle – Cluster Formation

$N = i^2 + ij + j^2$ $\quad Q \equiv \frac{D}{R} = \sqrt{3N}$ $\quad (S/I)_{downlink} = \frac{1}{6} Q^{\gamma}$,

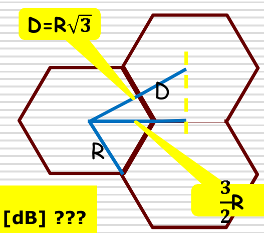
i, j	Cluster Size (N)	Co-channel Reuse Ratio (Q)	$SIR = (S/I)_{downlink}$ $(\gamma = 4)$
i = 1, j = 1	3	3	$\frac{1}{6} 3^4 = 13.5 = 11.3[\text{dB}]$
i = 1, j = 2	7	4.58	$\frac{1}{6} 4.58^4 = 73.3 = 18.7[\text{dB}]$
i = 2, j = 2	12	6	$\frac{1}{6} 6^4 = 216 = 23.3[\text{dB}]$
i = 1, j = 3	13	6.24	$\frac{1}{6} 6.24^4 = 252.7 = 24[\text{dB}]$

The Cellular Principle – Cluster Formation

$N = i^2 + ij + j^2$ $\quad Q \equiv \frac{D}{R} = \sqrt{3N}$ $\quad (S/I)_{downlink} = \frac{1}{6} Q^{\gamma}$,

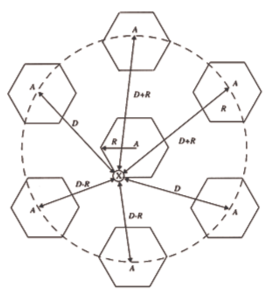
If $i = 0, j = 1 \rightarrow N = 1 \rightarrow Q = \sqrt{3} \rightarrow D = R\sqrt{3}$; i.e., the co-channel cells are adjacent cells. Is this possible?

Yes. Using CDMA, adjacent cells can use the same "channel", but …



$SNR = \frac{1}{6}\left(\frac{D}{R}\right)^{\gamma} = \frac{1}{6}\left(\frac{\sqrt{3}}{2}\right)^{\gamma}$ ≈0.09=-10.3 [dB] ???

Co-channel Interference – More Accurate Calculation



$$SIR \equiv \frac{S}{I} = \frac{P_t/R^{\gamma}}{2\,P_t/(D-R)^{\gamma} + 2\,P_t/R^{\gamma} + 2\,P_t/(D+R)^{\gamma}}$$

$$SIR = \frac{R^{-\gamma}}{2(D-R)^{-\gamma} + 2R^{-\gamma} + 2(D+R)^{-\gamma}}$$

$$SIR = \frac{1}{2(Q-1)^{-\gamma} + 2Q^{-\gamma} + 2(Q+1)^{-\gamma}}$$

Part #5:
Capacity Improvement in Cellular Systems

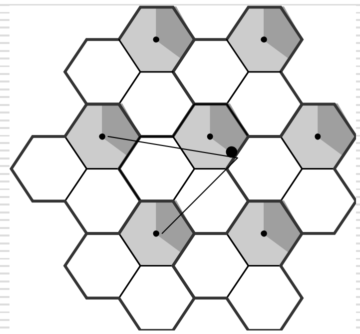
Goals:
- Present various schemes for capacity improvement
- Introduce the basic concepts of Traffic Engineering

Disclaimer:

Improving Capacity and Reducing Interference

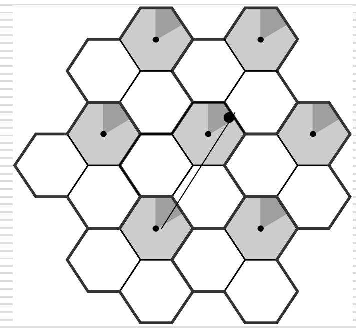
- Note that there is a close correspondence between the network capacity (expressed by N) and the interference conditions (expressed by *S/I)*.
- Capacity can be increased and interference can be reduced by:
  - Cell sectoring
  - Cell splitting
  - Cell sizing (micro-cellular networks, pico-cellular, nano-cellular)
- Cell sectoring reduces the interference by reducing the number of co-channel interferers that each cell is exposed to. For example, for 60 degrees sectorization, only one interferer is present, compared to 6 in omidirectional antennas.
- But, cell sectorization also splits the channel sets into smaller groups, reducing the trunking efficiency.
- Cell splitting allows to create more smaller cells. Thus, the same number of channels is used for smaller area. For the same prob. of blocking, more users could be allocated.

Improving Capacity and Reducing Interference



3-sector cells

$$({}^{S}/_{I})_{downlink} = \frac{1}{2}Q^{\gamma}$$

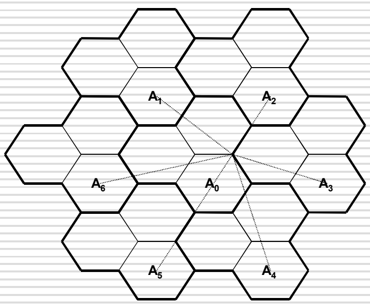


6-sector cells

$$({}^{S}/_{I})_{downlink} = Q^{\gamma}$$

Sectoring – An example

No Sectoring **N=3**



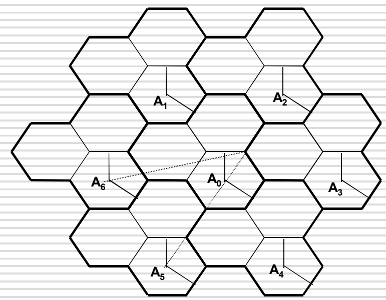
Interferer	ΔX	ΔY	Distance
A1	$2R$	$R\sqrt{3}$	$R\sqrt{7}$
A2			$2R$
A3	$2.5R$	$R\sqrt{3}/2$	$R\sqrt{7}$
A4	R	$R\sqrt{3}$	$R\sqrt{13}$
A5			$4R$
A6	$3.5R$	$R\sqrt{3}/2$	$R\sqrt{13}$

$$\left(\frac{S}{I}\right)_{rec} = \frac{P_t \cdot R^{-\gamma}}{P_t \cdot \left[(\sqrt{7}\,R)^{-\gamma} + (2R)^{-\gamma} + (\sqrt{7}R)^{-\gamma} + (\sqrt{13}\,R)^{-\gamma} + (4R)^{-\gamma} + (\sqrt{13}R)^{-\gamma}\right]} = \frac{1}{2\cdot(\sqrt{7})^{-\gamma} + 2\cdot(\sqrt{13})^{-\gamma} + 2^{-\gamma} + 4^{-\gamma}}$$

$$\left(\frac{S}{I}\right)_{rec} = 9.24\ dB$$ (assuming γ=4)

Sectoring – An example

120^0 Sectoring **N=3**



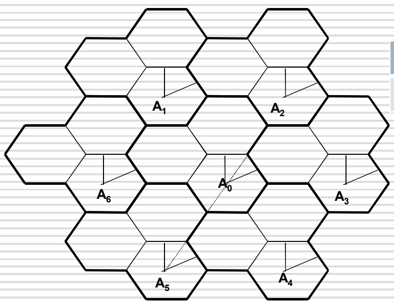
Interferer	ΔX	ΔY	Distance
A5			$4R$
A6	$3.5R$	$R\sqrt{3}/2$	$R\sqrt{13}$

- There are two potential "worst-case" locations of the mobile; on the cell circumference and on the "edge" of the sector lines.
- Consideration of both of the locations reveals that the worst-case condition is as marked in the figure above.

$$\left(\frac{S}{I}\right)_{rec} = \frac{P_t \cdot R^{-\gamma}}{P_t \cdot \left[((\sqrt{13})R)^{-\gamma} + (4R)^{-\gamma}\right]} = \frac{1}{(3.61)^{-\gamma} + (4)^{-\gamma}}$$

$$\left(\frac{S}{I}\right)_{rec} = 101.8 = 20.1dB$$ (assuming γ=4)

Sectoring – An example



60^0 Sectoring N=3

Interferer	ΔX	ΔY	Distance
A5			$4R$

- By properly orienting the antennas (sectors), as shown below, the number of first tier co-channel interferers can be reduced to one.

$$\left(\frac{S}{I}\right)_{rec} = \frac{P_t \cdot R^{-\gamma}}{P_t \cdot \left[(4 \cdot R)^{-\gamma}\right]} = (4)^{\gamma}$$

$$\left(\frac{S}{I}\right)_{rec} = 256 = 24.08dB$$ (assuming γ=4)

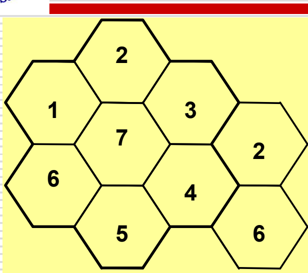
Sectoring – An example

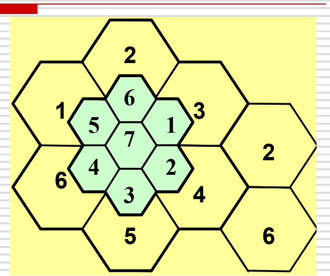
N=3 γ=4

Case	# Sectors per Cell	# of Interferers	SIR
No Sectoring	1	6	9.24 [dB]
120° Sectoring	3	2	20.1 [dB]
60° Sectoring	6	1	24.08 [dB]

- But what about capacity ?
- As N remains the same, the number of channels per cell remains the same.
- However, now these channels are partitioned into groups (equal to the number of sectors. How does this affect the capacity ?

Improving Capacity and Reducing Interference





- Advantages of cell splitting:
  - more capacity
  - only local redesign of the system
- Disadvantages:
  - more handoffs
  - increased interference levels
  - more infrastructure

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Microcellular/Picocellular/Nanocellular Systems - Cell Sizing

- To allow more capacity, the size of the cells are scaled down.
- Since the quality of service (S/I) depends only on the ration (D/I), the performance (i.e., interference level) is uneffected by the scaling.
- However, the same number of channels can now be used in a smaller area (i.e., larger user density), increasing the total number of concurrent users. The increase is as $1/\alpha^2$, where α is the scaling factor.
- Smaller cells also imply less transmitted power - thus smaller and lighter handsets are possible.
- However, smaller cells also imply:
  - more infrastructure
  - larger handoff rate (☹).

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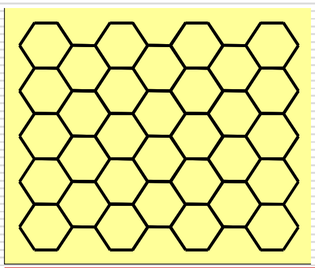
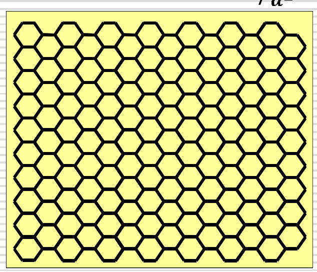
Microcellular/Picocellular/Nanocellular Systems - Cell Sizing – An Example

Case I:
Cell radius=1 [mile]
Number of cells = 32
Number of channels=336
Reuse factor=7
⇨48 channels per cell
⇨1536 concurrent calls

Case II:
Cell radius=0.5 [mile] ($\alpha = 0.5$)
Number of cells =128
Number of channels=336
Reuse factor=7
⇨48 channels per cell
⇨6144 concurrent calls $1/\alpha^2$





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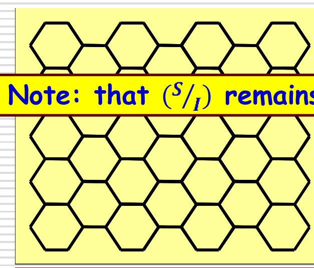

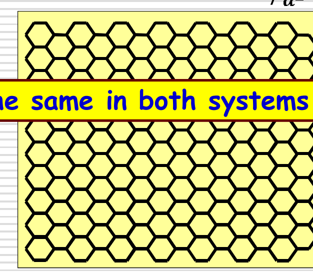

Note: that (S/I) remains the same in both systems !

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Erlang-B Formula

- To estimate the required number of channels to support some user population, the design takes into the account: the required quality of service, the average call duration, the traffic intensity, and the call activity factor.
- The quality of service is usually the percentage of blocked and/or dropped calls.
- Erlang-B formula (blocked calls cleared) is routinely used to perform these calculations. The formula allows to calculate the Probability of Blocking as a function of Number of Servers and the Traffic Load :

$$P_b(\Gamma, N) = \frac{\Gamma^N / N!}{\sum_{i=0}^{N} \Gamma^i / i!}$$

where Γ is the total offered load, N is the number of servers (channels), and $P_b(\Gamma, N)$ is the probability of call being blocked.

Traffic Engineering and Erlang-B Formula

- What is the offered load, Γ ?
- It is the "workload" that enters the system, where:

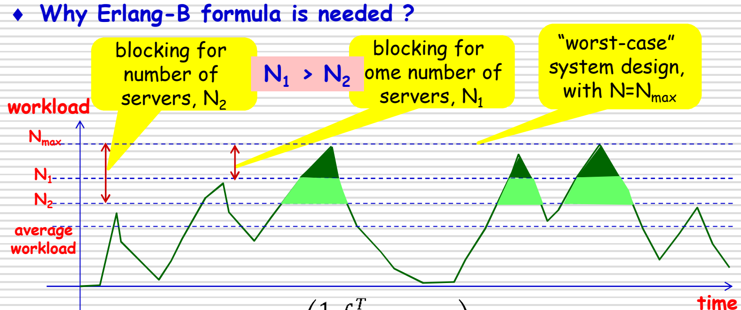
$$workload \equiv \lambda \cdot \tau,$$

where λ is the average call arrival rate [calls/time] and τ is the average call duration time [time/call].

- Note that workload (and, thus, Γ) are unit-less. However, we use units of [Erlangs] to denote workload.

"Blocked Calls Cleared"

- **Why Erlang-B formula is needed ?**



$$average\ load = \lim_{T\to\infty}\left(\frac{1}{T}\int_0^T load \cdot dt\right)$$

Note: As $N_1 > N_2$, $P_b(N_1) < P_b(N_2)$. The closer P_b gets to 0, the "larger" is the required increase in N.

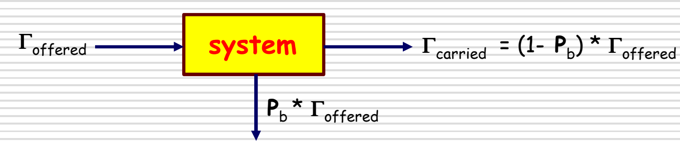
Erlang-B Formula and Trunking Efficiency

- **For example, the Public Switched Telephone Network (PSTN) system is designed for 1% blocked calls, while the Cellular Phone System is designed for 2% blocking probability. The PCS systems typically provide 1% blocking.**
- **The design of channelized access (such as FDMA) usually relies on the <u>truncking efficiency</u>, also called <u>channel group efficiency</u>. Due to the truncking efficiency, larger pool of available channels can serve larger user population with the same quality of service (i.e., the channel utilization is higher).**
- **For example, consider two cases: a pool of 15 channels and a pool of 45 channels. When designed for 1% blocking probability, the 15-channel pool can support, on the average, 8 calls (at 53% occupancy), while the 45-channel pool can support, on the average, 33 calls (at 73% occupancy). (See example that follows.)**

Erlang-B Traffic Tables
Maximum Offered Load vs. N and P_b

N/P_b	0.01%	0.1%	1%	2%	5%	10%	20%	40%
1	0.0001	0.0010	0.101	0.204	0.526	0.1111	0.2500	0.6667
2	0.0142	0.0458	0.1526	0.2235	0.3813	0.5954	1.000	2.000
5	0.4520	0.7621	1.361	1.657	2.219	2.881	4.010	6.596
8	1.422	2.051	3.128	3.627	4.543	5.597	7.369	11.42
10	2.260	3.092	4.461	5.084	6.216	7.511	9.685	14.68
20	7.701	9.412	12.03	13.18	15.25	17.61	21.64	31.15
30	14.25	16.68	20.34	21.93	24.80	28.11	33.84	47.74
40	21.37	24.44	29.01	31.00	34.60	38.79	46.15	64.35
50	28.87	32.51	37.90	40.26	44.53	49.56	58.51	80.99
100	69.27	75.24	84.06	87.97	95.24	104.1	120.6	164.3

Offered vs. Carried Load



When $P_b \ll 1$, $\Gamma_{carried} \approx \Gamma_{offered}$.

Trunking Efficiency – An example

In this problem, we will demonstrate the concept of trunking efficiency.

a. What is the average total carried load (in Erlangs) that 15 trunks can support with blocking probability of 1% ?
b. What is the average total carried load (in Erlangs) that 45 trunks can support with blocking probability of 1% ?
c. Using a. and b., explain the concept of trunking efficiency.

Solution

a) 15 trunks, $P_b = 1\%$

From the Erlang-B Traffic Tables, we find that the offered load for the system is:

$\Gamma_{offered} = 8.11$ [Erlangs]

$\Gamma_{carried} = (1 - P_b) * \Gamma_{offered} = 0.99 * 8.11 = 8.03$ [Erlangs]

b) 45 trunks, $P_b = 1\%$

From the Erlang-B Traffic Tables, we find that the offered load for the system is:

$\Gamma_{offered} = 33.44$ [Erlangs]

$\Gamma_{carried} = (1 - P_b) * \Gamma_{offered} = 0.99 * 33.44 = 33.11$ [Erlangs]

Trunking Efficiency – An example

c) Trunking efficiency

For 15 trunks with 1 % blocking, the trunking efficiency is:

$\eta_T = \Gamma_{carried}$ /(# of trunks) = 8.03/15 = **0.54 [Erlang/trunk]**

For 45 trunks with 1 % blocking, the trunking efficiency is:

$\eta_T = \Gamma_{carried}$ /(# of trunks) = 33.11/45 = **0.74 [Erlang/trunk]**

Thus, the 45 trunk system is more efficient than the 15 trunk system.

Another way to look at this is the carried load of 3 15-trunk systems is noticeably less that the carried load of 1 45-trunk system (even though both provide a total of 45 trunks)

$3 \cdot \Gamma_{carried} = 24.1$ [Erlangs] (for 3 "15-trunk" systems)

$\Gamma_{carried} = 33.1$ [Erlangs] (for 1 "45-trunk" system)

What's the point? Frequency reuse results in a loss in trunking efficiency.

(Add this to the "Disadvantages of Cellular Systems."

Blocked Calls Queued

But what if we could queue blocked calls ?

The formula for the probability that a call will be delayed (i.e., $delay > 0$) is:

$$P(delay > 0) = \frac{\Gamma^C}{\Gamma^C + C! \cdot (1 - \Gamma/_C) \cdot \sum_{k=0}^{C-1} \left(\Gamma^k/_{k!}\right)}$$

where Γ is the total offered load and C are the number of channels (servers).

This is the (well known) Erlang-C formula. Using the $P(delay > 0)$ we can calculate:

$$P(delay > t) = P(delay > 0) \cdot P(delay > t \mid delay > 0).$$

Now, since $P(delay > t \mid delay > 0) = \exp(^{-(C-\Gamma)t}/_\tau)$, then

$$P(delay > t) = P(delay > 0) \cdot \exp(^{-(C-\Gamma)t}/_\tau),$$

where τ is average call duration.

Part #6:
The Cellular Principle – Dynamic Channel Assignment Schemes

Goals:

- Discuss the various Dynamic Channel Assignment schemes and Maximal Channel Packing strategies

Channel Allocation Strategies

- Fixed Channel Allocation (FCA): repetitious pattern allowing frequency reuse based on the assumption that a mobile may be located anywhere within a cell.
- (Traffic Bounded) Dynamic Channel Allocation (DCA): allows pool of frequencies to be reused at every cell, based on time-varying traffic conditions (once a channel is used, it can be reused based on the "FCA" rule).
- (Interference Bounded) Dynamic Traffic Allocation: allows frequency reuse based on interference conditions (i.e., allows maximal packing); e.g., DECT.

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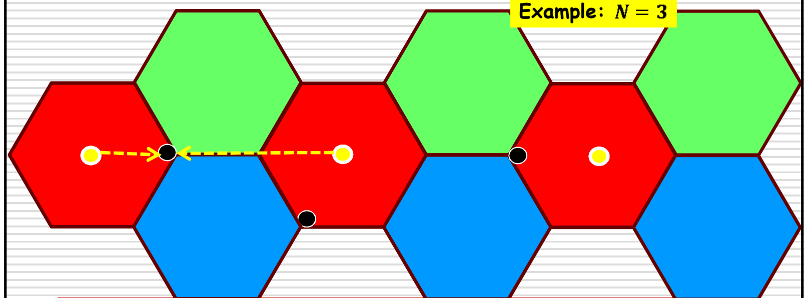
Channel Allocation Strategies – Fixed Channel Allocation (FCA)

- Fixed Channel Allocation (FCA): Assumes that mobile can be anywhere within a cell; in particular in the worst-case position – on the boundary of the cell.
- FCA is an optimal channel assignment when (1) the effect of co-channel interferers is undeterminable, and (2) the load is uniformly distributed among cells

Example: $N = 3$



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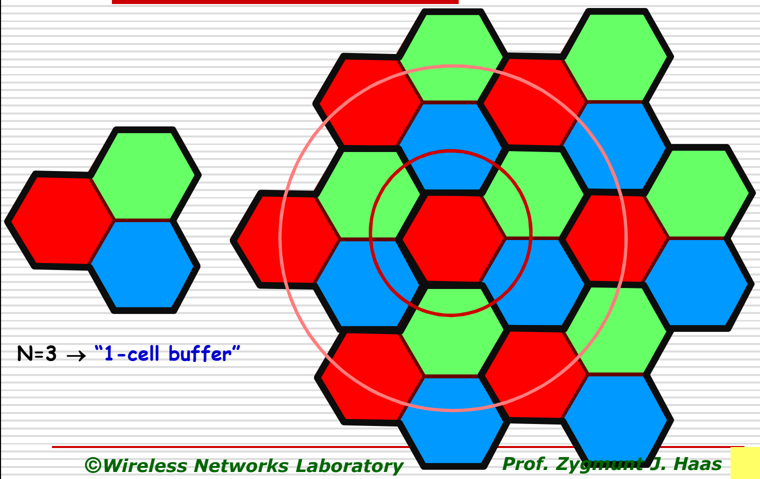
The notion of "buffer cells"



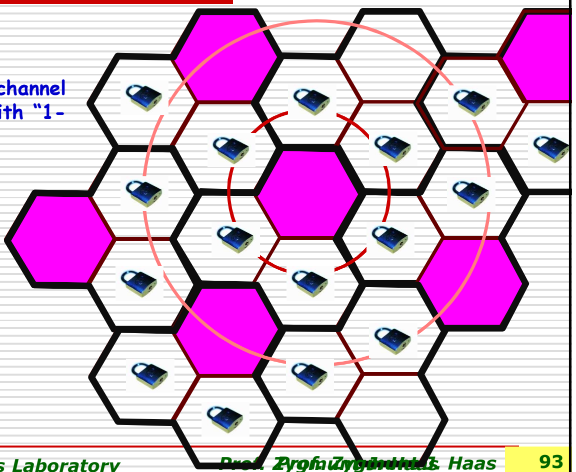
N=3 → "1-cell buffer"

Channel Allocation Strategies – Dynamic Channel Allocation (DCA)

- When the load in cells is not uniform, FCA becomes inefficient – channels are left unused in low-load cells, while there are not enough channels in high-load cells.
- In the most general Dynamic Channel Allocation (DCA), there is no fixed assignment of channels to cells.
  - ◊ All channels are placed in a pool of channels.
  - ◊ When a channel is needed, it is borrowed from the pool.
  - ◊ A borrowed channel must satisfy reuse requirements.
- Consider the following (simple) Dynamic Channel Allocation (DCA-II):
  When a channel is needed in a cell,
  1. Choose a (usable) channel from the channel pool based on some criteria (e.g., currently least used channel).
  2. Check whether its use violate the minimum reuse requirement; if it does not, accept the channel, if it does, make the channel as unusable, and go back to 1.

Channel Allocation Strategies – Dynamic Channel Allocation (DCA)

- For example, a channel could be reused with "1-cell buffer".

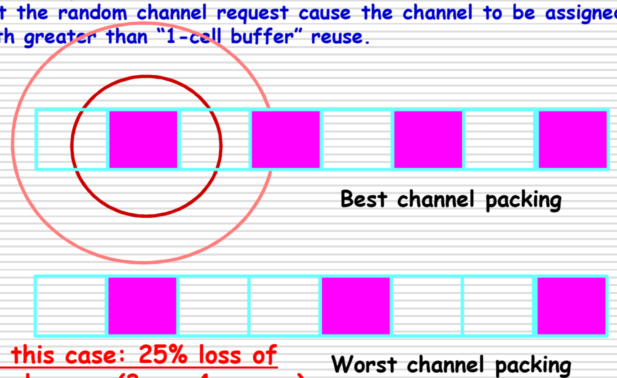


Channel Allocation Strategies – Dynamic Channel Allocation (DCA)

- DCA has it problems:
  - ◊ Due to random channel assignment, the channel reuse is not efficient; i.e., there is no maximal packing; i.e., the reuse distance is not minimal.
  - ◊ Satisfying the reuse requirement introduces high overhead.

Channel Allocation Strategies – Dynamic Channel Allocation (DCA)

- **For example, if a channel could be reused with "1-cell buffer" but the random channel request cause the channel to be assigned with greater than "1-cell buffer" reuse.**



<u>**In this case: 25% loss of channel reuse (3 vs. 4 reuses)**</u>

Chanel Borrowing

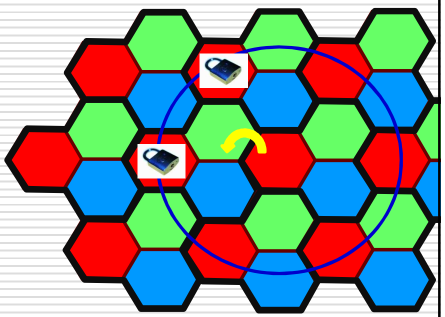
- <u>Channel Borrowing</u> is a hybrid allocation schemes.
- Initially, channels are assigned to cells, as in fixed allocation schemes; channels assigned to a cell are referred to as "nominal channels".
- If a cell needs a channel in excess of the allocated channels, the cell may borrow a channel from one of its neighboring cells given that:
  - a channel is available
  - use of this channel will not violate frequency reuse requirements.
- Once the borrowed channel is released, it is returned to the original cell.
- A key problem caused by channel borrowing is that, because of co-channel interference, the nearby cells are prohibited from using the borrowed channel, increasing the overall call blocking probability.

Chanel Borrowing – Borrowing with Channel Ordering

- An improvement is introduced, where it is ensured that the channels are borrowed from the most available neighbor cell; i.e., a neighbor cell with the most unused channels.
- Consider the following two extensions of the channel borrowing approach:
  - Borrowing with Channel Ordering
  - Borrowing with Directional Channel Locking
- Borrowing with Channel Ordering has the following distinctive features:
  - The ratio of fixed channels to dynamic channels varies with traffic load
  - The nominal channels are ordered. The lowest-numbered nominal channels of a cell have the highest priority of being used by a call within the cell, while the highest-numbered nominal channels are most likely to be borrowed by neighbor cells. Once a channel is borrowed, the channel is “locked” in the co-channel cells within the reuse distance of the cell in question (a "locked" channel cannot be used or borrowed).

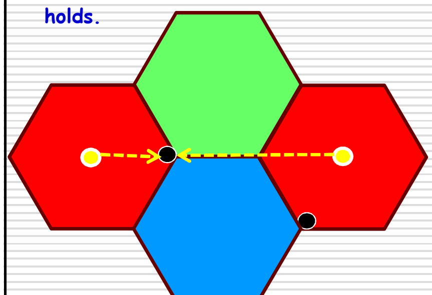
Chanel Borrowing – Borrowing with Directional Channel Locking

- Borrowing with Directional Channel Locking
  - An improvement over the Borrowing with Channel Ordering scheme
  - A borrowed channel is locked only in those co-channel cells where its use would negatively affect the SIR.
  - The scheme required channel use coordination across larger area and knowledge of the network topology



Channel Allocation Strategies – beyond Fixed Channel Allocation

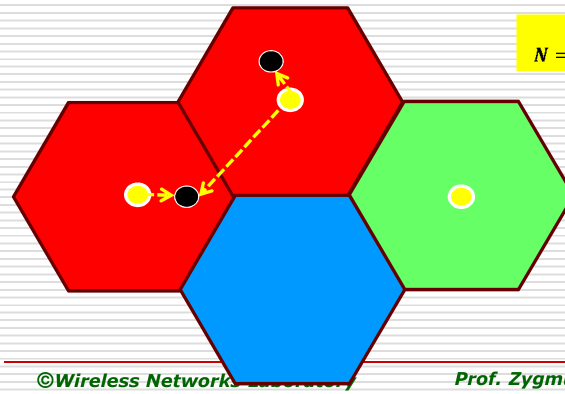
- Now, we discuss the effect of knowing the actual co-channel interference.
- For N=s, there is "1-cell buffer" between two channel reuses.
- The $D = R\sqrt{3N}$ is based on the fact that the mobile can be anywhere in a cell, in particular on the cell boundary.
- Indeed, if a mobile is on the cell boundary, then the formula for $SIR = \frac{Q^{\gamma}}{6}$ holds.



Example:
$N = 3 \rightarrow D = R\sqrt{3N} = 3R$

Channel Allocation Strategies

If the location(s) of the actual co-channel interferers is(are) known – perhaps the same set of channels could be reused more frequently … in this example, maybe even in adjacent cells!

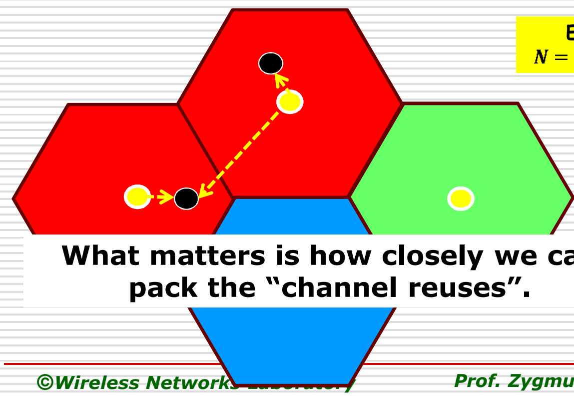


Example:
$N = 3 \rightarrow N = 1$

Channel Allocation Strategies

If the location(s) of the actual co-channel interferers is(are) known – perhaps the same set of channels could be reused more frequently … in this example, maybe even in adjacent cells!

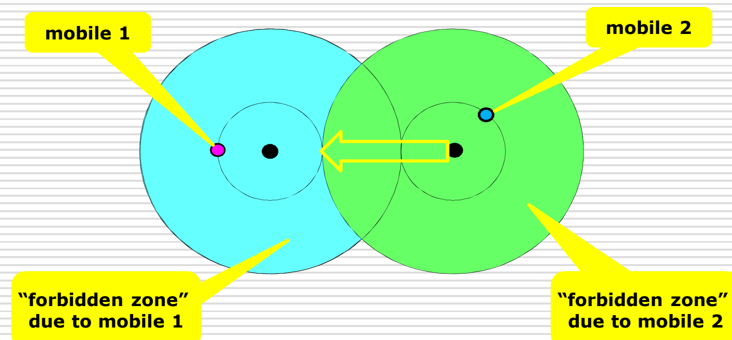
Example:
$N = 3 \rightarrow N = 1$



What matters is how closely we can pack the "channel reuses".

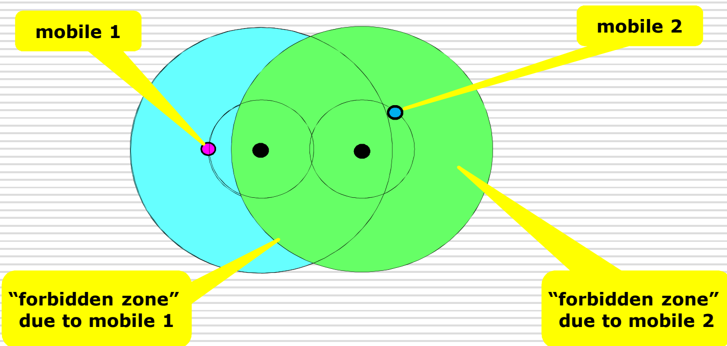
Channel Allocation Strategies

Maximal Packing with knowledge of the distance only



Channel Allocation Strategies

Maximal Packing with knowledge of the exact location



Maximum Channel Packing

- Two vertices are called adjacent if they are connected by an edge
- A graph, G, is complete, if there exists an edge between every two vertices in G
- A complete graph with n vertices is called an "n-clique" and labeled as K_n
- An n-clique is called a maximal clique, if there is no larger clique with the same vertices
- A set $S \subset V$ is called a stable set, if no two vertices in S are adjacent
- Stability number $\alpha(G)$ is the size of the maximal stable set: $\alpha(G) = \max_{S \in L} |S|$, where L is the set of all stable sets
- The chromatic number $\gamma(G)$ is the smallest number of colors needed to "color" the graph G

Maximum Channel Packing

- The maximum cardinality of a clique is $\varpi(G)$
- G is called γ -perfect is: $\gamma(G) = \varpi(G)$
- The chromatic number $\gamma(G)$ is the minimum number of channels required to carry some traffic load.

$$\gamma(G_n) = \varpi(G_n) = \max_j (\Sigma_{i \in qj}\ n_i)$$

Maximum Channel Packing - An example

Comparison of FCA, MPDCA, and Hybrid Channel Allocation (HCA)

Consider the case of a 2-dimensional grid of hexagonal cells with 1 buffer-cell between reused channels. In particular, consider one cell in the grid, cell-1, in which there are 8 calls in progress. Cell-1 is adjacent to 6 other cells, counting clockwise, cell-2, cell-3, ... cell-6, and cell-7 (cell-7 is adjacent to cell-2), in which there are the following number of calls in process of being set up, respectively: 11, 0, 14, 1, 7, and 9. There are total of 28 channels in the system. A new call arrives in cell-1. For each of the following cases, what is the minimum number of calls that needs to be blocked?

a. The Fixed Channel Allocation
b. The Maximal Packing Dynamic Channel Assignment (DCA-I) algorithm
c. A hybrid scheme in which 3 channels are permanently assigned to each cell and the rest use dynamic assignment (DCA-I).

Maximum Channel Packing - An example

a. Fixed Channel Allocation (FCA).

In the Fixed Channel Allocation scheme, we simply assign a fixed number of channels to each cell. Using a reuse factor of N=3 and assuming uniform user density, we arrive at:

28 channels for 3 cells → 9 [channels/cell]

Thus, the calls in cells 2 and 4 exceed this 9 channel/cell limit and thus some of them have to be blocked.

Specifically, 2 calls in cell 2 are blocked and 5 calls in cell 4 are blocked. This gives us a total of 7 blocked calls.

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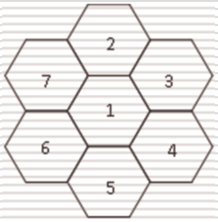
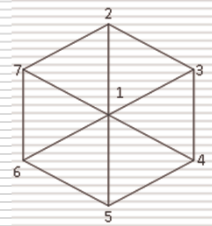
Maximum Channel Packing - An example

b. Maximally-Packed Dynamic Channel Allocation (MPDCA)



System of Seven Cells



Graph of System

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Maximum Channel Packing - An example

Maximally-Packed Dynamic Channel Allocation (MPDCA) (con't):

$$U^T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad U^T_{i,j} = \begin{cases} 1, & cell\ j \in clique\ i \\ 0, & otherwise \end{cases}$$

$$\vec{n} = \begin{bmatrix} 8 & 11 & 0 & 14 & 1 & 7 & 9 \end{bmatrix}^T \quad U^T \cdot \vec{n} = \begin{bmatrix} 19 \\ 22 \\ 23 \\ 16 \\ 24 \\ 28 \end{bmatrix}$$

where $\vec{n}$ is the demand vector.

The clique consisting of cells (1, 2, 7) is using all 28 channels. If a new call arrives in cell 1, the number of calls in that clique will increase to 29. Since there are only 28 channels in the system, the new call cannot be served and needs to be blocked.

Maximum Channel Packing - An example

c. Hybrid Channel Allocation (HCA)

Since each cell now has 3 fixed channels, we can first use these channels to take care of some of the load in each cell.

Cell 1: 8 – 3 = 5; Cell 2: 11 – 3 = 8; Cell 3: 0 – 3 = 0;
Cell 4: 14 – 3 = 11; Cell 5: 1 – 3 = 0; Cell 6: 7 – 3 = 4;
Cell 7: 9 – 3 = 6

These new demand values then need to be assigned channels dynamically using the remaining available channels. Since we are using 3 channels per cell, and each clique contains 3 cells, then instead of 28 channels, we only have 28 – 9 channels left to assign dynamically.

Using the same method as part b:

Maximum Channel Packing - An example

$$U^T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$U^T_{i,j} = \begin{cases} 1, & cell\ j \in clique\ i \\ 0, & otherwise \end{cases}$$

The new demand vector is: [5, 8, 0, 11, 0, 4, 6].

Multiplying by U^T, we get:

(1,2,3) = 13; (1,3,4) = 16; (1,4,5) = 16;

(1,5,6) = 9; (1,6,7) = 15; (1,2,7) = 19

The clique consisting of cells (1, 2, 7) is using all 19 channels. If a new call arrives in cell 1, the number of calls in that clique will increase to 20. Since there are only 19 channels in the system, the new call cannot be served and will be blocked.