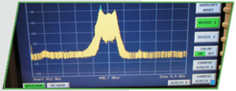

Radio Engineering

Lecture 8: Multiple Access and the Cellular Principle

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Previously on Radio Engineering...

1. Introduction
2. Technical Challenges
3. Noise and Interference
4. Antennas and Propagation
5. Statistical Channel Characterization
6. Wideband channels
7. MIMO channels
8. Channel sounding
9. Channel models
10. Channel simulation

This lecture

9. Multiple Access and the Cellular Principle
    - Introduction
    - Network Dimensioning
    - Multiple Access and Duplexing
    - The Cellular Concept
    - Cell planning

Introduction

- So far we have looked at issues related to a single base station (BS) and a single mobile station (MS)
- How can one BS communicate with many MS simultaniously?
- How can multiple BS operate concurrently?
- How can the number of users be maximized?

Network Dimensioning

What is the required number of communication channels so that a given number of users can be served with sufficient quality?

Definition (Erlang)

Erlangs are defined as the average number of concurrent calls over a period of time (e.g., one hour).
If λ is the arrival rate of the calls and h is the average call time $E = \lambda h$.

Example

A radio channel that is occupied by 1 user for one hour continuously is said to have a load of 1 Erlang.

Offered vs. carried traffic

- **Offered traffic** E_{offered} is the traffic requested by the users
- **Carried traffic** E_{carried} is the traffic supported by the network
- **Blocking Probability** P_b is the probability that a call is rejected because the network is busy

$$E_{\text{carried}} = (1 - P_b)E_{\text{offered}}$$

The Erlang B formula

EURECOM

If

- call attempts arrive following a Poisson process (call arrivals are statistically independent) with rate λ
- the duration of the calls is random according to an exponential distribution with average duration h
- a rejected call is not queued or retried, but lost forever

the probablity of call blocking is given by

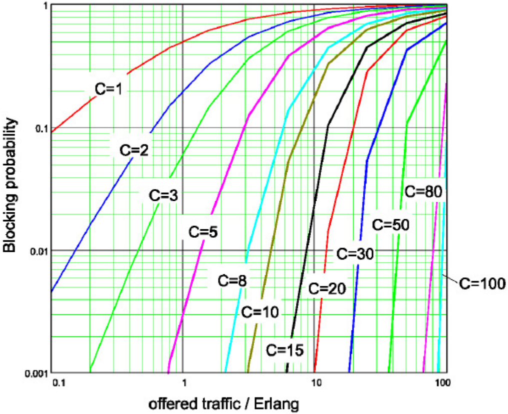
$$P_b(E, m) = \frac{E^m/m!}{\sum_{i=0}^{m-1} E^i/i!},$$

where $E = \lambda h$ is the offered traffic in Erlang and m is the number of channels.

The Erland B formula (2)

Erlang-B

Relation between blocking probability and offered traffic for different number of available speech channels in a cell.



The Erlang C formula

If a rejected call is queued, the probability that a user is put on hold is

$$P_w(E,m) = \frac{E^m}{E^m + m!\,(1 - E/m)\sum_{i=0}^{m-1} E^i/i!}.$$

The average waiting time is given by

$$t_w = P_w \frac{T_{\text{call}}}{m - E}$$

Example: Erlang B

In an Erlang-B system, 30 channel are available. A blocking probability of less than 2% is required. What ths the traffic that can be served if there is (1) one operator or (2) three operators?

1. $P_b = 0.02, m = 30 \Rightarrow$

$$P_b(E,m) = \frac{E^{30}/30!}{\sum_{i=0}^{29} E^i/i!},$$

   $\Rightarrow E = 21.9$

2. One operator: $P_b = 0.02, m = 10 \Rightarrow E = 5.1$
   Three operators: $E_{\text{tot}} = 3E = 15.3$

Example: Erlang C

Consider an Erlang-C system where users are active 50% of the time, and the average call duration is 5 minutes. No more than 5% of all calls should be put in a waiting loop. How many channels are required for $n = 1, 8, 30$ users? What is the average wait-time in each of those cases?

Example: Erlang C (2)

Since $E = 0.5n$ is the average offered traffic we need to find m that fulfills

$$0.05 \geq \frac{E^m}{E^m + m!\,(1 - E/m)\sum_{i=0}^{m-1} E^i/i!}.$$

With $T_{\text{call}} = 5\text{min}$, the average wait time is

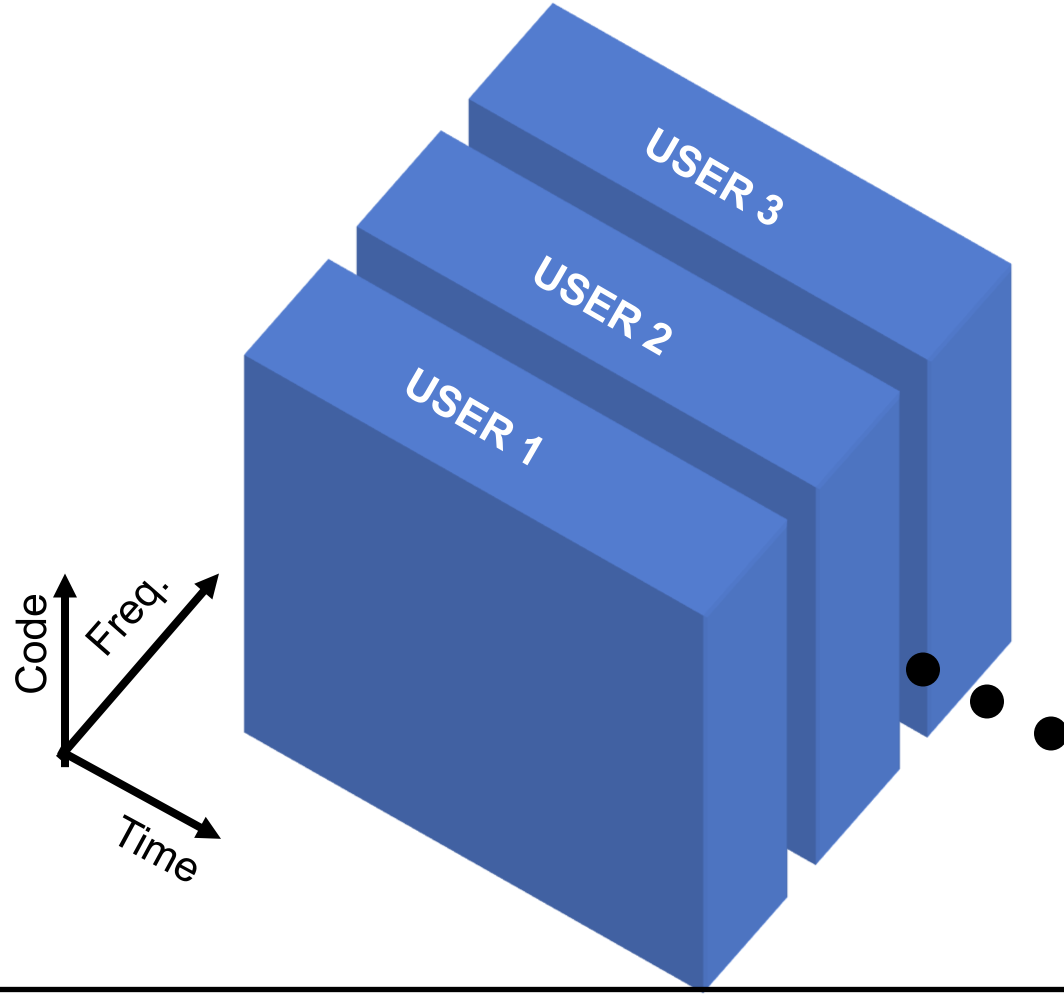
$$t_w = P_w \frac{5}{m - E}$$

n	1	8	30
E	0.5	4	15
m	3	9	23
P_w	0.0152	0.0238	0.0380
t_w	0.0304	0.0238	0.0238

Multiple Access Methods

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)
- Orthogonal frequency division multiple access (OFDMA)

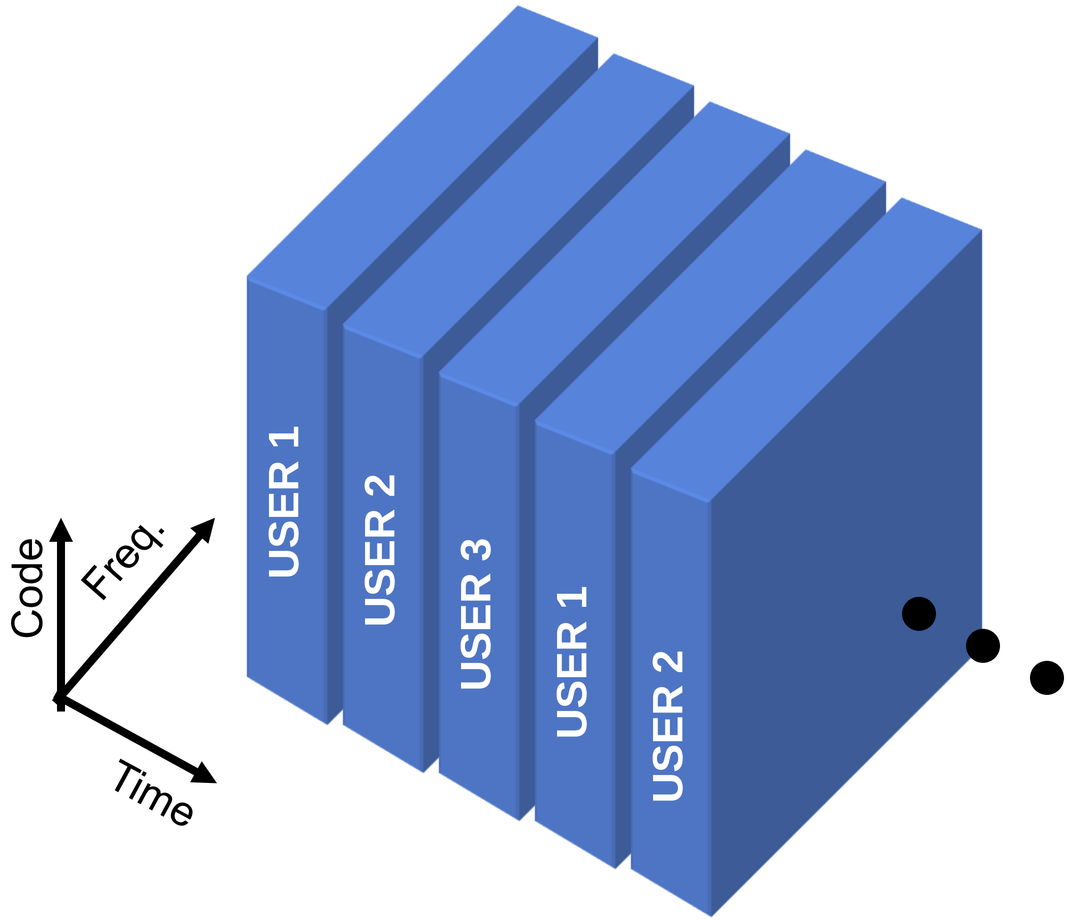
MULTIPLE ACCESS
Freq.-division multiple access (FDMA)



Users are separated in frequency bands.

Examples: Nordic Mobile Telephony (NMT), Advanced Mobile Phone System (AMPS)

MULTIPLE ACCESS
Time-division multiple access (TDMA)

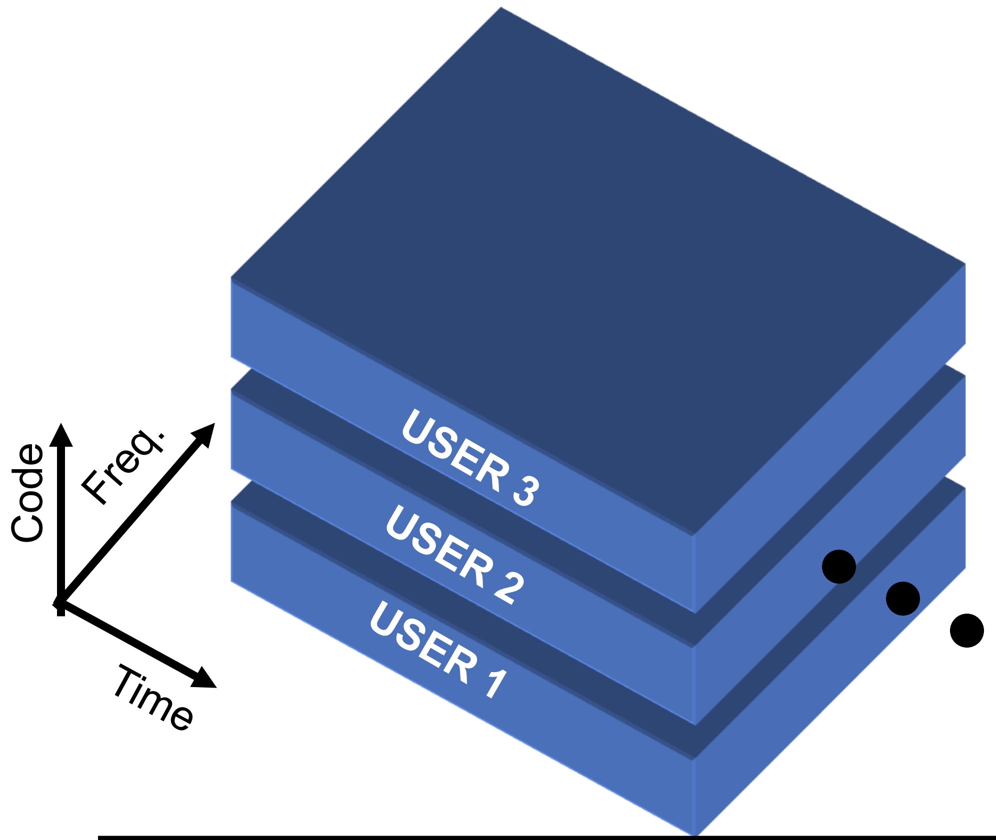


Users are separated in time slots.

Example: Global System for Mobile communications (GSM)

MULTIPLE ACCESS
Code-division multiple access (CDMA)

Users are separated by spreading codes.

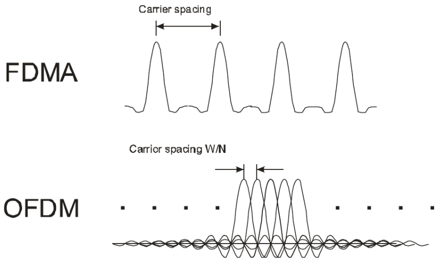


Examples: CdmaOne, Wideband CDMA (WCDMA), Cdma2000

Orthogonal frequency divison multiplexing

- OFDM is a special case of FDMA, where total bandwidth W is divided into N orthogonal sub-carriers ($f_n = nW/N$ frequency of sub-carrier n)

$$c_n c_k \int_{iT_S}^{(i+1)T_S} \exp(j2\pi f_n t)\exp(-j2\pi f_k t)\mathrm{d}t = c_n c_k \delta_{n,k}$$



- Implemented efficiently using a fast Fourier transform (FFT)

Orthogonal frequency divison multiple access

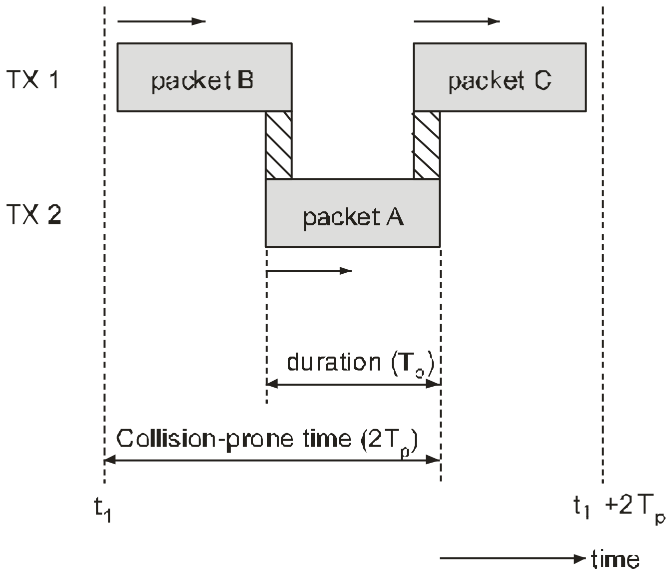
- Relies on orthogonal frequency-division multiplexing (OFDM) digital modulation scheme
- Assign subsets of sub-carriers to different users
- Advantage: different modulation and coding schemes (MCS) can be used for different users to exploit frequency diversity
- Can also be used for packet switched data
- Very popular: WiMAX, LTE

Packet switched networks

- Compared to circuit switched networks: No fixed time allocation, no fixed data rate
- In a decentralized (ad-hoc) network, each packet has to fight for its own ressources
  - (slotted) ALOHA
  - Carrier sense multiple access (CSMA)
- In a centralized network, polling and scheduling can be used to guarantee a specific Quality of Service (QoS)

ALOHA (1)

- Basic principle: send out data packets whenever TX has them, disregarding all other TXs
- When collision occurs, packet is lost



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ALOHA (2)

- Probability that there are *n* packets within time duration *t*

$$\Pr(n,t) = \frac{(\lambda_{\mathrm{p}} t)^n \exp(-\lambda_{\mathrm{p}} t)}{n!}$$

  where λ_{p} is the packet rate of arrival
- Probability of no collision (successfull transmission) in [0,t]

$$\Pr(0,t) = \exp(-\lambda_p t)$$

- Total throughput: $\lambda_{\mathrm{p}} T_{\mathrm{p}} \exp(-2\lambda_{\mathrm{p}} T_{\mathrm{p}})$
- Maximum throughput: 1/(2e)
- Slotted ALOHA: all packets start at certain discrete times
- Maximum throughput: 1/e

Carrier sense multiple access

- Principle: first determine whether somebody else transmits, send only when channel is free

  Collisions are deteckted based on ACK/NACK
- Why are there still collisions?
  - Delays are unavoidable: system delay and propagation delay
  - Collision, when there is a signal on the air, but device cannot sense it, because (due to delay) it has not reached it yet

  -- hidden terminal problem
- What does system do when it senses that channel is busy?
  - WAIT
  - Different approaches to how long it should wait

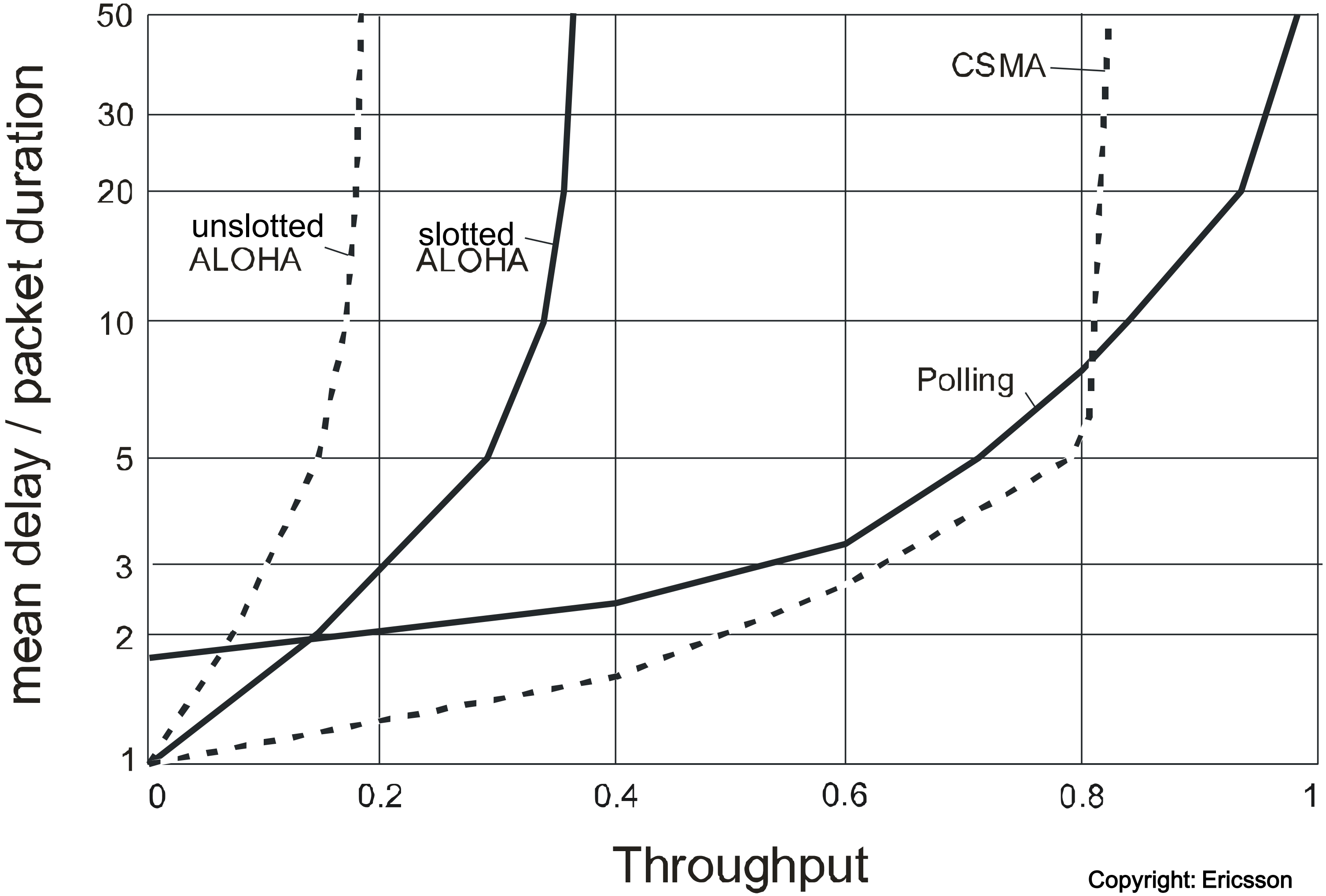
Carrier sense multiple access (2)

- In addition to two-way protocol, a 4-way protocol exists
- Ready-to-send (RTS), clear-to-send (CTS) packets are exchanged before actual transmission
- Collisions can only occur on these packets, not on the data
- Avoids hidden terminal problem

Polling and Scheduling

- In cellular networks with centralized access, base station is responsible to schedule users according to their demands
- Downlink: BS has all necessary information
- Uplink: BS asks (polls) users if they have data to transmit or users use a random access procedure to indicate transmission request
- Example: LTE

Performance comparison



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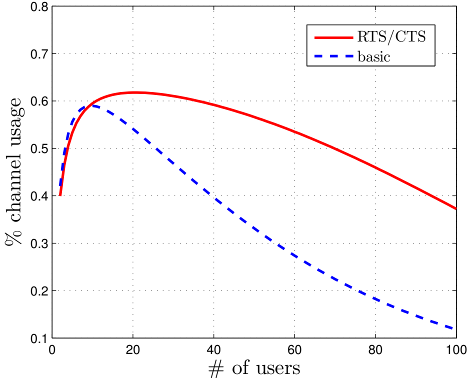
Performance comparison (2)

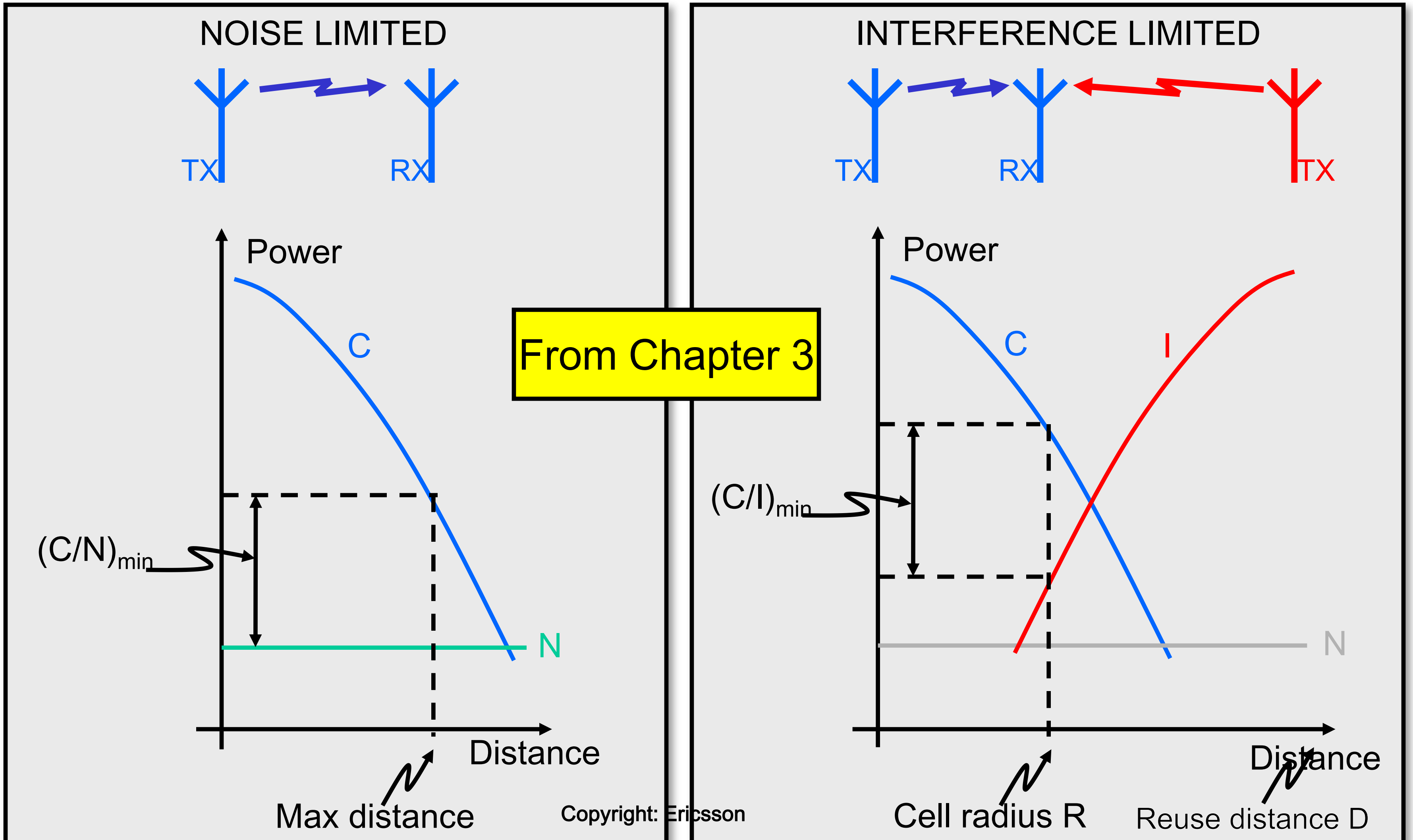


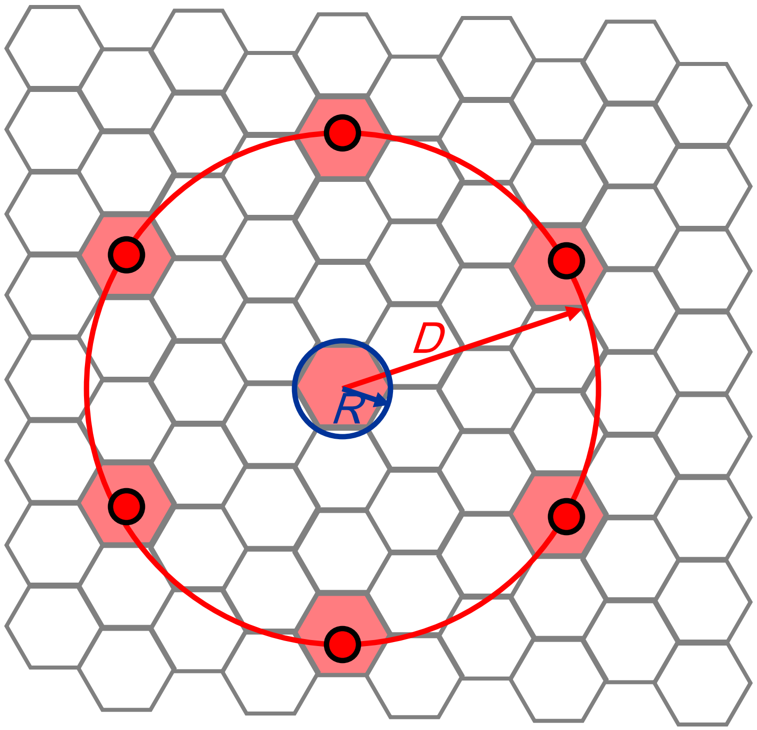
G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," Selected Areas in Communications, IEEE Journal on, vol. 18, no. 3, pp. 535–547, March 2000

Principle of Cellular Networks

- How can a wireless system cover a large area?
- Division of area into hexagonal cells $\Rightarrow$ Each frequency can be (re-)used in multiple cells.
- What is the minimum distance between cells using the same frequency (reuse distance)?
- How to assign frequencies to cells?

Interference and spectrum efficiency
Noise and interference limited links





R ... cell radius

D ... reuse distance (distance where same frequency can be reused)

D/R ... relative reuse distance

Cluster ... set of cells with unique frequencies

Assuming hexagonal cells, cluster size related to reuse distance

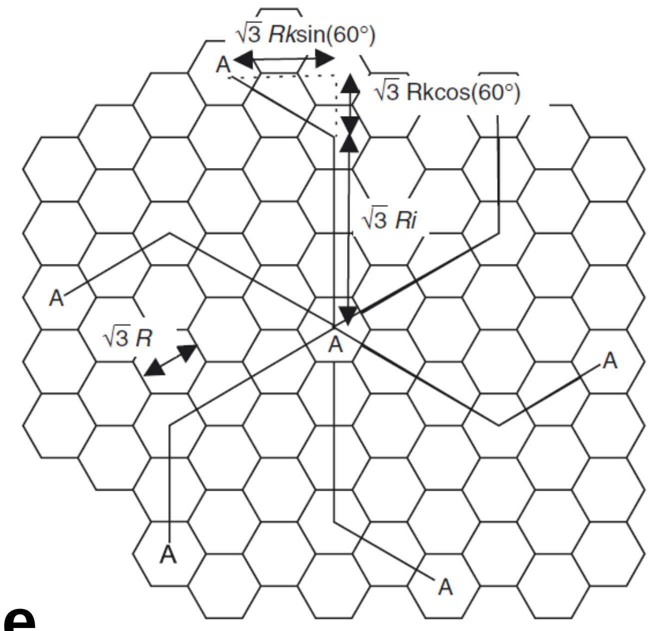
$$N_{cluster} = \frac{(D/R)^2}{3}$$

Cellular planning with hexagonal cells

- **Distance D between cells reusing the same frequency can be computed as**

$$D = \sqrt{3\left(iR + \cos\left(\frac{\pi}{3}\right)kR\right)^2 + \left(\sin\left(\frac{\pi}{3}\right)kR\right)^2}$$

$$= \sqrt{3(i^2 + ij + j^2)}R$$



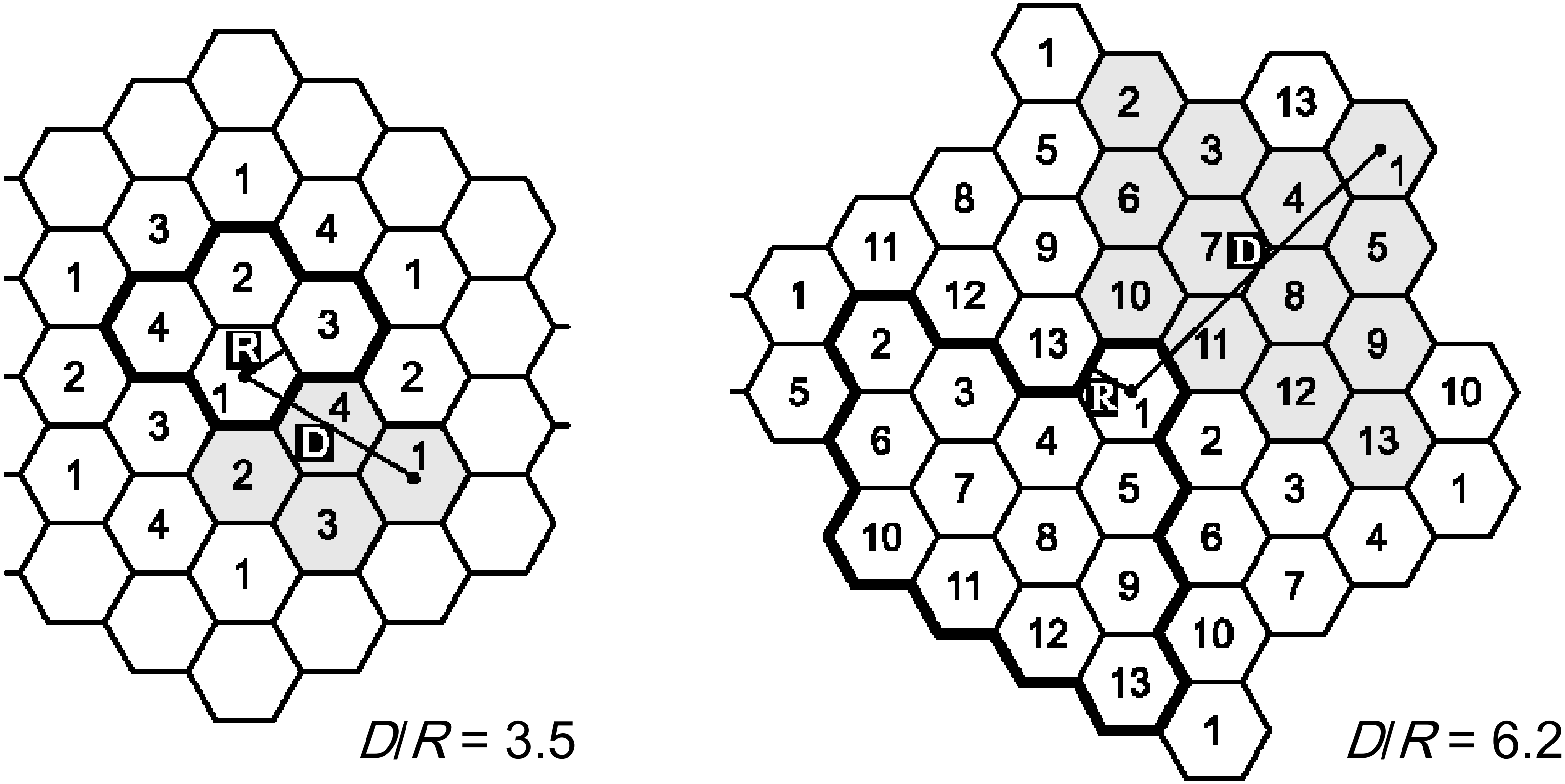
- **Cluster size** $N = i^2 + ij + j^2$ **(i and j are integer)**
- **N=1,3,4,7,9,12,13,16,19,21,…**
- **Relationship between cluster size and relative reuse distance**

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

Interference and spectrum efficiency Cellular systems, cont.

Cluster size: $N_{cluster} = 4$

Cluster size: $N_{cluster} = 13$



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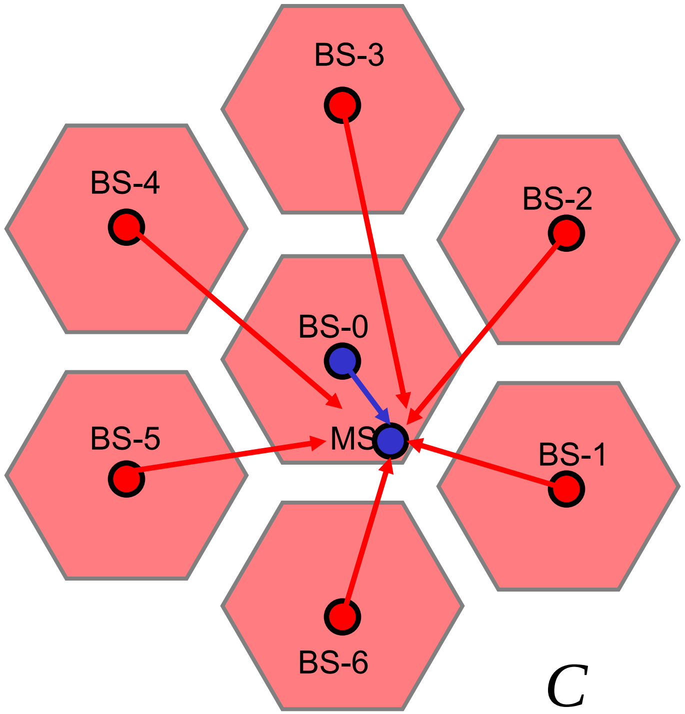
Interference and spectrum efficiency Cellular systems, cont.

Where do we get the necessary D/R?



Received useful power is

$$C \propto P_{TX} d_0^{-\eta}$$

With 6 co-channel cells interfering, at distances d_1, d_2, ... d_6, from the MS, the received interference is

$$I \propto \sum_{i=1}^{6} P_{TX} d_i^{-\eta}$$

Knowing that $d_0 < R$ and $d_1,\ldots,d_6 > D - R$, we get

$$\frac{C}{I} = \frac{P_{TX} d_0^{-\eta}}{\sum_{i=1}^{6} P_{TX} d_i^{-\eta}} > \frac{P_{TX} R^{-\eta}}{\sum_{i=1}^{6} P_{TX} \left(D-R\right)^{-\eta}} = \frac{1}{6}\left(\frac{R}{D-R}\right)^{-\eta}$$

Interference and spectrum efficiency Cellular systems, cont.

Assume now that we have a transmission system, which requires $(C/I)_{min}$ to operate properly. Further, due to fading and requirements on outage we need a fading margin M.

Using our bound

$$\frac{C}{I} > \frac{1}{6}\left(\frac{R}{D-R}\right)^{-\eta}$$

we can solve for a "safe" D/R by requiring

$$\frac{1}{6}\left(\frac{R}{D-R}\right)^{-\eta} \geq M\left(\frac{C}{I}\right)_{min}$$

We get

$$\frac{D}{R} \geq \left(6M\left(\frac{C}{I}\right)_{min}\right)^{1/\eta} + 1$$

Interference and spectrum efficiency Cellular systems, cont.

$N_{cluster}$	3	4	7	9	12	13	16	19	21	25	27
$D/R=\sqrt{3N_{cluster}}$	3	3.5	4.6	5.2	6	6.2	6.9	7.5	7.9	8.7	9

TDMA systems, like GSM

Analog systems, like NMT

Example: Advanced Mobile Phone System (AMPS, 1983)

- Channel bandwidth 30 kHz
- Required SIR: 15dB
- Fading margin: 10dB
- Pathloss exponent: $n = 4$

1. What is the reuse distance and the minimum cluster size?
2. Given that the operator has 5MHz of spectrum, how many channels per cell are there?
3. Assuming an Erlang-B system with a blocking probability of 2%, what is the capacity in Erlangs/cell?

Methods for increasing capacity

- Brute force
  - Increase spectrum
  - Reduction of cell radius
  - Use of sector cells
- Increase link spectral efficieny
  - More efficient modulation and coding
  - Adaptive modulation and coding and HARQ
  - Better receiver architecures
  - Use multiple antennas
- Reduce interference
  - Discontinious transmission
  - Multiuser detection
  - Power control
  - Soft frequency reuse
  - Use multiple antennas
  - Coordination between cells

Sectorization

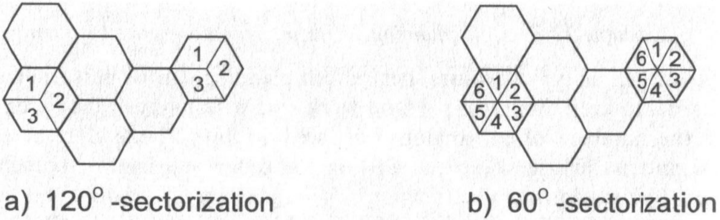
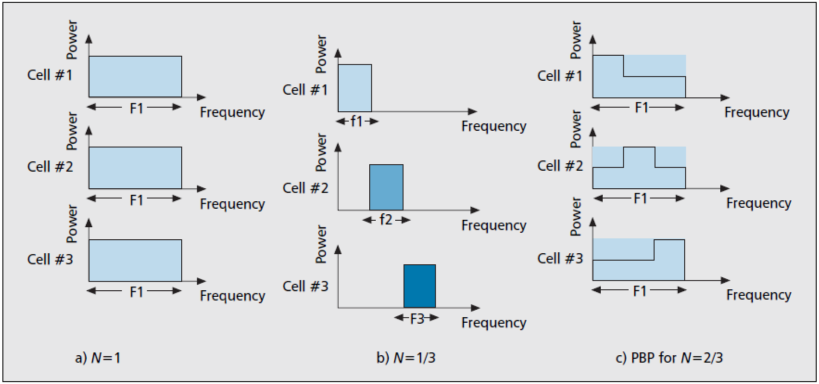


Figure 17.13 Principle behind sector cells.

Soft frequency reuse



Benefits of multiple antennas

- On a link level
  - Diversity $\Rightarrow$ increase in SNR
  - Spatial multiplexing $\Rightarrow$ increase in capacity
- On a system level
  - Spatial filtering for interference reduction (SFIR)
  - Space division multiple access (SDMA, MU-MIMO)
  - Interference alignment (IA)
  - Coordinated multipoint transmission (CoMP)
  - Network MIMO