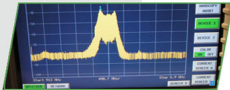




EURECOM

S o p h i a A n t i p o l i s



Radio Engineering

Lecture 7: Multiple Access and the Cellular Principle

Florian Kaltenberger

- 1 Introduction
- 2 Technical Challenges
- 3 Noise and Interference
- 4 Antennas and Propagation
- 5 Statistical Channel Characterization
- 6 Wideband channels
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9 Multiple Access and the Cellular Principle

- Introduction
- Network Dimensioning
- Multiple Access and Duplexing
- The Cellular Concept
- Cell planning

- 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 simultaneously?
- How can multiple BS operate concurrently?
- How can the number of users be maximized?

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.

If

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

the probability of call blocking is given by

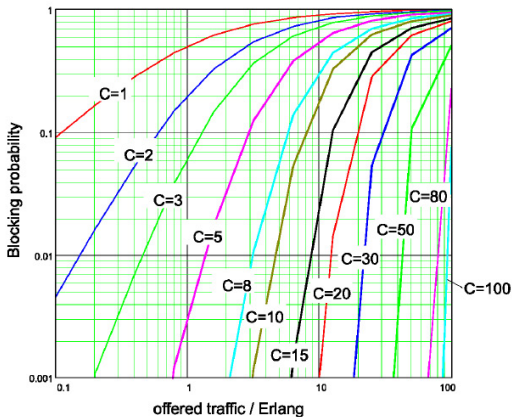
$$P_b(E, m) = \frac{E^m / m!}{\sum_{i=0}^{m-1} E^i / i!},$$

where E is the traffic in Erlang and m is the number of channels.

The Erlang B formula (2)

Erlang-B

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



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

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

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

① $P_b = 0.02, m = 30 \Rightarrow$

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

$$\Rightarrow E = 21.9$$

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

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

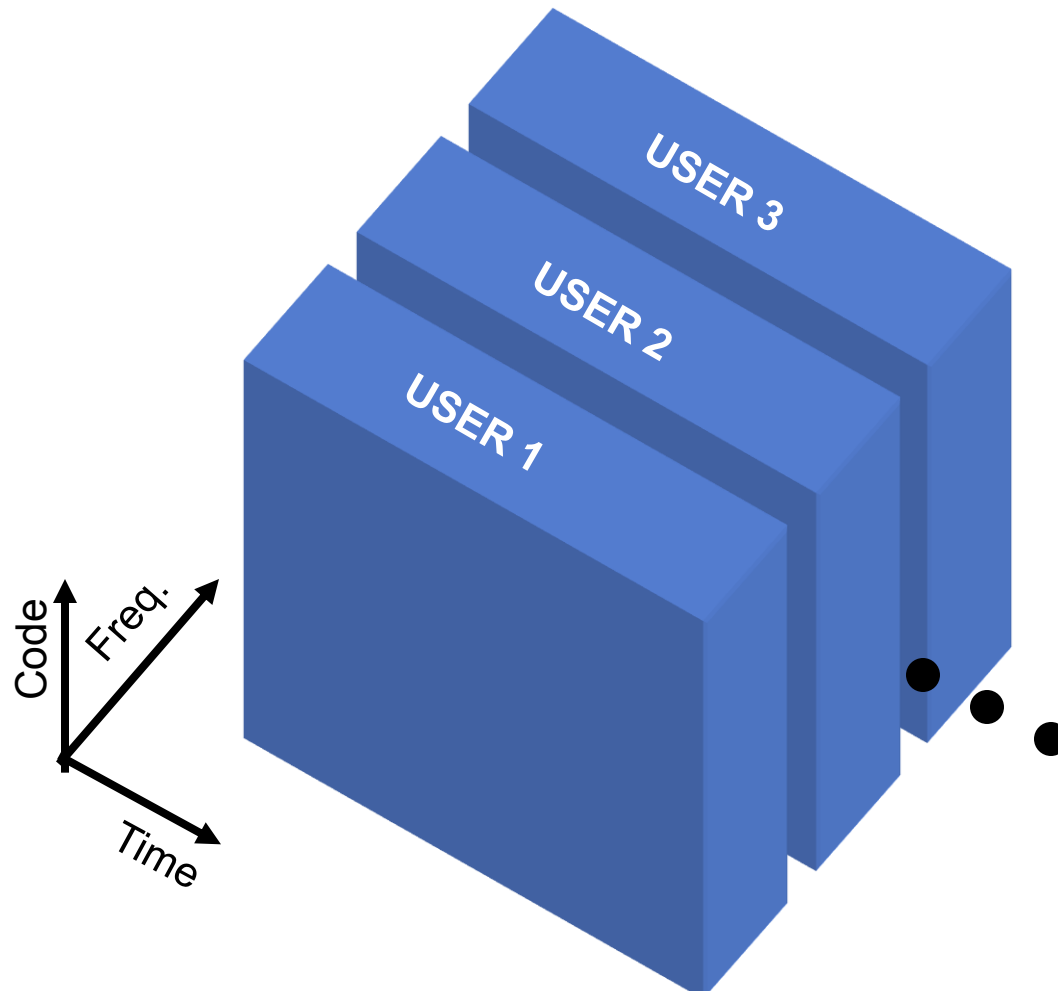
$$t_w = P_w \frac{5}{m - E}$$

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

- 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)

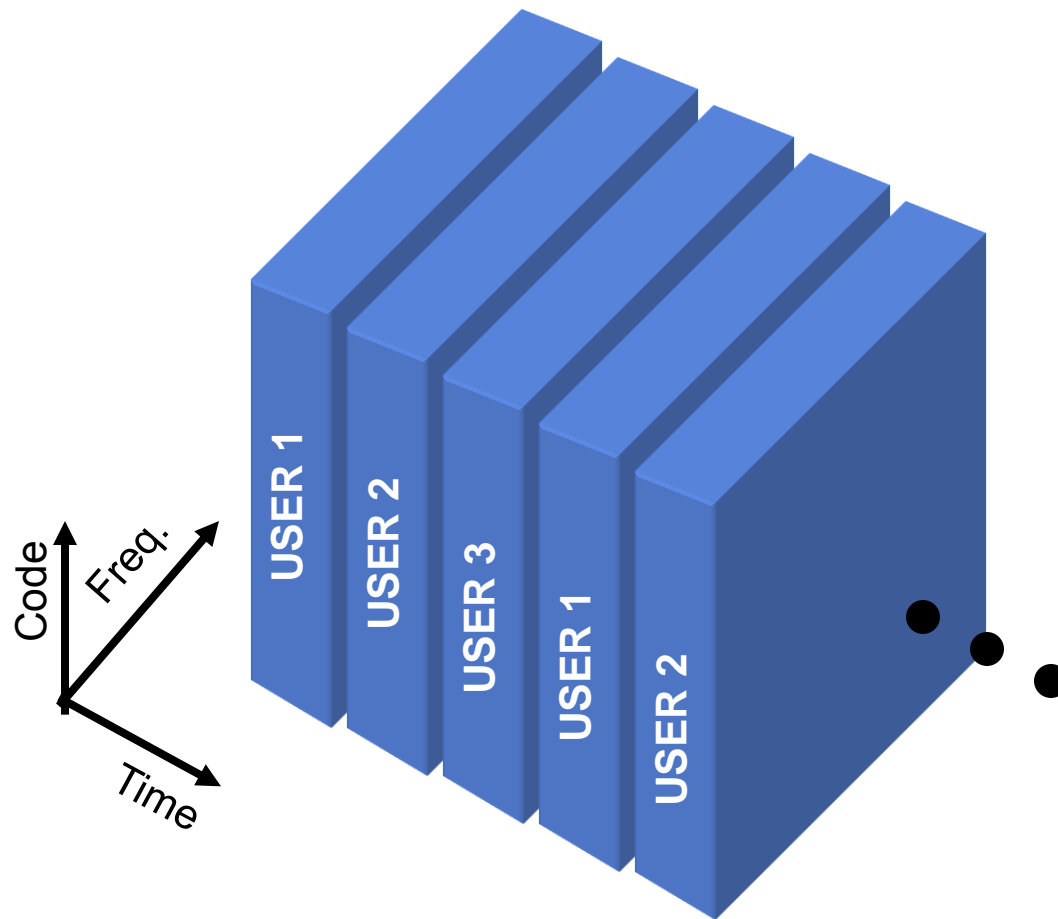


Users are separated in frequency bands.

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

MULTIPLE ACCESS

Time-division multiple access (TDMA)

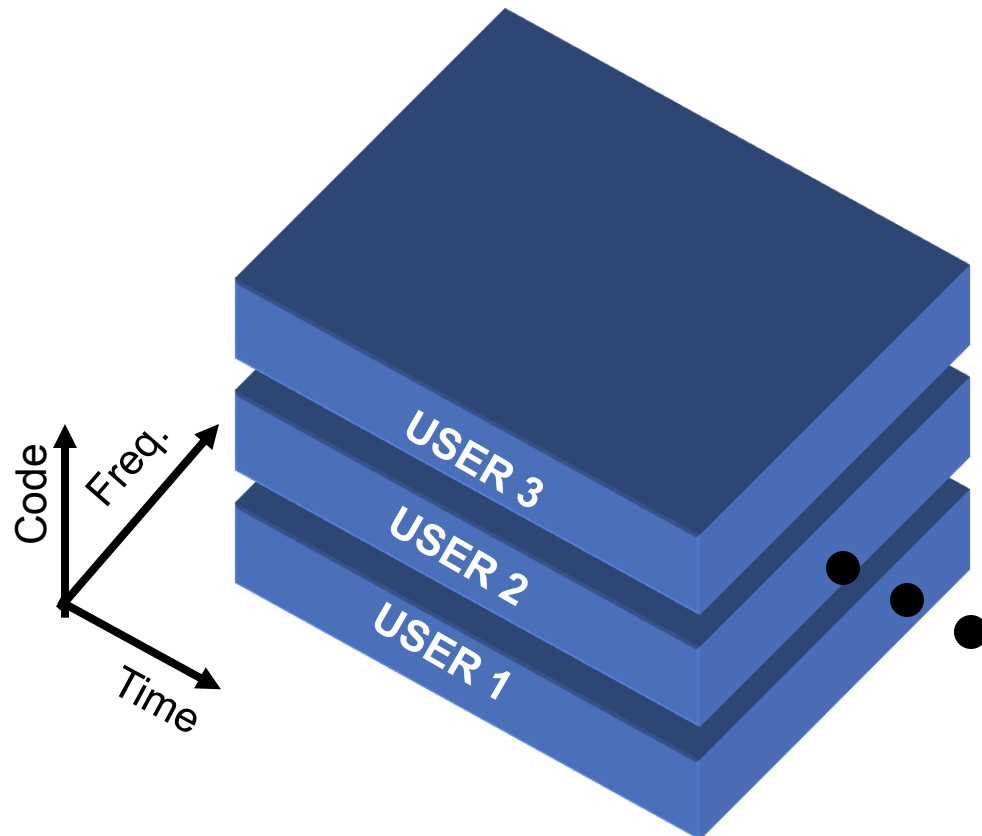


Users are separated
in time slots.

Example: Global System for Mobile communications (GSM)

MULTIPLE ACCESS

Code-division multiple access (CDMA)

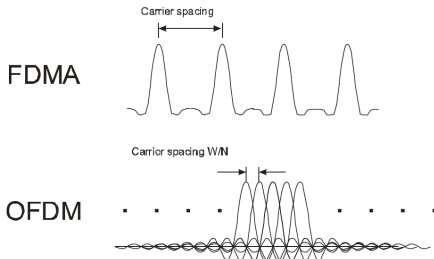


Users are separated by spreading codes.

Examples: CdmaOne, Wideband CDMA (WCDMA), Cdma2000

- 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)

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



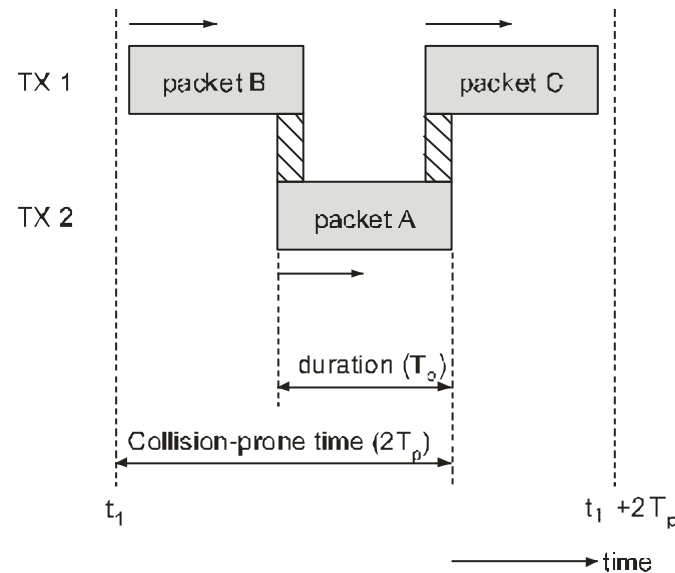
- Implemented efficiently using a fast Fourier transform (FFT)

- 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

- 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 resources
 - (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



Copyright: IEEE

ALOHA (2)

- Probability that there are n packets within time duration t

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

where λ_p is the packet rate of arrival

- Probability of no collision (successful transmission) in $[0, t]$

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

- Total throughput: $\lambda_p T_p \exp(-2\lambda_p T_p)$
- Maximum throughput: $1/(2e)$
- Slotted ALOHA: all packets start at certain discrete times
- Maximum throughput: $1/e$

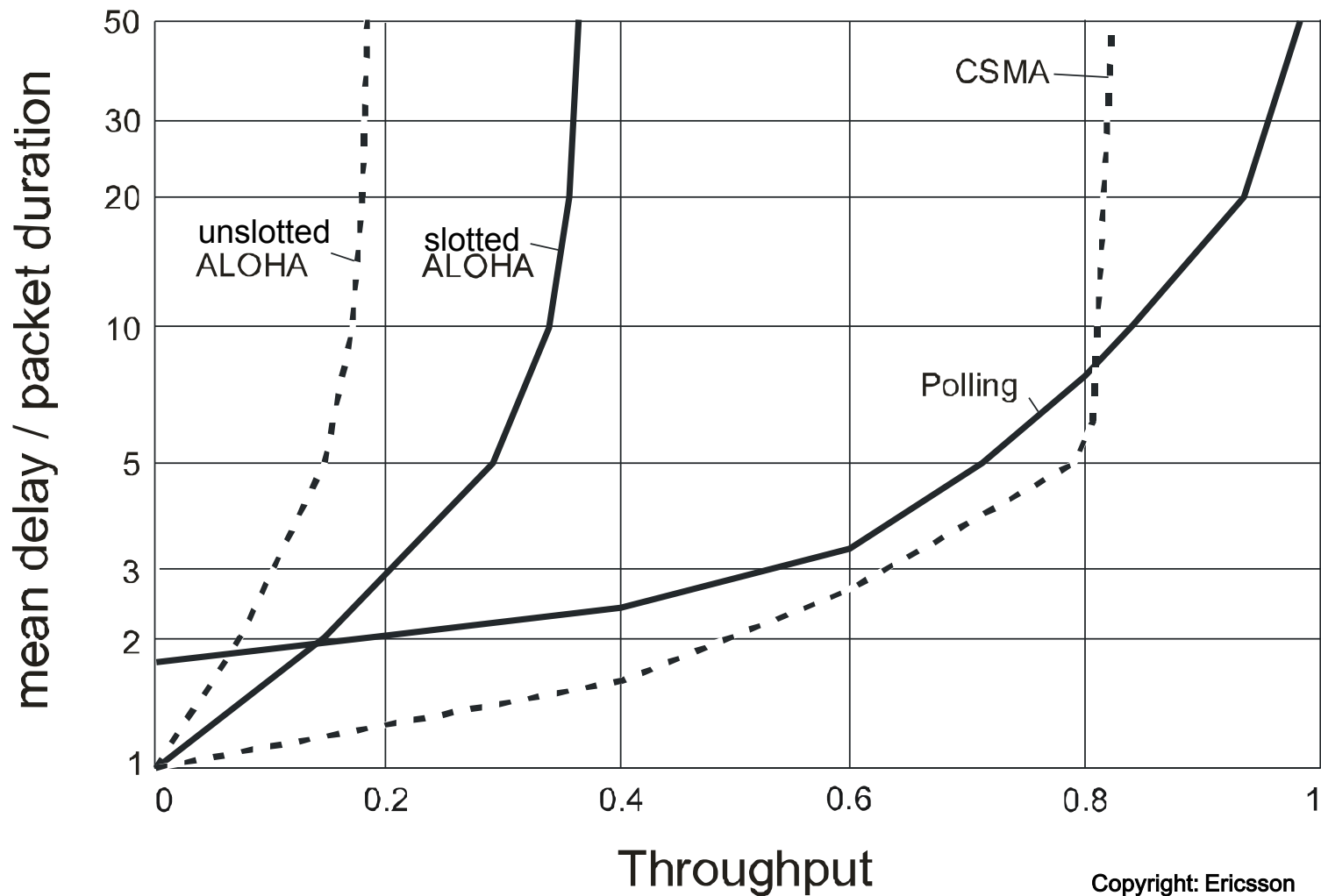
Carrier sense multiple access

- Principle: first determine whether somebody else transmits, send only when channel is free
- 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
- What does system do when it senses that channel is busy?
 - WAIT
 - Different approaches to how long it should wait

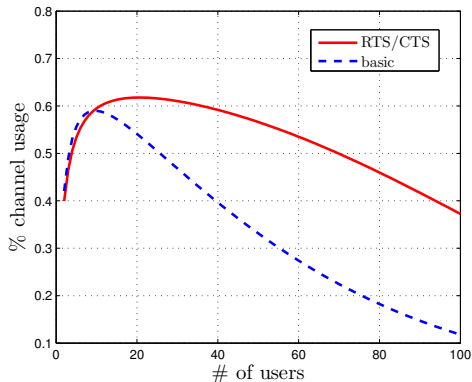
- In addition to two-way protocol, a 4-way protocol exists
- Ready-to-send (RTS), clear-to-send (CTS) packets are exchanged before actual transmission
- Collisions can only occur on these packets, not on the data
- Avoids hidden terminal problem

- 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



Performance comparison (2)

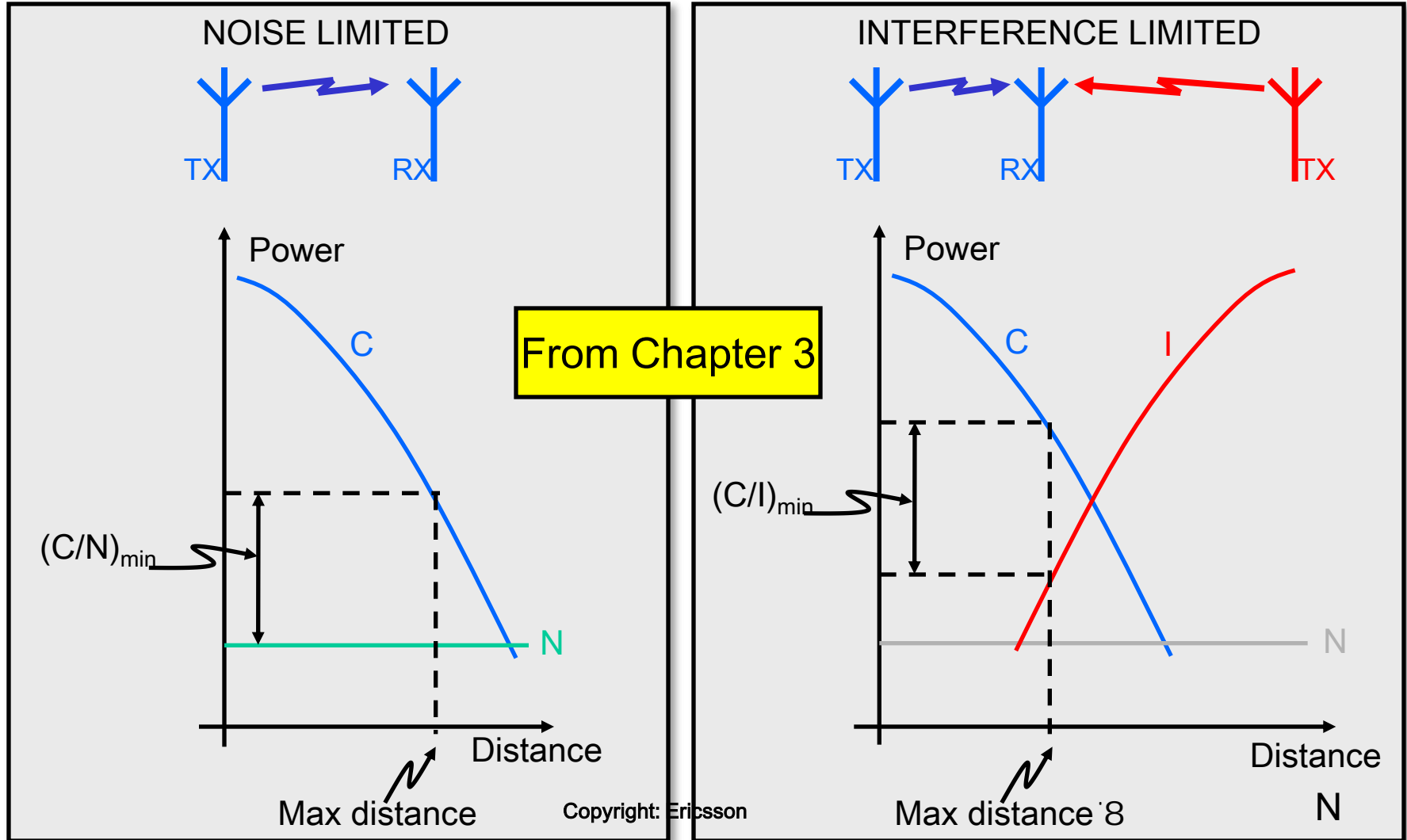


G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," Selected Areas in Communications, IEEE Journal on, vol. 18, no. 3, pp. 535–547, March 2000

- 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?

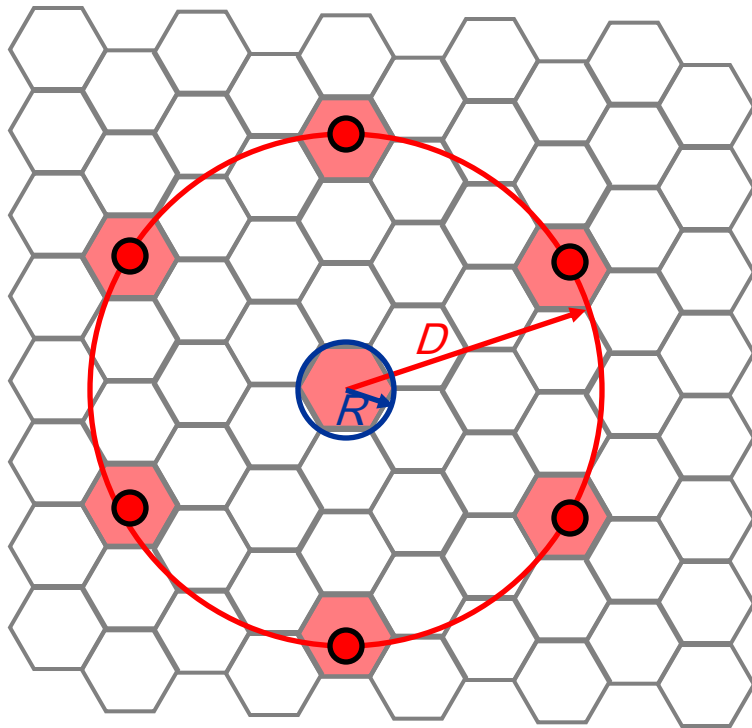
Interference and spectrum efficiency

Noise and interference limited links



Interference and spectrum efficiency

Cellular systems



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

Cluster ... set of cells with unique frequencies

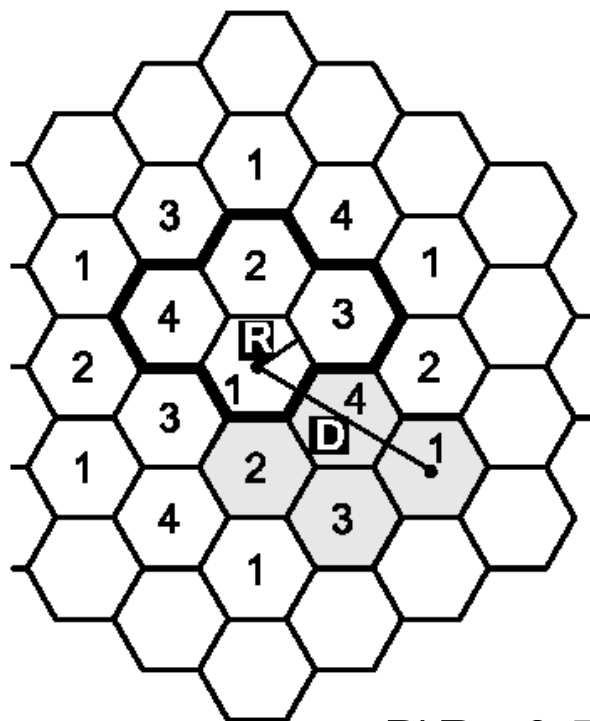
Cluster size related to reuse distance

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

Interference and spectrum efficiency

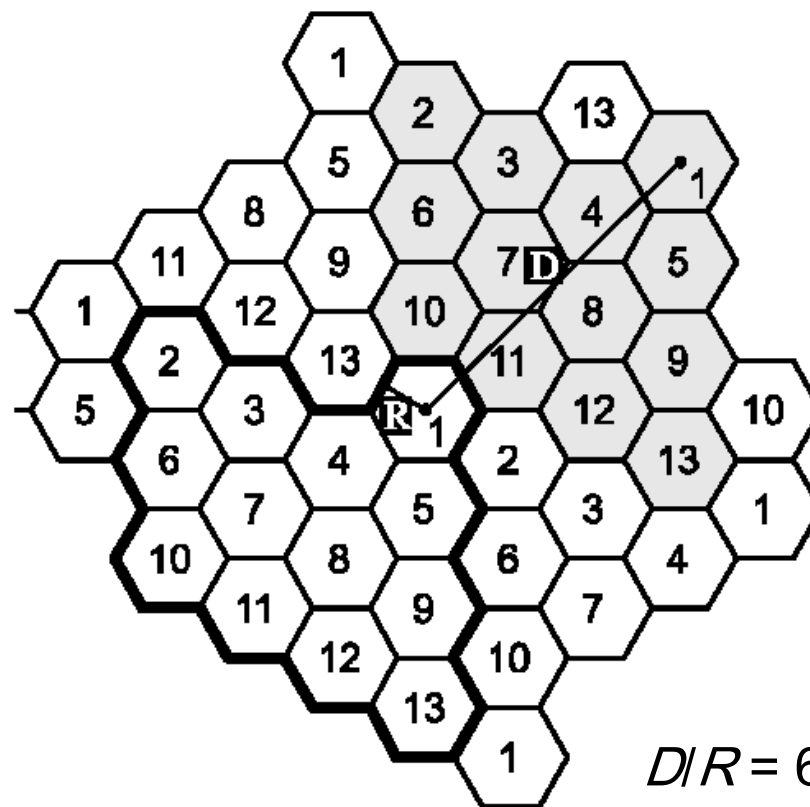
Cellular systems, cont.

Cluster size: $N_{\text{cluster}} = 4$



$$D/R = 3.5$$

Cluster size: $N_{\text{cluster}} = 13$



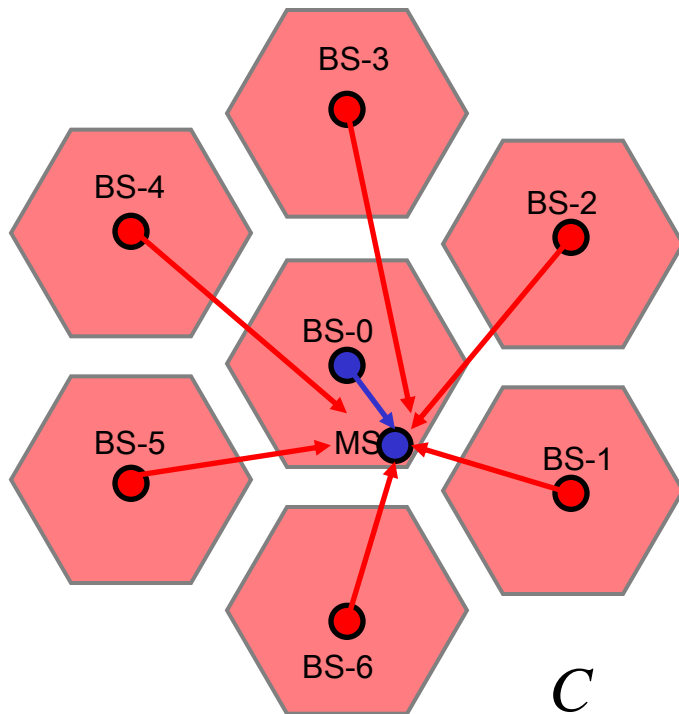
$$D/R = 6.2$$

Copyright: Ericsson

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, \dots, 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 $d_1, \dots, d_6 > D - R$, we get

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

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

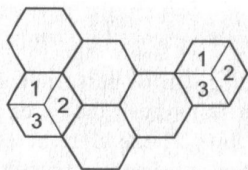


Analog systems,
like NMT

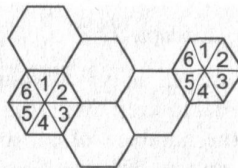
Example: Advanced Mobile Phone System (AMPS, 1983)

- 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?

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

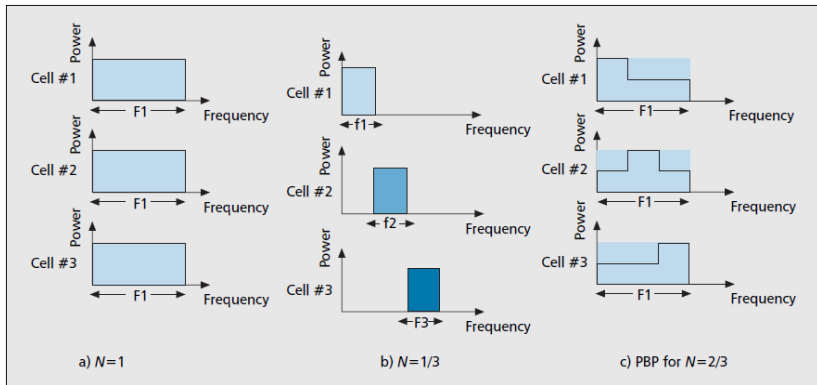


a) 120°-sectorization



b) 60°-sectorization

Figure 17.13 Principle behind sector cells.



- 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