NRA

Radio Systems

Radio Resource Assignment in Area Coverage Networks

Roberto Verdone
www.robertoverdone.org

roberto.verdone@unibo.it
+39 051 20 93817

Office Hours:
Monday 4 – 5 pm

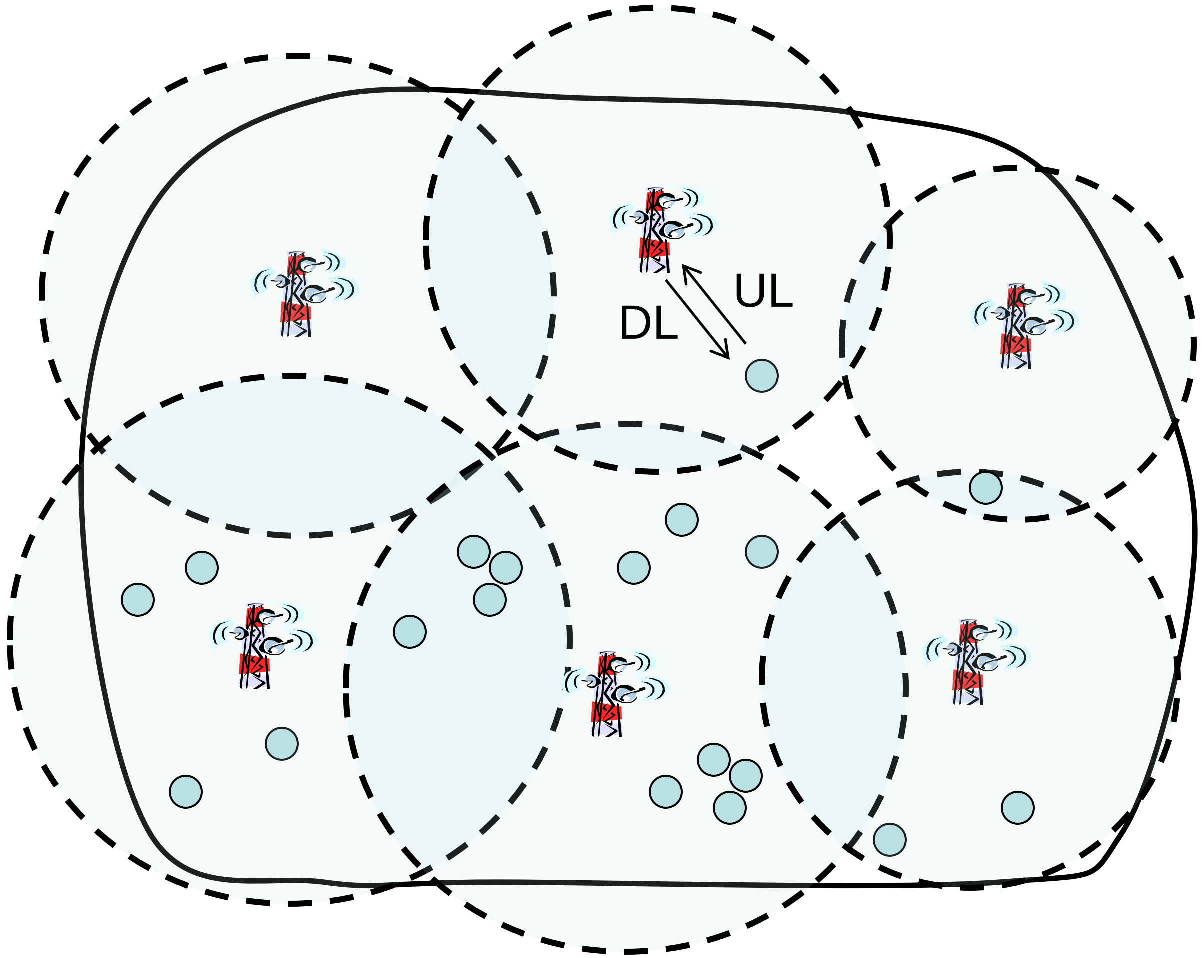
A.Y. 2015-16
Credits: 6

Outline

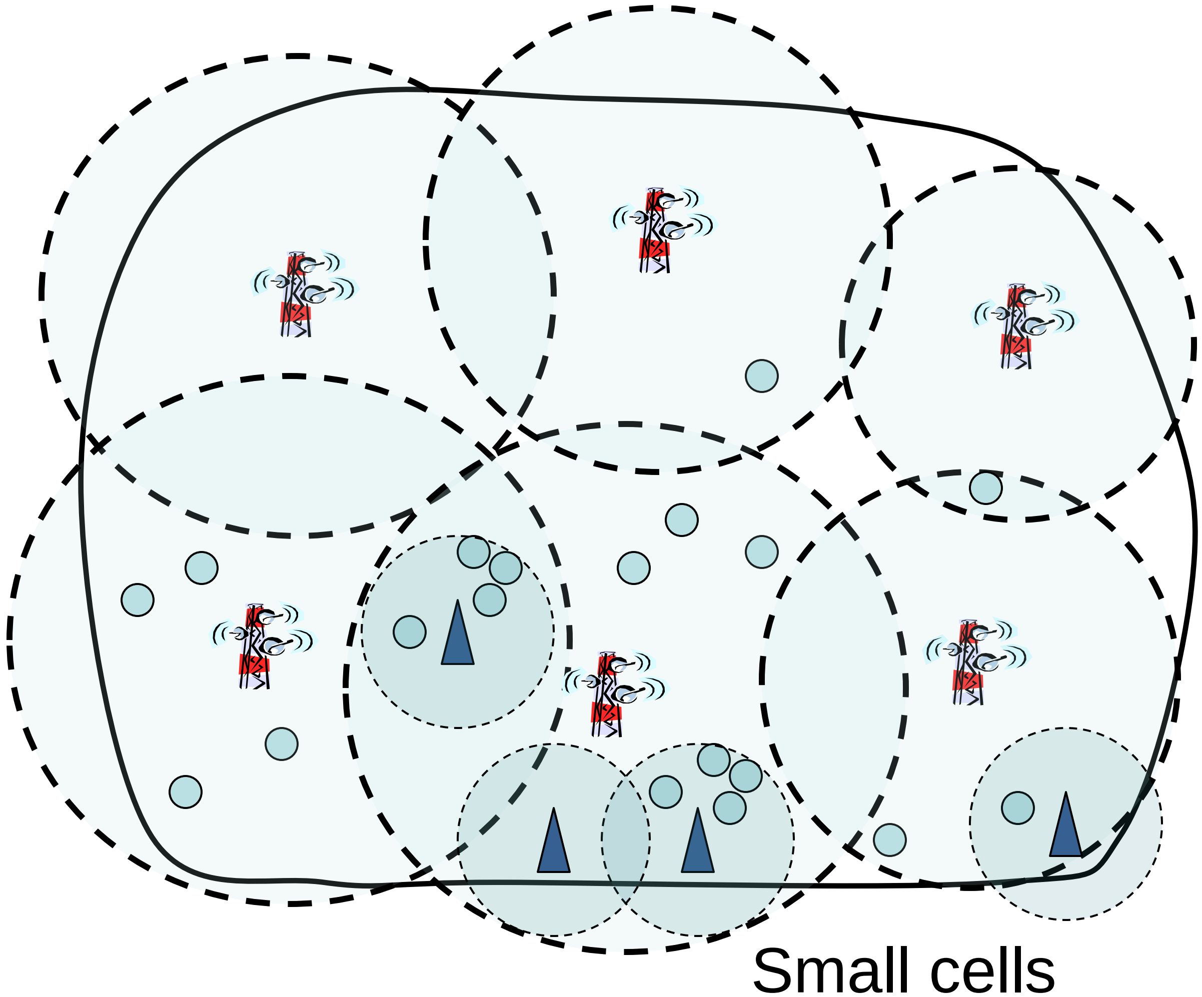
1. **Radio Resources**
2. **Radio Resource Assignment**
3. **Area Coverage Networks (Radio Access Networks - RANs)**
4. **Cellular Reuse**
5. **RANs: Network Spectrum Efficiency**

The scope of this lecture block is to introduce the basic concepts related to the use of the radio spectrum as a shared and limited resource in area coverage networks (including cellular networks).
Data Link (Medium Access Control) and Network protocol Layers are involved.

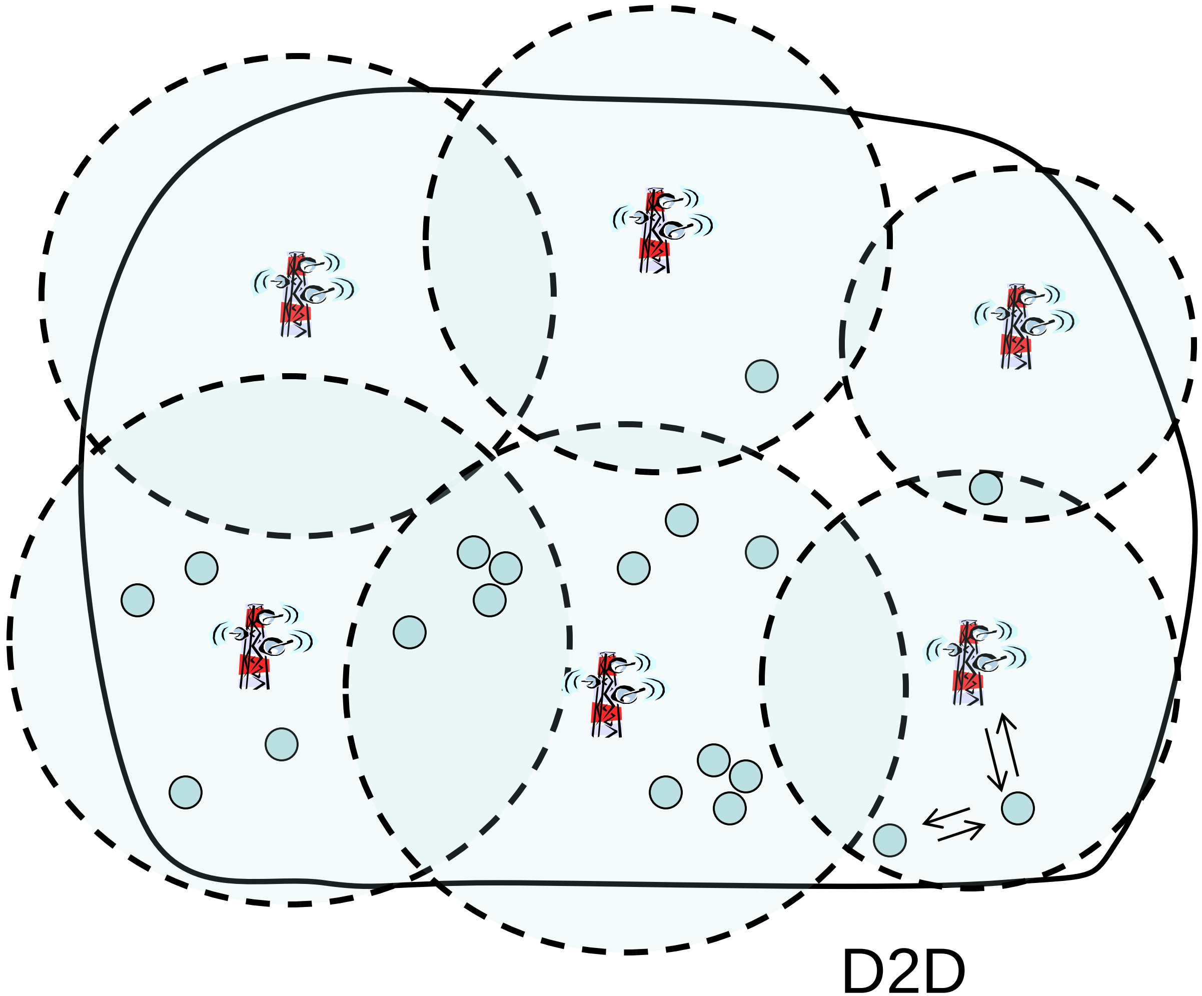
Area Coverage Networks / Cellular Networks



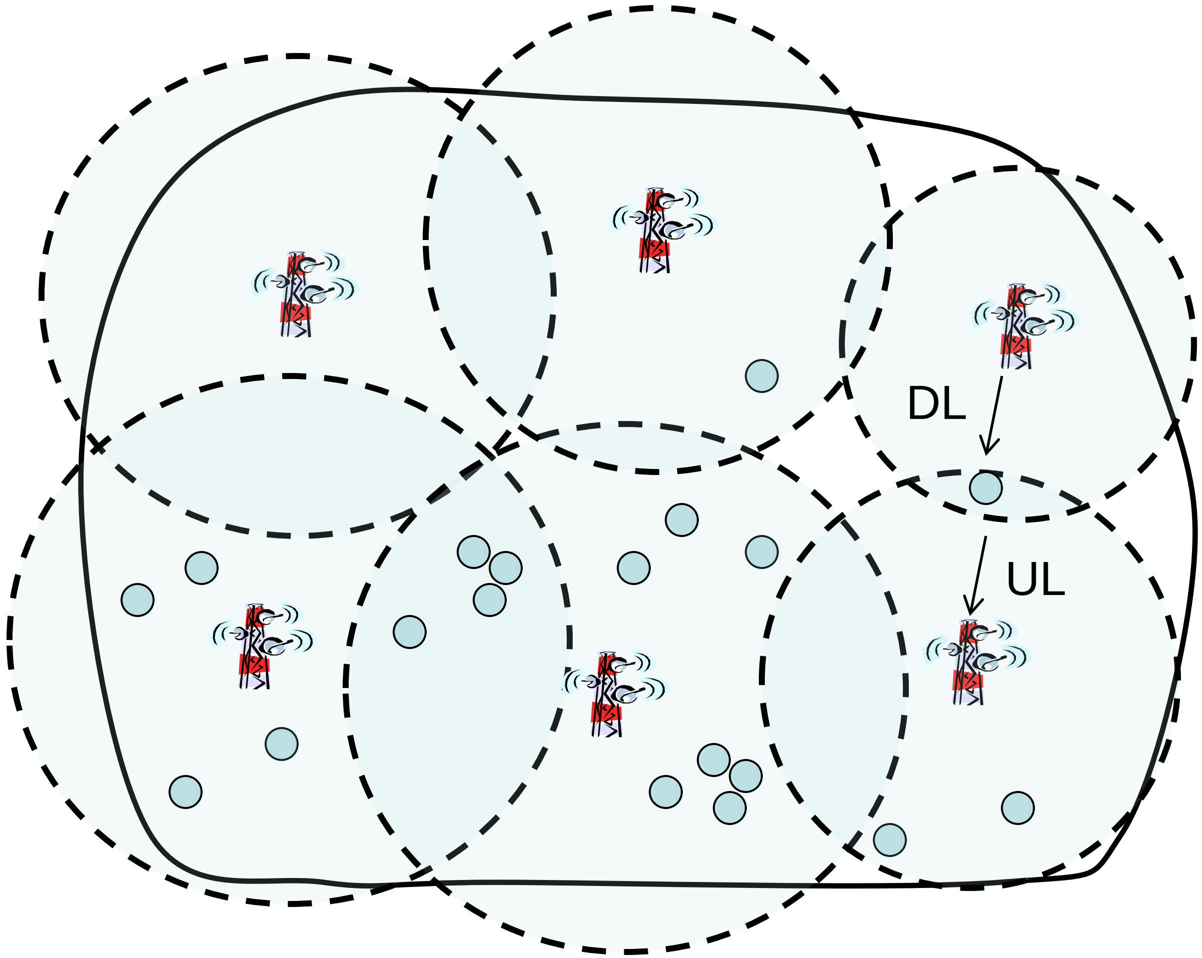
Area Coverage Networks / Cellular Networks



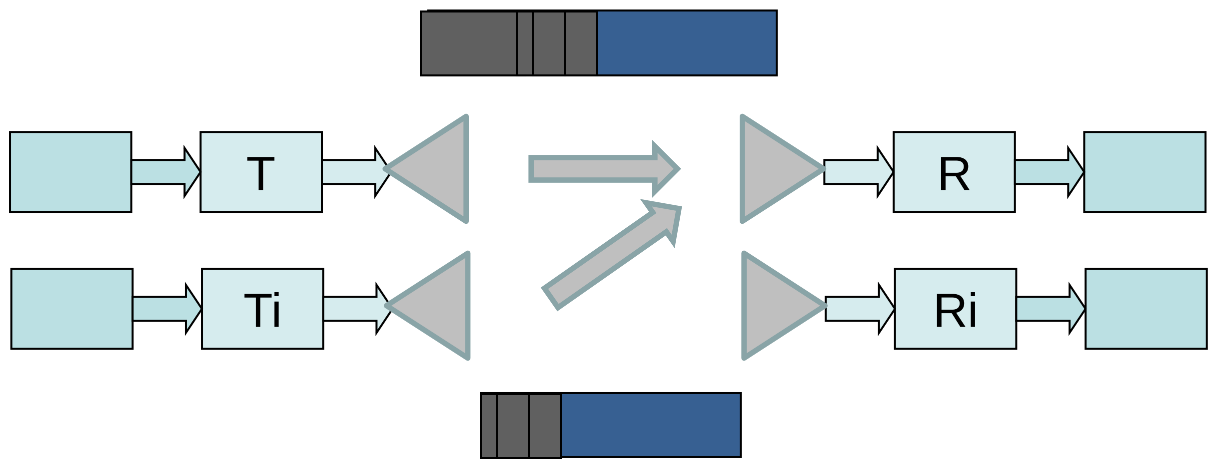
Area Coverage Networks / Cellular Networks

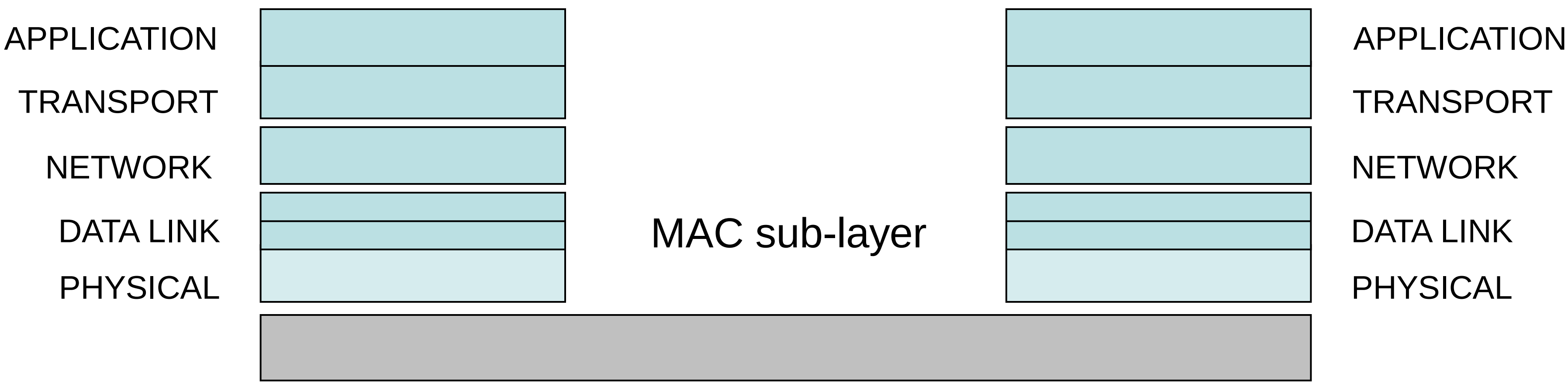


Area Coverage Networks / Cellular Networks

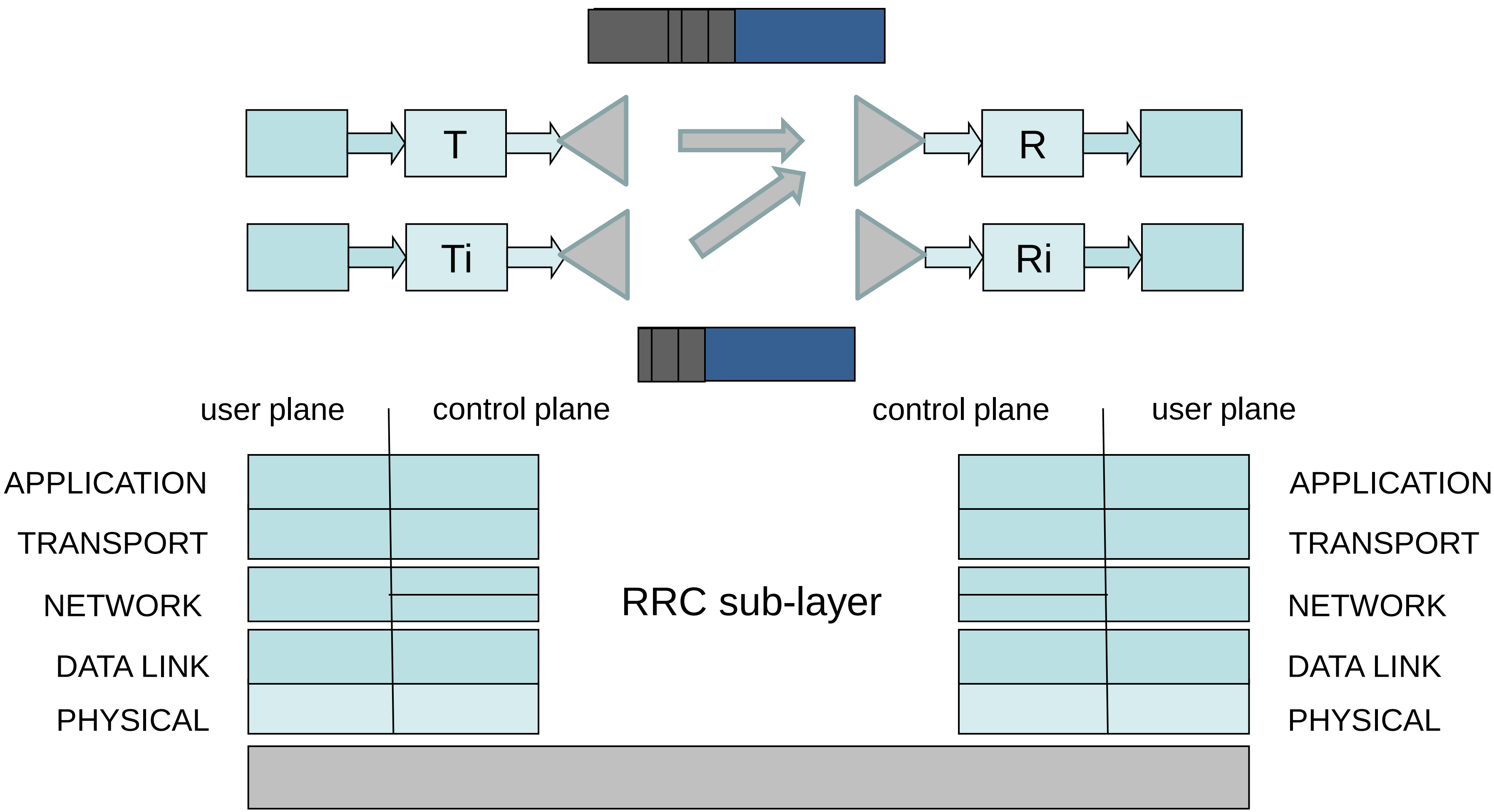


Medium Access Control





Radio Resource Control



1. Radio Resources

Radio Resources

Medium Access Control (MAC) and Radio Resource Control (RRC)

Both MAC and RRC address the problem of assigning radio resource units to data blocks in a shared radio environment, at a different pace

Radio Resource (RR)

A *radio waveform* allowing the transmission of a given data block (m bits)

Radio Resource Payload

Amount of information bits (as seen by data link layer) carried by the radio resource

Radio Resource Unit (RU)

A RR carrying the minimum value of Radio Resource Payload that can be assigned

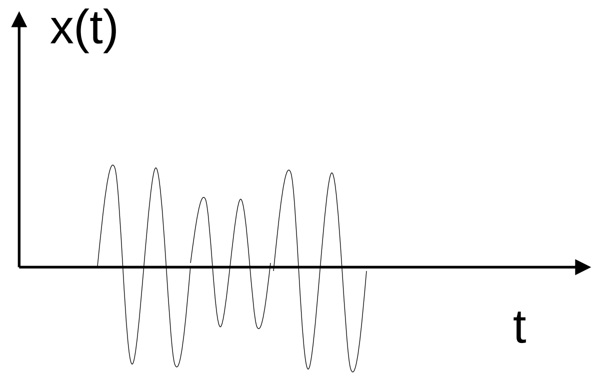
The scope of RR Assignment is to maximise the exploitation of the available RUs while fulfilling Quality of Service (QoS) requirements:

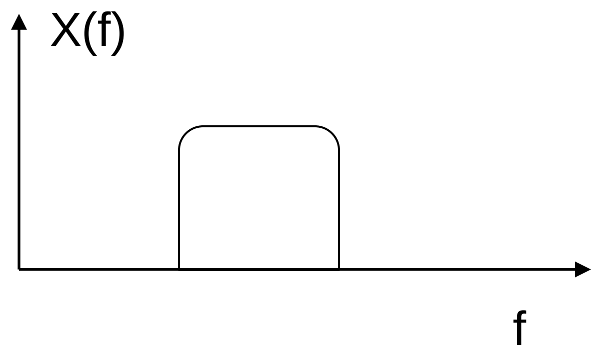
tradeoff between network spectrum efficiency and QoS

Radio Resources

The RU assignment implies the definition of all characteristics of the radio waveform.

From the signal viewpoint:





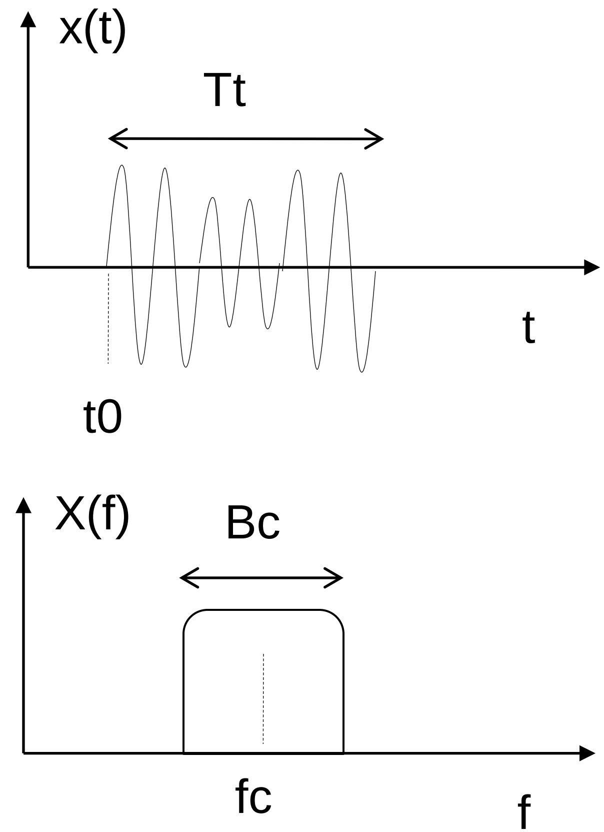
RU = [?]

Radio Resources

The RU assignment implies the definition of all characteristics of the radio waveform.

From the signal viewpoint:

- energy level (E),
- modulation and coding scheme (MCS),
- carrier frequency (fc),
- start time (t0),
- duration (Tt),
- bandwidth (Bc).



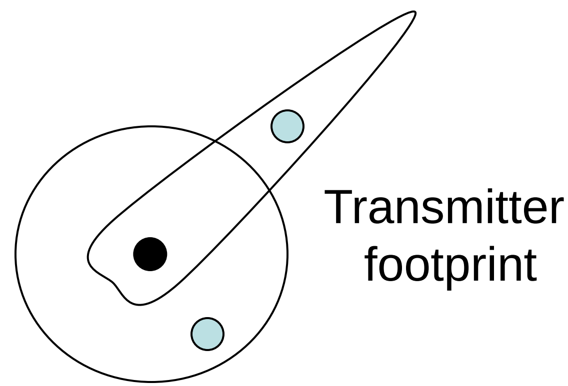
RU = [E, MCS, fc, t0, Tt, Bc]

Radio Resources

The RU assignment implies the definition of all characteristics of the radio waveform.

From the *radio* signal viewpoint:

- energy level (E),
- modulation and coding scheme (MCS),
- carrier frequency (fc),
- start time (t0),
- duration (Tt),
- bandwidth (Bc),
- antenna pattern (Ga)



RU = [E, MCS, fc, t0, Tt, Bc, Ga]

Radio Resources: Bi-directionality

FDD (Frequency Division Duplexing)

The two links use different frequency bands (e.g. 2G, 3G, 4G)

RU = [E, MCS, fc, t0, Tt, Bc, Ga]

TDD (Time Division Duplexing)

The time axis is divided in two, and fast alternate transmissions occur (e.g. Bluetooth, WiFi)

RU = [E, MCS, fc, t0, Tt, Bc, Ga]

Radio Resources: Bi-directionality

Duplexing Technique	Advantages	Disadvantages
FDD	simple	duplexer needed to avoid transmitter-to-receiver interference
TDD	cheaper	synchronisation at link level receiver sensitivity (larger overall bit rate) synchronisation at network level

With TDMA, the disadvantage of FDD is overcome by assigning separate slots to UL and DL in an area coverage network.

2. Radio Resource Assignment

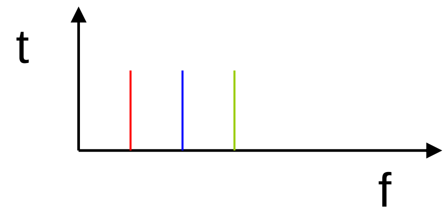
Radio Resource Assignment

Radio Resources can be assigned to users *orthogonally* within a given area:

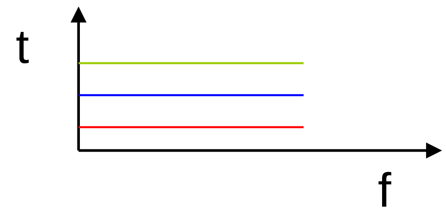
$$\text{Int}\,[\,x(t)\,y(t)\,] = 0$$

If they are orthogonal, users will not interfere.
Otherwise, *collision resolution* or *interference rejection* techniques must be used.

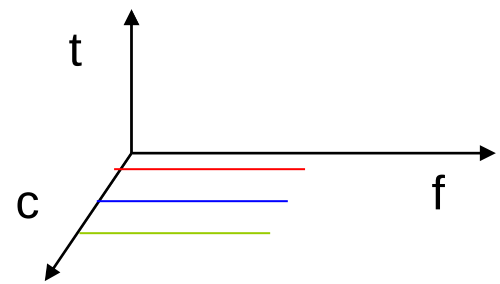
Orthogonality can be normally reached via Frequency (FD), Time (TD), Code (CD), Space Division (SD) or a mixture of them (e.g. FTD)



FD

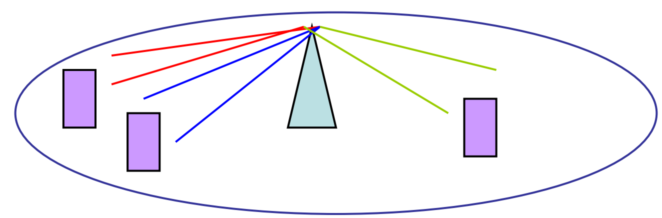


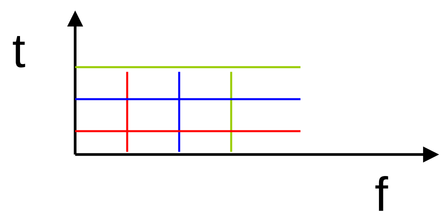
TD



CD

SD

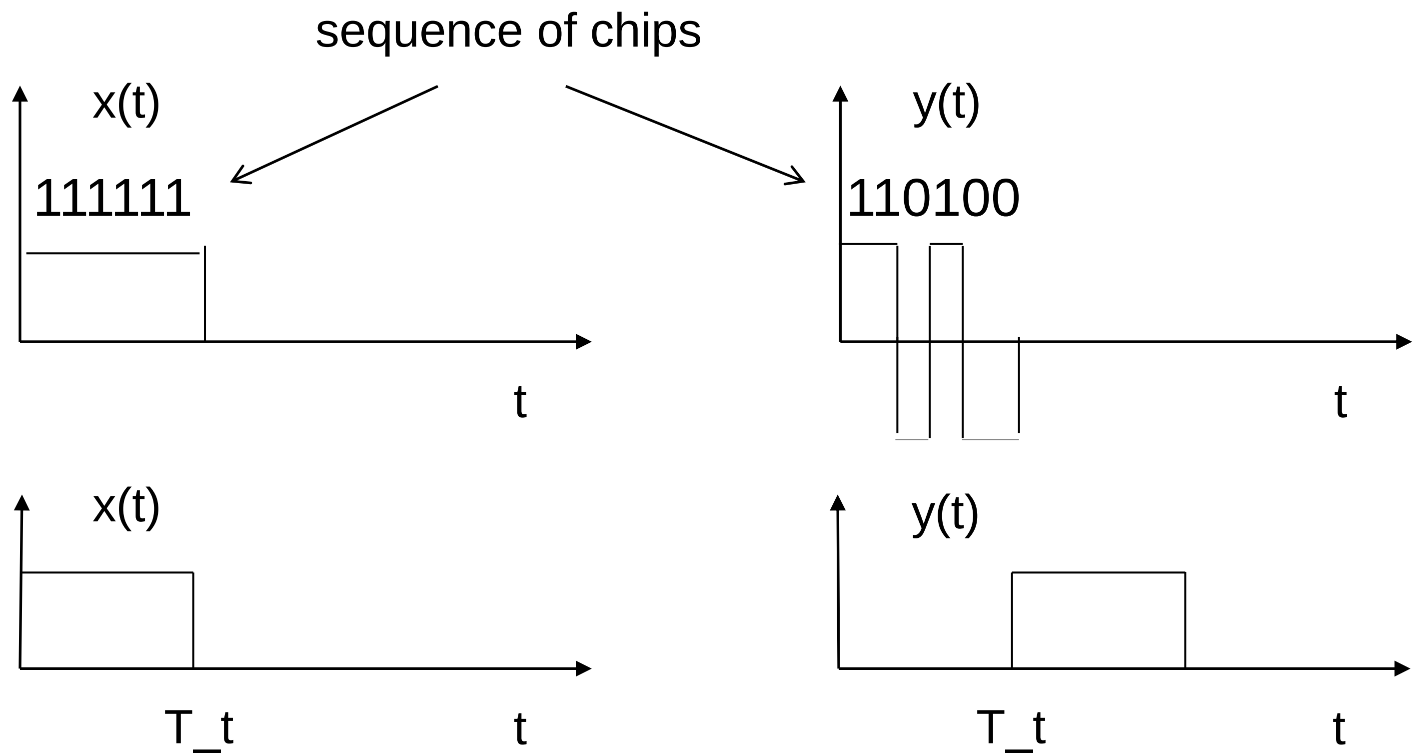




FTD

2G: FTDMA
3G: FCDMA
4G: FTDMA (OFDMA or SC-TFDMA)

Radio Resource Assignment



CDMA

TDMA

$x(t) = X \cos(2 \pi f_1 t) \operatorname{rect}(t/T)$

$y(t) = Y \cos(2 \pi f_2 t) \operatorname{rect}(t/T)$

$f_1 \neq f_2$

FDMA (approx)

$f_1 = f_2 + k / T$

OFDMA

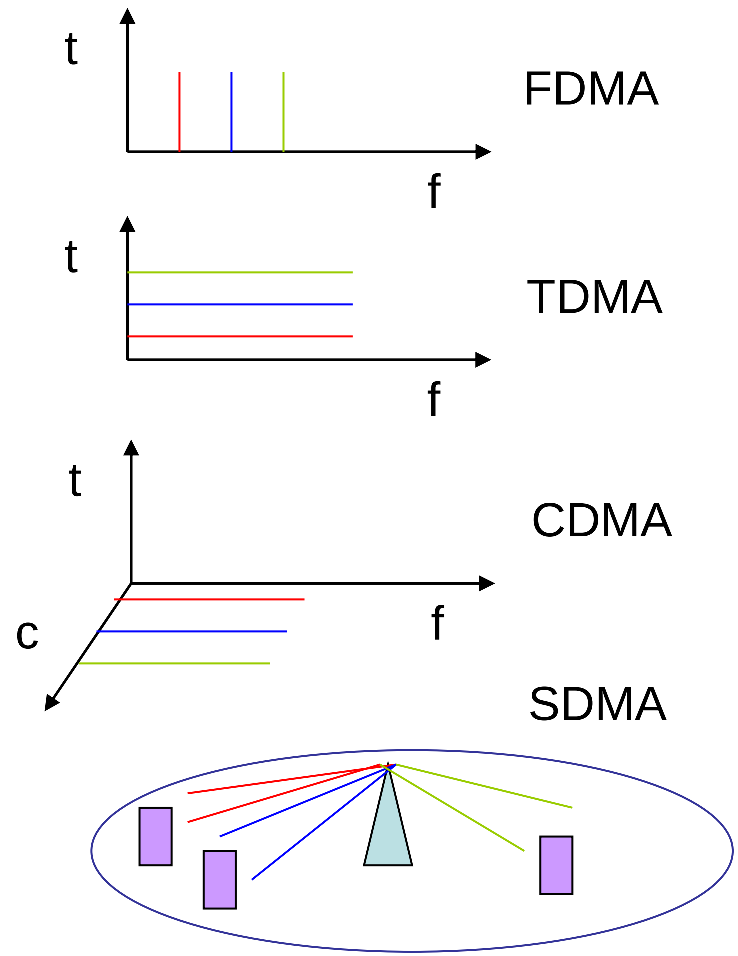
Radio Resource Assignment

RU = [E, MCS, fc, t0, Tt, Bc, Ga]

RU = [E, MCS, fc, t0, Tt, Bc, Ga]

RU = [E, MCS, fc, t0, Tt, Bc, Ga]

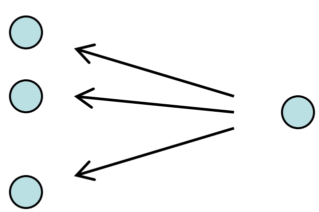
RU = [E, MCS, fc, t0, Tt, Bc, Ga]



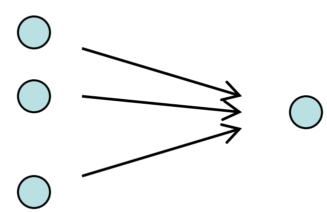
Radio Resource Assignment

MA technique	Advantages	Disadvantages
FDMA	simple	# of receivers in MPtoP systems non linear effects in PtoMP systems
TDMA	cheaper in MPtoP systems slots for measurements available	synchronisation thermal noise (larger overall bit rate)
CDMA	inherent encription time resolution	code orthogonality larger bandwidth
SDMA	protection against interference space is not limited resource	technological complexity

PtoMP



MPtoP



Radio Resource Assignment

(Centralised) Fixed RR Assignment

A centralised network entity assigns RUs to nodes based on pre-defined schemes

(Centralised) Dynamic RR Assignment

A centralised network entity assigns RUs to nodes based on dynamic schemes
[scheduling]

(Distributed) Controlled RR Assignment

Nodes self-assign RUs based on concerted policies

(Distributed) Random RR Assignment

Nodes self-assign RUs without concerted policies
[contention based]

Radio Resource Assignment

Radio Resource Set

It is the set of RUs available to the users in a given area.

Radio Resource Set Capacity

It is the number of RUs that can be assigned to the users in a given area under some QoS constraints.

Hard Capacity: in some cases the maximum number of RUs available is known
Soft Capacity: in some other cases this number has no fixed maximum value

2G: hard capacity
3G: hard capacity in the DL, soft capacity in the UL
4G: hard capacity

3. Area Coverage Networks

Area Coverage: Hot Spot

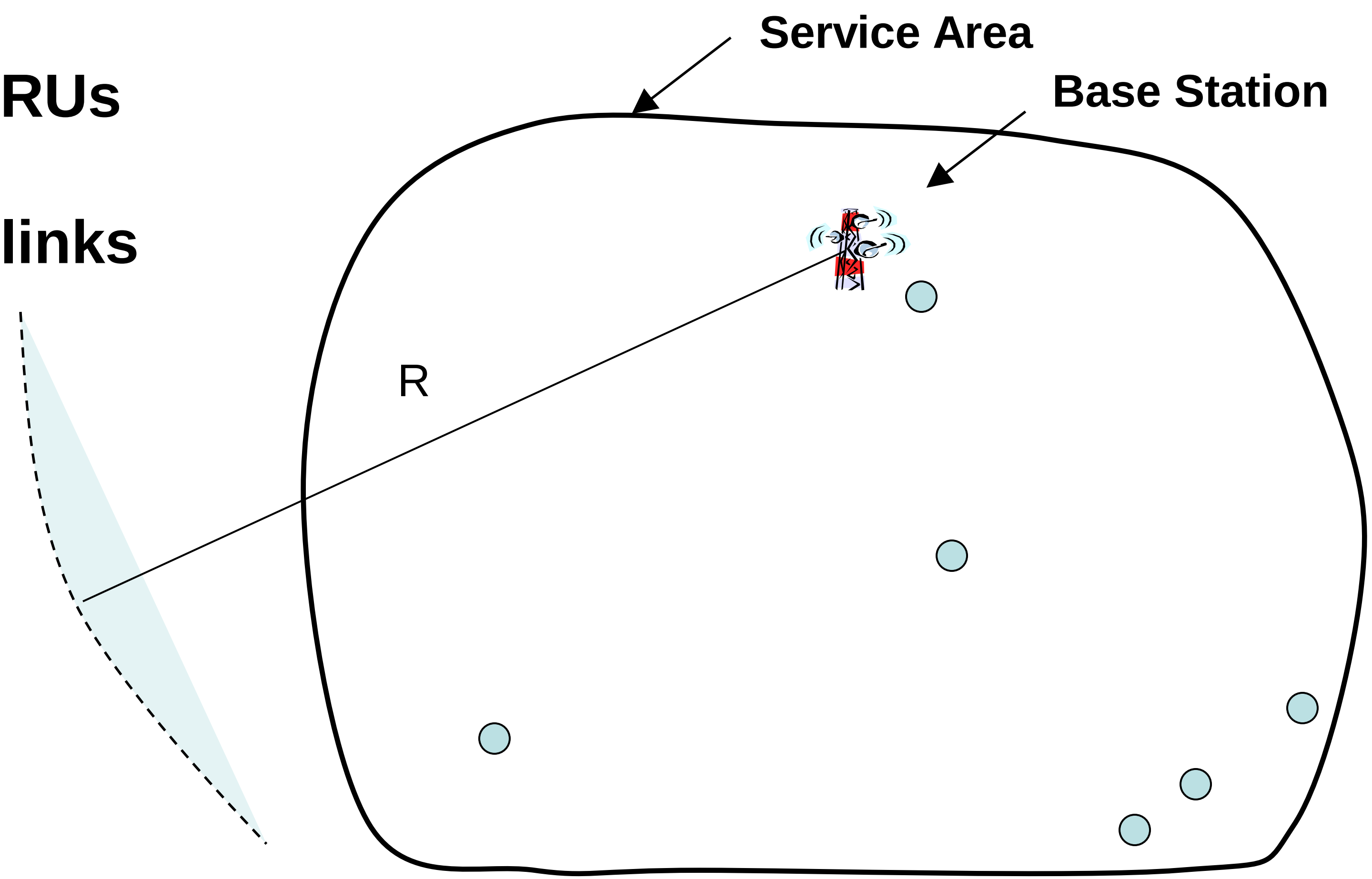
Ex.:

N RUs

N = 12

L links

L = 6

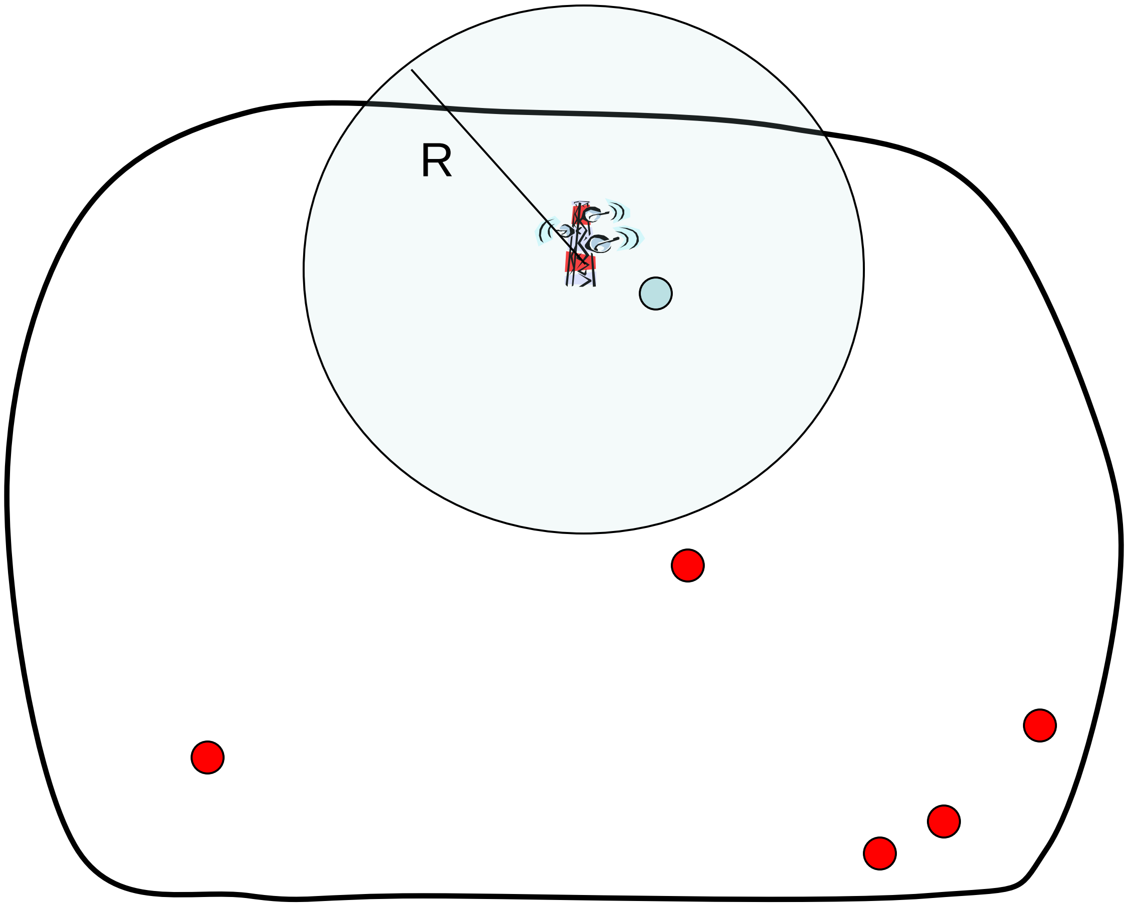


Assumptions: N > L R sufficiently large

Area Coverage: Cells

N RUs

L links



Ex.:

N = 12

L = 6

Assumptions: N > L R not sufficiently large

Area Coverage: Cells

Ex.:

N RUs

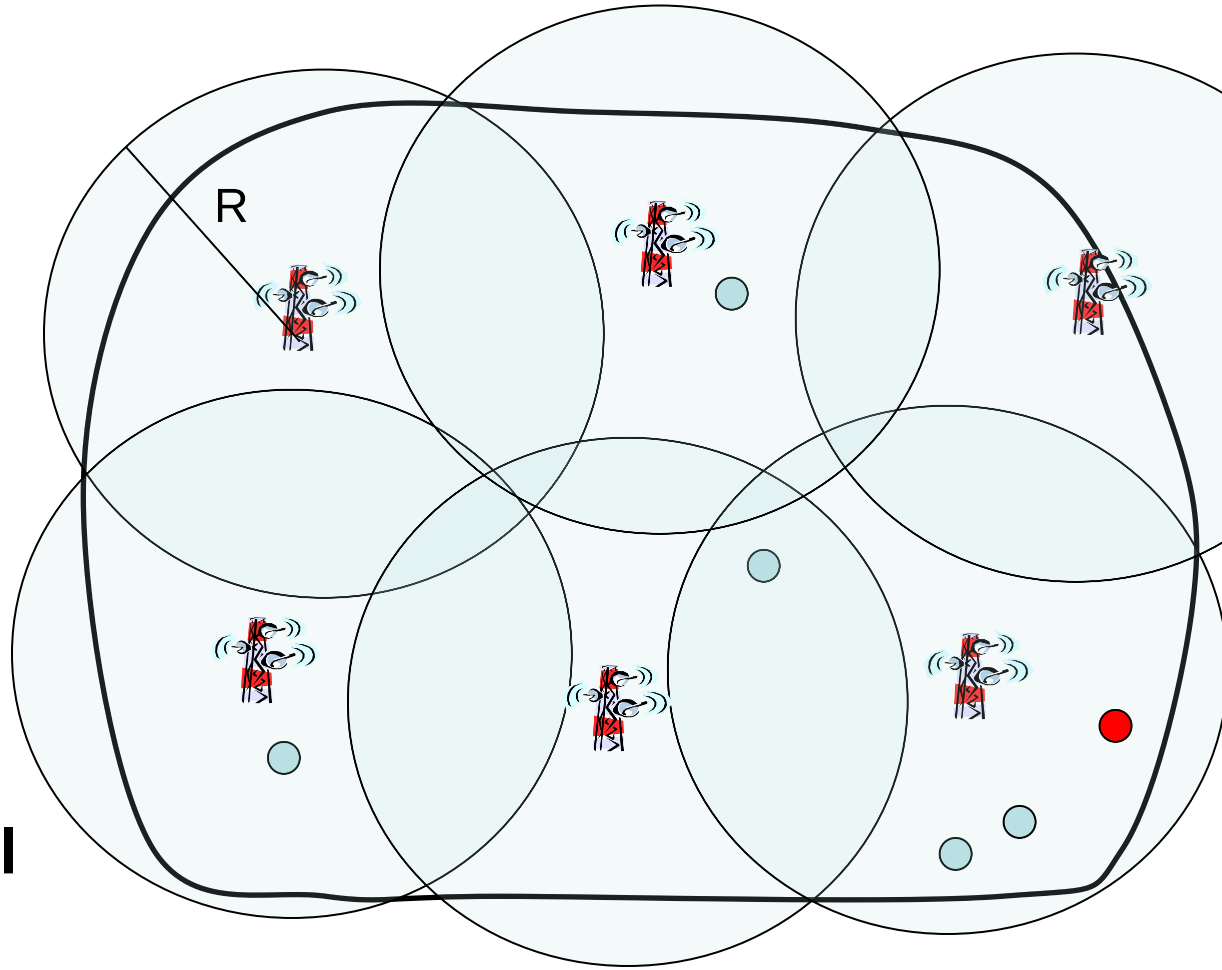
N = 12

L links

L = 6

Z cells

Z = 6

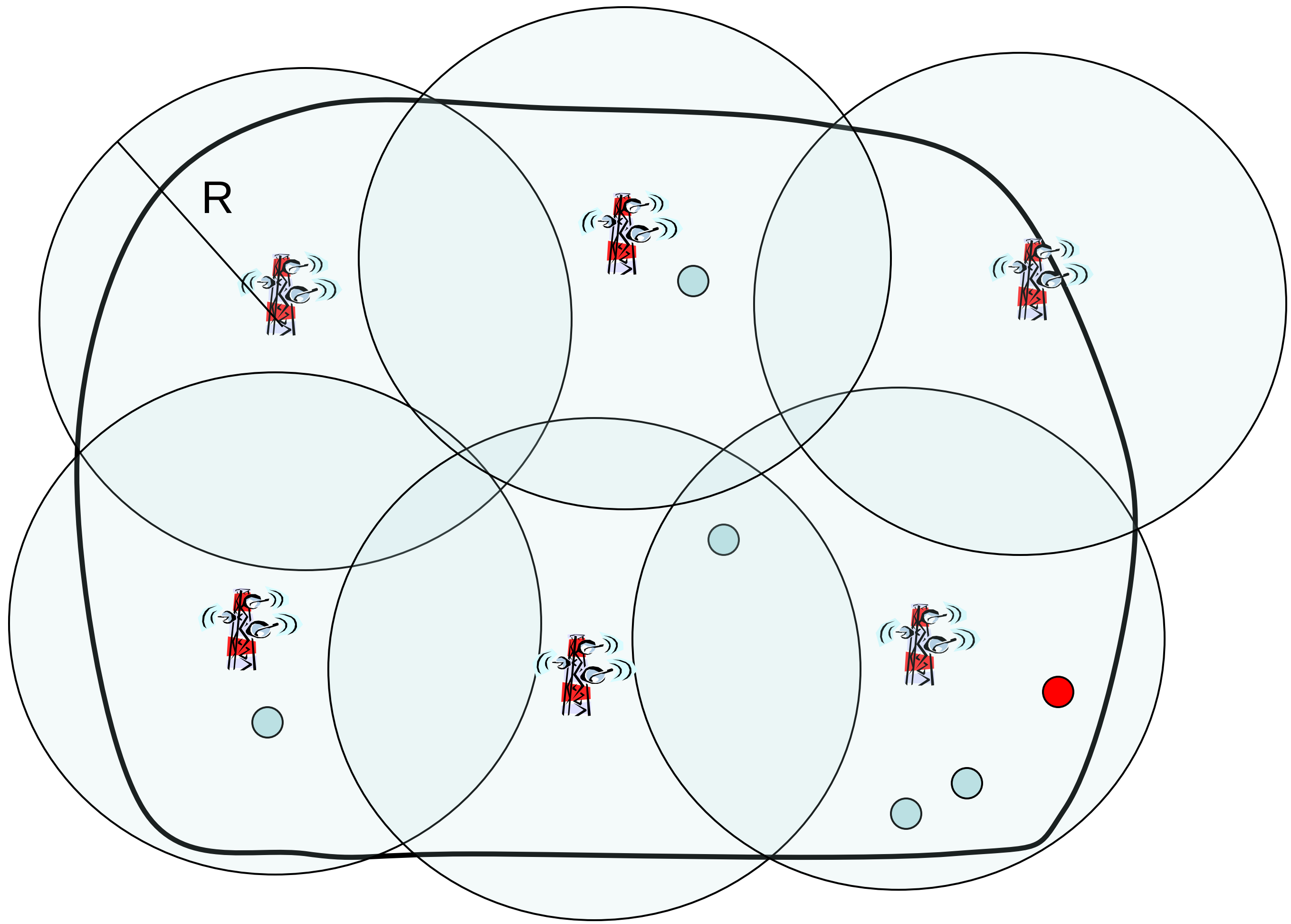


n RUs/cell

n = N / Z

n = 2

Area Coverage: Cells



Splitting resources in separate pools is bad!

Area Coverage: Reuse

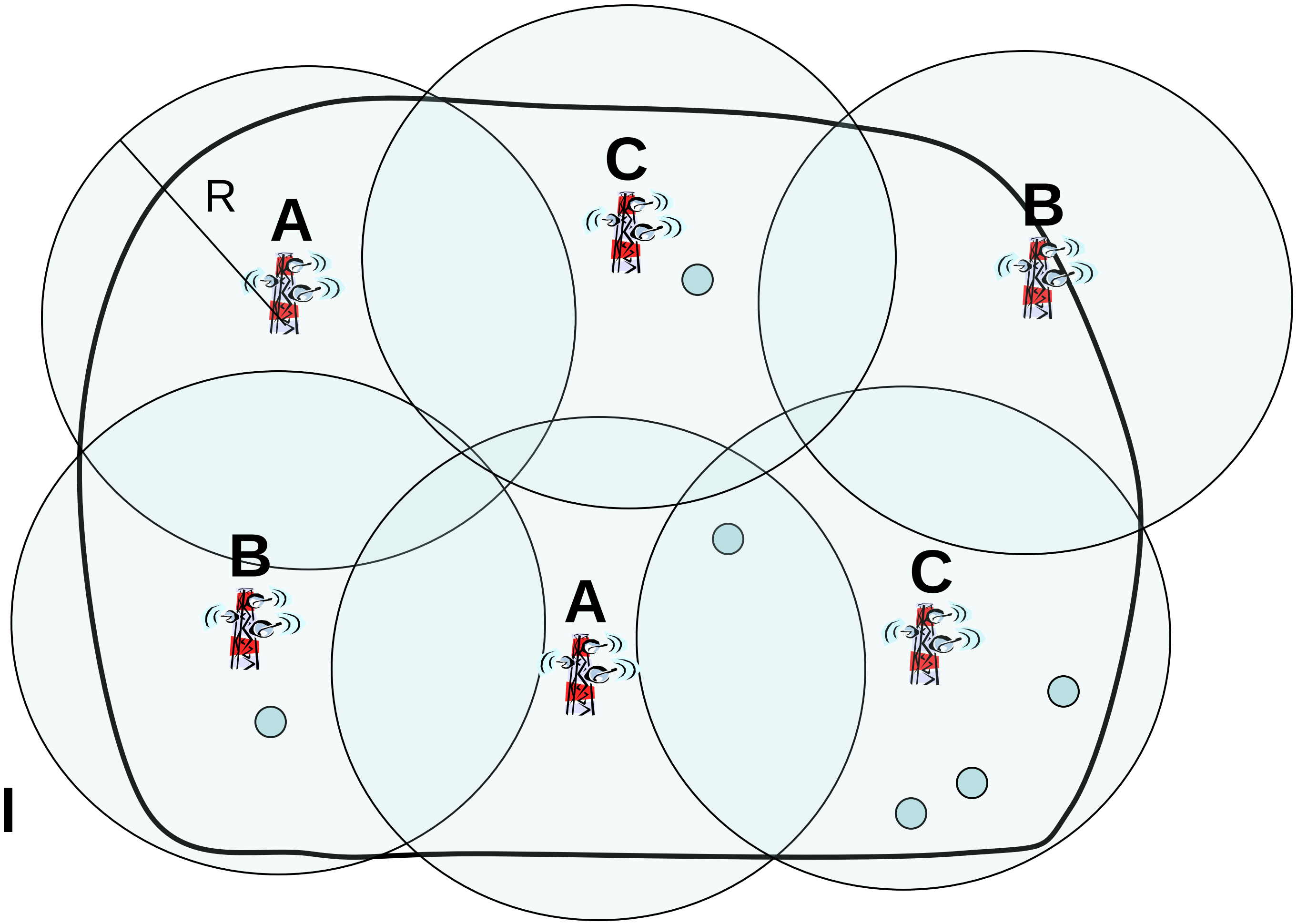
Ex.:

N RUs — N = 12

L links — L = 6

Z cells — Z = 6

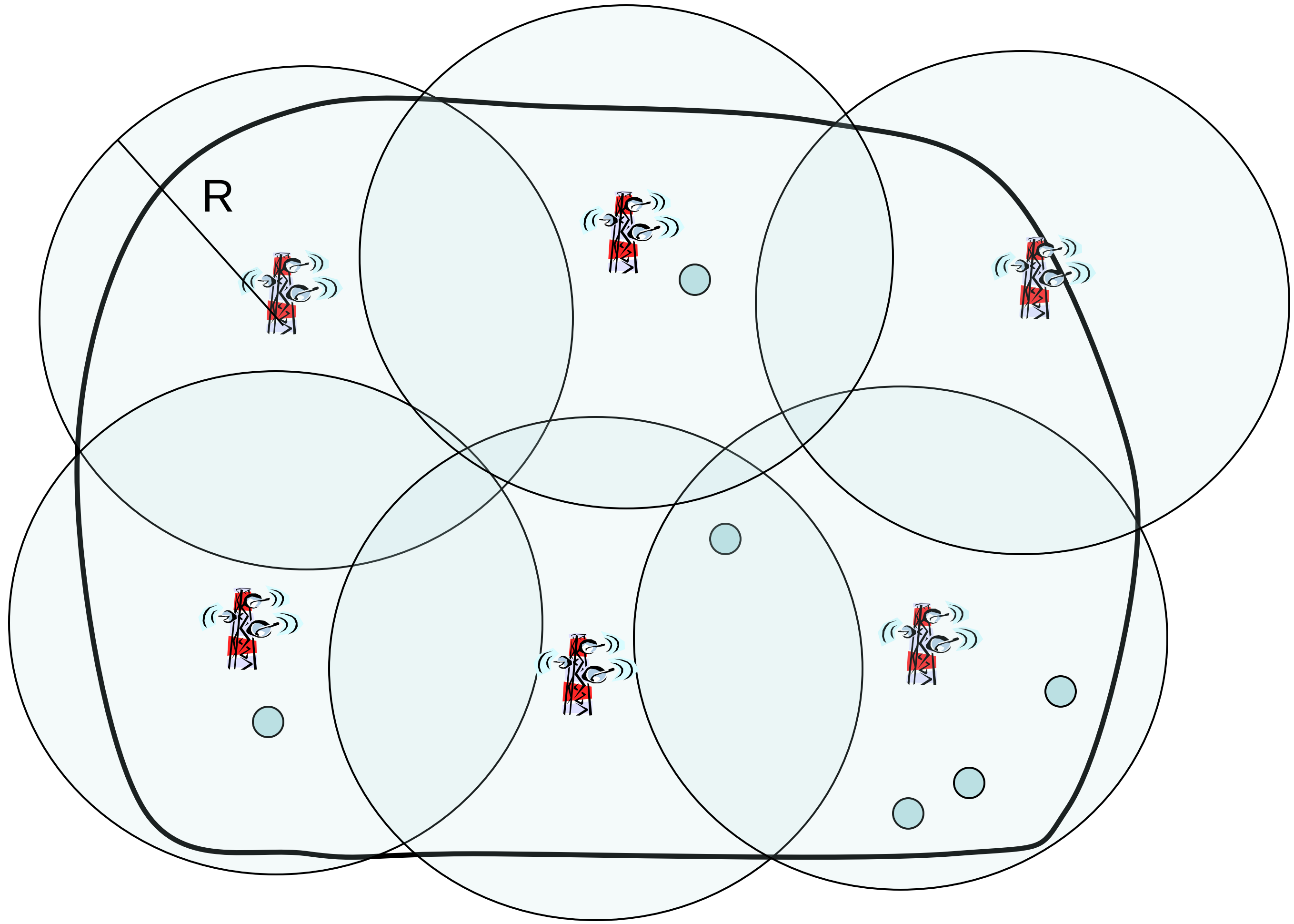
K cells / cluster — K = 3



n RUs/cell

n = N / K — n = 4

Area Coverage: Reuse



Reuse improves Radio Resource Utilisation

Radio Resource Utilisation

N	number of RUs available to the system
O	offered traffic within cell (traffic intensity) [Erlang/cell]*
o = O / n	offered traffic within cell per RU [Erlang/cell/RU]*
E	carried traffic within cell [Erlang/cell]*
e = E / n	carried traffic within cell per RU [Erlang/cell/RU]*

In an area coverage network providing voice call services,
e represents Radio Resource Utilisation,
and should be as LARGE as possible from
the network operator pov.

e can be interpreted as the percentage of time a RU in a cell is utilised

* Erlang = traffic unity; it is the amount of traffic that can be carried by one RU

Radio Resource Utilisation

The simplest way to measure the Radio Resource Utilisation is through the B Erlang formula (assuming a blocking system):

E = O (1 – Pb)

n	**number of RUs within cell**
Pb	**blocking probability**

$$Pb = B[O; n] = [O^n / n!] / [\Sigma^n_{j=0} O^j / j!]$$

if:
the number of users is infinite
arrivals follow a Poisson Time Process (rate λ)
service times follow an i.i.d. negative exponential (rate μ)

O	**offered traffic within cell**	$O = \lambda / \mu$

Radio Resource Utilisation

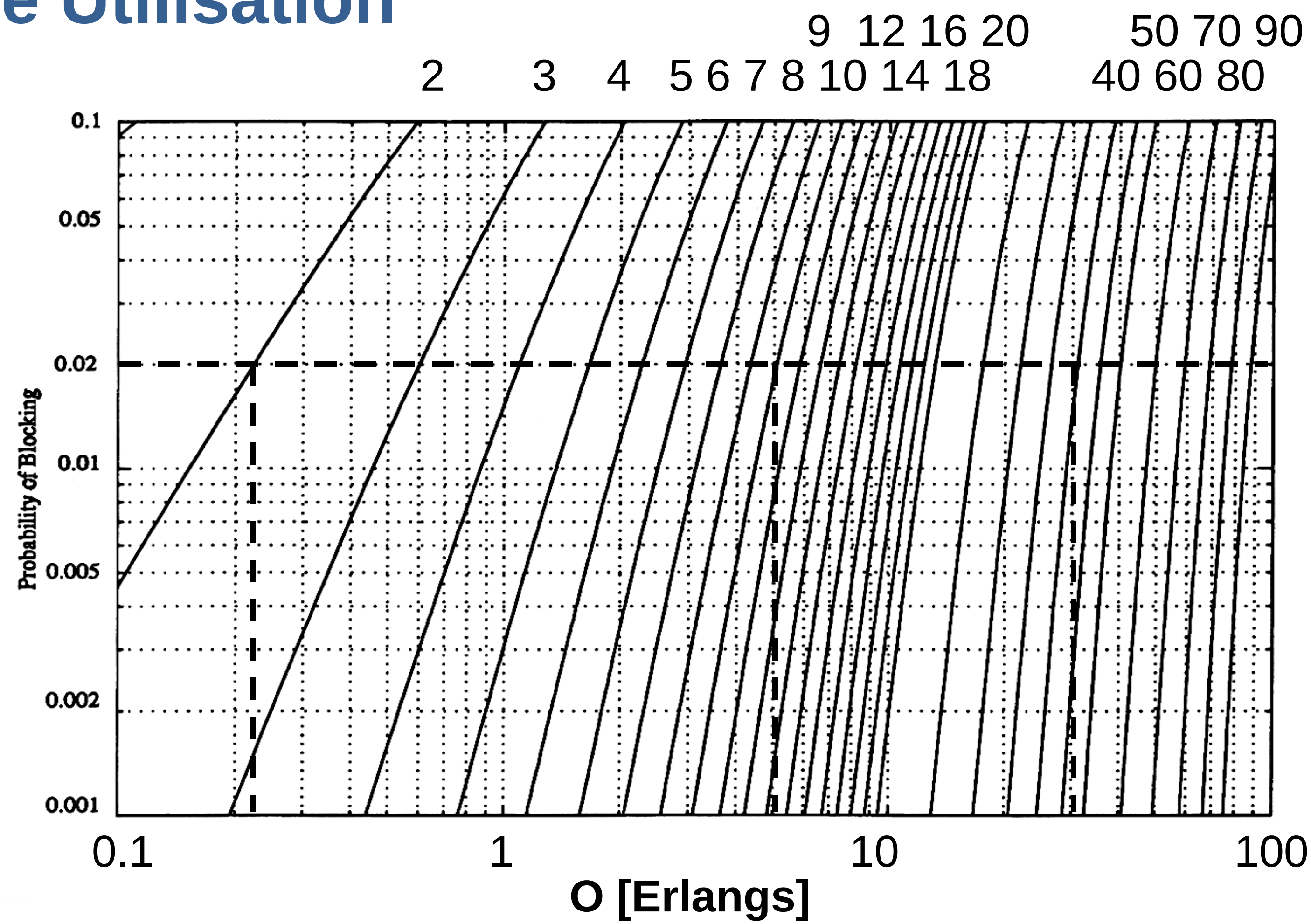
Pb = B [O ; n]

Example:

Pb = 0.02

E = O * 0.98 →
e = o * 0.98 where
o = O / n

n = 2 → e = 0.1
n = 10 → e = 0.5
n = 40 → e = 0.75



Radio Resource Utilisation increases if RUs are assigned to cells in large numbers. Dynamic is better than Fixed RR Assignment schemes.

Cell Size Dimensioning Based on Traffic

How to set R ?

Pb = 0.02

n fixed

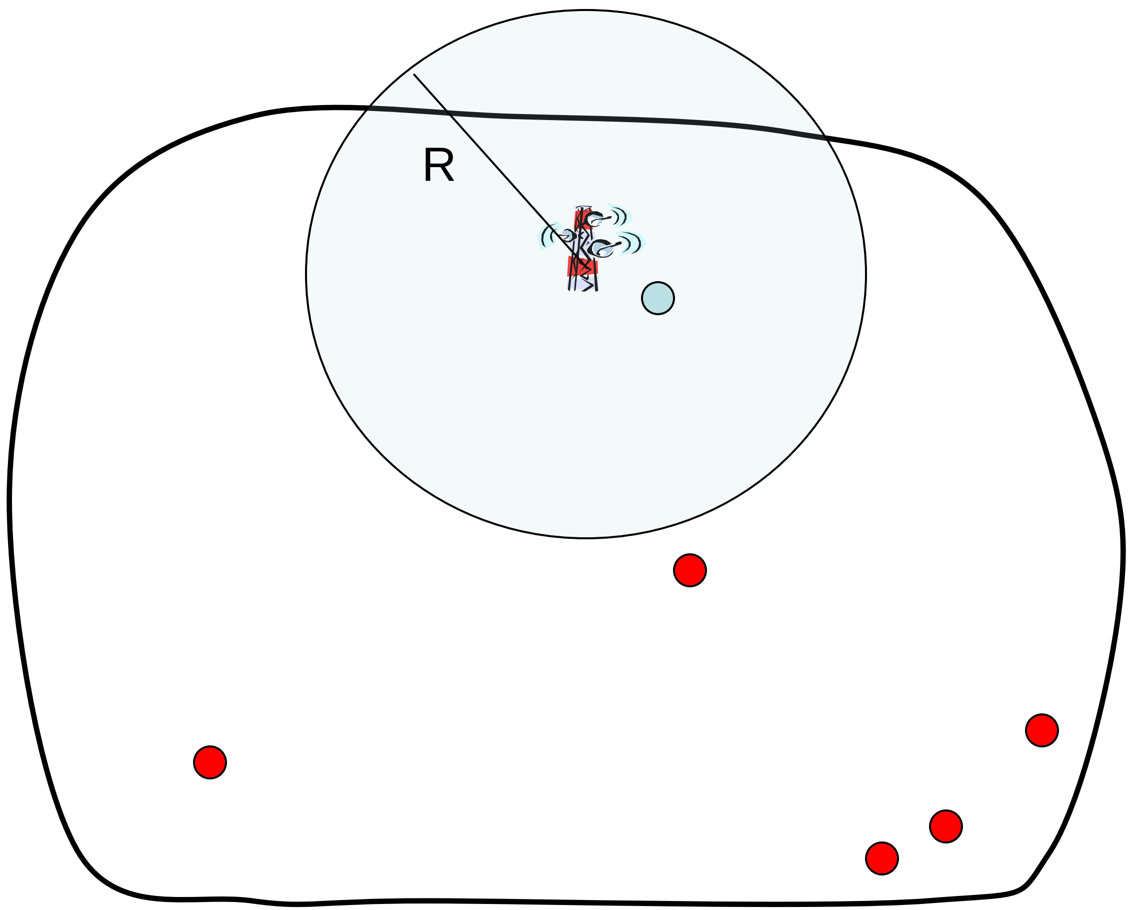
O is derived;

$O = A * \rho$

ρ is fixed

$A = \pi * R^2$

R is derived

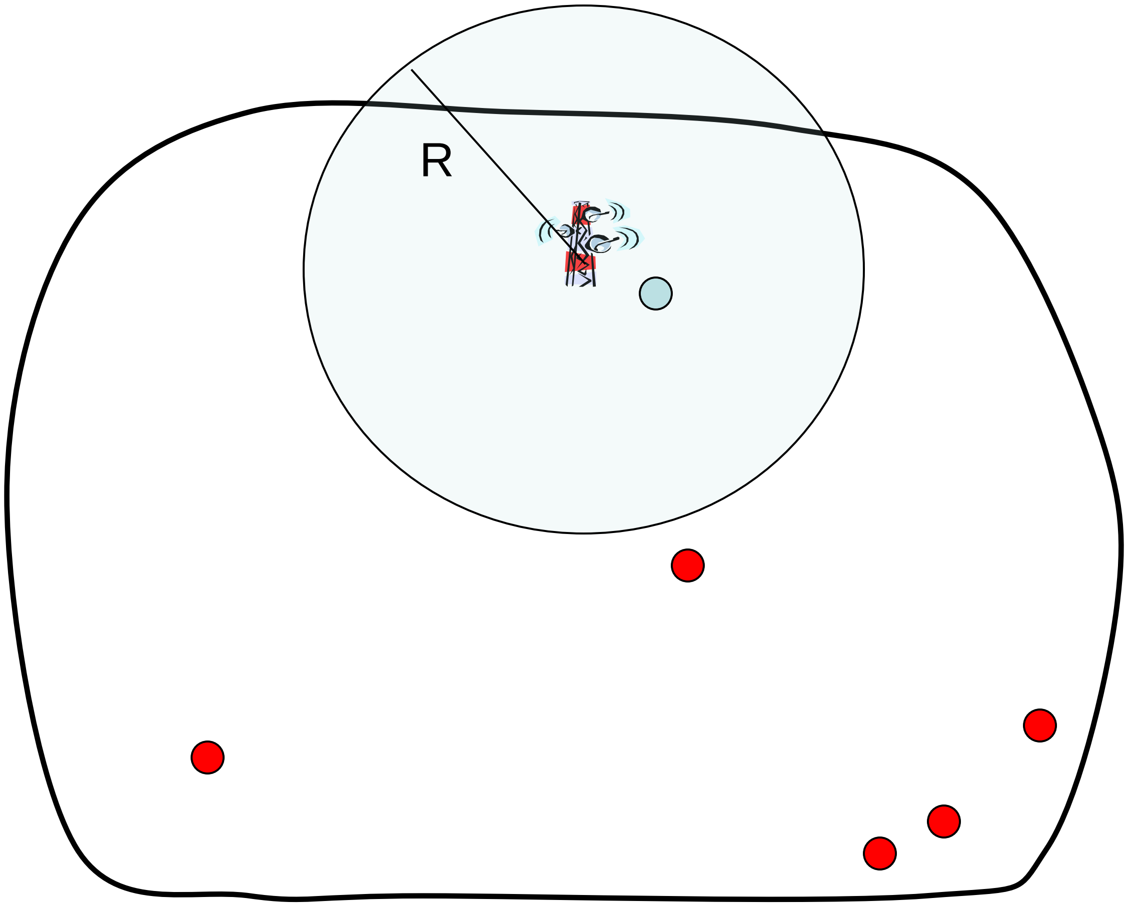


Cell Size Dimensioning Based on Traffic: Exercise

Assume:

Pb = 0.02
n = 60
ρ **= 50 Erl/sqKm**

R = ?



….

R = 0,570 Km

Cell Size Dimensioning Based on Traffic: Exercise / 2

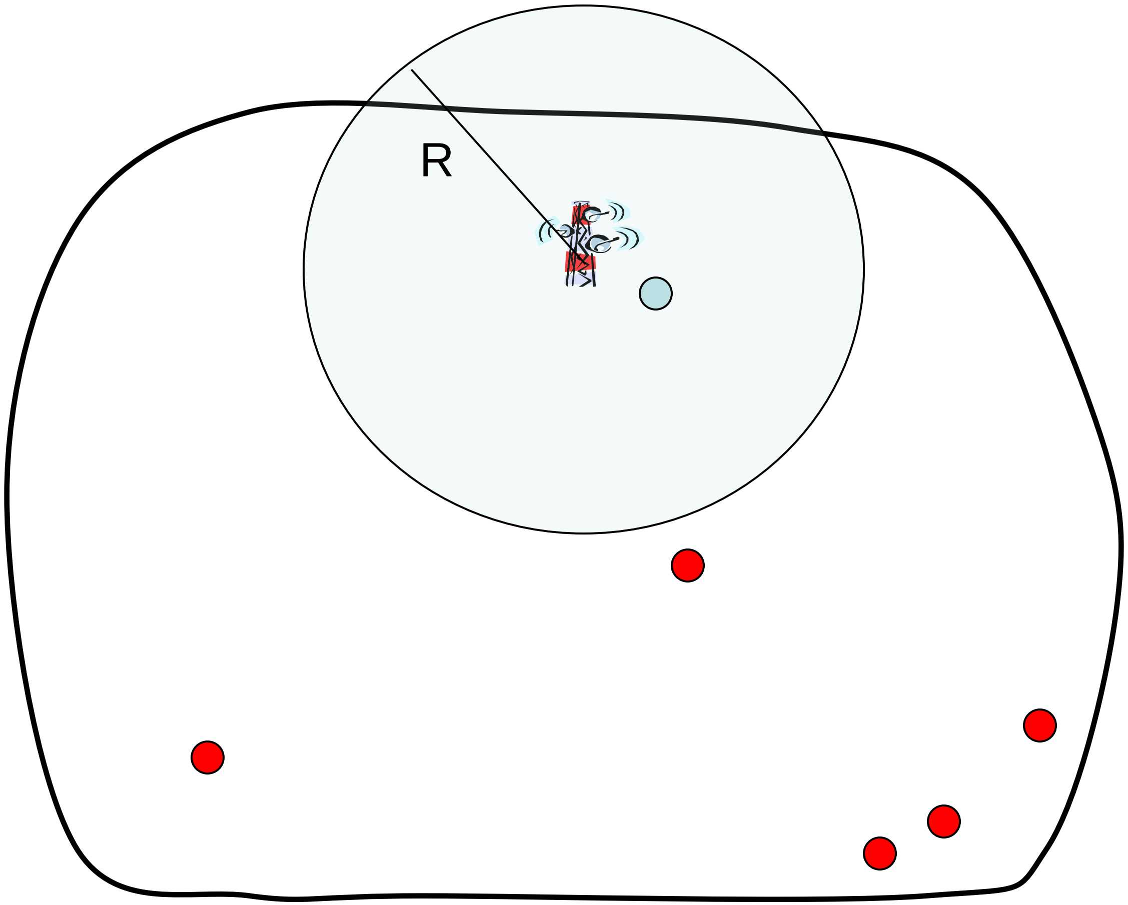
Assume:

Pb = 0.02
n = 15
ρ = 50 Erl/sqKm

R = ?

Pb = 0.02
n = 60
ρ = 200 Erl/sqKm

R = ?



4. Reuse

Reuse

N **orthogonal RUs**

K **cells/cluster**

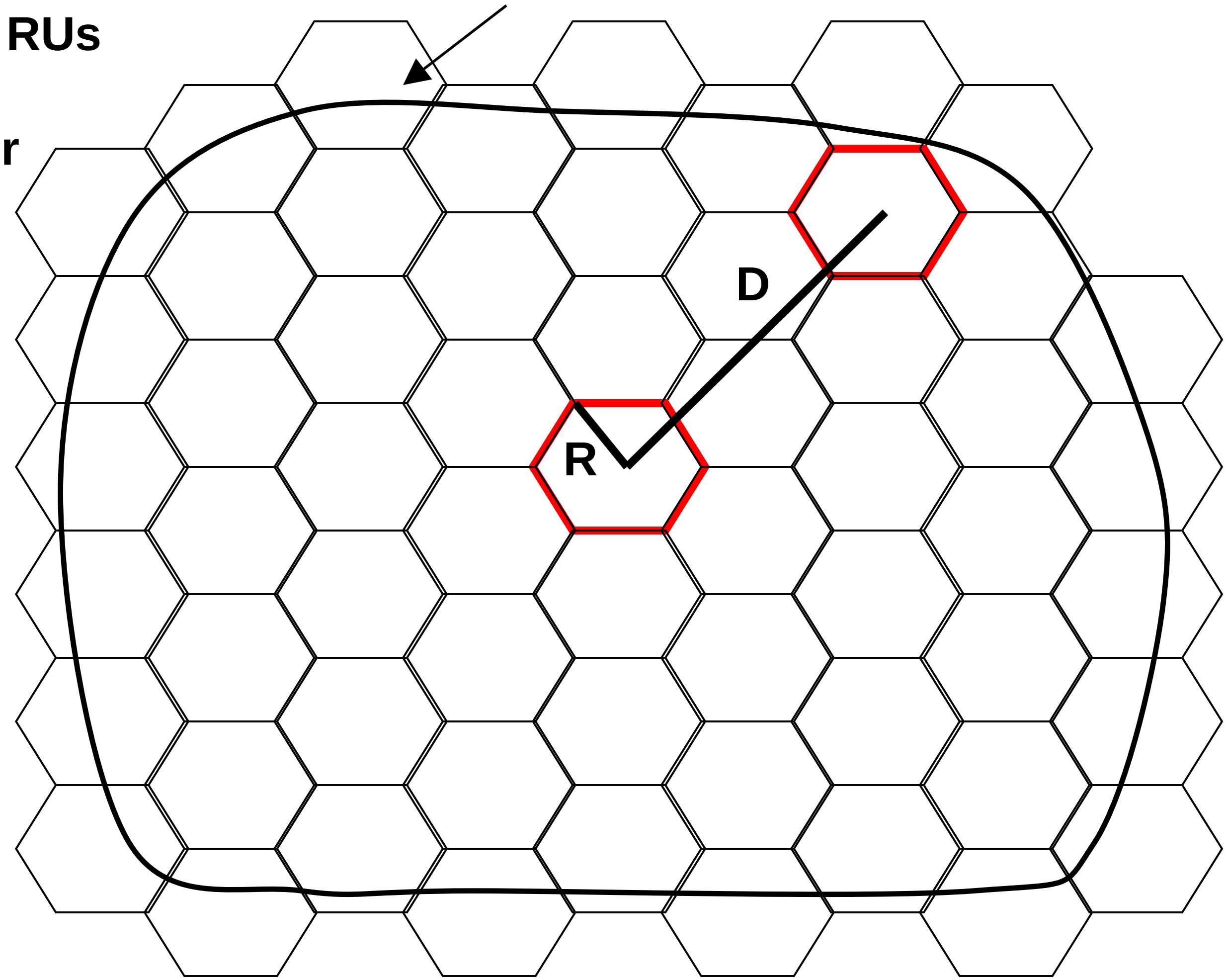
$n = N / K$
RUs/cell

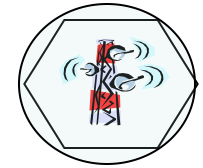
$A = 3^{3/2} R^2 /2$
cell area

$Q = D / R$
Reuse Factor

Z cells

Service Area (Z = 60 cells)





One base per cell

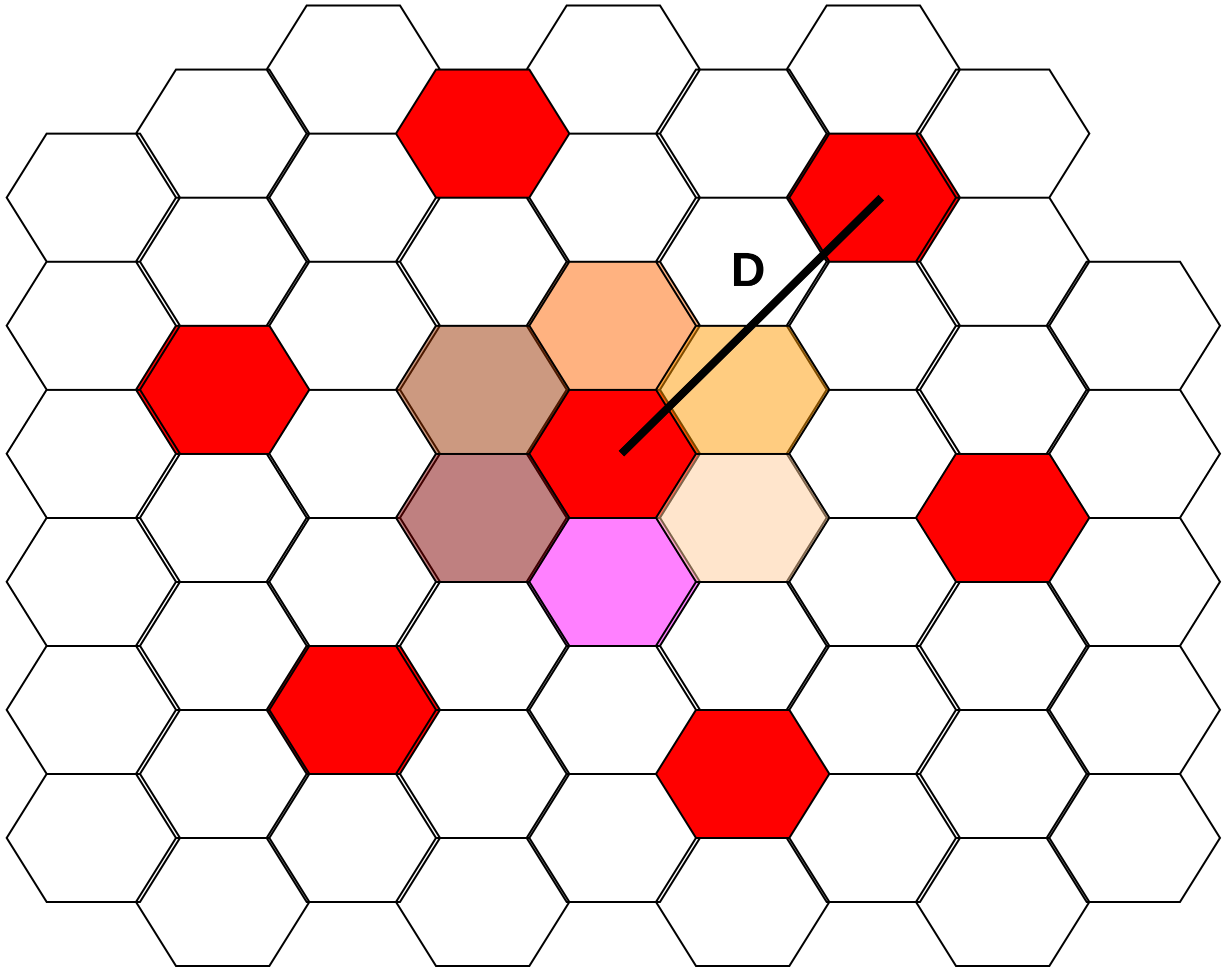
RR Set Capacity: $Z\, n = Z\, N / K$

Carrier-to-Interference Ratio (CIR or SIR): C / I

Reuse

K = 7

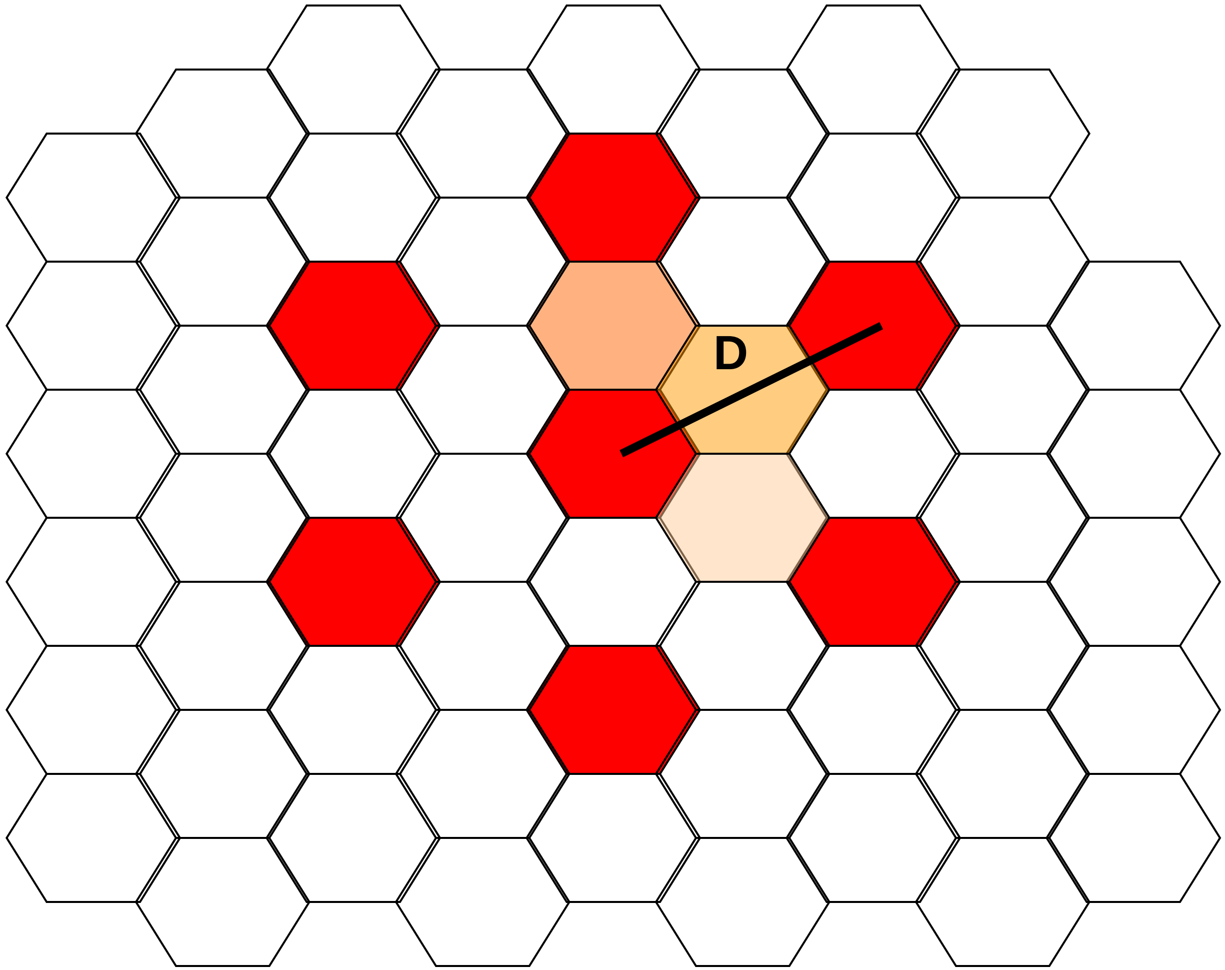
Six first – tier interferers



Reuse

K = 4

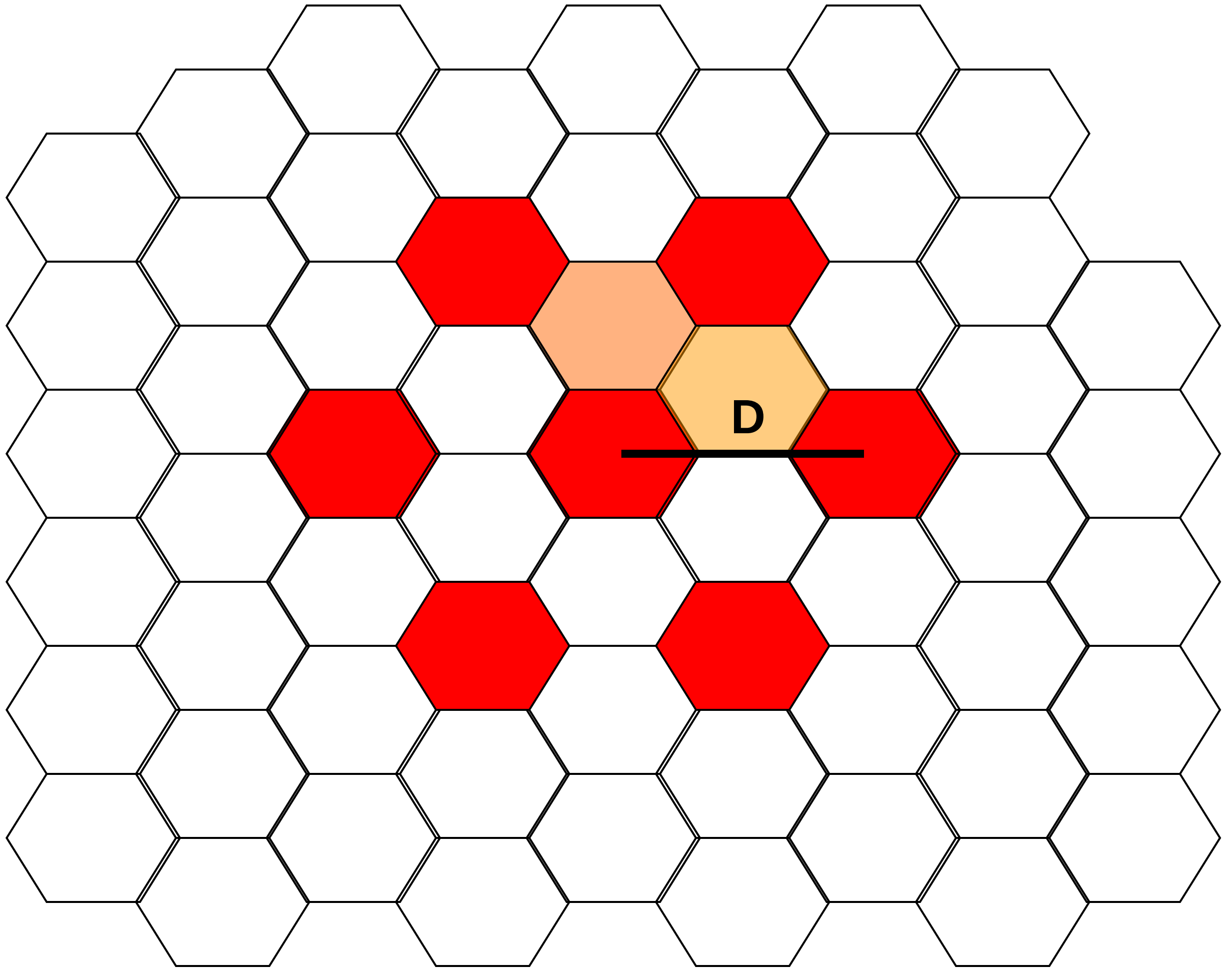
Six first – tier interferers



Reuse

K = 3

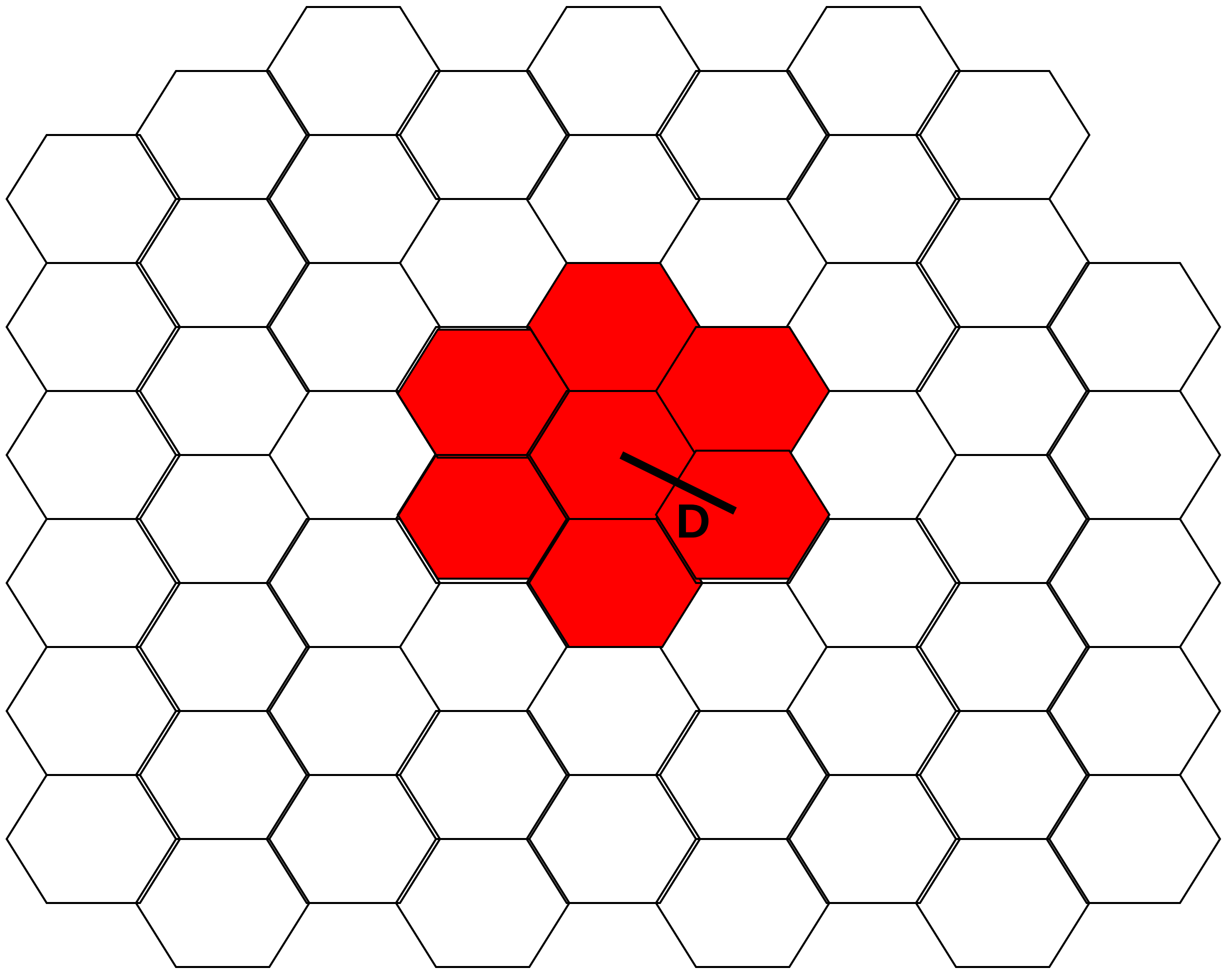
Six first – tier interferers



Reuse

K = 1

Six first – tier interferers



Reuse

$K = i^2 + j^2 + i\,j$ $\qquad$ $i = 0,1,2,3,4,\dots$ $\quad j = 0,1,2,3,4,\dots$

i	j	K	
1	0	1	(full reuse)
1	1	3	
2	0	4	
2	1	7	
3	0	9	
2	2	12	
…			

$D = R\,(3\,K)^{1/2}$ $\qquad$ $n = N / K$ is a (rough) measure of the cell capacity

$Q = (3\,K)^{1/2}$

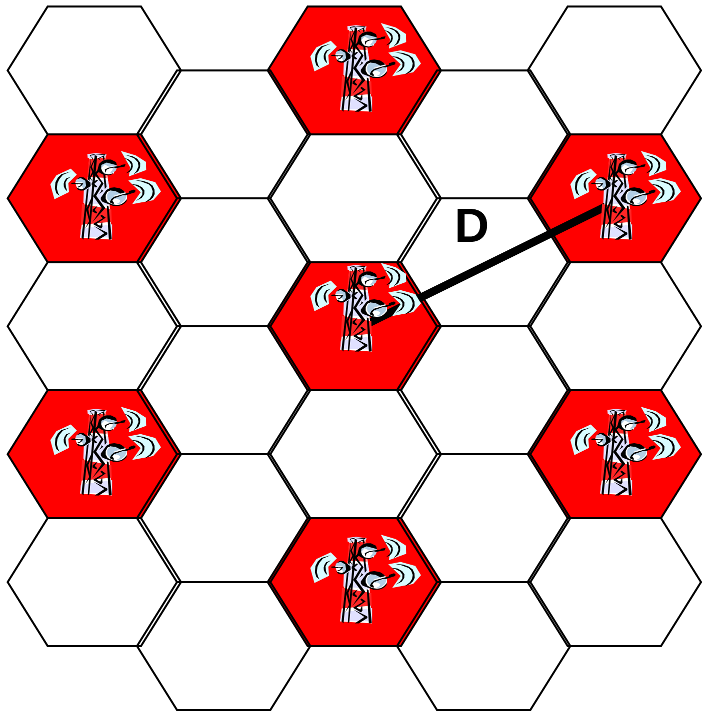
Increasing K, D increases, but n decreases
(less interference, at the expense of a smaller capacity)

Reuse: Deterministic Conditions – Omni Antennas

$C = k\,R^{-\beta}$ (worst situation)

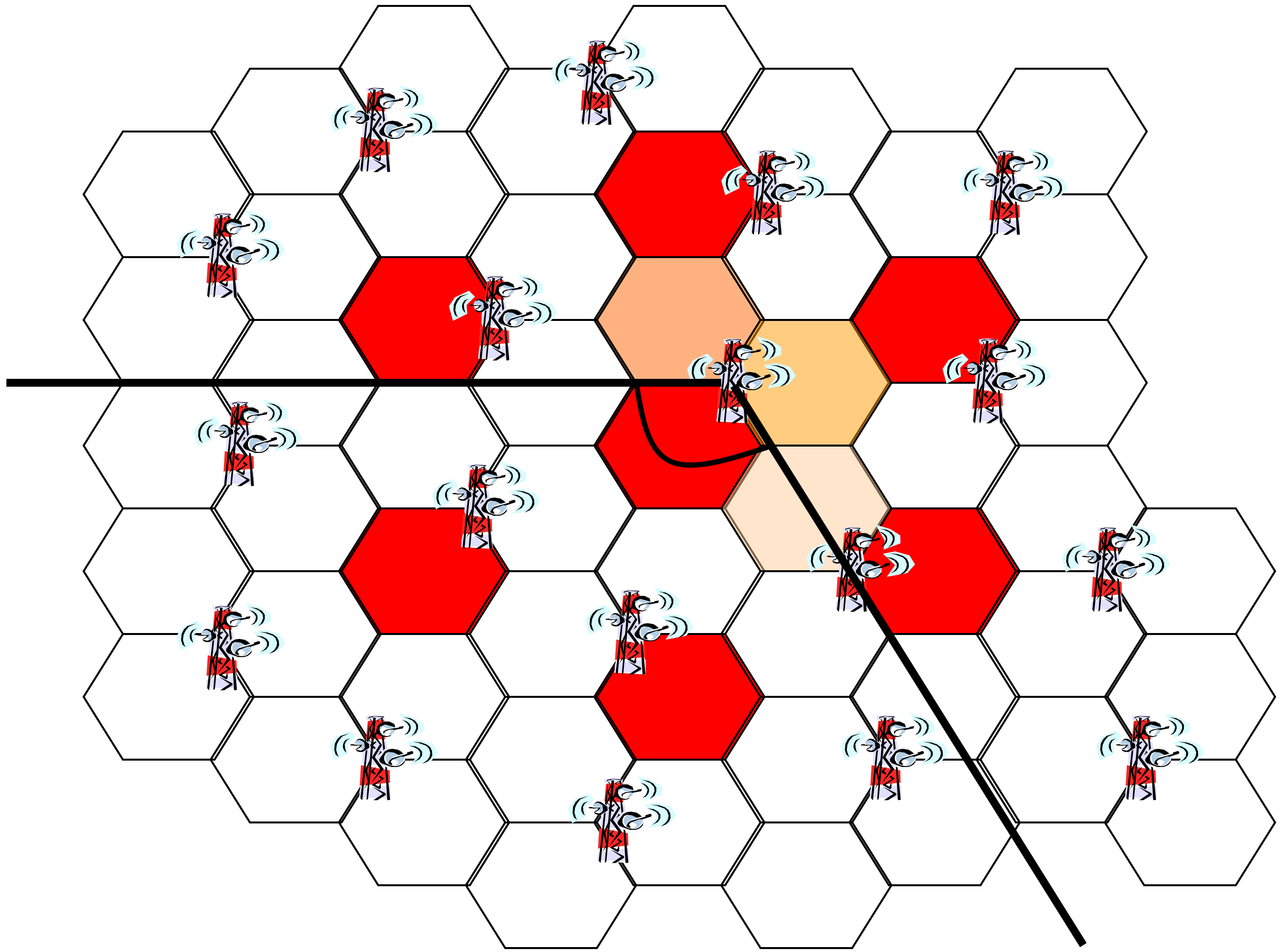
$I = N_{int}\,k\,D^{-\beta}$ (average situation)

uplink
or
downlink



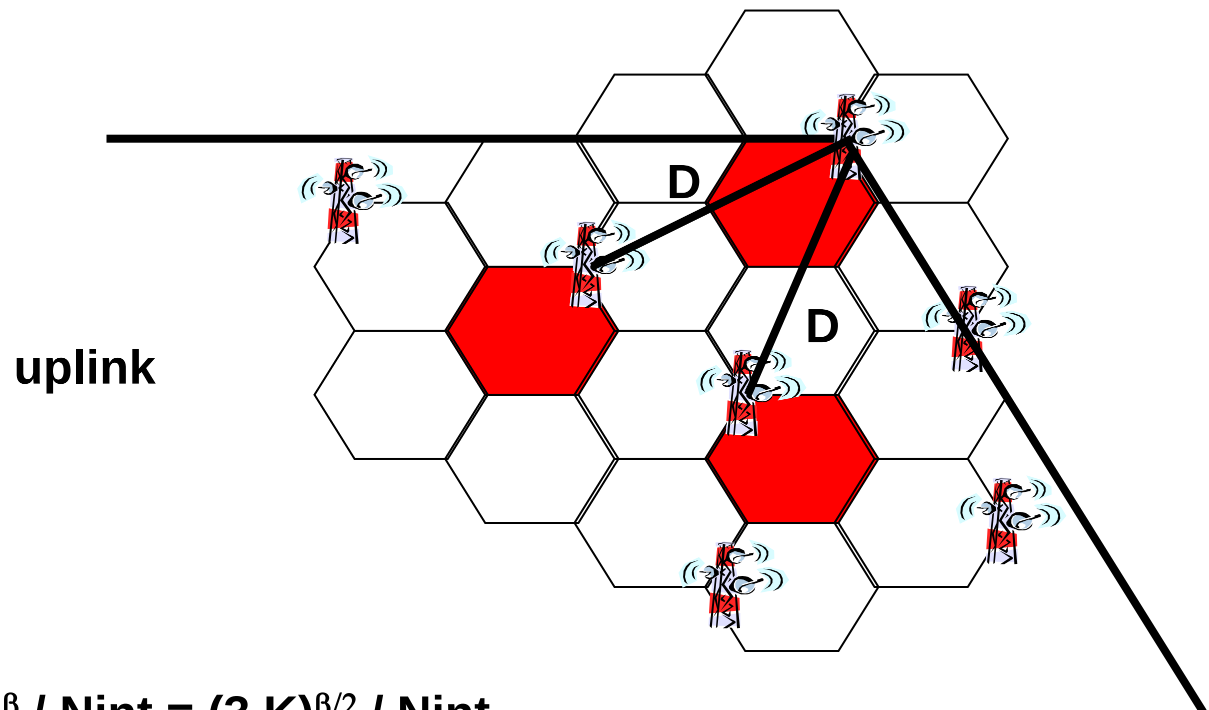
$C / I = Q^{\beta} / N_{int} = (3\,K)^{\beta/2} / N_{int}$

Reuse: Deterministic Conditions – Tri-Sect Antennas



Reuse: Deterministic Conditions – Tri-Sect Antennas

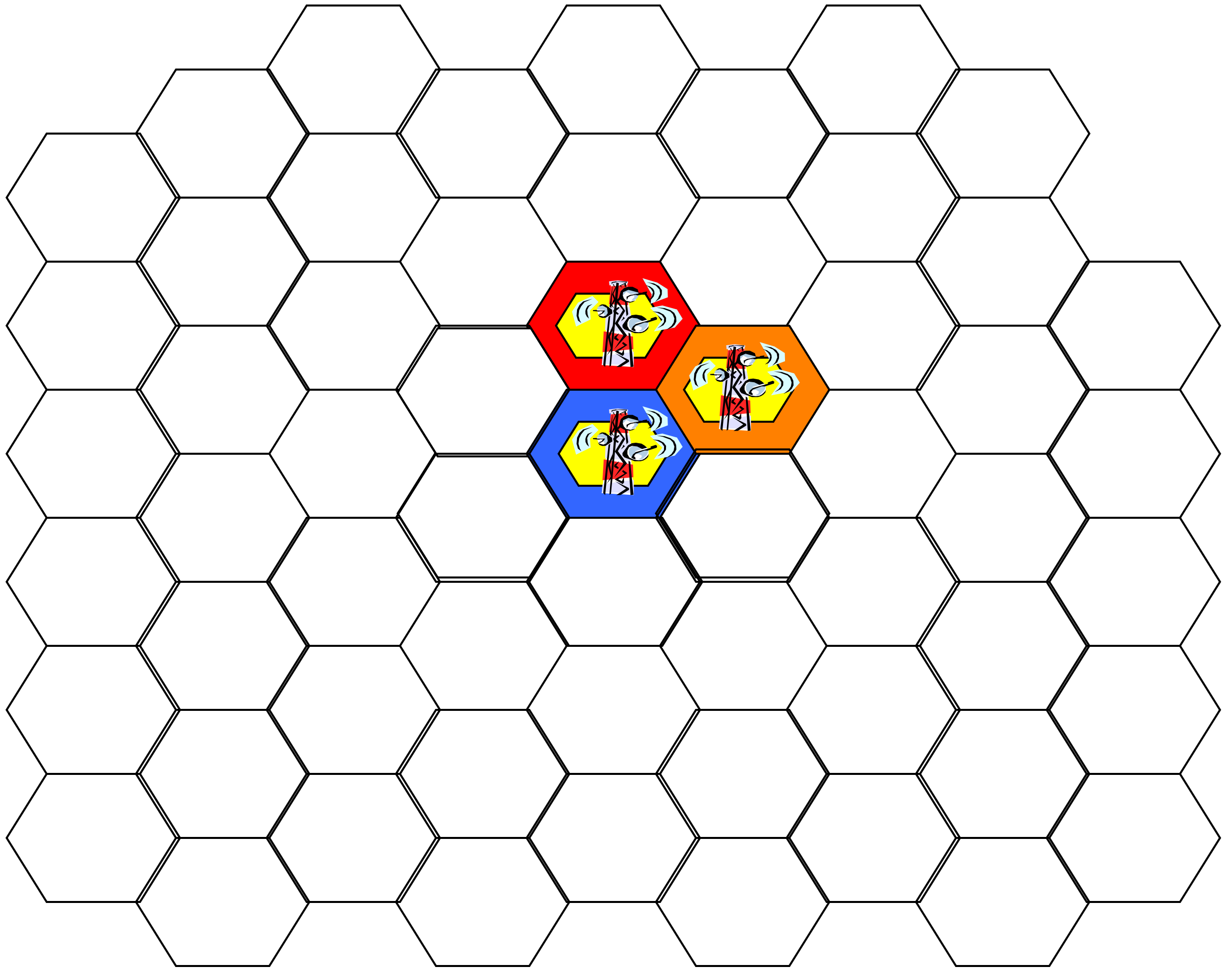
$C = k\,R^{-\beta}$ (average situation)
$I = N_{int}\,k\,D^{-\beta}$ (worst situation)



$C / I = Q^{\beta} / N_{int} = (3\,K)^{\beta/2} / N_{int}$

Reuse: Fractional Reuse

K = 1 / 3



Reuse: Cell Size

N orthogonal RUs

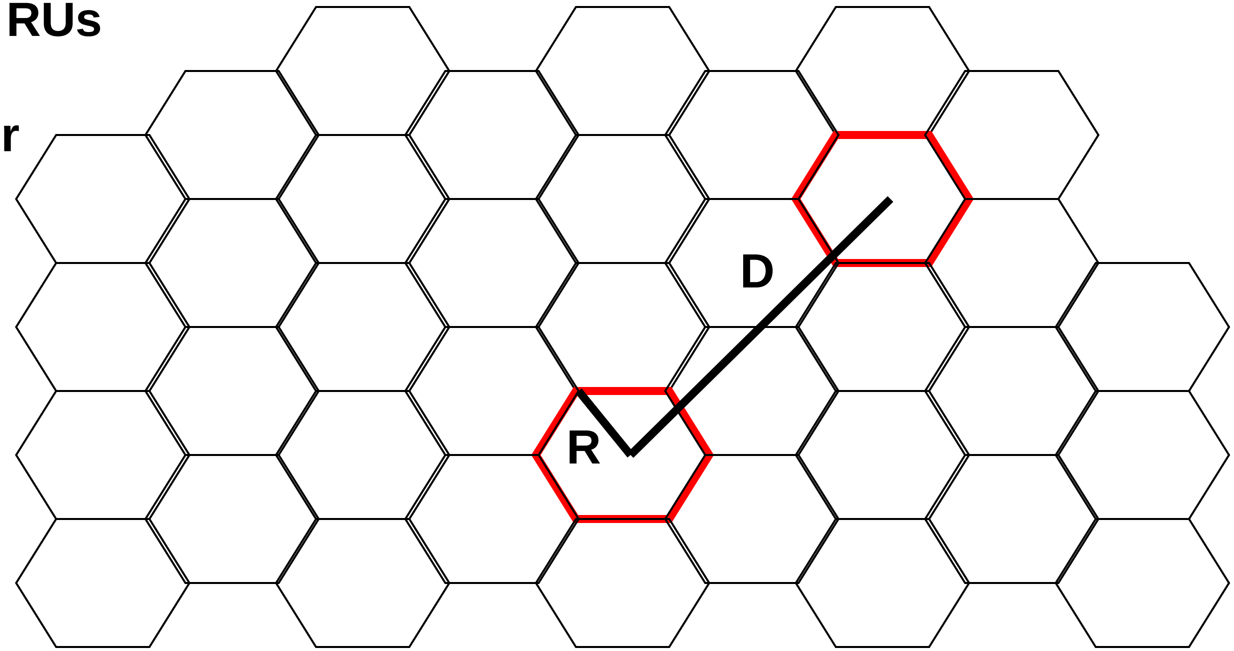
K cells/cluster

$n = N / K$ RUs/cell

$A = 3^{3/2} R^2 /2$ cell area

$Q = D / R$ Reuse Factor

Z cells



RR Set Capacity: $Z n = Z N / K$ **(proportional to Z)**

$C / I = Q^{\beta} / Nint = (3 K)^{\beta/2} / Nint$ **(independent on Z)**

Make cells as small as possible **Carrier-to-Interference Ratio scales!**

Reuse: Exercise

Compute the C / I under deterministic conditions with propagation exponent equal to 4, for cluster size equal to 7, 4, 3 with omnidirectional and tri-sectorial antennas. Repeat computation for propagation exponent equal to 3.

Reuse: Exercise

Compute the C / I under deterministic conditions with propagation exponent equal to 4, for cluster size equal to 7, 4, 3 with omnidirectional and tri-sectorial antennas. Repeat computation for propagation exponent equal to 3.

$C / I = (3\,K)^{\beta/2} / N_{int}$

	Omnidirectional antennas	Tri-sectorial antennas
$\beta = 4$		
K = 7	18.7 dB	23.4 dB
K = 4	13,8 dB	18.6 dB
K = 3	11.3 dB	16.1 dB
$\beta = 3$		
K = 7	12.1 dB	16.9 dB
K = 4	8.4 dB	13.2 dB
K = 3	6.5 dB	11.3 dB

Reuse: Exercise

Compute the C / I under deterministic conditions with propagation exponent equal to 4, for cluster size equal to 7, 4, 3 with omnidirectional and tri-sectorial antennas. Repeat computation for propagation exponent equal to 3.

$C / I = (3K)^{\beta/2} / N_{int}$

	Omnidirectional antennas	Tri-sectorial antennas
$\beta = 4$		
K = 7	18.7 dB	23.4 dB
K = 4	13,8 dB	18.6 dB
K = 3	11.3 dB	16.1 dB
$\beta = 3$		
K = 7	12.1 dB	16.9 dB
K = 4	8.4 dB	13.2 dB
K = 3	6.5 dB	11.3 dB

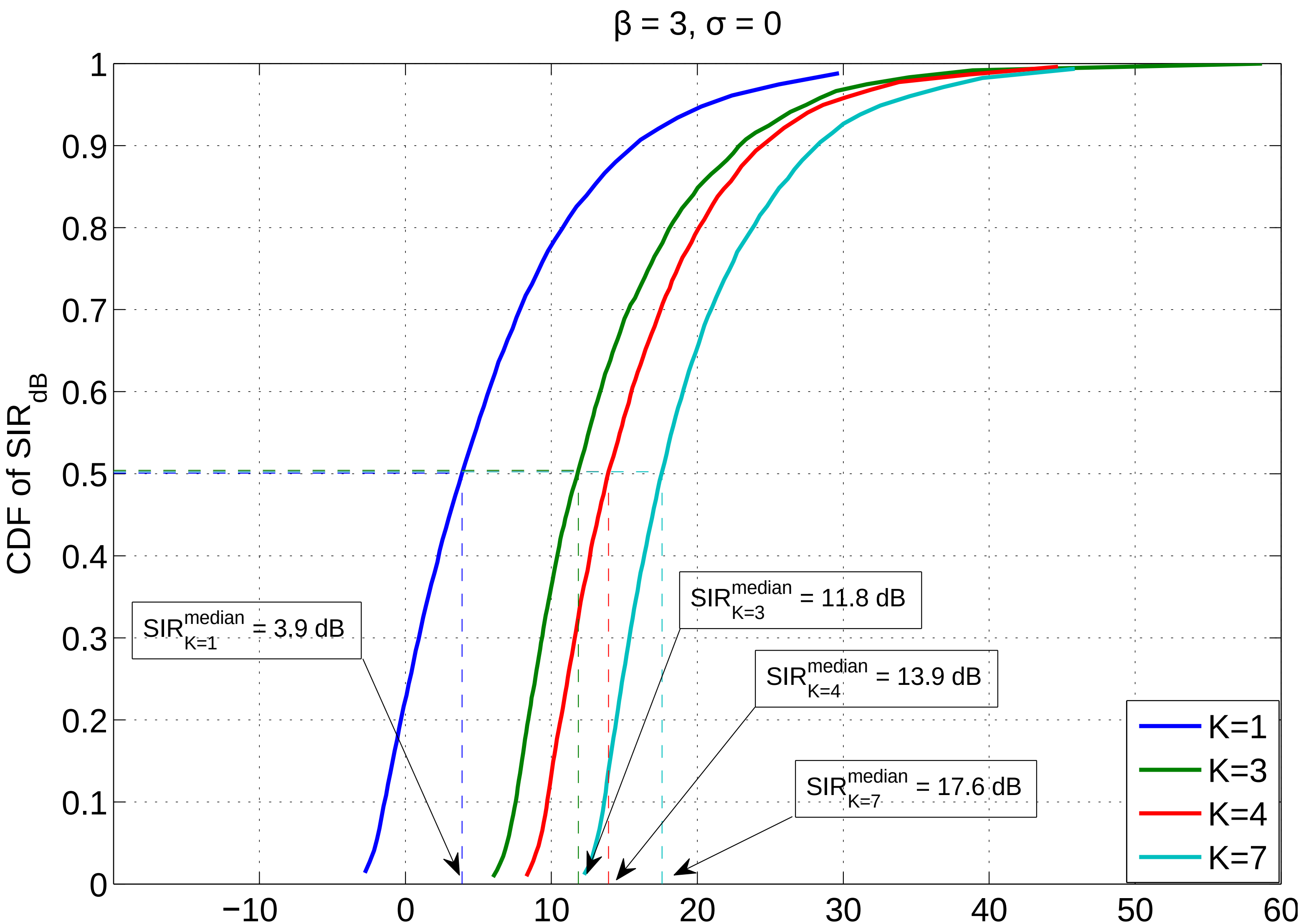
Reuse: Simulations

**Compute the (average) C / I under average conditions with propagation exponent equal to 4, for cluster size equal to 7, 4, 3 with tri-sectorial antennas.
Repeat computation for propagation exponent equal to 3.**

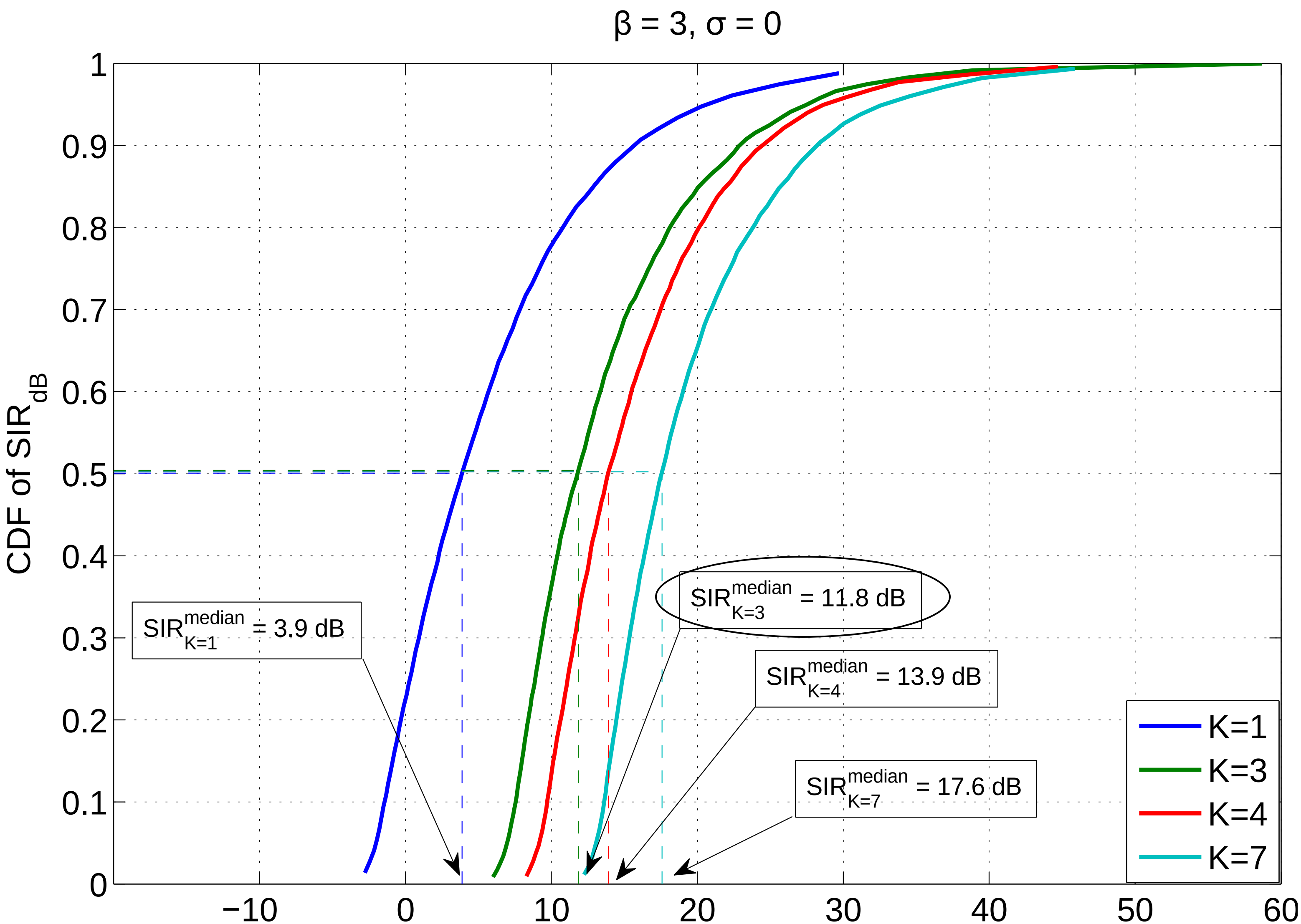
Under average conditions, users are randomly and uniformly distributed in the cells.

Repeat computation including shadowing with standard deviation 6 or 12.

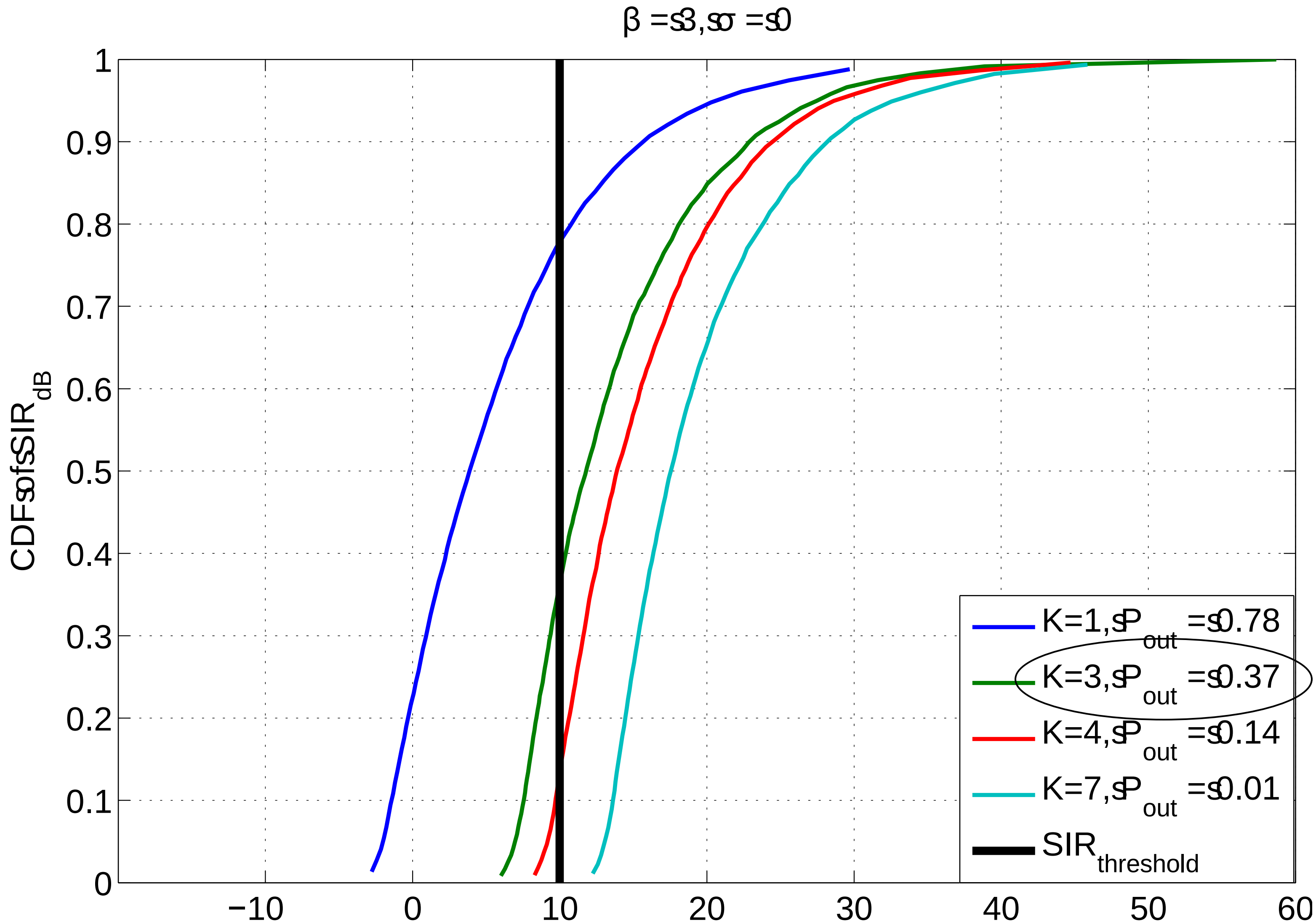
Reuse: Simulations



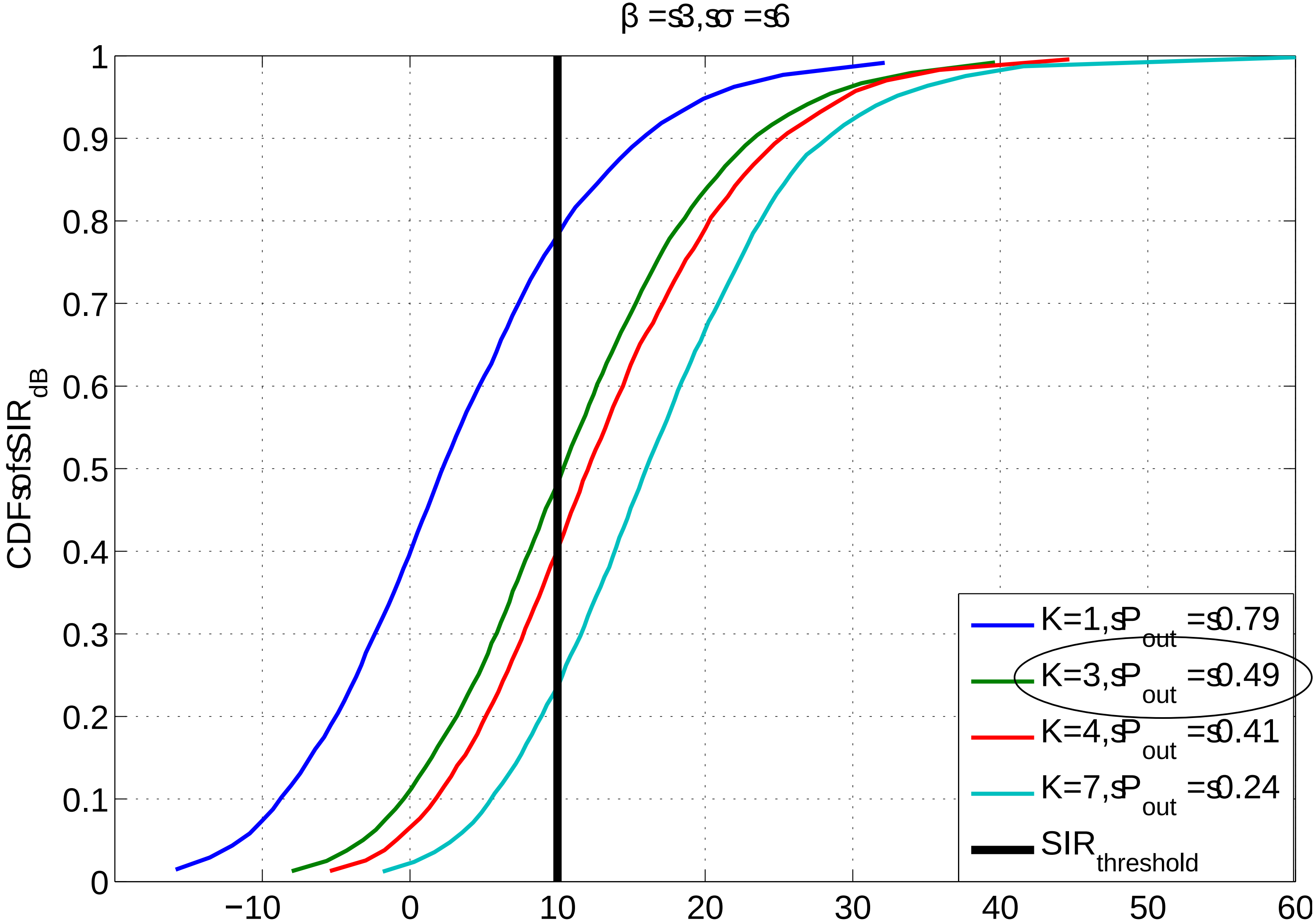
Reuse: Simulations



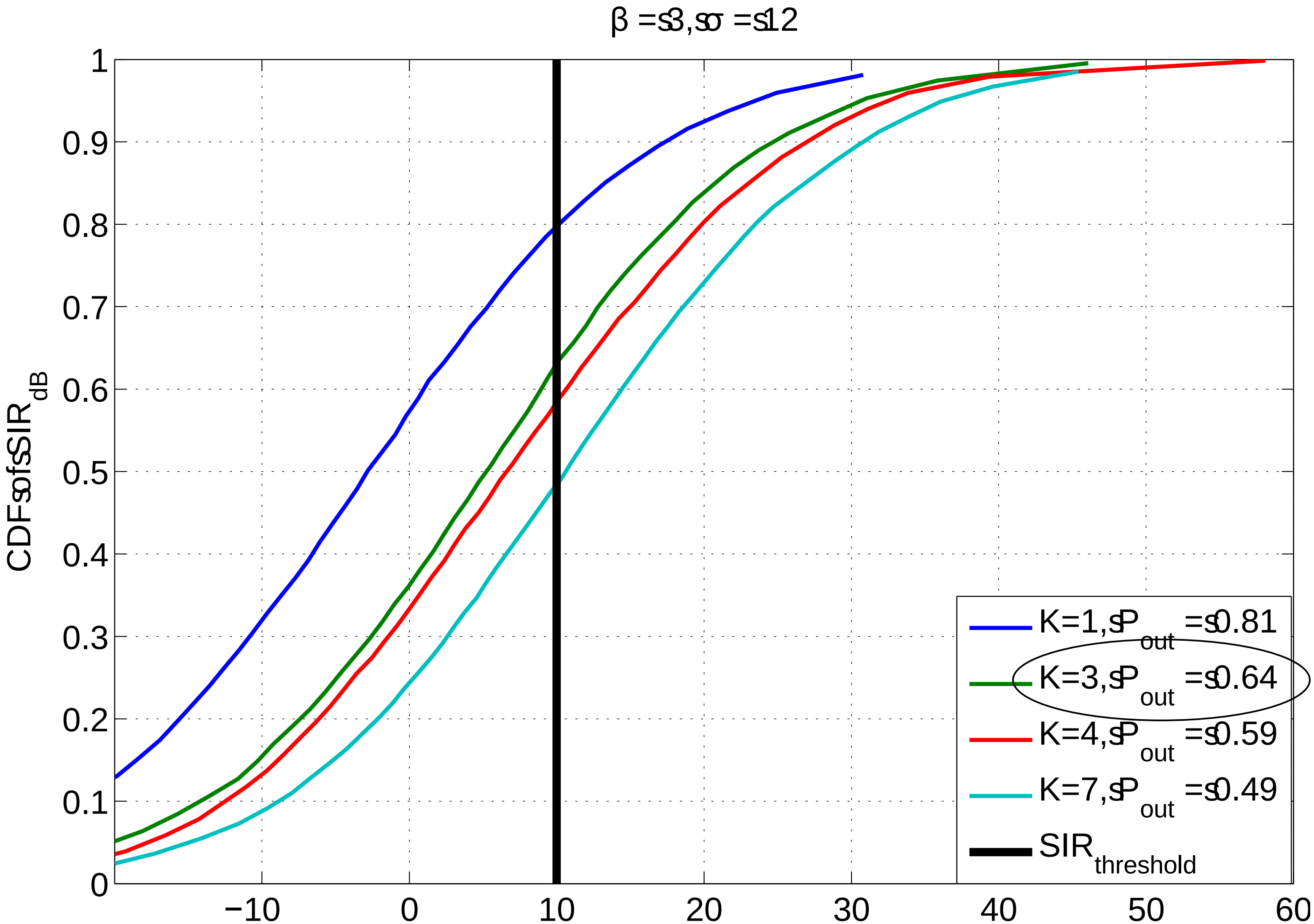
Reuse: Simulations



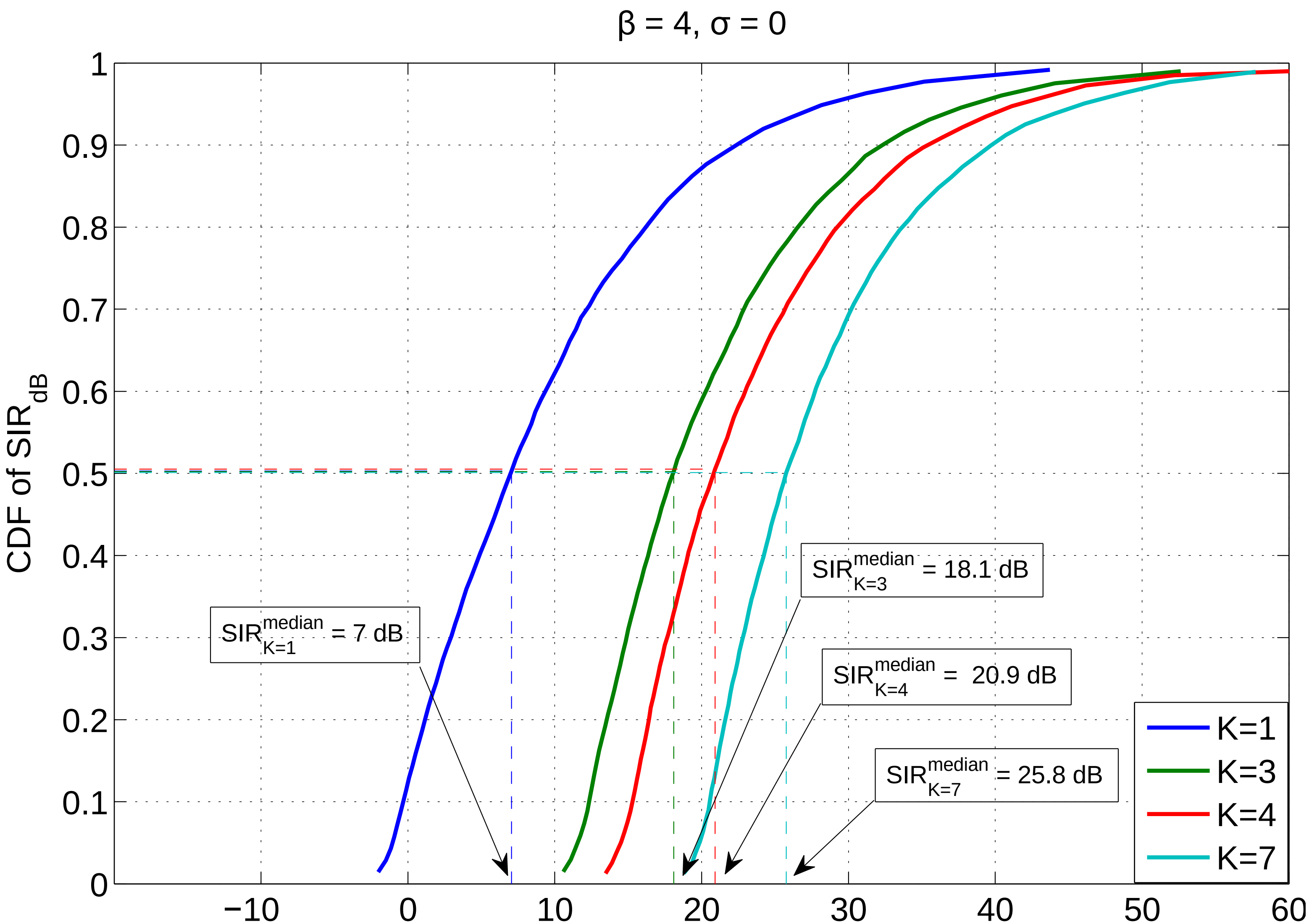
Reuse: Simulations



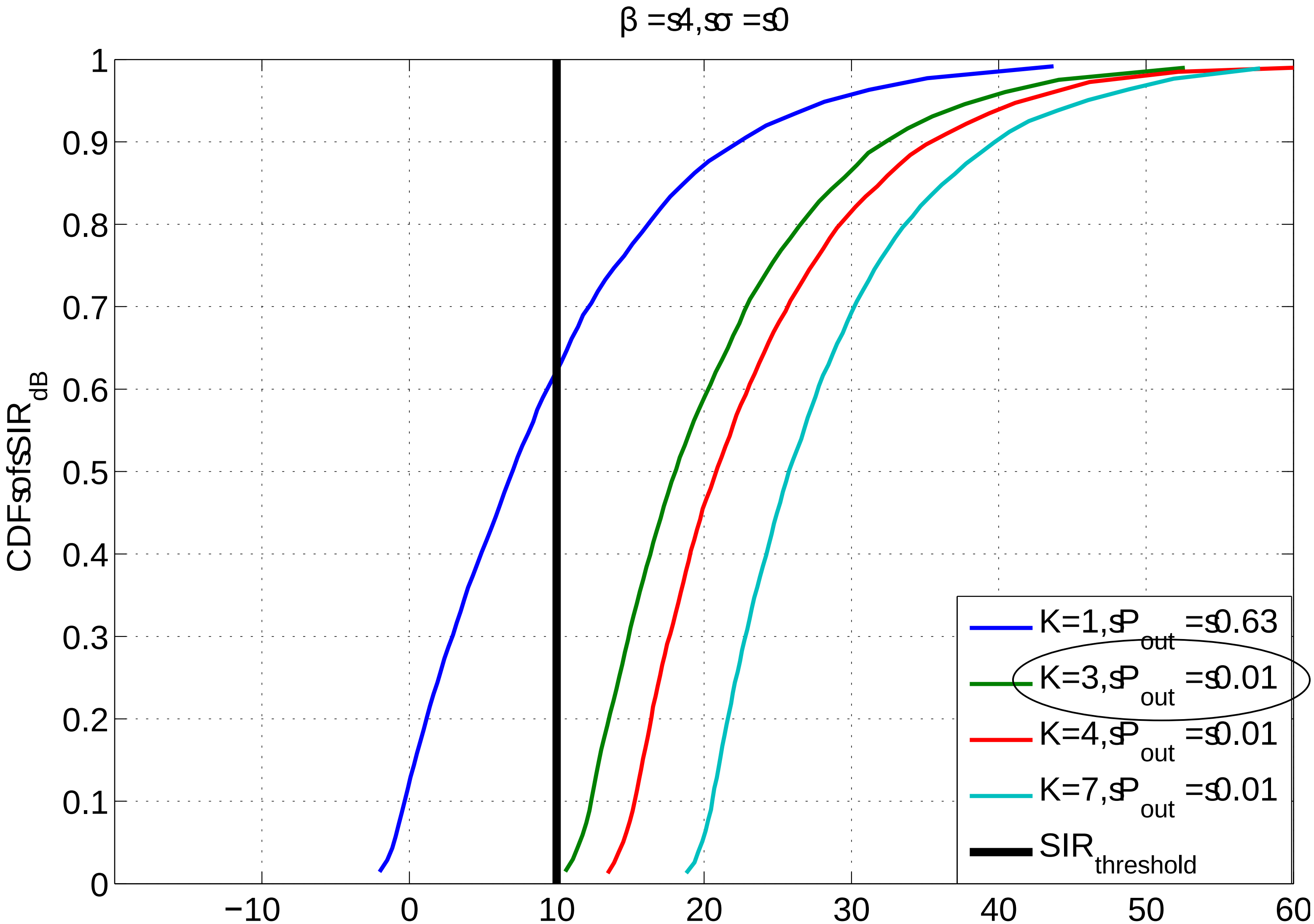
Reuse: Simulations



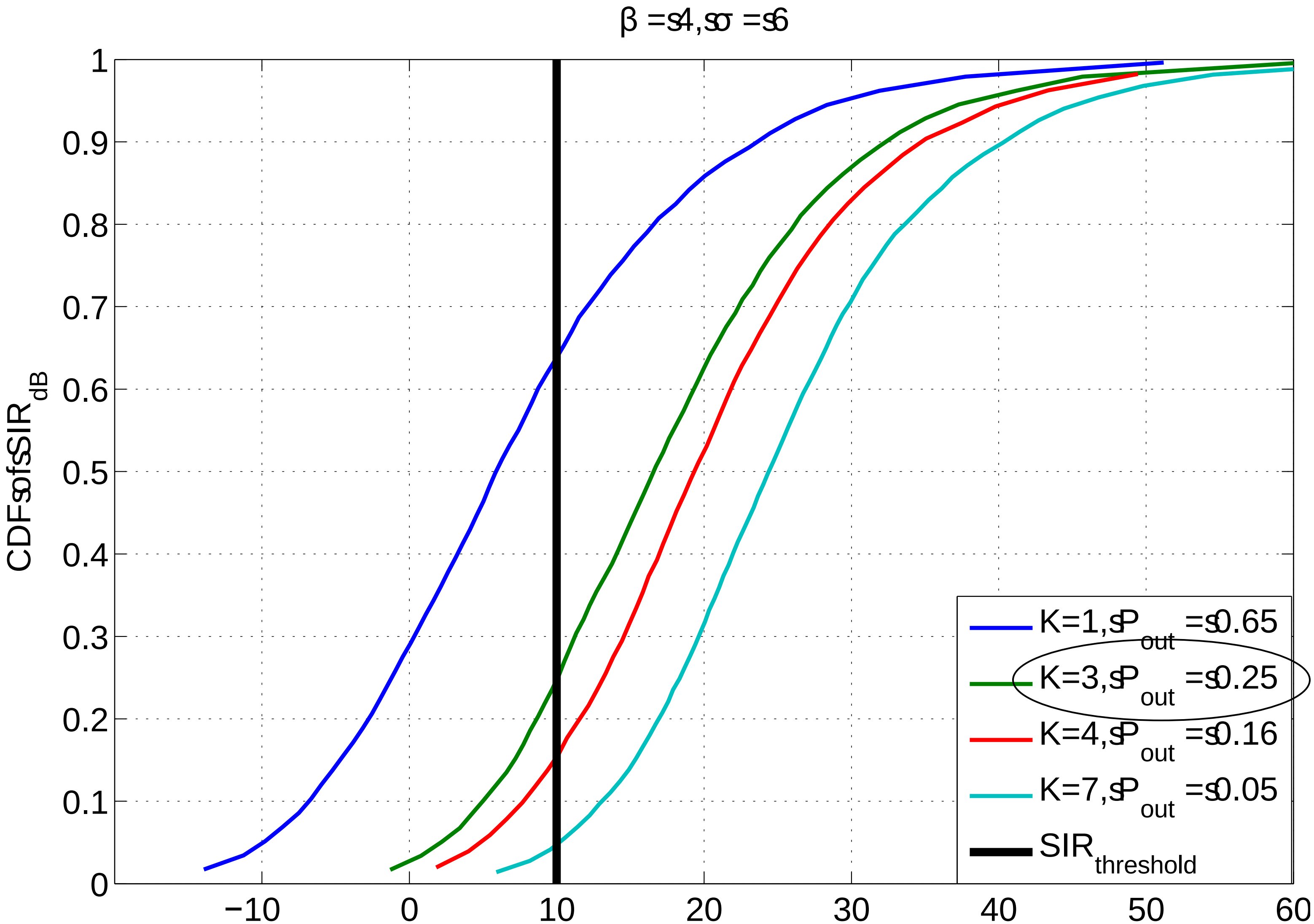
Reuse: Simulations



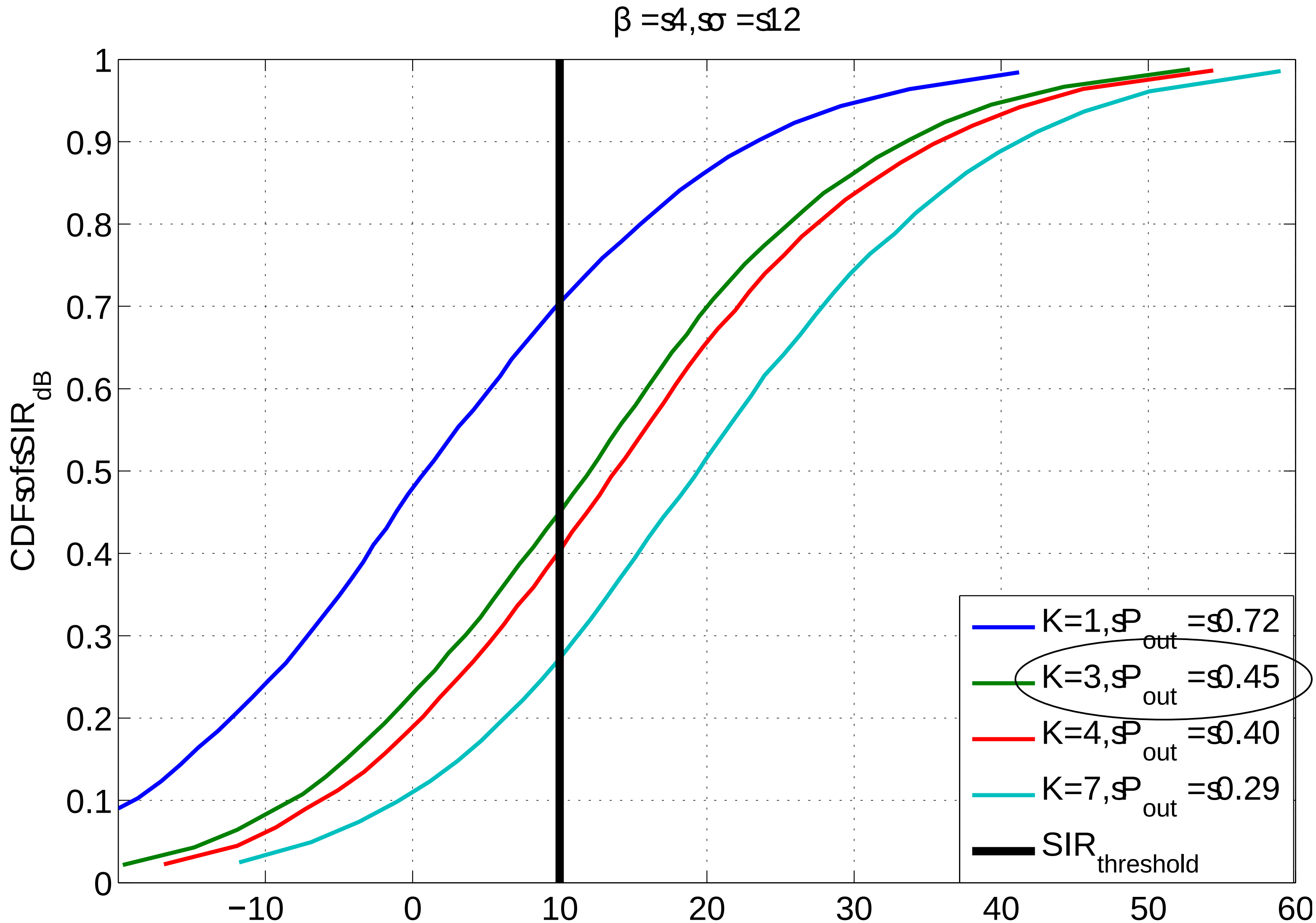
Reuse: Simulations



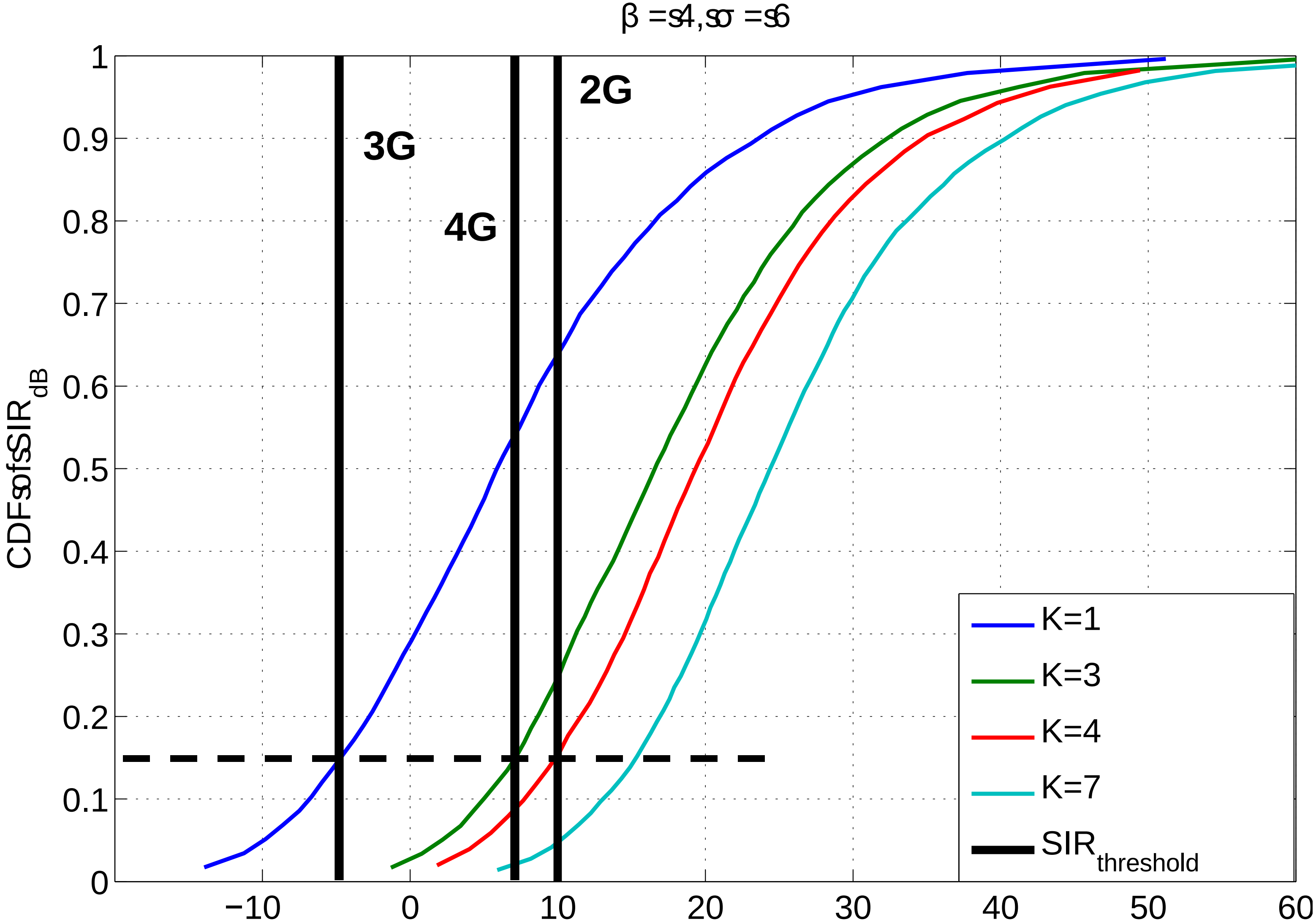
Reuse: Simulations



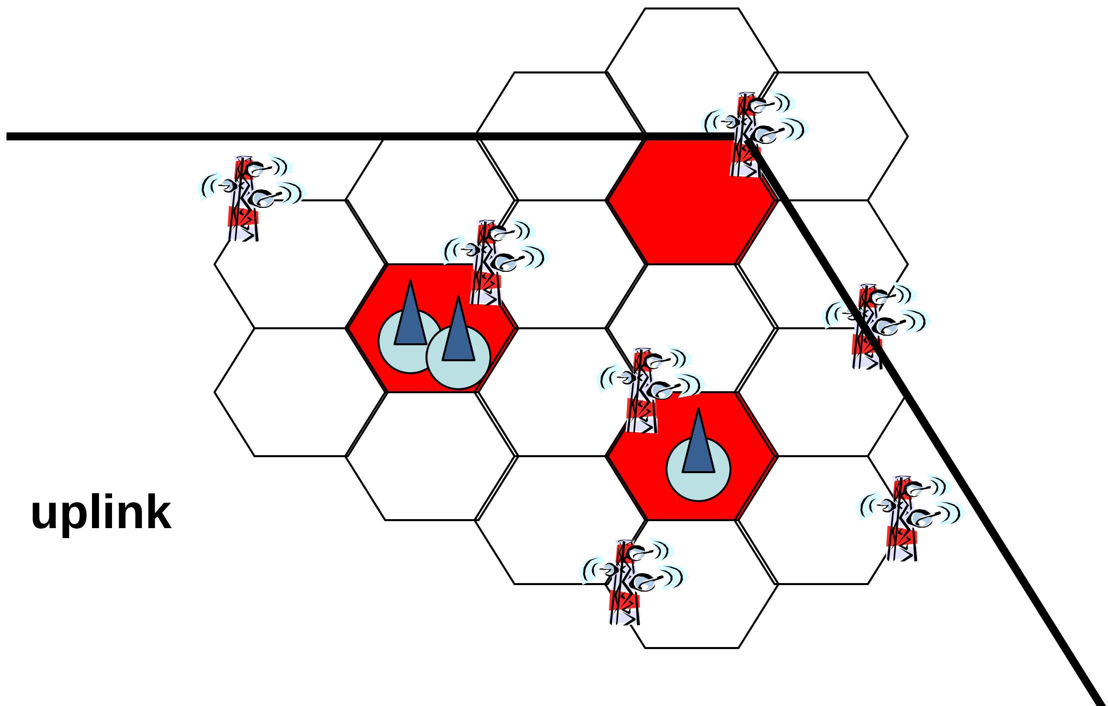
Reuse: Simulations



Reuse: Simulations; From 2G to 4G



Reuse: Tri-Sect Antennas and Small Cells

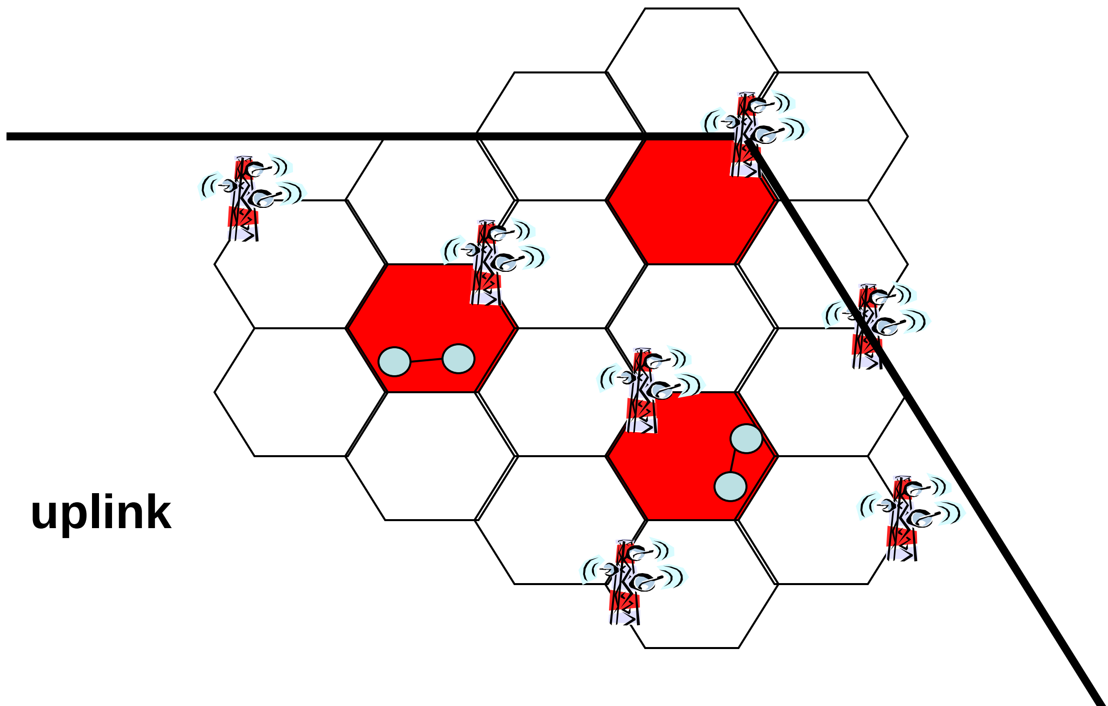


uplink

$C / I = (3\ K)^{\beta/2} / (Nint + \pi*SC)$

SC = number of interfering Small Cells
π = ratio of small cell / macrocell Tx powers

Reuse: Tri-Sect Antennas and D2D Links



uplink

C / I = (3 K)$^{\beta/2}$ / (Nint + θ * ND)

ND = number of interfering D2D links
θ = ratio of small cell / macrocell Tx powers

5. Network Spectrum Efficiency

Network Spectrum Efficiency

N	number of RUs available to the system
K	number of cells per cluster
n = N / K	number of RUs per cell available
Bt	total bandwidth available [MHz]
Bc = Bt / N	bandwidth per RU [MHz]
A	cell area [sqKm]
Rb	minimum bit rate
E	carried traffic within cell [Erlang/cell]
e = E / n	carried traffic within cell per RU [Erlang/cell/RU]

Link Spectrum Efficiency $\eta_{link} = Rb / Bc$ [bit / sec / Hz]

It measures the efficiency of modulation and coding schemes.

How to measure Network Spectrum Efficiency?

It measures the efficiency of spectrum usage with frequency reuse.
Many definitions available. None really general.

Network Spectrum Efficiency

Network Spectrum Efficiency **[Hatfield, 1982]**

$\eta = E / Bt\ A$ [Erl/MHz/sqKm]

(mainly valid for voice)

$\eta = E / Bt\ A = E / Bc\ N\ A = \eta_{link}\ E / Rb\ n\ K\ A = \eta_{link}\ e / Rb\ K\ A$

Network spectrum efficiency seems to be augmented if link spectrum efficiency is larger.

On the other hand, if the latter is increased at the expense of larger sensitivity to interference effects, K will be increased to fulfil QoS requirements.

So, this definition captures the tradeoff between QoS and efficiency, provided we succeed in expressing e as a function of K.

Network Spectrum Efficiency

N	number of RUs available to the system
K	number of cells per cluster
$n = N / K$	number of RUs per cell available
Bt	total bandwidth available [MHz]
$Bc = Bt / N$	bandwidth per RU [MHz]
A	cell area [sqKm]
Rb	minimum bit rate
S	**carried throughput within cell [bit/s/cell]**
$s = S / n$	**carried throughput within cell per RU [bit/s/cell/RU]**

Network Spectrum Efficiency (Hatfield modified)

$$\eta = S / Bt\,A \quad [\text{bit/s/MHz/sqKm}]$$

$$= s / Bc\,K\,A$$

Network Spectrum Efficiency

The maximum carried throughput per RU can be estimated through the concept of channel capacity (Shannon):

$$s = Bc \log_2 (1 + SNR)$$

Assuming SNR = C/I (not true, but good approximation for many interferers):

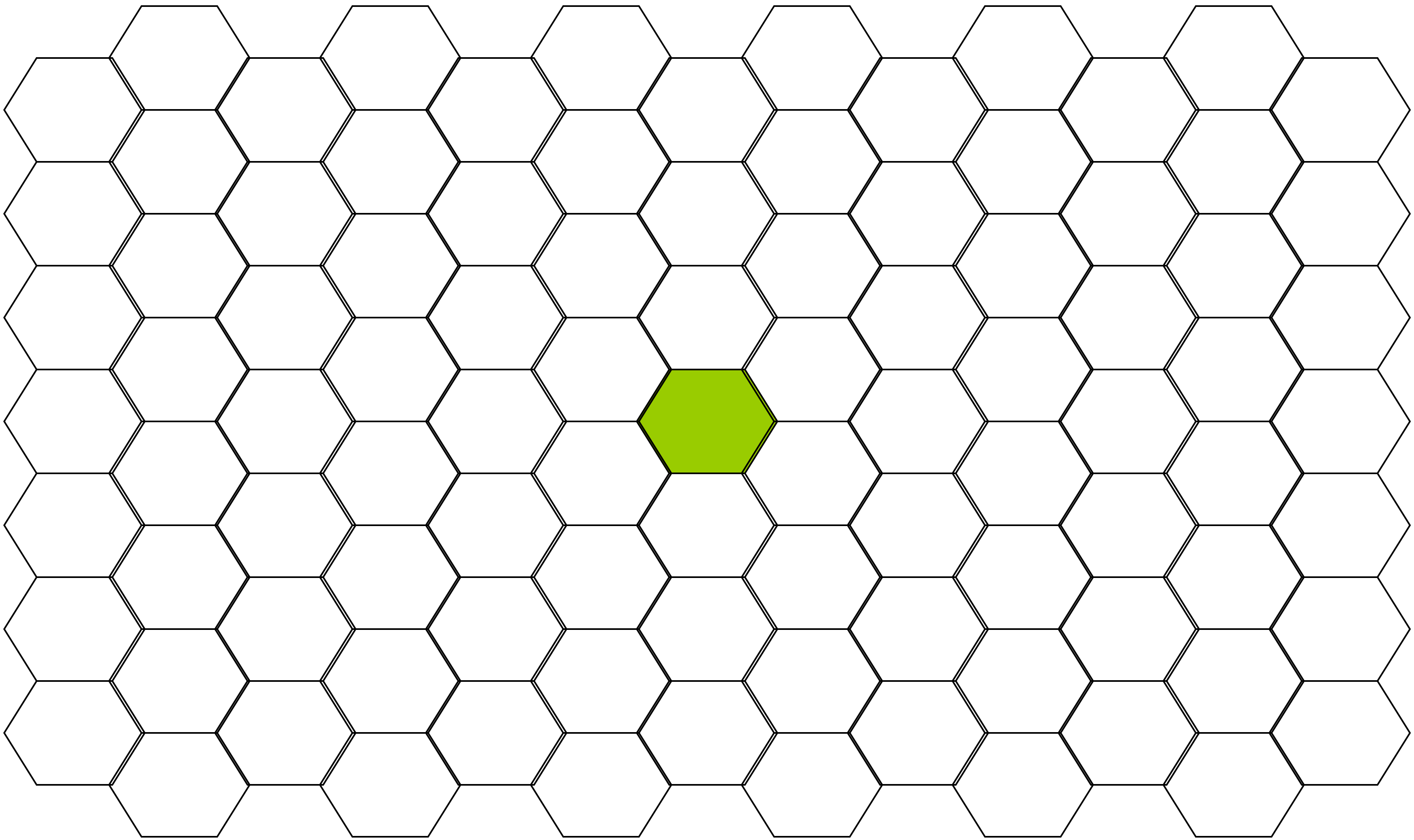
$$\eta = s / Bc\, K\, A = \log_2 (1 + C/I) / K\, A$$

$$= \log_2 (1 + (3\, K)^{\beta/2} / Nint) / K\, A$$

Network spectrum efficiency is maximum for K = 1.

However $C/I = (3\, K)^{\beta/2}$ does not account for very unlucky conditions (edge users with close interferers).

Homework



Homework

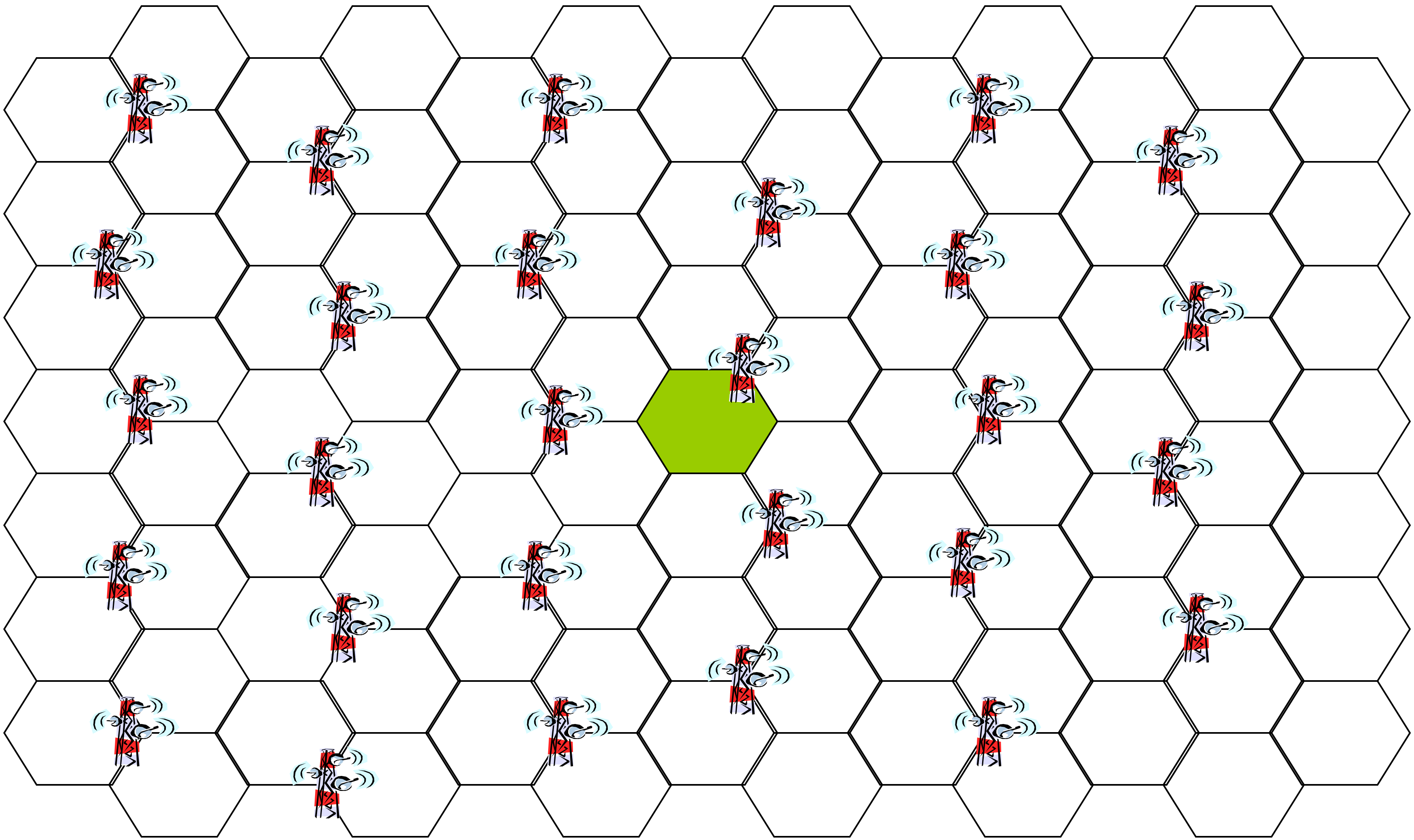
Assuming tri-sectorial antennas and K = 4, find the interfering cells of the central reference cell for uplink and downlink. The system uses FDD.

Are the two sets identical?

What does it change if the system uses TDD with asynchronous timing in separate cells?

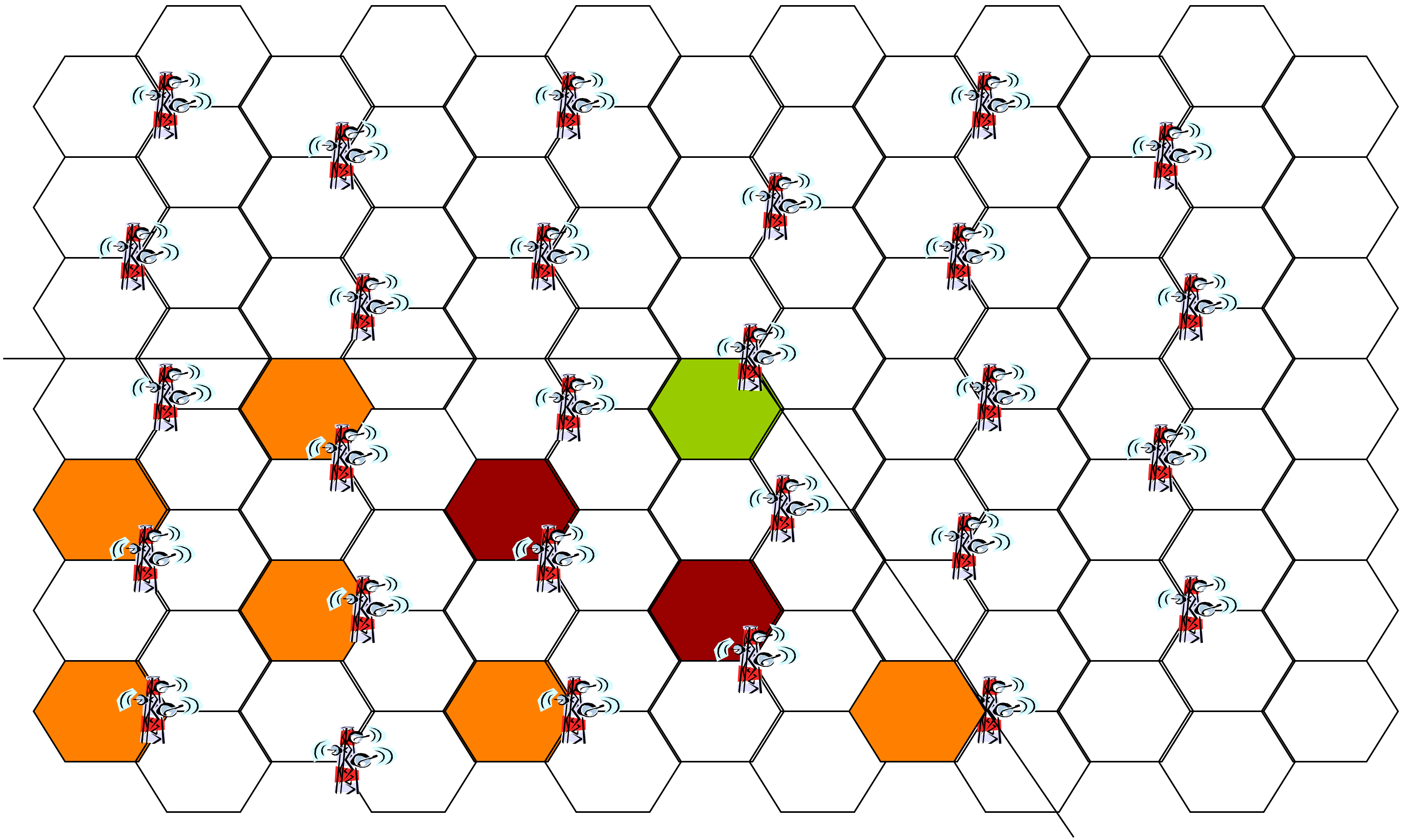
Homework

FDD



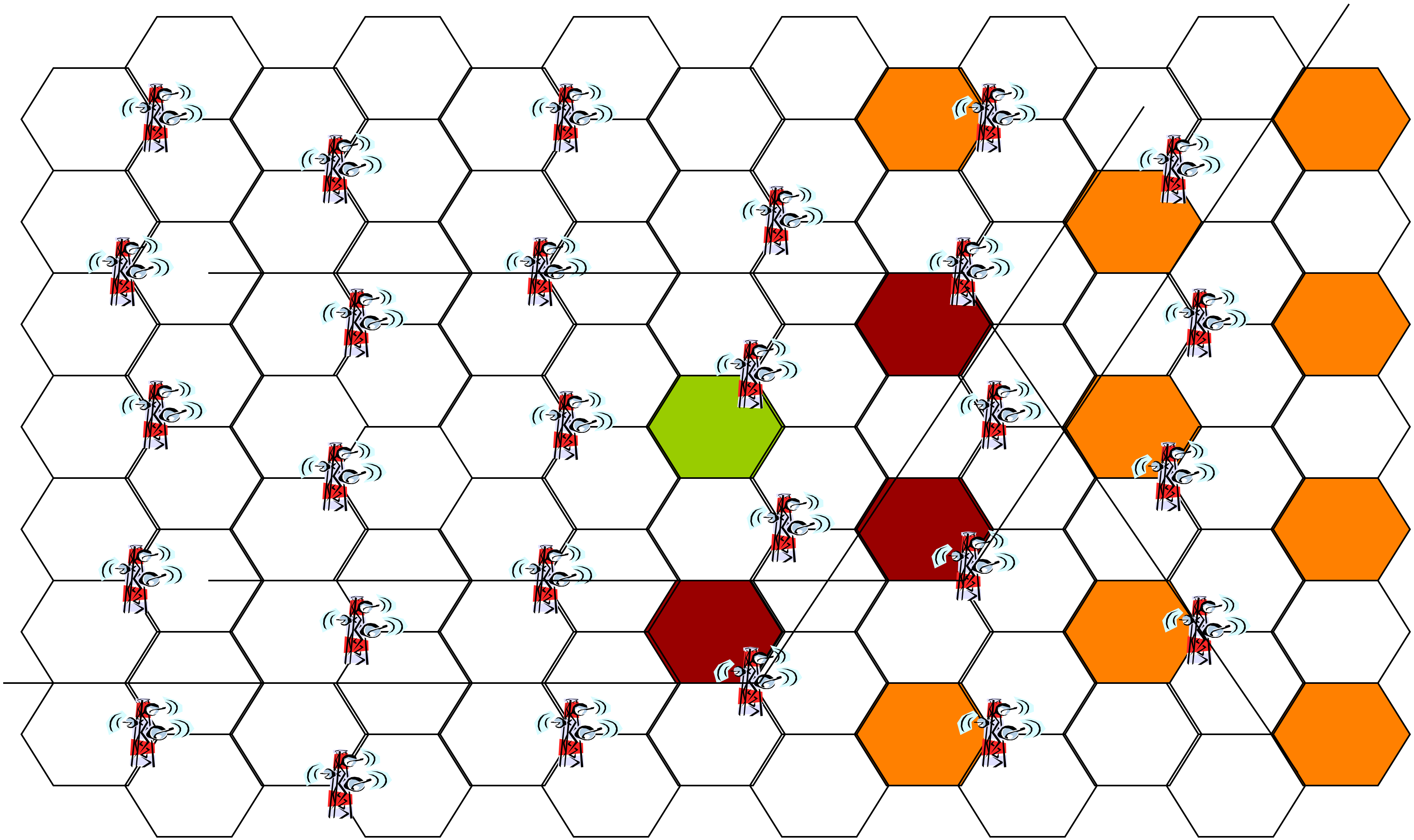
Homework

FDD: uplink



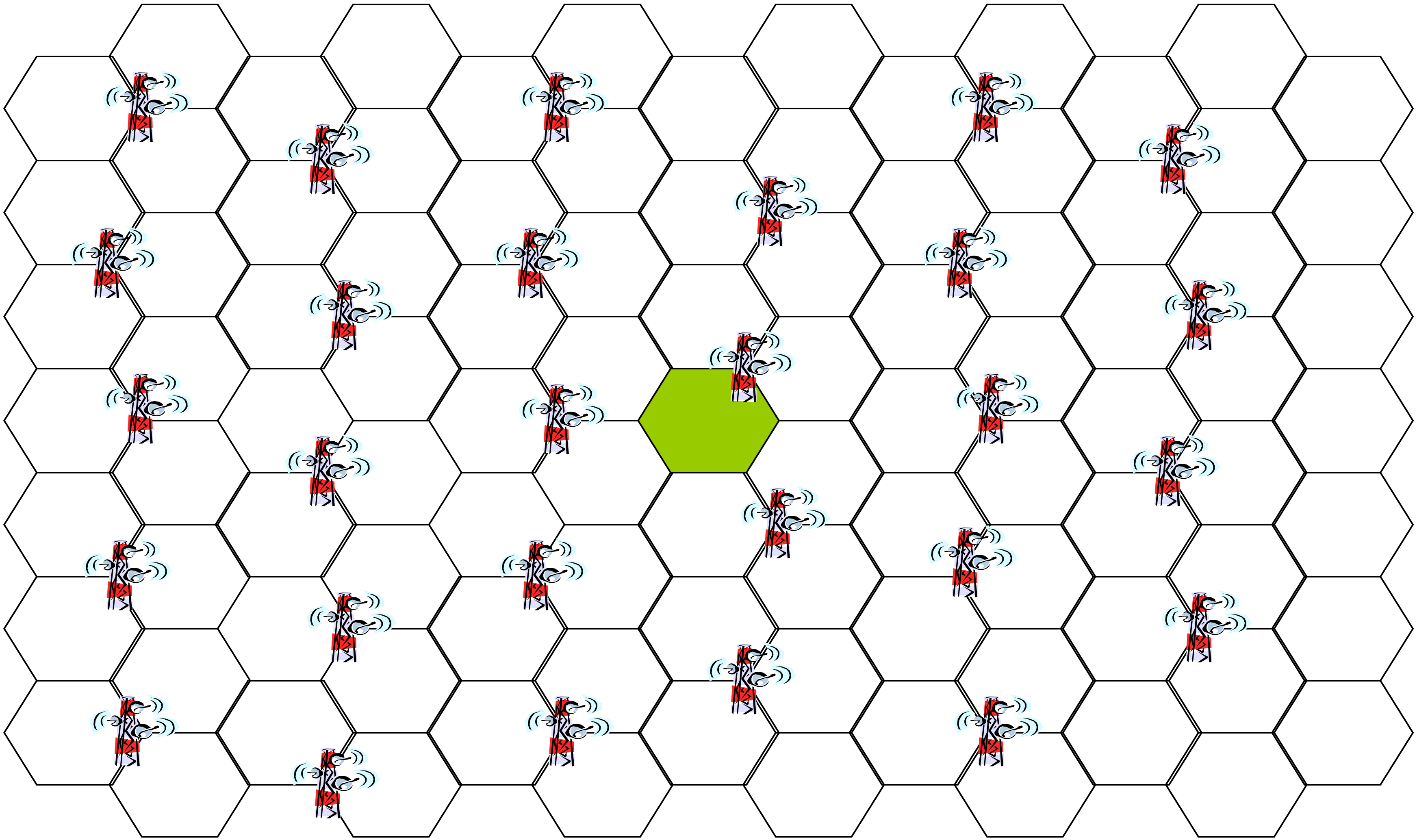
Homework

FDD: downlink



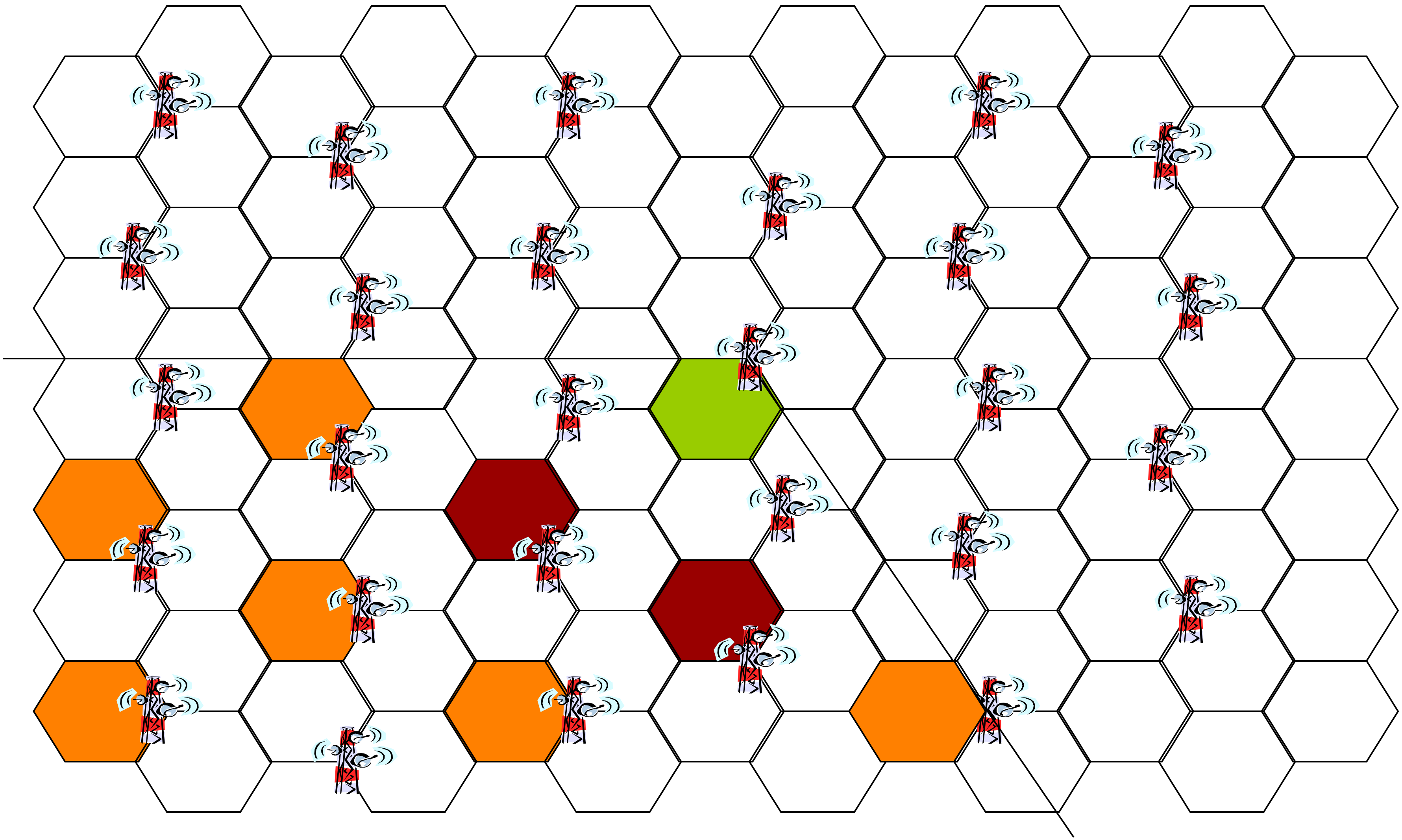
Homework

TDD



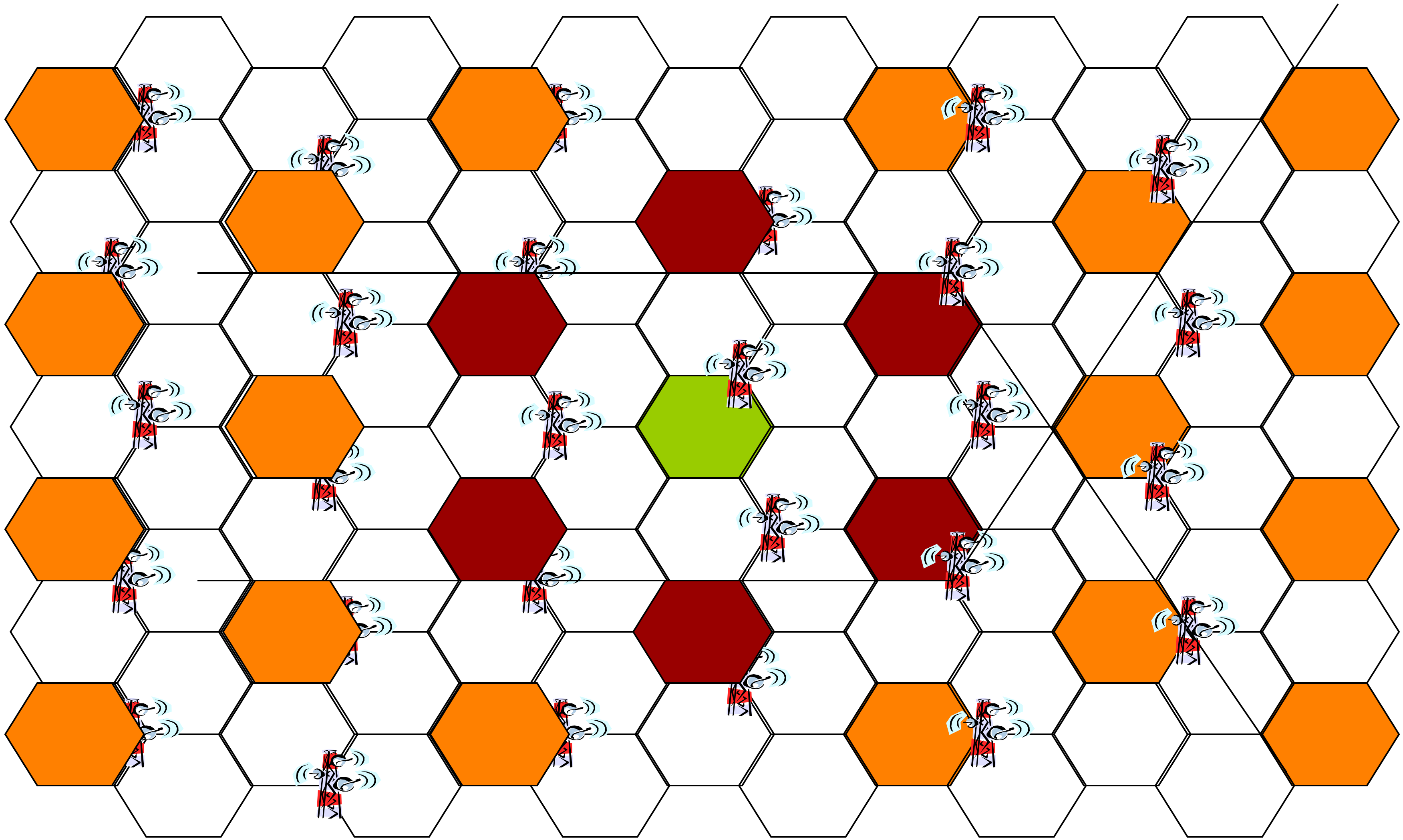
Homework

TDD: uplink



Homework

TDD: downlink



Homework

Assuming tri-sectorial antennas and K = 3, find the interfering cells of the central reference cell for uplink and downlink. The system uses FDD.

Are the two set identical?

Is the value of Nint equal to 2 in all cases?

Homework

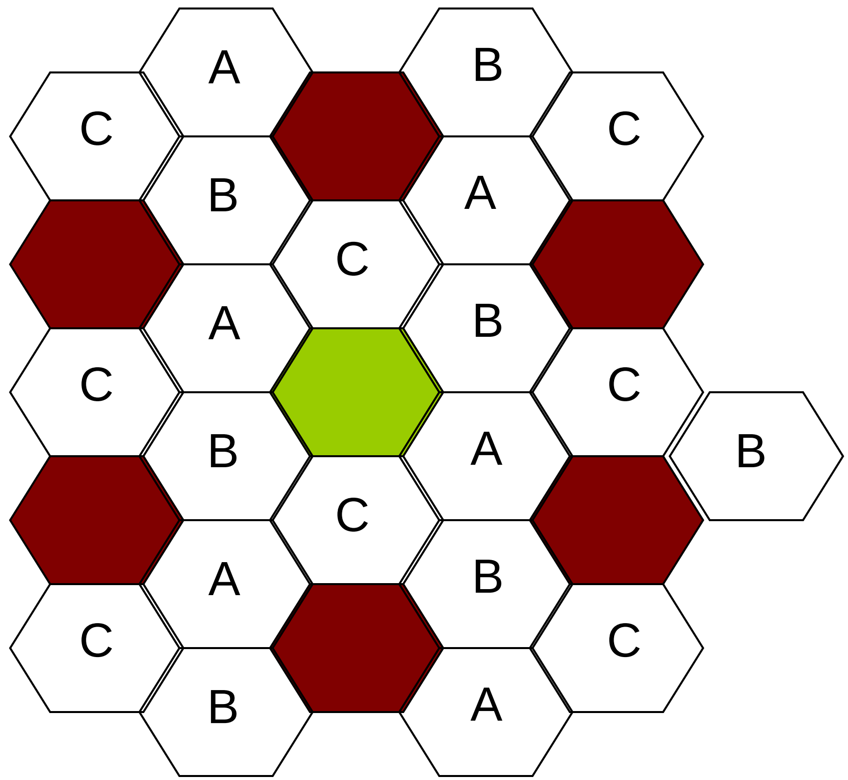
A service area is covered through 28 cells.
The radio resource set is composed of 120 RUs.
The minimum required CIR is 7 dB.
Antennas are trisectorial.

Assuming free space radio propagation, and uniform distribution of users, assign the RUs to the cells.

What is the maximum number of users that can be served in the service area?

Homework

C/I > 7 dB
→ K = 4
→ 7 clusters
→ n = 30
→ Max n. users = 30*28



Homework

A GSM operator has 30 frequency bands, each used with FTDMA and 8 RUs/carrier.
Each frequency band is 200 KHz wide.
The cluster size is 3.
The rate of new call arrivals per sqKm is one every second.
The average duration of a call is two minutes.
The desired blocking probability is 0.02.

How large is the maximum radius of the cells based on traffic considerations?

Based on Hatfield definition, what is the value of the network spectrum efficiency?