Interference & Co-existence

Ryszard Struzak

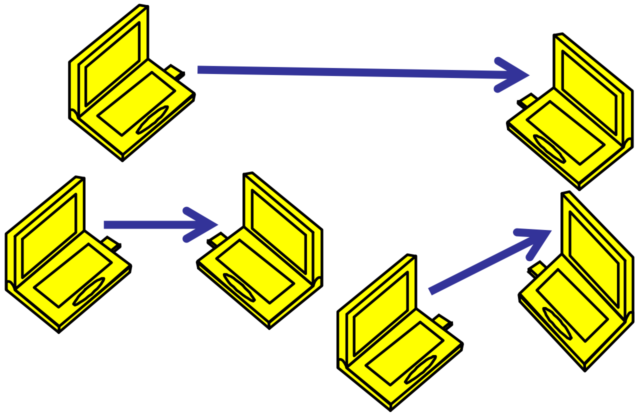
Outline

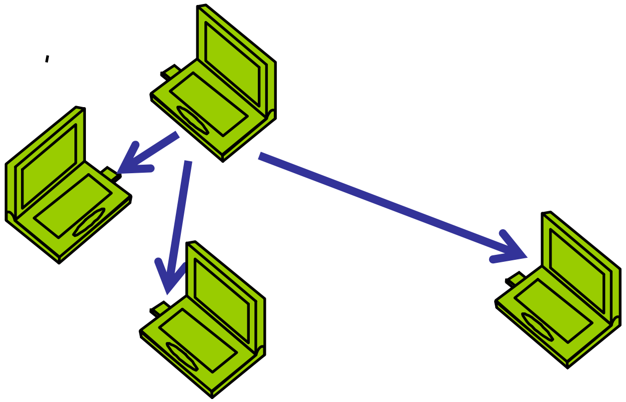
- Basic concepts
    - Communication range
    - Coverage area
    - Service degradation (throughput, error rate)
- Physical models
    - Interference mechanism
    - How to avoid interference

Radio link: basic concepts

- Transmitter – Receiver
    - » Radiator-Receptor; Source-Sink
  - Long distance – short range
  - Fixed – Transportable – Mobile
  - Terrestrial – Space
  - Simplex: Transmission in <u>one direction</u> (e.g. TV)
    - » A simplex link = 1 transmitter & 1 receiver
  - Duplex: Transmission in <u>both directions</u>
    - » A duplex link = 2 simplex links
    - » Full-duplex (FDX) circuit: <u>Simultaneous</u> transmission in <u>both directions</u>
  - Passive services

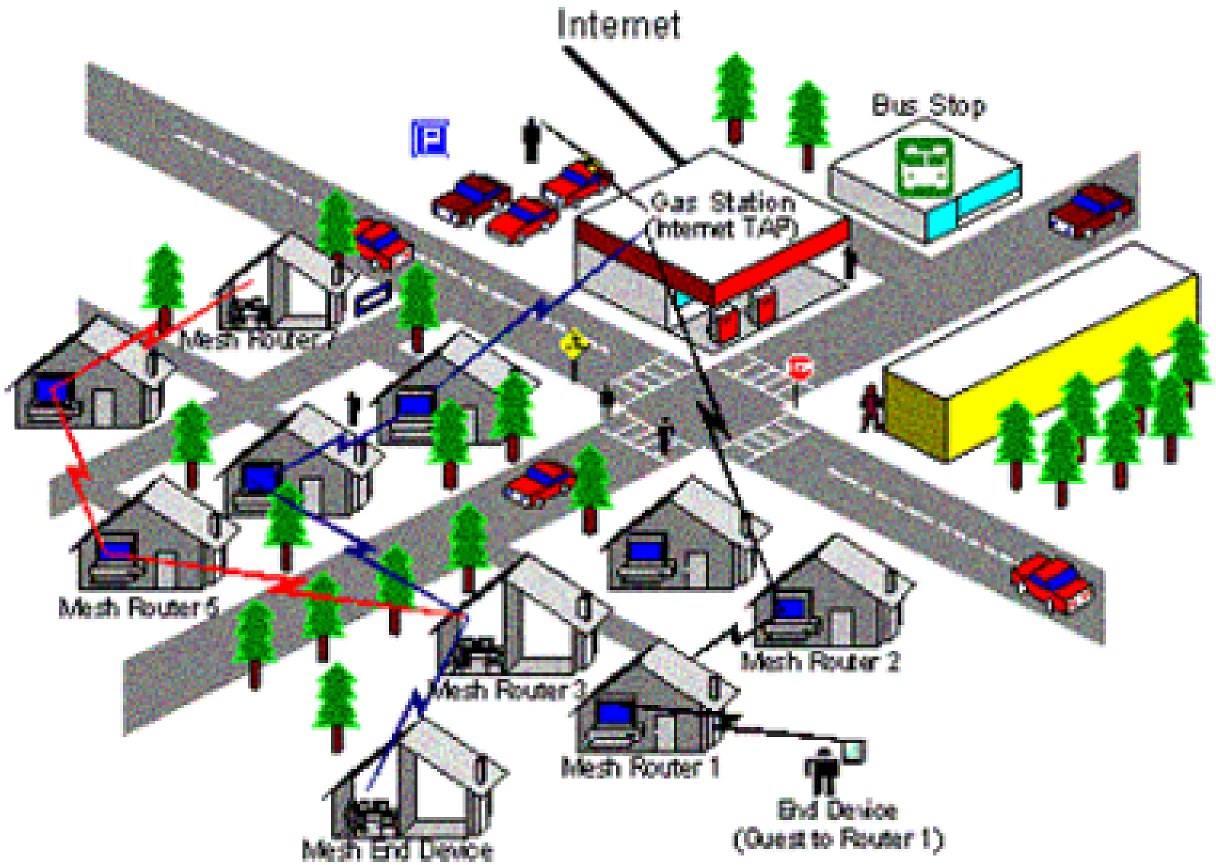
PTP & PMT network topologies





- PTP (point-to-point):
  One station (node) communicating with another one
- PMP (point-to-multipoint): One node communicating with two or more other nodes
  - Broadcasting
  – IEEE 802.11Basic Service Set - a set of stations controlled by a common “Coordination Function”

Mesh network



- Mesh network topology (fully connected): there is a direct communication path between any two nodes
- The principle is similar to the way packets travel around the wired Internet: with dynamic routing data hop from one device to another until the destination is reached.

Source: http://research.microsoft.com/mesh/

What is interference ?

- Effect of unwanted energy upon reception of the wanted signal
  - manifested by performance degradation, misrepresentation, or loss of information
  - which would not happen in the absence of that unwanted energy
- May be unacceptable or harmful !


• F-16 crash near transmitter Voice of America Germany

What causes interference?

- Radio waves are unguided
  - Propagate freely in the space
  - Cannot be confined to any specific volume, unless special screens are applied
- Radio interference may be intentional
  - Jamming
- Most often they are unintentional, due to
  - Wrong deployment of the equipment
  - Wrong frequency use (spectrum management)
  - Spurious receiver responses
  - Spurious emissions

What events are involved?

- Elementary probability of interference *P(I)* :

$$P(I) = P(A \text{ and } B \text{ and } C \text{ and } \underline{D^*})$$

  - A: “The desired transmitter is transmitting".
  - B: The wanted signal is satisfactorily received in the absence of unwanted energy
  - C: Another equipment is producing unwanted energy
  - D: The wanted signal is satisfactorily received in the presence of the unwanted energy
  - <u>D*</u> is the negation (opposite) of the event D
  - All the above refers to the same time period

What is coexistence?

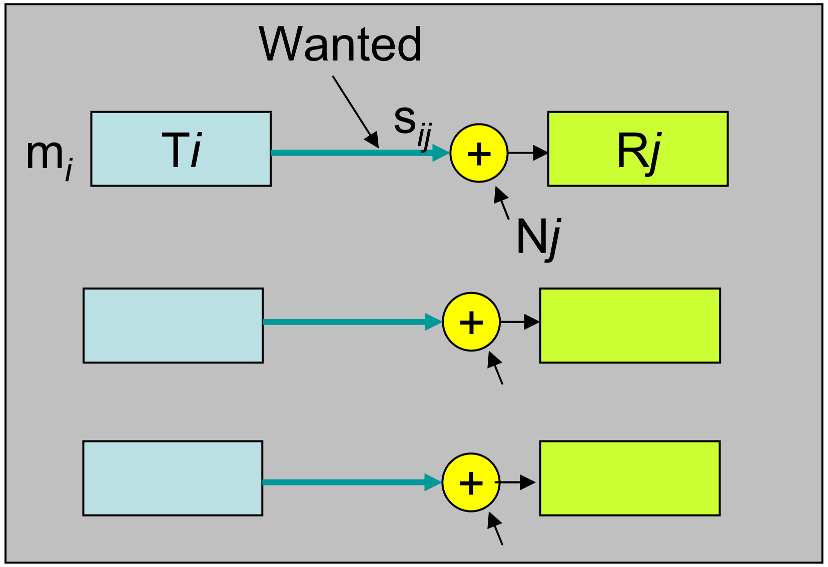
- Term known from politics. Popularized by IEEE's Task Group TG2-802.15
  - » TG2 "Coexistence" deals with radio interference between Wireless Local Area Networks (802.11) and Personal Area Networks (Bluetooth)
- Not defined in major telecommunication standards (e.g. American National Standard - Telecom Glossary *T1.523-2001)*.
- We use it here as a synonym of "*electromagnetic compatibility* (EMC)" defined internationally since 1970s

What is EMC ?

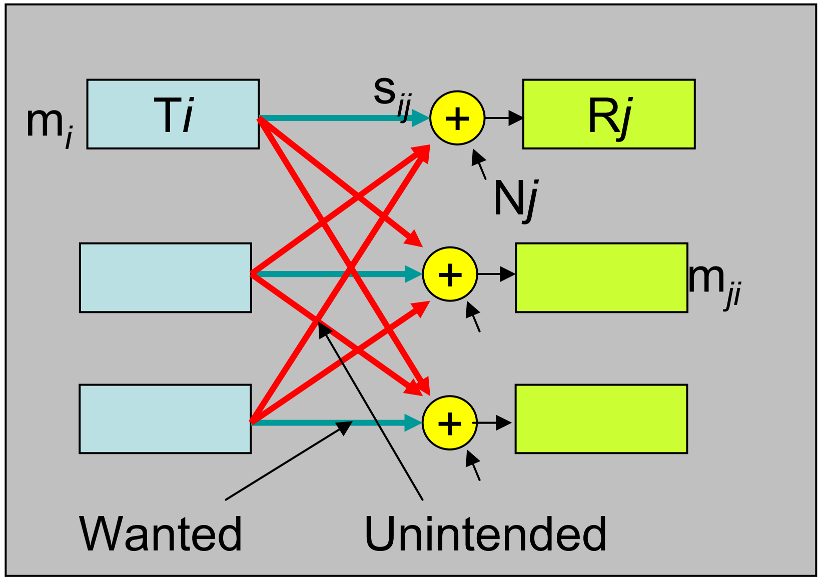
- Electromagnetic compatibility (EMC); the ability of a system (equipment, device) to operate in its intended operational environment
  - without suffering unacceptable degradation and
  - without causing unintentional degradation to the environment
  - due to EM radiation or EM response
    - It implies interference-free operation achieved by design, deployment and exploitation and by application of sound EMC-related policy, concepts, regulations, standards, etc.

Coexistence model

‘Wired’



‘Wireless’



Uncorrelated signals

$$C_{ij} = B_{ij} \log_2 \left(1 + \frac{S_{ij}}{N_j} \right)$$

$$C_{ij} = B_{ij} \log_2 \left(1 + \frac{\sum_i \left(D_{ij} S_{ij} \right)}{N_j + \sum_i \left(1 - D_{ij} \right) S_{ij}} \right)$$

$$D_{ij} = \begin{cases} 1 & \text{(intended)} \\ 0 & \text{(unintended)} \end{cases}$$

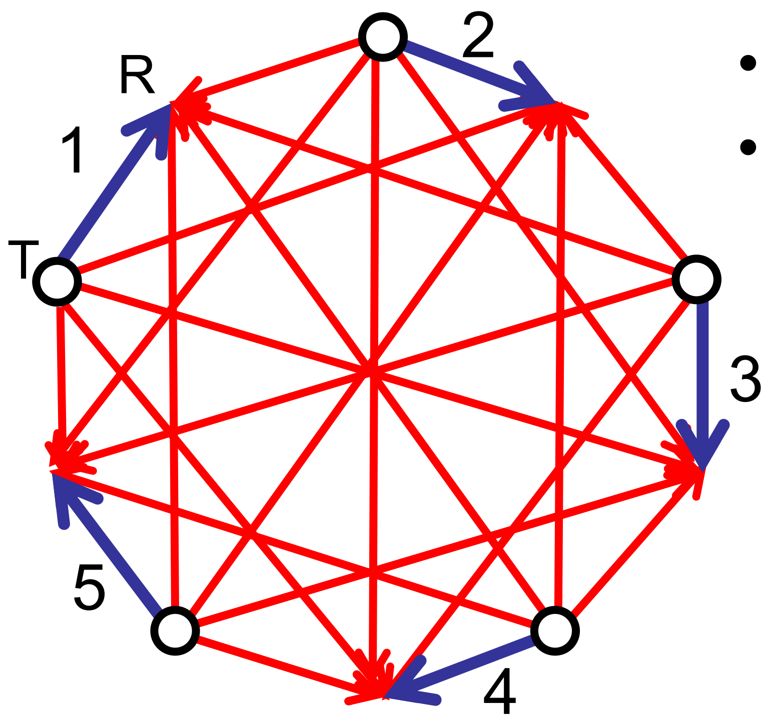
Spurious vs. regular links

Interference can be modeled as interaction among regular and spurious radio links

- Regular - intended
  - Useful / Wanted
  - Designed before deployment
  - Checked/ controlled
  - Regulated nationally and internationally
  - Require individual or group license (except ISM-type bands)

- Spurious - unintended
  - Useless/ Unwanted/ Harmful
  - Not designed/ Random
  - Unchecked, often unnoticed until harmful interference appear
  - Regulations?

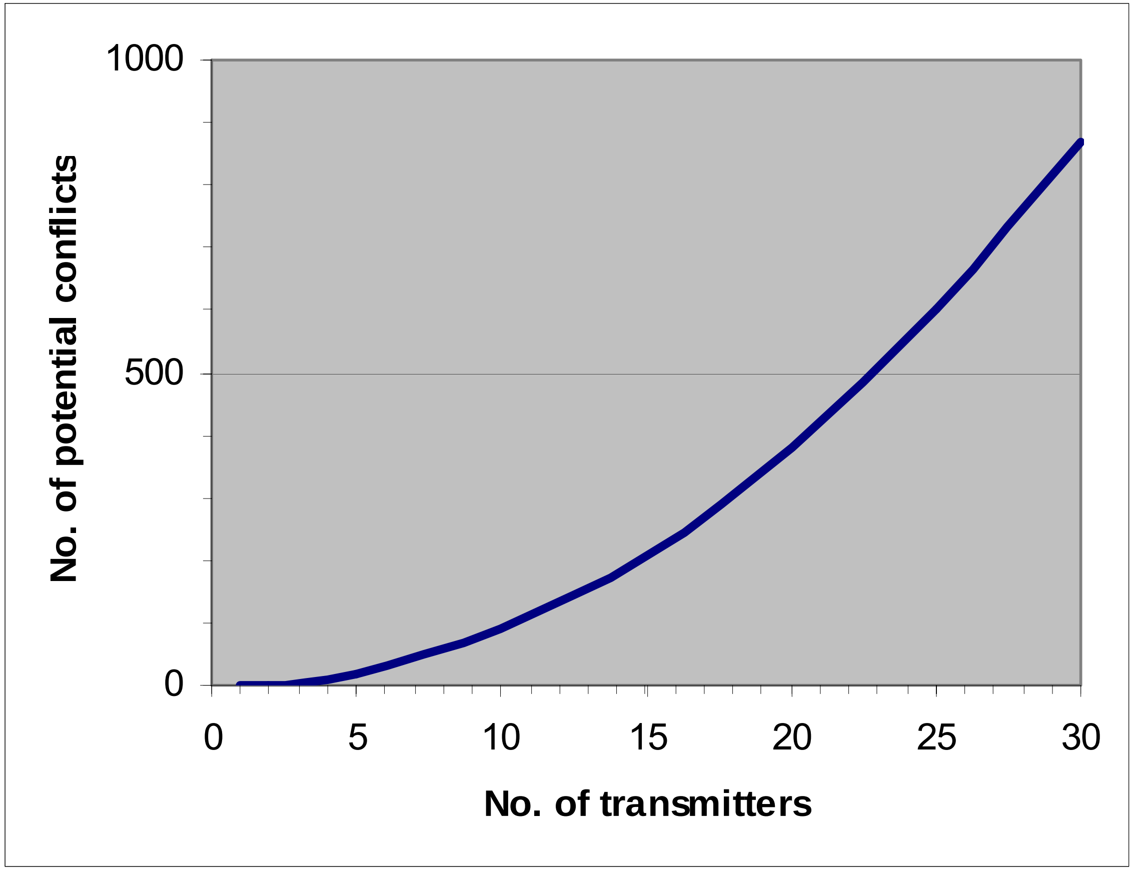
How many spurious links?



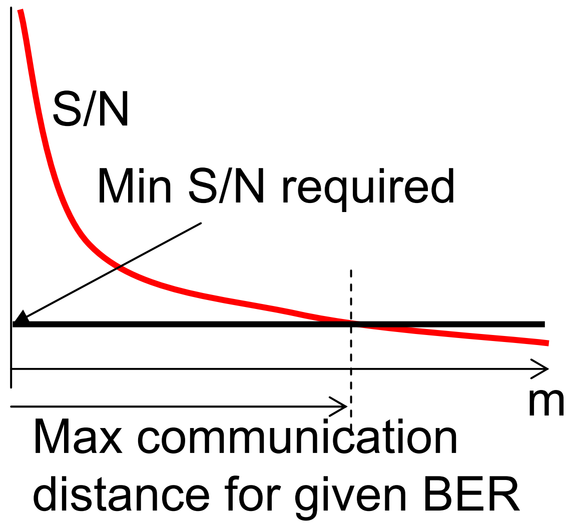
5 receivers
5 transmitters
5 wanted links
20 potential spurious links

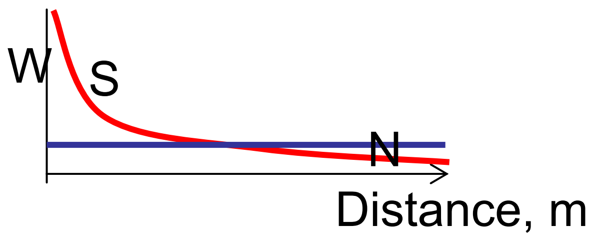
- Maximum – fully connected net
- n (designed) simplex links
  = n transmitters & n receivers
  - Each receiver may receive n signals.
  - One of these signals is wanted; the remaining (n-1) are unwanted
  - Each wanted signal may be in potential conflict with one or more unwanted signals
  - Thus, the maximum number of potential spurious links = n(n-1).

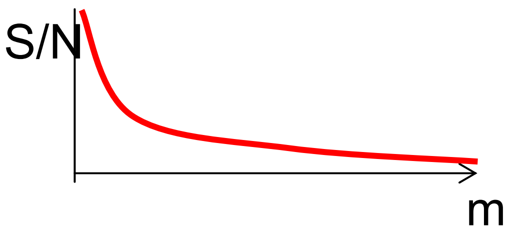
How many potential conflicts?



Communication range
(isolated radio link)





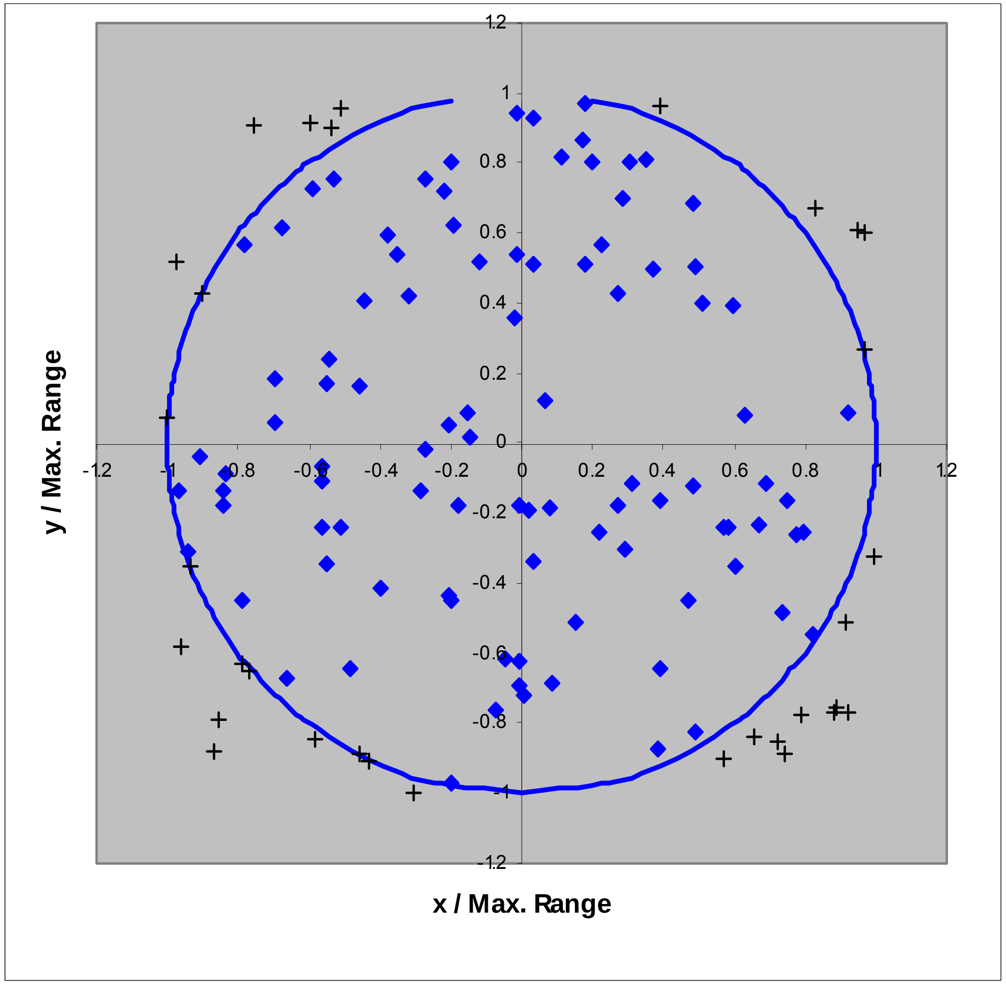


- Communication range = the distance from a transmitter at which the signal strength equals or exceeds the minimum usable level for a particular antennas and transmitter/receiver combination.
  - The usable signal level depends on required system performance (e.g. BER)
  - For isolated radio link it is associated with the equivalent system noise power N at the receiver input
  - With constant noise power N, the S/N and the range decrease in free space with the distance squared

Coverage area

- ‘Coverage’ = geographical area within which service from a radio communication facility can be delivered under specified conditions
    - E.g. BER < 10^{-4} ; S/N > 30 dB, etc.
    - In broadcasting, one uses ‘population coverage’
    - The coverage concept may be useful in analyzes of financial efficiency: “costs per unit area” or “cost per user”

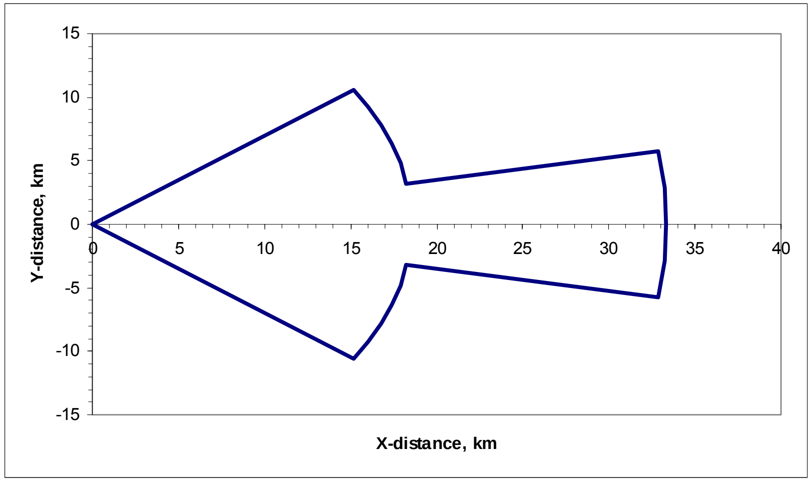
Coverage
(isolated omnidirectional link)

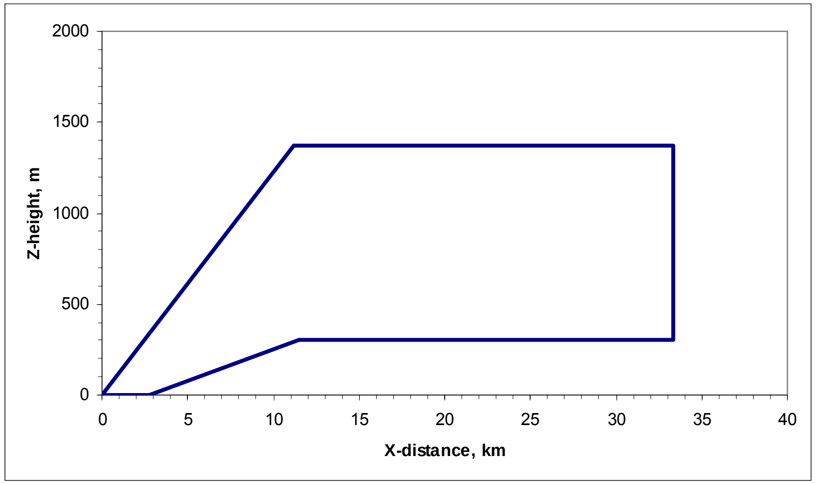


- Potential coverage of an isolated transmitter (omnidirectional)
- Blue line: border of coverage area (noise-limited)
- Test points
  - "blue" if the T_0-R link does operate correctly
  - "cross" if the T_0-R link does not operate correctly
- Coverage Loss = 0

- How close can we put neighboring stations?

Example: ILS service volume
(isolated link)





- **Instrument landing system (ILS)** is a radio-navigation system which provides aircraft with horizontal and vertical guidance just before and during landing and, at certain fixed points, indicates the distance to the reference point of landing. [NTIA] [RR]
- Aeronautical radio services use 108-130 MHz frequency band. If not properly coordinated, they may suffer interference from FM broadcast stations operating in the adjacent band of 88-108 MHz.

Coverage

Noise-limited vs. Interference-limited

- Isolated transmitter
- A minimum signal S/Nmin set
- A test receiver & test points specified
- The receiver moved form one test point to another and the measured S/N compared with the S/Nmin
- The potential, or noise-limited coverage is the set of the test points at which S/N >= S/Nmin
- Note: S/Nmin defines minimal signal level

- Transmitter + >1 interferer
- A minimum protection ratio S/Imin set
- A test receiver & test points specified
- The receiver moved form one test point to another and the measured S/I compared with the S/Imin
- The interference-limited coverage is the set of the test points at which S/N >= S/Imin
- *Note:* Thermal noise is disregarded

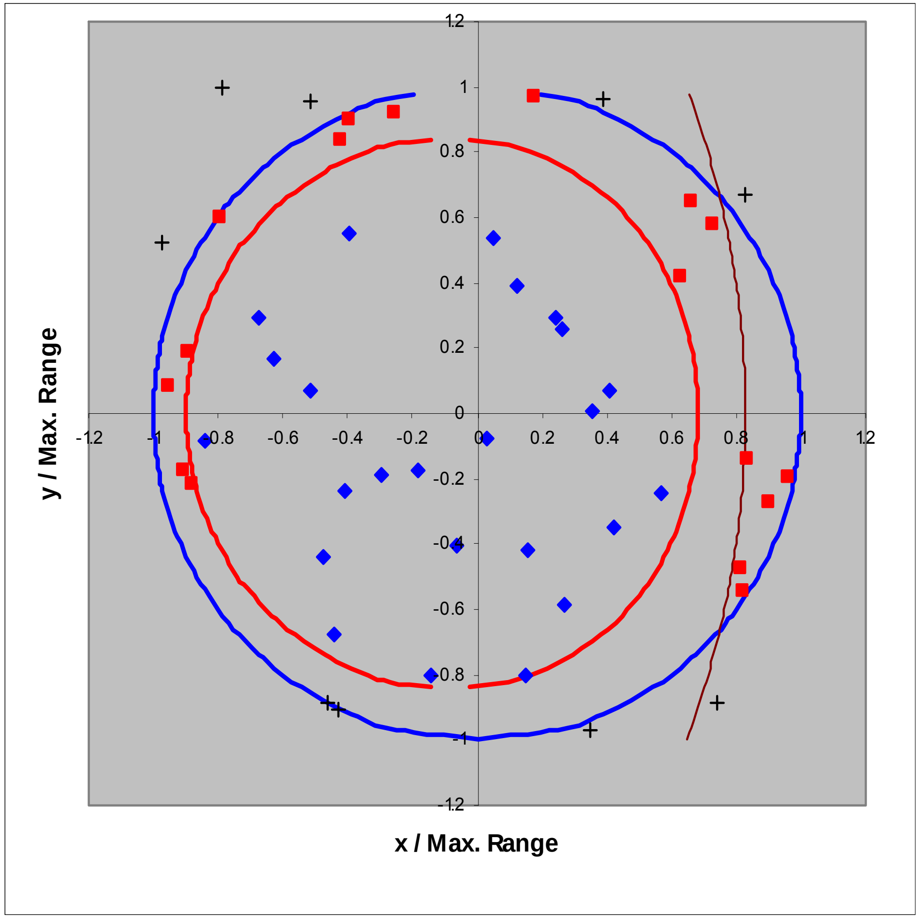
Coverage loss

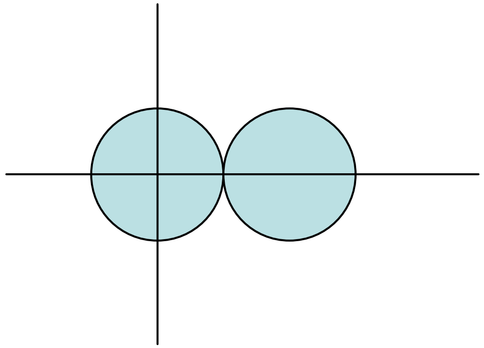
$$\text{Absolute Coverage Loss} = (\text{Potential Coverage}) - (\text{Actual Coverage})$$

$$\text{Relative Coverage Loss} = \frac{(\text{Absolute Coverage Loss})}{(\text{Potential Coverage})}$$

- May be expressed in terms of Volume, Surface, Population, Costs, etc. (absolute or relative)
  - It was proposed as an objective characteristics in evaluation of operation of radio systems in congested environment
    - » Struzak R: *Simulation model for evaluating interference threat to radiocommunication systems*; Telecommunication Journal, Vol. 57 – XII/1990, p. 827-839

Coverage map (simulation 1i)

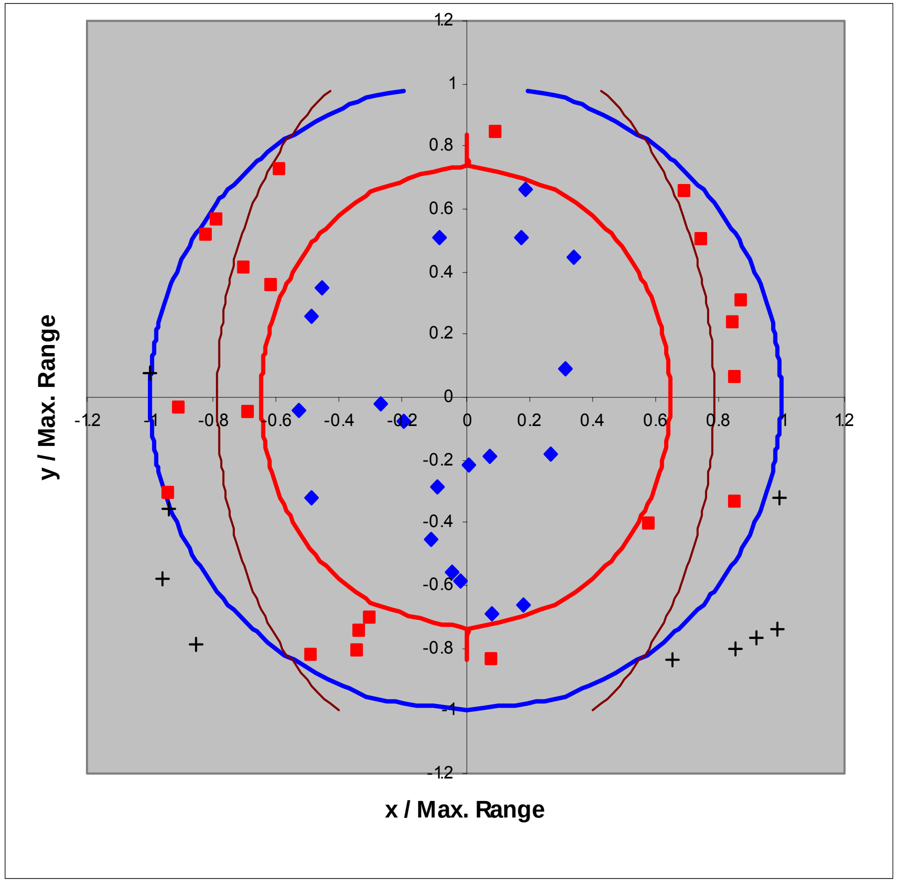


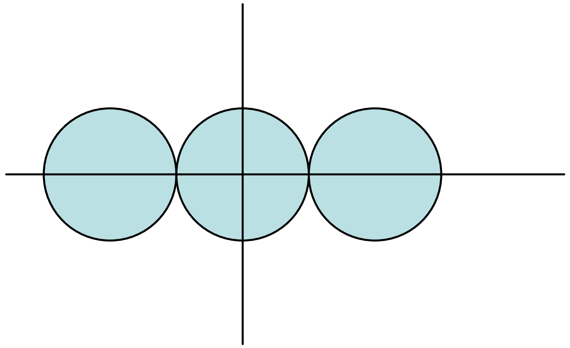


- 1 additional (identical omnidirectional transmitters in free-space with tangent potential coverage areas
  - Blue line: Potential coverage (the other transmitter switched-off)
  - Red line: actual coverage
  - Brown line: interference-limited coverage (noise-free receiver)

- Coverage loss = 33%

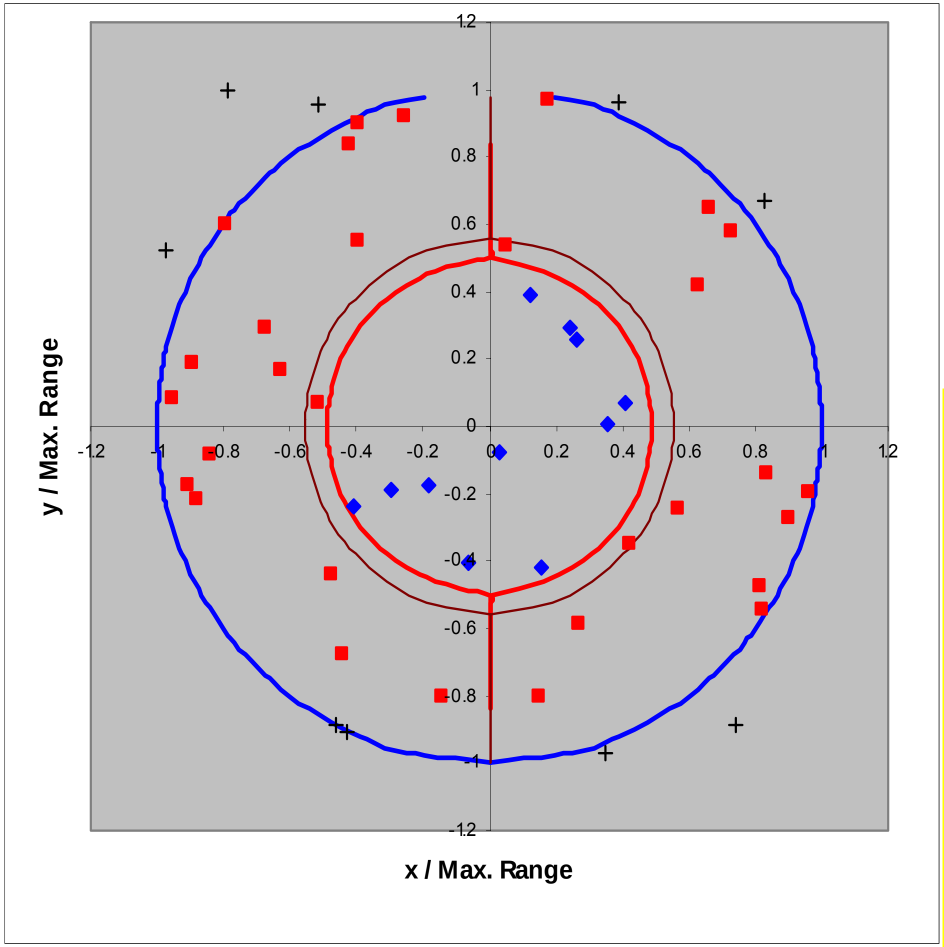
Coverage map (simulation 2i)

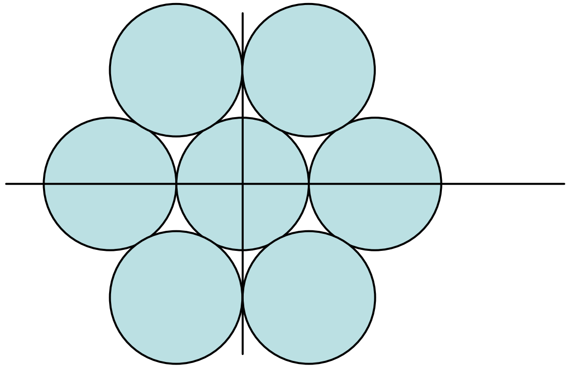




- 3 identical omnidirectional transmitters in free-space with tangent potential coverage areas
- Blue line: Potential coverage (the other transmitters switched-off)
- Red line: actual coverage
- Brown line: interference-limited coverage (noise-free receiver)
- Coverage loss = 52%

Coverage map (simulation 6i)

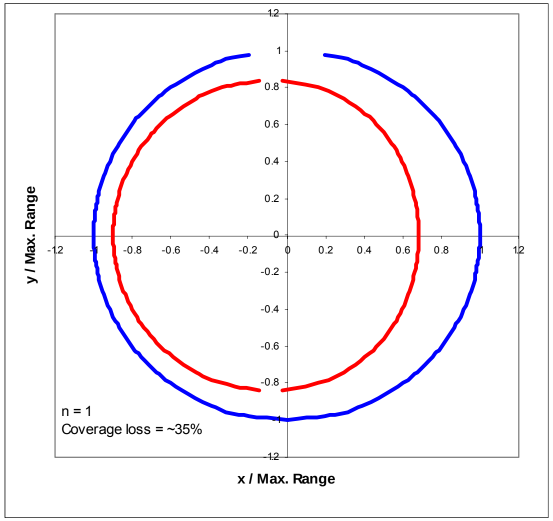


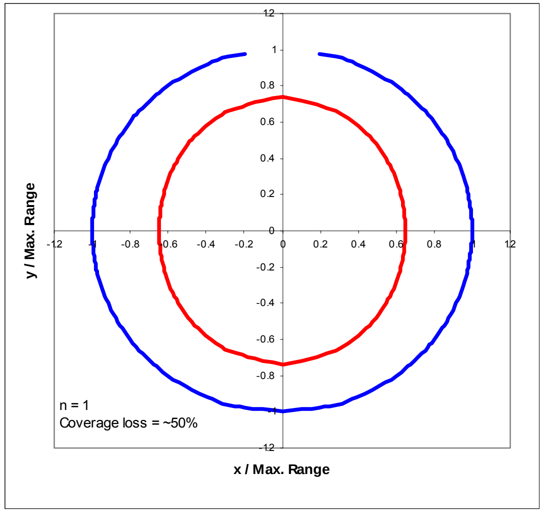


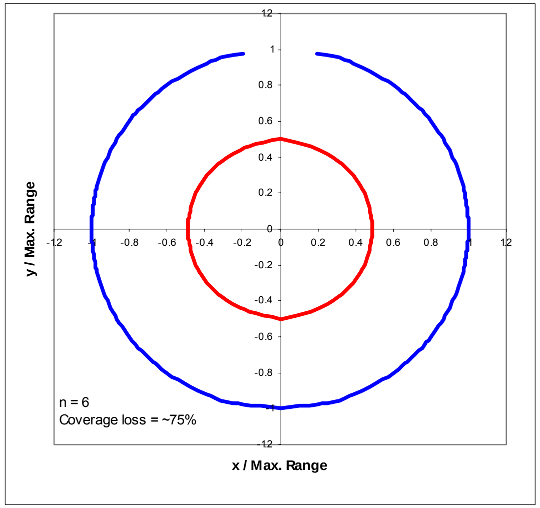
- 7 identical omnidirectional transmitters in free-space with tangent potential coverage areas
- Blue line: Potential coverage (the other transmitters switched-off)
- Red line: actual coverage
- Brown line: interference-limited coverage (noise-free receiver)

- Coverage loss = 76%

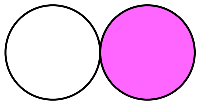
Impact of unintended radiations

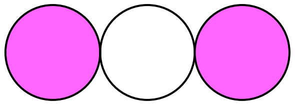


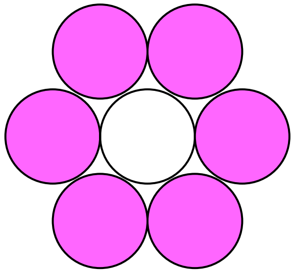




Coverage loss = 35%　　　= 50%　　　= 75%





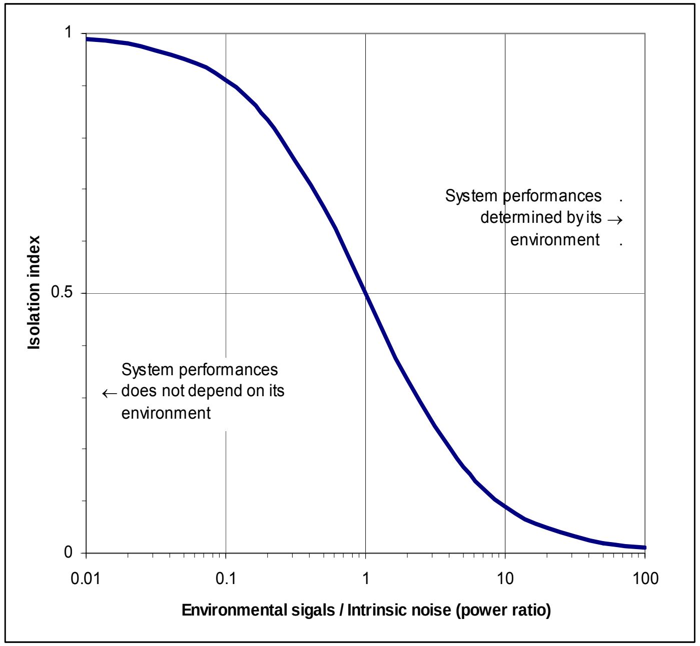


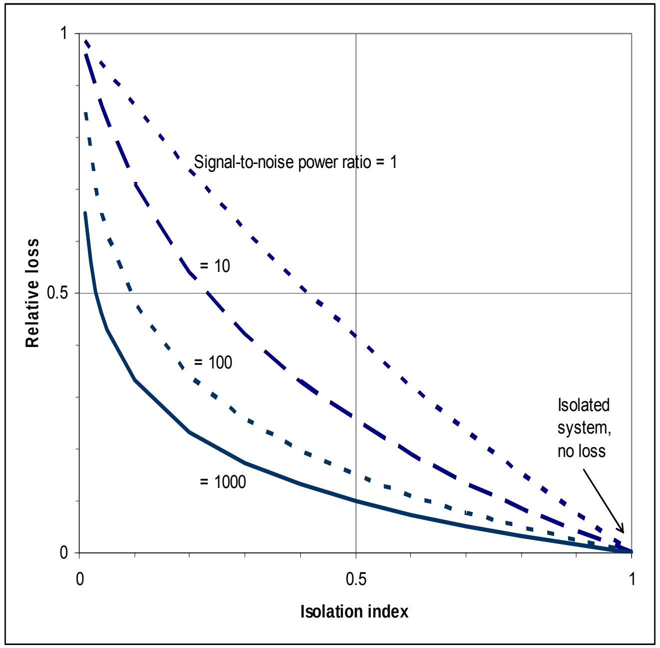
R Struzak

Open questions

- The coverage decreases with each new transmitter added and so does the income of the service provider
  - Should that decrease be accepted, or should a compensation be demanded for the loss?
  - Will this depreciate the value of the business?
  - Will this influence the investment decisions?

Isolation coefficient





Struzak R: On Spectrum Congestion and Capacity of Radio Links; Annals of Operations Research 107, 2001 (2002), pp. 339-347

- Except for sparsely deployed systems, the systems’ features depend on unintended interactions with other systems
- Interacting systems behave as a network
- Technical & operational characteristics of co-existing systems (network components) must be harmonized/ coordinated

Multiple interferers

- Energetic approach
  - Resultant power of a number of unwanted signals equals the sum of powers of individual interfering signals $I_{tot} = \Sigma(I_i)$
- Probabilistic approach
  - Resultant probability of interference due to a set of independent interferers

Signal protection

- Over the coverage/ service area, the wanted signal is to be protected against interfering signal
- The degree of protection is known as protection ratio
  - Protection ratio is the minimum value of the wanted-to-unwanted signal ratio at the receiver input, determined under specified conditions (Analogous to signal-to-noise ratio)
  - Specified performance (reception quality of the wanted signal) is assumed at the receiver output
  - The ratio of the carrier to the interference is also called *carrier-to-interference ratio* (C/I)

RF signals: multidimensional space

Radio-wave signal has a number of characteristics that generate a multidimensional space

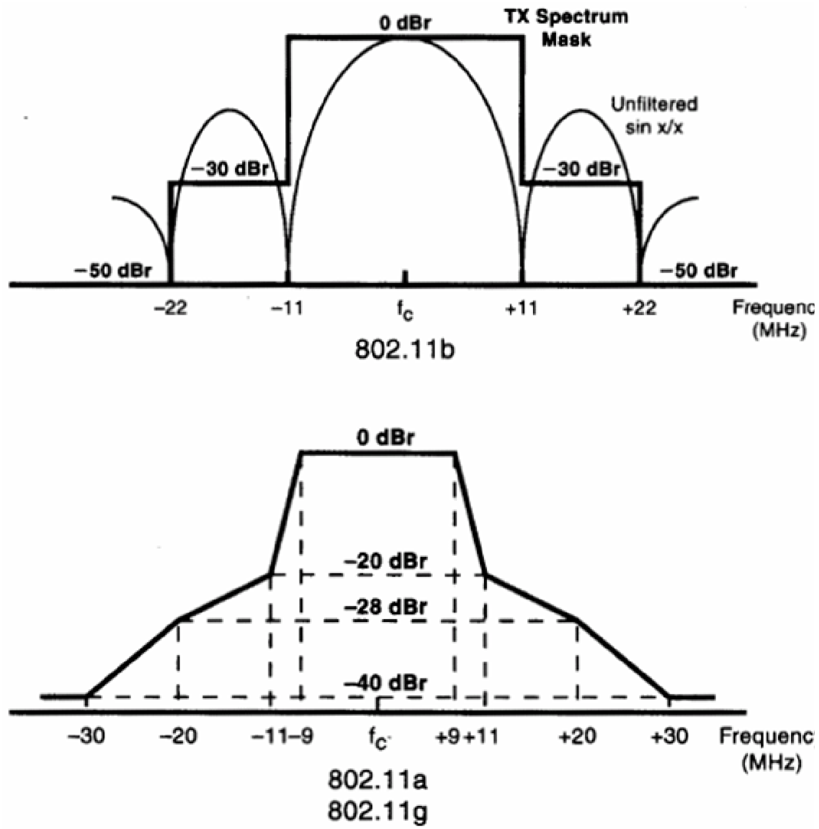
Quantity	Unit	No. of dimensions*
Frequency	Hz, MHz, GHz	1
Time	ms, s, hr, year	1
Spatial location (geographical longitude, latitude and altitude)	Degree, m, km,…	3
Elevation angle of launch/ arrival	Degree	1
Azimuth angle of launch/ arrival	Degree	1
Polarization	Sense (L, R)	1

* Per device

Radio channel or radio space?

- Channel → cable/ wire world
- Radio → unlimited space involved
    - Signals from distant galaxies
- How many dimensions?
    - Einstein & Minkowski: "*only a kind of union of space-and-time will preserve an independent reality*" *[http://en.wikipedia.org/wiki/Philosophy_and_space_and_time#Einstein]*

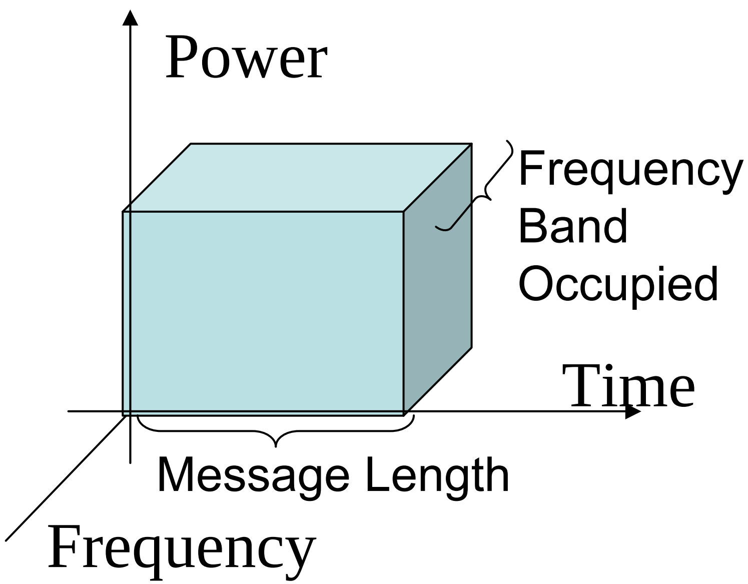
Visualization: Spectrum masks

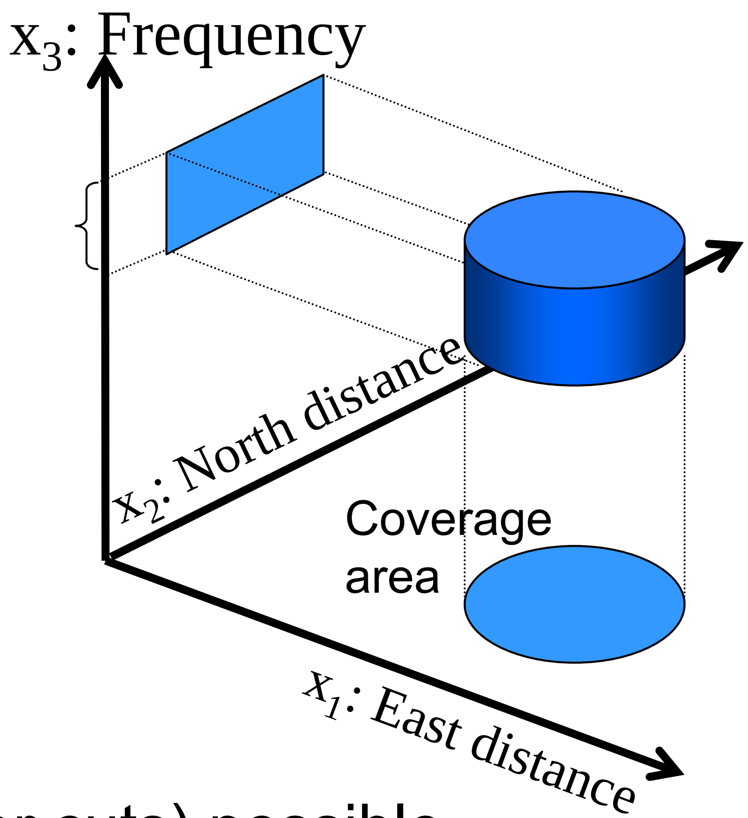


Spectrum masks for WiFi – examples of the projection of multidimensional signal solid onto the Frequency-Power plane

•Morrow R: Wireless network coexistence; McGraw-Hill 2004 p. 201 & 221

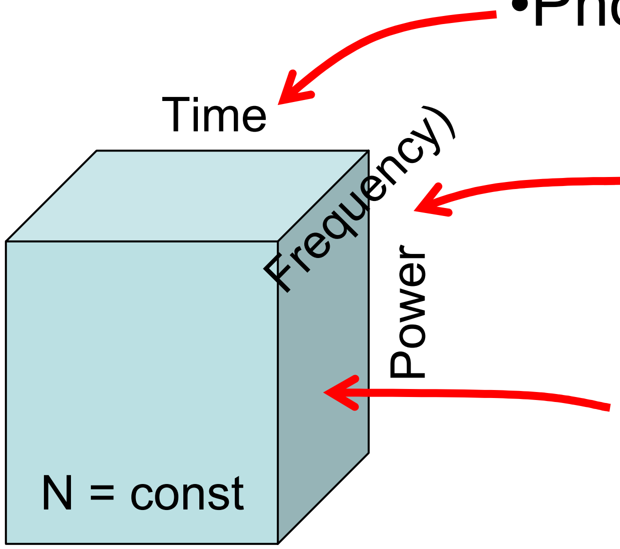
Visualization (isolated system)





Only projections on a plane (or cuts) possible

Dimensionality



- •Phone bills: 1D (T)
- •Licensing: 2D (F, P)

Shannon: 3D (F, T, P)

….

ITU, Berry, ….: 4D (F, T, X, Y) or 5D (F, T, X, Y, Z)

…

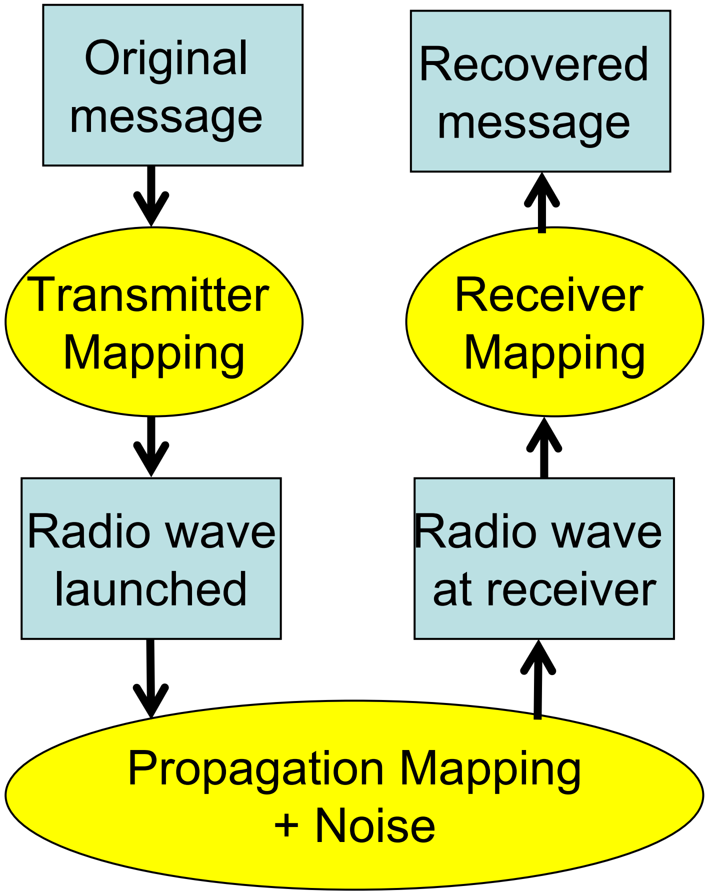
Matheson: 7D (F, T, X, Y, Z, θ, φ)

Until now: fixed dimensionality

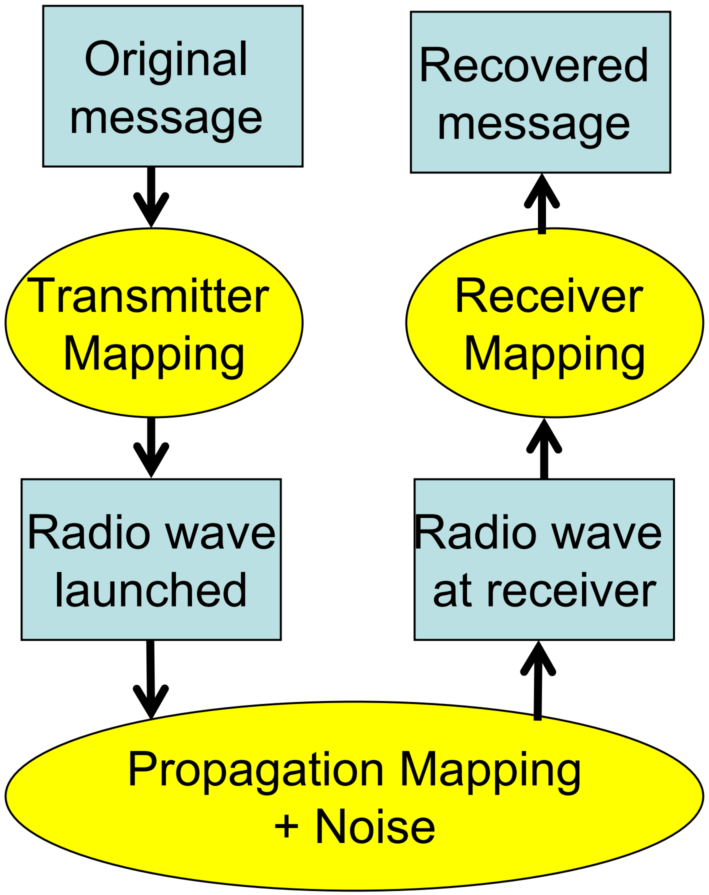
Dimensionality: new approach

- *No limits* imposed on the dimensionality
  - Include each orthogonal variable by which radio signals are distinguished one from another
    - » Variables depend on technology
    - » Technology develops → more dimensions
    - » More dimensions → more degrees of freedom →more flexibility in 'spectrum management'
- Past, current, and future radio system technologies embraced into one chain

How it works?



- A *message*, generated by a *source* of messages, to be delivered from the source to a distant *destination* via *telecommunication channel*
- The channel consists of a *transmitter node*, *propagation path* and *receiver node*.
  - Message in its most general meaning is the object of communication. Depending on the context, the term may apply to both the information contents and its actual presentation, or signal.
  - The baseband signal usually consist of a finite set of symbols. E.g. text message is composed of words that belong to a finite vocabulary of the language used. Each word in turn is composed by letters of a (finite) alphabet. (Analog-to-digital conversion)
- The transmitter and receiver process the signal using a common *communication protocol* under a common *communication policy*.



- A series of mappings
  - » Following the algorithm/ protocol/ policy
- Recovered message differs from the original - contain errors
  - Mapping errors due to interference, noise, distortions, etc.
- What errors are acceptable?

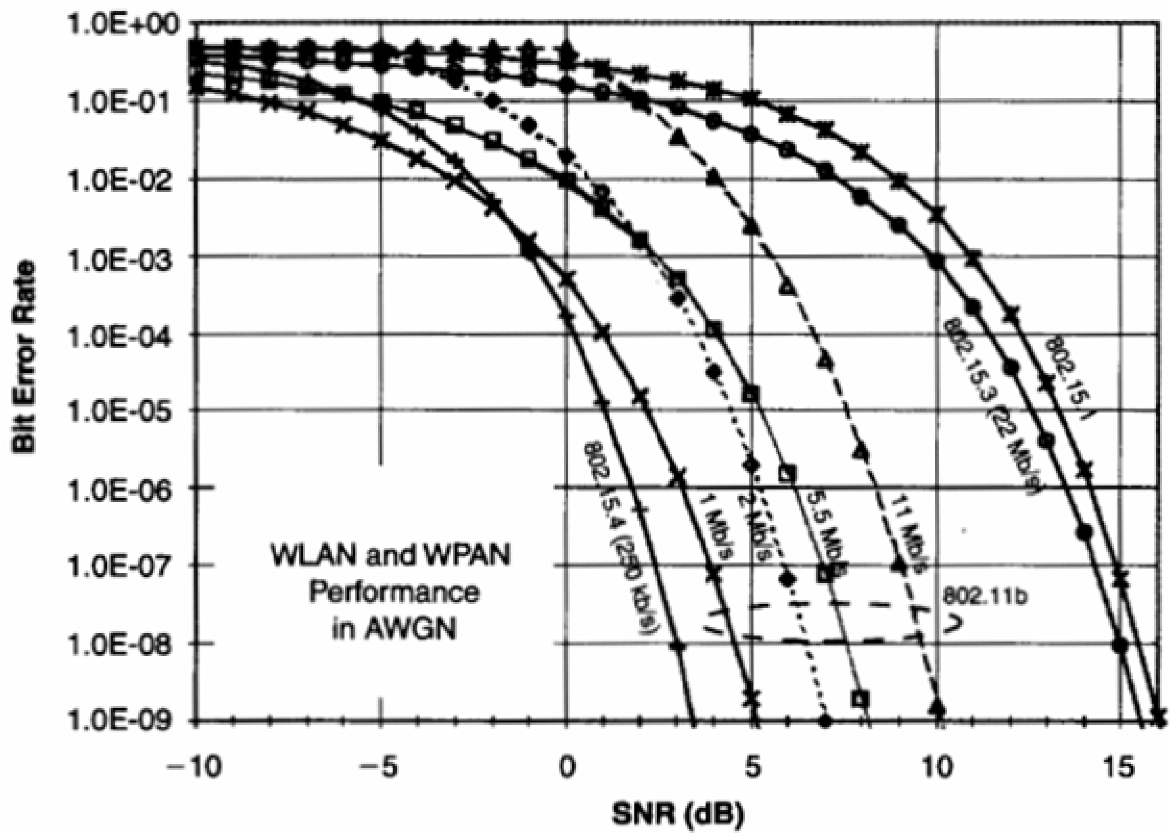
How big is “small” error?

It is application-dependent. In computer communications it is BER. People prefer subjective criteria.

BER	Subjective effect (voice)
10^{-6}	Not audible interference
10^{-5}	Barely audible
10^{-4}	Audible, but not disturbing
10^{-3}	Disturbing, but speech still understandable
10^{-2}	Most disturbing, speech difficult to understand

Source: Townsend AAR: Digital line-of-sight radio links, Prentice Hall, p.570

How BER relates to energy (SNR)?



BER versus SNR for the four data rates of WiFi (IEEE 802.11b) along with values for Bluetooth (IEEE 802.15.1), WiMedia (IEEE 802-15.3) and ZigBee (IEEE 802.15.4), all operating in the 2.4 GHz band

•Morrow R: Wireless network coexistence; McGraw-Hill 2004 p. 192

Transmitting station

maps the original message into the radio-wave signal launched at the transmitting antenna

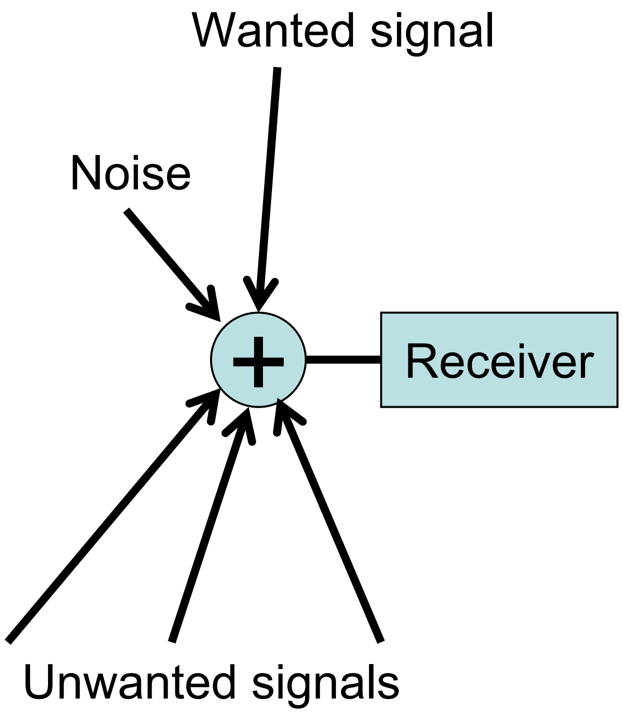
1. Generates a RF carrier
2. Combines it with the baseband signal into a RF signal through *modulation*
3. Performs additional operations
    - » E.g. *analog-to-digital conversion, formatting, coding, spreading,* adding additional messages/ characteristics such as *error-control, authentication*, or *location information*
4. Radiates the resultant signal in the form of a modulated radio wave

Propagation path

maps the radio-wave launched by the transmitter into the incident radio wave at the receiver

– Incident wave ≠ Radiated wave
– Propagation process involves extra variables (e.g. distance, latency) & radio waves (reflected wave, waves originated in the environment, etc.), random uncertainty (e.g. noise, fading) and distortions

Receiving station

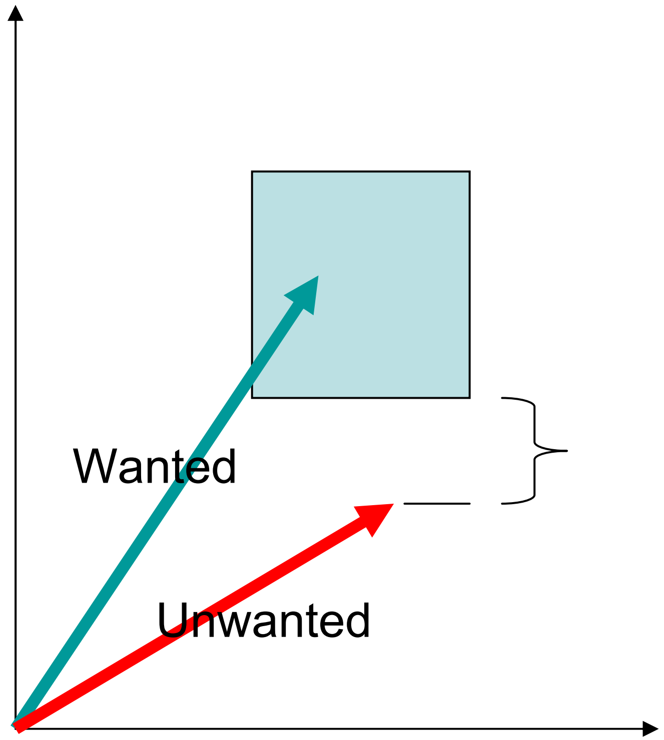


maps the incident radio wave into the recovered message

The receiver's response defines a (solid) "window" in the signal hyperspace through

- reversing the transmitter operations (demodulation, decoding, de-spreading, etc.),
- compensating propagation transformations, and
- correcting transmission distortions

How to keep error small?



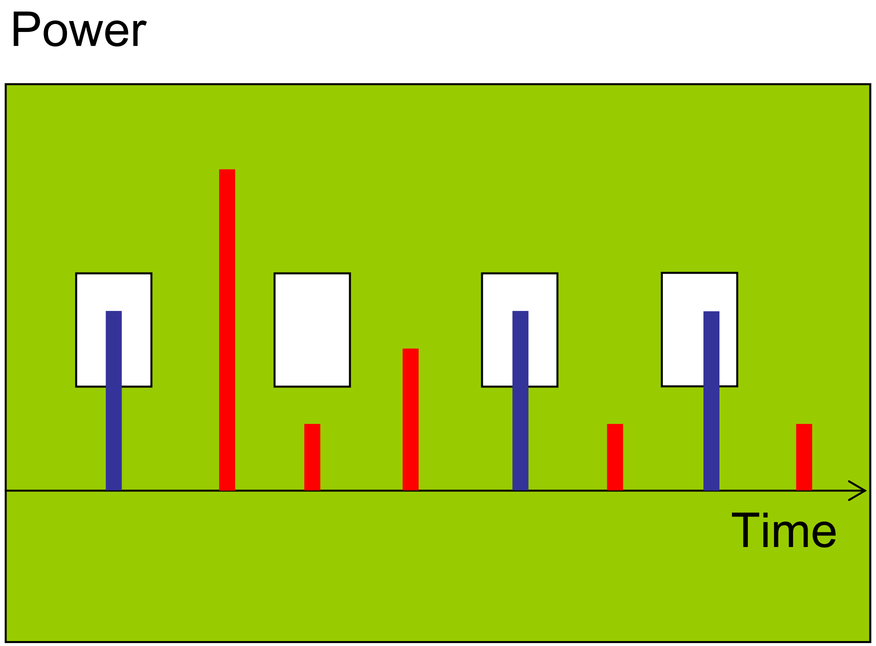
- Every component of the *wanted* signal must *fit exactly* into the receiver reaction window (RRW) in the signal hyperspace
- For each unwanted signal, *at least one* component must fall *outside* the RRW

Struzak R: Evolution of Spectrum Management Concepts; Electromagnetic Compatibility 2006.
Proceedings of the Eighteen International Wroclaw Symposium on Electromagnetic Compatibility, June 28-30, 2006, pp. 368-373

How to implement it?

- By signal filtering/ separation in multidimensional space
  - Frequency separation (e.g. FMDA)
  - Time separation (e.g. TDMA)
  - Code separation (e.g. CDMA)
  - Other (modulation, direction, distance, polarization, etc.)

Time filter

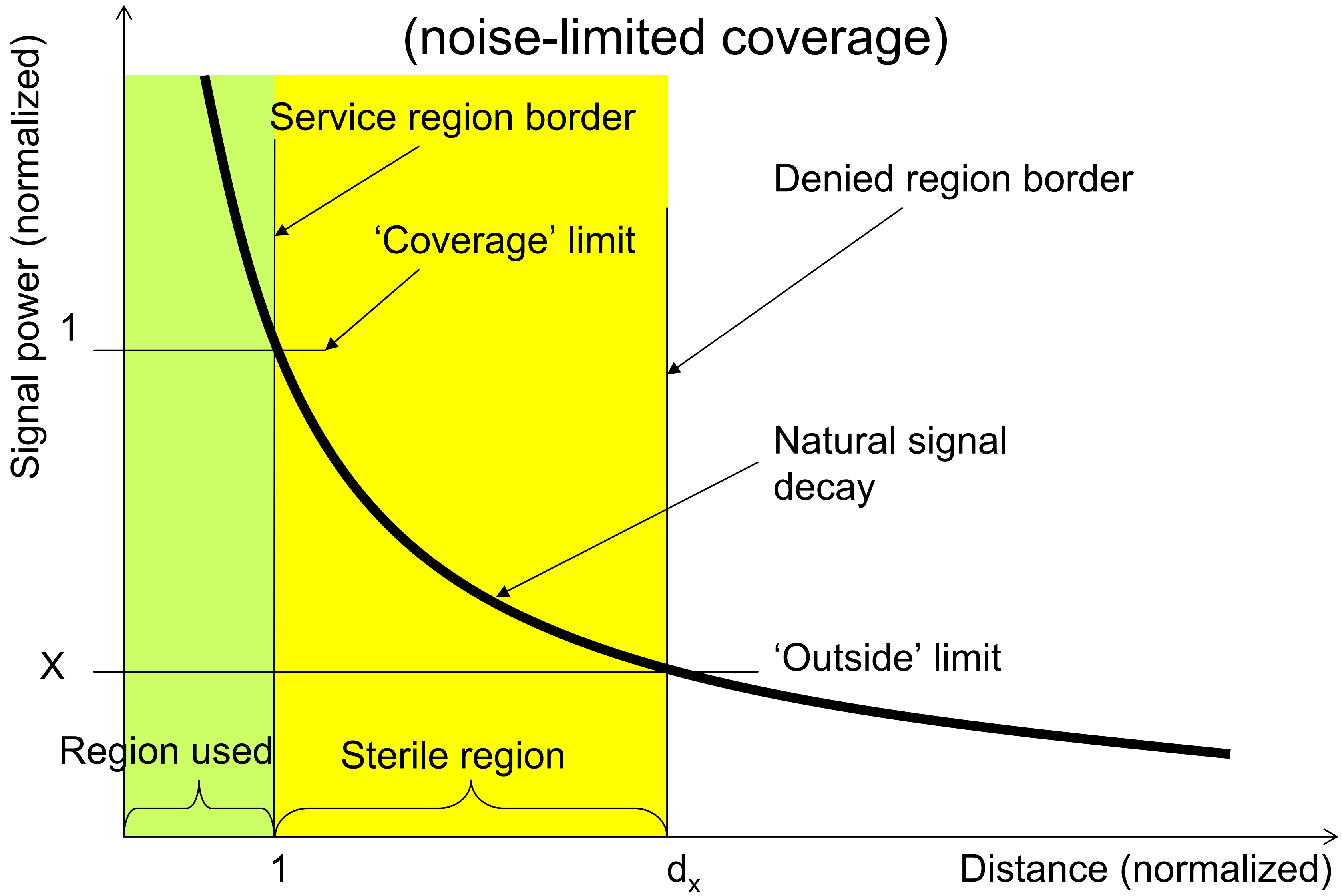


- The receiver time-window may consist of a number of separate openings at discrete time instances (white rectangles)
- The receiver rejects red impulses
  – Regular sampling
  – Irregular sampling

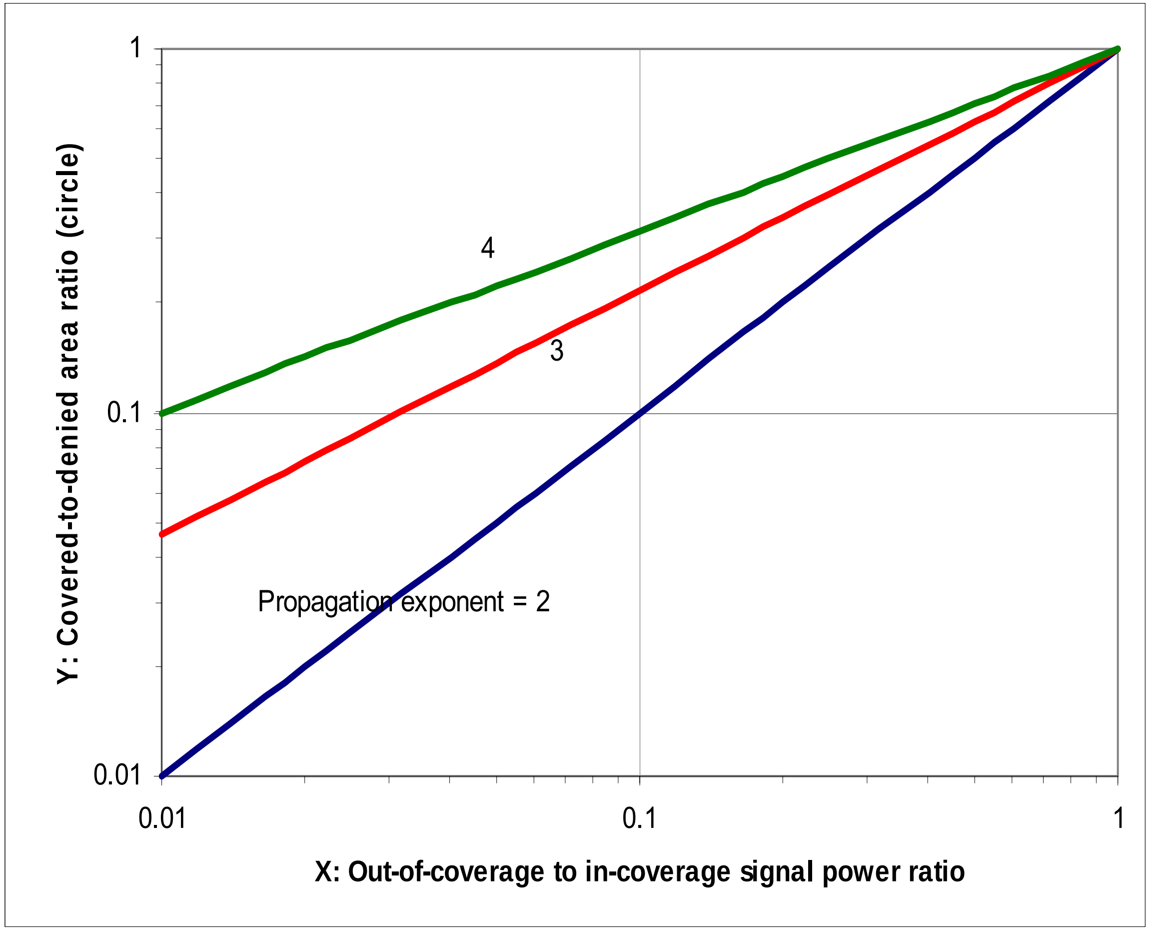
Example of time 'filtering'

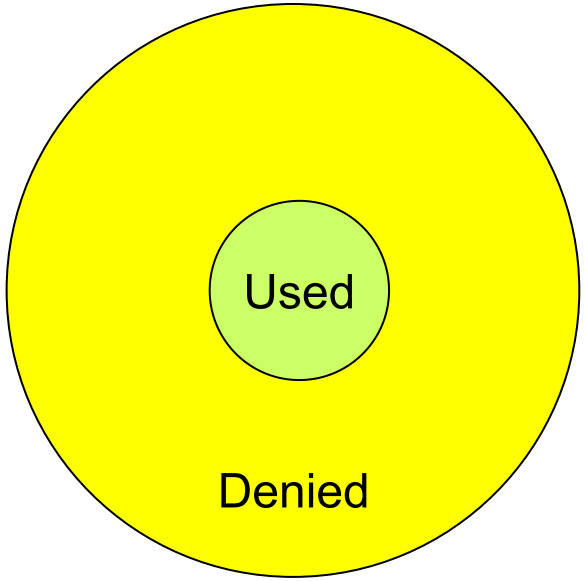
Distance factor

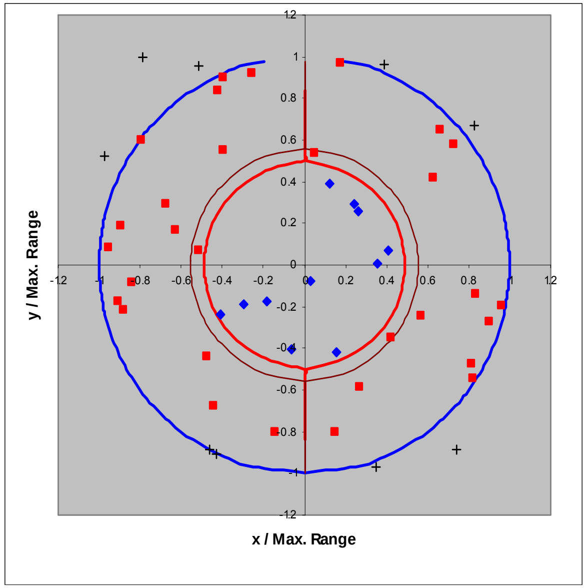
(noise-limited coverage)



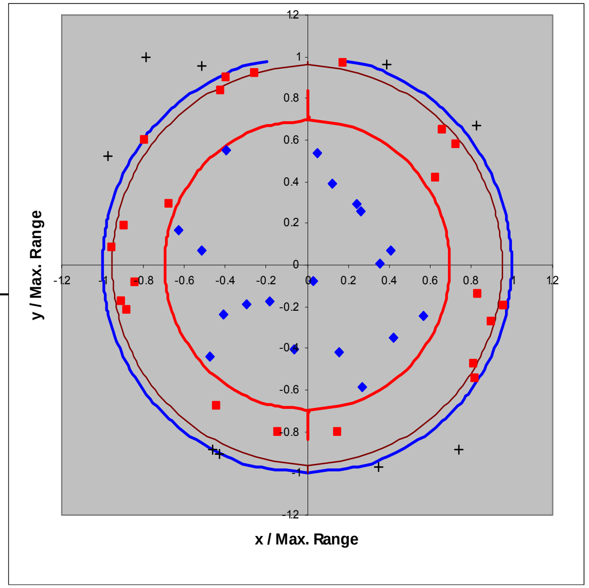
Covered area vs. denied area
(isolated link)



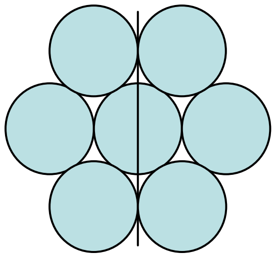




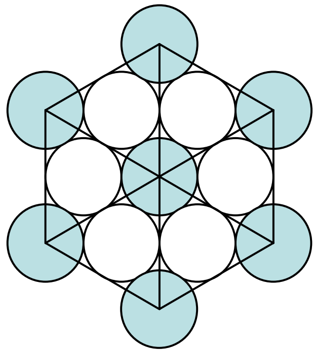
Coverage loss = 76%



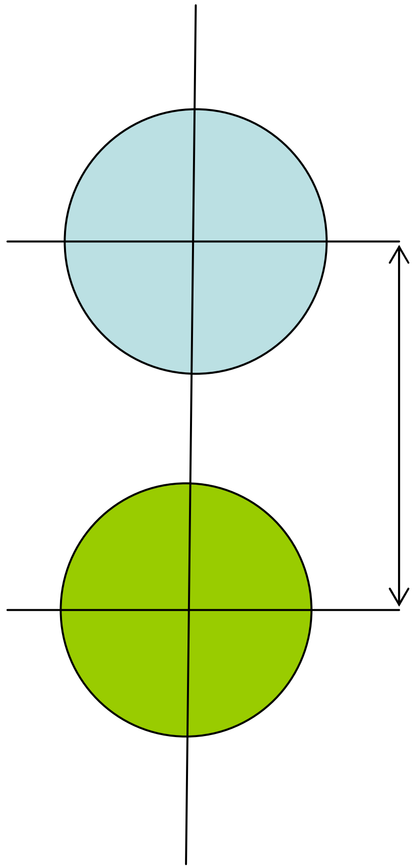
Coverage loss = 51%



- 7 identical omnidirectional transmitters in free-space Blue line: Potential coverage (the other transmitters switched-off)
- Red line: actual coverage
- Brown line: interference-limited coverage (noise-free receiver)



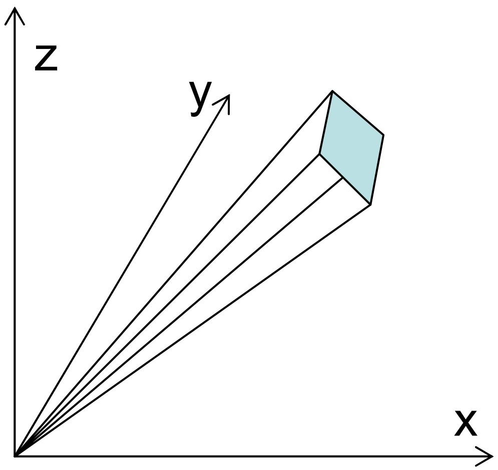
Frequency reuse & spectrum management

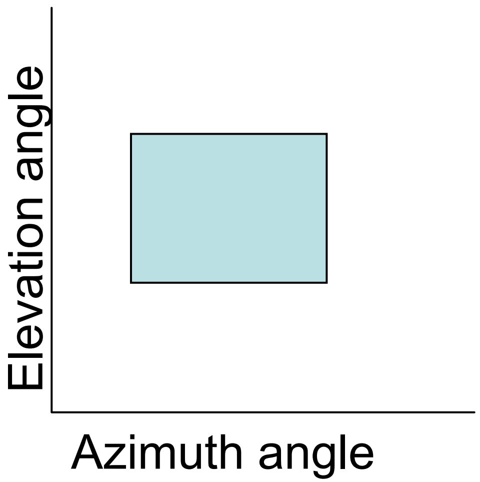


- “No common frequency may be used simultaneously by two transmitters which are separated by a distance less than ‘X’ km”
- Seems very simple, but very difficult with a large number of densely deployed radio systems
  – More complex rules required
  – Graph theory, Games theory, non-technical issues
  – Traditional task of national spectrum management and ITU radio conferences - (static) long-term frequency tables and plans
  – Automated in modern devices, prevailing in future Software-Defined, Cognitive, Adaptive Radio systems

Example of dimension adding

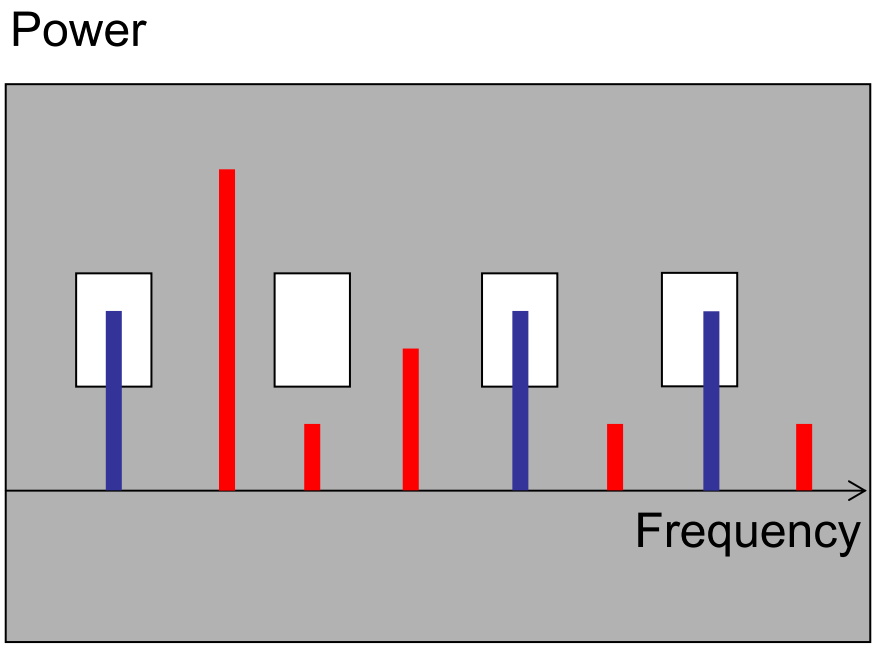
Direction filter





- The receiver's antenna rejects signals arriving at angles outside its direction-of-arrival window
- Usually the azimuth and elevation assumed to be independent

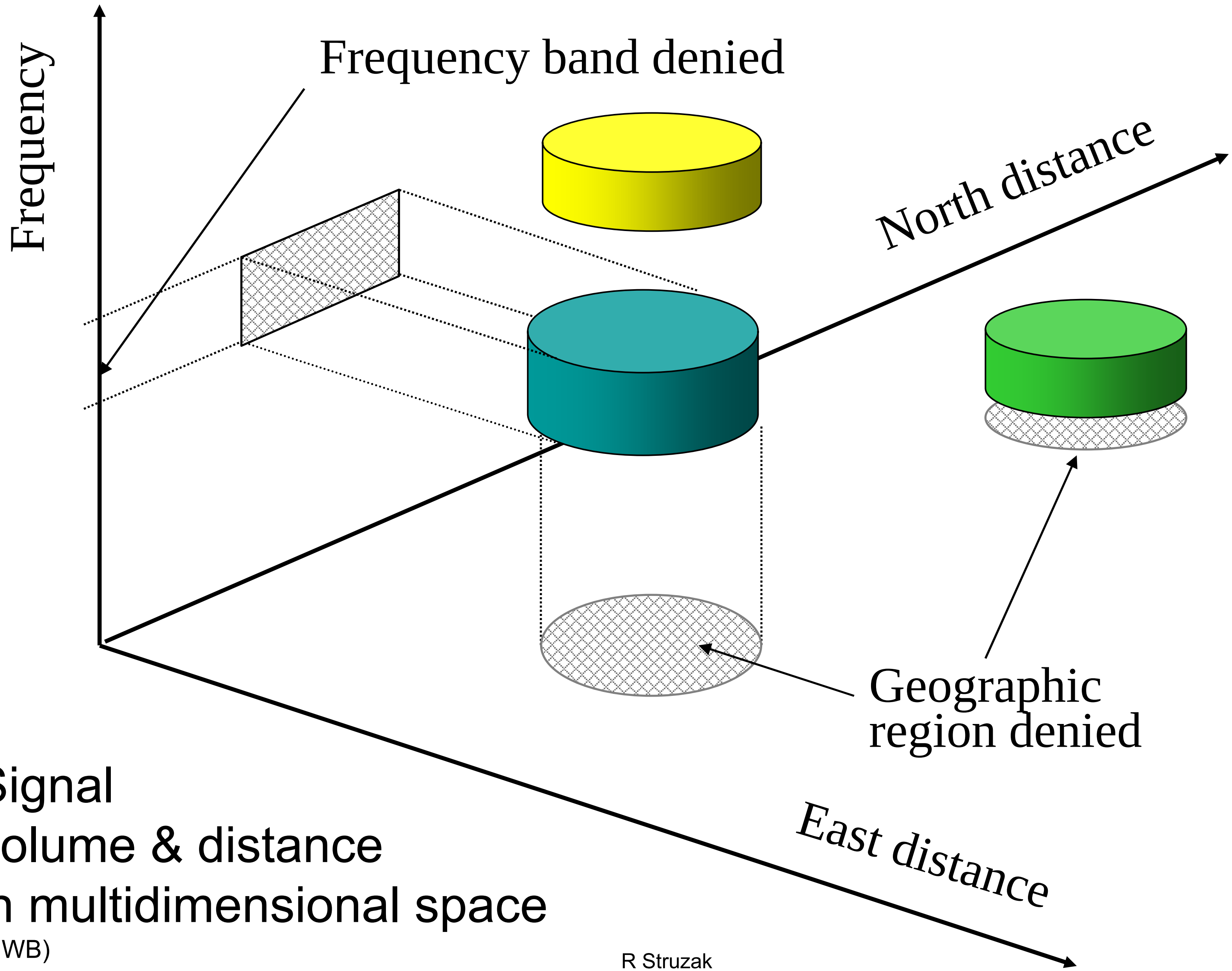
Frequency filter



- The receiver frequency-window may consist of a series of non-contiguous openings (white rectangles)
- The receiver rejects red frequencies
  - Regular sampling
  - Irregular sampling

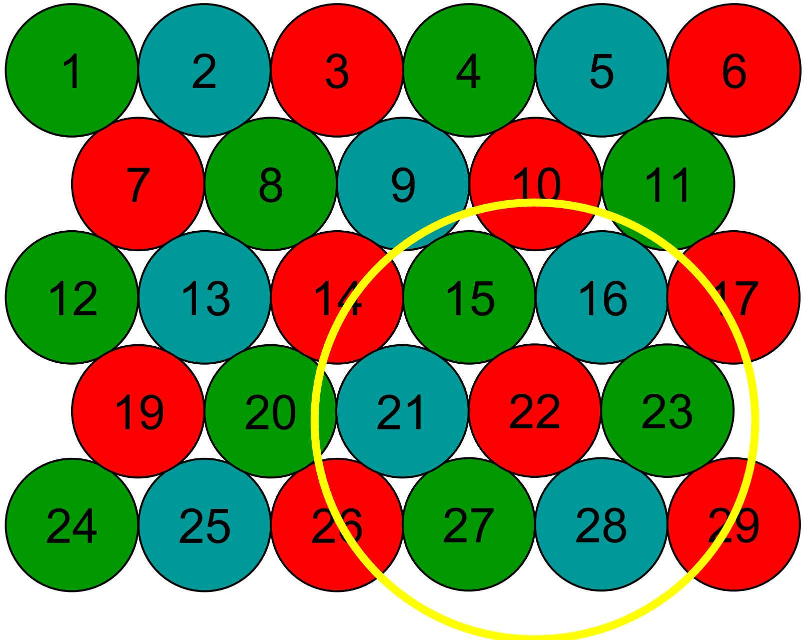
"Safe" distances

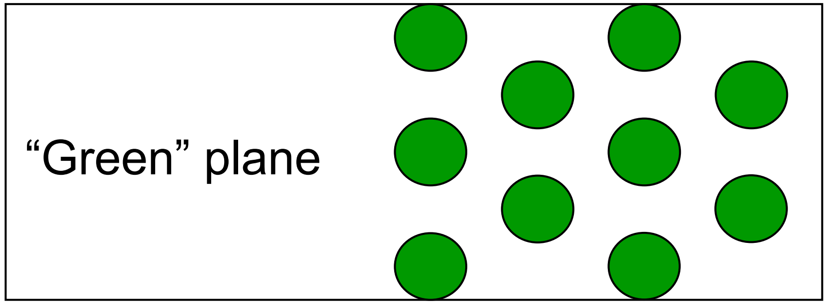
- Time (E.g.: TDMA systems)
- Frequency (E.g.: multi-frequency networks; FDMA systems)
- Direction
- Geographical distance
- Power difference (E.g. UWB systems sharing frequencies with narrow-band systems)
- …
- Degree of the correlation with the wanted signal
    - E.g. between the spreading functions in spread-spectrum systems
- Combination of the above

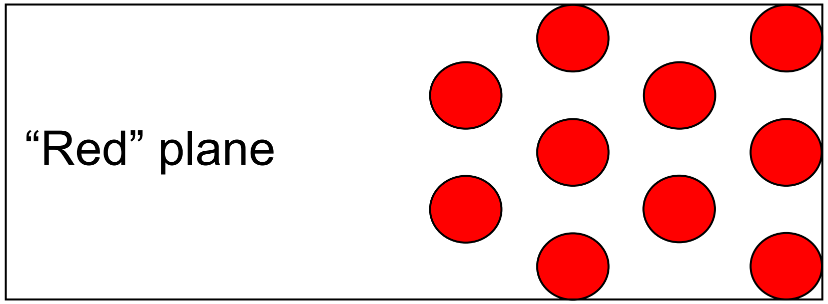


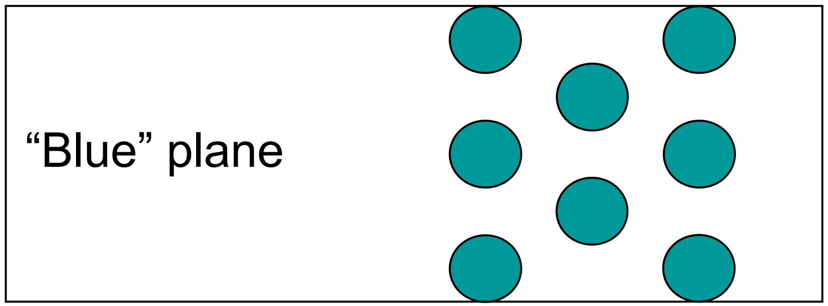
Signal
volume & distance
in multidimensional space
(UWB)

Regular grid (infinite)



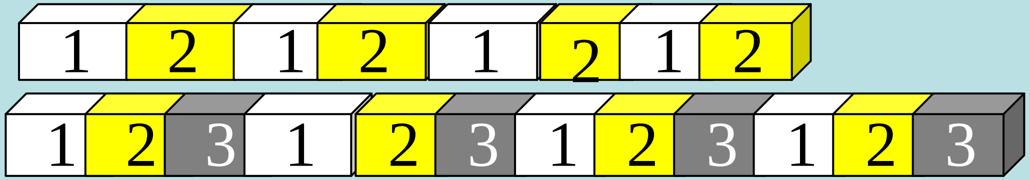




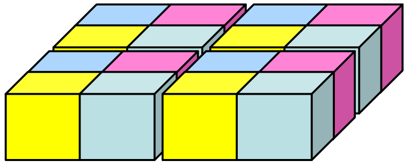


- 3 frequencies increase the co-channel distance 1.7 times

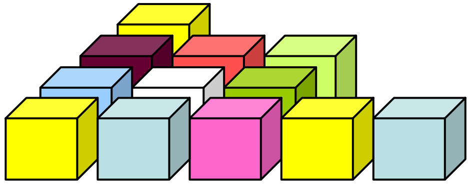
Distance separation vs. No. of frequencies



0*d: 1ch.
1*d: 2ch.
2*d: 3ch.
n*d: (n+1) ch.

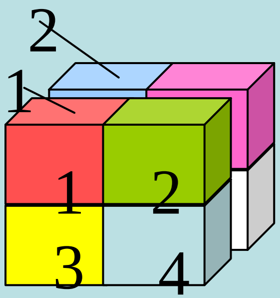


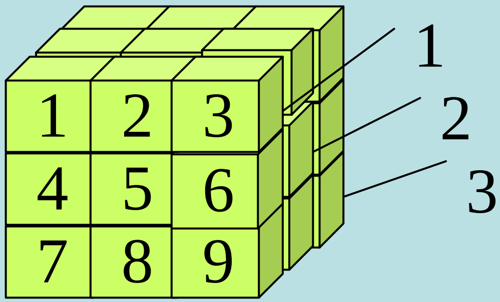
1 zone: 4 ch.



2 zones: 9 ch.

0*d: 1ch.
1*d: 4ch.
2*d: 9ch.
n*d: $(n+1)^2$ ch.

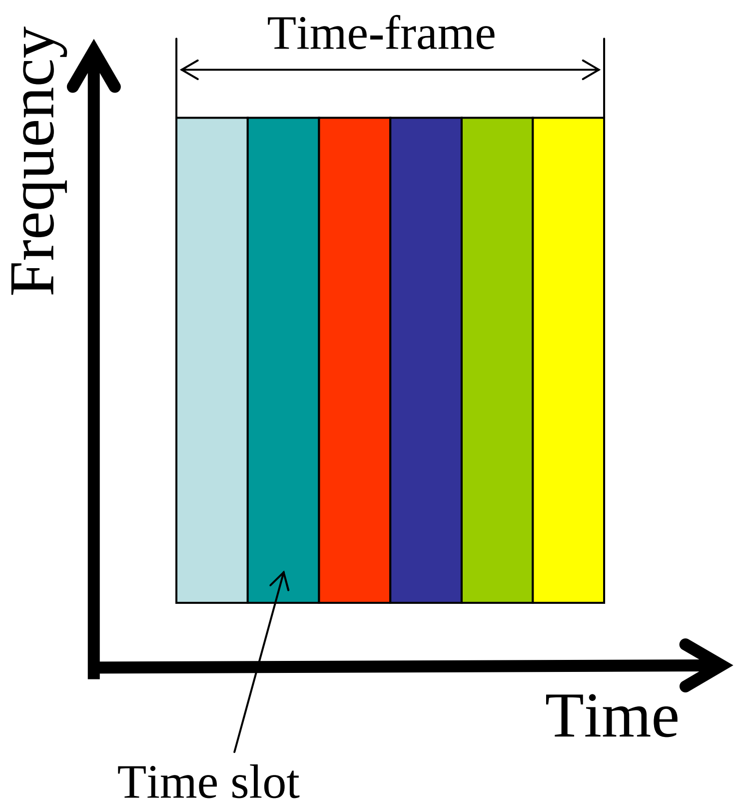


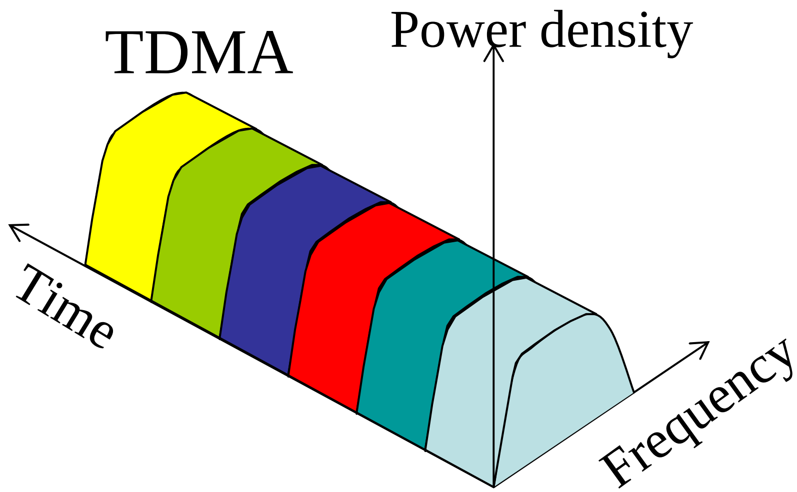


0*d: 1ch.
1*d: 8ch.
2*d: 27ch.
n*d: $(n+1)^3$ ch.

Coordination in time domain: TDMA

Time Division Multiple Access, Single-Frequency Network – kombinacja z OFDM, CODFM



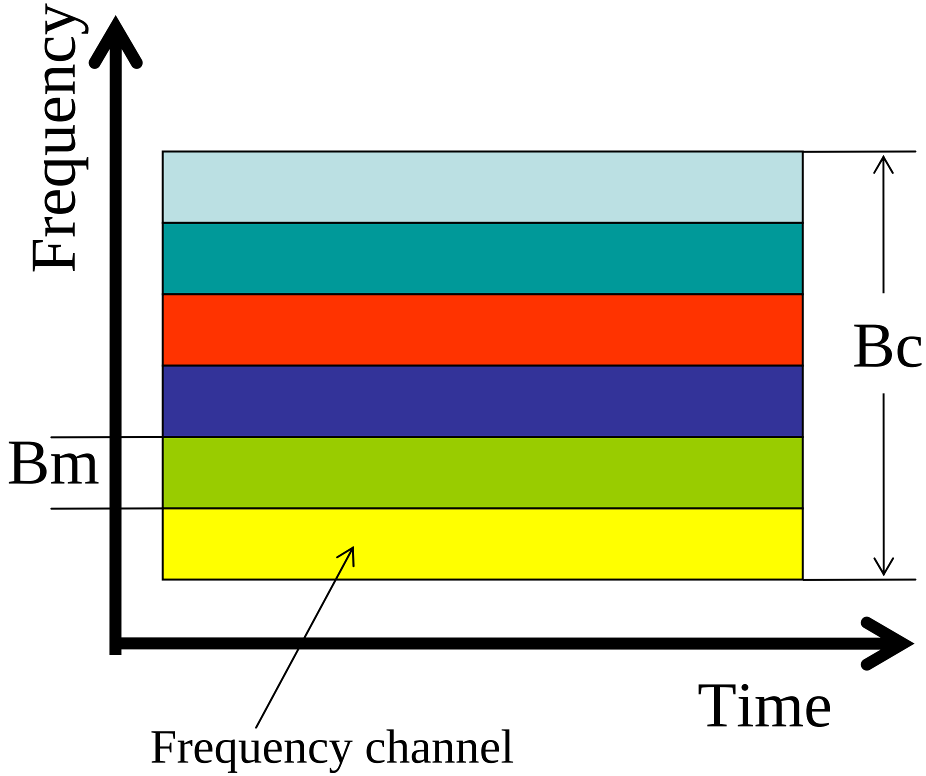


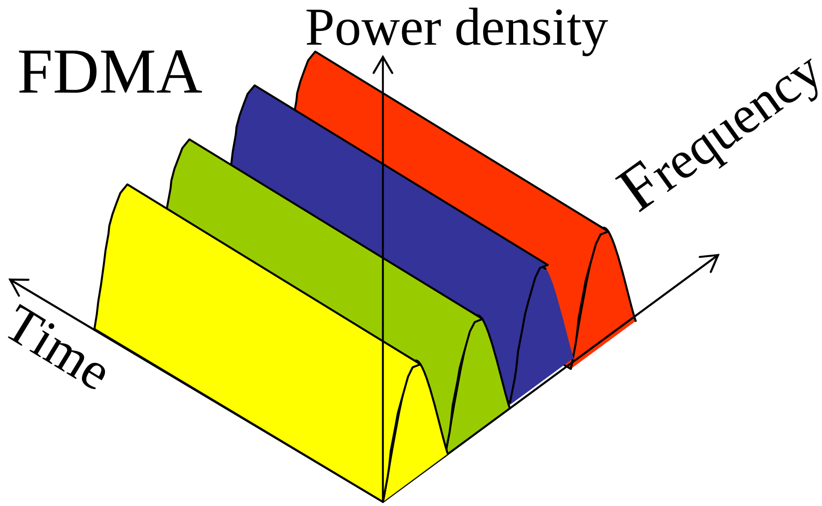
Each user has a time slot reserved within a frame repeated periodically

Example: DECT (Digital enhanced cordless phone) Frame lasts 10 ms, contains 24 time slots each 417μs

Coordination in frequency domain: FDMA, MFN...

Multiple-Frequency Networks, Frequency Division Miltiple Access, Orthogonal Frequency-Division Multiplexing





Each user has one (or more) frequency band reserved

Example: Telephony Bm = 3-9 kHz

Single frequency network: SFN

$$C = B\log_2\left(1+\frac{S_0+\sum_{i=1}^{n}|k_i|S_i}{N+\sum_{i=1}^{n}\left(1-|k_i|\right)S_i}\right)$$

$$C_0 \xrightarrow[n\to 0]{} B\log_2\left(1+\frac{S_0}{N}\right)$$ ← ***n* = 0** (Shannon)

|ki| = 1; → improvement

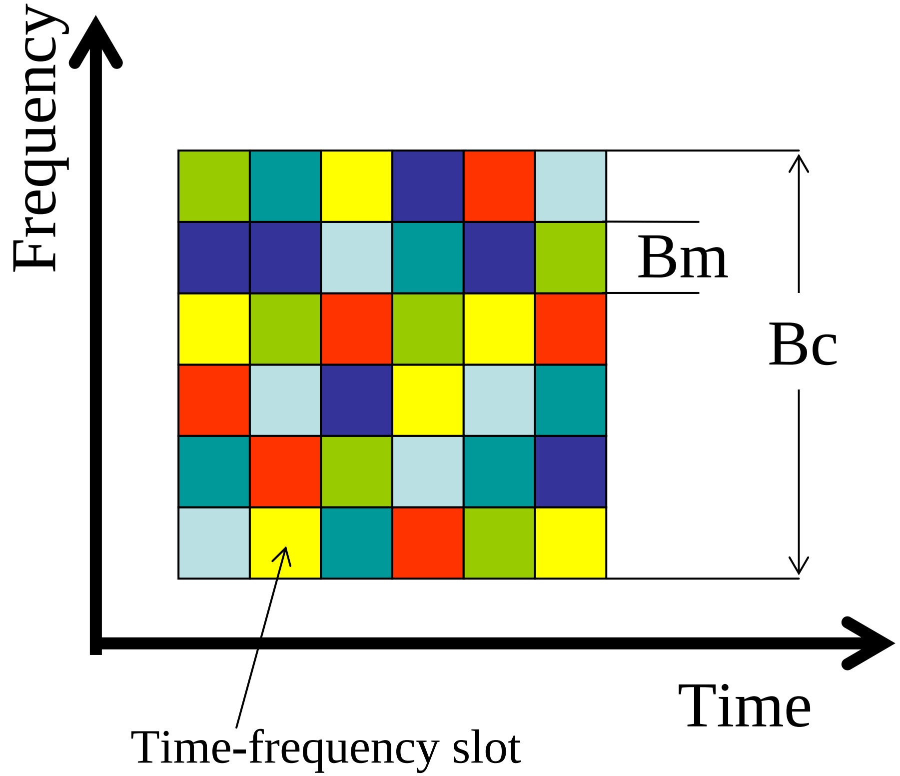
$$C \xrightarrow[k\to 1]{} B\log_2\left(1+\frac{S_0+\sum_{i=1}^{n}S_i}{N}\right) \geq C_0$$

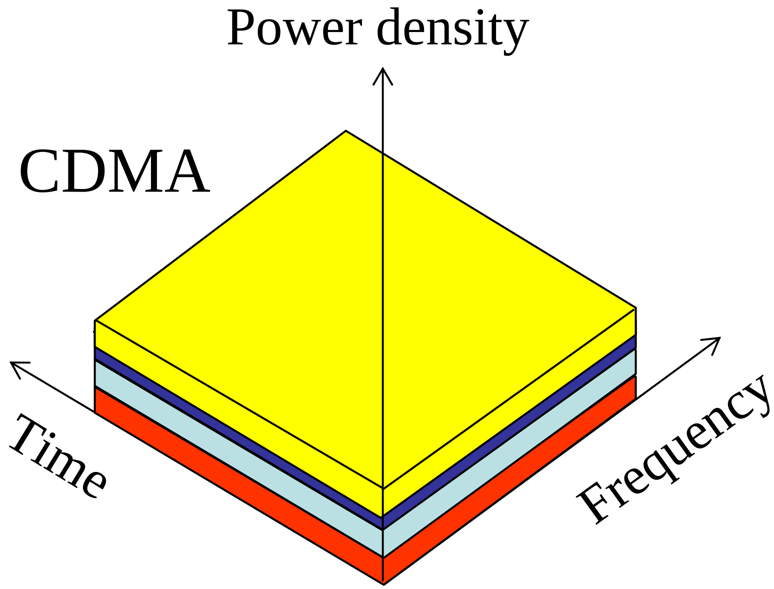
|ki| = 0; → worsening

$$C \xrightarrow[k\to 0]{} B\log_2\left(1+\frac{S_0}{N+\sum_{i=1}^{n}S_i}\right) \leq C_0$$

Coordination in frequency, time and code domains (CDMA, FHSS, DSSS, OFDM, COFDM)

Code Division Multiple Access, Frequency-Hopping Spread Spectrum, Direct-Sequence Spread Spectrum

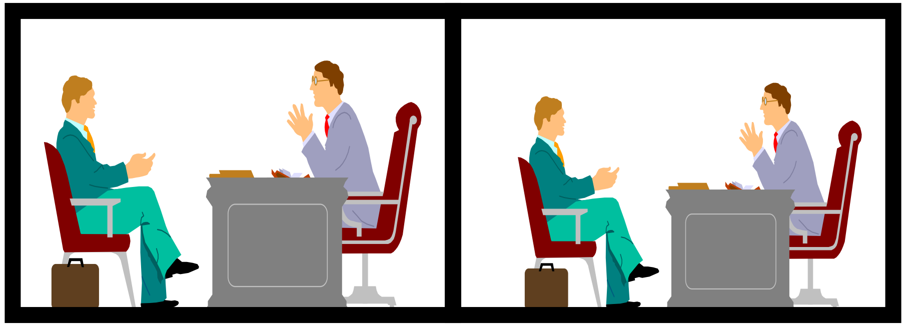




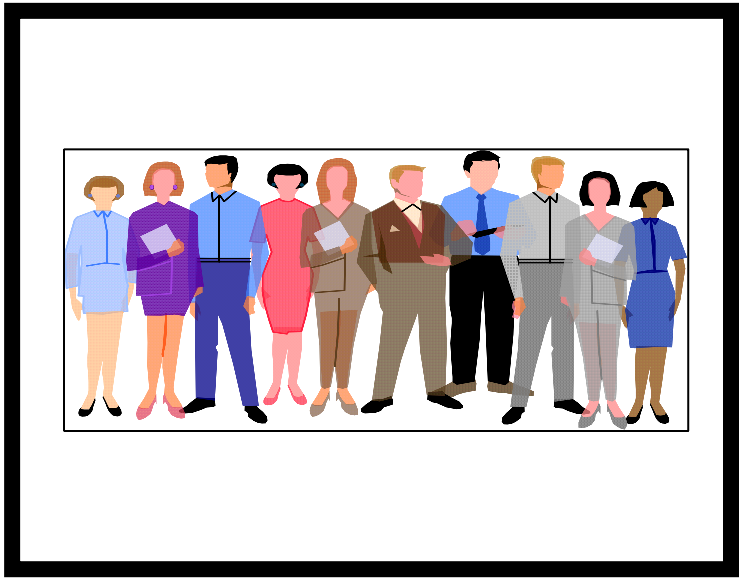
Each user has a time-frequency block repeated regularly or according to a specific pseudo-random code

Analogies

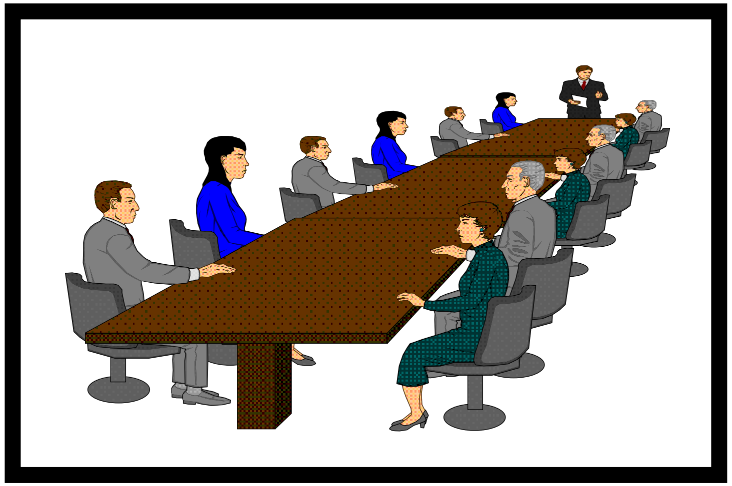
FDMA



CDMA



TDMA



Formalization

Utility coefficients

			Transmitters	
		…	T_i	…
Receivers	…	…	…	…
Receivers	R_j	…	D_{ij}	…
Receivers	…	…	…	…

Transmision coefficients

			Transmitters	
		…	P_i	…
Receivers	…	…	…	…
Receivers	N_j	…	H_{ij}	…
Receivers	…	…	…	…

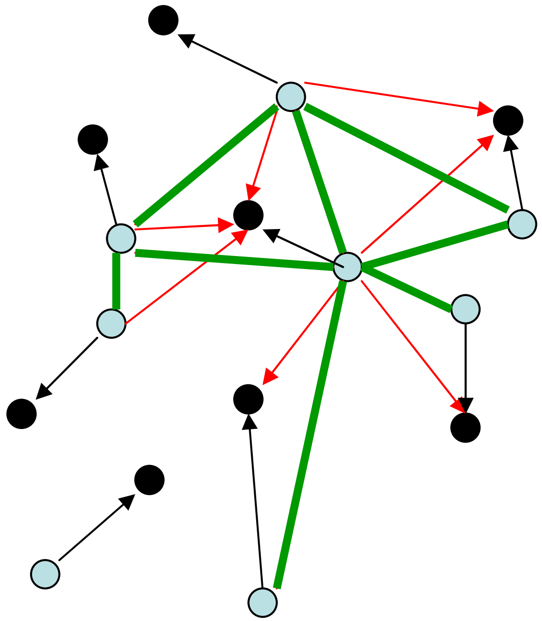
$$D_{ij} = \begin{cases} 1 \\ 0 \end{cases}$$

$$S_{jwant} = \sum_i P_i D_{ij} H_{ij}$$

$$S_{junwant} = \sum_i P_i \left(1 - D_{ij}\right) H_{ij}$$

QOS requirement:
$S_{jwant} / (N_j + S_{junwant})$ ♦ MinVal
or $\text{Probab}|_{OK}$ ♦ MinVal

Graph theory



Conclusion

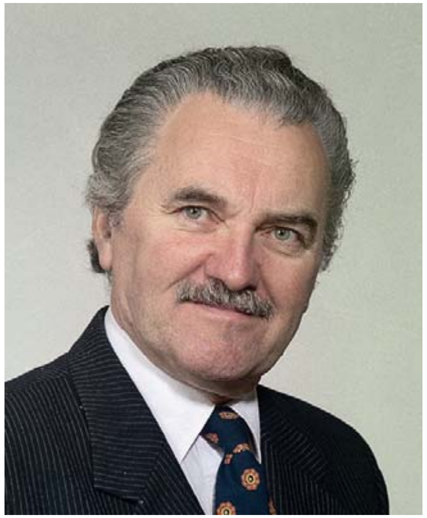
- No rational usage of the radio spectrum is possible without cooperation of all users

Future networks: vision

Systems
operate
like
an ant colony,
assisting
each other
in fulfilling
their tasks

http://ant.edb.miyakyo-u.ac.jp/INTRODUCTION/Gakken79E/Page_04.html

- Thank you for your attention



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Important notes

Beware of misprints!!! These materials are preliminary notes for my lectures and may contain misprints. If you notice some, or if you have comments, please send these to r.struzak@ieee.org.