ICTP-ITU-URSI School on Wireless Networking for Development
The Abdus Salam International Centre for Theoretical Physics ICTP, Trieste (Italy), 6 to 24 February 2006

Interference & Co-existence

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What is the purpose?

- To review basic physics of interference issues in microwave radio links
  - Communication range
  - Coverage area
  - Service degradation
  - Interference mechanism
  - How to avoid interference

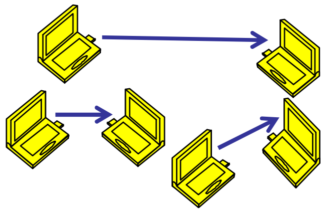
Outline

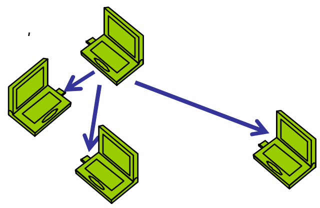
- Basic concepts
- Physical models
- Summary

Radio link: basic concepts

- Transmitter – Receiver
  - » Radiator-Receptor; Source-Sink
  - – Long distance – short range
  - – Fixed – Transportable – Mobile
  - – Terrestrial – Satellite – 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 transmitters & 2 receivers
    - » Full-duplex (FDX) circuit: <u>Simultaneous</u> transmission in <u>both directions</u>

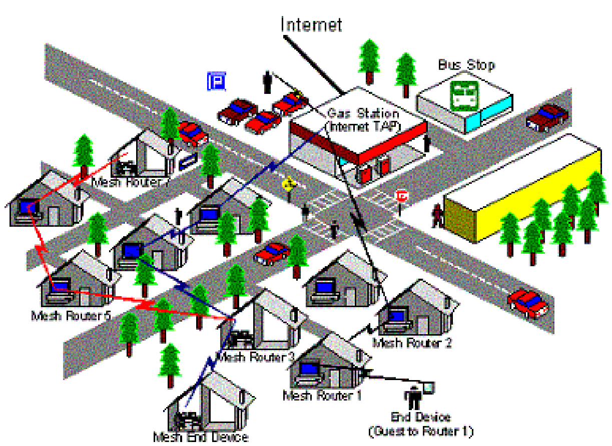
PTP & PMT network topologies





- 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 is controlled/ coordinated 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 !

Events involved

- The probability of interference *P(I)* during the small time period:

P(I) = P(A and B and C and 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
  - D* is the negation (opposite) of the event D

All these refer to the same small time period.

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
  - Faulty spectrum management (wrong use of frequencies)
  - Wrong deployment of the equipment
  - Spurious emissions
  - Spurious receiver responses

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
  - because of electromagnetic radiation or response
- It requires interference-free operation achieved by design, deployment and exploitation
    - application of sound EMC-related policy, concepts, regulations, standards, etc.

Outline

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- <u>Physical models</u>
- Summary

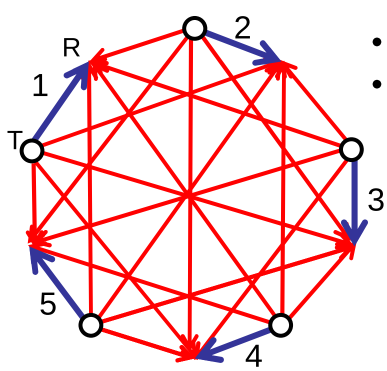
Spurious vs. regular links

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

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

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

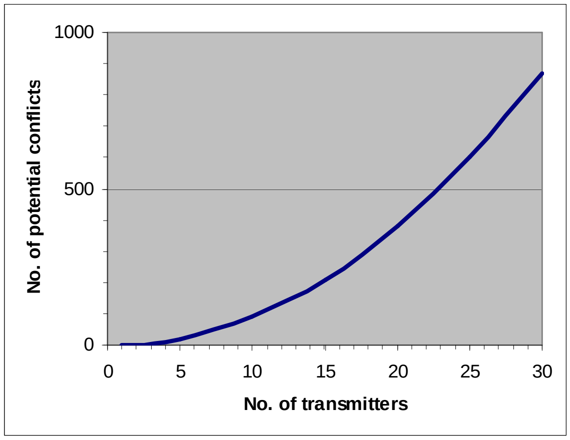
How many spurious links?



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) signals 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?



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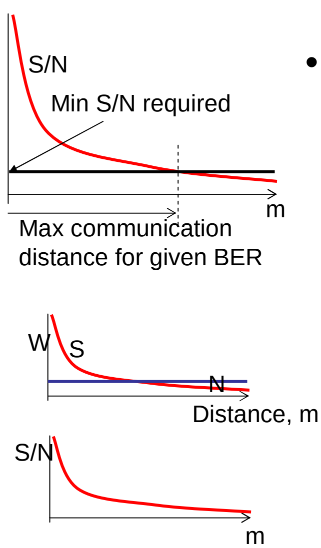
Communication range



- The distance from a transmitter at which the signal strength remains above the minimum usable level for a particular antenna and receiver combination.
  - The usable signal level depends on required system performance (e.g. BER) and is associated with noise power N
  - With constant noise power N, the S/N and the range decrease with the distance squared (in free space)

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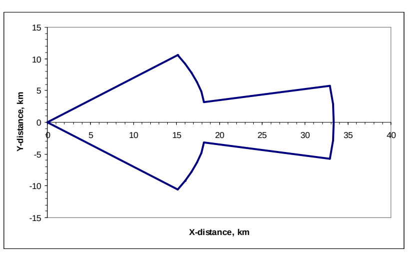
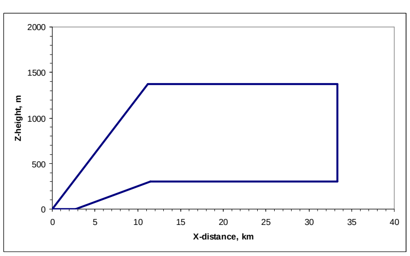
Coverage area

- ‘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”

Example: ILS service volume





- **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.

Signal protection

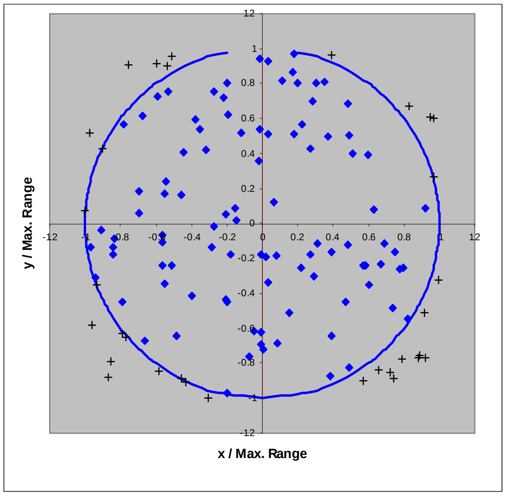
- Over the coverage/ service area, the wanted signal is to be protected against interfering signal
- The degree of protection is known as protection ratio
  - Protection ratio is the minimum value of the wanted-to-unwanted signal ratio at the receiver input, determined under specified conditions (Analogous 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)

Coverage: Noise/ 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

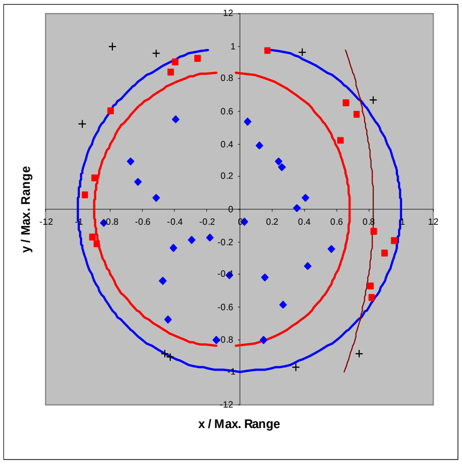
- Transmitter + >1 interferer
- A minimum protection ratio S/Imin set
- A test receiver & test points specified
- The receiver moved form one test point to another and the measured S/I compared with the S/Imin
- The interference-limited coverage is the set of the test points at which S/N >= S/Imin
-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

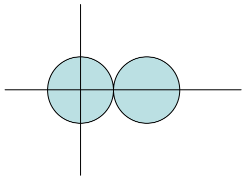
Coverage map (simulation 0i)



- 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?

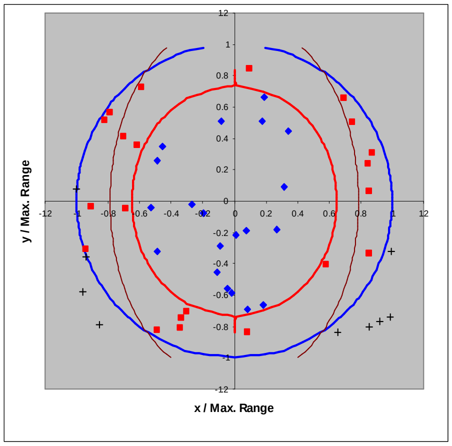
Coverage map (simulation 1i)

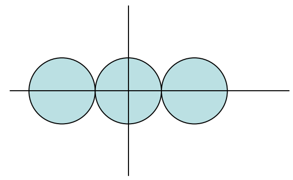




- 1 additional (identical omnidirectional transmitters in free-space with tangent potential coverage areas
  - Blue line: Potential coverage (the other transmitter switched-off)
  - Red line: actual coverage
  - Brown line: interference-limited coverage (noise-free receiver)
- Coverage loss = 33%

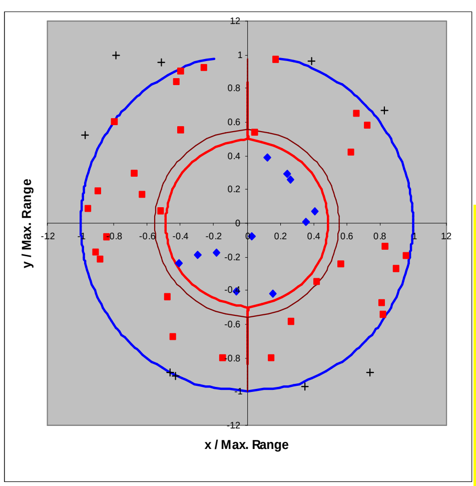
Coverage map (simulation 2i)

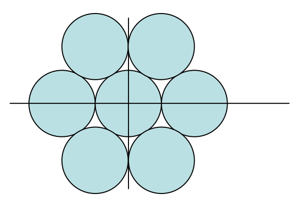




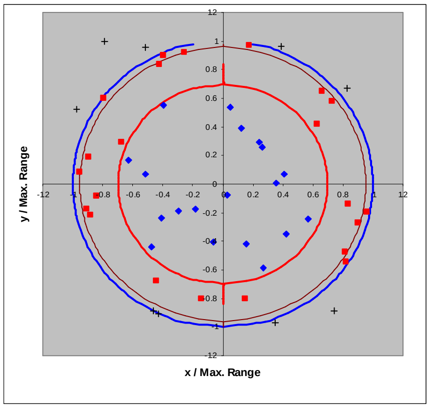
- 3 identical omnidirectional transmitters in free-space with tangent potential coverage areas
- Blue line: Potential coverage (the other transmitters switched-off)
- Red line: actual coverage
- Brown line: interference-limited coverage (noise-free receiver)
- Coverage loss = 52%

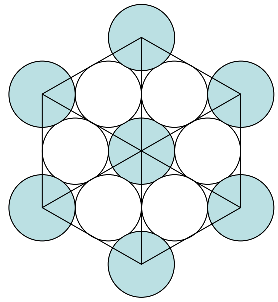
Coverage map (simulation 6i)





- 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%





- 7 identical omnidirectional transmitters in free-space at distance 3.44 times the potential range
- Coverage loss = 51%

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

Transmission system

- 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*.

The transmitting station:

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

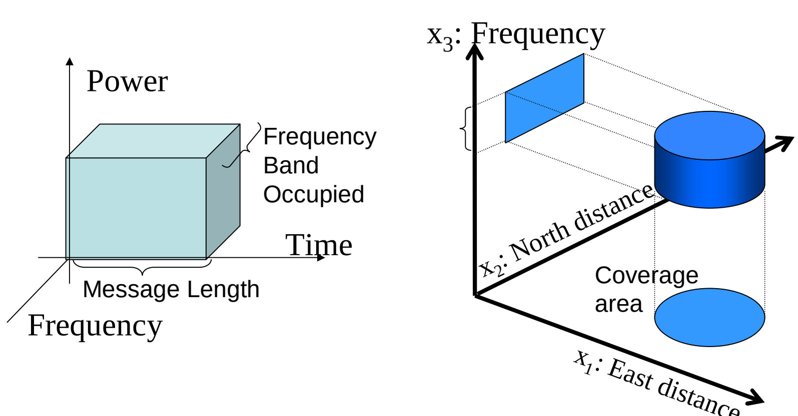
Shortly - it maps the original message into the radio-wave signal launched at the transmitting antenna

Some characteristics of RF wave

The radio-wave signal has a number of characteristics/ variables that generate a multidimensional space

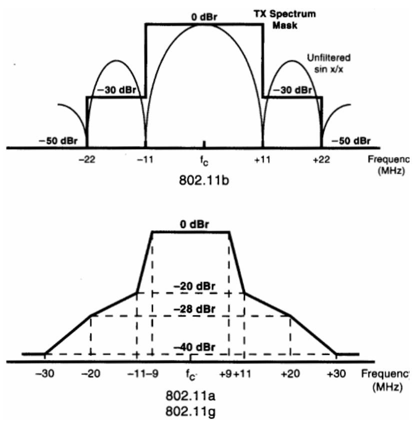
Quantity	Unit	No. of dimensions
Frequency	Hz, MHz, GHz	1
Time	ms, s, hr, year	1
Spatial location (geographical longitude and latitude and altitude)	Degree, m, km,…	3
Elevation angle of launch/ arrival	Degree	1
Azimuth angle of launch/ arrival	Degree	1
Polarization	Sense (left, right)	1

Visualization of radio-wave signals



Only projections on a plane (or cuts) possible

Spectrum masks



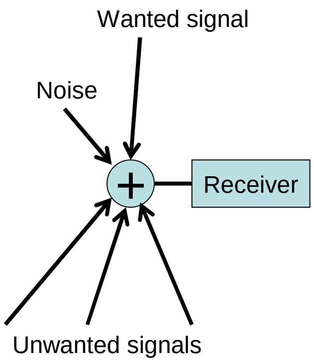
Spectrum masks for WiFi – examples of the projection of multidimensional signal solid onto the Frequency-Power plane

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

Propagation process:

- Transforms, or maps, the radio-wave signal launched by the transmitter into the incident radio wave at the receiver antenna
- The propagation mapping involves extra variables (e.g. distance, latency), additional radio waves (e.g. reflected wave, waves originated in the environment), random uncertainty (e.g. noise, fading)
  and distortions

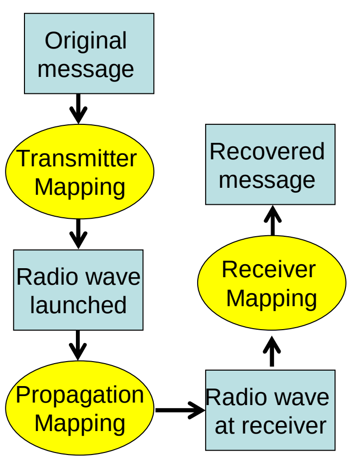
Receiver:



1. Filters the incident signals : rejects unwanted signals and extract the wanted signal
   – The receiver's response defines a solid "window" in the signal hyperspace
2. Recovers the original message through
   - reversing the transmitter operations (demodulation, decoding, de-spreading, etc.),
   - compensating propagation transformations, and
   - correcting transmission distortions

- Shortly: Maps the incident signals into the recovered message

How the whole system operates?



- A series of mappings
  » Following the algorithm/ protocol/ policy
- Mapping errors = effects of interference, noise, distortions, etc.
  – Incomplete (distorted) recovery of the original message, or its loss -- the recovered message differs from the original
- 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

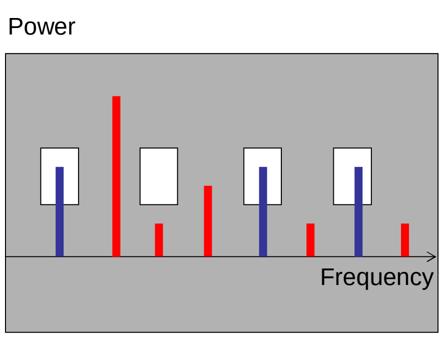
How to keep error small?

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

How to implement it?

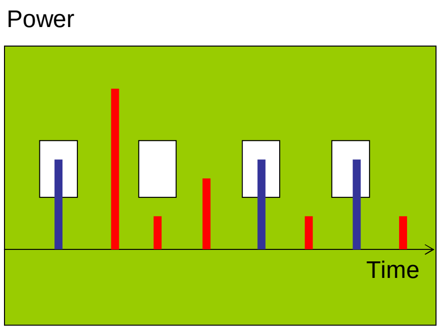
- By filtering/ separation in radio wave signal hyperspace
  - Frequency separation (e.g. FMDA)
  - Time separation (e.g. TDMA)
  - Code separation (e.g. CDMA)
  - Other (modulation, direction, distance, polarization, etc.) filters

Frequency filter



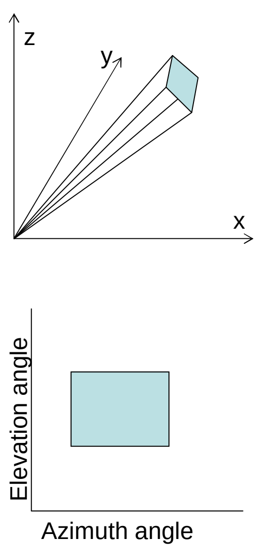
- The receiver frequency-window may consist of a series of non-contiguous openings (white rectangles)
- The receiver rejects red frequencies
  - Regular sampling
  - Irregular sampling

Time filter



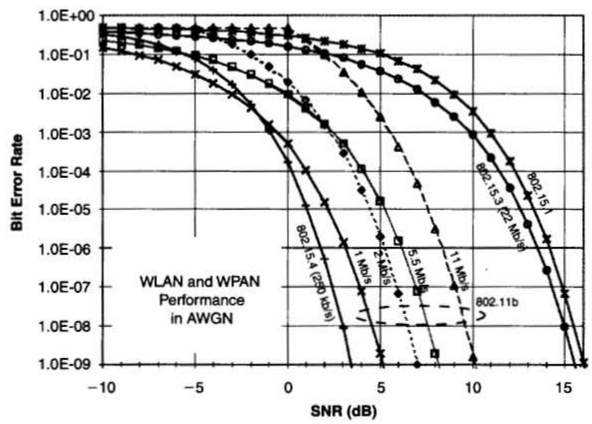
- The receiver time-window may consist of a number of separate openings at discrete time instances (white rectangles)
- The receiver rejects red impulses
  - Regular sampling
  - Irregular sampling

Direction filter



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

How BER relates to energy (SNR)?



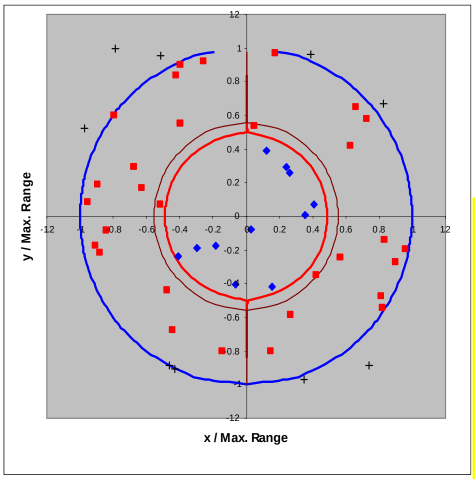
BER versus SNR for the four data rates of WiFi (IEEE 802.11b) along with values for Bluetooth (IEEE 802.15.1), WiMedia (IEEE 802-15.3) and ZigBee (IEEE 802.15.4), all operating in the 2.4 GHz band

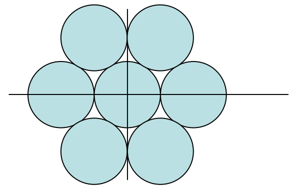
•Morrow R: Wireless network coexistence; McGraw-Hill 2004 p. 192

Frequency reuse

- Frequency assignment is very simple, on the surface.
- Very difficult with a large number of densely deployed radio links
  - 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

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)
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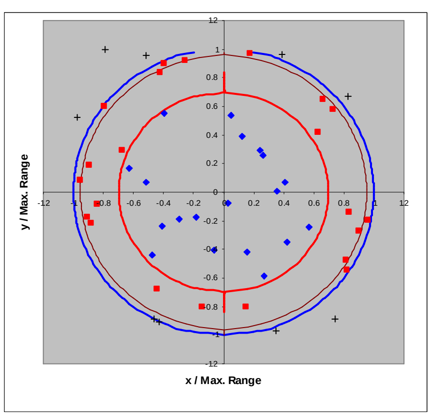
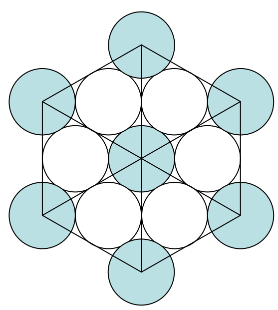
- Brown line: interference-limited coverage (noise-free receiver)
- Coverage loss = 76%





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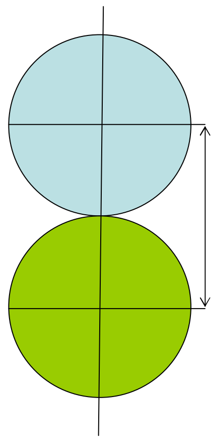
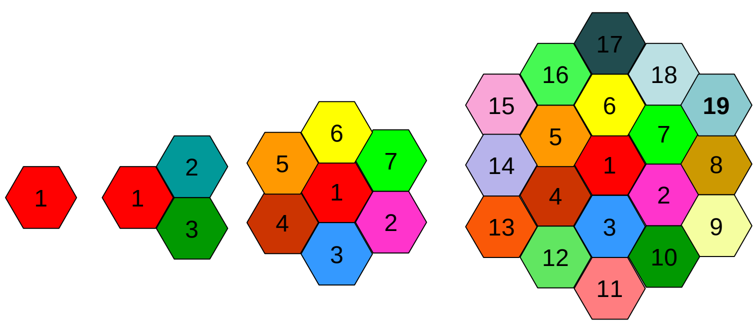
Basic selection criterion



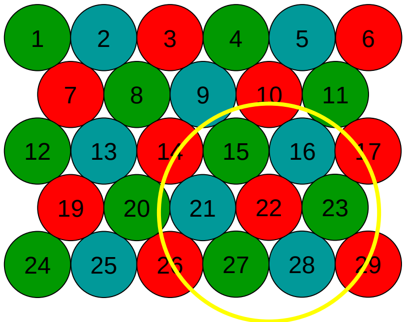
- "No common frequency (channel) may be used simultaneously by two transmitters which are separated by a distance less than 'Xcoch' km"
  - Relates to two co-channel transmitters
  - Xcoch – frequency reuse distance

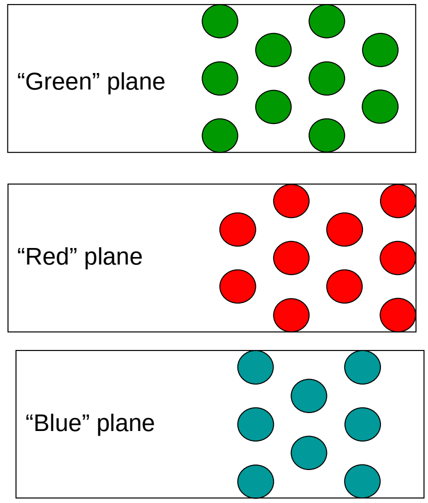
Increasing no. of channels



$2R\cos 30^0$? ? ?

Regular grid (infinite)





- 3 frequencies increase the co-channel distance 1.7 times

Multiple interferers

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

Outline

- Basic concepts
- Physical models
- <u>Summary</u>

- Thank you for your attention

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.