Introduction to wireless systems

Un. of Rome “La Sapienza”

Chiara Petrioli†

†Department of Computer Science – University of Rome “Sapienza” – Italy
• What is the difference with wired TCP/IP networks? Transmission medium..
  – Unique features of the transmission medium have a big impact on design (e.g., lower reliability, broadcast feature, hidden terminal problems demand for different solutions at the data link and transport layers)
  – Wireless systems have been designed to enable communication anywhere anytime
    ✓ Mobility must therefore be supported
    ✓ Portability comes with the fact depends rely on external sources of energy such as batteries to operate

Reasons for wireless success:
  No cabling
  Anywhere/anytime
  Cost vs. performance
• Broadcast medium - each mobile device transmission is overheard by all other devices within the source ‘transmission radius’
  – Poses security challenges
• Shared channel
  – Medium Access Control (MAC)
  – Limited resources must be shared among users
• High bit error rate
  – Error detection, correction & retransmission techniques needed for reliable communication
• Mobility must be supported at design stage
• Portable devices which rely on external sources of energy (batteries) to compute and communicate
  → Low power platforms and energy efficient protocols (green solutions)
  → Computation vs communication trade-offs (e.g., mobile device offloading)
  → Use of HW techniques to limit (wake up radio) energy consumption to the bare minimum and to harvest energy through renewal sources of energy (energy harvesting/scavenging)
• 1) Infrastructured networks

- Communication from the mobile user to the base station/access point and vice versa

Internet or Wired networks
1) Infrastructured networks

- Internet or Wired networks

- Communication from the mobile user to the base station/access point and vice versa
2) Ad Hoc Wireless Networks (wireless sensor networks, VANET, Mesh Networks,...)

- Peer to peer communication
- Each node can act as source, destination of a packet or as relay
- BER-Bit Error Rate can be significant compared to wired medium
- Attenuation, reflection, diffraction of the signal + multipath fading

Canale Radio

Forward Error Correction
Interleaving
Automatic Repeat Request

100110
-received packet

Canale Radio

100100
-transmitted packet
Broadcast channel
Channel access must be arbitrated by a medium access control protocol

Antenna cannot tx and rx simultaneously;
Carrier sense is possible
Collision detection based on ACK/NAK
Hidden terminal
If A and B transmit a packet a collision occurs in D. Neither A nor B can detect such collision directly.
Routing must account for mobility, dynamicity (e.g., due to varying link quality and nodes alternating between ON and OFF states) and different resources available at the nodes.

What’s the best path between A and B (routing)?
IETF MANET deals with routing
One of the peculiar aspects introduced by mobile peer to peer ad hoc networking
Energy efficient solutions at all different layers of the protocol stack: power control, MAC, data link, routing, transport.
Introduction

- Background needed to understand the motivations behind current wireless systems design
  - Wireless Channel & Signal Propagation – Basic Concepts
  - Channel Access problems
  - Energy efficient comms. techniques
  - Mobility management
• Much less reliable than wired channels
• While propagating the signal can face
  – Attenuation as function of the distance from transmitter and receiver
  – Attenuation due to obstacles
  – Propagation over multiple paths (resulting in multipath fading)
Signal propagation: challenges

- Line of sight
- Reflection
- Shadowing
**Diffraction**
- When the surface encountered has sharp edges
- Bending the wave

**Scattering**
- When the wave encounters objects smaller than the wavelength (vegetation, clouds, street signs)
Example scenarios

LINE OF SIGHT +
Diffraction, reflection, scattering
**LOS path non necessarily existing (and unique)**

Example: city with large buildings;
No LINE OF SIGHT;
Diffraction; reflection
Signal attenuation

Signal power

Distance BS → MS
Slow fading – fast fading

- Slow fading
  - Long term fading
- Fast fading
  - Short term fading

Signal power vs. Distance BS → MS (m)

- local mean
- total received power

Distance BS → MS (km)
What is the law to express the Attenuation of signal as function of the traversed distance?
• Assumption: A point source emits the signal uniformly in all directions (isotropic radiator) with a transmission power $P_T$.

• The power density at distance $d$ is equal to the ratio between the transmission power and the surface area of a sphere centered in the source and with radius $d$:

$$F = \frac{P_T}{4\pi d^2} \quad [\text{W/m}^2]$$
• Graphical representation of radiation properties of an antenna
• Depicted as two-dimensional cross section
• **Isotropic antenna (idealized)**
  – Radiates power equally in all directions (3D)
  – Real antennas always have directive effects (vertically and/or horizontally)

• **Antenna gain**
  – Power output, in a particular direction, compared to that produced in any direction by a perfect omni-directional antenna (isotropic antenna)

\[
\text{Directivity } D = \frac{\text{power density at a distance } d \text{ in the direction of maximum radiation}}{\text{mean power density at a distance } d} \\
\text{Gain } G = \frac{\text{power density at a distance } d \text{ in the direction of maximum radiation}}{\frac{P_T}{4\pi d^2}}
\]

• **Directional antennas “point” energy in a particular direction**
  – Better received signal strength
  – Less interference to other receivers
  – More complex antennas
• Let $g_T$ be the maximum transmission gain. The received power density in the direction of maximum radiation is given by:

$$F = \frac{P_T g_T}{4\pi d^2} \quad [\text{W/m}^2]$$

• $P_T g_T$ is the EIRP (Effective Isotropically Radiated Power) and represents the power at which an isotropic radiator should transmit to reach the same power density of the directional antenna at distance $d$. 
• The power received by a receiver at distance \( d \) from the source, in case of no obstacles and LOS, can be expressed as:

\[
P_R = P_T g_T g_R \left( \frac{\lambda}{4\pi d} \right)^2 \frac{1}{L}
\]

Friis transmission equation

- where \( P_T \) is the transmitter radiated power, \( g_T \) and \( g_R \) the gains of the transmitter and receiver antennas, \( \lambda \) is the wavelength \((c/f)\) and \( d \) the distance between the transmitter and the receiver. Finally, parameter \( L > 1 \) accounts for HW losses.
• Decibel (dB): expresses according to a logarithmic scale a ratio among powers

\[ 10 \log \left( \frac{P_1}{P_2} \right) \]

Log = base-10 logarithm

\[ P_A = 1 \text{ Watt} \]

\[ P_B = 1 \text{ milliWatt} \]

30 dB \( \Rightarrow \) PA = three orders of magnitudes higher than \( P_B \)

◆ Gain of an antenna is expressed in dB

3dB (una potenza è il doppio dell'altra), 10dB \( \Rightarrow \) un ordine di grandezza di differenza, 20dB due ordini di grandezza, 30db tre ordini di grandezza
- dBm = ratio between the power and a nominal power of 1mW
  - Power in dBm = 10 log(power/1mW)
  - Power in dBW = 10 log(power/1W)

Example
- 10 mW = 10 log_{10}(0.01/0.001) = 10 dBm
- 10 µW = 10 log_{10}(0.00001/0.001) = -20 dBm
- S/N ratio = -3dB → S = circa 1/2 N

- Properties & conversions
  - P(dBm) = 10 log_{10}(P (W) / 1 mW) = P (dBW) + 30 dBm
  - (P1 * P2) (dBm) = P1 (dBm) + P2 (dBW)
    - P1 * P2 (dBm) = 10 log_{10}(P1(W)*P2 (W)/0.001) = 10log_{10}(P1(W)/0.001) + 10 log_{10}P2(W) = P1 (dBm) + P2 (dBW)
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Computation with dB

- Transmit power
  - Measured in dBm
    - Es. 33 dBm
- Receive Power
  - Measured in dBm
    - Es. –10 dBm
- Path Loss
  - Transmit power / Receive power
  - Measured in dB
  - Loss (dB) = transmit (dBm) – receive (dBm)
    - Es. 43 dB = attenuation by factor 20.000

If received power is below a given threshold info. cannot be correctly received
• Path Loss

\[ PL = \left( \frac{\lambda}{4\pi d} \right)^2 \]

- Represents free space path loss, due to geometric spreading.
- Other attenuations are introduced by obstacles (reflections, diffraction, scattering etc.) and by atmosphere absorption (depending on frequency, water vapor etc).
Path Loss

\[ PL = \left( \frac{\lambda}{4\pi d} \right)^{-2} \]

\[ \frac{P_T}{P_R} = \frac{P_T}{P_T} \cdot \frac{P_T g_T g_R \left( \frac{\lambda}{4\pi d} \right)^2 \frac{1}{L}} \]

if

\[ g_T, g_R, L = 1 \]

\[ \frac{P_T}{P_R} = \left( \frac{\lambda}{4\pi d} \right)^{-2} \]
Indicata anche con $L_{\text{free}}$ nel seguito

$$PL(d)_{[dB]} = 10 \log_{10} \frac{P_t}{P_r} = 10 \log_{10} \left\{ \frac{L}{G_t G_r \left( \frac{4\pi d}{\lambda} \right)^2} \right\} =$$

$$= 20 \log_{10} \frac{P_T}{P_R}$$

$$= 20 \log_{10} \frac{P_T}{P_R}$$

$$10 \log_{10} \frac{c}{4\pi} =$$

$$= 20 \log_{10} \left( P_T G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2 \frac{1}{L} \right)$$

7.56
Path loss (propagation loss) in dB
(formula generale)

It depends on distance but also on frequency
If $L=1$, gains=1

\[ L_{\text{free}}(d) = \left( \frac{\lambda}{4\pi d} \right)^{-2} \]

\[ L_{\text{free}}(d)_{[dB]} = -20 \log \left[ \frac{\lambda}{4\pi d} \right] = -20 \log \left[ \frac{c/f}{4\pi d} \right] \]

\[ = 20 \log_{10} d + 20 \log_{10} f - 147.56 \]
Further comments on Friis transmission equation

\[ P_R = P_T g_T g_R \left( \frac{\lambda}{4\pi d} \right)^2 \]

If we know the value at a reference distance \( d_{\text{ref}} \)...

\[ P_R(d) = P_R(d_{\text{ref}}) (d_{\text{ref}}/d)^2 \]

\[ P_R(d) \text{ dBm} = P_R(d_{\text{ref}}) \text{ dBm} + 20 \log_{10} \left( \frac{d_{\text{ref}}}{d} \right) \]
If we know the value at a reference distance $d_{\text{ref}}$...

\[
P_R(d) = P_R(d_{\text{ref}}) \left(\frac{d_{\text{ref}}}{d}\right)^2
\]

\[
P_R(d) \text{ dBm} = P_R(d_{\text{ref}}) \text{ dBm} + 20 \log_{10} \left(\frac{d_{\text{ref}}}{d}\right)
\]
• In case signal propagates over LOS and one reflected ray...

\[
\frac{P_R}{P_T} = g_R g_T \left( \frac{h_1 h_2}{d^2} \right)^2
\]

...the ratio between received power and transmitted power takes the following form:
• In the two ray model the received power decreases much faster with distance ($\sim 1/d^4$) than in the free space model ($\sim 1/d^2$)

• Real life signal propagation is much more complex than what represented by the two models

• However, mean received power can be often expressed with a generalization of the Friis transmission equation (where the propagation coefficient is $\eta$ instead of 2). The propagation coefficient typically assumes values between 2 and 5 (as determined as a function of the propagation environment by empirical studies and models)

$$P_R = P_T g_T g_R \left( \frac{\lambda}{4\pi} \right)^2 \frac{1}{d^\eta}$$
Extended formula

\[ P_r(d)(dB) = 10 \log_{10} P_r(d_o) + 10\eta \log_{10}\left(\frac{d_o}{d}\right) \]

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Received power (dBm) vs. distance (Km)
While propagating from source to destination the signal can follow multiple paths. At the receiver different components (received over different paths, with different phases and amplitudes) are combined.

Signal can be reflected, diffracted, scattered based on the obstacles it founds over its path towards destination.

Low frequencies can traverse without or with low attenuation many objects; when frequency increases waves tend to be absorbed or reflected by obstacles (at very high frequency – over 5 GHz – communication is LOS).
- Signal replicas received via different propagation paths are combined at the receiver.
- The results depends on:
  - The number of replicas
  - Their phases
  - Their amplitudes
  - Frequency

**Received power differs, as a result from place to place, from time to time!**
- Resulting signal can be attenuated

\[ T = \frac{4}{5\pi} \]

- Or amplified

\[ T = \frac{\pi}{6} \]
\[ e_r(t) = \sum_{k=1}^{N} a_k \cos(2\pi f_0 t + \phi_k) = \]

\[ = \cos(2\pi f_0 t) \sum_{k=1}^{N} a_k \cos \phi_k - \sin(2\pi f_0 t) \sum_{k=1}^{N} a_k \sin \phi_k = \]

\[ = X \cos(2\pi f_0 t) - Y \sin(2\pi f_0 t) \]

In the assumptions:
- \( N \) large (many paths)
- \( \phi_k \) uniformly distributed in \((0,2\pi)\)
- \( a_k \) comparable (no privileged path such as LOS)

\( X, Y \) are gaussian, identically distributed random variables

**Rayleigh fading power distribution**

\[ f_p(x) = \frac{1}{2\sigma^2} e^{-x/2\sigma^2} \]
Rayleigh fading

\[ e_r(t) = \sum_{k=1}^{N} a_k \cos(2\pi f_0 t + \phi_k) = \]

recall that:

\[ \cos(2\pi f_0 t + \phi_k) = \cos(2\pi f_0 t) \cos(\phi_k) - \sin(2\pi f_0 t) \sin(\phi_k) \]

In the asymptotic limit, \( e_r(t) \) is Rayleigh distributed.

\( X, Y \) are Rayleigh distributed.
**FIGURE 2.19** Rayleigh-faded rf signal (a) and its power (b). The plots were generated from 11 multiple paths. The envelope was obtained by demodulating the rf signal.
**Answer 1:**

Outage Probability $\rightarrow$ Probability that received power is lower than a given threshold

$\Rightarrow$ Below which signal cannot be correctly received

$$P_{out} = \int_0^{p_{thr}} f(p) \, dp$$
Different delays experienced by the different signal replicas (*delay spread*) can widen the channel impulse response leading to intersymbol interference (ISI – Inter-Symbol Interference).

![Graph showing signal replicas with different delays](image)
Examples

(a) Transmitted pulse

(b) Pulses overlap and result in a broadened pulse
Examples
Impulse response

(a) Rural area

(b) Urban area

Relative power (dB) vs. Time (ms)
Impact of delay spread can be quantified by computing the root mean square (RMS Delay Spread):

\[ \tau_{RMS} = \sqrt{\frac{1}{\sum_{i=1}^{n} P_i} \sum_{i=1}^{n} (\tau_i^2 P_i) - \tau_d^2} \]

- \( \tau_{RMS} \): RMS delay spread
- \( \tau_i \): delay on path \( i \)
- \( P_i \): power received on path \( i \)
- \( n \): number of paths

\[ \tau_d = \frac{\sum_{i=1}^{n} (\tau_i P_i)}{\sum_{i=1}^{n} P_i} \]
Multipath fading

- The coherence bandwidth, which is a statistical measurement of the bandwidth interval over which the channel is ‘flat’ is approximated by the inverse of the delay spread.
- If coherence bandwidth is $>>$ signal bandwidth the channel is flat.
- If coherence bandwidth is comparable to the signal bandwidth then delay spread results into intersymbol interference and reception errors.

In case of intersymbol interference equalization is used, introducing complexity.