EE233C Lecture #2
The Wireless Channel: Impairments and Models

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Paper for Student Presentation # 1

- **When**

  Tuesday April 18

- **Paper**

  [Xia97] Xia, H.H. A simplified analytical model for predicting path loss in urban and suburban environments. IEEE Transactions on Vehicular Technology, vol.46, (no.4), IEEE, Nov. 1997. p.1040-6. Available on INSPEC.

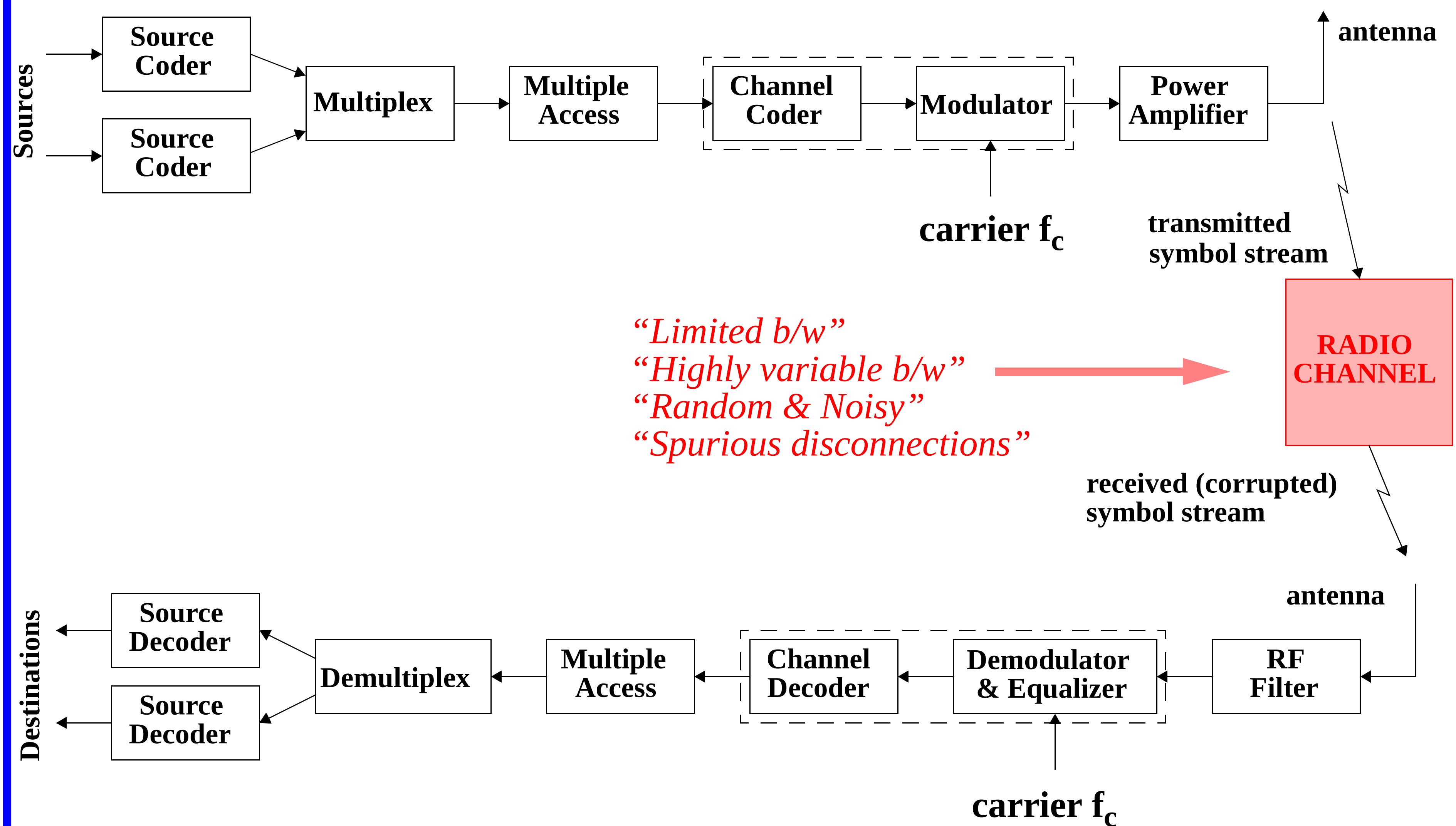
- **Who?**

Wireless Communications

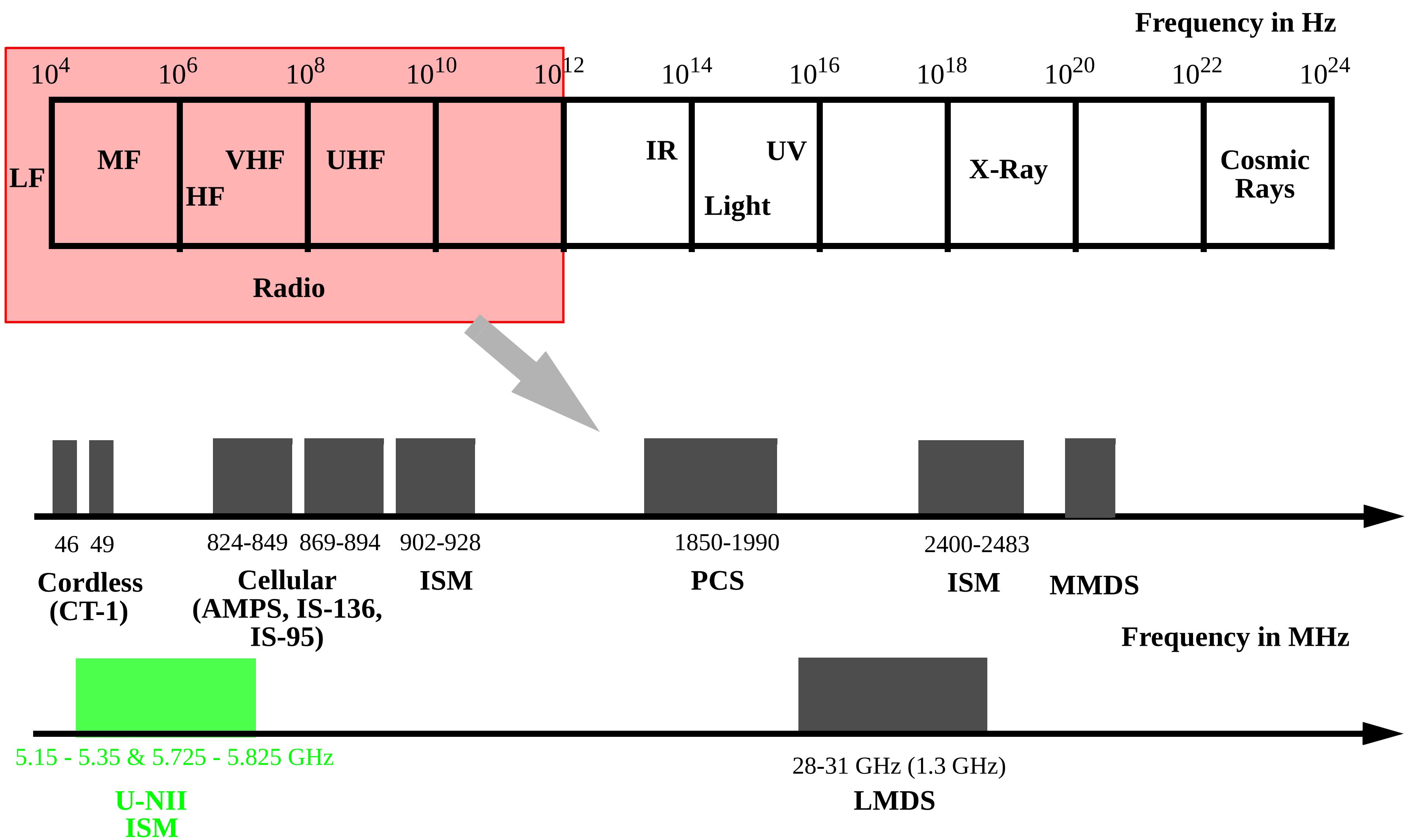
- **Last lecture:**
  - highly variable bandwidth
  - spurious disconnections
  - noisy
  - limited bandwidth

- **This lecture:**
  - why is it so
  - develop a "high level" view
  - quantify it

Simplified View of a Digital Radio Link



Wireless Spectrum of Interest



Lecture Outline

- **Physics of radio propagation**

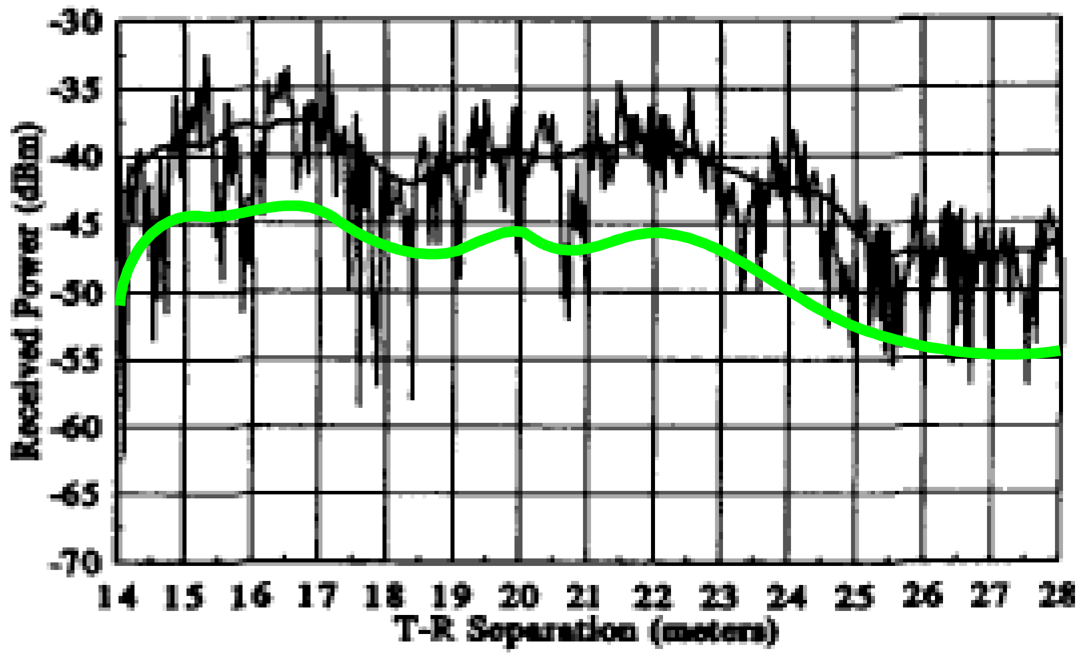
  free-space propagation, reflection, diffraction, scattering, multipath fading

- **Two types of propagation models:**

  1. Large-scale models
     - variation in mean received signal strength over large T-R distances (100s or 1000s of meters) and long time-scales
     - measured by averaging over 5λ to 40λ, i.e. 1-10m in cellular/PCS 1-2GHz band
     - d^n models
  2. Small scale effects
     - fluctuations of the received signal strength about a local mean over small travel distances (few λs) and short time intervals (seconds)
     - fading

- **Outdoor vs. indoor radio propagation models**
- **How to do simple "link budget" calculations**
- **Combating the radio channel impairments**

Small-scale and Large-scale Fading (Indoors)



- **Signal varies rapidly as T-R separation changes, but the local average signal changes much more slowly**
  - variation of received signal strength with distance from the transmitter
  - shadow fading (large timescale) caused by large obstructions
  - fading caused by local scatterers around the receiver

- **Three effects: mean path loss, slow variation about the mean, rapid variation**

Free Space Propagation Model

- **Used when Transmitter and Receiver have a clear, unobstructed, line-of-sight (LOS) path**

  - e.g. satellite channels, microwave LOS radio links

- **Free space power at a receiver antenna at a distance *d* from transmitter antenna is:**

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

where,

- G_t **and** G_r **are antenna gains**

- $L \geq 1$ **is the system loss factor not related to propagation (e.g. loss due to filter losses, hardware etc.)**

- ***Path loss* = signal attenuation as a positive quantity in dB**

$$PL(\mathrm{dB}) = 10\log\frac{P_t}{P_r} = -10\log\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

Free Space Propagation (contd.)

- **Model predicts P_r only for large enough d**

  - clearly, model not valid for $d = 0$
  - d must be in the "far-field" or *Fraunhofer Region* of the antenna
  - far-field distance is given by:

$$d_f = \frac{2D^2}{\lambda}$$

  where D is the largest physical linear dimension of the antenna
  - additionally, $d_f \gg D$ and $d_f \gg \lambda$

- **Large-scale models use a "received power reference point" = d_0**

  - $P_r(d)$ at $d > d_0 \geq d_f$ expressed in terms of $P_r(d_0)$

$$P_r(d) = P_r(d_0)\left(\frac{d}{d_0}\right)^2$$

  - $P_r(d_0)$ is calculated from the model, or measured

Free Space Propagation (contd.)

- $P_r(d)$ **is in practice expressed in units of *dBm* or *dBW***

$$P_r(d)\ \text{dBm} = 10\log\frac{P_r(d_0)\text{ in mW}}{1\text{ mW}} + 20\log\frac{d_0}{d}$$

- **Path loss too can be expressed relative to path loss at reference point** d_0

$$P_t\text{ in dBm} = P_r(d)\text{ in dBm} + PL(d)\text{ in dB} = P_r(d_0)\text{ in dBm} + PL(d_0)\text{ in dB}$$

so that,

$$PL(d) = PL(d_0) + 20\log\frac{d}{d_0}$$

Propagation Mechanisms in Space with Objects

- **Reflection (with Transmittance and Absorption)**

  - radio wave impinges on an object >> λ (30 cm @ 1 GHz)
  - surface of earth, walls, buildings, atmospheric layers
  - if perfect (lossless) dielectric object, then zero absorption
  - if perfect conductor, then 100% reflection
  - reflection a function of material, polarization, frequency, angle

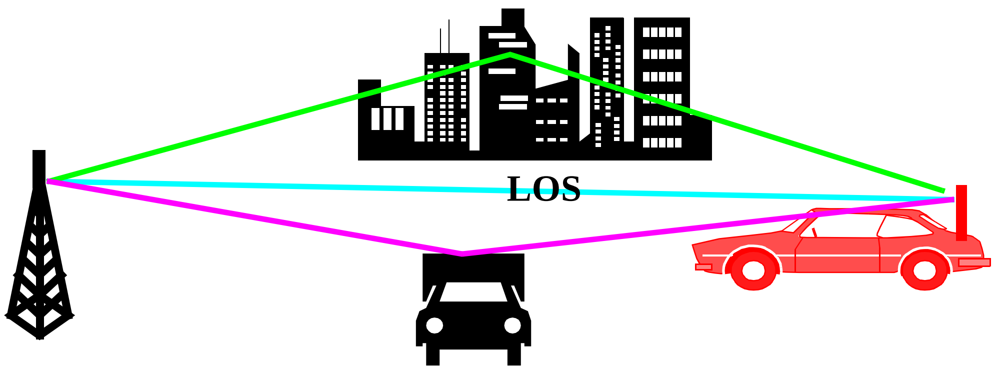
- **Diffraction**

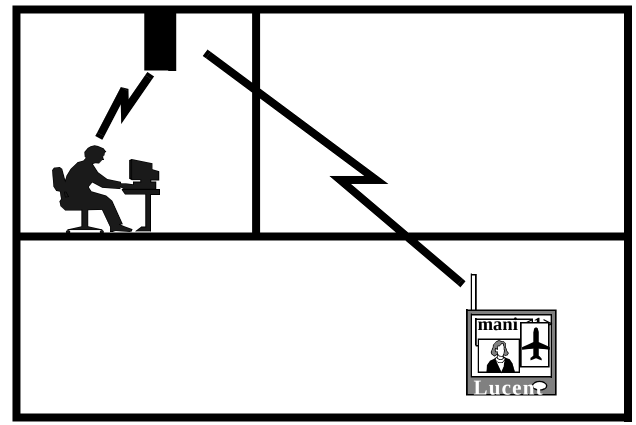
  - radio path is obstructed by an impenetrable surface with sharp irregularities (edges)
  - secondary waves "bend" around the obstacle (Huygen's principle)
  - explains how RF energy can travel even without LOS
  - a.k.a "shadowing"

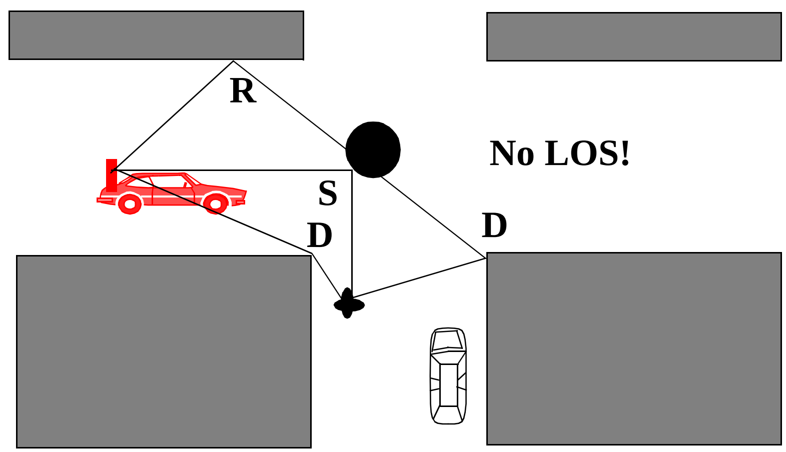
- **Scattering (diffusion)**

  - when medium has large number of objects < λ (30 cm @ 1 GHz)
  - similar principles as diffraction, energy reradiated in many directions
  - rough surfaces, small objects (e.g. foliage, lamp posts, street signs)

Reflection, Diffraction, and Scattering in Real-Life



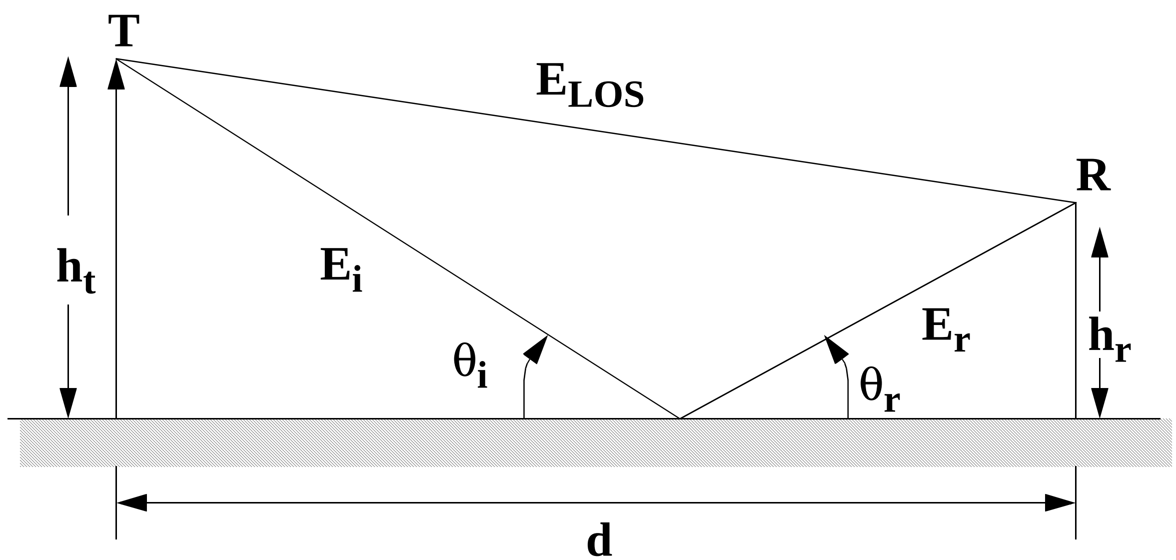




- **Received signal often a sum of contributions from different directions**

  - random phases make the sum behave as noise (Rayleigh Fading)

Example: Ground Reflection (2-Ray) Model



- **Model found a good predictor for large-scale signal strength over distances of several kilometers for mobile systems with tall towers (heights > 50m) as well as for LOS microcell channels**

- **Can show (physics) that for large** $d \gg \sqrt{h_t h_r}$

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$

- **Much more rapid path loss than expected due to free space**

Practical Link Budget Design Using Path Loss Models

- **Bit-error-rate is a function of SNR (signal-to-noise ratio), or equivalently CIR (carrier-to-interference ratio), at the receiver**

  - the "function" itself depends on the modulation scheme!

- **Link budget calculations allow one to compute SNR or CIR**

  - requires estimate of power received from transmitter at a receiver
  - also, estimate of noise and power received from "interferers"

$$SNR(\text{dB}) = P_r(d)\text{ dBm} - N\text{ dBm}$$

where, $N = KT_0BF$ or, $N\text{ dBm} = -174\text{ dBm} + 10\log B(\text{in Hz}) + F\text{ (dB)}$

where is the Boltzmann's constant, and F is the noise figure of the receiver

- **Many different models**

  - analytical
  - empirical (fitting curves to measured data)
  - combination

- **Classical (large scale) path loss models**

Log-distance Path Loss Model

- **Assume average power (in dB) decreases proportional to *log* of distance**

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

- **Justification?**

  - measurements
  - intuition/theory... recall: free-space, ground-reflection model

- **Path-loss exponent, *n*, depends on propagation environment**

Environment	n
Free Space	2
Urban area cellular radio	2.7 - 3.5
Shadowed urban cellular radio	3 to 5
In-building LOS	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

- **Problem: "Environment clutter" may differ at two locations at same *d***

  - measured $PL(d)$ may differ substantially from $\overline{PL}(d)$

Log-normal Shadowing

- **Measurements show that at a given d path loss has a normal distribution**

$$PL(d) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$$

  - X_σ is a zero-mean Gaussian r.v. (in dB) with standard deviation σ (in dB)
  - σ says how "good" the model is

- **Statistically describes random shadowing effects**

  - values of n & σ are computed from measured data using linear regression

- **Note that $P_r(d)$ also has a normal distribution: can calculate $Pr[P_r(d) > \gamma]$**

- **Exercise: calculate $U(\gamma)$ = percentage of "useful service area" where received signal is** $>$ threshold γ **in a radius R circular "cell" given a known likelihood of coverage at the cell boundary $Pr[P_r(R) > \gamma]$**

  - e.g., if $n = 4$ and $\sigma = 8$ dB, and boundary has 75% coverage, then area coverage is 94%

$$U(\gamma) = \frac{1}{\pi R^2}\int_0^{2\pi}\int_0^R Pr[P_r(d) > \gamma]\, r\, dr\, d\theta$$

Other Models for Outdoor Path Loss

- **Log-distance & Log-normal models lump everything into d and σ**
- **More sophisticated models take into account factors such as terrain. urban clutter, antenna heights, and diffraction**
  - Longley-Rice, Durkin, Okumura, Hata, COST-231, Walfisch & Bertoni etc.

- **Example: Okumura Model (and its parameteric version, the Hata model) is used in urban areas for 150-1920 (3000) MHz, distances of 1-100 Km, and antenna heights of 30-1000m**
  - based on *curves* of measured median attenuation relative to free space A_{mu}, & an environment specific gain G_{AREA} ... no analytical explanation
  - standard in Japan for “system planning”
  - accurate to 10-14 dB

from Okamura’s curves

$$L_{50}(\text{dB}) = L_F + A_{mu}(f, d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

where:

- $L_{50}(\text{dB})$ is the median (50-th percentile) propagation path loss
- L_F is the free space propagation path loss
- $G(h_{te}) = 20\log(h_{te}/200)$ for $h_{te} \in (10m, 1000m)$, and $G(h_{re}) = 10\log(h_{re}/3)$ for $h_{re} \le 10$ & $= 20\log(h_{re}/3)$ for $h_{re} \in (3(10)m, 10m)$ are basestation & mobile antenna height gains

Example Link Budget Calculation

- **Maximum separation distance vs. transmitted power (with fixed BW)**

Given:

- cellular phone with 0.6W transmit power
- unity gain antenna, 900 MHz carrier frequency
- SNR must be at least 25 dB for proper reception
- receiver BW is B = 30 KHz, and noise figure F = 10 dB

What will be the maximum distance?

<u>Solution:</u>

N = -174 dBm + 10 log 30000 + 10 dB = -119 dBm

For SNR > 25 dB, we must have $P_r > (-119+25) = -94$ dBm

$P_t = 0.6W = 27.78$ dBm

This allows path loss $\overline{PL}(d) = P_t - P_r < 122$ dB

$\lambda = c/f = 1/3$ m

Assuming $d_0 = 1$ km, $PL(d_0) = 91.5$ dB

For **free space**, $n = 2$, so that: 122 > 91.5 + 10*2*log(d/(1 km))

or, **d < 33.5 km**

Similarly, for s**hadowed urban** with $n = 4$, 122 > 91.5 + 10*2*log(d/(1 km))

or, **d < 5.8 km**

Indoor Path Loss Models (e.g. for WLANs, WPBXs)

- **Two characteristics of indoor environments:**

  - small distances
  - much greater environmental variability even for small T-R separations
    e.g. doors closed vs. opens, ceiling vs. desk mounted antennas
    walls, floors, furniture, people moving around

- **Partition losses on same floor**

  - wide variety of partitions.... with different electrical & physical characteristics
  - *hard partitions* (to the ceiling) vs *soft partitions*
  - extensive databases of measurements

- **Partition losses between floors**

  - depends on construction material, number of windows, presence of tinting...
  - characterized by "Floor Attenuation Factors" (FAF)

- **Our friend, the *Log-normal shadowing* path loss model, found to be valid!**

Indoor Path Loss Models (contd.)

Building	Frequency (MHz)	n	σ (dB)
Retail Stores	914	2.2	8.7
Grocery Store	914	1.8	5.2
Office, hard partition	1500	3.0	7.0
Office, soft partition	900	2.4	9.6
Office, soft partition	1900	2.6	14.1
Factory LOS			
Textile/Chemical	1300	2.0	3.0
Textile/Chemical	4000	2.1	7.0
Paper/Cereals	1300	1.8	6.0
Metalworking	1300	1.6	5.8
Suburban Home			

Indoor Path Loss Models (contd.)

- **Attenuation factor model**

  - reportedly reduces σ to 4 dB as opposed to 13 dB

$$PL(d)\ [\text{dB}] = PL(d_0)\ [\text{dB}] + 10 n_{SF} \log\left(\frac{d}{d_0}\right) + FAF\ [\text{dB}]$$

where n_{SF} is the exponent value for “same floor” measurement

More on Large Scale Path Loss

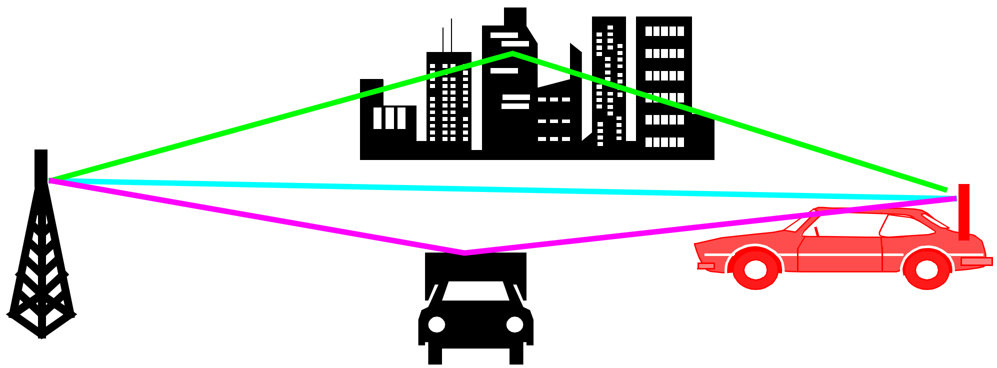
- **RF signal penetration into buildings**

  - depends on building material, height, percentage of windows, height, orientation, transmission frequency
    - e.g. signal strength inside the building increases with height (LOS to upper floor walls)
    - e.g. metallic tints can provide 3 to 30 dB attenuation in a single glass pane
  - n is between 3.0 and 6.2, with average of 4.5

- **Ray tracing CAD tools for site specific modeling**

  - deterministically model indoor and outdoor propagation using ray tracing
    - e.g. use building blueprints from, say, AutoCAD,
      or, aerial photographs
  - replacing statistical models

Small-Scale Fading Effects (over small Δt and Δx)



- **Fading manifests itself in three ways**

  1. time dispersion caused by different delays limits transmission rate
     - replicas of signals with different delays (reflection, diffraction etc.)
  2. rapid changes in signal strength (up to 30-40 dB) over small $\Delta x < \lambda$ or Δt
  3. random frequency modulation due to varying Doppler shifts

- **In urban areas, mobile antenna heights << height of buildings**

  - usually no LOS from basestation

- **Mobile receiver may stop in a deep fade (null)**
- **Moving surrounding objects also cause time-varying fading**

Fading affects available channel data rate

Factors Influencing Small-Scale Fading

- **Multipath propagation**
  - multiple waves arriving at random delays (phases), angles, & amplitudes
  - causes signal strength fluctuation, signal distortion, and signal smearing (due to "inter-symbol interference")
- **Speed of mobile**
  - causes random frequency modulation due to different Doppler shifts on each multipath component
- **Speed of surrounding objects**
  - time varying Doppler shift on multipath components
- **Transmission bandwidth of the signal**
  - signal distorted if signal bandwidth > "bandwidth" of multipath channel
  - signal not distorted in time, but amplitude fluctuates if signal bandwidth < "bandwidth" of multipath channel
  - "bandwidth" of multipath channel depends on its multipath structure

Parameters of a Multipath Channel

- **Multipath channel impulse response (measured by "sounding" techniques)**

$$h(t) = \sum_{i=1}^{N} a_i e^{\theta_i} \delta(t - \tau_i)$$

- **Four important parameters of interest**

  - ***RMS delay spread* σ_τ:** measure of time dispersion in the channel
    e.g. 1.3 μs for NYC @ 910MHzm, 10-25 μs for SF @ 892MHz,
    .2-.3 μs for typical suburban @ 910MHz, 2 μs for extreme suburban

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} \text{ where, } \bar{\tau} = [\textstyle\sum_k a_k^2 \tau_k] / [\sum_k a_k^2] \text{ and, } \overline{\tau^2} = [\sum_k a_k^2 \tau_k^2] / [\sum_k a_k^2]$$

  - ***Coherence bandwidth* B_C:** frequency varying nature of time dispersiveness
    frequency range over which channel is "flat" (equal gain & linear phase)
    "ball park" estimate: $B_C \approx 1/(50\sigma_\tau)$... inverse relationship

  - ***Doppler spread* B_D or f_m:** spectral broadening due to Doppler shift ($(v/\lambda)\cos\theta$)

$$B_D = f_m = max((v/\lambda)\cos\theta) = (v/c)f_{carrier}$$

  - ***Coherence time* T_C:** time varying nature of frequency dispersiveness - time duration over which spectral broadening is invariant (stationarity of $h(t)$)
    "rule of thumb": $T_C = \sqrt{9/(16\pi f_m^2)} = 0.423/f_m$

Types of Fading

- Two *independent* mechanisms: *Time Dispersion* (due to multipath delays), and *Doppler Spread* (due to motion of mobile or channel)

Fading due to Multipath Time Delay Spread

Flat fading ("amplitude varying")

1. BW of signal B_S << BW of channel B_C
2. Delay spread $\sigma\tau$ << Symbol period T_S
3. Causes deep fades: 20 to 30 dB - more power!
4. Amplitude distribution is either Raleigh (no LOS) or Ricean (LOS component) distribution

Frequency Selective Fading ("time dispersion")

1. BW of signal B_S > BW of channel B_C
2. Delay spread $\sigma\tau$ > Symbol period T_S
3. Induces ISI - channel has memory
4. Undone by signal processing: "equalization"

Fading due to Doppler Spread

Fast fading ("time selective")

1. BW of signal B_S < Doppler Spread B_D
2. Coherence time T_C < Symbol period T_S
3. Channel variations faster than baseband signal variations
4. Usually, occurs for very low data rates

Slow Fading (frequency dispersion)

1. BW of signal B_S >> Doppler Spread B_D
2. Coherence time T_C >> Symbol period T_S
3. Channel variations slower than baseband signal variations
4. Common case since typical B_D < 100 Hz whereas symbol rates are > 30 KHz

Raleigh and Rician Fading

- **Rayleigh fading happens when:**

  - flat fading or narrowband mobile radio channel
    bandwidth of applied signal is narrow compared to channel bandwidth
  - either transmitter or receiver is immersed in cluttered surrounding
    so that there is no LOS component
  - envelope of signal has Rayleigh distribution, which has pdf:

$$p(r) = \frac{re^{-(r^2/(2\sigma^2))}}{\sigma^2} \text{ for } \quad 0 \le r \le \infty$$

- **Rician fading happens when**

  - there is a dominant signal component such as LOS
  - random components arriving at different angles are superimposed on a stationary signal i.e. a dc component is essentially added to the multipath
  - envelope has Rician distribution

$$p(r) = \frac{r}{\sigma^2}e^{-\left(\frac{r^2 + A^2}{2\sigma^2}\right)}I_0(A_r/\sigma^2) \text{ for } A \ge 0, r \ge 0 \text{ , 0 otherwise}$$

  - described completely by parameter K, which is the ratio between the deterministic signal power and the variance of the multipath $K(dB) = 10\log A^2/(2\sigma^2)$
    degenerates to Raleigh when $A \rightarrow 0$, so that $K \rightarrow 0$

Error Bursts due to Raleigh Flat Fading

- **Received signal a sum of contributions from different directions**

  - random phases make the sum behave as noise (Rayleigh Fading)
  - "fades": intervals of increased BER, or reduced channel capacity

- **Function of speed of mobile as well as other objects, e.g.,**

  - a 50 kmph car in 900 MHz band: 1 ms long >20dB fade every 100 ms
  - a 2 kmph pedestrian in 900 Mhz band: 25 ms long >20dB fade every 2.5s

- **Also, a function of frequency, and fade depth**
- **Vanilla forward error correction techniques are ineffective**
- **Diversity techniques help**

  - multiple antennas, multiple frequencies

Raleigh Flat Fading: Statistical Model

- **Frequency of fades - *Level Crossing Rate***

  - rate at which envelope crosses a specified level in positive direction

$$N_R = \sqrt{2\pi} f_m \rho e^{-\rho^2} = \sqrt{2\pi} \frac{v}{\lambda} \rho e^{-\rho^2}$$

  where $\rho = \frac{R}{R_{RMS}}$ is the specified amplitude level relative to RMS

  and f_m is the maximum Doppler frequency.

- **Average fade duration**

  - approximation: $\bar{\tau} = \frac{e^{\rho^2} - 1}{\rho f_m \sqrt{2\pi}} = \frac{1 - e^{-\rho^2}}{N_R}$

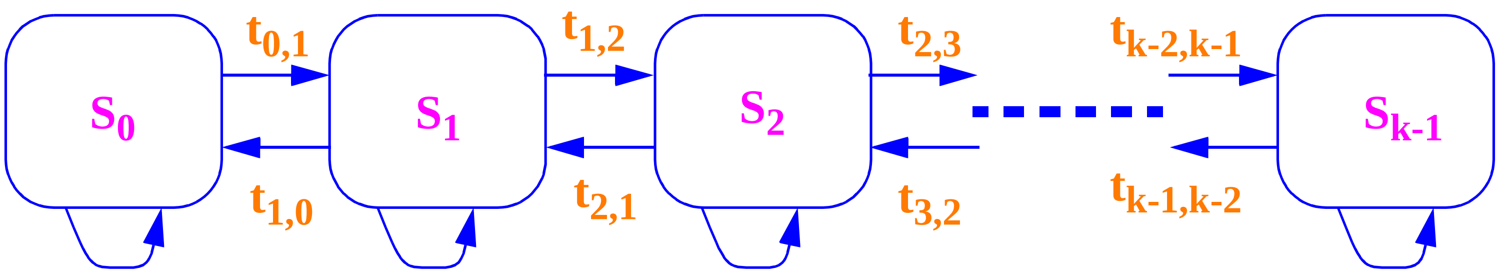
  - 0.957 ms @ 900 MHz, 50 km/h, -20 dB
  - 23.94 ms @ 900 MHz, 2 km/h, -20 dB
  - 6.308 ms @ 900 MHz, 24 km/h, -10 dB

- **Statistics depend primarily on speed of the mobile!**

Mapping Raleigh Fading to 2-state Markov Channel

- **Approach: use** N_R **&** $\bar{\tau}$ **to calculate transition probabilities for MC**
- **Let** P_G **and** P_B **be the probability of being in good (G) & bad (B) states.**
- **Also, let** P_{GB} **and** P_{BG} **be the transition probabilities from state G to B, and B to G respectively**
- **Mean time between two successive entries into state B is** $\frac{1}{N_R}$
- **Mean time spent in state B on every entry is** $\bar{\tau}$
- **It follows that:** $P_B = \frac{\bar{\tau}}{1/N_R} = 1 - e^{-\rho^2}$ **and** $P_G = 1 - P_B$
- **Assume: discrete time channel, i.e. state transitions may occur at symbol boundaries only**
  - R symbols are transmitted per unit time
- **Rate of transition from state B to G is** $P_B \times P_{BG}$ **transitions per symbol**
- **But, rate of transition from state B to G =** $\frac{N_R}{R}$ **transitions per symbol**
- **Therefore,** $P_B \times P_{BG} = \frac{N_R}{R}$ **or** $P_{GB} = \frac{N_R}{R \times P_G}$

Genralized Finite-State Markov Channel [Wang95]



- **Each state corresponds to an interval of SNR**
- **Assumes slow fading:**

  - received SNR remains at a certain level for the duration of a symbol
  - states associated with consecutive symbols are neigboring states
    i.e. no more than three outgoing transitions from a state

- **Analysis in [Wang95] (similar to previous slide) shows that:**

$$t_{k,\,k+1} \approx \frac{N_{k+1}}{p_k} \qquad \text{k=0,1,2,}\ldots K-2 \quad \textbf{and} \quad t_{k,\,k-1} \approx \frac{N_k}{p_k} \qquad \text{k=1,2,}\ldots K-1$$

  - p_k is the steady state probability of being in state k

Frequency Selective Fading

- **Data rate limitations due to inter-symbol interference (ISI) in frequency selective fading and receivers with no "equalizaters":**

$$\text{maximum data rate without significant errors} = max(R_b) = \frac{d}{\sigma_\tau}$$

where d depends on specific channel, modulation type etc.

- **Thumb rule for unequalized radio channels:** $max(R_b) = \frac{0.1}{\sigma_\tau}$
- **Data rate can be improved by "equalization"**

  - equalizer is a signal processing function (filter)
    cancels the ISI, usually implemented at baseband or IF in a receiver
  - must be adaptive since channel is unknown & time varying
    training, tracking, and re-training during data transmission
    equalizer needs to be "updated" at a rate described by Doppler spread
- **GSM example:**

  - GSM has a bit period of 3.69 µs, or a rate of 270 kbps
  - with its equalizer, GSM can tolerate up to 15 µs of delay spread
  - otherwise, with 15 µs of delay spread, GSM would be limited to 7 kbps
- ***Data rate = f(multipath delays, receiver complexity)***
- **Channel difficult to model: must be considered as a time-varying linear filter**

Combating the Channel Impairments

- **Increase transmitter power**

  - counters flat fading, but costly
- **(Adaptive) Equalization**

  - compensates for intersymbol interference due to time dispersion
- **Antenna or space diversity for "multipath**

  - usually, two (or more) receiving antennas, separated by $\lambda/2$
  - selection diversity vs. scanning diversity vs. combining diversity
  - also, "adaptive antenna arrays" or "smart antennas"
- **Forward error correction**

  - transmit redundant data bits - "coding gain" provides "fading margin"
  - not very effective in slowly varying channels or long fades
- **Automatic Repeat Request (ARQ)**

  - retransmission protocol for blocks of data (e.g. packets) in error
  - stop-and-wait, go-back-N, selective-repeat etc.
- **Other: packet length adaptation, spreading gain adaptation etc.**

Channel Characteristics in Wireless LANs

- **Many studies on characterization of cellular telephone channels**
- **But results do not necessarily apply to Wireless LANs**
  - outdoor and indoor signal propagation differ
    - wide assortment of material indoors
    - greater variation in Tx and Rx placement relative to obstructions
    - presence of people moving around
  - in WLANs it is the "packet level" behavior that is of interest
    - not obvious how to relate it to signal propagation
- **Signal propgation characteristics of WLANs in ISM band [Huang92]**
  - median delay spread = 40 ns
  - 75% of measured delay spreads < 50 ns
  - by comparison, WaveLAN has a chip time of 91 ns, and baud time of 11x91 ns = 1 us, which can be easily handled by WaveLAN
- **What about the packet level behavior?**

Packet Level Models of Wireless Channel

- **Using symbol level channel models too inefficient for network simulation & analysis**

  - computationally intensive or too detailed for high level modelling

- **But, simple packet loss models are too simplistic...**

  - don't take correlated packet losses into account (fading etc.)
    traditionally packet transmissions assumed to be independent
    and identically distributed (i.i.d)
  - many protocols were designed for iid channel
    techniques, e.g. interleaving, used to eliminate channel memory
  - but, one can do better by taking advantage of channel memory

- **First order binary Markov model for success/failure of data packets**

  - [Zorzi95] found it to be accurate for slow fading channels
    i.i.d. model more suitable for fast fading channels
    for high data rates the fading can typically be considered slow fading

- **"Train" generalized statistical models such as HMM**

  - non-stationary stochastic process represented by bit error traces from DSP simulation
  - packet-level wireless channel model using measured traces

Trace Modulation [Noble97]

- **Idea:**

  - performance of a real, wireless network is captured through trace collection
  - these complex network observations are reduced to a list of parameters of a simple, time-varying model
  - the performance described by these parameters is reproduced in a controlled manner

- **Trace modulation v.s. Trace replay and Trace-driven simulation**

  - creates a synthetic networking environment rather than a synthetic workload
  - accounts for all network traffic sent or received by the modulated host

- **Collection phase**

  - the mobile host traverses some path, packets from a known workload are generated, then records the observations
  - packet traffic information: times at which every outgoing and incoming packet was sent or received, sequence numbers, flags, and destination and source ports
  - characteristics of mobile network devices

Trace Modulation [Noble97] (contd.)

- **Distillation phase**

  - collected trace transformed into a replay trace consisting of a list of performance parameters
  - each entry in it specifies latency, bandwidth, and loss rate for the duration of time indicated in that entry
  - a simple, instantaneous network model

- **Modulation phase**

  - an in-kernel modulation layer between the IP layer and the network device driver
  - a user daemon controls it by writing tuples from the replay trace file
  - modulation layer subjects packets to the tuple parameters (loss, delay)
  - limited by scheduling granularity
  - application is unmodified

Measured Performance of Wireless LAN Channels

- **Studies by Duchamp at Columbia [Duchamp92] and Eckhardt at CMU [Eckhardt96] using WaveLAN in “promiscuous” mode**

  - DSSS, CSMA/CD, 1 Mbaud, QPSK, 11 chips/bit, two antennas
  - no transmit power control, but has receive threshold

- **Broad conclusions:**

  - very reliable within a certain range
    - packet loss well under one per thousand, bit error extremely low
  - beyond the threshold range, the behavior becomes worse rapidly with a sharp drop-off in capture success
    - relative placement of Rx & Tx becomes critical, with tiny movements making enormous difference in packet capture
  - once beyond the threshold range, packet length is a key parameter
    - smallest packets being captured much more successfully
  - signal quality returned by receive modem exhibits a large dynamic range
    - roughly correlated with distance
  - when packets are damaged (but captured), they tend to suffer from a small number of isolated bit error
    - long bursts dense with bad bits are absent even when signal is weak
  - receive threshold very effective in shutting out distant interferers

Ray Tracing Channel Models

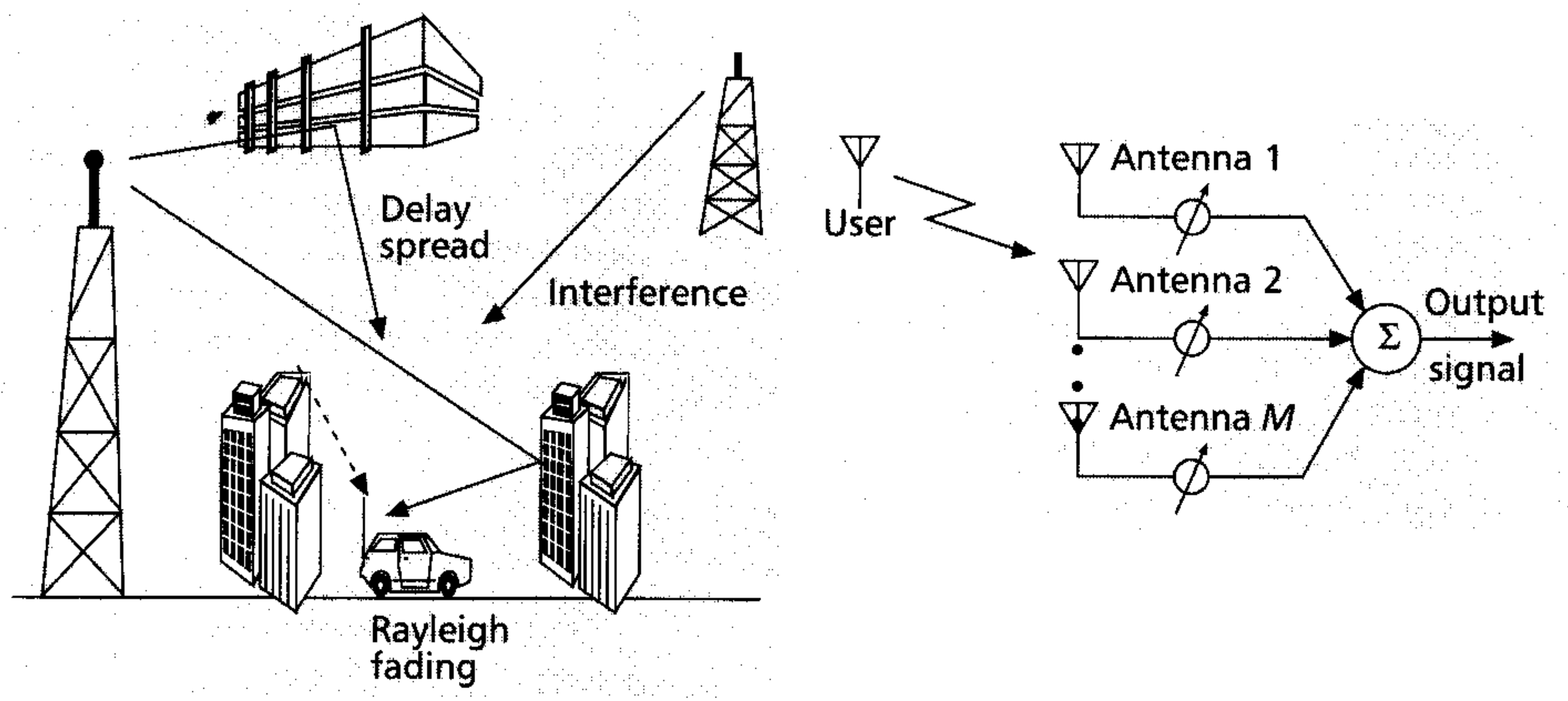
- **So far: *parameteric*, and *statistical* models**

  - mostly based on statistical analysis and measurements
  - provide average channel behavior (path loss, delay spread etc.)
    some parameters adjusted according to environment

- **Deterministic model: *ray tracing* proposed in recent years**

  - based on geometric theory, and reflection/diffraction/scattering models
    similar to ray tracing in graphics used to create 2D view of 3D world
  - site-specific information used
    cad models, architecture drawings, material properties
  - channel propagation is deterministically modeled
    used for basestation placement planning
  - however, several problems:
    high computation burden
    lack of detailed terrain and building models
  - to pursue further, see [Seidel94], [Valenzuela93]

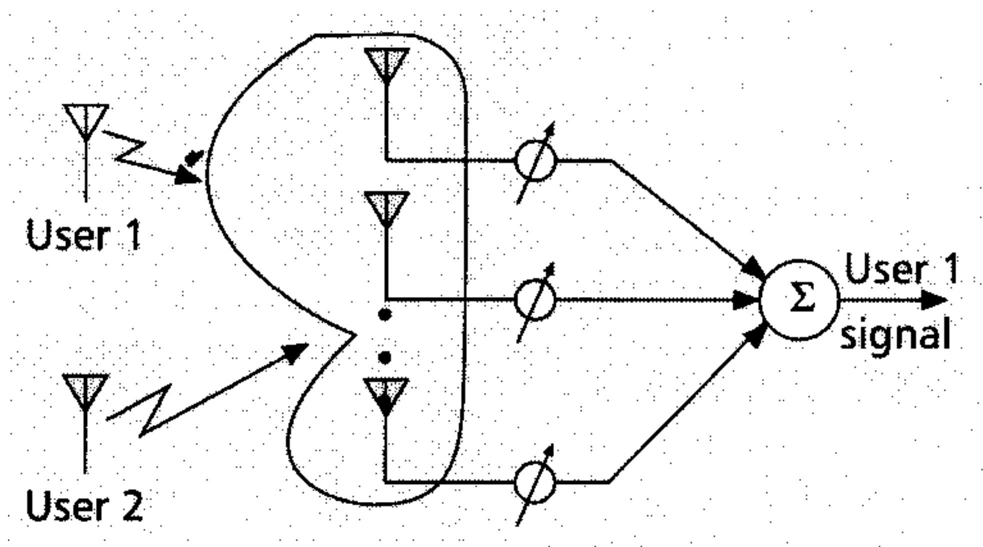
Smart Antennas or Antenna Arrays



- **Antenna arrays, or *Smart Antennas*, can combat wireless impairments**

  - an M-element antenna array provides
    antenna gain M (reduction in required receive power for given SNR)
    diversity gain against multipath reduction in required SNR for given BER)

Adaptive Antenna Array Beam Pattern



- **Set antenna array gains so that "main beam" is in the direction of the desired user, and a "null" is in the direction of interferers**

  - theoretically M elements can cancel N (< M) interferers and provide (M-N) fold diversity gain
  - can eliminate delay spread over (M-1)/2 symbols by treating delayed versions of a signal as separate signals... typically used together with equalizers

Smart Antenna Advantages

- ***Array Gain:*** **multiple antennas coherently combine the signal energy improving the carrier-to-noise ratio (C/N)**

  - available both on transmit and receive

- ***Diversity Gain:*** **spatial diversity obtained from multiple antennas helps combat channel fading**

  - available on transmit and receive

- ***Interference Suppression Gain:*** **multiple antennas can be adaptively combined to selectively cancel or avoid interference and pass the desired signal**

  - available on transmit and receive

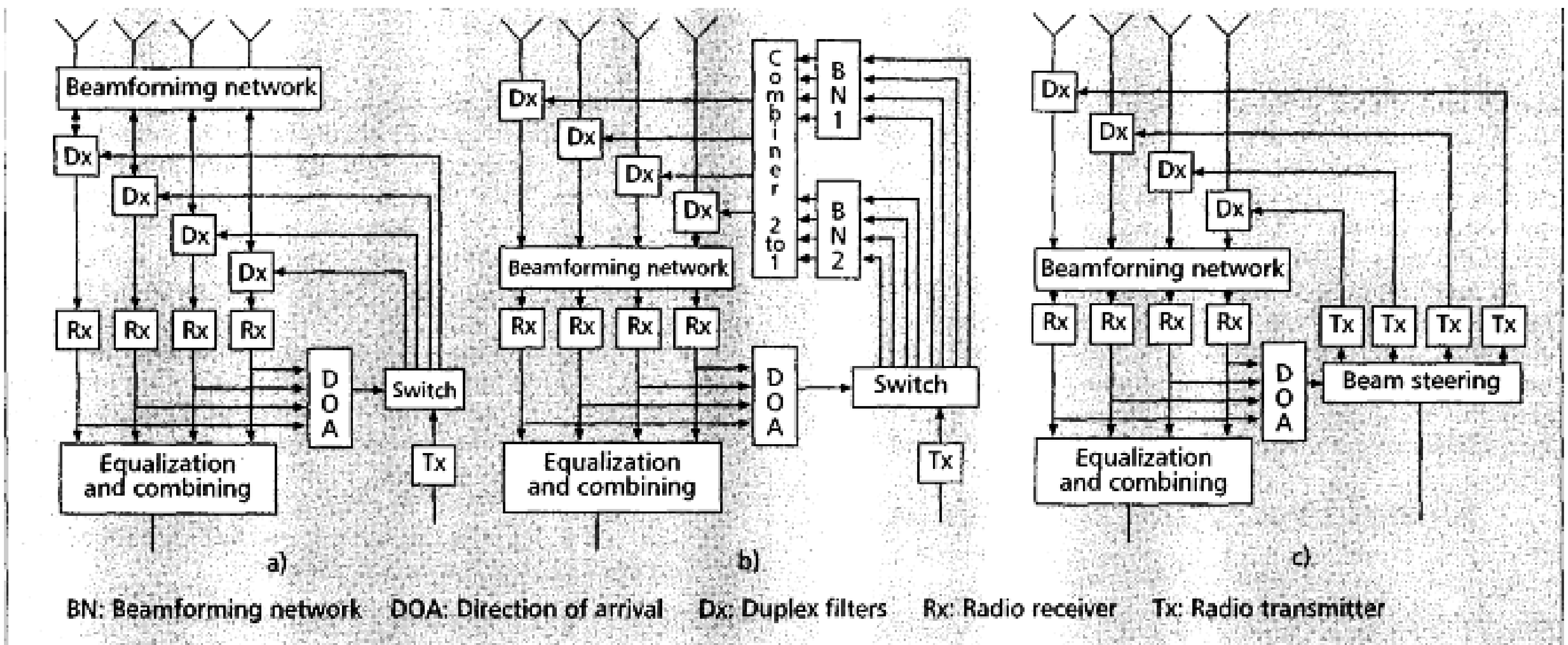
- ***Angle Reuse:*** **Frequency reuse in angle**

  - also known as Spatial Division Multiple access (SDMA)
  - exploits beamforming/directional antennas to support more than one user in the same frequency channel

- ***Spatial Multiplexing:*** **spatial multiplexing uses multiple antennas at both ends to create multiple channels and improves spectrum efficiency (bps/Hz)**

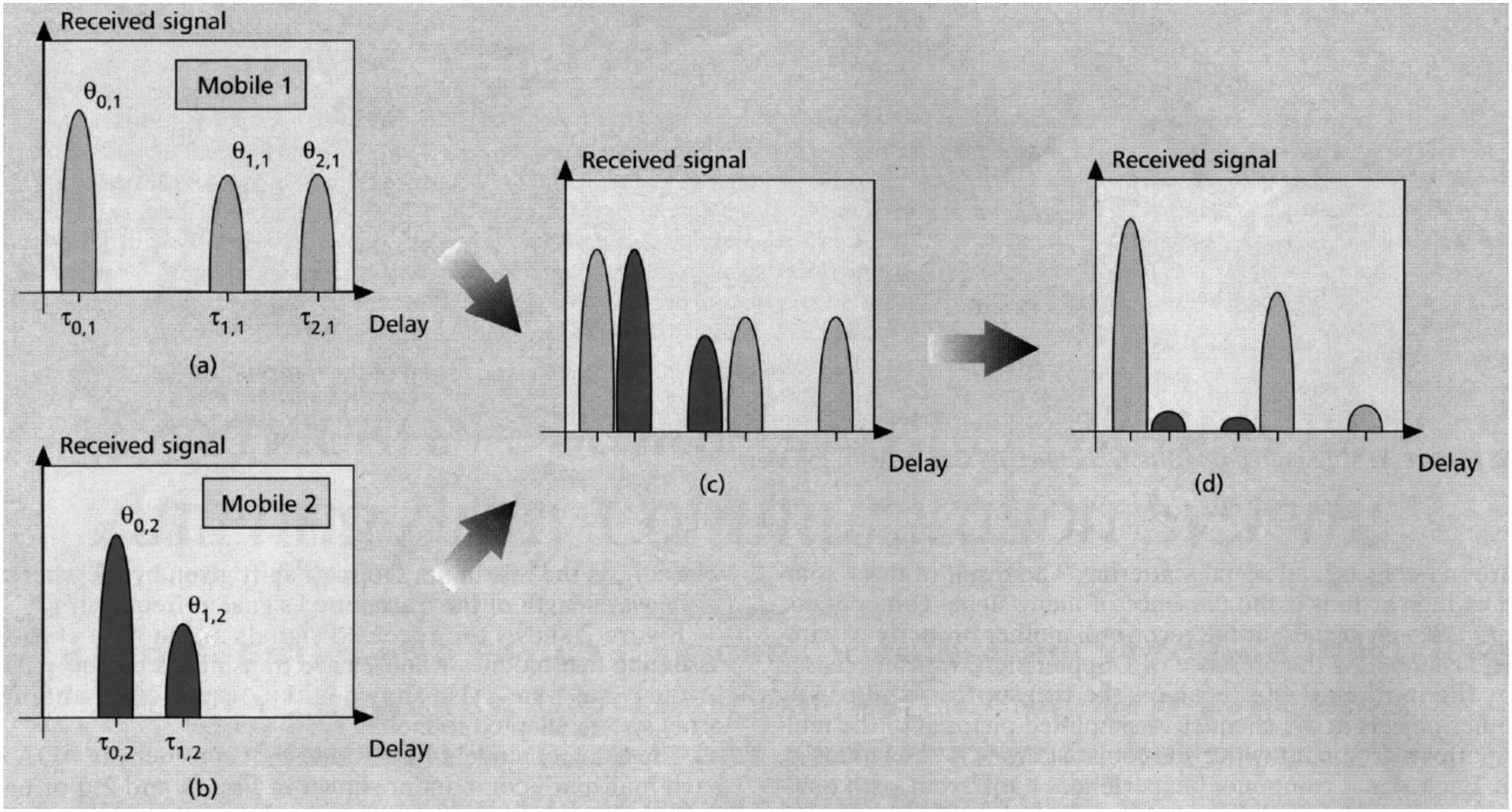
Antenna System Architectures

- **Two main strategies for downlink to mobile**
  - beam can be "steered" towards a mobile
  - beam can be "selected" from a set of beams with fixed directions
- **Selection or steering done using information derived from the reverse link**
  - direction of arrival
  - feedback regarding downlink conditions



Switched beam *Fixed interleaved beams* *Steered beam*

Beam Steering by an Adaptive Antenna Array



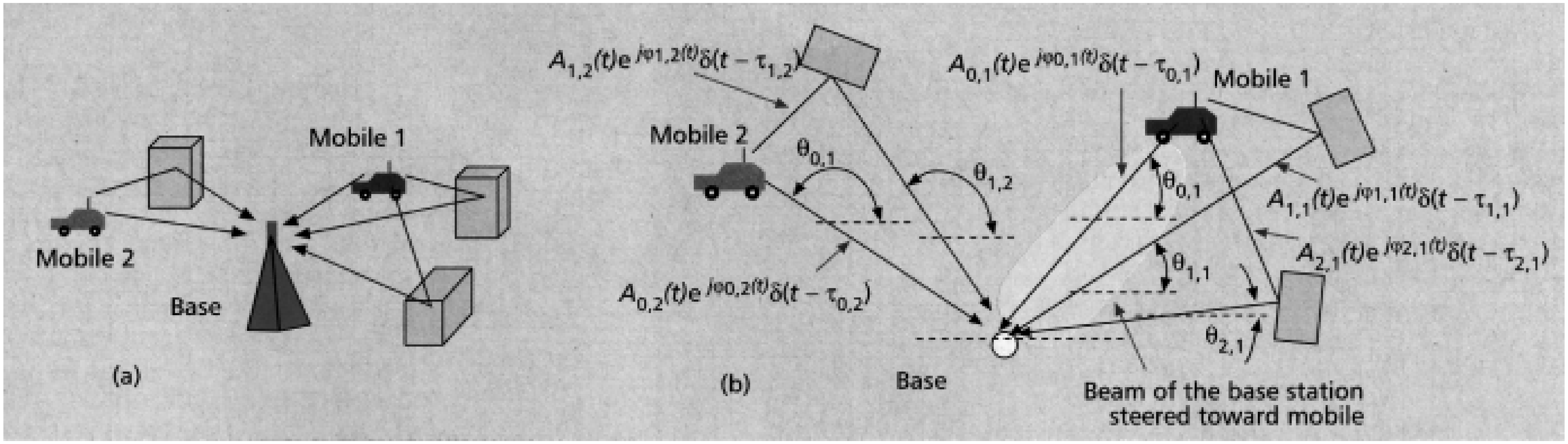
Space: The Final Frontier.... Spatial Channel Models

- **Classical models**

  - consider only received signal power and/or time varying amplitude (fading) distribution and Doppler shifts of the channel
  - sufficient for single antenna receivers... but not for wideband antenna arrays need info about signal multipath delay and angle-of-arrival (AOA)

- **Spatial channel models**

  - accurate model of distribution of scatterers around mobile & basestations
  - angle of arrival, and antenna array geometry



Reading List for This Lecture

MANDATORY READING:

[Rappaort] T. S. Rappaport, K. Blankenship, and H. Xu, "Propagation and Radio System Design Issues in Mobile Radio Systems for the GloMo Project," tutorial from Virginia Tech. Available in html and pdf.

RECOMMENDED READING:

[Wang95] H.S. Wang and N. Moayeri, “Finite-state Markov Channel - A Useful Model for Radio Communication Channels,” IEEE Transactions on Vehicular Technology, February 1995. Available on Melvyl.

[Winters98] Winters, J.H., “Smart antennas for wireless systems,” IEEE Personal Communications, vol.5, (no.1), IEEE, Feb. 1998. p.23-7.

OTHER READING:

[Duchamp92], [Eckhardt96], [Noble97]