1 TRAFFIC THEORY EXAMPLES
HIGH BLOCKING PROBABILITY SCENARIOS

- Recall that we said that the loss system traffic models could be ranked in terms of their conservatism:

  \[ \text{Poisson} \rightarrow \text{Erlang B} \rightarrow \text{Binomial} \rightarrow \text{Engset} \]

- This is only strictly true under conditions of low blocking probability, where the approximations implicit in each of the models are reasonably valid.

- For high blocking probabilities, the model predictions are less accurate, and the Poisson model actually produces non-sensical results.

**P(N,A) & B(N,A) - High Blocking**

- We recognize that Poisson and Erlang B models are only approximations but which is better?
  - Compare them using a 4-trunk group offered A=10E

<table>
<thead>
<tr>
<th>Erlang B</th>
<th>Poisson</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ B(4,10) = 0.64666 ]</td>
<td>[ P(4,10) = 0.98966 ]</td>
</tr>
<tr>
<td>[ T_c = \lambda \times (1 - P(B)) = 10 \times (1 - 0.64666) ]</td>
<td>[ T_c = \lambda \times (1 - P(B)) = 10 \times (1 - 0.98966) ]</td>
</tr>
<tr>
<td>[ T_c = 3.533E ]</td>
<td>[ T_c = 0.103E ]</td>
</tr>
<tr>
<td>[ \rho = \frac{3.533}{4} = 0.88 ]</td>
<td>[ \rho = \frac{0.103}{4} = 0.026 ]</td>
</tr>
</tbody>
</table>

- How can 4 trunks handle 10E offered traffic and be busy only 2.6% of the time?
  - Obviously, the Poisson result is so far off that it is almost meaningless as an approximation of the example.
    - 4 servers offered enough traffic to keep 10 servers busy full time (10E) should result in much higher utilization.
  - Erlang B result is more believable.
    - All 4 trunks are busy most of the time.
  - What if we extend the exercise by increasing A?
    - Erlang B result goes to 4E carried traffic
    - Poisson result goes to 0E carried
  - Illustrates the failure of the Poisson model as valid for situations with high blocking
    - Poisson only good approximation when low blocking
    - Use Erlang B if high blocking

Source: [1]
Efficiency of Large Groups

- Already seen that for same P(B), increasing servers results in more than proportional increase in traffic carried

  example 1: \( P(10, 4.14) = 0.01 \) and \( P(100, 78.2) = 0.01 \)

  example 2: \( P(32, 20.3) = 0.01 \) and \( P(33, 20.1) = 0.005 \)

  example 3: \( B(8, 2.05) = 0.001 \) and \( B(80, 57.8) = 0.001 \)

- What does this mean?
  - If it's possible to collect together several diverse sources, you can
    - provide better gos at same cost, or
    - provide same gos at cheaper cost

  Source: [1]

Notes

1. Greater efficiency is achieved by combining small groups into larger groups, since the small groups are not likely to be receiving high demand simultaneously
   - By combining, overload traffic from the 'busy' group has access to any idle servers in the other group

2. Efficiency of large groups is one of the primary motivations for the hierarchical structure of the PSTN
   - Traffic is aggregated by switches onto shared trunk groups (between two toll centers serving two cities, for example)

Adding 1 extra server lowers \( P(B) \) by 50% (in this particular example) for the same offered traffic

For given gos, much higher circuit utilization for larger server groups

Two trunk groups offered 5 Erlangs each, and \( B(N,A) = 0.002 \)

\[ 5 \text{ E} \rightarrow N_1 = 13 \]

How many trunks total?
From traffic tables, find \( B(13,5) = 0.002 \)
\( N_{\text{total}} = 13 + 13 = 26 \) trunks

Trunk efficiency?
\[ \rho = \frac{T_c}{N} = \frac{10(1 - 0.002)}{26} = 0.384 \]

38.4% utilization

One trunk group offered 10 Erlangs, and \( B(N,A) = 0.002 \)

\[ 10 \text{ E} \rightarrow N = 20 \]

How many trunks?
From traffic tables, find \( B(20,10) = 0.002 \)
\( N = 20 \) trunks

Trunk efficiency?
\[ \rho = \frac{T_c}{N} = \frac{10(1 - 0.002)}{20} = 0.499 \]

49.9% utilization

For same gos, we can save 6 trunks!

Source: [1]
Sensitivity to Overload

- Consider 2 cases:

**Case 1:** $N = 10$ and $B(N,A) = 0.01$

$B(10,4.5) \approx 0.01$, so can carry $4.5$ E

What if 20% overload ($5.4$ E)? $\rightarrow B(10,5.4) \approx 0.03$

3 times $P(B)$ with 20% overload

**Case 2:** $N = 30$ and $B(N,A) = 0.01$

$B(30,20.3) \approx 0.01$, so can carry $20.3$ E

What if 20% overload ($24.5$ E)? $\rightarrow B(30,24.5) \approx 0.08$

8 times $P(B)$ with 20% overload!

"Trunk Group Splintering"

- if high possibility of overloads, small groups may be better

5. The example above also illustrates that $GOS$ calculations are very dependent on accurate knowledge of the offered traffic (20% uncertainty in $A$ implies 8x uncertainty in $P(B)$ for Case 2)

$\rightarrow$ Conservative models and traffic predictions allow for some uncertainty, and accommodate some growth in service demand (offered traffic)

**Examples**
Incremental Traffic Carried by Nth Trunk

- If a trunk group is of size N-1, how much extra traffic can it carry if you add one extra trunk?
  - Before, can carry: \( T_{C1} = A \times [1-(B(N-1,A))] \)
  - After, can carry: \( T_{C2} = A \times [1-(B(N,A))] \)

\[
A_N = T_{C2} - T_{C1} = A \left( [1 - B(N, A)] - [1 - B(N-1, A)] \right) = A \left( B(N-1, A) - B(N, A) \right)
\]

- What does this mean?
  - **Random Hunting**: Increase in trunk group's total carried traffic after adding an Nth trunk
  - **Sequential Hunting**: Actual traffic carried by the Nth trunk in the group

\[
A_N \approx (N - A) \times B(N, A)
\]

for very low blocking

**Random Hunting - Available servers are chosen at random (for example, by a switch) when a call request arrives**

**Sequential Hunting - servers are prioritized in a certain order (e.g., 1 to N)**

- **Lowest # (Highest priority) server is used when a call request arrives**
- **High priority servers used much more heavily on average**

**Example**

- Individual trunks are only economic if they can carry 0.4 E or more. A trunk group of size N=10 is offered 6 E. Will all 10 trunks be economical?

\[
A_N = A \left( B(N-1, A) - B(N, A) \right)
\]

\[
A_{10} = 6 \left( B(9, 6) - B(10, 6) \right) = 6 \left( 0.07514 - 0.04314 \right) = 0.192 \text{ E} < 0.4 \text{ E}
\]

\[\therefore\text{ At least the 10th trunk is not economical} \]

**References**

WIRELESS LINKS & CELLULAR TELEPHONY

As reviewed briefly in LEC. 8, wireless communication has increased in importance for network access (especially mobile access), while declining in importance in the 'backbone' of the PSTN.

Modern wireless commun. employs very sophisticated signal processing techniques in trans/arrays, to enable high fidelity comm. over a relatively poor quality channel.

Channel quality suffers from:

1. Multipath distortion
2. Fading (time dependent properties) — especially when one end is in motion (i.e., a cell phone user in a car, etc.)
3. Interference (from other users) — a key limitation in cell phone systems, where a limited spectral b/w must be shared in some way.

In cellular telephone, a mobile user communicates via a base station antenna that lies at the center of their cell. As a user crosses a cell boundary, they are 'handed-off' to the adjacent base station (transparent to the user).

Notes:

1. The main impetus for the cellular architecture is frequency (spectrum) reuse.

Generally, base stations can use identical carrier frequencies, provided they are not contiguous.
Frequency reuse patterns

- Reuse allows a small set of frequencies, $K$ to service a large area (numbers refer to transmitters with same frequencies)
- Reuse patterns are designed to minimize co-channel interference (interference from other base stations using the same frequency)
- A larger reuse pattern (e.g. $K=7$) results in a larger distance between base stations that use the same frequency

$$D = \sqrt{3K}R$$

- We define the co-channel interference reduction factor by

$$q = \frac{D}{R} = \sqrt{3K}$$

  - Note that the radius $R$, is the distance from the centre of the cell (base station) to an outer corner.

  $$R_f = R \sin(60^\circ)$$

  - The distance $D$, is the distance from one transmitter (base station, or centre of the cell) to the next transmitter of the same frequency.

- In most cases, only the first tier of interfering cells are considered

Third tier
Second tier
First tier

Clearly, the transmit powers must also be controlled carefully.
Wireless pre-cellular systems

- Wireless transmission was originally shown as a method to remain in continuous contact with ships (Marconi in 1897)
- In 1946, FM consumer mobile phone systems were introduced.
  - A group of frequencies allocated to a large geographic zone
  - when moving to a new zone, calls had to be reinitiated
  - 120 kHz per channel (voice transmission was only 3 kHz) due to poor filter technology
  - half-duplex system (only one person could speak at a time)
  - most users not connected to PSTN
  - Later progressed to GMTS (general mobile telephone system)
- By the 1960’s, IMTS (improved mobile telephone system)
  - 30 kHz channels in the 450 MHz range
  - Only 12 channels in NYC in 1976
    - poor service due to call blocking and usage over a few channels
  - still in use in the U.S. in 1995!
4. Cellular systems demonstrate a key factor common to wireless systems of all kinds: interference (from other users) is often the main limiting factor on signal fidelity, bit-rate, etc.

As a result, wireless link design is often considerably more complicated than wired link design.

In addition to channel attenuation & distortion, noise, and bandwidth (which are limitations for all channels), wireless systems have capacity that inherently depends on the density of users (i.e., how many users per square km, etc.), sharing the same frequency band.

4 Generations of Cellular

1G AMPS 800 MHz
2G Digital 800 MHz
3G CDMA 1.9 GHz

- Telus coverage map
  - from web site
  - (circa 2002)

As technology has matured, numerous cellular standards have been adopted and implemented in various world regions. In North America, the evolution (which is on-going) has been from:

- Analog → Digital → CDMA (digital spread spectrum)
- 1G → 2G → 3G

The boundaries between generations are not well defined, as hybrid solutions, etc., exist.

The current state of the art is 3G technology:

CDMA, voice + low speed data
(Cell phone camera, etc.)

References:
**Design Considerations**

- A cellular telephone system is essentially a line-of-sight wireless system (review lectures 8-9), except:

  1) Multiple obstructions partially block the path between antennas (typically)

  → leads to increased attenuation, severe multipath effects.

2) One end of the link is moving (typically)

  → leads to rapid fading and dynamic multipath effects.

3) The level of interference (from other users) is typically very high.

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**Path Loss Balance Equation**

As stated in Lec. 9, the free-space path loss is found (mostly from empirical evidence) to scale as 

\[ \frac{1}{4\pi d^2} \]

\[ \text{where } 2 \leq n \leq 4 \]

\[ n = \text{Path Loss Factor} \]

→ Following Lec. 9, we can write:

\[ P_R = \left( \frac{P_T}{4\pi d^n} \right) \cdot G_t \cdot A \]

→ and the link budget equation is modified slightly (compared to pure LOS):

\[ P_R [\text{dBm}] = P_T [\text{dBm}] + G_t [\text{dB}] + G_r [\text{dB}] + 20 \log_{10} (A) [\text{dB}] \]

\[ - 20 \log_{10} (4\pi) [\text{dB}] - 10n \log_{10} (d) [\text{dB}] - L_o [\text{dB}] \]

**Note:**

- \( L_o \) must be in same units (\([\text{m}]\))
- \( L_o \) = excess losses, as before
B. FADING AND MULTIPATH EFFECTS IN CELL SYSTEMS

As discussed in Lec. 9, fading (time-varying channel properties) in wireless links can occur on many different time scales:

- Hourly variations due to changes in weather patterns, etc.
- Rapid variations due to motion of a mobile user, etc.

Also recall that multipath effects are highly frequency-dependent, in general.

- Due to constructive or destructive interference (of the signal arriving over 2 or more paths), the received power can be very high for some ranges of frequency, very low for others.

Notes:

1. Normally, a wireless link will experience only partial fading. The received signal has time-dependent power, but the power fluctuation is moderate and easily predictable. In this case, excess transmitted signal power (called a fade margin) and adaptability in the receiver (auto gain control, etc.) can deal with fading issues.

2. A deep fade corresponds to nearly complete loss of signal power due to nearly completely destructive interference. Since very frequency-dependent, only affects one channel (one carrier freq.) in a frequency-division-multiplex (FDM) wireless system, at a given time.
- Since the fade is frequency- and path-dependent, deep multipath fades can be dealt with using:
  1. Frequency Diversity - A signal experiencing a deep fade is temporarily switched to another spare carrier frequency.
  2. Space Diversity - Two receiving antennae used to rx the same signal to two primary paths, which won't experience simultaneous deep fades (provided the 2 antennae are separated by a distance much greater than the carrier wavelength).

Figure 1.23 Space diversity.

Source: [2]

3. For a relatively narrowband signal on a high frequency carrier (such as a voice signal in a traditional FDM cellular system), multipath fading can effectively be flat fading:
   - There is a certain bandwidth associated with the multipath-induced fade:
     \[ B_c = \frac{1}{\sigma_d} \] bandwidth [2]

\( \sigma_d \) - RMS delay spread
   - A measure of the range of delay in arrival times for multiple paths
   - A measure of signal dispersion due to multipath

\[ B_c \] - Bandwidth

- We must consider 2 possible scenarios:
  1. \( B \gg B_c \) - The fading invokes distortion to the signal
     - Attenuation that is not flat across the bandwidth of the signal
     - In general, the distortion is time-dependent, and can be compensated by adaptive equalization of the signal.
- The multipath effect introduces a time-dependent attenuation that is approximately the same over the entire signal band (flat fading).
- The same basic effect as a rain-induced fade, but can vary much more rapidly with time.
- Must be compensated by automatic gain control or similar.

For example, the signal received from a mobile cell user is shown at right.
- We can define the coherence time \( T_c \) as the time over which the signal RX power does not change significantly.
- To first order, \( T_c = \frac{9}{16\pi f_m} = \frac{9c}{16\pi V f_c} \).

\[
f_m = \text{max. Doppler shift} = \frac{V}{\lambda}
V = \text{mobile user velocity} \quad \text{(m/s)}
\lambda = \text{carrier wavelength}
f_c = \text{carrier frequency} \quad (f_c = \frac{c}{\lambda})
\]

- As you might intuitively expect, the coherence time scales inversely with the mobile user's velocity.

4. As discussed, the RX power for a mobile link varies with time (around some average value), due to various fading effects. We can separate the sources of loss as follows:

1) Mean path loss
- Given by the loss balance expressions above, \( L = \frac{1}{4\pi d^2} \).
ii) **LONG-TERM FADEING (SHADOWING DUE TO LARGE OBSTRUCTIONS)**

- *When a cellular user enters a tunnel or passes behind a large building etc., the RX power levels (both at the handset and at the base station) can drop for an extended period of time → unpredictable (random), but can be treated statistically (see [4], p. 682)*

  - The range of extra loss due to shadowing, and how often it occurs with a given severity, can be predicted.

iii) **SHORT-TERM FADEING**

- Discussed in LEC. 10 *due to multipath effects (reflections from multiple objects) → can be flat or frequency-selective.*

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**C. CARRIER TO INTERFERENCE RATIO (C/I) IN CELL SYSTEMS**

As discussed, the major source of noise in a cellular system is often interference from other users sharing the same carrier frequency (but in adjacent cells).

- The Carrier-to-Interference ratio, C/I, of the signal at the mobile from the transmitter in a given cell, can be found in an approximate manner by summation of interference from all base stations using the same frequency, usually expressed in dB.

\[
\frac{C}{I} = \frac{R^n}{\sum_{i=1}^{M} D_i^n}
\]

- Keep in mind that RX power drops off as \( \frac{1}{d^2} \)

- If we assume all base stations are identically spaced, and are at the centres of their cells, we have the C/I approximation of:
  - \( M \) is the number of interfering base stations in the first tier (this is always \( M=6 \) for hexagonal cells with the standard reuse patterns \( K=3, 4, 7, 12, 19... \))
  - \( C \) = \( \sqrt{3k} \) \( n \) = using geometric factor divisor

\[
\frac{C}{I} = \frac{\sqrt{3k}}{M}
\]

- \( R \) = approx. distance from communicating base station to user
- \( D_i \) = approx. distance from interfering base stations

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![Hexagonal Cell Diagram with Label](source: [3])
NOTES

1. This equation assumes that interference is only significant from the first tier of adjacent cells.

2. Obviously, the exact value will depend on the mobile user's location within the communicating cell.
   - The equation assumes worst-case; the user is at the outer boundary of the cell ($d = R$).
   - Note, however, that using $d = D$ also involves a first-order approx. for the interference.

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EXAMPLE

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REFERENCES

[1] MODERN DIGITAL AND ANALOG COMM. SYSTEMS, 3RD ED., LATHI
[4] COMMUNICATIONS SYSTEM ENGINEERING, 2ND ED., PROAKIS/SALEH
1. **TIME-VARYING MULTIPATH CHANNELS**

As discussed (Lecs. 9 and 19), various effects (multipath, rain, fog) can contribute to **fading** in a wireless channel. While the time-scales can vary greatly (e.g., atmospheric effects evolve over minutes-hours), while multipath effects due to reflections from moving objects can vary on sub-second time-scales, the key point of commonality is that the channel is **time-varying**.

\[ f(t) \rightarrow F(w) \rightarrow \text{TIME-VARYING SYSTEM} \rightarrow y(t) \]

\[ y(w) = H(w) F(w) \]

- From EE 235, EE 390, a system must be linear and time-invariant (LTI) in order to be analyzed using the simple concepts of impulse response \((h(t))\) and transfer function \((H(w))\).

**Notes**

1. Recall that for an LTI system, the range of frequencies in the output signal is the same as for the input signal \((y(w) = H(w) F(w))\). The output signal contains no 'new' frequencies that were not in the input signal.

2. However, an LTI system can (if it induces linear distortion) cause signals to spread in time, i.e., pulses spread outside their time slots, leading to **INTER-SYMBOL INTERFERENCE (ISI)**.

- A **fading** (time-variant) channel in general can cause signals to spread both in time (due to multipath and other sources of distortion) and frequency (due to time-varying properties).

  This is illustrated at right for the simple case of 2 independent paths.

- A fixed pulse is spread in time and reshaped due to normal linear distortion (non-flat amplitude response and/or non-linear phase response over each individual path).

**Recall from EE 390 that an Amplitude Modulation (AM) system is a linear, time-varying system that certainly creates new frequencies.**
IF PRESENT, MULTIPATH DISTORTION CAUSES SPREADING IN TIME THAT IS TYPICALLY MUCH GREATER THAN THAT DUE TO I.

→ TWO COPIES OF THE PULSE ARRIVE AT THE RXER OVER DIFFERENT PATHS, WITH DIFFERENT ATTENUATION & DELAY, ETC.

→ FOR A MOBILE CELLULAR SYSTEM, THERE ARE TYPICALLY MULTIPLE PATHS (> 2), AND MULTIPATH DISTORTION APPEARS AS AN EFFECTIVE SPREADING IN TIME OF A SINGLE PULSE (RATHER THAN DISTINCT ARRIVAL OF MULTIPLE PULSES).

\[ \Downarrow \quad T_1 \quad \xrightarrow{\text{MULTIPATH}} \quad \Downarrow \]

As shown in the figure, each path has time-dependent response; this causes the input signal to be spread in frequency (not shown).

→ i.e., the output signal is not restricted to the exact range of frequencies as the input signal.

Clearly, signal propagation over fading channels can be quite complex. However, we can often perform a useful first-order analysis using a few simple parameters:

1. **Multipath (time) spread, \( T_m \)** - A measure of the range in delay over the multiple paths; thus, a measure of how much an input pulse is spread (in time) by multipath effects.

   → For a fixed wireless link, \( T_m \) might be fairly constant (e.g., the case where the 2 dominant paths are direct LOS and 1-skip reflection from the earth).

   → For a mobile system, the multiple paths (\( \cdot T_m \)) are varying fairly rapidly with time, so a statistical analysis is required.
2. Coherence Bandwidth, $B_c = \frac{1}{T_m}$ - a signal with bandwidth $B < B_c$ experiences flat fading, etc. (see Lec. 19)

For a mobile cellular system [2]:

$B_c \geq \frac{1}{5\sigma_t}$

6 - RMS Delay Spread [1,2]

3. Doppler Frequency Spread, $B_d$ - a measure of how rapidly the channel properties are changing with time. Consider the case of transmitting an unmodulated carrier:

$C(t) = A \cos(\omega_0 t + \theta)$

- For a fixed wireless link, Doppler frequency spread is caused by changing weather patterns and (mostly) by changes in the Earth's atmosphere (i.e., called 'Doppler' because the clouds, ionosphere, etc. are in motion relative to the antennae).

- For a mobile wireless, primary cause is the motion of the mobile antenna, with smaller contribution from motion of other objects in the velocity.

4. Coherence Time, $T_c$ - a measure of the interval over which channel characteristics change very little

$T_c = \frac{1}{B_d}$

- For a mobile cellular channel [2]:

$\frac{T_c}{\sigma_t} \geq \frac{5}{16\pi V_f}$

$V_f$ - Mobile User Velocity

$V_c$ - Carrier Frequency

Source: [2]
5. Channel spread factor, \( T_m B_d = \frac{T}{T_c} \). Generally, we need \( T_m B_d < 1 \) → underspread, \( T_m B_d > 1 \) → overspread.

Note: The spread factor includes impairments caused both by multipath delay and by Doppler effects.

**Notes**

1. Most wireless channels of interest have spread factors \( < 1 \) (fortunately).
   → For mobile cellular, the relatively large Doppler spread is offset by small multipath duration (due to the relatively small path lengths involved).

2. As discussed in lecture 18, if the signal \( B/W \) (a) exceeds the coherence \( B/W \) (roughly speaking), the signal experiences frequency-selective fading (and is).
   → Using the Nyquist criterion, we can write for a digital signal:
   \[ \frac{1}{T} \geq B \]
   \( T \) = symbol interval
   \( B \) = signal \( B/W \).
   → If \( B >> B_c \):
   \( T << T_o \) → equalization required at \( \text{Rx/Er} \)
   \( B << B_c \):
   \( T >> T_o \) → no equalization required (flat fading).

3. The Doppler spread imposes a limit on bit rate that can be received reliably and is very dependent on the mobile velocity in a cell system (the # in the table above is a representative average).
   → For example [3, p 460], a target for third generation (3G) cell systems is that they will support data rates of \( \sim 64 \) [kbits/s] for high-speed vehicles, \( \sim 384 \) [kbits/s] for users moving at pedestrian speeds, and \( \sim 2 \) [Mbps] for stationary users.

**References**

1. Methods of Sharing Spectrum in Cellular Systems

As shown at left, approximately 50-200 MHz has been allocated to cell systems by regulators. In each the original (800-900 MHz) BAND and the newer "personal communication services" (PCS) BAND

→ Typically, a given cell uses only a portion of this total allocation (to avoid interference with neighboring cells), and this portion must be shared between many users.

* The way that users share the available B/W is termed the 'multiple access' method
* The way that mobile-to-base station (uplink) and base-station-to-mobile (downlink) traffic shares the available B/W is termed the 'duplexing' method

---

- **Multi-access (MA) method**
  - the manner in which radio resources are allocated into voice channels
    - FDMA (frequency division) - each voice channel is assigned a separate frequency
    - TDMA (time division) - each voice channel is assigned segments of time (slots). Mobiles are commonly assigned in a round-robin fashion.
    - CDMA (code division) - each voice channel is assigned a specific code. At the receiver, the voice channels can be separated with minimal interference.

- **Duplexing method**
  - FDD (frequency division duplex) - voice channels for the downlink and uplink are separate in frequency (common - IS TYPICAL
  - TDD (time division duplex) - the downlink and uplink transmission alternate in time over the same channel

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Source: [5]
3. The original analog cellular service (AMPS) used FDMA, but newer digital systems typically employ combined methods, as shown at right.

4. The net required A/W per voice channel is a measure of spectral efficiency. \[ \text{Note the progression from AMPS (\( \approx 30 \text{ kHz} \) per voice channel) to GSM (\( \approx 2.5 \text{ kHz} \)) to CDMA (The IS-95 systems, \( \approx 20 \text{ kHz} \) per voice.) \]

- Both the compress low algorithm and the way the system deals with co-channel interference and other impairments impact the spectral efficiency.

### Table 8.13 Characteristics of Various Cellular Radio Standards

<table>
<thead>
<tr>
<th>Feature</th>
<th>AMPS</th>
<th>GSM</th>
<th>CDMA (IS-95)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier separation</td>
<td>30 kHz</td>
<td>200 kHz</td>
<td>1.25 MHz</td>
</tr>
<tr>
<td>No. channels/cell</td>
<td>1</td>
<td>8</td>
<td>61</td>
</tr>
<tr>
<td>Accessing technique</td>
<td>FDMA</td>
<td>TDMA-FDMA</td>
<td>CDMA-FDMA</td>
</tr>
<tr>
<td>Frame duration</td>
<td>NA</td>
<td>4.6 ms with 0.58 ms slots</td>
<td>20 ms</td>
</tr>
<tr>
<td>User modulation</td>
<td>FM</td>
<td>GMSK, 87 = 0.3</td>
<td>BPSK, 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Binary, diff. encoded</td>
<td>64-ary orthog. RCL</td>
</tr>
<tr>
<td>DUAL pairing</td>
<td>2 channels</td>
<td>2 slots</td>
<td>2 codes</td>
</tr>
<tr>
<td>Cell reuse pattern</td>
<td>7</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>Cochannel interfer. protect.</td>
<td>( \leq 15 \text{ dB} )</td>
<td>( \leq 12 \text{ dB} )</td>
<td>NA</td>
</tr>
<tr>
<td>Error correction coding</td>
<td>NA</td>
<td>Rate 1/2 convolutional</td>
<td>Rate 1/2 convol., FL</td>
</tr>
<tr>
<td>Diversity methods (TDMA-FDMA)</td>
<td>NA</td>
<td>Constraint length 5</td>
<td>Rate 1/2 convol., RL</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Both constr. length 9</td>
</tr>
<tr>
<td>Speech representation</td>
<td>Analog</td>
<td>Residual pulse excited, equalization</td>
<td>Wideband signal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linear prediction coder</td>
<td>Interleaving</td>
</tr>
<tr>
<td>Speech coder rate</td>
<td>NA</td>
<td>13 kbps</td>
<td>9.6 kbps max</td>
</tr>
</tbody>
</table>
Systems: AMPS

- Advanced mobile phone system (First generation system)
  - Still used in Alberta (the only service in rural areas) and across North America
  - analog system (FM) developed in 1977, introduced in 1983
- FDMA system as 'pairs' of frequencies assigned. Each pair of frequencies is dedicated to a call in each cell.
- Downlink (MHz)
  - Block A: non-wireline companies (Cantel etc.)
  - Block B: wireline (Telus)
  - FDD: uplink frequencies are the same, but 45 MHz less for the same channel (i.e. uplink 829-874 MHz range)
- Since 1988, bandwidth increased from 666, to 832 channels.
  - 30 kHz channels
  - Channel 1: downlink=870.03 MHz, uplink =825.03 MHz
  - 416 channels/system (or per block)
  - 21 control channels / 395 voice channels per system

- C/I=18 dB generally found to be acceptable for voice quality
  - generally has a frequency reuse pattern ($k_0 = 7$)

Source: [2]

- TYPICAL CELLS HAVE RADIUS OF $5-18 \text{ km}$ (LJ, p. 130)
- CELLS Aren't REALLY HEXAGONAL IN PRACTICE. THEY HAVE SOMEWHAT IRREGULAR SHAPES, DETERMINED BY GEOGRAPHY AND ANTENNA PLACEMENT AND POPULATION DENSITY ...

Notes

1. REGULATORS GENERALLY AVOID TO STIMULATE COMPETITION, BY DIVIDING THE TOTAL ASSIGNED SPECTRUM BETWEEN TRADITIONAL TELCOs AND NEW SERVICE PROVIDERS

2. EACH OF THE UPLINK/DOWNLINK BANDS (AS DESCRIBED HERE) CONSTITUTE 25 MHz) ASSIGNED B/W.

3. TOTAL B/W = $\frac{25 \text{ MHz}}{32 \text{ MHz}} = 832$ CHANNELS

4. IF THIS IS DEVELOPED BETWEEN 2 COMPETITORS, EACH HAS 416 CHANNELS TO WORK WITH (395 VOICE CHANNELS)

5. 3 MHz ADJOINT SIGNALS TRANSMITTED VIA FM, USING A 30 MPH CHANNEL B/W

   THIS EXTRA B/W (10X) ALLOWS LOWER TX POWER (RECALL TRADEOFF BETWEEN B/W <-> SWR FROM EE 330)
6. Power of base stations must be carefully controlled to avoid interference with neighboring cells: typically (110, 0 dB). Therefore:

- Base station transmit < 35 [W] analog
- Cell phone transmit < 3 [W]

These powers can be significantly reduced (i.e., extending cell phone battery life) in the digital case.

3. Digital AMPS (D-AMPS)

D-AMPS is also known as North American Digital Cellular (NADC) and US Digital Cellular (USDC).

- A digital upgrade to AMPS, designed for compatibility (they can coexist: a dual-mode phone can place analog or digital calls, depending on its location).
- D-AMPS standards are controlled by EIA/TIA and are under interim standards IS-54 and IS-126.

**Systems: Digital AMPS**

- Digital system in AMPS bands (Advanced digital cellular (ADC), IS-54) (2nd generation).
- The first digital to arrive here ("WOW, digital cell phones...")
- Digital (π/4-DQPSK modulation, 41.15 μs symbol duration)
- Intended to be backwards compatible with AMPS
- FDD and same frequency band as AMPS and
  - 30 kHz channels, 832 frequency channels in 800 MHz band
- In this manner, the MSC and many components of the BS are the same.
  
- **TDMA method** - each frequency channel is divided into 3 time channels.
  
  - total channels = 832 x 3
  - total voice channels per system = 395 x 3
  - so 3 times the number of channels as AMPS in the same bandwidth

  **Source:** [2]

3. D-AMPS allows much more sophisticated channel monitoring, TX power control, handoff, etc., compared to analog AMPS.

**NOTES**

1. A 4-bit digital scheme is used (2 bits per symbol)
   - In each 30 kHz channel, an effective bit rate of 19.6 kbps is carried (i.e., 29.7 x 10^3 [symbols/sec])

2. The 48.6 kbps channel accommodated three compressed voice channels (excluding error control overhead) at ~13 [kbits/ sec], plus
   - 29.6 [kbits/sec] for signaling and control.
4. **Note:** The multiple access scheme is combined FOMA/FOMA, each call is assigned a carrier frequency and one of three time-slots on that carrier frequency.

4. **Global System for Mobile Communications (GSM)**
   - Many analog standards were being used in Europe, so GSM was designed without any consideration for backward compatibility (a 'slow start')
   - This gave GSM a technological advantage over D-AMPS.
   - In general, base station cost was lower and cell phone battery life longer.

**Systems: GSM (European Specs.)**

- Originally, Groupe Special mobile, until 1992. Then Global System for Mobile Communications. (2nd generation)
- European digital standard, later brought to Canada by Microcell (Montreal) and later, Rogers.
- In Europe, usually used in 800/900 MHz band (in PCS as well)

- TDMA system, that 'hops' from one frequency channel to the next to avoid being in a frequency-selective fade for a long period of time (slow frequency hopping [SFN], ~217 hops/sec)
  - Sometimes termed 'FHRQ, hopping spread spectrum'
- Digital (GMSK, ~3.69 μs symbol duration)
- 8 time channels (slots) per frequency channel
  - Total channels = 125 x 8
  - 200 kHz bandwidth
    - frequency equalization is usually required
- FDD system
- C/I=9 to 12 dB is acceptable. Frequency reuse patterns of K>=3 are generally required (K=4, 7, or 12 used) [11, 33]

- **Maximum cell radius in GSM is**
  - Approx 35 km [17, p. 767]
- Each voice signal is compressed to ~22.8 [kbps] (including error control)

**NOTES**

1. Each 200 [kHz] frequency channel carries an effective bit rate of 270.833 [kb/s] (≈ 33 [kb/s] per voice channel)

2. 1000 channels total
   - 50 [MHz], 25 for uplink, 25 for downlink
   - Of total assigned spectrum to be shared amongst competitors using the GSM standard

3. The spectral efficiency is 25 [kHz] per voice channel; not nearly as good as D-AMPS (10 kHz)
Figure 10.42 TDMA frame in GSM.

Each frame (for a given voice conversation) is sent on a different carrier frequency.

→ A form of frequency diversity (frequency hopping) to combat fading and interference.

→ The frequency hopping rate is \( \frac{4615500}{217} \approx 217 \text{ Hz/sec} \).

→ The cell phone and base station exchange an algorithm, so that they hop in unison.

<table>
<thead>
<tr>
<th>Table 10.5: Summary of Parameters in GSM System</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Parameter</td>
</tr>
<tr>
<td>Uplink frequency band</td>
</tr>
<tr>
<td>Downlink frequency band</td>
</tr>
<tr>
<td>Number of carriers/brand</td>
</tr>
<tr>
<td>Bandwidth/carrier</td>
</tr>
<tr>
<td>Multiple-access method</td>
</tr>
<tr>
<td>Number of users/cell</td>
</tr>
<tr>
<td>Data rate/carrier</td>
</tr>
<tr>
<td>Speech coding rate</td>
</tr>
<tr>
<td>Speech encoder</td>
</tr>
<tr>
<td>Coded-speech rate</td>
</tr>
<tr>
<td>Modulation</td>
</tr>
<tr>
<td>Demodulation</td>
</tr>
<tr>
<td>Interleaver</td>
</tr>
<tr>
<td>Frequency-hopping rate</td>
</tr>
</tbody>
</table>

5. Each frame (for a given voice conversation) is sent on a different carrier frequency.

6. 26 known bits are sent in each timeslot (with each voice sample).

→ This allows the channel characteristics to be determined.

→ A matched filter/equalizer is adjusted for optimal detection of a given timeslot of data.

References:


TABLE 10.3  SUMMARY OF PARAMETERS IN IS-95 SYSTEM

<table>
<thead>
<tr>
<th>System Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplink frequency band</td>
<td>824-849 MHz</td>
</tr>
<tr>
<td>Downlink frequency band</td>
<td>894-914 MHz</td>
</tr>
<tr>
<td>Number of carriers/band</td>
<td>20</td>
</tr>
<tr>
<td>Bandwidth/carrier</td>
<td>1.25 MHz</td>
</tr>
<tr>
<td>Multiple-access method</td>
<td>CDMA</td>
</tr>
<tr>
<td>Number of users/can</td>
<td>60</td>
</tr>
<tr>
<td>Chip rate</td>
<td>1.2288 MHz</td>
</tr>
<tr>
<td>Speech coder</td>
<td>Variable rate CELP</td>
</tr>
<tr>
<td>Speech rate</td>
<td>9600, 4800, 2400, 1200 bps</td>
</tr>
<tr>
<td>Interleaver</td>
<td>Block</td>
</tr>
<tr>
<td>Channel encoder</td>
<td>$R = \frac{1}{2}, L = 96(D)$</td>
</tr>
<tr>
<td>$R = \frac{1}{3}, L = 96(U)$</td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK with QPSK Spreading (D)</td>
</tr>
<tr>
<td></td>
<td>64-ary Orthogonal with QPSK</td>
</tr>
<tr>
<td></td>
<td>Spreading (U)</td>
</tr>
<tr>
<td>Demodulation</td>
<td>RAKE-aided filter with</td>
</tr>
<tr>
<td></td>
<td>maximal ratio combining</td>
</tr>
<tr>
<td>Signature sequences</td>
<td>Hadamard (Walsh) of length 64</td>
</tr>
<tr>
<td>PN sequence</td>
<td>$N = 2^m - 1$ (Long code)</td>
</tr>
<tr>
<td></td>
<td>$N = 2^3$ (Spreading codes)</td>
</tr>
</tbody>
</table>

SOURCE: [3]

**Systems: CDMA (IS-95)**

- A 2-2.5 generation standard (there is also an IS-95b standard).
- A mobile is assigned a channel code,
  - Transmissions occur at the same time and over the same frequency band
- bandwidth of channel is 1.25 MHz in PCS band (~1850-2000 MHz)
- FDD system
- uses fast power control on uplink
  - helps to prevent deep 'fades' (troughs) in received power

SOURCE: [5]

- **FREQUENCY BANDS**
  - IN THE 1.9 [GHz] RANGE HAVE ALSO BEEN ASSIGNED (PCS BAND)

- IN THEORY THE ENTIRE FREQUENCY BAND CAN BE SHARED BY ALL USERS.
  - FREQUENCY RE-USE FACTOR $N = 1$

- A BAND CAN ACCOMODATE $\approx$ 1200 VOICE CHANNELS, TO BE SHARED AMONGST SERVICE PROVIDERS
  - TOTAL BAND $\approx 25$ [MHz]
  - $\frac{25}{1.25}$ [MHz] = 20 CARRIERS
  - 20 SIMULTANEOUS CALLS PER CARRIER

(20×60 = 1200)
SPREAD SPECTRUM TECHNIQUES

Es - 95 uses DIRECT - SEQUENCE SPREAD - SPECTRUM (DSSS), which is characterized by:

- a modulated signal that has B/W much greater than that of the baseband modulating signal
- use of a code, shared by transmitter and receiver. Spectral spreading (modulation) and de-spreading (demodulation) is achieved by a code multiplication process.

The code is a periodically repeating sequence of 1's and 0's, at a much higher rate than the baseband modulating signal.

Thus, \( y(t) \cdot c(t) m(t) \) is spread over a much wider frequency band than \( m(t) \).

**Source:** [1]

\[ N = \frac{B_{ss}}{B} \]

Essential B/W of \( y(t) \)

Essential B/W of \( m(t) \)

**Notes**

1. By assigning unique codes to each user signal, multiple users can share the same band. The user signals are made orthogonal through choice of appropriate codes.

2. The codes are not truly random, but are so-called pseudo-noise (PN) codes (because they are an attempt to mimic the random nature of noise).

3. The codes are not truly mutually orthogonal, but are designed to have the lowest possible correlation with each other.

4. N is called processing gain because de-spreading a desired signal increases its power by \( 2^N \) times (effectively), relative to the residual noise level (which is mostly due to other users sharing the band).

**Source:** [1]

Figure 5.2 Signals at the spread spectrum generator.

Figure 5.3 A direct sequence spread spectrum system.
5. Assume a square-wave baseband digital signal and code (and that each is a random sequence of 1's and 0's). The PSD's have the usual sinc² shape.

$$N = \frac{R_c}{R_b} = \frac{T_b}{T_c}$$

where

$$R_c \text{ (Tc)} = \text{'chip' rate (interval)}$$

$$R_b \text{ (Tb)} = \text{'bit' rate (interval)}$$

6. While y(t) is shown as a baseband signal, it is generally used to modulate a carrier (typically using DSB-SC modulation of I and Q (orthogonal) carriers). The modulator (at TxER) and demodulator (at RxER) are not shown in the block diagram on p. 1

CDMA cellular using DS/SS

DS/SS offers the following advantages for cellular telephony applications:

- Possibility for increased spectral efficiency - since users are distinguished by a unique code, the frequency reuse factor can be k = 1 for CDMA - cell systems.

- This increases the overall spectral efficiency of a CDMA system by 4x relative to TDMA/FDMA.

- More service providers can share a given band.

- Security - the DS/SS signal can be detected only by knowing the PN code.

- Further, it is difficult to even detect the presence of a DS/SS signal, since its PSD is very small and spread over a wide band (i.e., 'buried' in the noise).

---

TABLE 9.4 1G-95 CDMA Mobile Telephone System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel bandwidth</td>
<td>1.25 MHz</td>
</tr>
<tr>
<td>Voice Coding Rate</td>
<td>9.6 kbps (maximum)</td>
</tr>
<tr>
<td>Error control overhead</td>
<td>19.2 kbps (downlink)</td>
</tr>
<tr>
<td>Aggregate channel rate</td>
<td>19.2 kbps (uplink)</td>
</tr>
<tr>
<td>Code length</td>
<td>64 chips</td>
</tr>
<tr>
<td>Spread spectrum channel rate</td>
<td>1.2288 MHz</td>
</tr>
<tr>
<td>Modulation format</td>
<td>QPSK (base to mobile), offset QPSK (mobile to base)</td>
</tr>
</tbody>
</table>

Source: [1]

Source: [2]
RESISTANCE TO NARROWBAND NOISE (INTERFERENCE) JAMMING MULTIPATH EFFECTS — ANY NARROWBAND IMPAIRMENT ON THE CHANNEL WILL HAVE A RELATIVELY SMALL IMPACT ON THE DS/SS SIGNAL, AS ITS POWER IS SPREAD OVER A WIDE BAND.

NO HARD LIMIT ON # OF USERS — UNLIKE FDMA/TDMA SYSTEMS, MORE USERS CAN BE ACCOMMODATED SIMPLY BY ADDING MORE CODES.

A SOFT LIMITING PROCESS HOLDS; AS THE # OF USERS INCREASES, THE SIGNAL QUALITY OF ALL USERS IS DEGRADED (IN A 'GRADUAL' WAY).

NOTES

1. ONE CHALLENGE IN CDMA SYSTEMS IS THE SO-CALLED NEAR-FAR PROBLEM: SIGNALS FROM VARIOUS MOBILE USERS ARE NOT NECESSARILY RXED AT THE BASE STATION IN EQUAL POWER (DUE TO VARYING DISTANCES).

   IF AN UNWANTED SIGNAL IS STRONG DUE TO ITS CLOSERNESS TO THE BASE STATION, NO THE DESIRED SIGNAL WEAK DUE TO ITS REMOTENESS, THE UNWANTED SIGNAL CAN CAUSE GREAT DEGRADATION TO THE DESIRED SIGNAL.

   Thus, ADAPTIVE POWER CONTROL of the MOBILE TXERS is TYPICALLY REQUIRED. THE IS-95 BASE STATIONS SEND OUT a CONTROL SIGNAL to EACH MOBILE EVERY 1.25 MS, INDICATING HOW ITS TX POWER SHOULD BE ADJUSTED.

SOURCE: [3]
2. The reverse link presents a greater challenge in CDMA communications, partly due to the near-far problem, and partly because the transmissions from multiple users are not synchronous.

- This lack of synchronism on the uplink makes it harder to achieve orthogonality of signals.
- The SNR is lower on the uplink, due to greater co-channel interference.

To combat this, IS-95 uses a more sophisticated error-correction scheme (requiring more overhead bits; see Table on p 3) on the uplink.

3. IS-95 employs the QCELP algorithm to encode and compress digitized voice signals.

- A variable data rate of 2.4 - 9.6 [kb/s] is used, reflecting the fact that higher compression is possible during gaps and pauses in speech.
- Also, IS-95 reduces interference between channels by having each TXER reduce its power by >20 dB during gaps and pauses [17].

4. CDMA is not only resistant to multipath, it can actually exploit it.

- A DS/SS signal has a low correlation with a delay-co version of itself, so by adjusting delays in the RXER, each multipath component can be isolated from the others.
- A RAKE RXER is designed to coherently combine the signals RXED over several (typically 4 or more) paths; this increases the SNR at the RXER.
A \textbf{Performance of a DS/SS System}

A DS/SS system effectively spreads unwanted signals over a wide band, so that the in-band noise (interference) level at the receiver is reduced.

It can be shown (in the case that the noise is due to interference from other users) that the SNR at the receiver (detector) is given by [133, p. 738]:

\[
(SNR)_0 = \frac{2P_s}{(P_i/N)}
\]

- $P_s$ - Average power of desired signal
- $P_i$ - Average power (total) of interfering signals
- $N$ - Processing gain

We can increase the SNR at the receiver by increasing the processing gain (up to practical limits set by other sources of noise).
For a coma system assuming all users signals have equal average power at the receiver (not a bad assumption with adaptive power control), we can estimate:

\[
\frac{P_i}{P_e} = \frac{P_s}{(m-1)P_s} = \frac{1}{m-1}
\]

(A) \[ m \text{ - # of simultaneous users} \]

\[ \text{Signal to interference ratio is inversely proportional to # of simultaneous users sharing the same freq. band} \]

**Notes**

1. This equation assumes perfect orthogonality between all user signals (so that they are power-additive, see EE390).

   \[ \rightarrow \text{In fact, real systems do not achieve this, so that the ratio } \left( \frac{P_i}{P_e} \right) \text{ given by this equation is optimistic (best-case)} \]

2. While IS-95 allows for up to 61 simultaneous users in a single 1.25 MHz band, it is not typically possible to realize this (with acceptable GoS) in practice.
Note that the result (a) is $\approx$ independent of signal power (assuming equal powers received from all users). In practice, the powers are chosen to be just high enough such that other noise sources (such as thermal noise generated in axers) are negligible relative to the noise from interfering users.

This is a best-case scenario, since $\frac{p_i}{P_e}$ is fixed and represents the hard limit on SNR.

The $axer$.

References
1. **EMERGING WIRELESS TELEPHONE STANDARDS: 3G AND BEYOND**

Formally, most 3G standards are maintained by the International Telecommunications Union (ITU) under the International Mobile Telecommunications 2000 (IMT-2000) banner.

- **3G systems have some defining characteristics:**
  - Will support multimedia (voice, data, video)
  - Will support high bit rates (typically \( \geq 2 \text{ Mbps} \))

2. **SOME SECONDARY GOALS FOR 3G SYSTEMS INCLUDE:**
   - Global roaming (take your cell phone anywhere, and it works)
   - Both terrestrial and satellite wireless channels supported
   - Support for Global Positioning System (GPS)
   - Improved GOS, longer battery life

3. **TWO MAIN COMPETING APPROACHES, BOTH CDMA-BASED:**
   - **CDMA 2000** — Evolution of the IS-95 standard and backwards compatible with IS-95
   - **Wideband CDMA (WCDMA)** — Also known as Universal Mobile Telecommunication System (UMTS)

4. **NOTES**
   - The main goals for 3G systems, as specified under the umbrella standard IMT-2000:
     - Worldwide coverage / Common standards
ENCOMPASSES ALL MOBILE COMM. (CELL, SATELLITE ETC.)  
SUPPORTS BOTH PACKET SWITCHED (INTERNET) AND 
CIRCUIT SWITCHED DATA  
HIGH DATA RATES UP TO 2 [MBIT/S], DEPENDENT 
on MOBILITY/VELOCITY OF USER  
OFFER HIGH SPECTRAL EFFICIENCY (SUPPORT 
MANY SIMULTANEOUS USERS)

2. DECT (DIGITAL ENHANCED 
CORDLESS TELEPHONE) IS 
FOR INDOOR OFFICE 
ENVIRONMENTS

3. FORWARD LINK (F) = DOWNLINK 
REVERSE LINK (R) = UPLINK

4. IN GENERAL HIGHER DATA 
RATES REQUIRE ONE OR 
MORE OF:

- HIGHER TX POWERS
- SMALLER CELL 
SIZE
- LOWER MOBILE 
USER VELOCITY

Table 7.2 Comparison of Physical Layer Characteristics of Various Telephone Network Standards.

<table>
<thead>
<tr>
<th></th>
<th>DECT</th>
<th>GSM</th>
<th>IS-95</th>
<th>WCDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>1880-1900 MHz</td>
<td>933-960 MHz (F)</td>
<td>869-894 MHz (F)</td>
<td>1920-1980 MHz (F)</td>
</tr>
<tr>
<td></td>
<td>890-915 MHz (R)</td>
<td>824-849 MHz (R)</td>
<td></td>
<td>2110-2171 MHz (R)</td>
</tr>
<tr>
<td>Channel BW</td>
<td>1.228 MHz</td>
<td>200 kHz</td>
<td>1.25 MHz</td>
<td>5 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>GMSK</td>
<td>GMSK</td>
<td>BPSK</td>
<td>QPSK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data rates</td>
<td>1.152 Mbps</td>
<td>270.8 kbps</td>
<td>1200, 2400, 4800, 9600 bps</td>
<td>up to 2 Mbps</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell size</td>
<td>&lt;300 m</td>
<td>&lt;35 km</td>
<td>&lt;35 km</td>
<td>&lt;35 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward error-correction coding</td>
<td>none</td>
<td>variable incl. rate-1/2 convol.</td>
<td>variable incl. rate-1/2, -1/3 convol.</td>
<td>Variable incl. rate-1/2, -1/3 convol.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame size</td>
<td>10 ms</td>
<td>4.61 ms</td>
<td>20 ms</td>
<td>10 ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voice encoding</td>
<td>ADPCM at 32 kHz</td>
<td>RELP at 13 kbps</td>
<td>CELP at 9.6 kbps and 14.4 kbps</td>
<td>Adaptive multirate ACELP 4.75 to 122 kbps</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic channels</td>
<td>12</td>
<td>8</td>
<td>up to 63 in theory</td>
<td>Depends upon data rate</td>
</tr>
<tr>
<td>RF channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diversity</td>
<td>Antenna diversity at BS</td>
<td>Frequency hopped</td>
<td>Spread spectrum with RAKE receiver</td>
<td>Space-time block coding with transmit diversity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: [27]

Figure 14.13 A vision of 3G networks

Source: [3]

5. THIRD GENERATION NETWORKS WILL BE
HIERARCHICAL, WITH SMALLER CELL SIZES SERVING DENSELY POPULATED AREAS

- DATA RATES THAT A USER CAN ACCESS WILL ALWAYS DEPEND ON LOCATION, MOBILE VELOCITY, AND NETWORK USAGE

- SMALLER CELLS GIVE FEWER USERS PER CELL, MORE BANDWIDTH PER USER (HIGHER BIT RATES)
DATA COMMUNICATION OVER WIRELESS CELLULAR NETWORKS

1. All of the digital cellular networks can support transfer of digitized voice or data (mobile email, web browsing, etc.), at least in theory. The main limitation is that cellular voice networks are designed to have as low as possible per-channel bit rates (typically < 14.4 kbps).

To support higher rates of data transfer, standards have been modified to allow a single user to simultaneously use several 'voice' channels.

2. Wireless local area networks (WLANs) are becoming increasingly popular in office environments and even in residential areas (ad hoc wireless networks).

The term 'Wi-Fi' (wireless fidelity) is sometimes applied to this sector.

### Table 7.3: Comparison of Physical Layer Characteristics of Various Data Network Standards

<table>
<thead>
<tr>
<th></th>
<th>GPRS</th>
<th>WCDMA</th>
<th>IEEE 802.11b</th>
<th>Bluetooth</th>
<th>IEEE 802.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>935–960 MHz (F)</td>
<td>1920–1980 MHz (F)</td>
<td>2.4 GHz</td>
<td>2.4–2.4835 GHz</td>
<td>5.2 GHz</td>
</tr>
<tr>
<td>Channel BW</td>
<td>200 kHz</td>
<td>5 MHz</td>
<td>50 MHz</td>
<td>80 MHz</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>GMSK</td>
<td>CDMA</td>
<td>BFSK/QPSK/FH or DS</td>
<td>GMSK/FH</td>
<td>BFSK, 64-QAM, OFDM</td>
</tr>
<tr>
<td>Data rates</td>
<td>up to 116 kbps</td>
<td>up to 2 Mbps</td>
<td>up to 11 Mbps</td>
<td>&lt;1 Mbps</td>
<td>up to 54 Mbps</td>
</tr>
<tr>
<td>Access strategy</td>
<td>FDMA/TDMA</td>
<td>FDMA/CDMA</td>
<td>CDMA/CA</td>
<td>FH/TDD</td>
<td>FDMA/CSMA, High</td>
</tr>
<tr>
<td>Cell size</td>
<td>up to 35 km</td>
<td>up to 35 km</td>
<td>1–20 m</td>
<td>1–10 m</td>
<td>1–1000 km</td>
</tr>
<tr>
<td>Forward error-correction coding</td>
<td>variable incl. rate 1/2 convol.</td>
<td>variable incl. rate 1/2, 1/3 convol.</td>
<td>Variable repetition, Humming, ARQ</td>
<td>rate 1/2, 2/3, 3/4 convol.</td>
<td></td>
</tr>
<tr>
<td>Frame size</td>
<td>4.61 μs</td>
<td>10 ms</td>
<td>up to 20 ms</td>
<td>n × 62.5 μs</td>
<td>24 μs to 5 ms</td>
</tr>
<tr>
<td>Diversity</td>
<td>Frequency-hopped</td>
<td>Space–time block coding with Tx diversity</td>
<td>Dual antenna</td>
<td>none</td>
<td>Dual antenna</td>
</tr>
<tr>
<td>Network topology</td>
<td>point-to-multipoint/cellular</td>
<td>point to multipoint/cellular</td>
<td>point to multipoint</td>
<td>point-to-point connection and connectless</td>
<td>point to multipoint</td>
</tr>
</tbody>
</table>

Numerous standards (including some not shown in the table) have been developed.

→ Eventually, the goal is for seamless integration into 1 (or a few) standards that can support variable cell sizes and bit rates.

Source: [4]
A BRIEF SUMMARY OF SOME OF THE MAIN STANDARDS FOLLOWS:

A. GENERAL PACKET RADIO SERVICES (GPRS)
   - OFTEN TERMED A '2.5 G' TECHNOLOGY, ENABLES USERS TO MAKE VOICE CALLS AND TRANSMIT DATA AT THE SAME TIME.
   - IT IS ESSENTIALLY A PACKET-SWITCHED SERVICE OVERLAYED ON A TRADITIONAL CIRCUIT-SWITCHED ARCHITECTURE.
     - ie. SOME (#(N_0)) OF THE VOICE CHANNELS ARE SET ASIDE AS BANDWIDTH DEDICATED TO PACKETIZED DATA.
     - MOSTLY TARGETED TO GSM NETWORKS; A SINGLE CARRIER (8 TIME SLOTS) CAN ACCOMMODATE UP TO 115 [kbit/s], BUT WOULD BE SHARED AMONGST USERS.
   - D-AMPS CAN ALSO SUPPORT A GPRS OVERLAY.
   - AN ENHANCED VERSION OF GPRS, CALLED 'ENHANCED DATA RATE SERVICE FOR GLOBAL EVOLUTION' (EDGE), CAN SUPPORT DATA RATES UP TO 384 [kbit/s].

B. WCDMA
   - AS DISCUSSED ABOVE, INTENDED TO PROVIDE CONVERGENCE OF VOICE/DATA SERVICES WITHIN TRADITIONAL CELLS.

C. IEEE 802.11b (WIRELESS ETHERNET)
   - THE STANDARD TYPICALLY SYNONYMOUS WITH 'WIFI'.
   - OPERATES IN THE UNLICENSED 2.4 GHz BAND, ALLOWING USERS TO SELF-CONFIGURE NETWORKS WITHIN COMMUNITIES, AIRPORTS, HOTELS, COFFEE SHOPS, ETC.
     - 'AO-HOC' NETWORKS
     - WIRELESS 'LILY PAD'
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- The 802.11 b standard specifies
  i) Max transmit power, < 100 mW
  ii) Spread spectrum with > 10 dB processing gain, to reduce interference
      → Direct sequence or freq. hopping SS can be used.

![Diagram of data processing for IEEE 802.11b (DS).](image)

**Source**: [4]

D. **IEEE 802.11a**

- A somewhat more "future-oriented" [4] approach to wireless Ethernet
  → Use of more sophisticated line code/modulation format to combat severe fading in typical indoor environments
  → Orthogonal freq. div. mux (OFDM) uses 52 sub-carriers, each with 3.125 kHz sideband bandwidth (total bandwidth 220 MHz)
  → Each sub-carrier is subject to flat fading.

- Transmit power is limited to < 200 mW
  → Can typically accommodate < 100 m at 6 [mbit/s] and < 13 [m] at 54 [mbit/s]
  (Source: [4])
E. Bluetooth (IEEE 802.15.1)

- Intended as a wireless replacement for short-range cables linking consumer products
  - Computer to printer, etc.

- Max. transmit power is typically < 10 mW.

- In homes, microwave source of interference is the same band.
  - Freq. hopping employed to spread spectrum is combat this.

- Up to 8 Bluetooth devices can self-configure into a network of 1 'master' and 7 'slaves', called a 'piconet'.
  - Ex. VCR, TV, computer, printer, fax...

References

1. **Point-to-Point Fiber Links**

While more complex optical networks are envisioned for the future, nearly all current fiber installations can essentially be analyzed as point-to-point one-direction links.

The design of a fiber link involves inter-related variables due to choice of source, fiber, photodetector, and other factors. Ex. the impact of dispersion depends on the type of fiber used and on the choice of source...

An iterative design approach is usually required; the goal (as always) is to meet GOS objectives (bit rate, BER, ...) at minimum cost of installation/maintenance and with max. reliability.

- **Basic Requirements** that must be considered as inputs are (for a digital link, which is usual):
  - The transmission distance (link length)
  - The data (bit) rate
  - The bit-error rate (GOS)

**Notes**

1. Initially, we will consider the case of a single carrier (single λ), modulated by a digital information signal.

   → To first order, each λ channel in a WDM system can be treated independently of the others, using the techniques for the point-to-point link.

2. In-line optical amplifiers and/or dispersion compensators can extend max. link length.

   → Link design is more complicated in this case, and will be considered later.
A BASIC POINT-TO-POINT LINK, WITHOUT OPTICAL AMPLIFIERS OR DISPERSION COMPENSATORS, THE ENGINEER HAS ESSENTIALLY THE FOLLOWING CHOICES TO MAKE:

A. TYPE OF FIBER
   - MULTIMODE (MMF) VERSUS SINGLE-MODE (SMF)
   - STANDARD OR 'SPECIALTY'
   - THE CHOICE OF FIBER IMPACTS:
     - CHOICE OF SOURCE
     - DISPERSION
     - AVAILABLE DATA B/W
     - ATTENUATION
     - MAX LINK LENGTH
     - POWER COUPLING EFFICIENCY (THE % OF SOURCE POWER THAT CAN BE LAUNCHED INTO THE FIBER CORE AT THE TXER)
     - MAINTENANCE COSTS/INSTALLATION COSTS

B. TYPE OF SOURCE TXER
   - SEMICONDUCTOR LED VERSUS SEMICONDUCTOR LASER
   - THE CHOICE IMPACTS:
     - THE AMOUNT OF FUSEL SPREADING (ISE), THROUGH THE FIBER DISPERSION
     - POWER COUPLING EFFICIENCY
     - ATTENUATION (WHICH IS SOMewhat A-DEPENDENT FOR ANY FIBER)
     - THE METHOD OF MODULATION AND/OR THE MAX MODULATION RATE
     - COST

C. TYPE OF PHOTODETECTOR RXER
   - PIN PHOTODIODE VERSUS AVALANCHE PHOTODIODE
   - THE CHOICE IMPACTS:
     - THE RXER SENSITIVITY, MAX LINK LENGTH
     - THE MAX BIT RATE (AS A GIVEN RXER HAS A GIVEN BANDWIDTH)
     - COST
Typically, two analyses are used to assess whether a given combination (of source, fiber, photodetector) can satisfy a given performance spec:

1. **Link Power Budget** — Essentially adding up all sources of loss to determine if the received power exceeds the receiver sensitivity (for a specified BER).

2. **Rise-Time Budget** — Essentially adding up all sources of pulse spreading to determine if the system can accommodate the desired bit rate.

→ Main causes of pulse spreading are amplitude/phase distortion inside the TXER and RXER, and phase distortion (dispersion) imparted by the fiber.

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**The Building Blocks for Fiber Link Design**

- Silica fiber places a limitator on the range of wavelengths over which fiber communication is practical.
- Accordingly sources, amplifiers, and detectors have been developed for these bands:
  - **Sources** — LEDs/lasers based on GaAlAs (800 nm band) or InGaAsP (1300 and 1550 nm bands).
  - **Amplifiers** — Either semiconductors or fiber based. Only the erbium-doped fiber amplifier (EDFA), which provides gain in the 1550 nm band, has been deployed commercially.
  - **Photodetectors** — Different semiconductors used, depending on λ.
Two types of photodetectors (mainly) are used in commercial systems:

- PIN detectors are essentially reverse-biased P-N junctions (diodes)
- Avalanche photodetectors (APDs) have internal gain and are more sensitive (but have drawbacks).

Source: [1]

3) Link Power Budget

This analysis is intended to ensure adequate power at the receiver over the operating lifetime of a link.

A somewhat deceptively simple calculation (the complexity is "hidden" in the calculations of receiver sensitivity, source coupling efficiency, etc.):

\[ P_{TR} (\text{dBm}) = P_A (\text{dBm}) + C_L (\text{dB}) + M_S (\text{dB}) \]

- \( P_{TR} \) - launched (coupled) power
- \( P_A \) - receiver sensitivity
- \( C_L \) - channel loss
- \( M_S \) - system margin

Notes:
1. As a general rule, system components for the 800 nm band are less costly.
2. MMF is more economical to install and maintain.

Source: [1]

Figure 8-2: Optical power loss model for a point-to-point link. The losses occur at connectors \( (l_c) \), at splices \( (l_s) \), and in the fiber \( (\alpha_f) \).

\[ C_L (\text{dB}) = \alpha_f \frac{L}{\text{km}} + \alpha_{\text{conn}} (\text{dB}) + \alpha_{\text{splice}} (\text{dB}) \]

- \( \alpha_f \) - fiber attenuation
- \( L \) - fiber (link) length
- \( \alpha_{\text{conn}} \) - connector losses (total for link)
- \( \alpha_{\text{splice}} \) - splice losses (total)
1. **The system margin is included to allow for aging-related degradation of components, temperature fluctuations, etc.**

2. **A typical system margin is 6-8 [dB], which is based on experience, empirical evidence, and theoretical knowledge of component behavior.**

3. **Splice and connector losses arise from having to interconnect sections of fiber in practice.**

**Examples**
REFERENCES