Computer Engineering  
Electronics and Communications Systems  
Basics of 3G Communications  

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3G systems
3G systems: The need for more throughput

- When GSM was designed (late 1980s), **voice** services were the main (only?) focus for mobile networks

- GSM extensions (GPRS and EDGE) improved the bitrates, but the demand (late 1990s) was growing **larger and larger**

- The only way to meet the rate demands was to **increase the bandwidth**:

\[
R_b \propto B
\]
Baseband Data (PAM) Signal

\[ s(t) = \sum_{k=\infty}^{\infty} a_k \cdot p(t - kT) \]

Binary Pulse-Amplitude Modulation (PAM)

Symbol Interval: \( T = \) Bit Interval: \( T_b \)
Symbol Rate: \( R = 1/T = \) Bit Rate: \( R_b = 1/T_b \)

Basic Pulse \( p(t) \):

Bipolar Format

\{a_k\} = \pm 1

Binary Data
Power Spectral Density (PSD) of the PAM Signal

\[ S_s(f) = \frac{A^2}{T} |P(f)|^2 \]
Energy of Square-root Raised Cosine (SRC) pulse

\[ E_p = \int_{-\infty}^{+\infty} |p(t)|^2 \, dt = \int_{-\infty}^{+\infty} |P(f)|^2 \, df = T \]

Average power of PAM signal

\[ P_s = \frac{E_p}{T} = 1 \]
Baseband Data Detection with Noise

\[ h(t) = \frac{1}{T} p(-t) \]

\[ r(t) = [s(t) + w(t)] \otimes h(t) = \sum_{i=-\infty}^{\infty} a_i g(t - iT) + n(t) \]

\[ g(t) = p(t) \otimes h(t) \]

\(^\wedge a_k \]

\[ a_k \]

\[ r_k \]

\[ kT \]

**Matched Filter**

**Received Signal**

**White, noise, PSD \( N_0/2 **
\[
X_{BP}(f) = A(t) \cos(2\pi f_0 t + \theta(t))
\]
\[
= A(t) \cos(\theta(t)) \cdot \cos(2\pi f_0 t) - A(t) \sin(\theta(t)) \cdot \sin(2\pi f_0 t)
\]
\[
= X_I(t) \cos(2\pi f_0 t) - X_Q(t) \sin(2\pi f_0 t)
\]
The I/Q Modulator

\[ x_{BP}(t) = x_I(t) \cos(2\pi f_0 t) - x_Q(t) \sin(2\pi f_0 t) \]

**Two signals are “multiplexed” on the same carrier**
Recovering the Baseband Signals 1/2

\[ X(f) \]

\[ x_{BP}(t) \]

\[ x_{BP}(t)e^{-j2\pi f_0 t} \]

\[ \tilde{x}(t) = 2 \left( x_{BP}(t)e^{-j2\pi f_0 t} \right) \otimes h(t) \]
 Recovering the Baseband Signals 2/2

\[ x_{BP}(t) = \Re\{\tilde{x}(t)e^{j2\pi f_0 t}\} = x_I(t)\cos(2\pi f_0 t) - x_Q(t)\sin(2\pi f_0 t) \]

The complex “baseband equivalent”

\[
\tilde{x}(t) = 2\left(x_{BP}(t)e^{-j2\pi f_0 t}\right) \otimes h(t) = x_I(t) + jx_Q(t) = A(t)\exp(j\theta(t))
\]
\[ \tilde{x}(t) = 2 \left( x(t) e^{-j2\pi f_0 t} \right) \otimes h(t) = x_I(t) + jx_Q(t) \]

- Allows to recover I/Q components from bandpass modulated signal
- B is the modulation bandwidth
BPSK and QPSK Modulations

\[ x_{BPSK}(t) = a_k \cos(2\pi f_0 t) \]

\[ \tilde{x}_{BPSK}(t) = a_k \]

\[ T = T_b \]

\[ x_{QPSK}(t) = a_{2k} \cos(2\pi f_0 t) - a_{2k+1} \sin(2\pi f_0 t) \]

\[ \tilde{x}_{QPSK}(t) = a_{2k} + j a_{2k+1} \]

\[ T = 2T_b \]

\textbf{\textit{k-th signaling interval}} \ kT \leq t < (k+1)T
“Constellations” of signals

- **BPSK**
- **QPSK**
- **8PSK**
- **16-QAM**

**Table of Constellations**

<table>
<thead>
<tr>
<th>BPSK</th>
<th>QPSK</th>
<th>8PSK</th>
<th>16-QAM</th>
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</thead>
<tbody>
<tr>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>0000</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>0000</td>
</tr>
</tbody>
</table>

**Binary Representation**

- **BPSK**: +1 = 1, -1 = 0
- **QPSK**: +1 = 0111, -1 = 1011
- **8PSK**: 0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111
- **16-QAM**: 0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111, 1000, 1001, 1010, 1011, 1100, 1101, 1110, 1111
Band-Limited I/Q Modulation...

\[ x(t) = \sum_{k=-\infty}^{\infty} a_k \left( \frac{1}{T_b} \right) \cos(2\pi f_0 t) - j \sin(2\pi f_0 t) \]

\[ \tilde{x}(t) = \sum_{k=-\infty}^{\infty} \tilde{s}_k p(t - kT) = \sum_{k=-\infty}^{\infty} (s_{I,k} + j s_{Q,k}) p(t - kT) \]

\[ T = T_b \cdot \log_2 M \]

\[ M = \# \text{ of points in constellation} \]
...and I/Q Demodulation

The receiver may produce errors when the noise is large

The diagram shows a receiver with matched filters for I and Q channels. The output of the matched filters is then subjected to a decision process, resulting in complex decision maps. The text explains that the receiver may produce errors when the noise is large.
How an Error is Made

\[ P_e = Q \left( \sqrt{\frac{2E_b}{N_0}} \right) \]

\[ E_b = (C / N_0) \cdot T_b \]

Energy-per-bit

BPSK, QPSK
Baseband Data (PAM) Signal

\[ s(t) = \sum_{k=-\infty}^{\infty} a_k \cdot p(t - kT) \]

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Basic Pulse \( p(t): \)

Bipolar Format

\( \{a_k\} = \pm 1 \) Binary Data
The Spread-Spectrum signals runs at the same clock (the chip-rate) as the spreading code.
Spread Spectrum !!

Linear Scale

Log (dB) Scale

GPS: chip rate 1.023 Mchip/s
bit rate 50 bit/s $\Rightarrow M=20460$
The DS/SS Receiver

\[ z(t) = [s(t)c(t) + w(t)]c(t) = s(t)c^2(t) + w'(t) \]

=1!
Narrowband Interference Rejection

**In-band Interfering Power**

\[ P_i = \frac{P}{\frac{1}{T_c}} \cdot \frac{1}{T} = \frac{P T_c}{T} = \frac{P}{M} \]

**Before Despreading**

1. De-spread SS signal
2. Spread Interference

**After Despreading**

1. Narrowband Interference
2. Power P
3. SS signal
4. Frequency

\[ 1/T_c \]
BER of the DS/SS Receiver

\[ P_e = Q\left( \sqrt{\frac{TC}{N_0/2}} \right) = Q\left( \sqrt{\frac{2E_b}{N_0}} \right) \]

**NO difference w.r.t a narrowband modulation!**

**Spectrum spreading/despreading is a transparent operation**

\[ BER(6.8 \text{ dB}) = 10^{-3} \]
\[ BER(9.6 \text{ dB}) = 10^{-5} \]
Frequency-Hopping SS Transmitter...

The overall spectrum is partitioned in $2^M$ bins

FSK Modulation is most often used
The receiver just demodulates the SS signal via a hopping oscillator with the same hop pattern.

Not used in multiple-access communications or positioning.
Just to know..

Who’s invented Spread-Spectrum?
Can you believe?

Hedy Lamarr, actress
The CODE POLYNOMIAL describes the outputs that are to be XORed:

\[ G(x) = 1 + x + x^2 + x^4 + x^6 \]
Maximal-Length Sequences

**Def:** G(x) has no prime factors and divides 1+x^L in GF(2^P)

**Properties:**

- M-sequences have the maximum possible periodicity: \( L=2^P-1 \)
- They contain \( 2^P/2 \) 1s and \( 2^P/2-1 \) 0s (BALANCED sequences)
- XORing an M-sequences with a delayed replica of itself gives the same M-sequence with a third phase
- If you slide a P-bit window on the sequence, you get all of the numbers between 1 and \( 2^P \)
- There is a limited number of M-sequences for a given \( P \)
Gold Codes

- Family of $L+2$ codes with period $L=2^P-1$
- (Logical) sum of two $M$-sequences of length $L$
- May be done balanced (preferentially phased)
- Used in GPS, UMTS
- Good spectrum
- The average cross-correlation is low (quasi-orthogonal codes)

$$
\mu = \frac{1}{N-1} \sum_{k=2}^{N} \left( \frac{1}{L} \sum_{m=0}^{L-1} C_m^{(1)} C_m^{(k)} \right)^2 = 1
$$
Autocorrelation Functions of a PN sequence

Periodic Autocorrelation

$$R_p[k] = \frac{1}{L} \sum_{m=0}^{L-1} c_m c_{m+k}$$

for an M-sequence

Linear (Aperiodic) Autocorrelation

$$R_l[k] = \frac{1}{L-k} \sum_{m=0}^{L-k-1} c_m c_{m+k}$$

Determines the spectral properties of a DS/SS signal with short codes and data modulation
The True Spectrum of SS Signals

The code is only PSEUDO random (actually, it is periodic!)

\[ S_{ss}(f) = \frac{|C(f)|^2}{T} |Q(f)|^2 \]

The “Code Spectrum” \( C(f) \) depends on the autocorrelation properties of \( c(t) \)

\[ C(f) = \sum_{m=0}^{L-1} c_m e^{-j2\pi f T_c} \]
Multiplexing: Time- and Frequency-Division

**TDMA:** The user signals are separated in **TIME** (overlapped in frequency)

**User data signals to be multiplexed**

**FDMA:** The user signals are separated in **FREQUENCY** (overlap in time)
Each user is assigned a signature code used to spread his/her own data signal.

The users are overlapped both in time and frequency - They can be separated only via de-spreading with the appropriate code.
\[ \int_0^1 c^{(i)}(t) c^{(k)}(t) dt = 0, \quad i \neq k \]

**Orthogonal Codes**

\[ H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \]

**WALSH-HADAMARD Matrices & Functions**

\[ H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \]

\[ H_H = \begin{bmatrix} H_{H/2} & H_{H/2} \\ H_{H/2} & -H_{H/2} \end{bmatrix} \]
The user signals are ORTHOGONAL (but synchronicity is needed)

The integral of the product of any two different Walsh-Hadamard functions is zero:

\[ \int w_i(t)w_k(t)dt = 0, \quad i \neq k \]

**Synchronous Orthogonal CDMA**

**Table of Walsh-Hadamard Functions L=8**

- \( w_0(t) \)
- \( w_1(t) \)
- \( w_2(t) \)
- \( w_3(t) \)
- \( w_4(t) \)
- \( w_5(t) \)
- \( w_6(t) \)
- \( w_7(t) \)
**Synchronous multiplexing:** all users share the same data and chip clock

- Co-located user signals
- Broadcast Pilot Signal

**Asynchronous multiple access:** no need of user synchronization (sort of random access)
The universal mobile telecommunications system (UMTS), designed in the late 1990s, and operational in Europe, Asia and Australia since 2002, offers:

- **throughput:**
  - 2 Mb/s for fixed users (very low mobility)
  - 384 kb/s for pedestrian users (low mobility)
  - 144 kb/s for vehicular users (up to 500 km/h)

- **latency:** 100 ÷ 200 ms

- multiplexing of multiple services with different quality of service (QoS) requirements

- asymmetric traffic for uplink and downlink channels
Two modes are supported by the UMTS standard:

- **UMTS terrestrial radio access FDD (UTRA-FDD)**
- **UMTS terrestrial radio access TDD (UTRA-TDD)** (not covered)
The UTRA-FDD mode adopts **CDMA** as the multiple-access technique.

Since $B = 5$ MHz, this technology is called **wideband CDMA (WCDMA)**.

In both the uplink (UL) and the downlink (DL), the input signal is processed as follows:

\[ R_b = \frac{1}{T_b} \quad \text{and} \quad R_c = \frac{1}{T_c} = 3.84 \text{ Mc/s} \]
Uplink:

- **Spreading codes**: used to separate the streams at the transmit side (MS)
- **Scrambling codes**: used to separate the users in the network
**Downlink:**

- **Spreading codes:** used to separate the messages for each receiver at the transmit side (BTS)

- **Scrambling codes:** used to separate a BTS from each other in the network
The spreading codes used in UTRA-FDD belong to the family of **orthogonal variable spreading factor (OVSF)** codes, built upon Walsh-Hadamard codes:

\[
\begin{align*}
CC_{1,0}(0) & \quad CC_{2,0}(0,0) \\
& \quad CC_{2,1}(0,1) \\
& \quad CC_{4,0}(0,0,0) \\
& \quad CC_{4,1}(0,0,1,1) \\
& \quad CC_{4,2}(0,1,0,1) \\
& \quad CC_{4,3}(0,1,1,0)
\end{align*}
\]

\[
\begin{array}{cccc}
M=1 & M=2 & M=4 & M=512
\end{array}
\]
In the OVSF codes used by UTRA-FDD, the chiprate is fixed:

\[ R_c = 3.84 \text{ Mc/s} \Rightarrow R_b = \frac{R_c}{M} \]

- **slow streams:** large M’s
- **fast streams:** small M’s

**Distinctive features of the OVSF codes:**

- **orthogonal codes:**
  \[ \frac{1}{T} \int_0^T c(t) \cdot c'(t) dt = 0 \quad \text{if } c(t) \text{ is not a parent of } c'(t) \]

- **careful management** of the codes to avoid code shortage

- **need for synchronization** across the codes: all codes are generated by the same transmitter
UTRA-FDD: Scrambling codes (1/2)

- Orthogonal codes such as the OVSF codes cannot be used for aggregate signals (e.g., the signals from all MSs in the UL)

- To separate users/cells in the UL/DL, the UTRA-FDD makes use of different PN codes with chiprate $R_c = 3.84$ Mc/s (no bandwidth spreading):
  - autocorrelation $R_{cc}(\tau) = \frac{1}{T} \int_0^T c(t) \cdot c(t + \tau) dt \neq 0 \quad \forall \tau \neq 0$
  - crosscorrelation $R_{cc'}(\tau) = \frac{1}{T} \int_0^T c(t) \cdot c'(t + \tau) dt \neq 0 \quad \forall \tau$

UTRA-FDD uses non-orthogonal codes as scrambling codes
Frequency Reuse Patterns

- **F/TDMA Seven-cell cluster**
- **CDMA Universal Frequency Reuse**
Channelization (spreading) and Scrambling Codes

Intra-cell Channelization Codes:
\[ w_i \]

Inter-cell Scrambling Codes:
\[ S_k \]

Composite Codes:
\[ C_{k,i} = S_k \oplus w_i \]

Code Reuse !!
Gaussian approximation for the Multiple-Access Interference

\[ P_e = Q \left( \sqrt{\frac{2E_b}{N_0 + I_0}} \right) \]

\( I_0 \) is the MAI PSD
F/TDMA with RE-USE factor Q (number of cells/cluster)

- Each cell is allocated $1/Q$ of the total spectrum
  - Total bit-rate in a cell $NR_b$
  - Total Bandwidth $= QNR_b$

\[ S = \frac{1}{Q} \]

GSM: $Q=9$, $S=0.11$

The re-use factor is determined by the level of the co-channel interference coming from the nearest cell using the same frequency
CDMA with UNIVERSAL RE-USE

Worst-Case user location

FWD LINK

\[ S = \frac{1}{E_b / I_0} \frac{2\beta}{\beta} \]

With \( M=63 \), \( \beta=0.4 \), \( BER=10^{-3} \)

\[ S = 0.26 \]

Similar computation for the return link

\[ I_0 = \frac{\beta N + \beta N + 0}{M} E_b \]
### Spreading and scrambling codes: A summary

<table>
<thead>
<tr>
<th></th>
<th>spreading codes</th>
<th>scrambling codes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>groups</strong></td>
<td>UL: streams</td>
<td>UL: MSs</td>
</tr>
<tr>
<td></td>
<td>DL: MSs</td>
<td>DL: BTSs</td>
</tr>
<tr>
<td><strong>length</strong></td>
<td>UL: $M=4\div256$</td>
<td>$38,400$</td>
</tr>
<tr>
<td></td>
<td>DL: $M=4\div512$</td>
<td>$512$</td>
</tr>
<tr>
<td><strong>cardinality</strong></td>
<td>$M$</td>
<td>$2^{24}$</td>
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<tr>
<td></td>
<td></td>
<td>$512$</td>
</tr>
<tr>
<td><strong>family</strong></td>
<td>OVSF</td>
<td>Gold codes</td>
</tr>
<tr>
<td><strong>spreading factor</strong></td>
<td>$M$</td>
<td>$1$</td>
</tr>
</tbody>
</table>
Each frame has a duration

\[ T_f = \frac{L_c}{M_c} = \frac{38,400 \text{ c}}{3.84 \text{ Mc/s}} = 10 \text{ ms} \]

<table>
<thead>
<tr>
<th>frame 1</th>
<th>frame 2</th>
<th>frame 3</th>
<th>frame 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>38,400 chips</td>
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<td>38,400 chips</td>
<td>38,400 chips</td>
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</table>

Time slot: 2,560 chips

Power control rate: \( \frac{15}{10 \text{ ms}} = 1,500 \text{ Hz} \)
UTRA-FDD: Downlink structure (1/2)

The DL makes use of a quaternary phase shift keying (QPSK) constellation, using a root-raised cosine (RRC) with rolloff $\alpha = 0.22$ as the shaping filter.

Considering the guard bands, the dedicated physical channel (DPCH) occupies 5 MHz.

$$B = 3.84 \cdot 1.22 \text{ MHz} \approx 4.7 \text{ MHz}$$
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Computer Engineering

3G systems

UTRA-FDD: Downlink structure (2/2)

Time slot structure:

frame, 10 ms

time slot #

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<th>14</th>
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</table>

DPCH

control data control data control

M = 4, 1,248 bits/slot

Since each user can be assigned up to 3 parallel DPCHs, we get data rates around 2 Mb/s

\[ R_b = \frac{1/2 \times 1,248 \text{ bits/slot} \times 15 \text{ slots}}{10 \text{ ms}} = 936 \text{ kb/s} \]

QPSK

2,560 chips; variable SF (M=4+512) = 5,120 M bits (data+control)

2,560 chips; variable SF (M=4+512) = 5,120 M bits (data+control)
UTRA-FDD: Uplink structure (1/2)

The UL makes use of a dual-code binary phase shift keying (BPSK) constellation, using a root-raised cosine (RRC) with rolloff $\alpha = 0.22$.
Time slot structure:

- **M=4** 640 bits/slot

**Channel coding rate**

\[ R_b = \frac{1/2 \times 640 \text{ bits/slot} \times 15 \text{ slots}}{10 \text{ ms}} = 480 \text{ kb/s} \]

Since each user can be assigned up to 6 parallel DPCHs, we get again data rates around 2 Mb/s.
Discontinuous transmission

The UL channel uses a dual-code BPSK in order to:

- improve the **efficiency** of the power amplifier, by **reducing** the peak-to-average power ratio (PAPR)
- avoid a 1,500 Hz oscillation during **discontinuous transmission (DTX)**
The UMTS standard supports three different handover (HO) procedures:

- **intersystem HO**: backward compatibility with 2G systems ensures HOs when the 3G coverage is not available

- **hard HO**: the connectivity when moving across cells is ensured by the BTS of the cell just entered, and is available for both FDD and TDD modes

- **soft HO**: in the FDD mode, the MS can be connected simultaneously to both the BTS of the exiting cell, and the BTS of the entering cell, by exploiting the frequency diversity recovered by the rake receivers
Let’s consider code spreading when the **near-far effect** takes place:

If the MSs are received at the BTS with very unbalanced powers, the despreading is not successful due to a non-negligible multiple-access interference (MAI).
The received signal-to-interference (SIR) $\gamma$ is:

- measured by the receivers using **pilot** symbols
- fed back to the transmitter to regulate the transmit power level (**closed-loop power control**)

Powers are increased/decreased on a **logarithmic** scale every 2/3 ms (1500 Hz)
Due to power control, UMTS cells have **variable** coverage areas:

As the number of users increases, so does the **level of MAI**: to keep an acceptable level of $\gamma$, the radius of the cell is **reduced**.
UMTS evolution: The HSPA/HSPA+ standards

The high-speed packet access (HSPA) improves data rates (DL: 14.4 Mb/s, UL: 5.76 Mb/s) and latencies (<100 ms), by introducing:

- **16-QAM (quadrature amplitude modulation)**
- **hybrid automatic repeat-request (HARQ)**

The HSPA+ has eventually increased the UMTS performance, achieving 56 Mb/s for the DL, and 22 Mb/s for the UL:

- **64-QAM constellation**
Due to the use of WCDMA ($B=5$ MHz), the receiver needs to estimate the channels taps, with parameters $\{\rho_i\}_{i=1}^{N}$, $\{\theta_i\}_{i=1}^{N}$, and $\{\tau_i\}_{i=1}^{N}$.

This can be done by using rake receivers:

This significantly increases the receiver complexity, thus limiting the bandwidth of the CDMA signal.


