Computer Engineering
Electronics and Communications Systems

Basics of 4G Communications (and Beyond)

Giacomo Bacci, Marco Luise
marco.luise@unipi.it

Dip. Ingegneria dell'Informazione, Univ. Pisa, Pisa, Italy
4G systems
Evolution of Cellular Standards

- **EDGE**
  - DL: 474 kbps
  - UL: 474 kbps

- **HSPA**
  - DL: 14.4 Mbps
  - UL: 5.76 Mbps
  - In 5 MHz

- **HSPA+**
  - Rel 7 HSPA+ DL: 28 Mbps
  - UL: 11.5 Mbps
  - In 5 MHz
  - Rel 8 HSPA+ DL: 42 Mbps
  - UL: 11.5 Mbps
  - In 5 MHz

- **LTE**
  - DL: 88 Mbps
  - UL: 85 Mbps
  - In 20 MHz

- **LTE Advanced**
  - DL: > 1 Gbps

- **EV-DO Rev A**
  - DL: 3.1 Mbps
  - UL: 1.8 Mbps
  - In 1.25 MHz

- **EV-DO Rev B**
  - DL: 14.7 Mbps
  - UL: 4.9 Mbps
  - In 5 MHz

- **CDMA2000**
  - Fixed WiMAX

- **Fixed WiMAX**
  - Mobile WiMAX Release 1.0 DL: 46 Mbps
  - UL: 4 Mbps
  - 10 MHz 3:1 TDD

- **Rel 1.5**

- **IEEE 802.16m**

---

Dip. Ingegneria dell’Informazione
University of Pisa, Pisa, Italy
4G systems

IMT-advanced requirements

- peak data rates of 100 Mb/s for high-mobility users, and 1 Gb/s for low-mobility users
- larger bandwidths (up to 40 MHz)
- lower latencies (< 15 ms)
4G deployment status

- 76 Countries with LTE
- 18 LTE scheduled

02/2014
There were two competing systems labeled as 4G technologies:

- **LTE-advanced (LTE-A)**, standardized by the 3rd generation partnership project (3GPP)
- **IEEE 802.16m**, standardized by the Institute of Electrical and Electronic Engineers (IEEE)
The long-term evolution – advanced (LTE-A) has been standardized by the 3GPP in March 2011, as 3GPP Release 10 (current version: Release 13).

- LTE-A adopts OFDMA for the DL, and SC-FDMA for the UL, achieving peak rates of 3 Gb/s (DL) and 1.5 Gb/s (UL), and maximum latency 10 ms.

- Carrier frequencies: 700 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz
- Carrier spacing: 15 kHz
- Bandwidths: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz
- Constellations: QPSK, 16-QAM, 64-QAM
Two-ray channel Amplitude response

\[ H(f) = 1 + \rho e^{j\theta} e^{-j2\pi f\tau} \]

or

\[ H(f) = 1 - \rho e^{-j2\pi (f-f_N)\tau} \]

\( \tau = 1 \mu s \)

\( f_N = 0.5 \text{ MHz} \)

See the notch frequencies!
## Time-Invariant Channel of DVB-T

<table>
<thead>
<tr>
<th>$\theta_i$ [rad]</th>
<th>$\tau_i$ [(\mu\text{s})]</th>
<th>$\rho_i$</th>
<th>$i$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,057 662</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,176 809</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,407 163</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,303 585</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,258 782</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,061 831</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,150 340</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,051 534</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,185 074</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,400 967</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,295 723</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,350 825</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,262 909</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,225 894</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,170 996</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,149 723</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,240 140</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,116 587</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,221 155</td>
<td>20</td>
</tr>
</tbody>
</table>

### Parameters
- $R_s = 6$ Mbit/s
- $T_s = 0.16$ \(\mu\text{s}\)
Amplitude Response of the DVB-T Channel

Normalized Frequency, $fT_s$

| $|H(f)|$ (dB) |
|-----------|
| -25       |
| -20       |
| -15       |
| -10       |
| -5        |
| 0         |
| 5         |
| 10        |
| 15        |
| 20        |
| 25        |
| 30        |
| 35        |
| 40        |
| 45        |
| 50        |

Dip. Ingegneria dell’Informazione
University of Pisa, Pisa, Italy

Giacomo Bacci, Marco Luise
Basics of 4G communications and beyond
How to cope with severely selective channels? 1/2

Too many notches!

The equalizer is too complicated!

|H(f)| (dB)

Normalized Frequency, fT_s

Modulated Signal Spectrum

DVB-T 20-ray Channel Model
Split your (single-carrier) high-rate stream into many “parallel” low-rate streams on different subcarriers that “see” each a FLAT channel response!!
Multi-Carrier Modulation (DVB-T, ADSL, WLAN)

$m$ = block index

$k$ = intra-block subcarrier index,

$0 \leq k \leq N-1$

$\sum \exp\{j2\pi m f_{sc} t\}$

Symbol time: $NT_s = T_{MC}$

$mN+k$

$m=0,1,\ldots,N-1$

$C_m$

$C_m^{(0)}$

$C_m^{(1)}$

$C_m^{(N-1)}$

$x_{MC}(t)$

$N$ = number of subcarriers

$f_{sc}$ = subcarrier spacing

$S/P$ (DeMUX)

Dip. Ingegneria dell’Informazione
University of Pisa, Pisa, Italy

Giacomo Bacci, Marco Luise
Basics of 4G communications and beyond
The I/Q Modulator

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

\[ x_I(t) \]
\[ \cos(2\pi f_0 t) \]
\[ -\sin(2\pi f_0 t) \]
\[ x_Q(t) \]
\[ \text{I/Q Carrier Generator} \]
\[ x_{BP}(t) \]

Equivalent to

\[ x_I(t) + jx_Q(t) \]
\[ \exp(j2\pi f_0 t) = \cos(2\pi f_0 t) + j\sin(2\pi f_0 t) \]
To convey the stream of information symbols on multiple subcarriers without any interference, we use a set of orthogonal subcarriers:

This solution requires the minimum bandwidth occupancy.
The OFDM Signal Format

\[ x(t) = \sum_{k=0}^{N-1} \sum_{m=-\infty}^{+\infty} c^{(m)}_k p(t - mT_{MC}) e^{j2\pi kt/T_{MC}} \]

\[ m \text{ is the time index of an OFDM symbol} \]

\[ k\text{-th data stream} \quad k\text{-th subcarrier} \]

\[ x(t) = \sum_{k=0}^{N-1} x_k(t) e^{j2\pi kt/T_{MC}} \]

\[ S_x(f) = \sum_{k=0}^{N-1} S_{x_k}(f - k/T_{MC}) \]
### Power Spectrum of OFDM

The power spectrum of an OFDM signal is given by:

$$S_x(f) = \sum_{k=0}^{N-1} S_{x_k}(f - k/T_{MC})$$

where $S_{x_k}(f)$ is the power spectrum of the $k$th subcarrier, $N$ is the number of subcarriers, and $T_{MC}$ is the symbol time.

For $N=64$ and $N=2048$, the following systems are shown:

- **IEEE 802.11 Wireless LAN**
- **DVB-T Terrestrial Digital Video Broadcasting**
- **4G LTE**

The graph shows the power spectrum in dB vs. normalized frequency $fT_s$. The spectrum is plotted for $N=64$ and $N=2048$. The peaks and nulls are clearly visible for each case.
Orthogonal FDM again

To convey the stream of information symbols on multiple subcarriers without any INTERFERENCE, we use a set of orthogonal subcarriers:

This solution requires the **minimum** bandwidth occupancy
How can we implement OFDM?

- Using $N$ local oscillators to synthesize $e^{j2\pi kt / T_{MC}}$, $k = 0, \ldots, N - 1$ at the transmitter and the receiver is a highly inefficient architecture.

- Let us try to sample our signal at intervals $nT_s$:

$$x[n] = x(nT_s) = \sum_{k=0}^{N-1} c_m^{(k)} e^{j2\pi kn / N}$$
Digital Implementation

\[ x(t) = \sum \exp\{ j2\pi (m-1) f_{sc} t \} \]

\[ \exp\{ j2\pi 0 f_{sc} t \} \]

\[ \exp\{ j2\pi 1 f_{sc} t \} \]

\[ \exp\{ j2\pi (N-1) f_{sc} t \} \]

\[ C_m^{(0)} \]

\[ C_m^{(1)} \]

\[ C_m^{(N-1)} \]

S/P (Demultiplexer)
**Digital Implementation**

4G systems

- **S/P (DeMUX)**
- **IFFT**
- **P/S (MUX)**
- **DAC**

Symbols:
- $c_{mN+k}$
- $x(t)$
Digital Implementation

4G systems

S/P (DeMUX) -> IFFT -> P/S (MUX) -> DAC

$x(t)$

$C_{mN+k}$
OFDM is very efficient, as it can exploit both at the TX and at the RX (fast) FFT processing with $L=2^D$ (e.g., $L=2048$ for LTE)
Symbols \( N - N_v, \ldots, N-1 \) are set to 0 to control signal bandwidth.
Reducing the signal BW to eliminate the aliasing error!

NO Virtual Carriers

WITH Virtual Carriers
Electronics and Communications Systems

Computer Engineering

Giacomo Bacci, Marco Luise
University of Pisa, Pisa, Italy

Basics of 4G communications and beyond

4G systems

Channel equalization in OFDM (1/3)

OFDM receiver (orthogonal carriers)

\[ y(t) \xrightarrow{\times} \frac{1}{T_{MC}} \int_{0}^{T_{MC}} z^{(k)}(\cdot)dt \xrightarrow{\bigtriangleup} \hat{c}^{(k)} \]

\[ x(t) \xrightarrow{\exp \{-j2\pi kf_{sc}t\}} y(t) \]

OFDM symbols (blocks) with IBI

Multipath propagation leads to inter-block interference (IBI)
Channel equalization in OFDM (2/3)

To mitigate the ICI, we can add a special guard interval, called the cyclic prefix (CP), with length:

\[ T_G \geq \tau_{\text{max}} \]

Using the CP, we have “artificially” introduced a cyclic *inter-block* interference, that can now be controlled.
Adopting the same receiver technique,

\[ z_m^{(k)} = H \left( \frac{k}{T_{MC}} \right) c_m^{(k)} + n_m^{(k)} = H_k c_m^{(k)} + n_m^{(k)} \]

In this case, channel equalization is extremely simple:
Channel Estimation with known PILOT SYMBOLS (1 every a few)
How can the receiver estimate the coefficients $H_k$ in practice?

OFDM symbols contain sparse pilot subcarriers, with known symbols, to let the receiver get an accurate estimation of the channel response:

$$z_m^{(k)} = H_k \cdot 1 + n_m^{(k)} \Rightarrow \hat{H}_k = z_m^{(k)}$$

Of course there are estimation errors caused by the presence of the noise term $n_m^{(k)}$.
Channel equalization in OFDM (5/5)

How can the receiver estimate the coefficients $H_k$ in practice?

OFDM symbols contain sparse **pilot subcarriers**, with **known** symbols, to let the receiver get an accurate estimation of the channel response:
Features:

- **optimal implementation via (I)FFT**
- **no ICI due to carrier orthogonality**
- **controlled OOB emissions thanks to the virtual carriers**
- **frequency-domain equalization thanks to the CP**
Orthogonal frequency division multiple access (OFDMA)

How can we adapt the OFDM technology to the **multiuser** case?

Each user can be assigned a **subset** of subcarriers, by zeroing the **inactive** subcarriers.

- **Subcarrier allocation** is critical to exploit the **frequency diversity**.
- This allocation introduces some **overhead** in the network.
End of 1950s/beginning of 1960s: introducing **cells** to provide **seamless** coverage

Cluster with size (reuse factor) $K=4$
Introduction to modern wireless communications systems

Universal Frequency Reuse of CDMA ($K=1$)

Typical of 3G systems
Fractional frequency reuse (FFR)

available bandwidth
The superposition of \( L \) sinusoidal signals (carriers) yields a large PAPR, thus calling for linear radio-frequency (RF) amplifiers.

To improve the efficiency of the Power Amplifier of the MSs, the uplink adopts a modified version of OFDMA, called single-carrier FDMA (SC-FDMA).
Single-carrier FDMA (SC-FDMA)

- **FFT precoding** significantly reduces the PAPR
- The IFFT at the transmitter operates on the **Fourier coefficients** rather than on information symbols (as in OFDMA)
- The distinctive feature with respect to a traditional FDMA is the presence of the CP, that allows for **frequency-domain equalization**
The long-term evolution – advanced (LTE-A) has been standardized by the 3GPP in March 2011, as 3GPP Release 10 (current version: Release 13)

LTE-A adopts OFDMA for the DL, and SC-FDMA for the UL, achieving peak rates of 3 Gb/s (DL) and 1.5 Gb/s (UL), and maximum latency 10 ms

- Carrier frequencies: 700 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz
- Carrier spacing: 15 kHz
- Bandwidths: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz
- Constellations: QPSK, 16-QAM, 64-QAM
Structure of the LTE-A frame
LTE DL Pilots

Frequency domain


R₁: First reference symbol
R₂: Second reference symbol
D: Data

0.5 ms
Structure of the LTE-A frame

- Frame duration: 0.5 ms
- 20 time slots
- 12 subcarriers: 180 kHz
- 7 OFDM symbols
- 15 kHz carrier spacing
- Resource block
- Resource element

**Nominal Channel BW:** 20 MHz

\[
B_{RF} = 1201 \times 15 = 18 \text{ MHz}
\]

\[
f_{sc} = 15 \text{ kHz}
\]

\[
N = 2048, \ N_v = 847
\]
Enabling technologies for 4G standards

- carrier aggregation
- network MIMO
- relaying
With carrier aggregation (CA), we can increase the signal bandwidth by grouping physical channels, in both TDD and FDD configurations.

- **Intraband, contiguous CA:**
- **Intraband, non-contiguous CA:**
- **Interband CA:**

By grouping up to 5 carriers, we can obtain a **100-MHz bandwidth**.
Network MIMO, known as coordinated multipoint (CoMP) in LTE-A, and coordinated MIMO (CO-MIMO) in IEEE 802.16m, consists in coordinating (at the transmit side) or combining (at the receive side) signals using multiple antennas.

- this form of distributed MIMO achieves significant performance improvements, especially for cell-edge users (improving coverage and cell-edge rates)
- it requires a significant feedback overhead to exchange CSI across BTSs
Relay nodes can be introduced in the network as low-power BTSs, to provide enhanced system performance

- improved network coverage
- increased energy efficiency
- increased spectral efficiency
- some form of coordination between the relays and the network is required


