Evolution into 4G

- In 4G systems, a peak data rate of around 1Gbps is demanded.
- Available radio bandwidth may be limited to 100MHz.
- Some advanced wireless techniques to achieve more than 10bps/Hz/BS are necessary; e.g., multi-input/multi-output (MIMO) antenna techniques, powerful error control, etc.

Wireless Propagation Channel

- In terrestrial wireless communications, the transmitted signal is reflected or diffracted by large buildings between transmitter and receiver, creating a number of propagation paths having different time delays.

Frequency-selective Channel

- For broadband signal transmission, the transfer function of wireless channel varies over the signal bandwidth.
- Challenge is to transmit data at high speed (around 1 Gbps) with high quality over such a severe frequency-selective channel.

\[ L = 16, \text{ Uniform power delay profile, } l\text{-th path time delay}=100l + [-50,50]ns \]
Frequency-domain Equalization for Taking Advantage of Channel Selectivity

- Strong inter-symbol interference (ISI) can be produced by the severe frequency-selectivity of the channel.
- This has been long time a big problem for achieving high speed and high quality data transmissions.
- Equalization techniques play an important role to remove ISI and improve the transmission performance.
- Single-carrier (SC) system has been using a time-domain equalization technique, but this can be helpful only in a channel with a moderate number of paths.
- Multicarrier (MC) system representing OFDM carries the transmitting data symbol sequence by a number of orthogonal subcarriers. Simple one-tap frequency-domain equalization (FDE) can provide a good transmission performance in a severe frequency-selective channel.
- One-tap FDE can also be applied to SC system including DS-CDMA to significantly improve the transmission performance.

CDMA Transmitter/Receiver

- One-tap FDE can take advantage of the channel frequency-selectivity and achieve an improved BER performance irrespective of DS- or MC-CDMA.
- Their transmitter/receiver structures also are similar.

![Diagram of CDMA Transmitter/Receiver](image)

Space-Time Block Coded Transmit Diversity

- MC- and DS-CDMA performances coincide for all the modulation levels.
- For 16QAM and 64QAM, however, OFDM provides a better BER performance than either MC- or DS-CDMA.
- This performance degradation of CDMA is owing to the inter-code interference (ICI) produced by the channel frequency-selectivity.

![Diagram of Space-Time Block Coded Transmit Diversity](image)
Frequency-domain STBC-JTRD for \( N_r = 2 \) \((G=Q=2)\)

- **Encoding**
  \[
  \left( \tilde{s}_{0,n} (k), \tilde{s}_{1,n} (k) \right) = \left( \frac{1}{N_r} \sum_{n=0}^{N_r-1} \sum_{i=0}^{N_c-1} w_{n,i} (k) w_{n,i}^*(k) \right) \left( S_0 (k) w_{0,n} (k) + S_i (k) w_{1,n} (k) \right)^T + \left( \frac{1}{N_r} \sum_{n=0}^{N_r-1} \sum_{i=0}^{N_c-1} w_{n,i} (k) \right) \left( S_0^* (k) w_{0,n}^*(k) + S_i^* (k) w_{1,n}^*(k) \right)^T
  \]

  where \( w_{n,r} (k) \) is the MMSE pre-equalization weight, given as
  \[
  w_{n,i} (k) = H_{n,i}^* (k) \left( \frac{1}{N_r} \sum_{n=0}^{N_r-1} \sum_{i=0}^{N_c-1} |H_{n,i} (k)|^2 + \left( \frac{U}{SF} \frac{E_b}{N_0} \right)^{-1} \right)
  \]

  and \( H_{n,r} (k) \) is the channel gain between the \( n \)-th transmit antenna and the \( r \)-th receive antenna at the \( k \)-th subcarrier.

- **Decoding** (for \( t = 0 \sim N_c - 1 \))
  \[
  \left( \tilde{r}_0 (t), \tilde{r}_1 (t) \right) = \left( r_{0,0} (t) + r_{1,0}^* (N_c - t) \right) + \left( r_{0,1} (t) - r_{1,0}^* (N_c - t) \right)
  \]

Hybrid ARQ (HARQ) with Incremental Redundancy (IR)

- An automatic repeat request (ARQ) combined with the channel coding, called hybrid ARQ (HARQ), is an inevitable technique, since an error-free transmission must be guaranteed for packet data services.
- HARQ combined with FDE can take advantage of the channel frequency-selectivity and can significantly improve the throughput.

HARQ w/FDE & ICI Cancellation

- Joint use of FDE and ICI cancellation significantly improves the throughput.
- MC- and DS-CDMA provide better throughput than OFDM due to the frequency-diversity gain.
**Frequency-Domain SDM**

- MIMO space division multiplexing (SDM) is a promising technique to increase the throughput with limited frequency bandwidth.
- To achieve the frequency-diversity gain, joint MMSE-FDE/parallel interference cancellation (PIC) is repeated for signal detection. This is called iterative FDIC.

**Iterative FDIC can improve throughput for both CDMA and OFDM, but is more effective for CDMA.**

**Broadband MA Schemes Based On Frequency-domain Signal Processing**

- Uplink capacity is limited by MAI resulting from asynchronous users.
- For the uplink applications, SC is more suitable than MC because of its lower PAPR property.
- Two approaches:
  - Frequency-domain approach separates users so that their spectra do not overlap in the frequency-domain ➔ Frequency-domain interleaved spread spectrum SCMA
  - Time-domain approach separates users thanks to code orthogonality property of block spreading (users' spectra are overlapped) ➔ 2D block spread CDMA

**Frequency-domain interleaved SSMA**

- Spread spectrum SC signal is first transformed into frequency-domain signal and then, mapped to different subcarriers, similar to SC-FDMA.
Orthogonal Interleave Patterns

- Equal-spacing pattern

\[ c_{t} = \begin{cases} 1, & \text{subcarrier } 0 \text{ to } SF_t - 1 \\ 0, & \text{otherwise} \end{cases} \]

\[ c_{f} = \begin{cases} 1, & \text{subcarrier } 0 \text{ to } SF_f - 1 \\ 0, & \text{otherwise} \end{cases} \]

- Localized pattern

\[ c_{t} = \begin{cases} 1, & \text{subcarrier } 0 \text{ to } SF_t - 1 \\ 0, & \text{otherwise} \end{cases} \]

\[ c_{f} = \begin{cases} 1, & \text{subcarrier } 0 \text{ to } SF_f - 1 \\ 0, & \text{otherwise} \end{cases} \]

- Random pattern

2D Block Spread CDMA

- 2D block spread CDMA uses a product code of two orthogonal spreading codes, \( c_{t} \) and \( c_{f} \), of spreading factors, \( SF_{t} \) and \( SF_{f} \), respectively.
  - Block-time spreading code \( c_{t} \) allows MAI-free multi-access
  - Chip-time (or frequency) spreading code \( c_{f} \) allows reduction of the residual ISI after FDE.
  - MAI-free code combination is \( (SF_{t}, SF_{f})=(U, SF/U) \)
  - \( c_{t} \) and \( c_{f} \) codes can be chosen from orthogonal variable spreading factor (OVSF) codes.

\[ \begin{align*}
  c_{t} &= \begin{cases} 1, & \text{block-time } 0 \text{ to } SF_{t} - 1 \\ 0, & \text{otherwise} \end{cases} \\
  c_{f} &= \begin{cases} 1, & \text{chip-time } 0 \text{ to } SF_{f} - 1 \\ 0, & \text{otherwise} \end{cases}
\end{align*} \]

2D block spreading can be introduced into both DS- and MC-CDMA.
(SF_u^f, SF_v^f) = (U, SF/U) gives the best uplink performance since
- MAI can be mitigated, without using a sophisticated MUD, thanks to orthogonal block-time spreading
- chip-time spreading factor SF_u^f can be maximized so that the residual ISI can be minimized.

Conclusion
- 4G systems are a broadband packet network and requires Giga-bit wireless technology of around 1Gbps transmission capability.
- Frequency-domain signal processing is an important technique to achieve the goal.
  - Either MC or SC with FDE can be used since both can provide similar performance.
  - Frequency-domain HARQ and MIMO can be used to take advantage of the channel frequency-selectivity.
- Network issue
  - Power problem is an important technical issue in 4G networks. Some fundamental change needs to be introduced to the wireless network.
  - E.g., multi-hop virtual cellular network, collaborative network, distributed antenna network, etc.