WiMAX Nuts and Bolts:

An Introduction to the IEEE 802.16e Standard

Steve Hilton
Motorola, Inc.
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Abstract

IEEE 802.16 is a standards family that defines a wireless network on a metropolitan area (WMAN). Its objective is to detail a technology that provides wireless broadband connectivity to fixed and nomadic users. IEEE 802.16e is an evolution of 802.16 that is aiming to fill the gap between wireless local area networks (WLAN) and cellular networks by adding mobility and increased data speeds. This discussion is an introduction to the 802.16e standard with a focus on some of the key constructs of the physical layer, including the basics of orthogonal frequency division multiplexing (OFDM), which will help facilitate the development of mobile broadband wireless access systems.

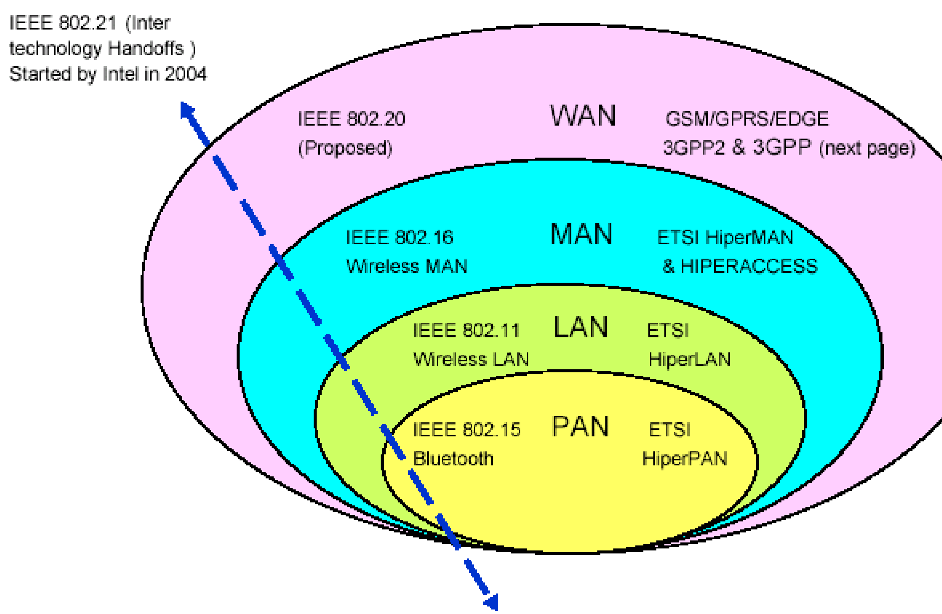
Scope of Presentation

- Background
- Overview of 802.16 Standards
- OFDM Basics
- 802.16e Physical Layer Constructs
- Other 802.16e Features
- Q&A

Definition of Terms

- **What is 802.11?**
  - IEEE standard that defines a wireless network on a local area network (WLAN).
- **What is Wi-Fi?**
  - Generic term applied to any 802.11 network.
  - The Wi-Fi Alliance is a global, non-profit organization with the goal of driving the adoption of a single worldwide-accepted standard for high-speed wireless local area networking.
- **What is 802.16?**
  - IEEE standard that defines a wireless network on a metropolitan area (WMAN). It is designed to support fixed and nomadic users.
- **What is 802.16e?**
  - Evolution of 802.16 that adds mobility (vehicular speeds) and increased data rates.
- **What is WiMAX?**
  - The WiMAX Forum is an industry-led, non-profit corporation formed to promote and certify compatibility and interoperability of broadband wireless products. Our member companies support the industry-wide acceptance of the IEEE 802.16 and ETSI HiperMAN wireless MAN standards.

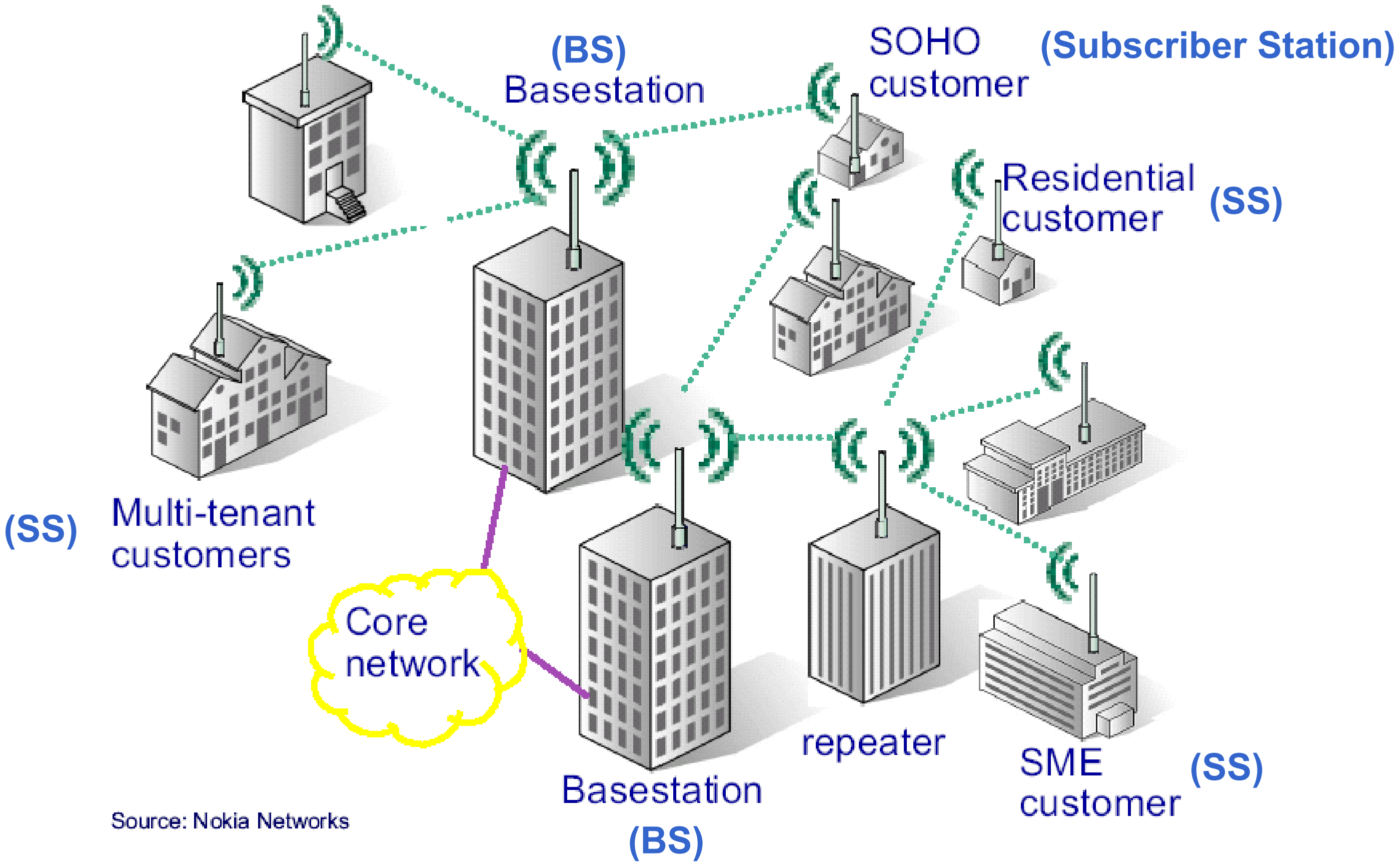
Global Wireless Standards



IEEE Standard for Local and Metropolitan Area Networks —

Part 16: Air Interface for Fixed Broadband Wireless Access Systems

WirelessMAN: Wireless Metropolitan Area Network



Source: Nokia Networks

802.16 General Characteristics

- Point-to-multipoint architecture
- TDD or FDD modes of operation
- Support of multiple services with QoS
- MAC layer designed for optimizing spectrum usage
- Four physical layer modes providing considerable flexibility in support of multiple frequency allocations in < 11GHz and 10-66 GHz range

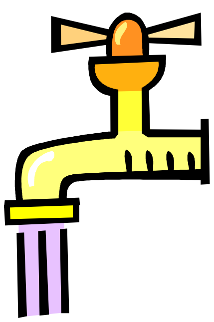
OFDM Basics

Why the Focus on OFDM?

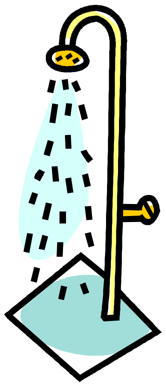
- The OFDM signal is able to support NLOS performance while maintaining a high level of spectral efficiency maximizing the available spectrum.
- Superior NLOS performance enables significant equalizer design simplification.
- Supports operation in multi-path propagation environments.
- Usage of cyclic prefix provides additional multi-path immunity as well as tolerance for time synchronization errors.
- Scalable bandwidths provide flexibility and potentially reduces capital expense.

OFDM Basic Concept

- OFDM is a multi-carrier modulation scheme that transmits data over a number of orthogonal sub-carriers
- A conventional transmission uses only a single carrier, which is modulated with all the data to be sent
- OFDM breaks the data to be sent in to small chunks, allocating each sub-data stream to a sub-carrier and the data is sent in parallel orthogonal sub-carriers.



FDM

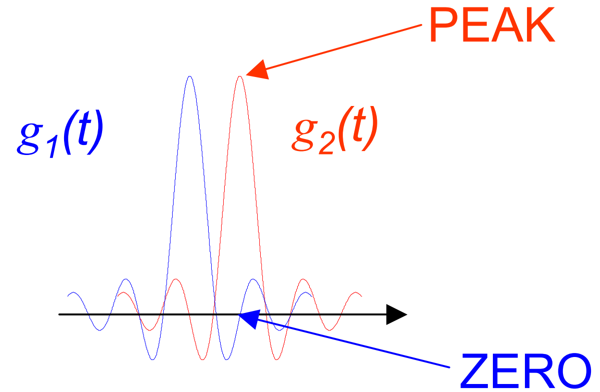


OFDM

Orthogonality Principle

Two signals $g_1(t)$ and $g_2(t)$ are said to be orthogonal over the period Ts if:

$$\int_0^{T_s} g_1(t)\, g_2^*(t)\, dt = 0$$

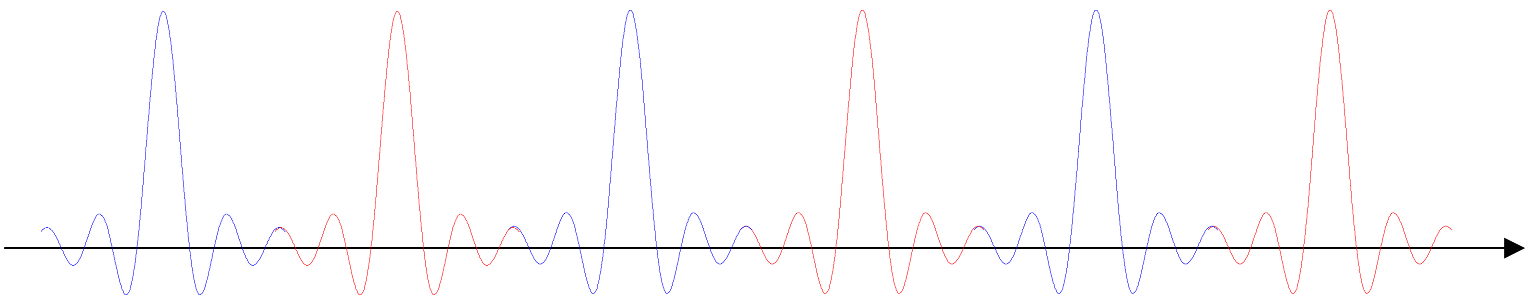


For example:

$$\int_0^{T_s} e^{j2\pi f_p t} . e^{-j2\pi f_q t}\, dt = 0$$

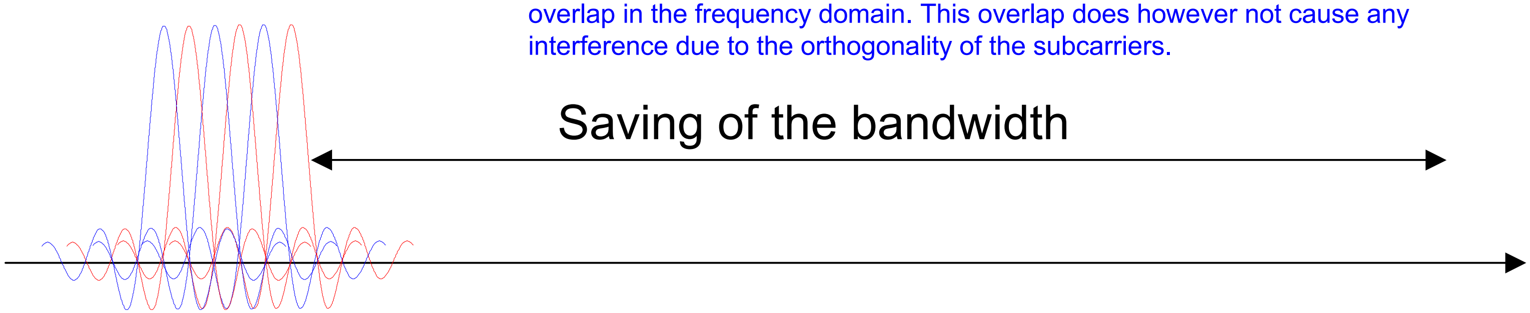
for $p \neq q$, where $f_k = k/T$

OFDM Spectral Overlap



Conventional Frequency Division Multiplex (FDM) Multi-carrier Modulation Technique

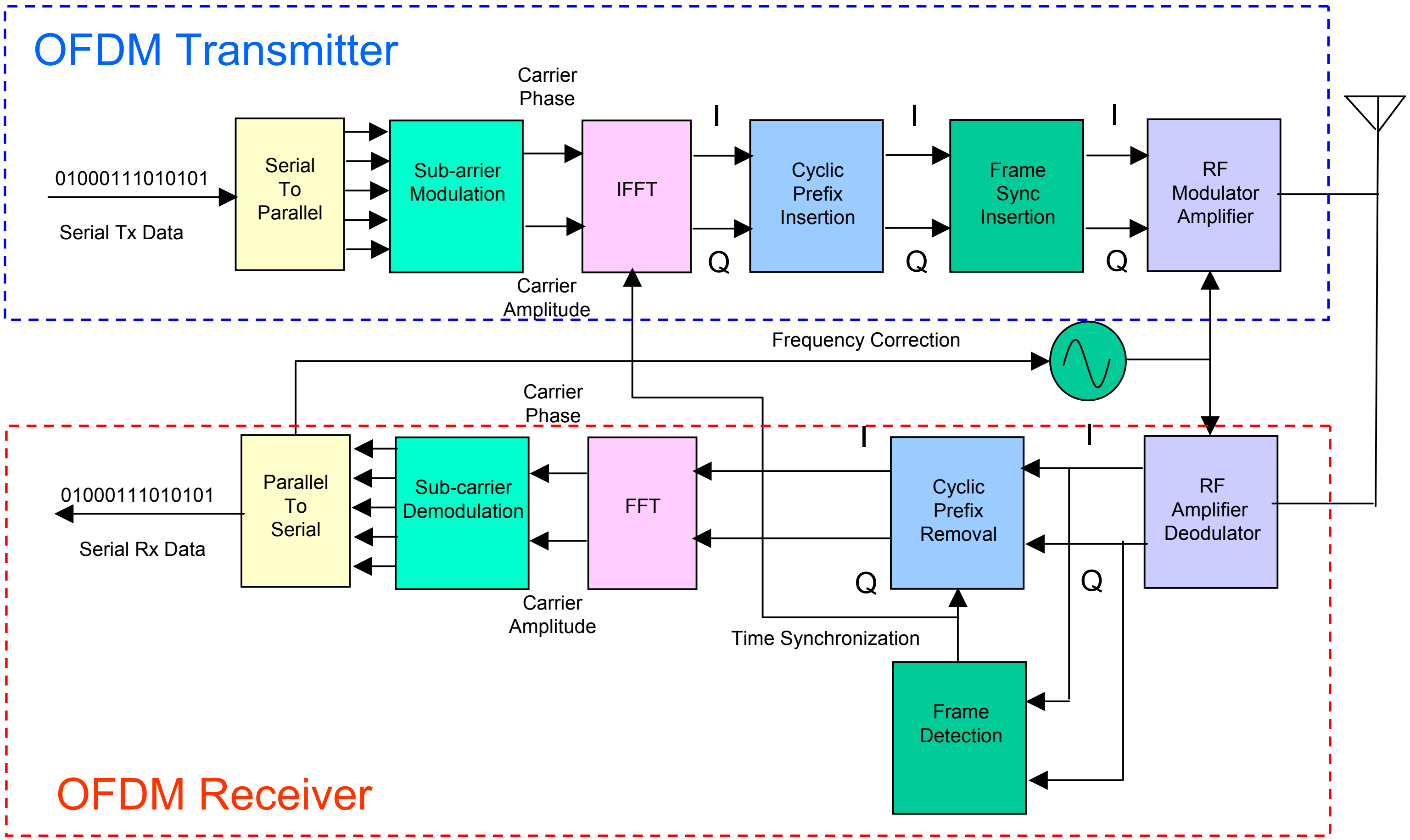
OFDM subcarriers have a sinc (sin(x)/x) frequency response resulting in overlap in the frequency domain. This overlap does however not cause any interference due to the orthogonality of the subcarriers.



Orthogonal Frequency Division Multiplex (OFDM) Multi-carrier Modulation Technique

The OFDM receiver uses a time and frequency synchronized FFT to convert the OFDM time waveform back into the frequency domain. In this process the FFT picks up discrete frequency samples, corresponding to just the peaks of the carriers. At these frequencies, all other carriers pass through zero amplitude eliminating any interference between the subcarriers.

OFDM Transceiver



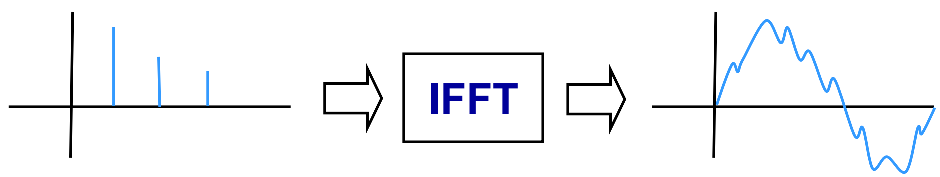
IFFTs and FFTs in OFDM

Why is there an IFFT in the transmitter?

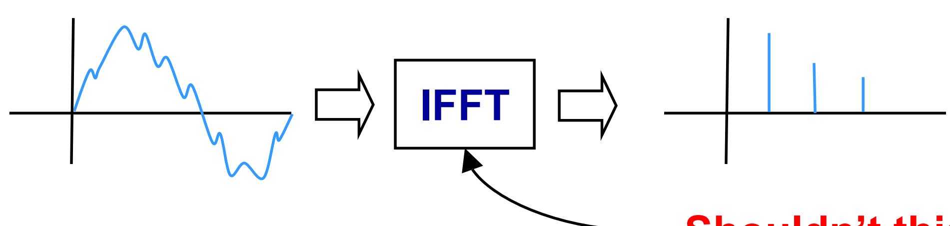
IFFT :

$$X(n) = \sum_{n=0}^{N-1} x(k)\sin\left(\frac{2\pi kn}{N}\right) - j\sum_{n=0}^{N-1} x(k)\cos\left(\frac{2\pi kn}{N}\right)$$

We’re used to thinking:
IFFT takes in frequency domain samples and outputs time domain samples



But this is what’s happening…right?



Shouldn’t this be an FFT?

IFFTs and FFTs in OFDM

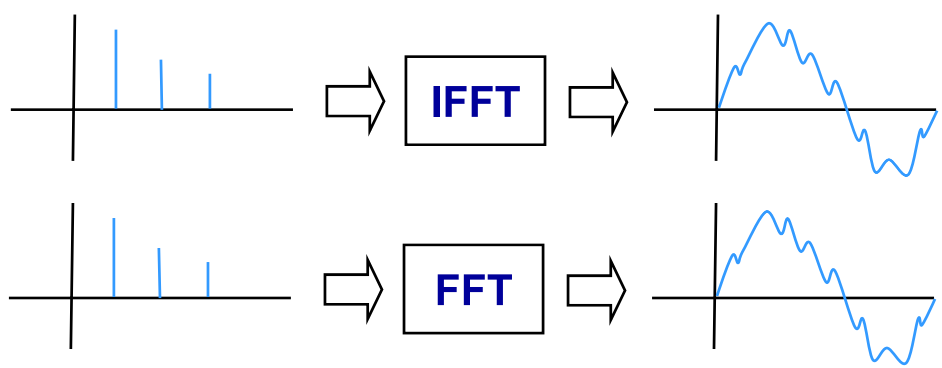
IFFTs and FFTs really do the same thing!

IFFT :

$$X(n) = \sum_{n=0}^{N-1} x(k)\sin\left(\frac{2\pi kn}{N}\right) - j\sum_{n=0}^{N-1} x(k)\cos\left(\frac{2\pi kn}{N}\right)$$

FFT :

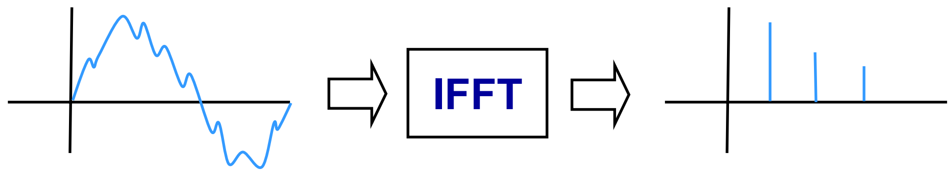
$$x(k) = \sum_{n=0}^{N-1} x(n)\sin\left(\frac{2\pi kn}{N}\right) + j\sum_{n-0}^{N-1} x(n)\cos\left(\frac{2\pi kn}{N}\right)$$



An FFT could be in the transmitter as long as IFFT is in receiver.

IFFTs and FFTs in OFDM

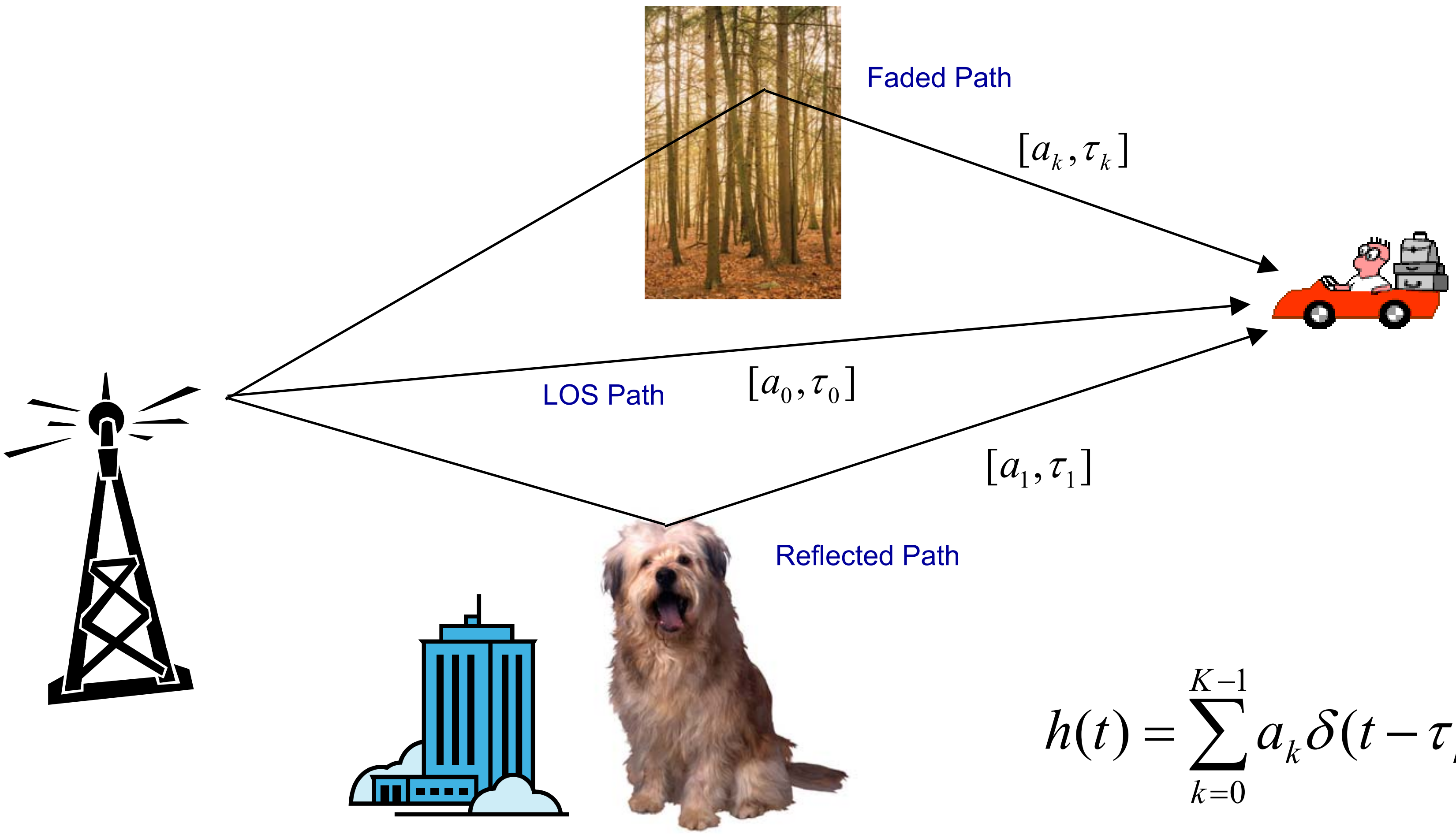
But time domain amplitudes (bits) are still input to the IFFT...
No problem!



Think of the bits as time domain amplitudes pretending to be frequency domain amplitudes.

IFFT computes the OFDM time domain signal all at once!
Much more efficient than processing one subcarrier at a time.

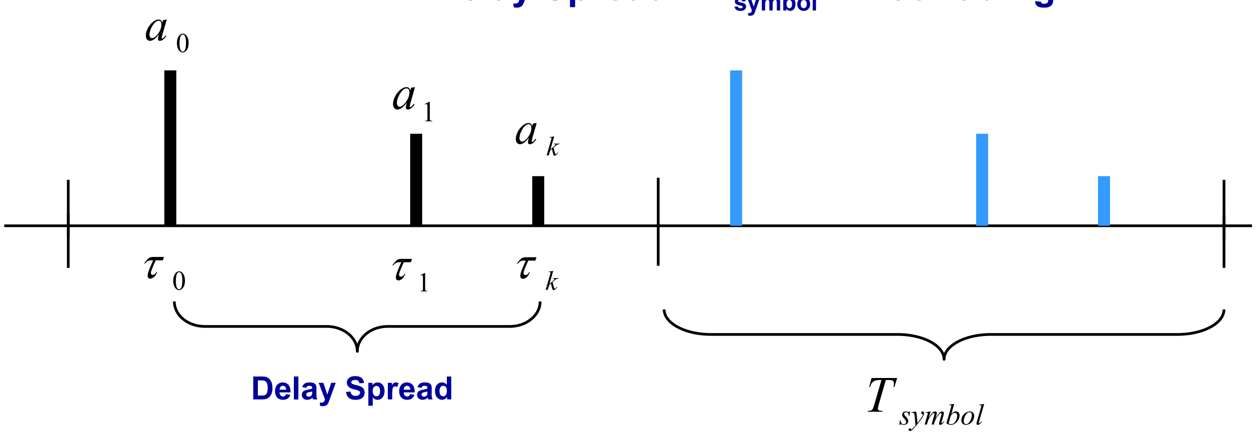
Multipath and OFDM



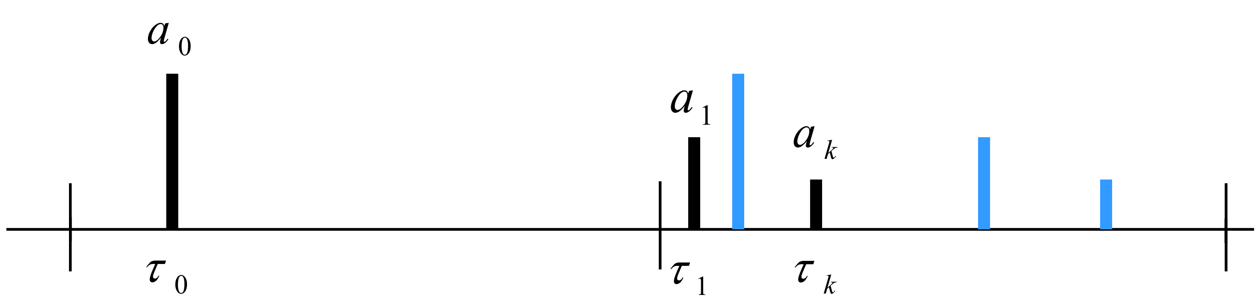
$$h(t) = \sum_{k=0}^{K-1} a_k \delta(t - \tau_k)$$

Multipath and OFDM

Delay Spread < T_{symbol} : Flat Fading

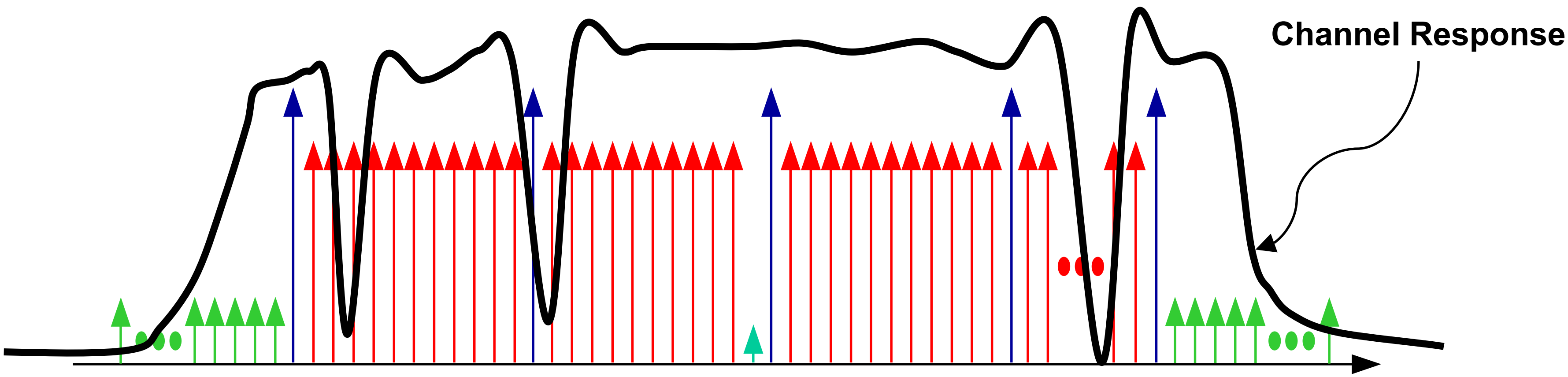


Delay Spread > T_{symbol} : Frequency Selective Fading



Multipath and OFDM

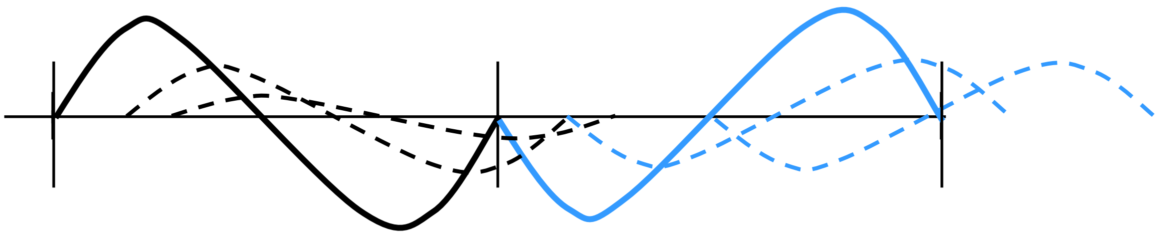
OFDM Offers Advantage in Frequency Selective Fading Environments



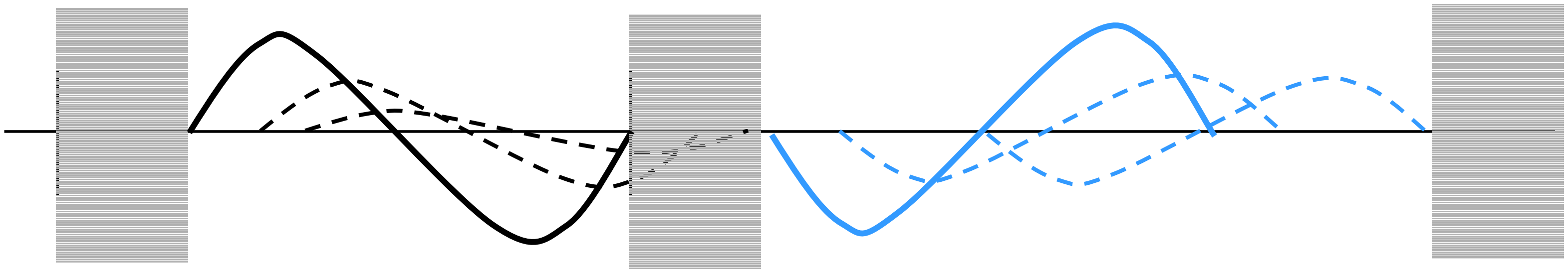
Only a few subcarriers are lost due to fading. This can be overcome with proper channel coding.

More Multipath Mitigation…Cyclic Prefix

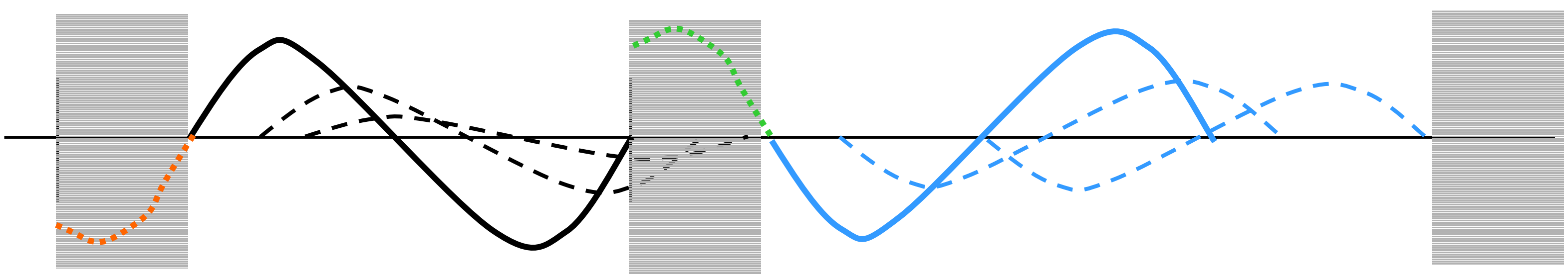
Delay spread exceeds symbol time



Add a gap to capture delay spread

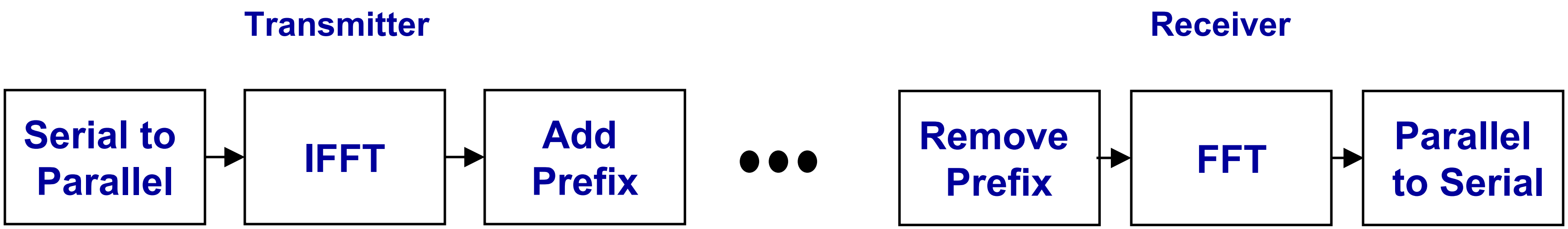


Can't have gaps in transmission…copy part of symbol and put it in the front



More Multipath Mitigation…Cyclic Prefix

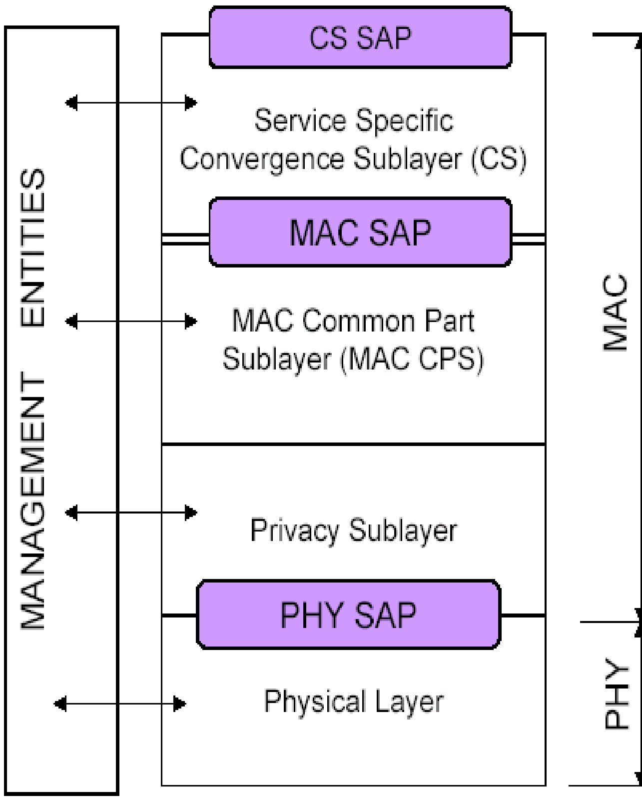
Cyclic prefix can be added to composite signal instead of to each subcarrier.



Cyclic prefix helps mitigate multipath fading and inter-symbol interference at a price of increasing bandwidth

802.16e Physical Layer (OFDMA) Overview

802.16 Layer Characteristics



Service Specific Convergence Sublayer (CS) provides mapping or transformation of external network data received through the CS Service Access Point (SAP) into MAC Service Data Units received by the MAC CPS through the MAC SAP. This Includes: classifying external network SDUs and associating them to the proper MAC service flow and Connection Identifier, payload header suppression, etc.

MAC CPS provides the core MAC functions, such as, uplink scheduling, bandwidth request & grant, connection establishment, connection maintenance, ARQ and ranging. Receives data through MAC SAP classified to particular MAC connections. QoS is applied to the transmission and scheduling of data over PHY. MAC contains a separate Privacy Sub-layer providing authentication, secure key exchange and encryption.

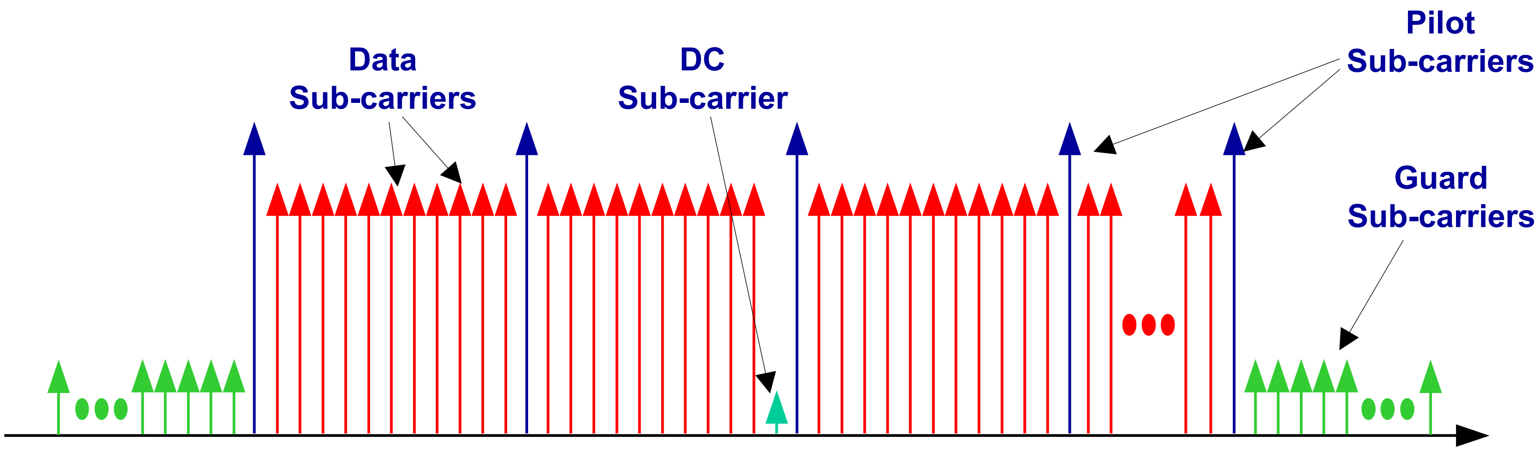
Data, PHY control and statistics are transferred between the MAC CPS and the PHY via the PHY SAP. The PHY may include multiple specifications, each appropriate to a particular frequency range and application.

Physical layer defines the characteristics of the hardware

802.16 PHY Layer Characteristics

- **Four physical layers (SC, SCa, OFDM, OFDMA)**
  - OFDMA is the focus today
  - Non-line of sight operation
- **Multiple options for:**
  - Channel bandwidths
  - Frame lengths
  - Duplexing modes (TDD, FDD)
  - Channel coding
  - Cyclic prefixes
- **Support for multiple antenna technology**
  - Adaptive antennas (AA)
  - TX diversity (STC, MIMO)
- **Link adaptation**
  - Adaptive modulation and coding per subscriber
  - Trade off capacity and robustness in real time
  - Burst profile of broadcast information is well known

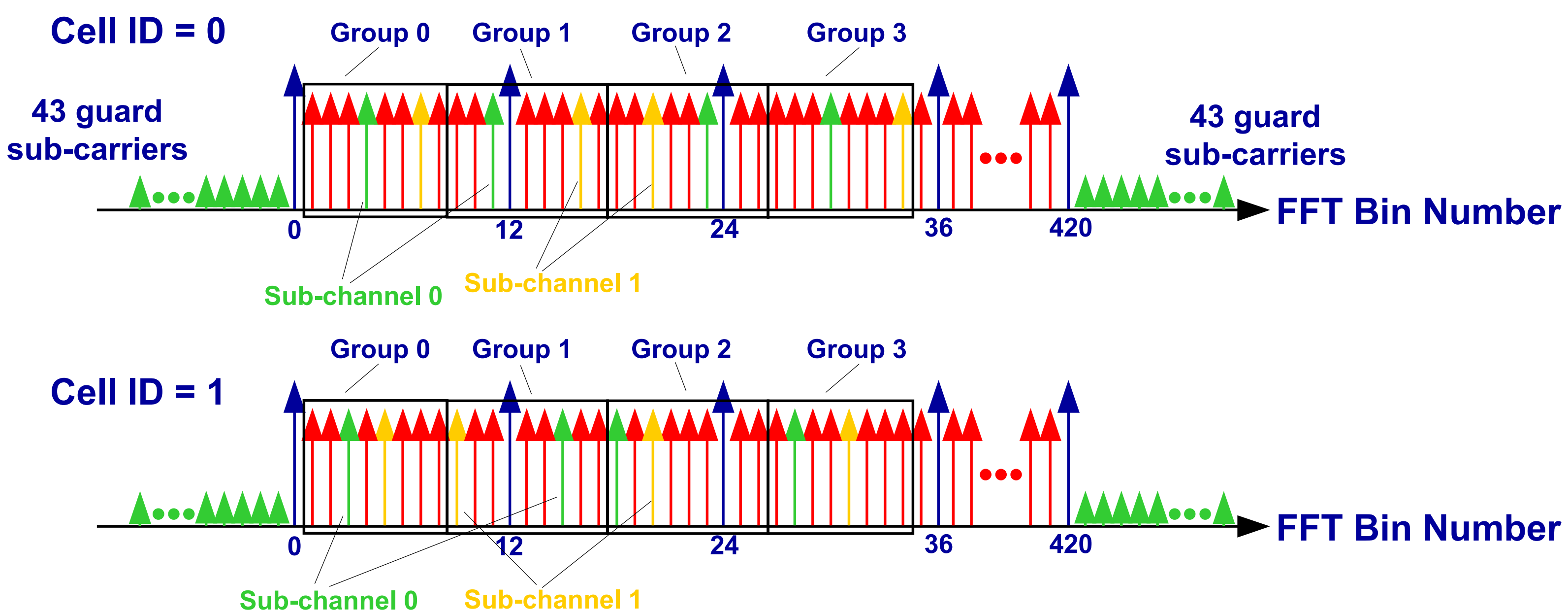
OFDM Fundamentals – Signal in Frequency Domain



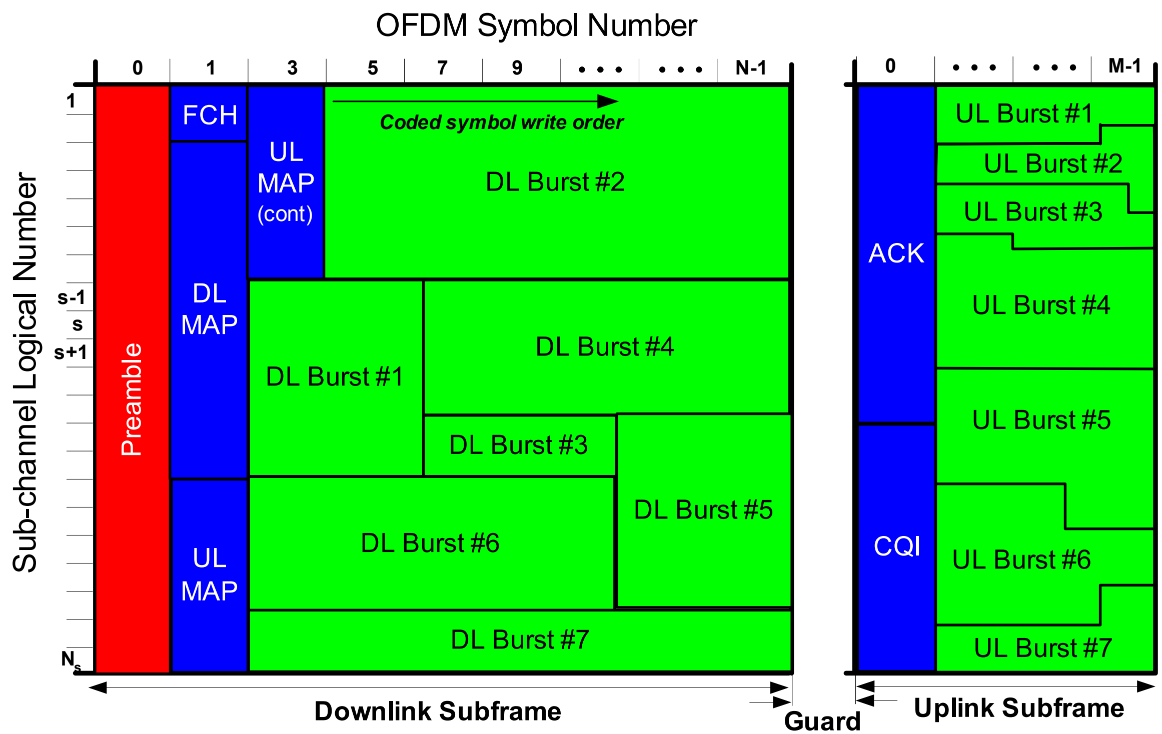
- **OFDM Sub-carrier Organization**
  - **Data Sub-carriers**
    - Transport QPSK, 16-QAM, 16-QAM, 256-QAM etc. symbols
  - **Pilot Sub-carriers**
    - Transport known pilot symbol sequence (frequently at elevated power level) to permit channel estimation and coherent demodulation at receiver
  - **Guard Sub-carriers**
    - Suppressed – permits spectrum shaping
  - **DC Sub-carrier**
    - Frequently suppressed to support direct-conversion receivers (with significant zero-frequency component ingress due to 1/f noise etc.)

Downlink Sub-Channel Construction

- ***Distributed*** **Sub-carrier Allocation (NFFT = 512)**
  - **Available data sub-carriers divided into N contiguous groups**
    - Each sub-channel assigned one data sub-carrier from each group
  - **Sub-channel size constant – 48-sub-carriers per sub-channel**
  - **Sub-carriers comprising sub-channel permuted using Cell ID**
  - **Additional optional sub-channel decomposition also defined**

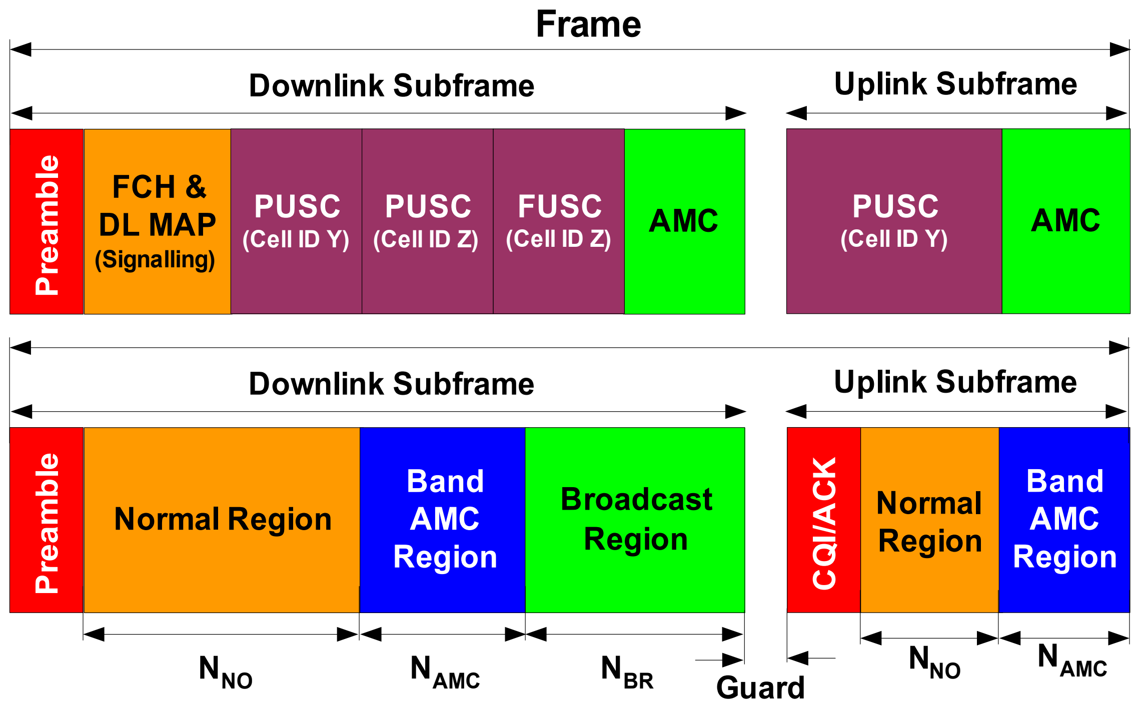


Frame Structure



- **Key Elements**
  - DL bursts are arbitrary congruent blocks – uplink follow in sequence
  - DL and UL maps indicate per burst data regions, modulation, coding etc.
  - Allocated regions for UL for random access, channel quality (CQI), ACK's

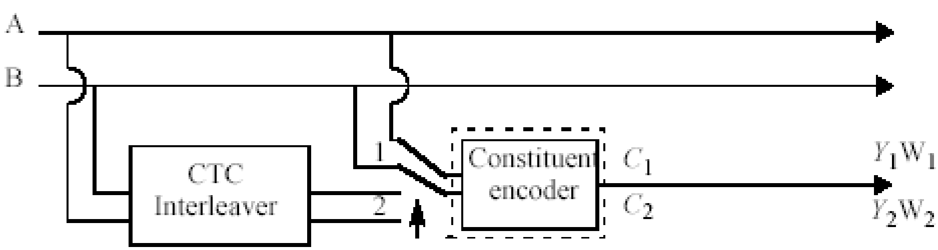
Frame Partitioning into Zones – Broadcasting Support

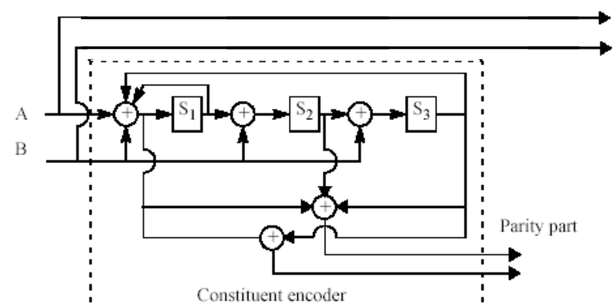


- **Zone Partitioning**
  - ***Normal* region – frequency-diverse sub-channels**
    - Time scheduling possible but no frequency-specific scheduling
      - e.g. used for voice services without scheduling or for flat channels
  - ***Band AMC* region – adjacent sub-channels**
    - Time *and* frequency scheduling possible
  - ***Broadcast* region – frequency-diverse sub-channels in simulcast mode**
    - Borrows concept of single frequency network (SFN) from DVB/DAB etc.

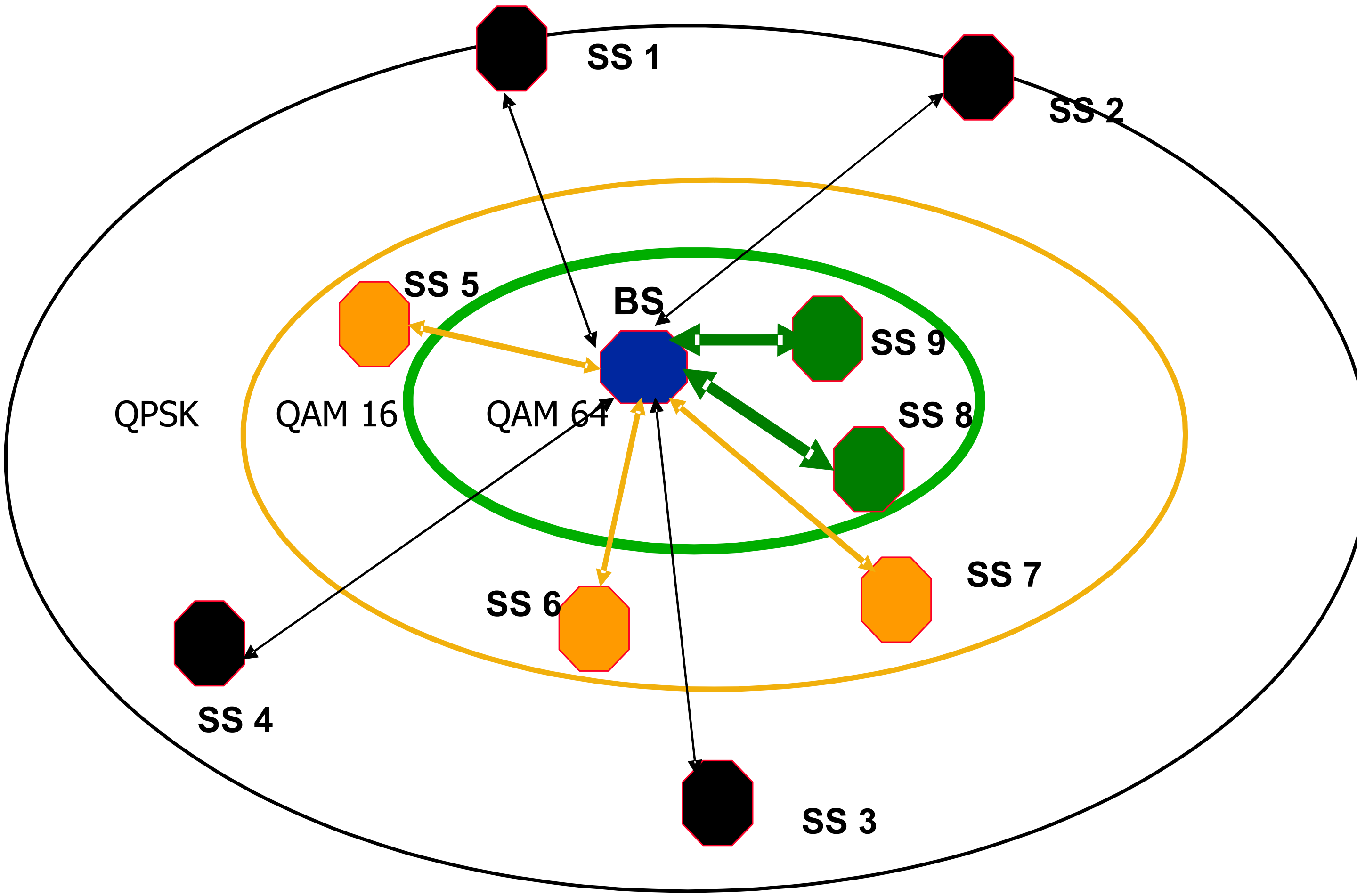
802.16e Modulation and Coding

- **Modulation & Coding**
  - **QPSK, 16-QAM, and 64-QAM *nominally* support at BS and MS**
  - **Mandatory : tail-biting convolutional code (K=7)**
  - **Optional: Block turbo code (BTC), Convolutional turbo code (CTC)**
    - CTC encoder adopted from DVB-RCT specification – similar perf. to 3GPP
  - **Optional LDPC code under study**



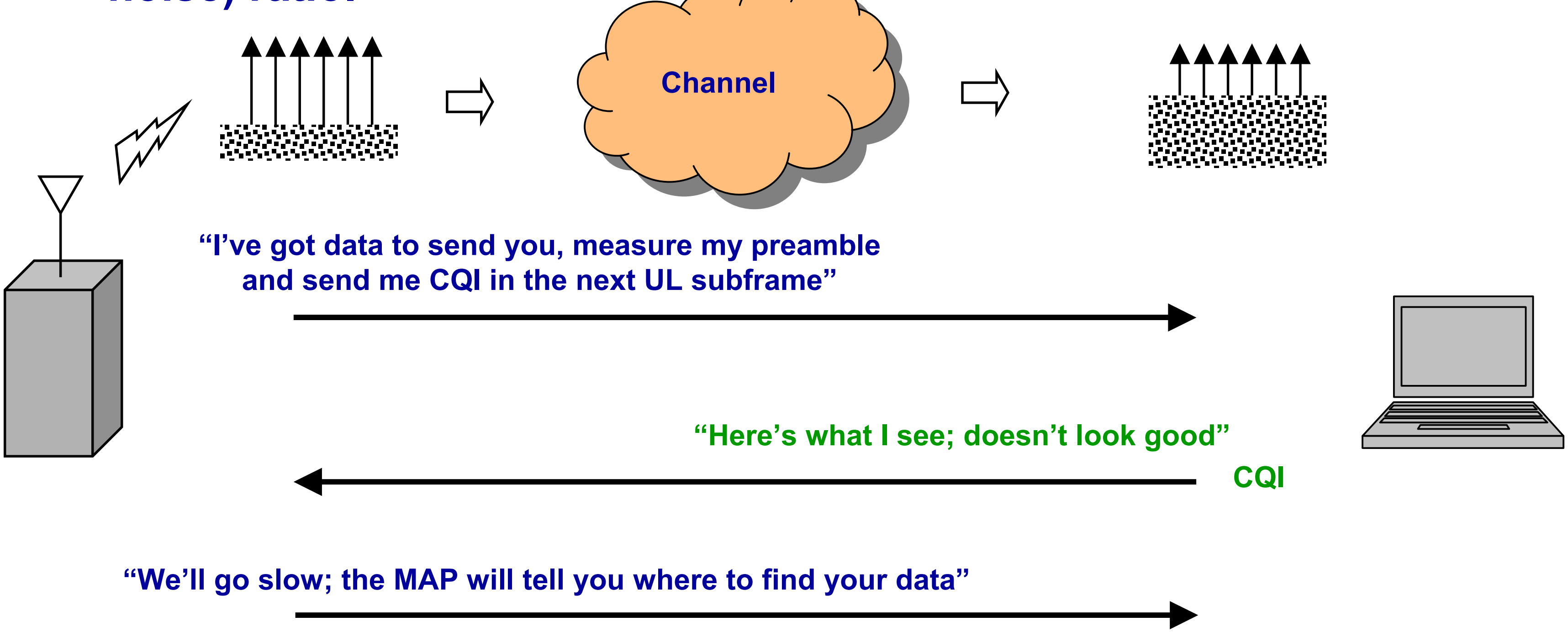


Adaptive Modulation and Coding

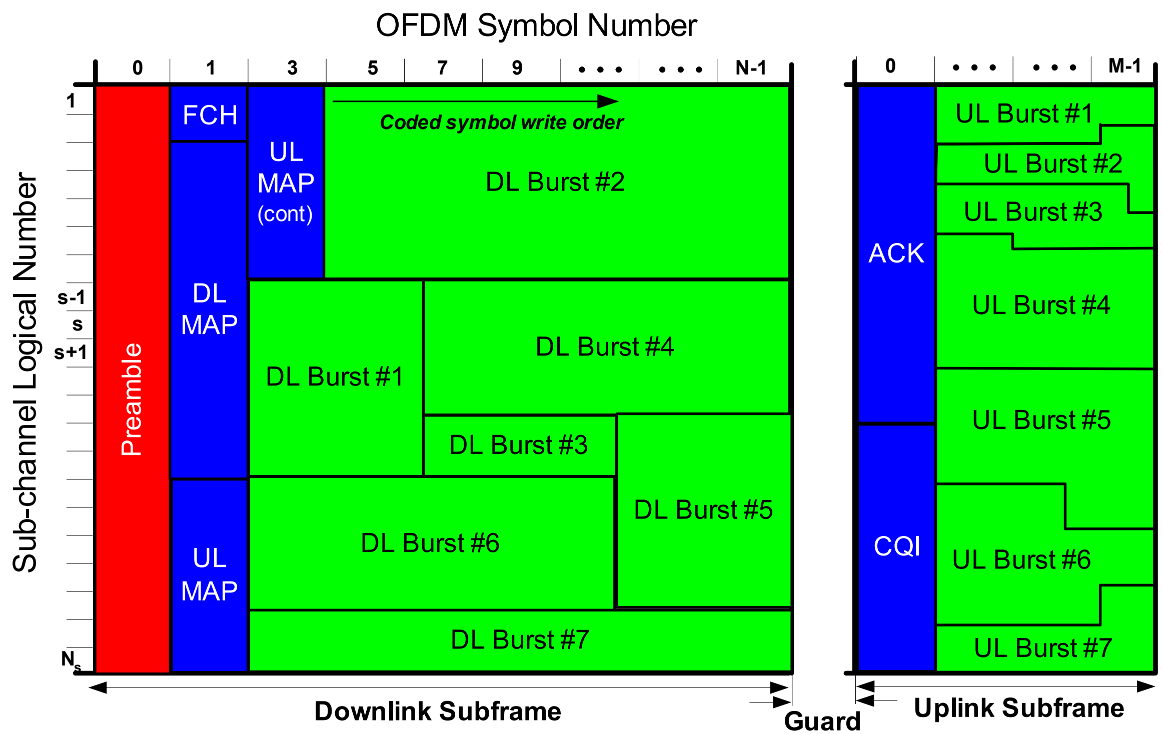


Channel Quality Indicator

- Base Station uses Adaptive Modulation and Coding (AMC) to send data to the subscriber stations to optimize throughput.
- Base Station needs to know how the channel looks to the subscriber so it tells subscriber to measure the carrier to (interference plus noise) ratio.



Where's the CQI?



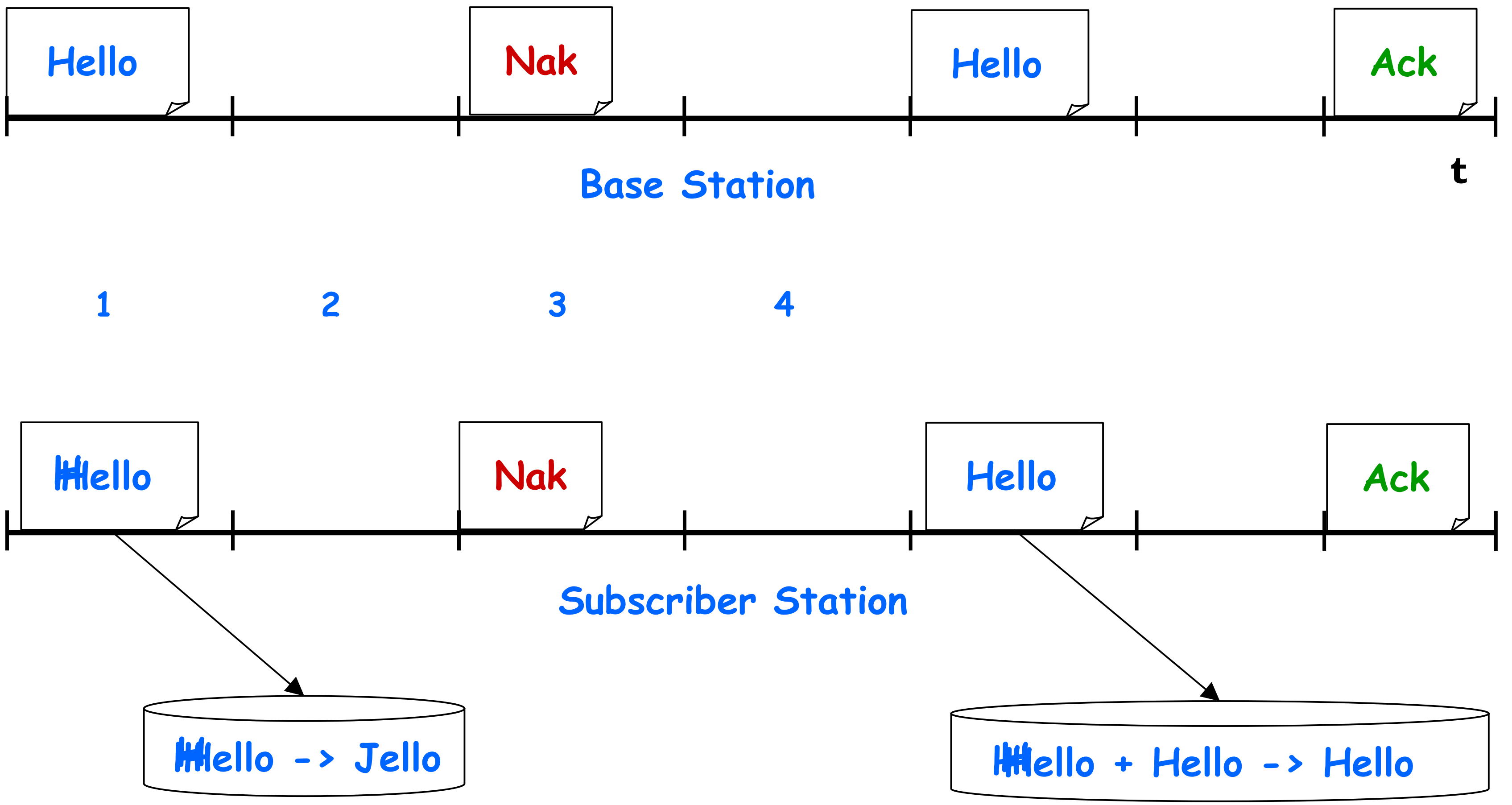
- **CQIs are periodically requested so that there is room in the UL subframe for data to be sent.**

Features: Hybrid Automatic Repeat-Request (HARQ)

- **Self-optimizing and adjusts automatically to channel conditions without requiring frequent or highly accurate C/I measurements**
  - Adds redundancy only when needed
  - Receiver saves failed transmission attempts to help future decoding (Chase Combining)
  - Every transmission helps to increase the packet success probability

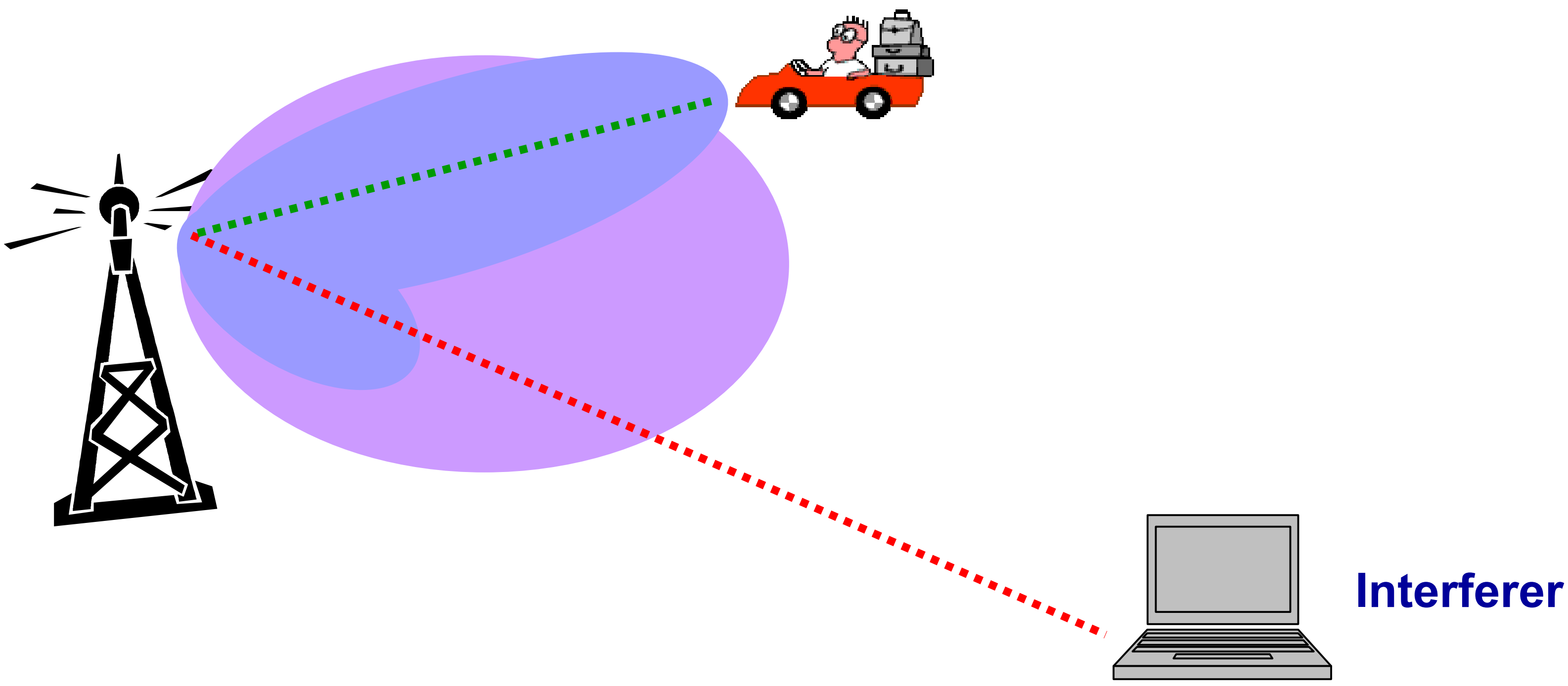
- **Enabled by *N*-Channel Stop-and-Wait ARQ**
  - Receiver sends an ACK or NAK in response to each transmission

HARQ: N Stop and Wait HARQ Protocol



Features: Adaptive Antennas

- Make measurements of channel
- Compute gain and phase coefficients to adapt beam pattern
- Increase link gain, reduce interference



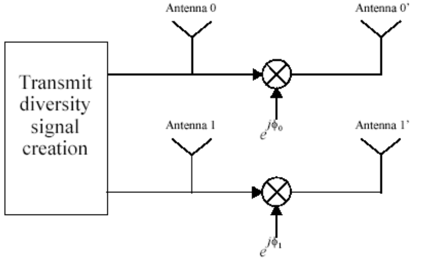
Transmit Diversity and MIMO

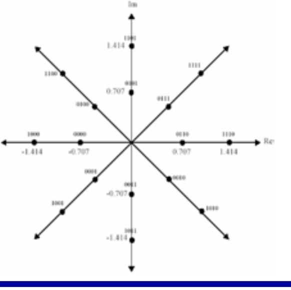
- **Transmit Diversity – Space-Time Coding (STC) (*All optional*)**
  - **Downlink (DL) open-loop transmit diversity**
    - 2nd-order transmit diversity – same as 3GPP open-loop transmit diversity
    - 4th-order transmit diversity – 3 approaches defined – varying STC coding rates

$$M_1 = \begin{bmatrix} s_1 & -s_2^* & 0 & 0 \\ s_2 & s_1^* & 0 & 0 \\ 0 & 0 & s_3 & -s_4^* \\ 0 & 0 & s_4 & s_3^* \end{bmatrix} \qquad M_2 = \begin{bmatrix} s_1 & -s_2^* & s_5 & -s_7^* \\ s_2 & s_1^* & s_6 & -s_8^* \\ s_3 & -s_4^* & s_7 & s_5^* \\ s_4 & s_3^* & s_8 & s_6^* \end{bmatrix} \qquad M_3 = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}$$

  - **Uplink (UL) open-loop transmit diversity**
    - 2nd-order transmit diversity – same as 2nd-order DL approach
- **'MIMO'**
  - **Applicable to 4 transmit antenna configurations (used *with* STC)**
    - Fast-feedback element specifies transmit weighting coefficient
    - Effectively, a closed-loop extension of 2nd-order open-loop Tx diversity

Transmitter Configuration





Feedback Elements

Conclusions

Conclusions

- **802.16e Pros**
  - Scalable Bandwidths
  - Performs well in high delay spread environments
  - Higher data rates
  - TDD allows for deployment with less spectrum
  - Supports multiple antenna technologies
- **802.16e Cons**
  - High peak-to-average power
  - How will it perform in high interference environment?
  - What is performance in high Doppler?
  - Signaling overhead
  - Spectrum availability
  - Network layers not clearly defined yet

Still lots of good problems to solve!

Q&A

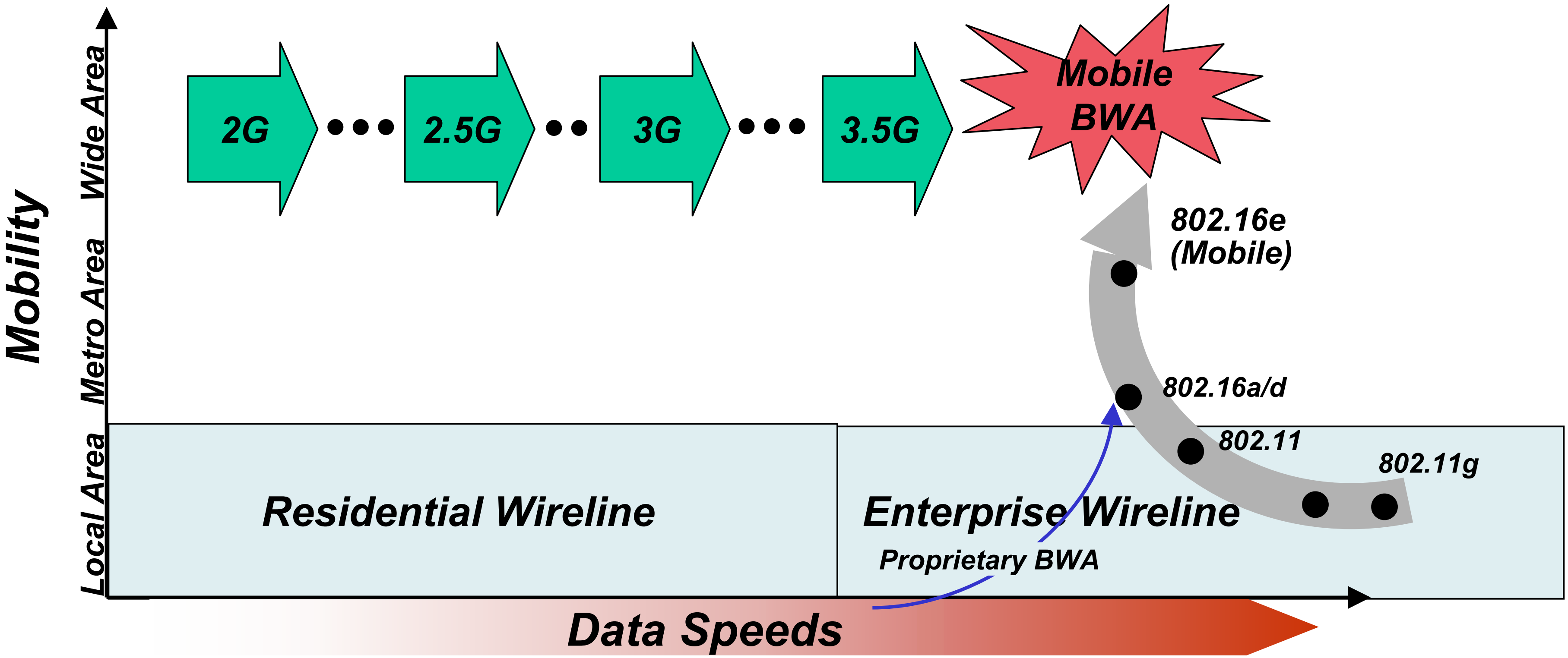
Questions?

Steve.Hilton@motorola.com

Thank you!

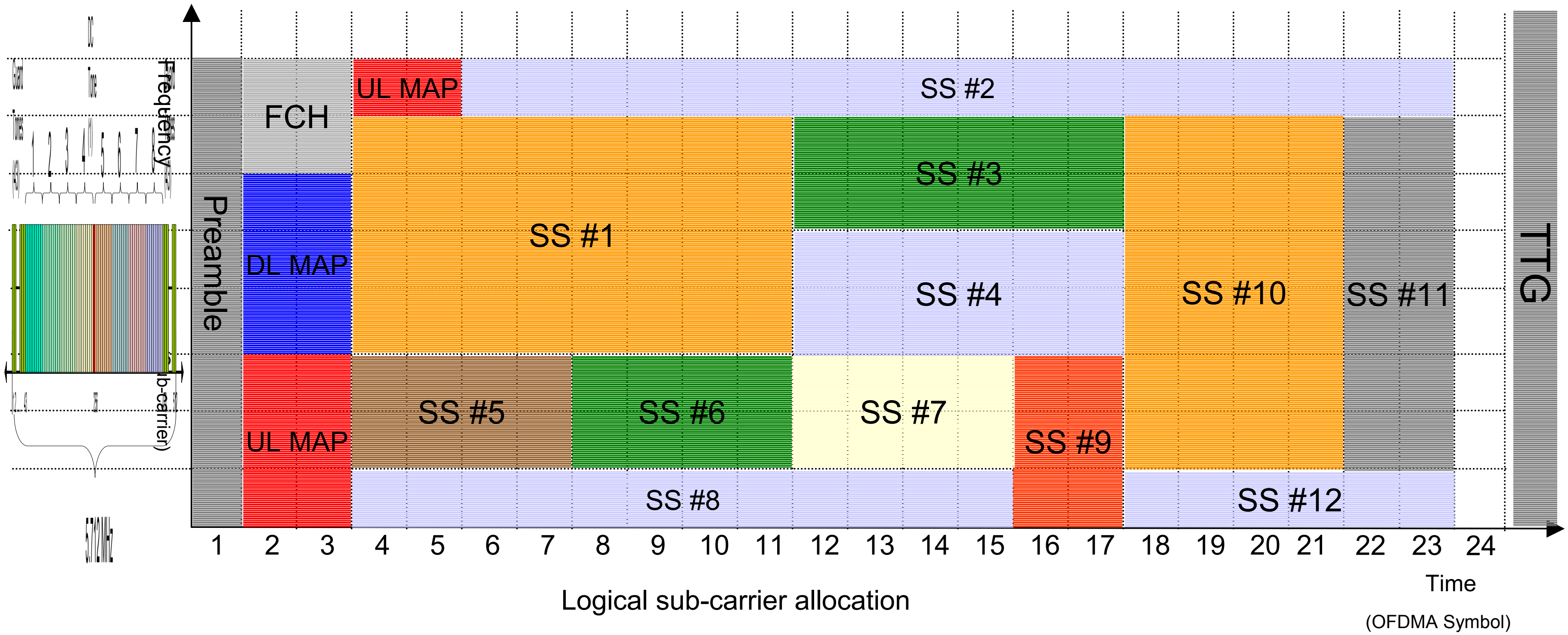
Backup

3GPP/3GPP2 vs. 802.x Convergence



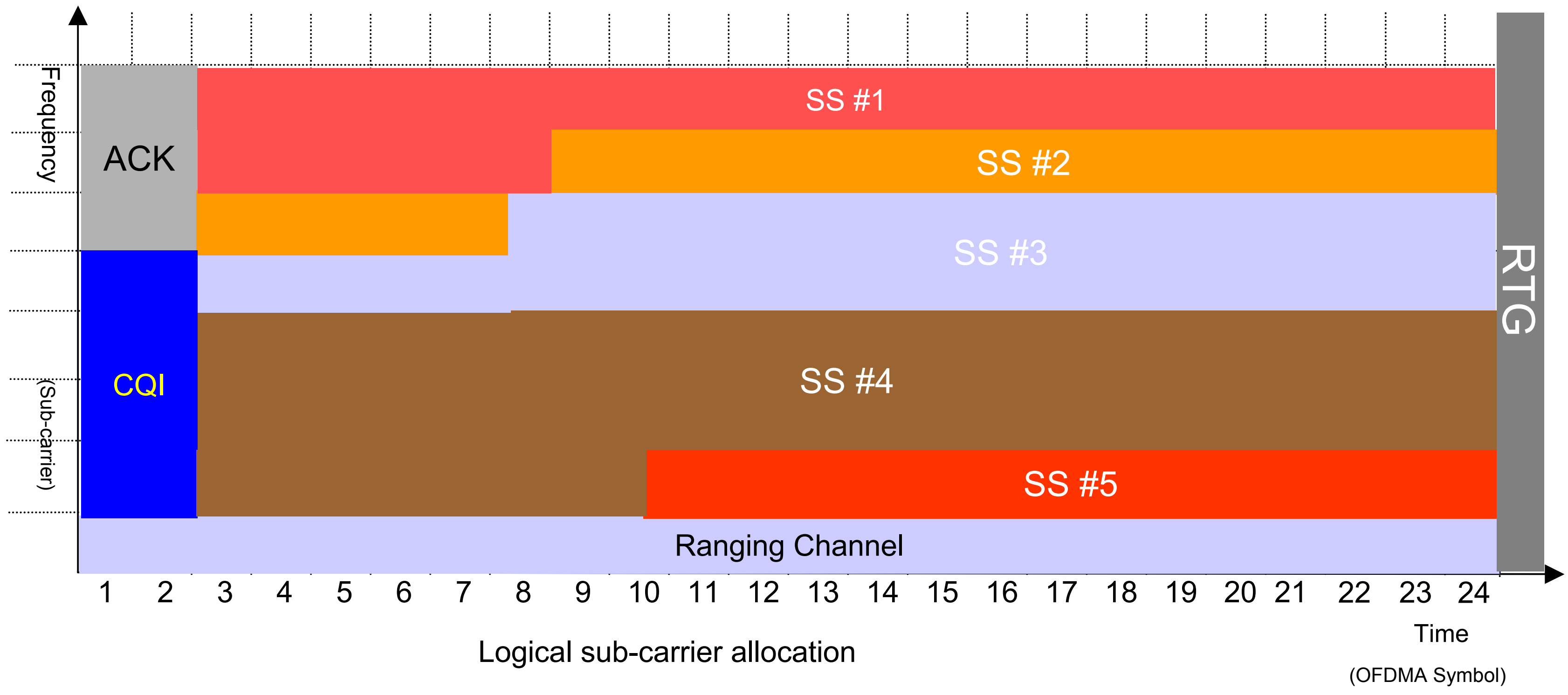
- **Initial deployments of 802.16 will be for fixed or nomadic systems**
  - **Using 802.16-2004, based on OFDM-256 mode**
- **But, migration to the fully mobile 802.16e specification will occur**
  - **Most likely based on Scalable OFDM mode**

OFDMA Physical Channel (Downlink) Allocation – An Example



PUSC: each allocable slot is 2 OFDM symbols × 1 Sub-channel
FUSC: each allocable slot is 1 OFDM symbol × 1 Sub-channel

OFDMA Physical Channel Allocation – Uplink (example)



References

[1] “Orthogonal Frequency Division Multiplex (OFDM) Tutorial”, Charan Langton, 1998.

[2] “Broadband Wireless RMTR Presentation”, Nat Natarajan, Motorola, Inc., March 15, 2004.

[3] “Simulation and Modeling of a Generic 802.16d/e TDD Implementation”, Yishen Sun, Motorola, Inc., October 2004.

[4] “802.xx WAN Standards Status and Technical Overview”, Motorola PCS, June 2004.