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# 18-759: Wireless Networks

## Lecture 18: Cellular

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**Spring Semester 2010**  
<http://www.cs.cmu.edu/~prs/wirelessS10/>

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1

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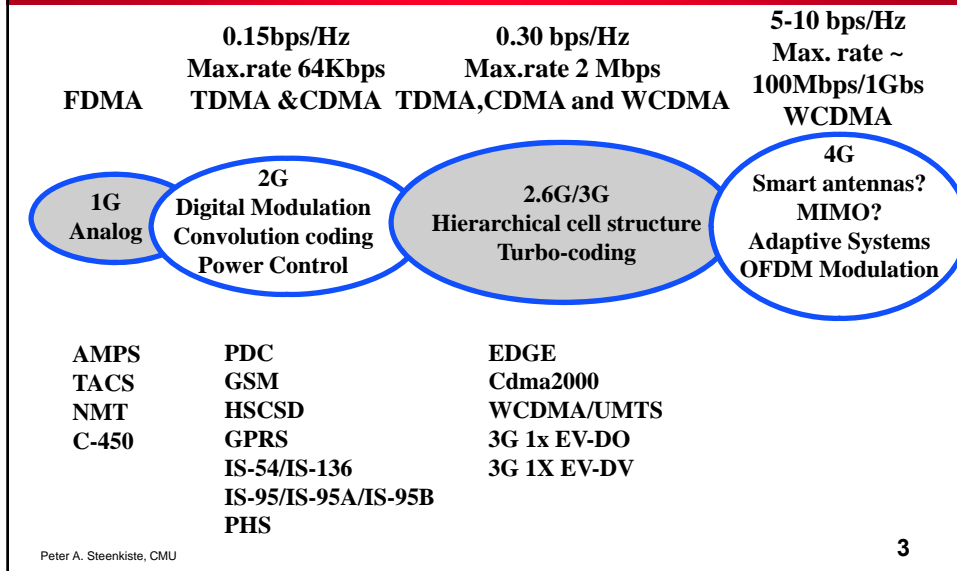
## Overview

- The cellular evolution
- OFDM
- OFDMA/SC-FDMA
- WiMAX
- LTE
- Comparison

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## The Cellular Landscape



## Cellular Standards

- **2G systems: digital voice**
  - » GSM - FDMA/TDMA, most widely deployed, 200 countries, a billion people
  - » IS-95 - first CDMA-based cellular standard, developed by Qualcomm
  - » IDEN - TDMA, Nextel, merged with Sprint, being phased out for CDMA2000
  - » IS-136 - uses FDMA/TDMA, North America, Cingular and US Wireless, being phased out for GSM, CDMA2000
- **2.5G systems: voice and data channels**
  - » GPRS - evolved from GSM, packet-switched, 170 kbps (30-70 in practice)
  - » CDMA2000 1xRTT - evolved from IS-95, 144 kbps

# Cellular Standards

- **2.75G - almost 3G in speed**
  - › EDGE - another enhancement of GSM, 384 kbps, 2.75G
  - › Thanks to new modulation scheme (8PSK) – may coexist with GMSK
- **3G: voice (circuit-switched) and data (packet-switched)**
  - › UMTS - W-CDMA, successor to GSM networks, 384 kbps - 2 Mbps, European, some Japan, Cingular in U.S.
  - › CDMA2000 1xEV - CDMA2000 with high data rates - 3.1 Mbps up, 1.8 Mbps down, U.S., Japan, Korean, Canada – Verizon, Sprint
- **4G: 10 Mbps and up, seamless mobility between different cellular technologies, mesh, etc.**

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5

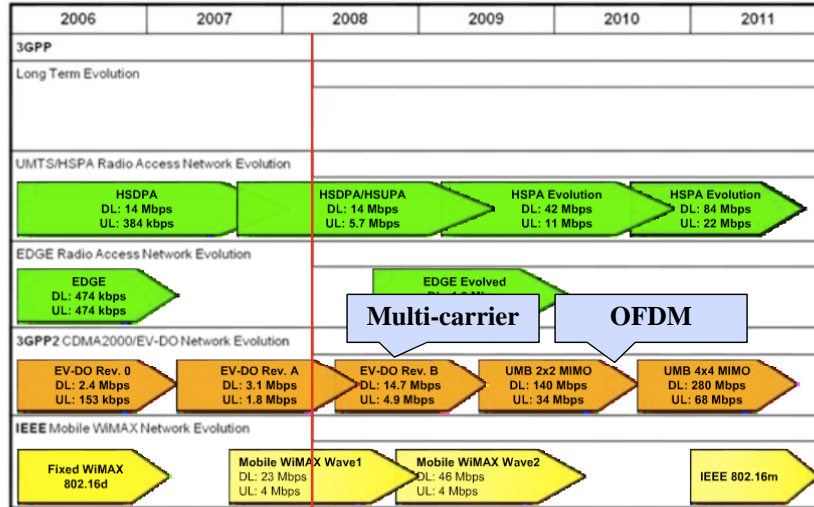
## Radio Access Technology Roadmap



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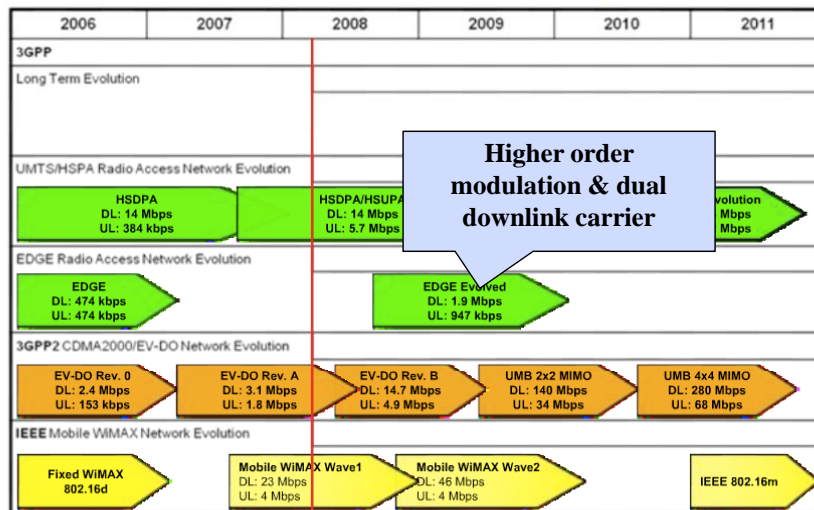
## Radio Access Technology Roadmap



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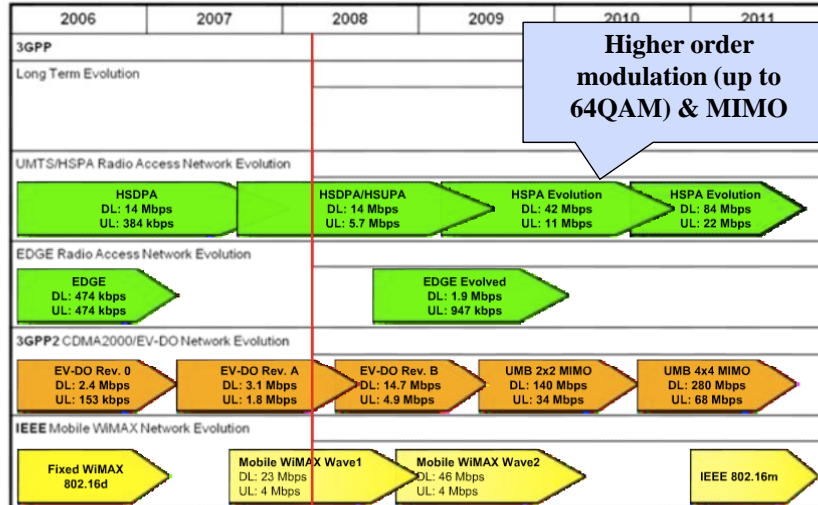
## Radio Access Technology Roadmap



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## Radio Access Technology Roadmap

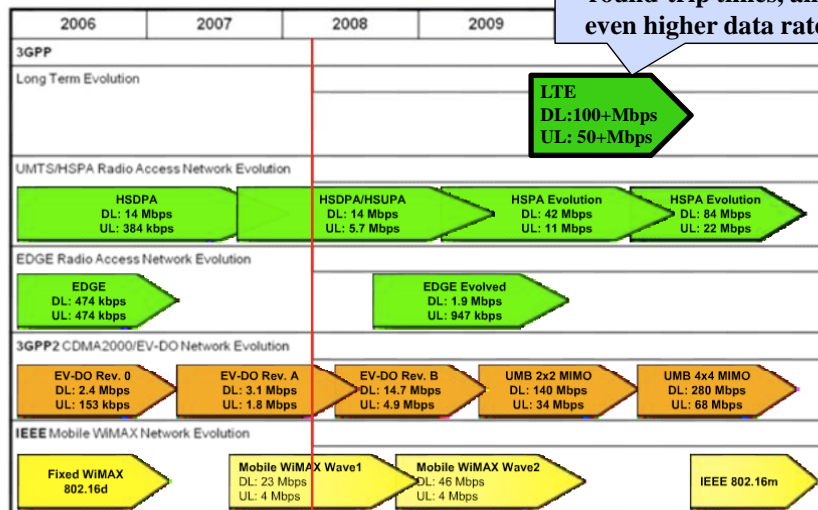


Higher order modulation (up to 64QAM) & MIMO

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## Radio Access Technology Roadmap



Spectral efficiency, lower round-trip times, and even higher data rates

LTE  
DL: 100+Mbps  
UL: 50+Mbps

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## Orthogonal Frequency Domain Modulation (OFDM)

- 40 year old technology!
- Wireline Asymmetric Digital Subscriber Line (ADSL)
- DAB and DVB-T (Digital Audio Broadcast and Digital Video Broadcast – Terrestrial used in Europe and elsewhere)
- HD Radio
- UWB
- WiFi
- ... among others...

Content adopted from

[http://www.mwjjournal.com/2008/DownloadablePDFs/Whipple\\_OFDM\\_Agilent.pdf](http://www.mwjjournal.com/2008/DownloadablePDFs/Whipple_OFDM_Agilent.pdf)

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11

## Cellular Adoption and Variants

- Low-cost, low power chipsets that can support the complex mathematics involved in creation and demodulation of OFDM transmission now possible
- 3GPP Long Term Evolution (LTE, GSM family of technologies)
- 3GPP2 – cdma2000
- IEEE 802.16 WiBro and WiMAX

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12

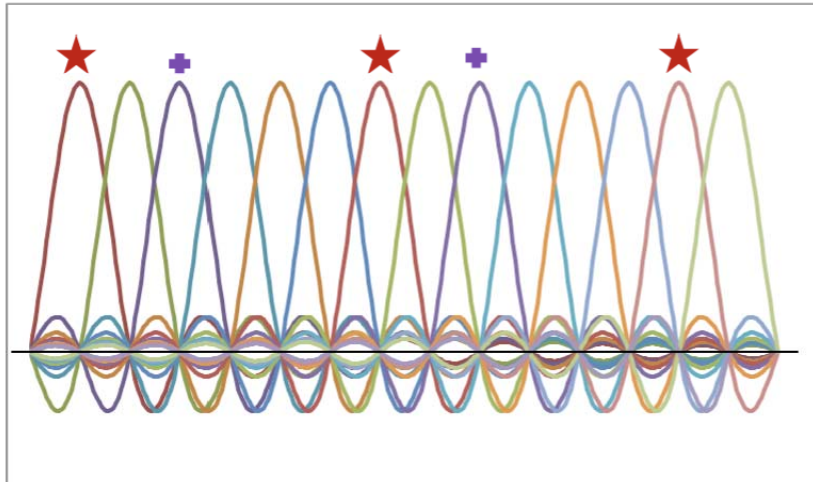
## Packet access only!

- Support for data and voice
- No provision for circuit-switched connections
- Voice over IP
- Requirement to reduce delay and round trip times across the network
- Quality of Service is important

## Why OFDM?

- Benefits of CDMA carry over
  - » Better immunity to fading as only a small portion of the energy for any one link is typically lost due to a fade
  - » Fast power control to keep the noise floor as low as possible
- Additional advantages
  - » Highly resistant to fading and inter-symbol interference
  - » Modulation is applied at a much lower rate on each of the many sub-carriers
  - » Sophisticated error correction
  - » Scales rates easier than CDMA
  - » Allows more advanced antenna technologies, like MIMO
- Breaks information into pieces and assigns each one to a specific set of sub-carriers

## Two channel assignments



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15

## How Does It Work?

- The sub-carriers for each user are spread across the entire spectrum
- Each particular assignment good for one symbol
- At the new symbol, the user has the same number of carriers and the same type of modulation on each
- Error correcting code is spread over all sub-carriers
- The reference signal of each sub-carrier needs to be known to allow for demodulation

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16

## Example

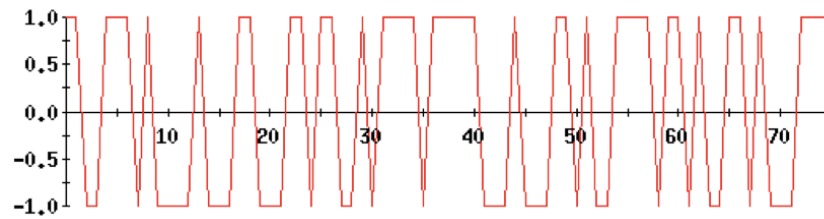


Fig. 7 – A bit stream that will be modulated using a 4 carrier OFDM.

First few bits are 1, 1, -1, -1, 1, 1, 1, -1, 1, -1, -1, -1, 1, -1, -1, -1, 1,...

## Example

Table I – Serial to parallel conversion of data bits.

c1	c2	c3	c4
1	1	-1	-1
1	1	1	-1
1	-1	-1	-1
-1	1	-1	-1
-1	1	1	-1
-1	-1	1	1

## Example

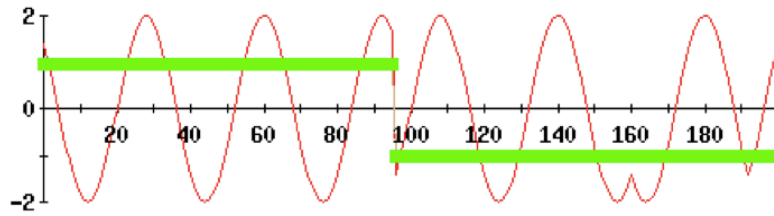


Fig. 8 – Sub-carrier 1 and the bits it is modulating (the first column of Table I)

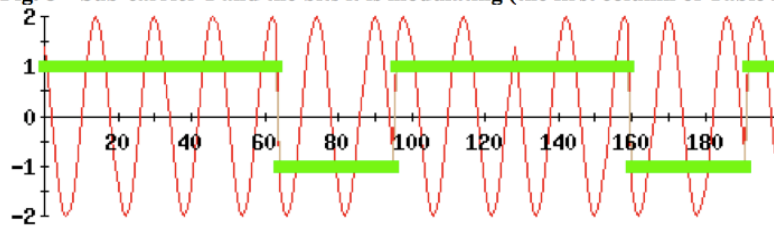


Fig. 9 – Sub-carrier 2 and the bits that it is modulating (the 2nd column of Table I)

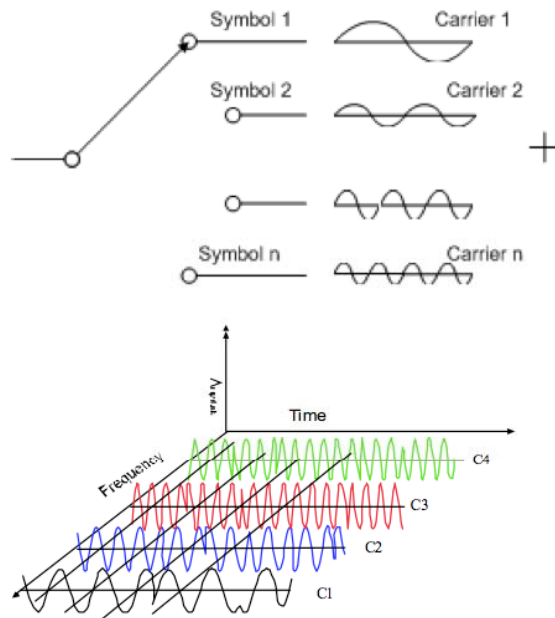


Fig. 11 – OFDM signal in time and frequency domain.

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20

## IFFT/FFT

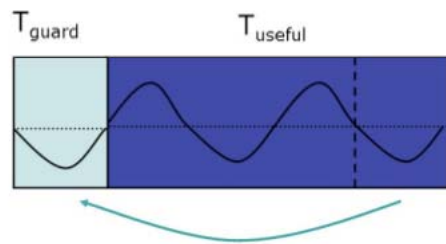
- OFDM signals best described in the frequency domain with information carried in the amplitude and the phase
- Conversion to the time domain through Inverse Fast Fourier Transform (IFFT)
- Demodulation through Fast Fourier Transform (FFT)

## Multi-path considerations

- Guard interval protects against inter-symbol interference caused by multi-path reception over path delays up to the length of the guard interval
- Guard interval also known as cyclic prefix (CP in LTE)
- It's a copy of the end of a symbol which is added at the beginning

## LTE Guard Interval

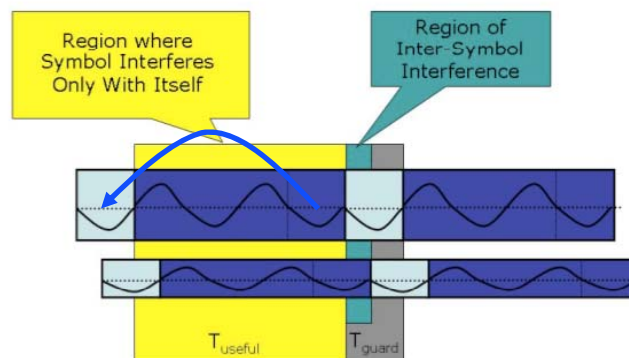
- For LTE, equal to  $4.69\mu\text{s}$ , out of a symbol length of  $66.7\mu\text{s}$
- Loss of capacity = 7%
- Copes with path delay variations up to 1.4Km



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23

## Robustness to ISI



**If time-sampling of the symbol is within the useful part, equalizers can take care of the path delay and the second path can be combined with the first to increase the probability of correct reception**

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24

## Symbol Length

- For OFDM systems symbol length defined by the reciprocal of the subcarrier spacing and chosen to be long compared to expected delay spread
- LTE – 15 KHz subcarrier spacing -> 66.7 $\mu$ s symbol length
- GSM – 200 KHz spacing with 270.883 ksps -> 3.69 $\mu$ s symbol length (18x shorter than LTE)
- W-CDMA – 5 MHz spacing with 3.84 Msps -> 0.26 $\mu$ s symbol length (256x shorter than LTE)
- The LTE CP would decrease capacity by more than half for GSM and by a factor of 20 for W-CDMA
- Systems that use short symbol lengths compared to delay spread need to rely on receiver-side channel equalizers

## Other benefits

- OFDM channel equalizers are much simpler to implement than are CDMA equalizers as the OFDM signal is represented in the frequency domain rather than the time domain
- OFDM is better suited to MIMO. The frequency domain representation of the signal enables easy pre-coding to match the signal to frequency and phase characteristics of the multipath radio channel

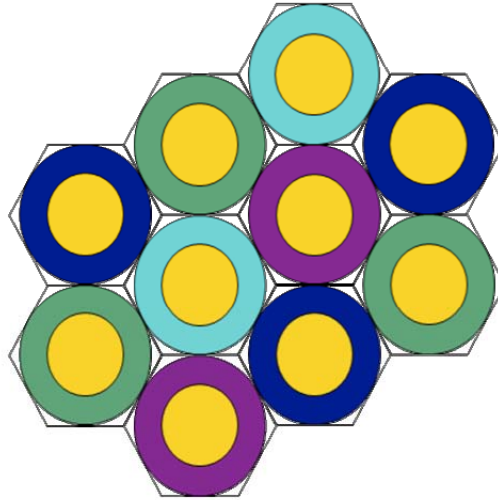
## OFDM disadvantages

- **As the number of sub-carriers increases, the composite time-domain signal starts to look like Gaussian noise, which has high peak-to-average Power ratio (PAPR) and can cause problems for amplifiers**
- **Avoiding distortion requires increases in cost, size and power consumption**

## OFDM disadvantages

- **To minimize the lost efficiency due to CP, desire to have long symbols, which means closely spaced subcarriers**
  - » Increase in processing overhead
  - » Subcarriers start losing their orthogonality due to frequency errors
- **Close subcarriers cause lost performance:**
  - » Frequency errors in the receiver cause energy from one subcarrier's symbol to interfere with the next
  - » Phase noise in the received signal causes similar ISI on the subcarriers but on both sides
  - » Doppler shift can cause havoc

## No protection against inter-cell interference at the edge



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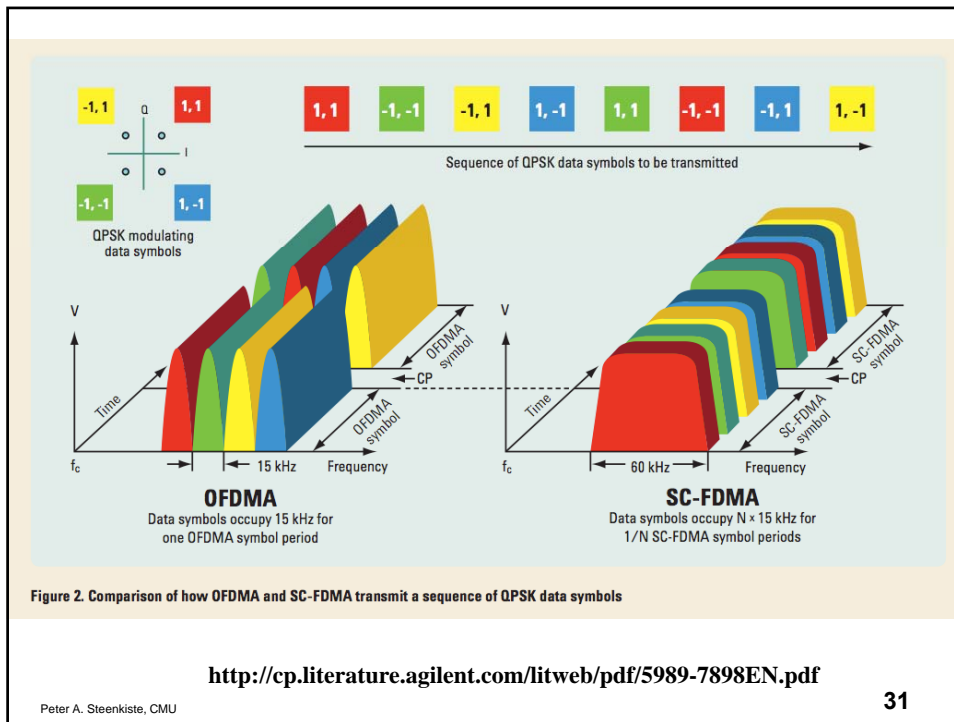
29

## SC-FDMA and OFDMA

- **High PAPR led to SC-FDMA for uplink**
  - » Applies linear precoding to the signal
  - » Reduces PAPR, which helps the mobile terminal in terms of power efficiency and complexity
- **OFDMA is the LTE OFDM elaboration**
- **Increases system flexibility by multiplexing multiple users onto the same subcarriers – efficient trunking of low-rate users onto a shared channel**
- **Enables per-user frequency hopping to mitigate effects of narrowband fading**

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30



## WiMaX

- Maximum transfer data rates of 50Mbps
- Sustained user data rates of 0.5-2Mbps
- Effective services at 3-5 miles for mobile users (without direct line of sight)
- 20 miles or more is expected for line of sight
- 7-% of globally issued WiMaX licenses are for 3.5 MHz, in the U.S. for 2.5 MHz
- WiMaX is likely to enjoy greater frequency utilization and lower royalty overheads as compared to 3G
- Less expensive deployments and lower voice and data prices for the consumer

# WiMAX

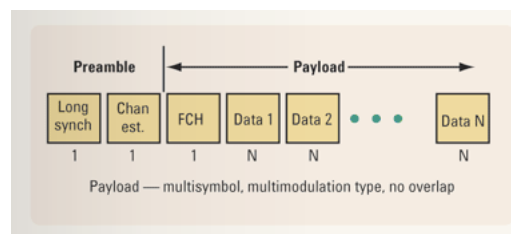
- **Three types of carriers**
  - » Pilot – always BPSK, location and content known to the receiver
  - » Data - BPSK, QPSK, 16QAM, 64QAM
  - » Null
- **In the 256 channel case**
  - » 56 unused channels as guard carriers
  - » 192 transport
  - » 8 pilot

## WiMAX Adaptive Modulation

- **During the start of each transmission, the channel is evaluated**
- **Decision on whether to use the next higher-order modulation**
- **The transmitter can maximize the data rate when conditions are good (high SNR, LOS)**
- **The transmitter can sacrifice data rate in favor of more robust transmission with low error rates under adverse conditions**

## Downlink subframe

- Preamble used for synchronization and channel estimation (QPSK)
- Within the Frame Control Header, the downlink frame prefix (DLFP) determines modulation and number of symbols in subsequent bursts



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## Time Division Duplex in Fixed WiMAX

- After downlink burst, transmit transition gap (TTG)
- After last uplink burst, receive transition gap (RTG)

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## Mobile WiMAX (802.16e)

- Often called OFDMA
- Enables multiple users to share the available spectrum in parallel for both uplink and downlink
- Supports mobility by allowing handoffs from one cell to the next without breaking the IP connection

## Long Term Evolution (LTE)

- Evolution of 3GPP's Universal Mobile Telecommunications System (UMTS)
- Uses OFDMA on the downlink
- SC-FDMA on the uplink
- Use of MIMO
  - » Baseline 2 transmit antennas on the BS and 2 receive antennas on the mobile
  - » From the mobile to the BS Multi-User MIMO that can also support a single antenna on the mobile
- System Architecture Evolution (SAE)

## WiMAX vs. LTE (technical)

- **Both use orthogonal frequency division multiple access (OFDMA) in the downlink.**
  - » WiMax optimizes for maximum channel usage by processing all the information in a wide channel – high channel utilization comes at the price of 1000-point FFT (higher power consumption)
  - » LTE organizes the available spectrum into smaller chunks – 16-point FFTs adequate
- **LTE uses SC-FDMA for uplink with lower peak to average power ratio (single largest power consumer on the handset)**
  - » LTE PA ~ 5dB versus WiMAX PA ~ 10dB
  - » See <http://to.swang.googlepages.com/peaktoaveragepowerratioireduction>

<http://blogger.xs4all.nl/jurjen1/archive/2008/07/06/400647.aspx>

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39

## WiMAX vs. LTE (technical)

- **Duplexing**
  - » WiMAX primarily TDD – simpler radio design
  - » LTE heads for FDD – uses adjacent frequencies for uplink/downlink – very severe latency requirements for forward error correction

**From the handset perspective there is no winner**

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40

## WiMAX vs. LTE (other)

- **WiMAX first to market**
- **WiMAX is IEEE standard – equipment cheaper**
- **LTE out of GSM, with a great install base already!**
- **All 3GPP operators already have spectrum that can be used for LTE – not true for WiMAX**
- **802.16m (in 2009) comparable speeds to LTE**

**UMB (Qualcomm) also in that race, but abandoned**

([http://www.nationmultimedia.com/2009/01/09/technology/technology\\_30092821.php](http://www.nationmultimedia.com/2009/01/09/technology/technology_30092821.php))

Table 1. Growth in cellular peak data rates and spectral efficiency

Radio system	Peak data rate	Channel BW	Freq reuse	Spectral efficiency
AMPS	9.6 kbps	30 kHz	7	0.015
GSM	9.6 to 14.4 kbps	200 kHz	4	0.032
GPRS	171 kbps	200 kHz	4	0.07
IS-95C (cdma2000)	307 kbps	1.25 MHz	1	0.25
EDGE	474 kbps	200 kHz	4	0.2
W-CDMA	2 Mbps	5 MHz	1	0.4
1xEV-DO(A)	3.1 Mbps	1.25 MHz	1	2.4
HSDPA	14 Mbps	5 MHz	1	2.8
HSDPA+ 2x2*	42 Mbps	5 MHz	1	8.4
802.16e WiMAX	74.8 Mbps	20 MHz	1	3.7
LTE	100 Mbps	20 MHz	1	5
802.16m 2x2*	160 Mbps	20 MHz	1	8.0
LTE 2x2*	172.8 Mbps	20 MHz	1	8.6
802.16m 4x4*	300 Mbps	20 MHz	1	15.0
LTE 4x4*	326.4 Mbps	20 MHz	1	16.3

\* 2x2 and 4x4 = Downlink MIMO (multiple-input/multiple-output)

## Growth Explanat

No impact on spectral efficiency or network capacity

- Allocating more time (TDMA duty cycle)
- Allocating more bandwidth
- Improving frequency reuse
- Reducing channel coding protection
- Using higher order modulation
- Taking advantage of spatial diversity (MIMO)

Increase peak data rates

Increase spectral efficiency and can increase network capacity

## Average vs. peak rate

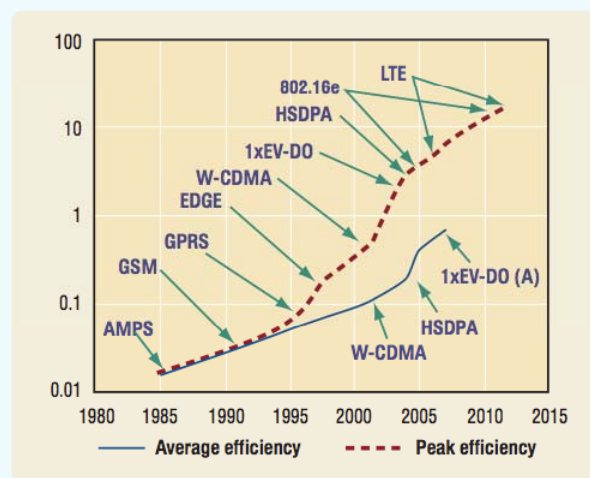


Figure 4. Average versus peak spectral efficiency over time

AMPS, GSM designed to operate at their maximum rate at the edge of the cell

## Femto cells

- **Tiny, low-power cellular base stations**
- **Could be integrated into home gateways**
- **Connected to the provider network through broadband**
- **They operate in licensed frequency bands**
- **Benefits in terms of coverage, battery consumption, speed, latency**
- **(could even allow you to interact with other devices inside the home)**
- **Technical challenges at <http://en.wikipedia.org/wiki/Femtocell>**

## CDMA and OFDM

- **Both offer high capacity but different strength**
  - » CDMA effective for voice but concerns about high bandwidths and multipath
  - » OFDM easy to equalize to deal with multipath fading
- **Why not combine them: Multicarrier CDMA**
  - » MC-CDMA: spreading code applied to a number of subcarriers in the frequency domain
  - » MC-DS-CDMA: apply CDMA to substreams that are then transmitted over orthogonal subcarriers
  - » MT-CDMA (multi-tone): same as above but subcarriers are not orthogonal
- **See Garg, Section 6.10 for more details**

## Other References

- [http://www.unstrung.com/insider/details.asp?sku\\_id=1460&skuitem\\_itemid=993&promo\\_code=&aff\\_code=&next\\_url=%2Finsider%2Flist%2Easp%3Fpage%5Ftype%3Dall%5Freports](http://www.unstrung.com/insider/details.asp?sku_id=1460&skuitem_itemid=993&promo_code=&aff_code=&next_url=%2Finsider%2Flist%2Easp%3Fpage%5Ftype%3Dall%5Freports)
- <https://mentor.ieee.org/802.22/file/05/22-05-0005-00-0000-ofdma-tutorial-ieee802-22-jan-05.ppt>
- <http://www.complextoreal.com/chapters/ofdm2.pdf>

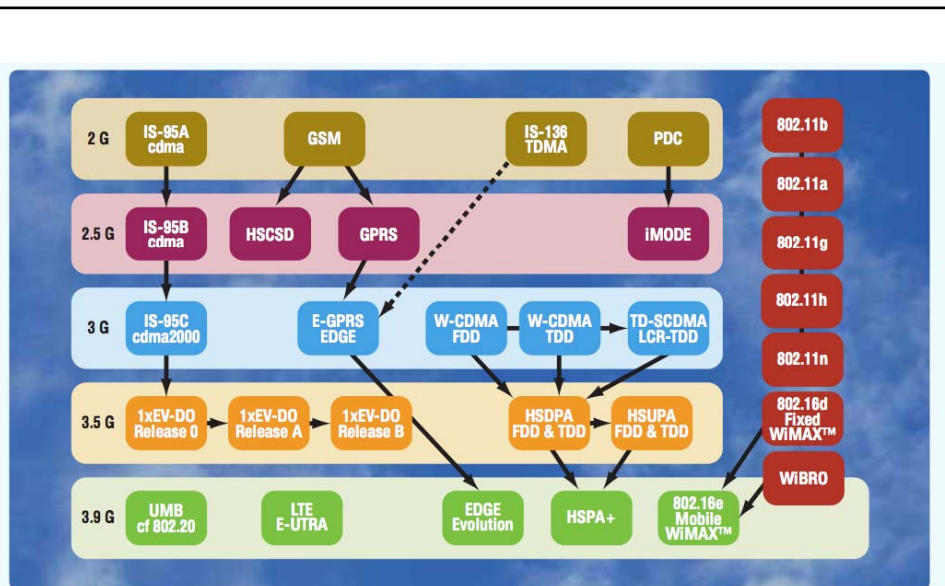


Figure 1. The evolution of wireless showing five competing new systems

### Technology Comparative

	WiMAX 802.16e	WiMAX 802.16m	LTE
Network Equipment Availability	2007	2010	2009
Handset Availability	2008	2011	2010
Standard Body	IEEE & WiMAX Forum	IEEE & WiMAX Forum	3GPP
Spectrum band Plan	TDD	TDD, FDD	FDD
Frequency*	2300, 2500, 3300 3500, 3700	Under 6 GHz TBD	700, 850, 900, 1800 1900, 2100, 2500
Channel Bandwidth	3.5, 5, 7, 8.75, 10 MHz	Scalable bandwidth 5 – 20 MHz TBD	1.4, 1.6, 3.5, 10, 15, 20 MHz
Channel Throughput	~3.5 Mbps / Hz downlink 35 Mbps, 1 Sector, 10 MHz channel	~5.0 Mbps / Hz downlink 50 Mbps, 1 Sector, 10 MHz channel	~5.0 Mbps / Hz downlink 50 Mbps, 1 Sector, 10 MHz channel
Spectrum Type	Licensed		
Radio Technology DL	Scalable OFDMA		
Radio Technology UL	Scalable OFDMA		
Antennas	MIMO & Advanced Antenna Techniques		
Core Technology	Flat, All IP		
Application Layer	IMS		
IPR	More distributed than existing 3GPP & 3GPP2 networks		
Application	VoIP, Data, Video		
Terminal Variety	Fixed CPE, Mobile handsets, Data Cards, Consumer Electronics		
User Plane Latency	<20 ms	<5 ms	<5 ms
Control Plane Latency	<100 ms	<100 ms	<100 ms

\* WiMAX Forum Certification Profiles currently specified for 2300, 2500, and 3500 MHz.

### NGN Functional Architecture Overview

