University of Puerto Rico

Electrical and Computer Engineering

Radio Frequency Spectrum
Management Workshop

Presented at the UPR/RUM Radio Frequency Spectrum Management Workshop

Wireless Telecommunications Technologies

ITU OM3 – WTT

May 24, 2015

James S. Avilés

Senior RF Spectrum Engineer

Workshop Briefing Outline

- ITU Spectrum Management Training Program (SMTP)
- ITU SMTP Reference Model for RF Workshop – OM3/EM1
- WTT When it Started “Radio” then “ Wireless”
- Mobile Telephone Service and Improved MTS
- Advanced Mobile Telephone Service – 1G
- Digital Mobile Cellular Voice/Data Service – 2G
- Broadband Wireless Mobile Services – 3G
- Long Term Evolution (LTE)
- International Mobile Telecommunications Advance – 4G
- Where no Human has Gone before – 5G

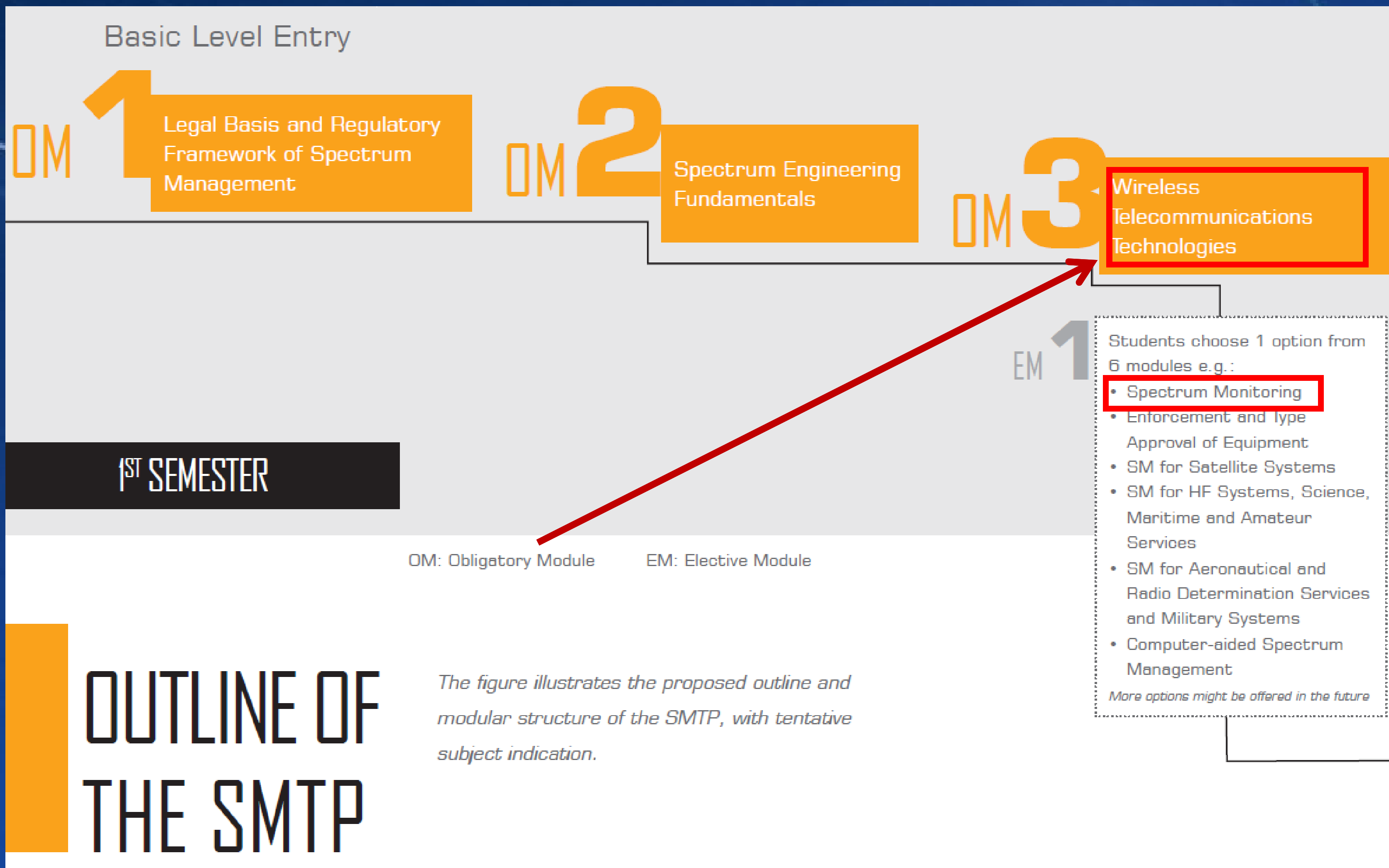
RF Workshop Reference Model

ITU Academy
empowering minds

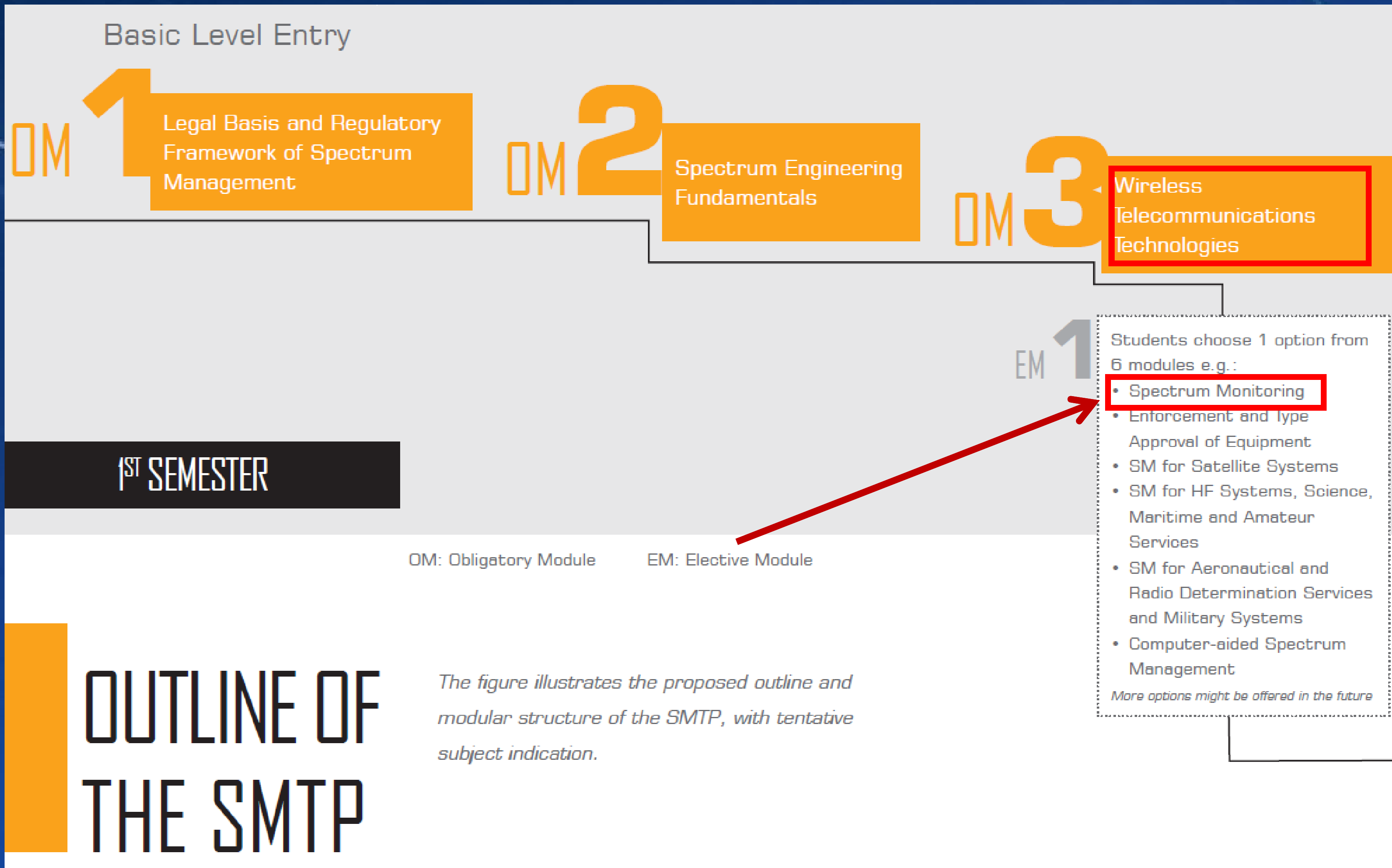
International Telecommunications Union Initiative for:

Spectrum Management Training Program

Obligatory Module OM3 – WTT



Elective Module EM1 – SMM



Other SMTP Modules

Advanced Level

2ND SEMESTER

OM 4 — Economic and Market Tools of Spectrum Management

OM 5 — Strategic Planning and Policies for Wireless Innovation

EM 2 — Students choose 2 options from 4 modules:

- Advanced Spectrum Authorization Regimes
- Terrestrial TV Broadcasting Planning and Digital Transition
- Socio-economic Impact of Spectrum Regulation; Competition and Consumer Protection
- Opportunistic Spectrum Access and Cognitive Radio

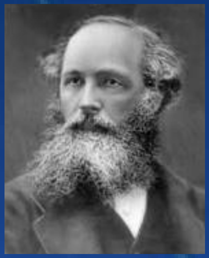
More options might be offered in the future

Optional Master Thesis in case of pursuing MSc academic diploma

3RD SEMESTER

Possibility of Advanced entry point subject to test

Start of RADIO



- **1865, James Clerk Maxwell Equations demonstrated that Electric and Magnetic fields travel through space as waves moving at the speed of light.**

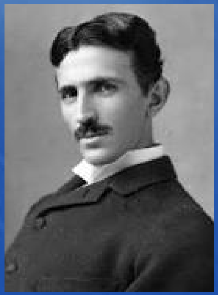
$$\oint \vec{H} \cdot d\vec{l} = \int_s (J_c + \frac{\partial D}{\partial t}) \cdot d\vec{S} \quad \text{(Ampère's law)}$$

$$\oint \vec{E} \cdot d\vec{l} = \int_s (-\frac{\partial \vec{B}}{\partial T}) \cdot d\vec{S} \quad \text{(Faraday's law; } S \text{ fixed)}$$

$$\oint_s \vec{D} \cdot d\vec{S} = \int_v \rho dv \quad \text{(Gauss' law)}$$

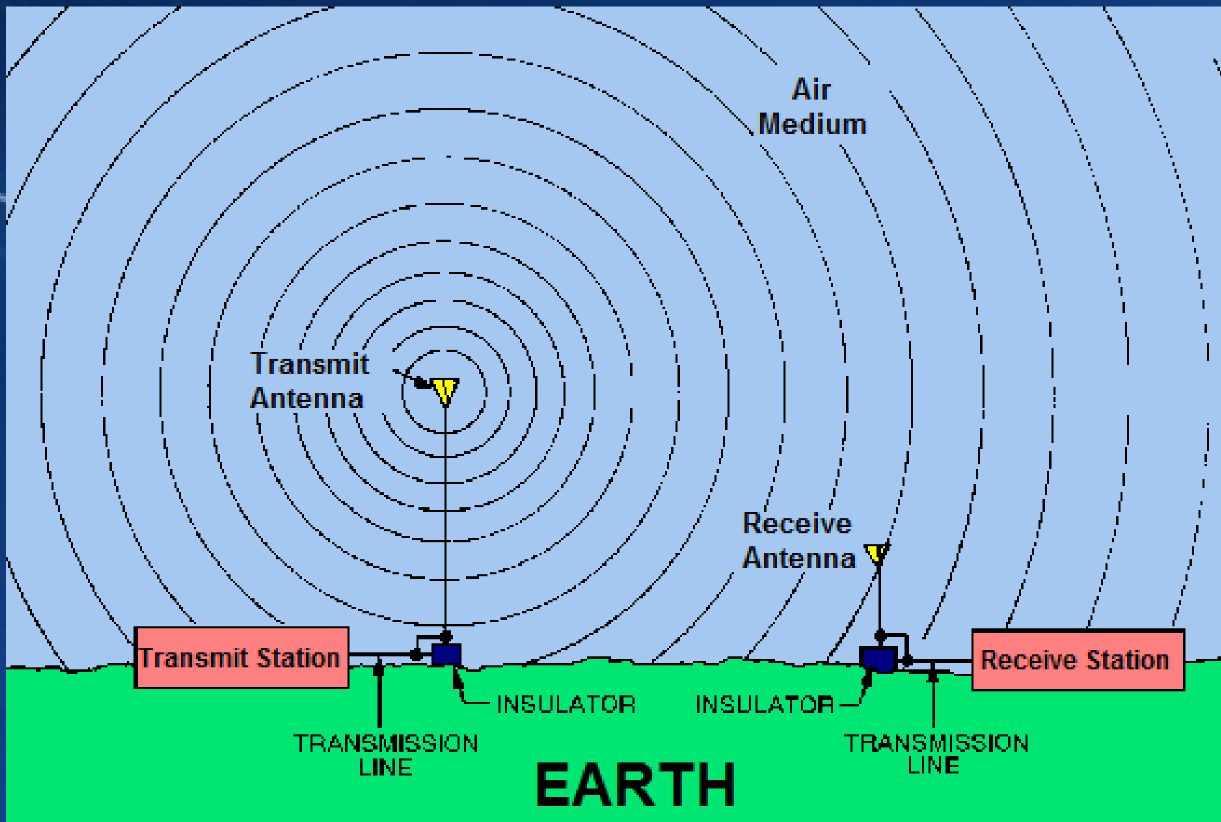
$$\oint_s \vec{B} \cdot d\vec{S} = 0 \quad \text{(nonexistence of monopole)}$$

- **1893, 28 years after Maxwell – Nikola Tesla pronounce the possibility of wireless communication. He tried to put these ideas to practical use in an unsuccessful attempt at the intercontinental wireless transmission project.**



- **1899, 34 years after Maxwell – Guglielmo Marconi performs historical radio telegraph transmissions from a ship in New York Harbor to the Twin Lights in Highlands New Jersey ushering the era of practical mobile radio communication.**

Two-Way RADIO Communications



Until 1940, For 40 years – Two-Way Radio was the only means of mobile radio communication with the Push-To-Talk (PTT) Half-Duplex (Speak or Listen – Not Both). Most Radio Stations – Fixed Stations. Still in use at present times.

Mobile Telephone Service – MTS

- **1947, Mobile Telephone Service was initiated creating a total of more than 40 channels in the 150 MHz band for mobile telephony and a group of new entities called Radio Common Carriers (RCCs).**

- **Luggage-Size Transceiver (30 - 45 lbs.)**
- **Required Operator Assistance**
- **VHF Frequencies (152 – 159 MHz)**
- **Half-Duplex (Speak OR Listen – Not Both)**
- **Standard Lasted For 13 Years**

Improved MTS Service – IMTS

- 1964, The Improved MTS (IMTS) is the pre-cellular system that linked to the PSTN. A replacement to MTS offering direct-dial rather than connections through a live operator).

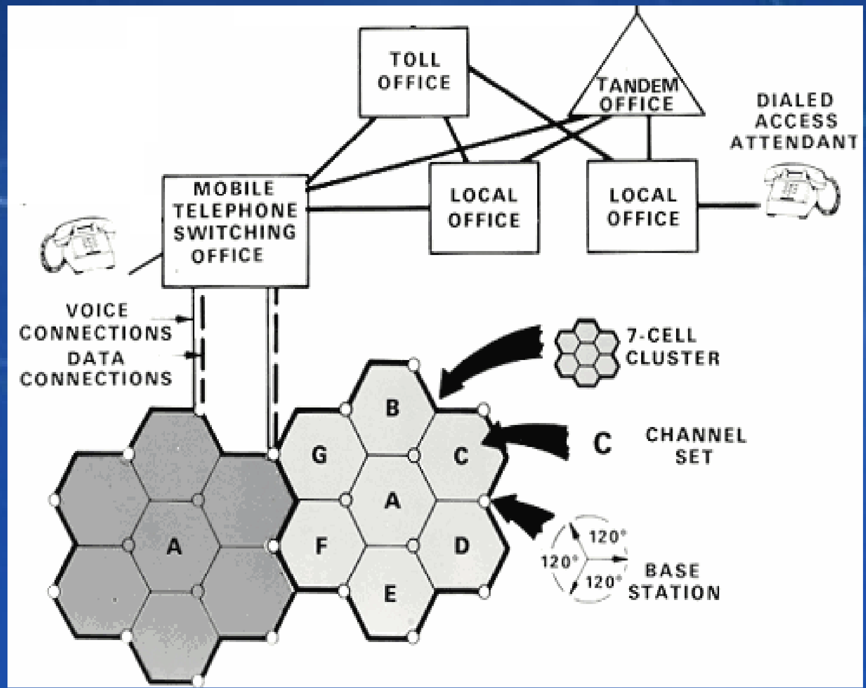
- No Operator Interface Required
- Multiple Channels (allowing more users)
- Mobile Units weight typically 25 lbs
- VHF Low (35-44 MHz), VHF High (152-158 MHz) and UHF (454-460 MHz)
- Simultaneous Duplex
- No Privacy (All Channels Were Public)
- Required Separations of more than 50 miles

Advanced Mobile Phone Service – AMPS

- **1968**, FCC Docket 18262 opened proposals to allocate the upper portion of 800 MHz to mobile systems for both private and public uses.
- **1981**, FCC Final Order – half of 800 MHz spectrum was allocated for trunked systems. The other half was allocated for cellular systems (850 MHz)
- **1983**, AMPS launched in Chicago – an analog mobile cell phone system standard built on a 30 kHz channel BW. The 1G technology for cellular communications begins.

AMPS – 1G Design

- First systems used large cell areas and omni-directional base station antennas covering 2,100 square miles.
- Ten base stations, with antenna tower height between 150 ft. and 550 ft designed for a carrier-to-interference ratio of 18 dB for satisfactory voice quality. Deployed in a 7-cell frequency reuse pattern with 3 sectors per cell.



Start of Wireless – 2G

- 1989, CDMA is proposed as a more efficient wireless voice technology using digital signal processing and 2G begins.

- 2G systems used digital modulation. Shifting from analog to digital enabled several improvements in performance. System Capacity was improved through:
- (1) the use of spectrally efficient digital speech codecs,
- (2) multiplexing users on the same frequency channel via time division or code division multiplexing allowing more calls to be transmitted in same amount of radio bandwidth,
- (3) tighter frequency re-use enabled by better error performance of digital modulation, coding, and equalization techniques, which reduced the carrier-to-interference ratio from 18 dB to just a few dB.

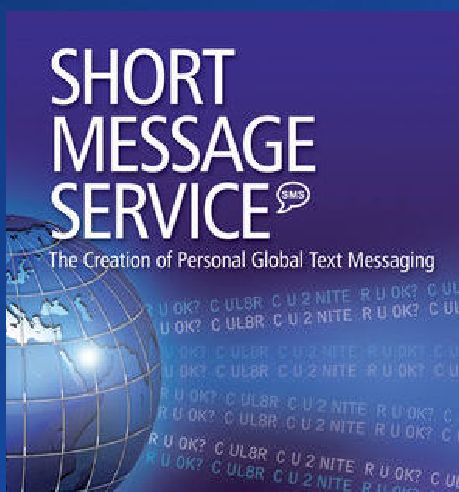
Wireless – 2G Cellular Systems

- **1990**, 2G systems use simple encryption to provide security against eavesdropping or fraud, which was a major concern with 1G analog. FCC allocated 120 MHz of additional spectrum around 1.9 GHz for what came to be called Personal Communications Services (PCS).

	GSM	IS-95	IS-54/IS-136
Year of Introduction	1990	1993	1991
Frequency Bands	850/900MHz, 1.8/1.9GHz	850MHz/1.9GHz	850MHz/1.9GHz
Channel Bandwidth	200kHz	1.25MHz	30kHz
Multiple Access	TDMA/FDMA	CDMA	TDMA/FDMA
Duplexing	FDD	FDD	FDD
Voice Modulation	GMSK	DS-SS:BPSK, QPSK	$\pi/4$QPSK
Data Evolution	GPRS, EDGE	IS-95-B	CDPD
Peak Data Rate	GPRS:107kbps; EDGE:384kbps	IS-95-B:115kbps	$\sim$ 12kbps
Typical User Rate	GPRS:20-40kbps; EDGE:80-120kbps	IS-95B: $<$64kbps;	9.6kbps
User Plane Latency	600-700ms	$>$ 600ms	$>$ 600ms

2G Short Messaging Service (SMS)

- **1991**, SMS was first deployed in Europe and quickly became a popular conversational tool among Younger mobile subscribers.
- Over 2.5 billion SMS messages are sent each day in the United States alone, used for delivering news updates, business process alerts, mobile payments, voting, and micro-blogging, among other things.

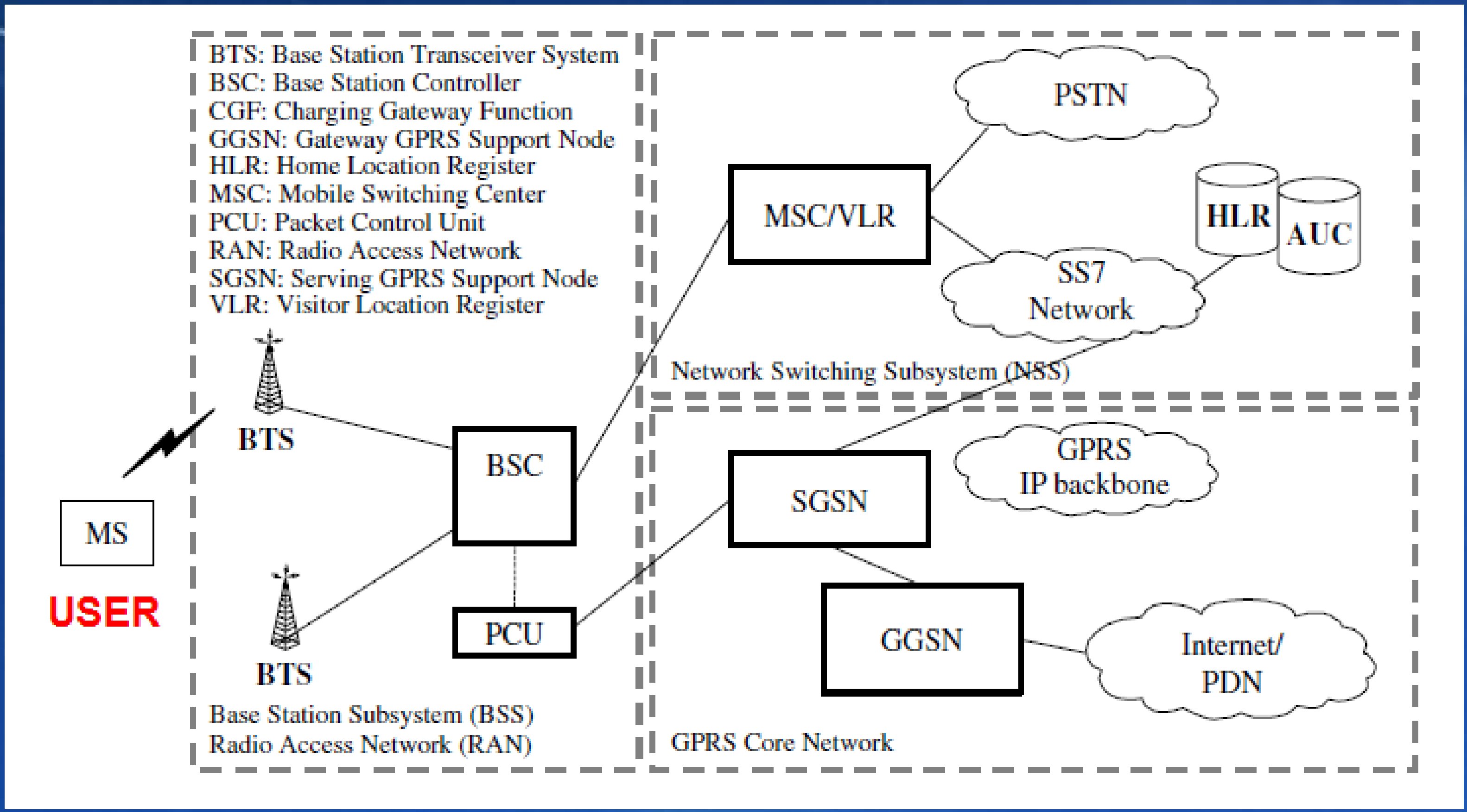


From 2G to 2.5 to 2.75

- 2000, 2G networks were built mainly for voice services and slow data transmission defined ITU's International Mobile Telecommunications-2000 (IMT-2000) specification documents and standards. The work of Global System for Mobile (GSM) by the Groupe Sp´ecial Mobile (GSM).
- 2.5G implemented packet-switched domains in addition to the circuit-switched domains. CDMA2000 networks evolved through this introduction supporting switched data rates at 9.6 kbps.
- 2.75G introduced 8PSK encoding evolving to Enhanced Data rates for GSM Evolution (EDGE). EDGE was deployed on GSM networks in 2003 – an upgrade that provided an increase in capacity. Typical user data rates of 20 – 40 kbps were achieved.

GSM Network Architecture

- **2001**, GSM/GPRS network architecture which formed the basis from which later 3G systems evolved.



3G – Broadband Wireless

- 2002, 3G provides much higher data rates, significant increase in voice capacity, advanced services and applications, including web browsing, e-mail, and streaming Multimedia. ITU laid out the following data rate requirements for IMT-2000 (3G):
  - 2 Mbps in fixed or in building environments.
  - 384 kbps in pedestrian or urban environments.
  - 144 kbps in wide area vehicular environments.
- Third Generation Partnership Project (3GPP/3GPP2) proposed a series of IMT-2000 standards with CDMA showing to be the preferred access technique for the majority of 3G systems.

Summary of Major 3G Standards

	W-CDMA	CDMA2000 1X	EV-DO	HSPA
Standard	3GPP Release 99	3GPP2	3GPP2	3GPP Release 5/6
Frequency Bands	850/900MHz, 1.8/1.9/2.1GHz	450/850MHz 1.7/1.9/2.1GHz	450/850MHz 1.7/1.9/2.1GHz	850/900MHz, 1.8/1.9/2.1GHz
Channel Band-width	5MHz	1.25MHz	1.25MHz	5MHz
Peak Data Rate	384–2048kbps	307kbps	DL:2.4–4.9Mbps UL:800–1800kbps	DL:3.6–14.4Mbps UL:2.3–5Mbps
Typical User Rate	150–300kbps	120–200kbps	400–600kbps	500–700kbps
User-Plane Latency	100–200ms	500–600ms	50–200ms	70–90ms
Multiple Access	CDMA	CDMA	CDMA/TDMA	CDMA/TDMA
Duplexing	FDD	FDD	FDD	FDD
Data Mod-ulation	DS-SS: QPSK	DS-SS: BPSK, QPSK	DS-SS: QPSK, 8PSK and 16QAM	DS-SS: QPSK, 16QAM and 64QAM

Beyond 3G – HSPA, WiMAX, LTE

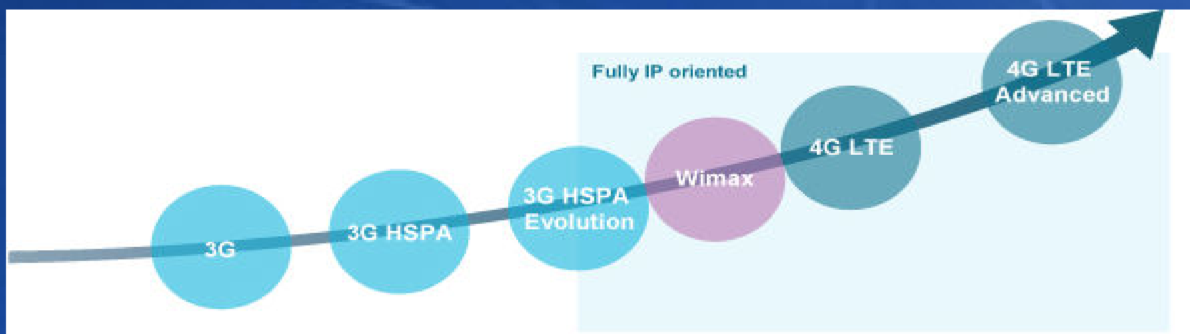
- **2009**, The wireless industry refer to WiMAX and LTE as 4G systems although they do not meet the requirements for 4G as laid out by the ITU:
  - High-Speed Packet Access (HSPA) is the combination of two key enhancements by 3GPP. Deployed as a software upgrade to existing UMTS systems using a fix 5 MHz BW providing typical user throughputs from 500 kbps to 2 Mbps.
  - Worldwide Interoperability for Microwave Access (WiMAX) is the IEEE 802.16e standard. WiMAX is designed using IP protocols, and does not offer circuit-switched voice telephony. It can be provided using the VoIP (voice over IP). Using 5 MHz spectrum, the peak physical layer (PHY) data rate is 18 Mbps.
  - Long Term Evolution (LTE) is the mobile broadband system that is commensurate with landline DSL and capable of supporting growth in IP traffic. With 20 MHz spectrum BW LTE can support up to 326 Mbps on the downlink and 86 Mbps on the uplink.

HSPA, WiMAX, LTE Comparison

	HSPA+	Mobile WiMAX	LTE
Standard	3GPP Release 7&8	IEEE 802.16e-2005	3GPP Release 8
Frequency Bands (Early Deployments)	850/900MHz, 1.8/1.9GHz,	2.3GHz, 2.6GHz, and 3.5GHz	700MHz, 1.7/2.1GHz, 2.6GHz, 1.5GHz
Channel Bandwidth	5MHz	5, 7, 8.75, and 10MHz	1.4, 3, 5, 10, 15, and 20MHz
Peak Downlink Data Rate	28–42Mbps	46Mbps (10MHz, 2 × 2 MIMO, 3:1 DL to UL ratio TDD); 32Mbps with 1:1	150Mbps (2 × 2 MIMO, 20MHz)
Peak Uplink Data Rate	11.5Mbps	7Mbps (10MHz, 3:1 DL to UL ratio TDD); 4Mbps with 1:1	75Mbps (10MHz)
User-Plane Latency	10–40ms	15–40ms	5–15ms
Frame Size	2ms frames	5ms frames	1ms sub-frames
Downlink Multiple Access	CDMA/TDMA	OFDMA	OFDMA
Uplink Multiple Access	CDMA/TDMA	OFDMA	SC-FDMA
Duplexing	FDD	TDD; FDD option planned	FDD and TDD
Data Modulation	DS-SS: QPSK, 16QAM, and 64QAM	OFDM: QPSK, 16QAM, and 64QAM	OFDM: QPSK, 16QAM, and 64QAM
Channel Coding	Turbo codes; rate 3/4, 1/2, 1/4	Convolutional, turbo RS codes, rate 1/2, 2/3, 3/4, 5/6	Convolutional and Turbo coding: rate 78/1024 to 948/1024
Hybrid-ARQ	Yes; incremental redundancy and chase combining	Yes, chase combining	Yes, various
MIMO	Tx diversity, spatial multi-plexing, beamforming	Beamforming, open-loop Tx diversity, spatial multiplexing	Transmit Diversity, Spatial Multiplexing, 4 × 4 MIMO Uplink: Multi-user collaborative MIMO
Persistent Scheduling	No	No	Yes

Demand Drivers for LTE

- **2013**, Dramatic growth of the Internet is clearly the underlying driver for mobile broadband. Is the media of choice for all our information, communication and entertainment needs:
  - Growth in High-Bandwidth applications: Music downloads, Video sharing, IPTV and YouTube are driving more and more users to access, view, and share video using their mobile devices.



Market impact	2003	2006	2009	2010	2016
Peak rate	384 kbps	7 Mbps	42 Mbps	~150 Mbps	~1 Gbps
Typical user rate downlink	~200 kbps	1–2 Mbps	2–10 Mbps	10–20 Mbps	~30–100 Mbps
Typical user rate uplink	64 kbps	64–884 Mbps	0.5–4.5 Mbps	5–10 Mbps	~10–60 Mbps

Smart Mobile Devices Proliferation

- 2011, Dramatic growth in the variety and availability of smartphones.
  - Availability of full browsing, e-mail, and music and video playing capabilities in mobile devices are turning cell phone subscribers into prodigious consumers of wireless data services.
  - Packaging of cameras, camcorders, GPS navigation systems, and other technologies into mobile phones has enabled a variety of exciting mobile applications.
  - In 2008, there were almost 162 million smartphones sold, surpassing laptop sales for the first time.

Requirements of LTE Design

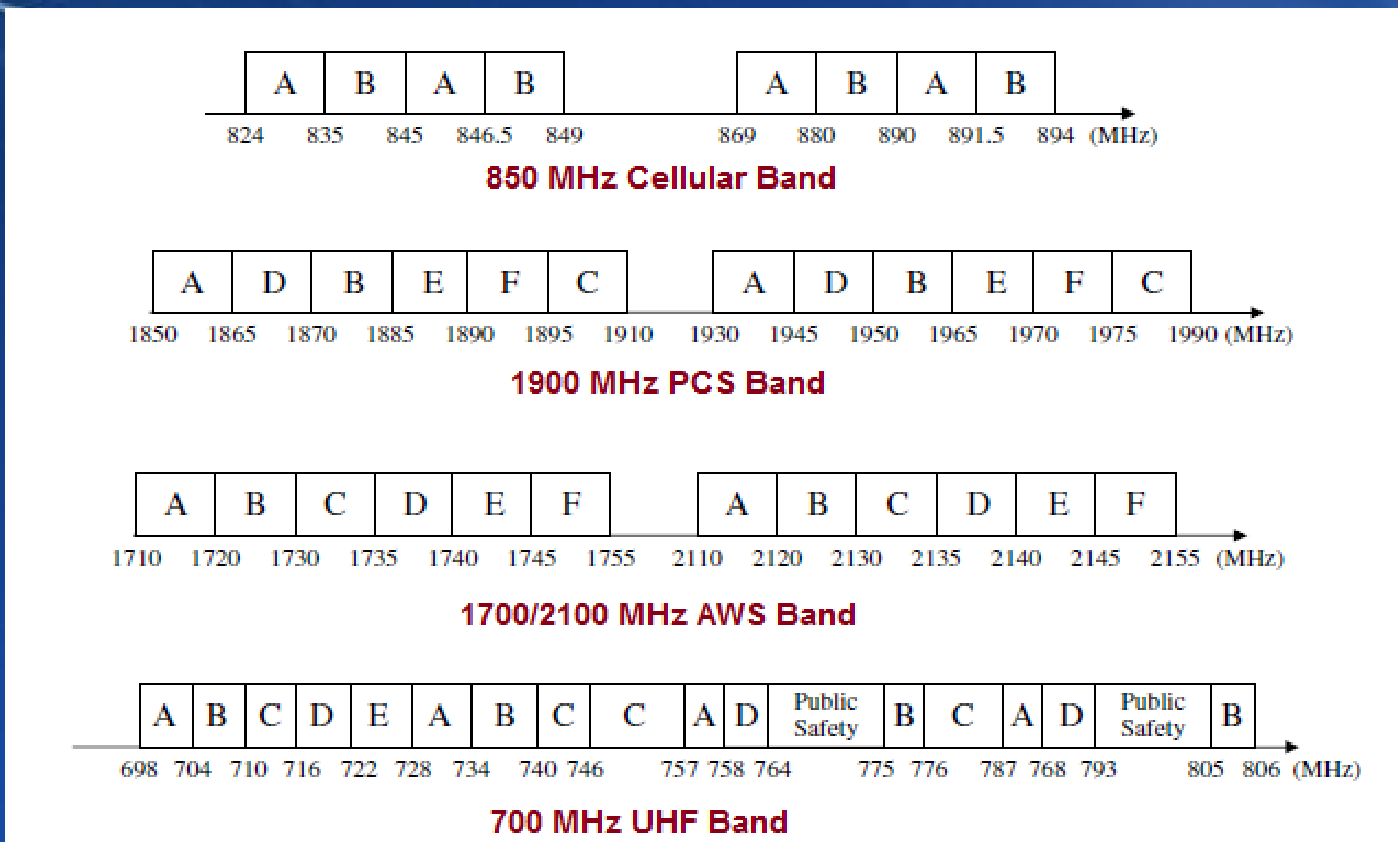
- **Performance on Par with Wired Broadband:**
  - Make Mobile Internet experience as good as or better than that achieved by residential wired broadband access systems.
  - Key network performance parameter for success is High Throughput combined with Reduce Latency for better user experience.
  - Flexible Available Spectrum Usage in 900 MHz, 1800 MHz, 700 MHz, and 2.6 GHz bands supporting a variety of channel bandwidths: 1.4, 3, 5, 10, 15, and 20 MHz.
  - LTE networks interwork seamlessly with existing 2G and 3G systems and as a truly global standard extended to non-3GPP systems such as the 3GPP2 CDMA and WiMAX networks.
  - Reducing Cost per Megabyte for substantial reductions be achieved in the total network cost to deliver data to end users.

LTE Technologies for the Challenge

- **Enabling Radio and Core Network Technologies:**
  - Orthogonal Frequency Division Multiplexing (OFDM).
  - Single Carrier Frequency Domain Equalization (SC-FDE).
  - Channel Dependent Multi-User Resource Scheduling.
  - Multi-Antenna Techniques.
    - Transmit Diversity
    - Beamforming
    - Spatial Multiplexing
    - Multi-User MIMO
  - IP-Based Flat Network Architecture.

LTE Spectrum Options/Migration

- Deployable in any of the Existing Spectrum for 2G/3G cellular as well as the new 1700/2100 MHz Advanced Wireless Services (AWS) and 700 MHz UHF Band – Key for System Capacity.



4G – Broadband – Beyond LTE

- 2016, ITU definition of a 4G system, called IMT-Advanced, requires a target peak data rate of 100 Mbps for high mobility and 1 Gbps for low mobility applications:
  - Necessary Radio Spectrum to achieve the 100 Mbps and 1 Gbps requirements is a challenge but critical for System Capacity.
  - The World Radio Conference (WRC) identified new IMT spectrum in 2.6 GHz and 3.5 GHz which must be use very Efficiently.
  - The 3GPP developed requirements for LTE-Advanced to meet the IMT-Advance. Technologies for the challenge:
    - Higher order MIMO and Beamforming (up to 8 × 8)
    - Inter-cell/ Inter-symbol Interference Co-ordination and Cancellation
    - Multi-Hop relay nodes for high data rate coverage
    - Carrier aggregation to support larger bandwidths
    - Femto-cell/Home Node-B using self-configuring/optimizing networks

Summary LTE-Advanced Requirements

	LTE-Advanced Requirement
Peak Data Rate	1Gbps downlink and 500Mbps uplink; assumes low mobility and 100MHz channel
Peak Spectral Efficiency	Downlink: 30bps/Hz assuming no more than 8×8 MIMO Uplink: 15bps/Hz assuming no more than 4×4 MIMO
Average Downlink Cell Spectral Efficiency	3.7bps/Hz/cell assuming 4×4 MIMO; 2.4bps/Hz/cell assuming 2×2 MIMO; IMT-Advanced requires 2.6bps/Hz/cell
Downlink Cell-Edge Spectral Efficiency	0.12bps/Hz/user assuming 4×4 MIMO; 0.07bps/Hz/user assuming 2×2 MIMO; IMT-Advanced requires 0.075bps/Hz/user
Latency	$<$10ms from dormant to active; $<$50ms from camped to active
Mobility	Performance equal to LTE; speeds up to 500kmph considered
Spectrum Flexibility	FDD and TDD; focus on wider channels up to 100MHz, including using aggregation
Backward Compatibility	LTE devices should work on LTE-Advanced; reuse LTE architecture; co-exist with other 3GPP systems

5G – The *NEXT GENERATION*

- **The Next Generation Mobile Networks Alliance defines the following requirements for 5G networks by 2020:**
  - **Data rates of 10 Gbps should be supported for tens of thousands of users in the open air environment.**
  - **1 Gbps to be offered simultaneously to many workers on the same office floor.**
  - **Several hundreds of thousands of simultaneous connections to be supported for massive sensor deployments.**
  - **Spectral Efficiency should be significantly enhanced.**
  - **Coverage with increased infrastructure should be improved.**
  - **Latency should be reduced significantly to an order of 1 ms.**
  - **Enable Internet of Things (IoT) devices to run on battery for up to 10 years.**

Summary and Conclusions

- **We are in the Era of 4G IMT Advance for every day life:**
  - **Wireless services have grown at a remarkable rate over the past 25 years with over 4 billion users around the world.**
  - **Voice telephony and data consumption continues to grow rapidly dominating future needs for Spectrum Use Efficiency.**
  - **Wireless systems evolved from early cell systems to 1G analog voice to 2G digital voice/data to 3G packet data systems to 4G mobile broadband wireless systems with an ever increasing number of Network Infrastructure Sites.**
  - **We provided an overview of various wireless standards: AMPS, GSM, CDMA, HSPA, WiMAX, and LTE.**
  - **We discussed the market drivers, salient features, and key technologies included in the LTE standard.**
  - **We discussed the Spectrum options for LTE deployments emphasizing the newer Spectrum Availability.**
  - **Then 5G – Yet to come and takes us to where our Imagination can be.**

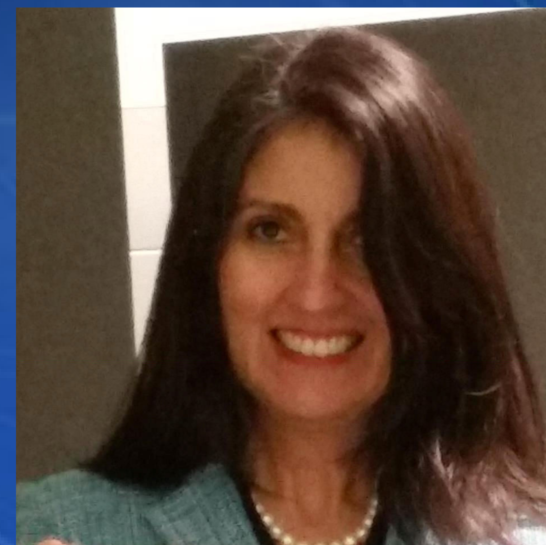
UPRM RFSMW Committee Thank You

Dr. Rafael Medina-Sánchez

Assistant Professor

Dr. Leyda León

Assistant Professor



Dr. Sandra Cruz-Pol

Professor

References

[1] ITU Telecommunications indicators update—2009. www.itu.int/ITU-D/ict/statistics/

[2] UMTS Forum. www.umts-forum.org

[3] Holma, H. et al. "High-Speed Packet Access Evolution in 3GPP Release 7." IEEE Communications Magazine, 45(12):29–35, December 2007.

[4] World Cellular Information Service. Iforma Telecoms and Media. May 2009.

[5] IEEE Communications Magazine, Special issue on LTE—LTE Part I: Core Network, February 2009.

[6] IEEE Communications Magazine, Special issue on LTE—LTE Part II: Radio Access, April 2009.

[7] 3G Americas White Paper. 3GPP technology approaches for maximizing fragmented spectrum allocations. July 2009.

[8] ITU-R Report M.2134, "Requirements Related to Technical Performance for IMT Advanced Radio Interface(s)," November 2008.

[9] EURASIP Journal on Wireless Communications and Networking, Special issue on 3GPP LTE and LTE Advanced, August 2009.