COM5120 Communications Theory

Class Web Site: NTHU eLearn
Google meet: https://meet.google.com/gda-qcpq-zsc

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Fall, 2021

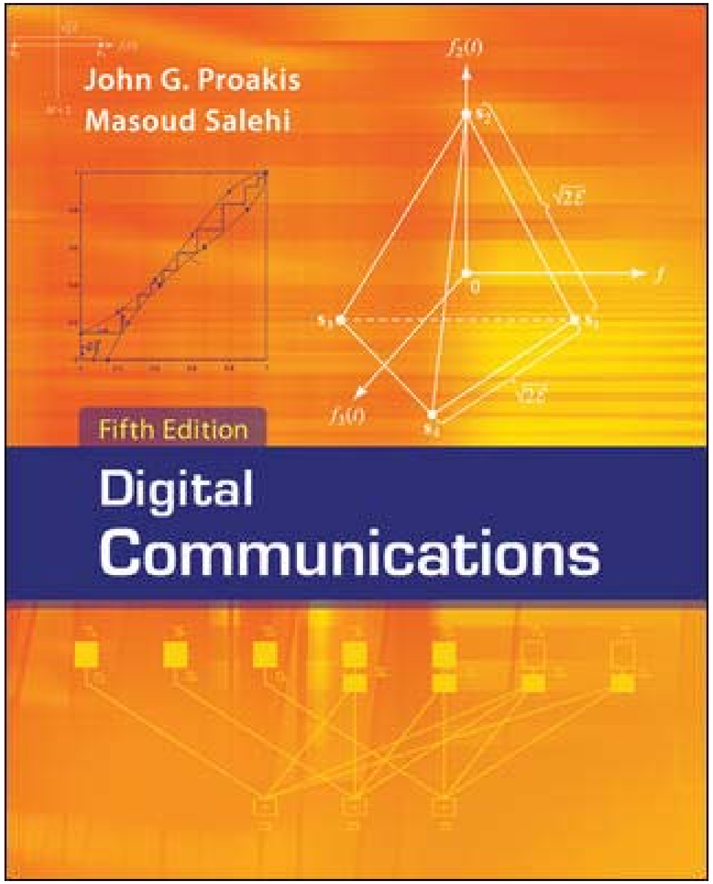
國立清華大學
National Tsing Hua University

Course Information

- Class Time: RaRbRc (18:30 -19:45, 20:00-21:15)
- Place: Google meet
  https://meet.google.com/gda-qcpq-zsc
- Class Website: NTHU eLearn
- Grading:
  - Homeworks 20%
  - Midterm 1 25%
  - Midterm 2 25%
  - Final Exam 30%
- Honest and Honor principle. No copying and no cheating for home works and exams.
- Lecture: Viewgraph + Black Board

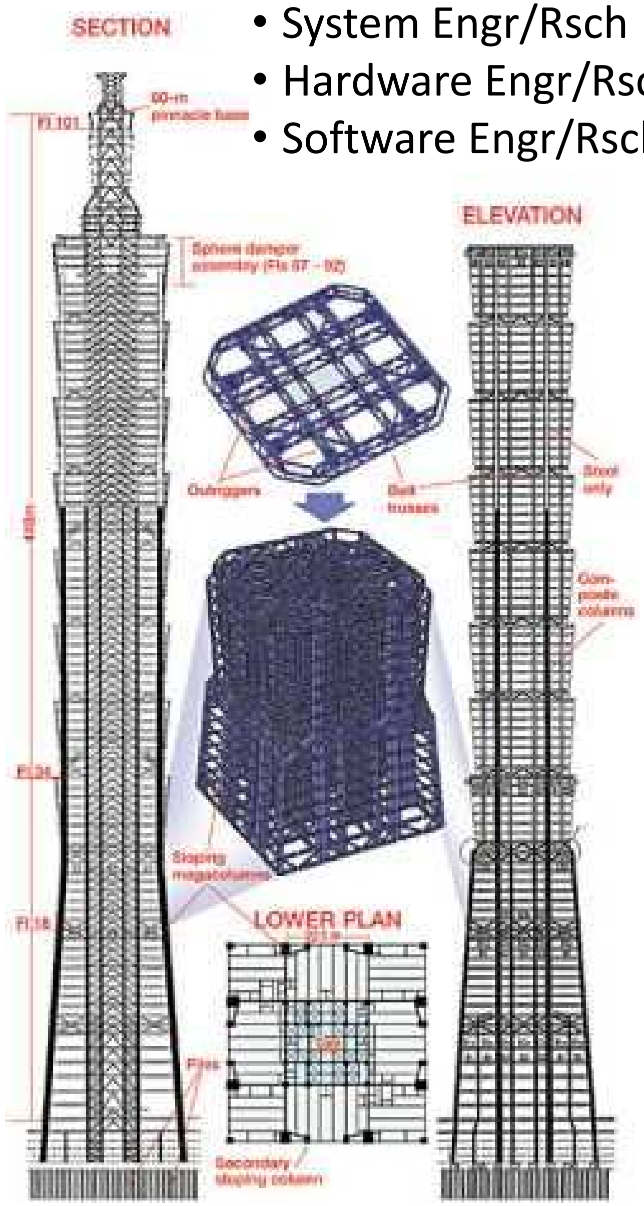
Major Text Book

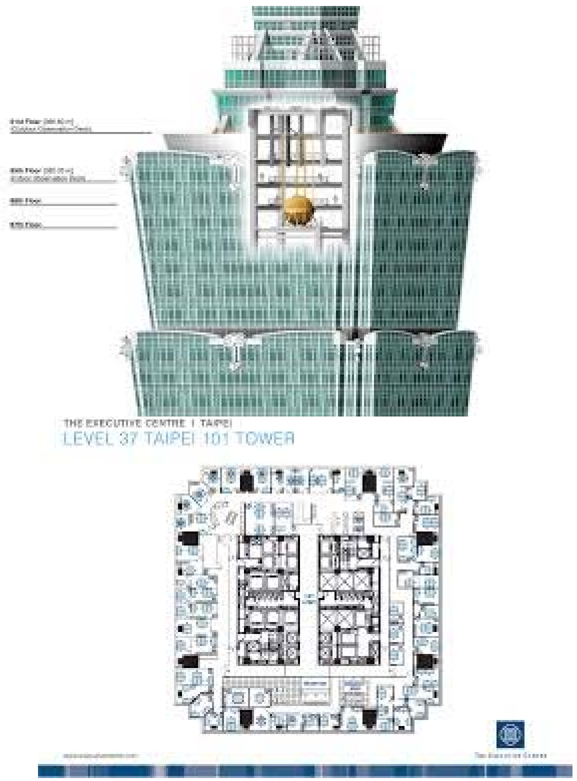
- **John G. Proakis and Masoud Salehi, "Digital Communications", 5th Ed., McGRAW-HILL 2008.**
  - Included recent advances in digital communication, OFDM and MIMO systems for modern wireless communications
  - As a graduate course, we will not follow the book page-by-page, or word-by-word. Instead, major concepts will be focused.
  - This book is hard to read by yourself.



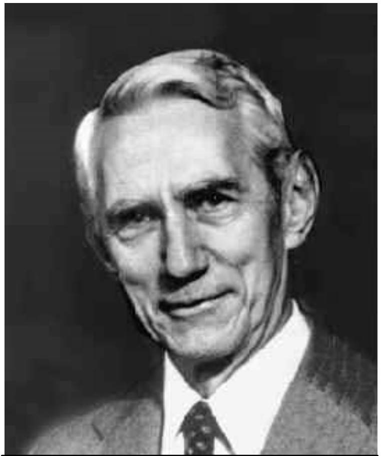
Should I learn communications theory?

- System Engr/Rsch
- Hardware Engr/Rsch
- Software Engr/Rsch



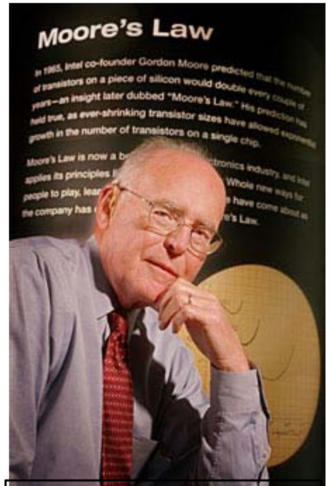


Communication Systems and IC Design

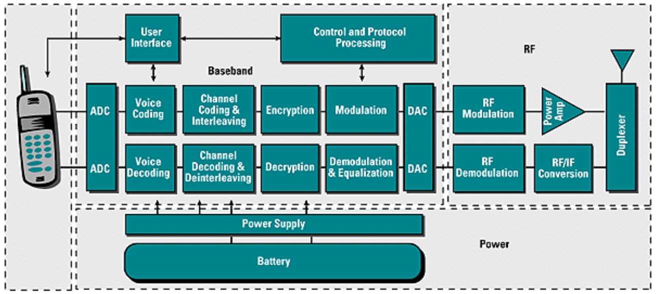


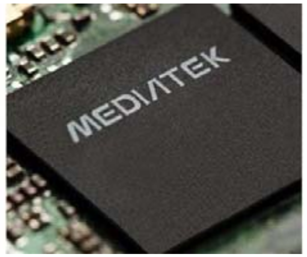
Claude Shannon

meets with



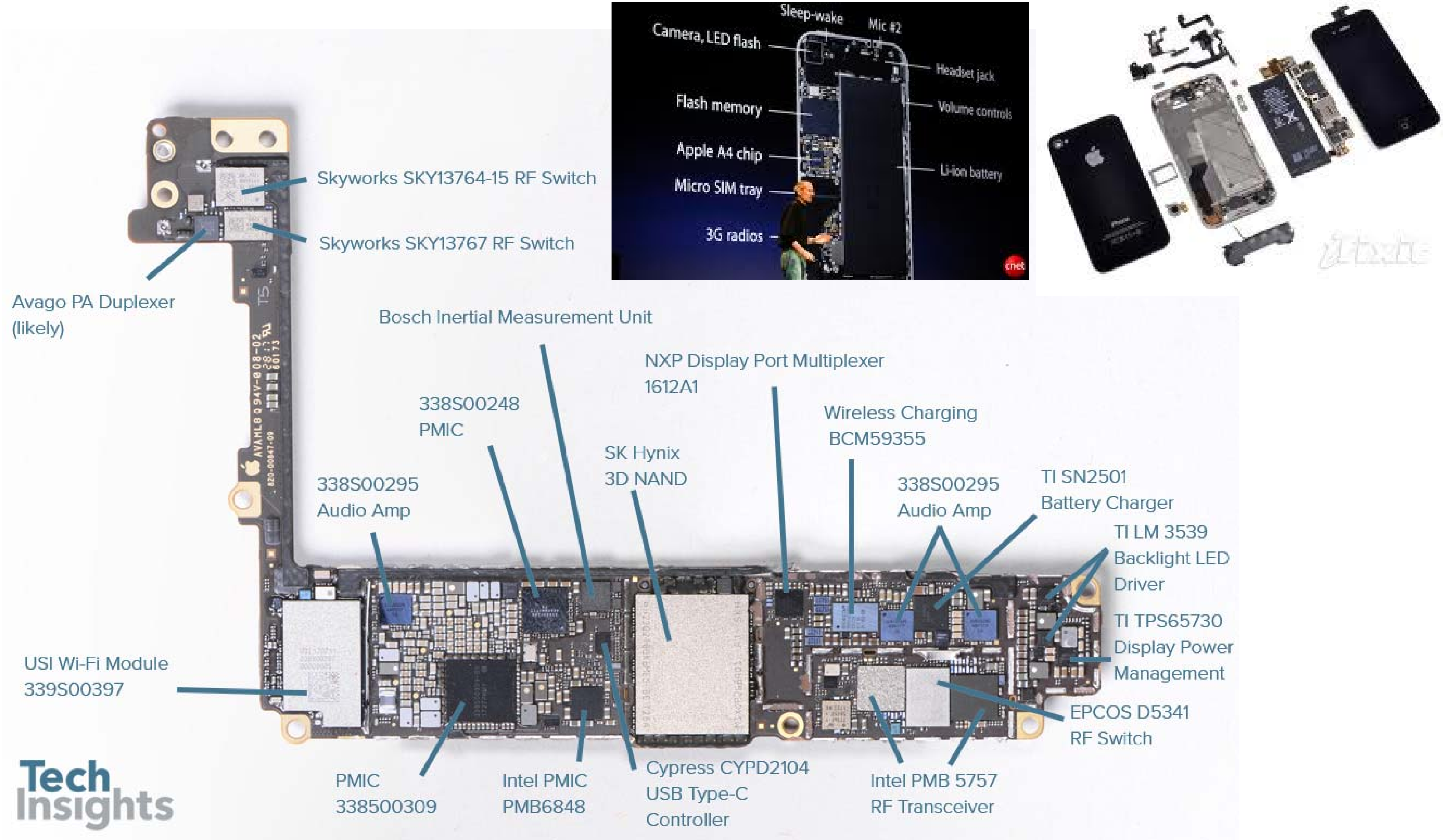
Gordon Moore





- Exponentially increasing number of (ultra-)small devices: from "Moore's Law" to "More Than Moore" or "Beyond Moore"
- Driven by heterogeneous integration of innovative technologies. ARM delivers 20+ billion devices in 2017, mostly in cell phone devices.
- Opportunity: System and application considerations

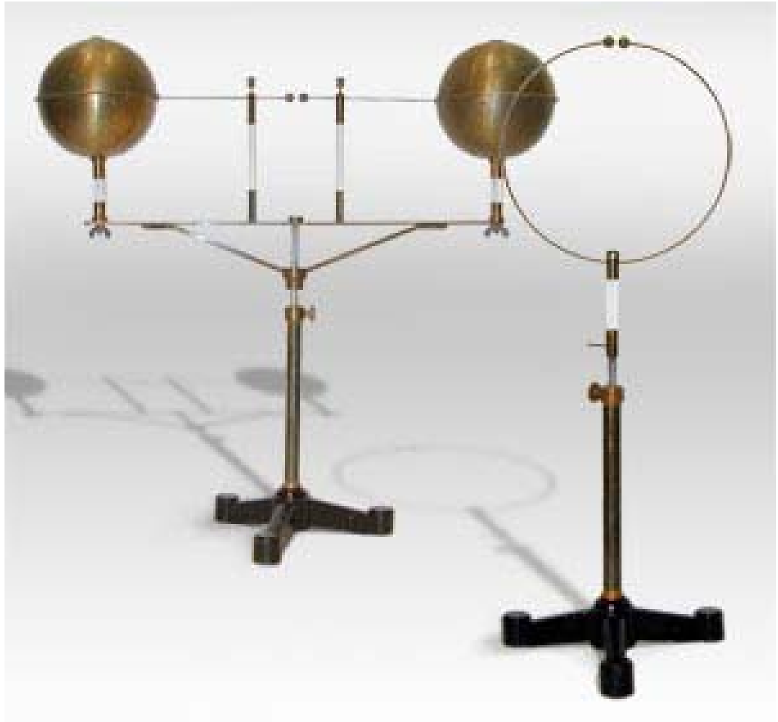
From Communication Theory to Realization



https://www.techinsights.com/blog/apple-iphone-8-plus-teardown

The First Wireless Tranceiver in History

- 1885年, Hertz invented electromagnetic transmitter and receiver. It is the first experiment that proved Maxwell theory. A historical milestone !!!
- 1930年, IEC(International Electro-technical Commission)為了紀念Hertz的貢獻, 在頻率測量的單位 每秒重複事件發生的次數 稱為 Hertz(赫茲).



電磁波之父 赫茲
Heinrich Rudolf Hertz
1857 - 1894

✓ **What have happened today, after 130 years, are far beyond the imagination of Dr. Hertz. But all are impossible without the experiment in 1885 .**

Highlights of Communications History

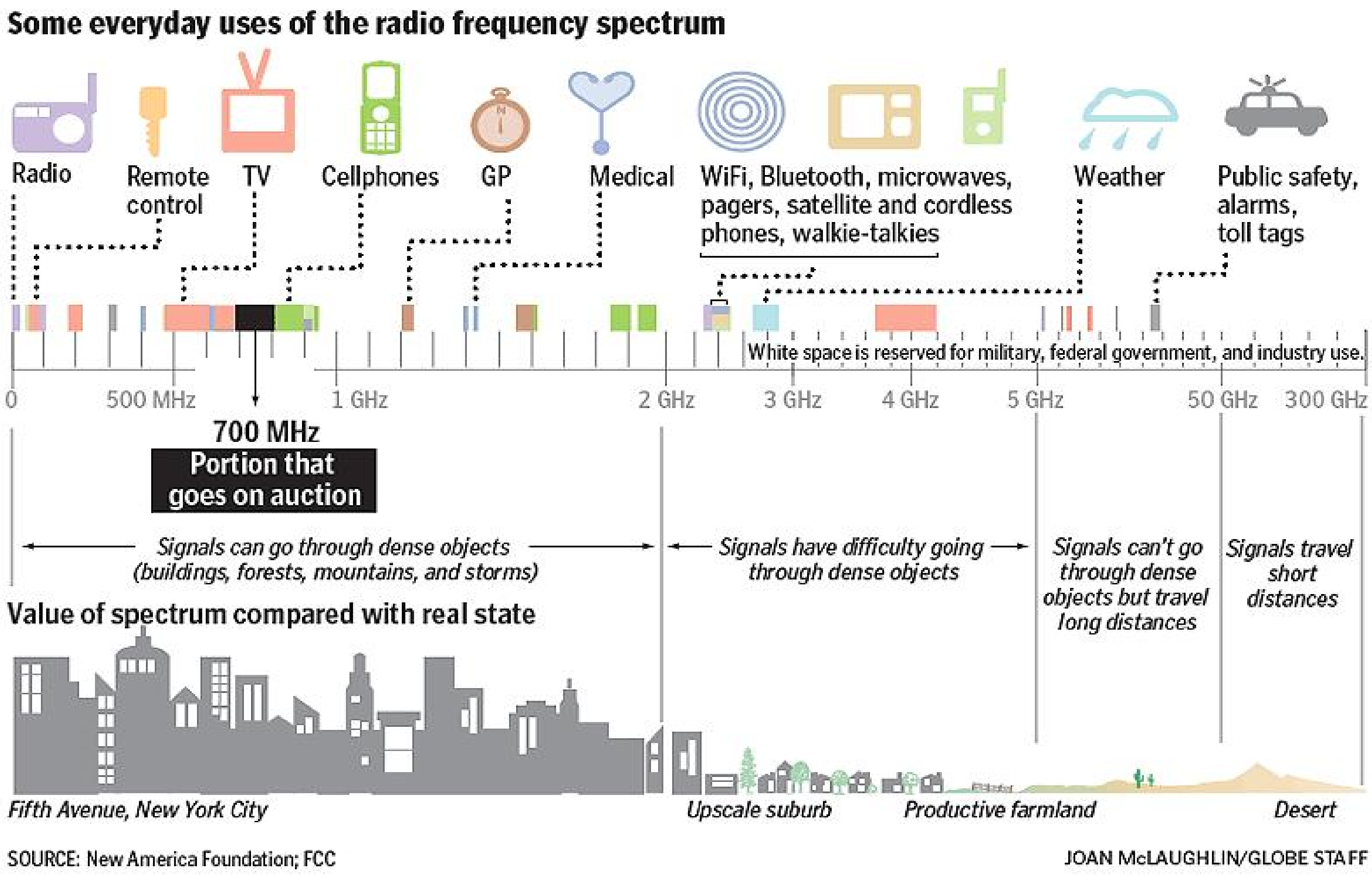
- The Legacy History: Smoke signals, horses, birds, flags…
- The Rising History of Modern Communications

  - 1837 (Morse): Morse Code (a Variable Length Code)
  - 1885 (Hertz): First RF wireless experiment
  - 1895 (Tesla): First demo of 50 miles radio transmissions in NY
  - 1901 (Marconi): Demo of cross Atlantic radio transmissions

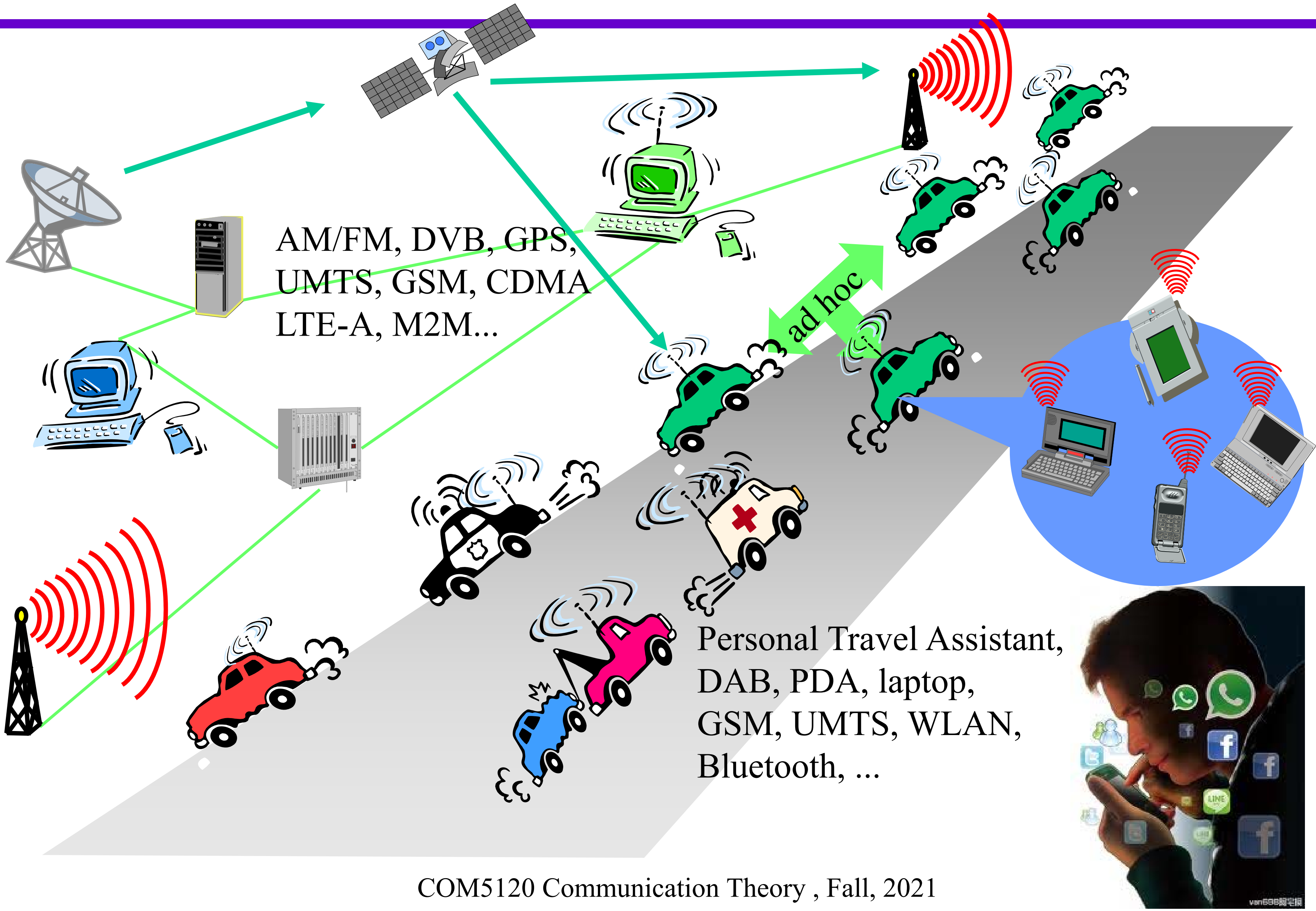
  - 1924 (Nyquist): Nyquist Rate, Nyquist Channel
  - 1939 (Kolmogorov), 1942 (Wiener): Estimation Theory
  - 1948 (Shannon): Channel Capacity
  - 1950 (Hamming): Error Correcting Code
  - 1960 (Gallegar): Low Density Parity Check Code (LDPC)
  - 1957 (Doeltz), 1966 (Chang): multi-carrier comm (OFDM)
  - 1977(Lempel & Ziv): Source coding
  - 1993 (Wittneben, Seshadri & Winters): MIMO
  - 1998 (Tarokh): Space-Time Code for MIMO
  - 20xx (You)

Wireless Communication Spectrum

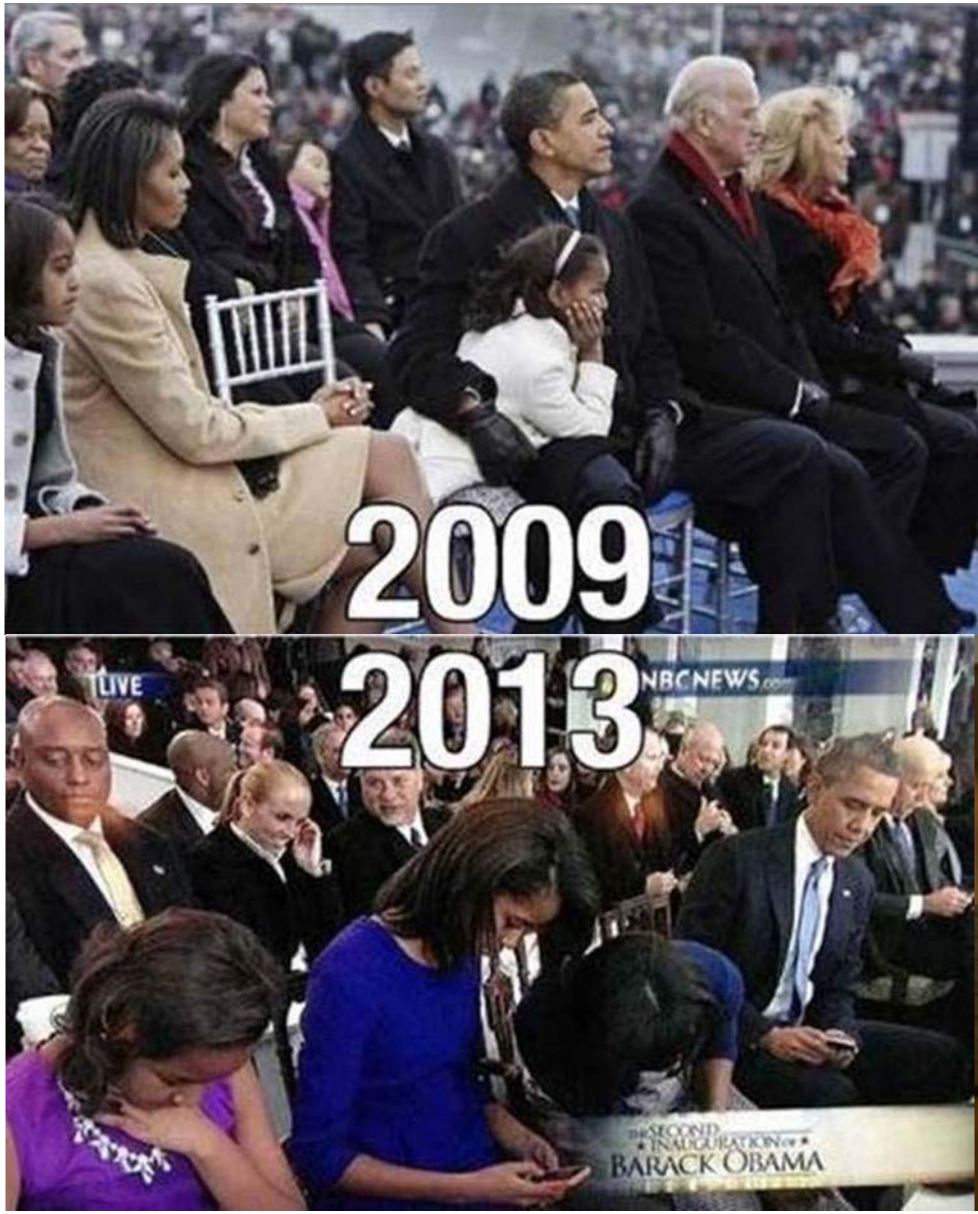
- **Wireless communication over the carrier frequency with finite bandwidth**
- **Micro Wave** (Lower: 300MHz – 1GHz, Upper: 1GHz – 10GHz)
- **Millimeter Wave (mmWave)** (30GHz – 300GHz, 1cm – 1mm)



The Era of Immersive Wireless has Come



The **Era** of Immersive Wireless



The **Era** of Immersive Wireless

The **Era** of Immersive Wireless

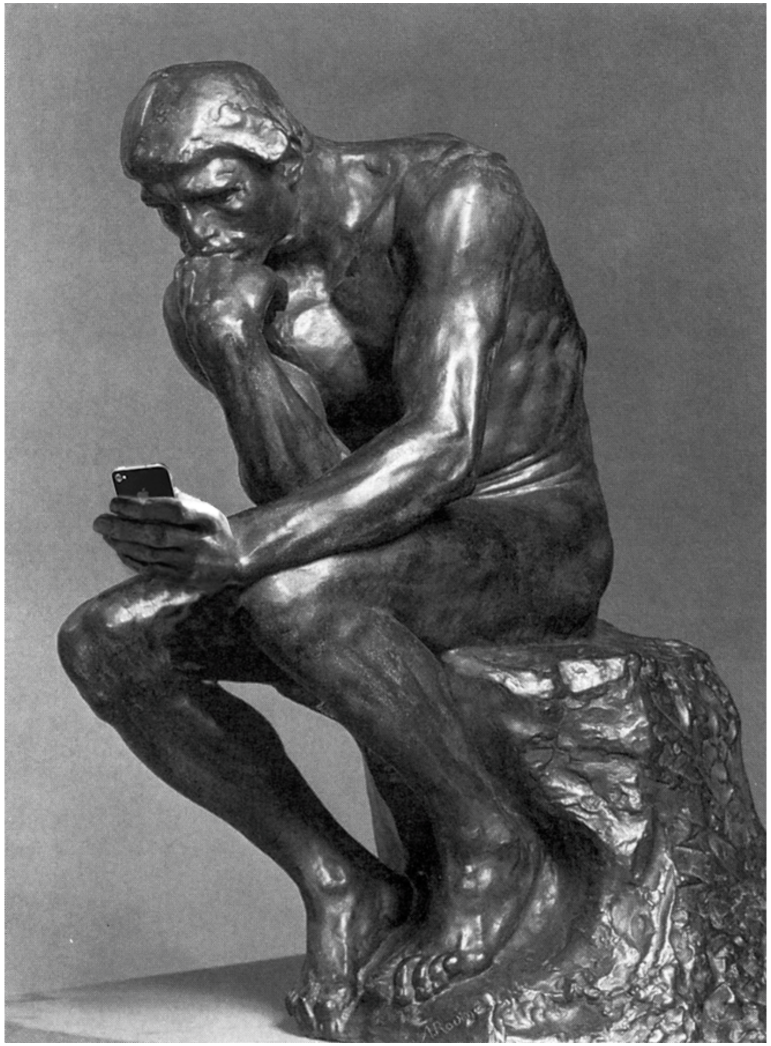
The **Era** of Immersive Wireless

- ✓ **Facebook Live Video Gets an Interactive Map**

In addition to showing where a stream has come from, when you click on a video, it also shows where it's being viewed.

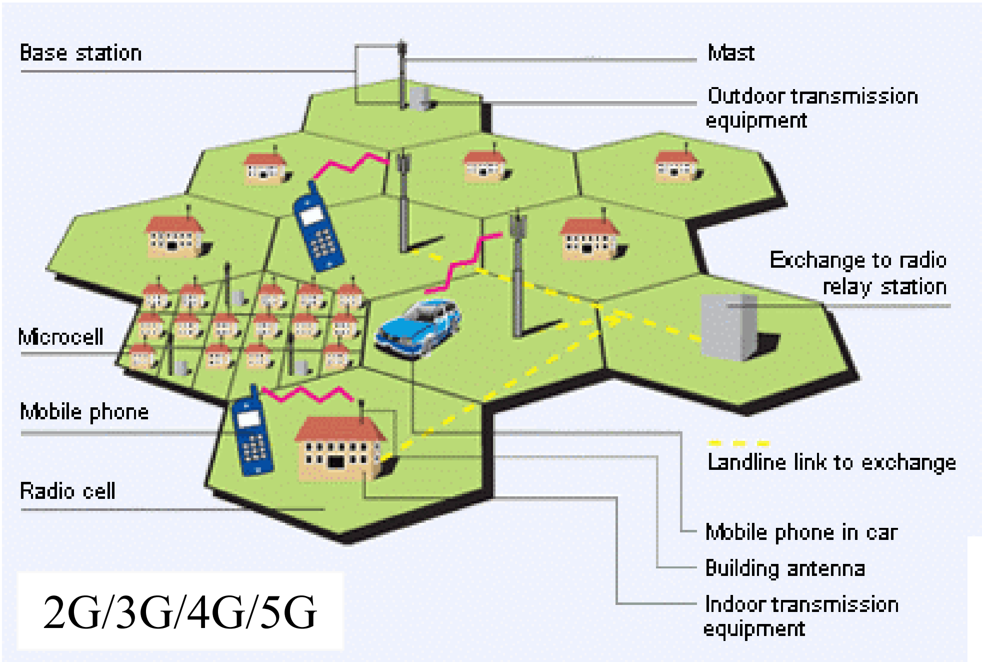
Image: Engadget

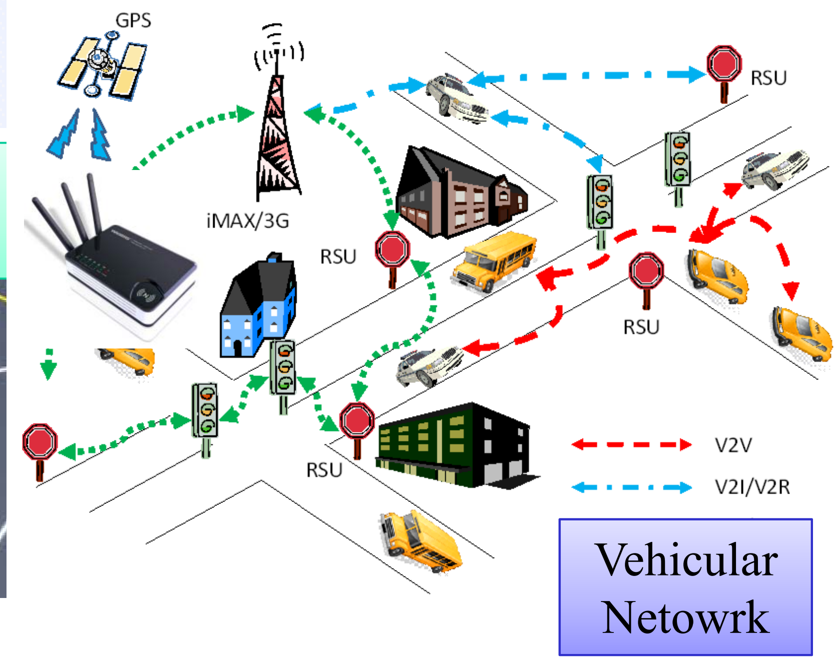
The Era of Immersive Wireless

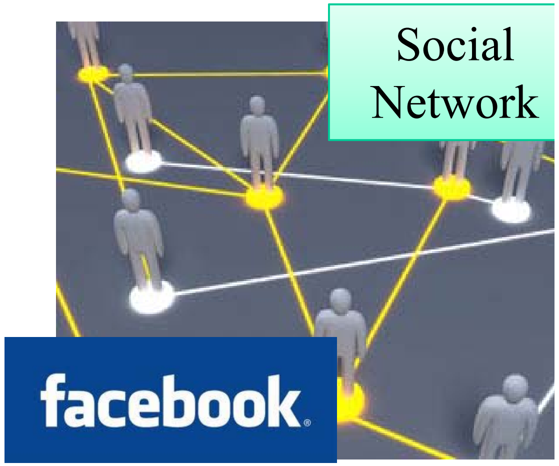


✓ **The phenomenon of phubbing (= phone + snub) is not just a phenomenon, but represents opportunities for you and me.**

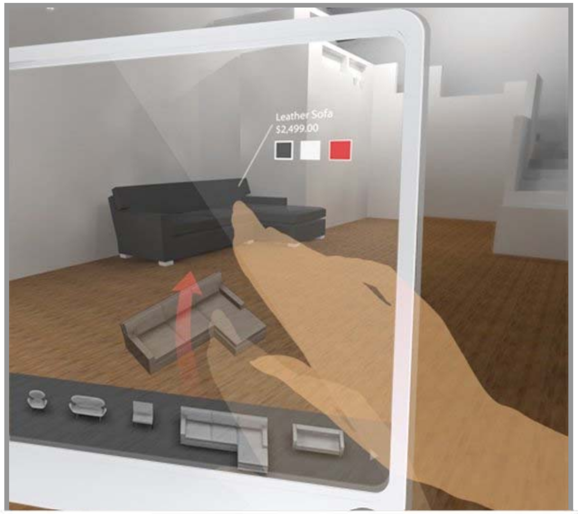
Ubiquitous Modern Wireless Communication Systems and Network







Google’s Future Tablet Concept -Augment Reality



What really enables the cloud applications is the Communication Technologies!

Social Demands – 2021 and Beyond

- Remote comm. from audio/text to Virtual Reality

傳統行動通訊內容

Mobile Voice

Mobile Text

擬真行動通訊內容

Better Quality

More Reality by Hologram Technology

Social Demands – 2021 and Beyond

- Instant connections for more efficient working environment

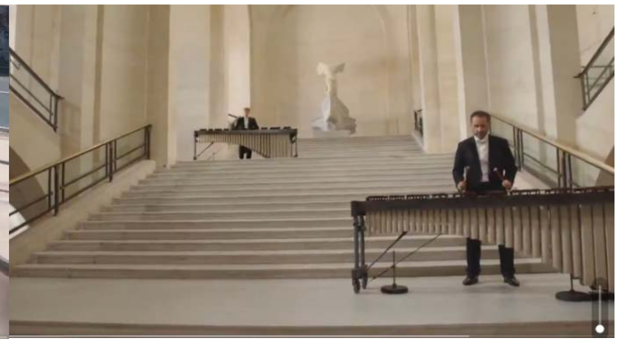
資料來源：NTT DoCoMo、Microsoft；工研院IEK整理

Tokyo Olympics 2020 and 5G NR

- **Ultra-reliable Low Latency Communication (URLLC) demo – Synchronization of symphony performance**

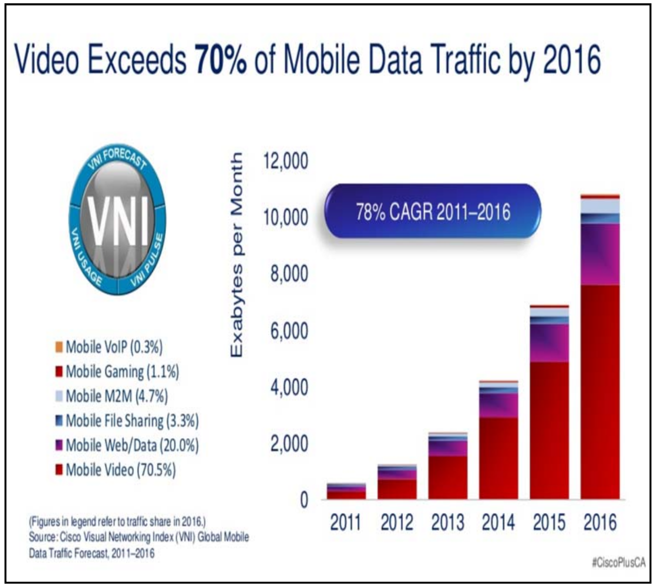


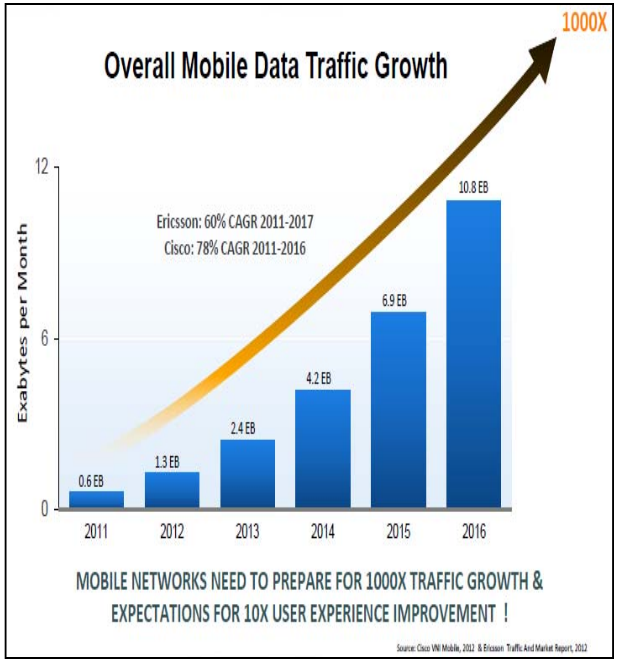


Mobile Data Traffic Grows Explosively

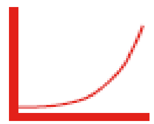
- **Smart Handheld**, **high-speed data access** and the most extreme **video services** demand are the main drivers of mobile traffic explosion
- **Video Exceeds 70% of Mobile Data Traffic**
- **Overall mobile traffic grows exponentially. Statistics shown 70% traffic originated from Indoor**
- **Mobile data traffic is expected to grow beyond 1000x in 10 years**





Massive growth in
Traffic Volume

Further expansion of mobile broadband
Additional users and increased usage
+
New use cases due to communicating machines

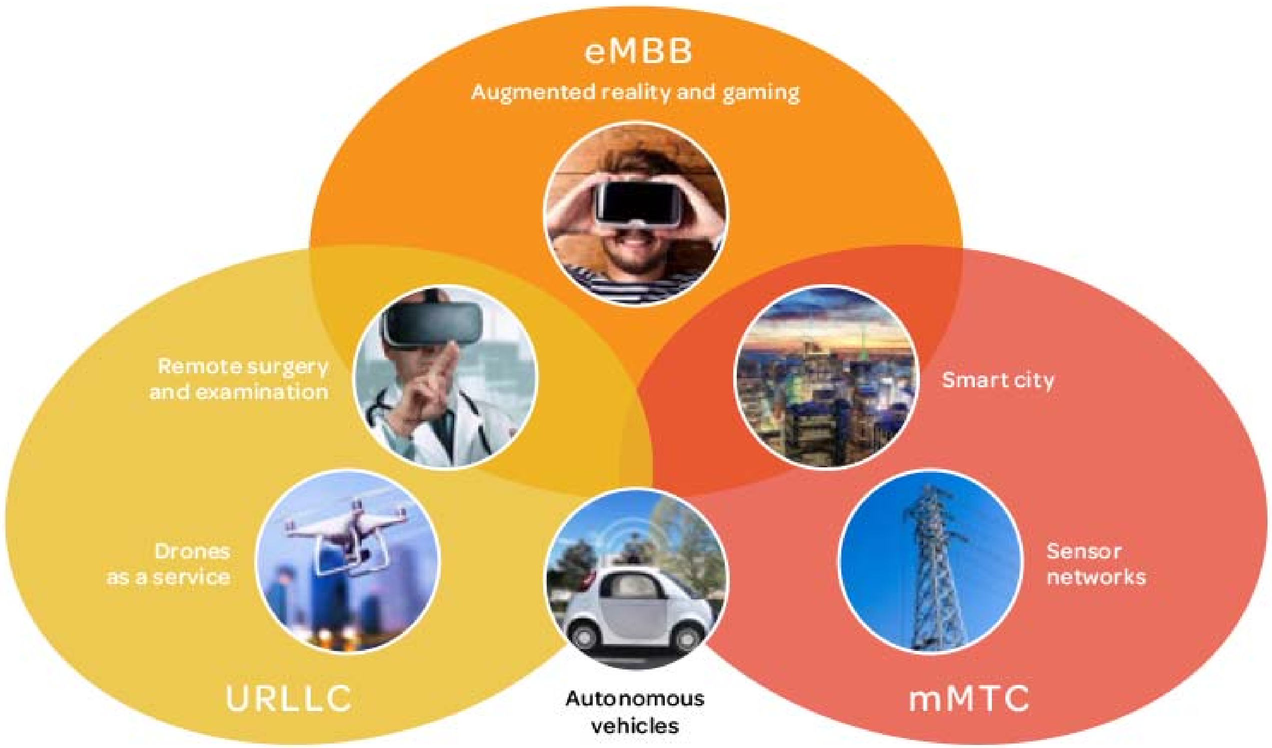


"1000x" in ten years

Source: Ericsson

Next Generation 5G Objectives in 3GPP

SLICING AND DICING 5G



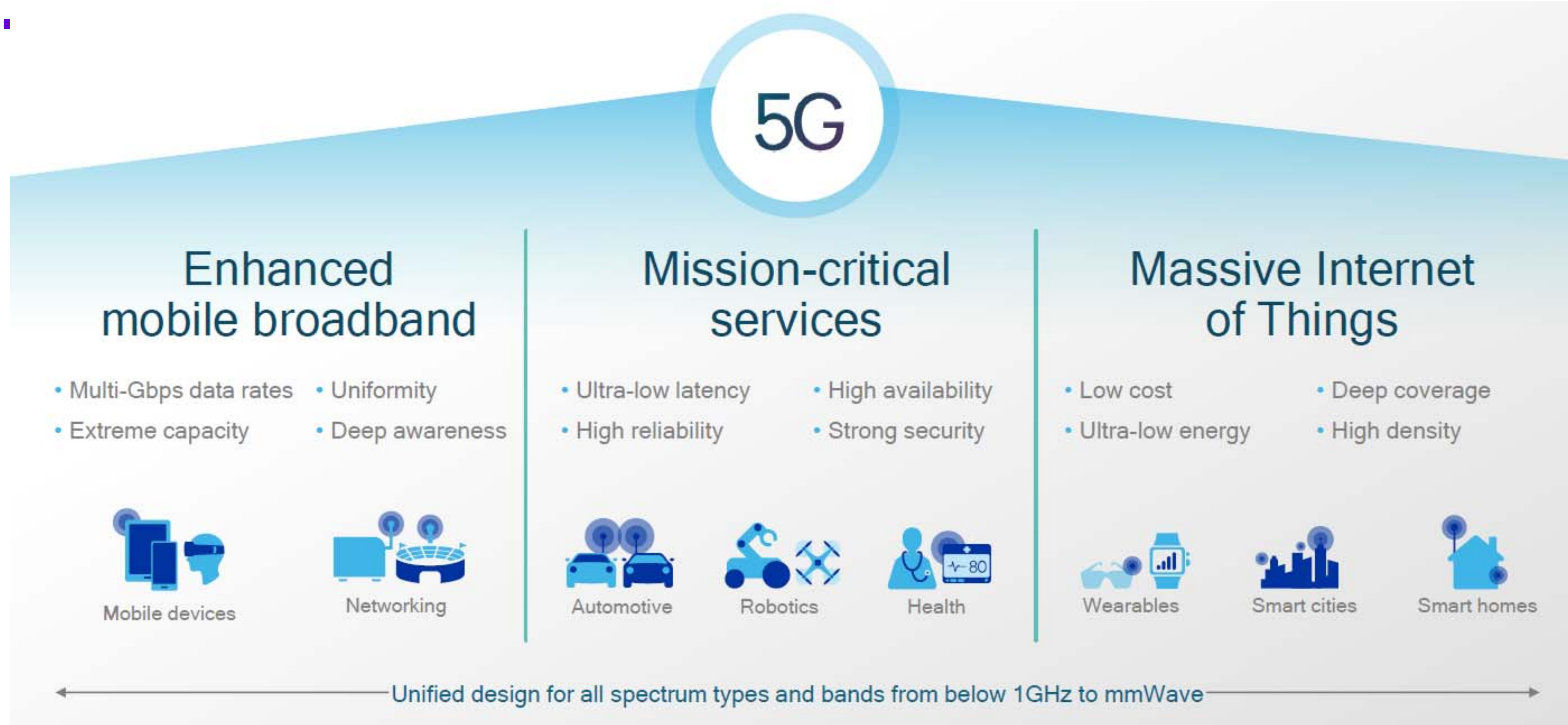
eMBB (enhanced mobile broadband) – Use cases require speed and capacity. Examples include 4K and 8K video, immersive augmented reality and gaming, and tactile internet applications such as remote surgery and examination.

uRLLC (ultra-reliable and low latency) – Sometimes called cMTC or critical machine-type communications, the use cases demand reliability and millisecond latency. Examples are autonomous vehicles or even drones as a service.

mMTC (massive machine-type communications) – Use cases are concerned with connecting millions or billions of low-power sensors with low data rates. Examples include sensor networks for smart grids and smart cities.

Source: Based on Ericsson graphic, TM Forum, 2017

Next Generation 5G Objectives in 3GPP

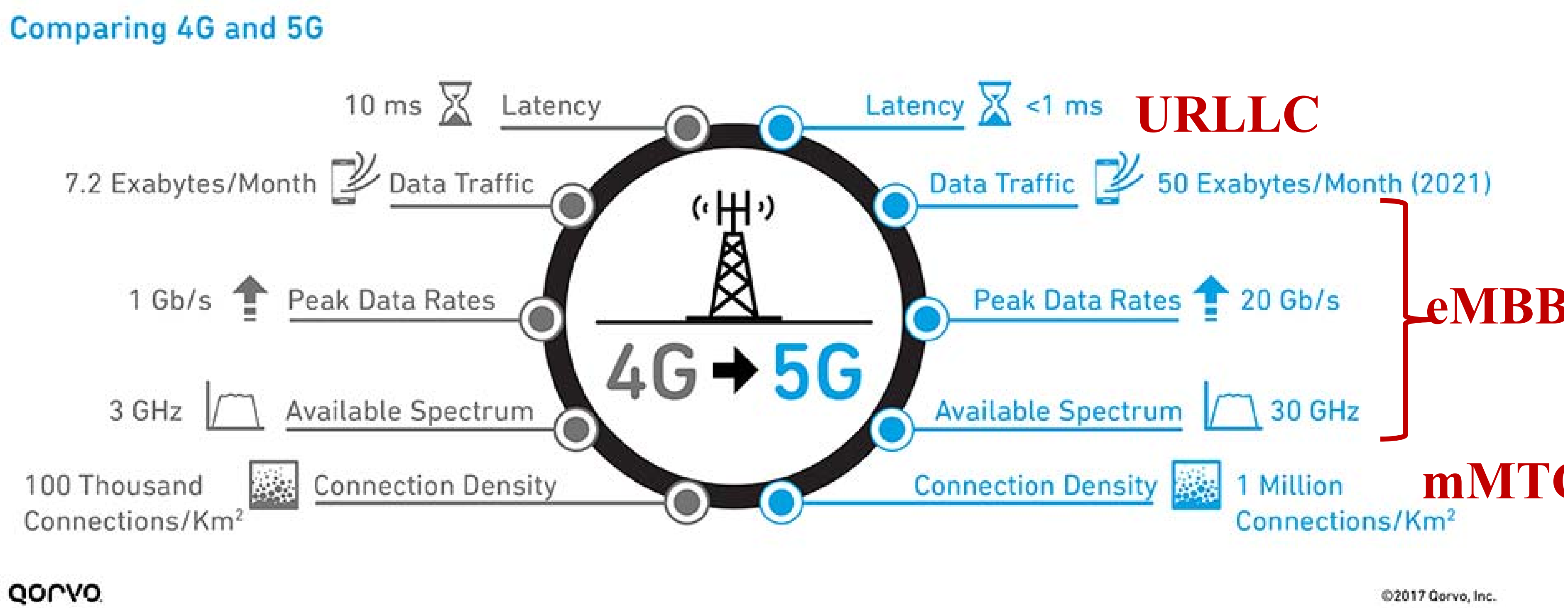


eMBB (Enhanced Mobile Broadband):
- Low latency
- Higher spectral efficiency/throughput

URLLC(Ultra reliable low latency communications):
- High reliability (low packet error rate)
- Low latency

mMTC(massive machine type communications):
- Sporadic traffic
- Short message length
- Low device complexity
- Massive connections

From 4G to 5G


Comparing 4G and 5G
10 ms
Latency
7.2 Exabytes/Month
Data Traffic
1 Gb/s
Peak Data Rates
3 GHz
Available Spectrum
100 Thousand Connections/Km²
Connection Density
4G → 5G
Latency
<1 ms
URLLC
Data Traffic
50 Exabytes/Month (2021)
Peak Data Rates
20 Gb/s
eMBB
Available Spectrum
30 GHz
Connection Density
1 Million Connections/Km²
mMTC
qorvo
©2017 Qorvo, Inc.

How to Achieve 1000x Capacity in 5G and beyond?

Bandwidth (3-10X)

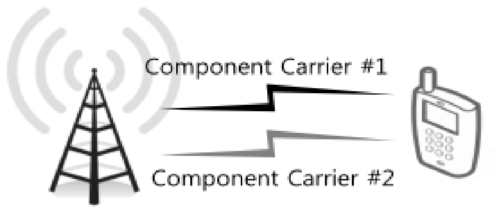
- Acquisition of new spectrum resources
- Carrier Aggregation
- Cognitive Radio

Resource Reuse (56X)

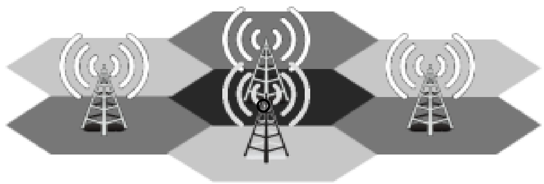
- Small cell
- HetNet

Spectral Efficiency (6X)

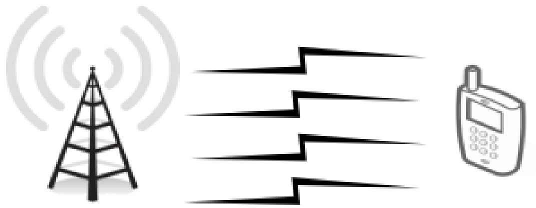
- Active Array Antenna
- High order MIMO
- Tx / Rx cooperation



[Carrier Aggregation]

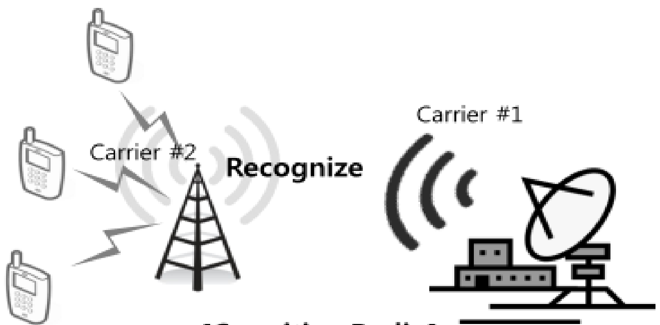


[Small Cell Deployment]

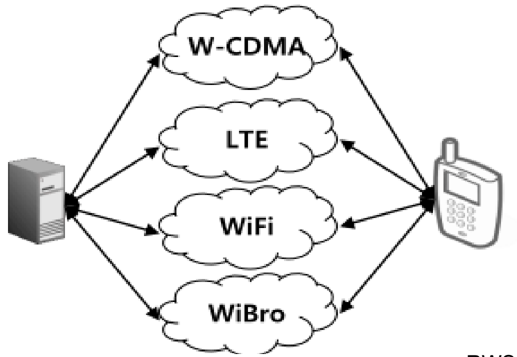


[Higher order MIMO]

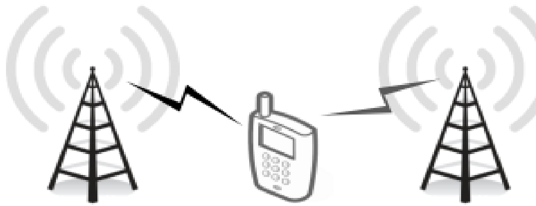
[mmWave]



[Cognitive Radio]



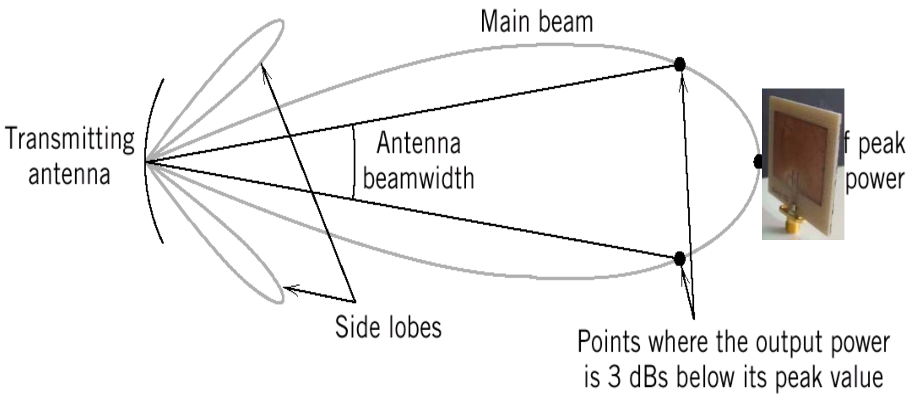
[HetNet]



[CoMP]

More Bandwidth
- How to find more bandwidth?

- **How about going from microwave to mmWave Communications?**
  - Pros – Vast amount of spectrum available in mmWave bands
    - – Smaller form factor of antenna array, highly packed mmWave RFIC
  - Cons – Smaller wavelength leads to smaller antenna aperture and less capture energy
    - – The mmWave suffers from higher path loss and penetration loss
    - – More bandwidth means more noise power and lower SNR
    - – Less multipath and scatterings



[Haykin, Comm Systems, 4th Ed.]

- ✓ Effective aperture of receiving antenna

$$A_r = \frac{\lambda^2}{4\pi} G_r$$

where λ is the wavelength
G_r is antenna's power gain

- ✓ The received power is

$$P_r = \frac{P_t G_t}{4\pi d^2} A_r$$

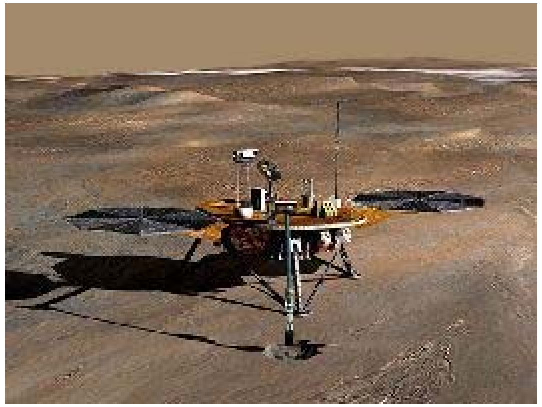
More than Daily Life:

Wireless Communications above the Earth

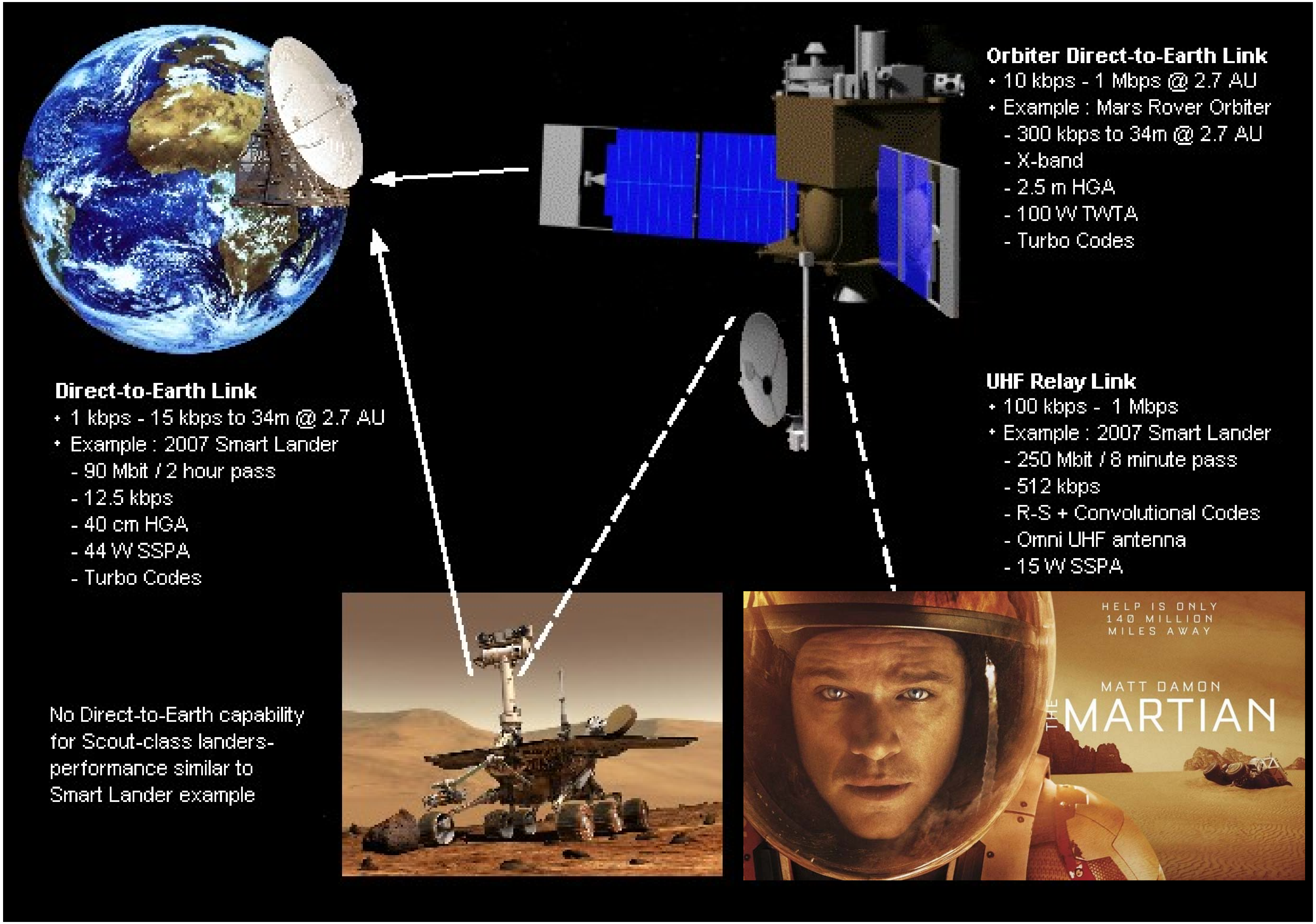
How to communicate from Mars to Earth?

The Facts

- Distance: 56 millions km (Moon-to-Earth is 0.28 M km, Sun-to-Earth 150M km)
- Delay Time: 3 minutes and 7 seconds for a signal emitted by the DSN to reach Mars
- Noise source: cosmic rays and thermal noise (from the Sun and the Rx)
- Noise Level: -215 dBW/Hz
- Tx RF power: 15W ~ 100W
- Rx Signal Power: 2×10^{-16} W or -157 dBW
- SNR : 8 dB
- Carrier Frequency: S-, X- and K-bands at frequencies of 2.2, 8.4 and 32 GHz
- Bandwidth: 100 kHz
- Bit Rate: 166 kbit/s (with BPSK modulation)

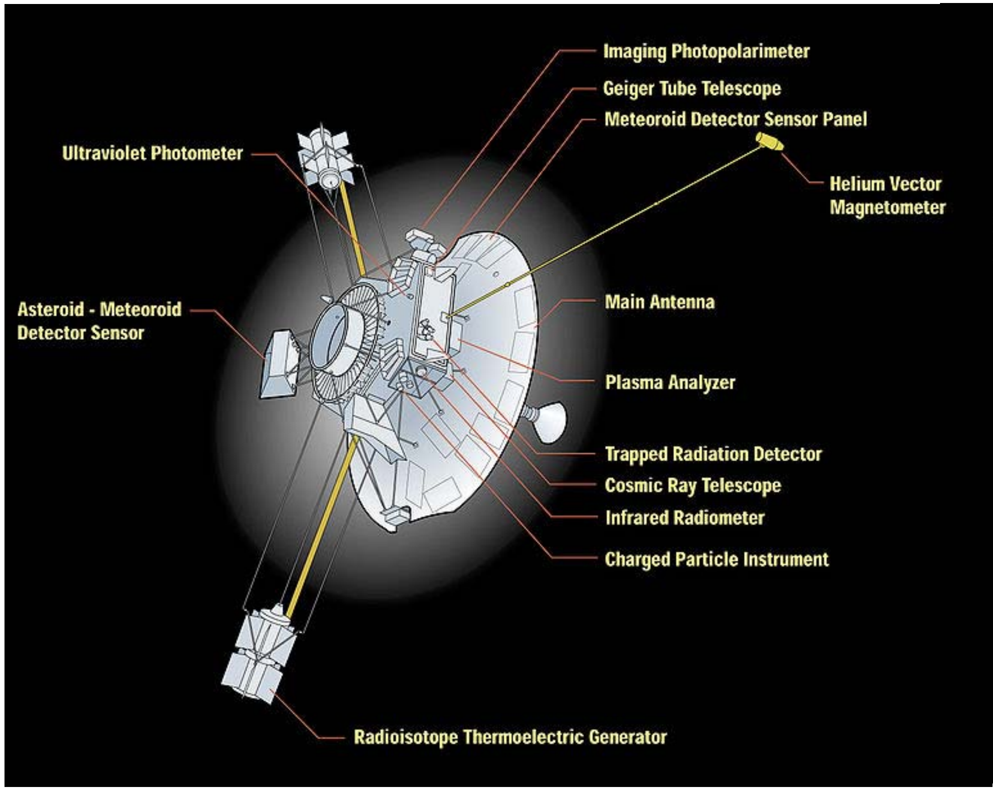


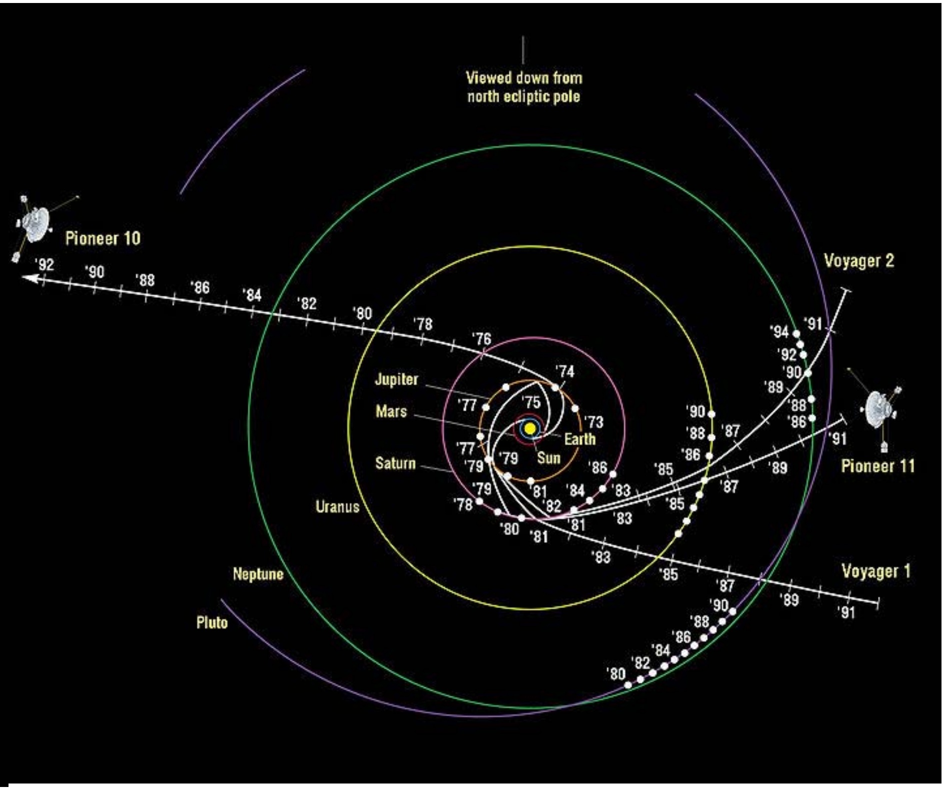
Source: http://www.astrosurf.com/luxorion/qsl-mars-communication3.htm


Orbiter Direct-to-Earth Link
• 10 kbps - 1 Mbps @ 2.7 AU
• Example : Mars Rover Orbiter
- 300 kbps to 34m @ 2.7 AU
- X-band
- 2.5 m HGA
- 100 W TWTA
- Turbo Codes
UHF Relay Link
• 100 kbps - 1 Mbps
• Example : 2007 Smart Lander
- 250 Mbit / 8 minute pass
- 512 kbps
- R-S + Convolutional Codes
- Omni UHF antenna
- 15 W SSPA
Direct-to-Earth Link
• 1 kbps - 15 kbps to 34m @ 2.7 AU
• Example : 2007 Smart Lander
- 90 Mbit / 2 hour pass
- 12.5 kbps
- 40 cm HGA
- 44 W SSPA
- Turbo Codes
No Direct-to-Earth capability for Scout-class landers- performance similar to Smart Lander example
HELP IS ONLY 140 MILLION MILES AWAY
MATT DAMON
THE MARTIAN

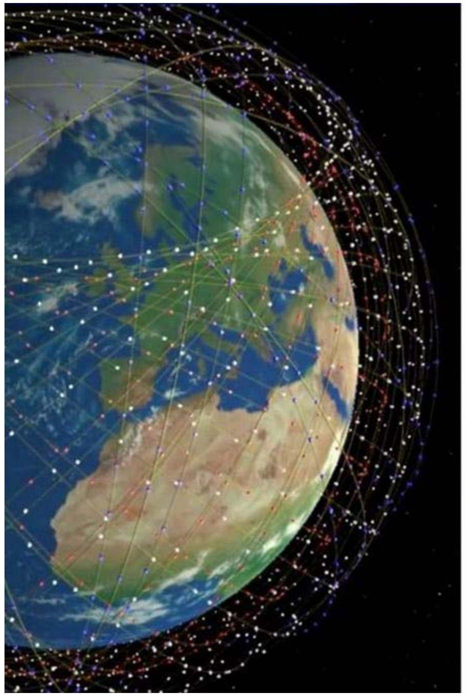
Exploration from Outer Solar Space

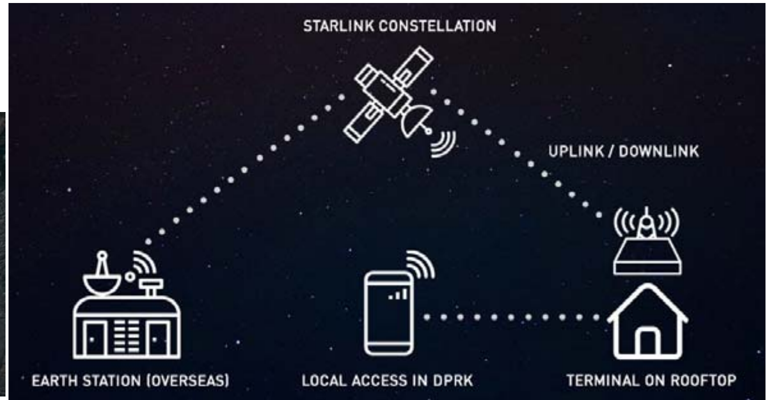
- It is wireless that makes outer space exploration possible.
- As of 2021, the Voyager I communicates from 20.8×10^9 km distance to the earth (since 1977).
- Way beyond the imagination since the experiment of Hertz at 1885.





Starlink Project – 12000 Sats by 2027





Syllabus

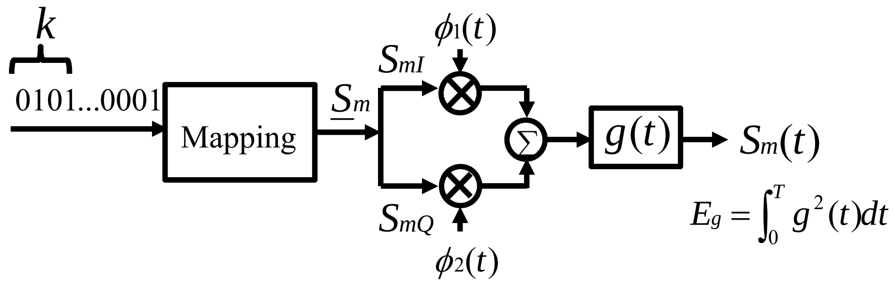
1. Communication Systems and Random Process (Ch.2)
2. Digital modulations (Ch 3)
3. Optimum Receivers and AWGN Channels (Ch. 4)
4. Introduction to Information Theory and Channel Capacity (Ch. 6)
4. Bandlimited Channels and Inter-Symbol Interference (Ch 9)
5. Linear Equalizers (Ch 9)
6. Multichannel and multicarrier Systems (Ch11)
7. Multiple Antenna Systems (Ch15) (Optional)

Ch. 2. Deterministic and Random Signal Analysis

- Deterministic Signal Analysis
  - Fourier Transform and Hilbert Transform
  - Bandpass and low pass signal representation
    - ✓ Pre-envelopes and complex envelopes
- Random Variables
  - Bounds on tail probability
  - Limit theorem for sums of random variables
  - Complex random variables
- Random Process
  - Stationary random process, Gaussian random process
  - Serial expansion of random process

Ch. 3. Digital Modulations

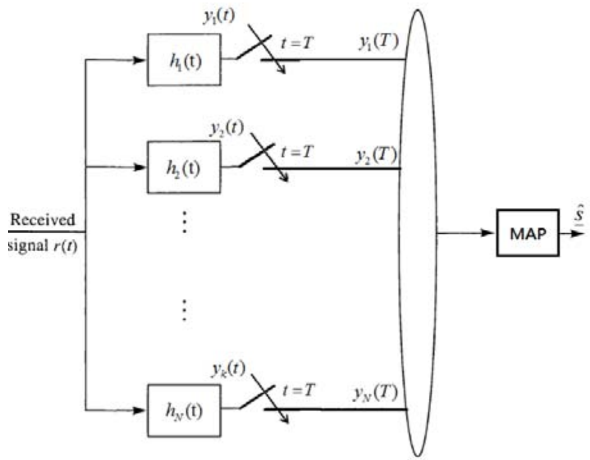
- Representation of Digitally Modulated Signals
- Memoryless Digital Modulations
  - PAM
  - Phase Modulation
  - QAM

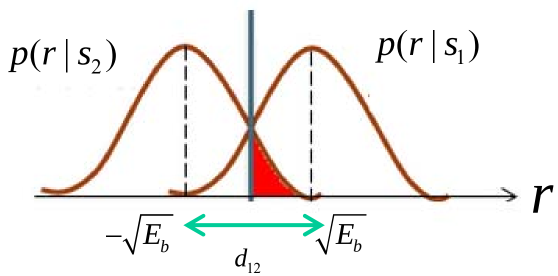


- Digital Modulations with Memory
  - Continuous Phase FSK
  - Continue Phase Modulation (CPM)
- Power Spectrum of Digitally Modulated Signals

Ch. 4. Optimum Receivers and AWGN Channels

- Optimum detection for a general vector channel
- Optimum detection for a vector AWGN Channel
- Optimum detection and P_e for band-limited signal
- Optimum detection and P_e for power-limited signal
- Optimum detection for coherent/non-coherent modulations
- Optimum detection for CPM Signals



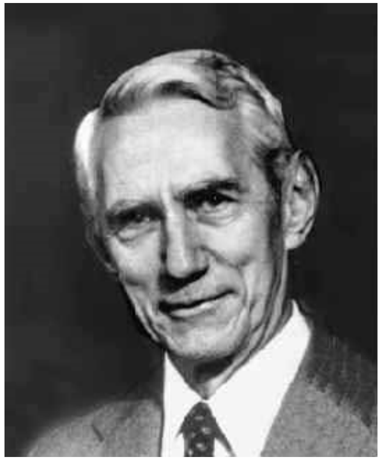


$$p(r \mid s) = \frac{1}{\sqrt{\pi N_0}} \exp\left(-\frac{1}{N_0}(r-s)^2\right)$$

Ch. 6. Information Capacity Theorem

- How to deliver reliable communication under limited resources
  - Limited transmit power
  - Limited channel bandwidth
  - Limited cost to build the system
- Reliability is quantified in terms of BER (Bit Error Rate)
- Shannon's Information Capacity Theorem (1948)
  - Under Additive White Gaussian Noise (AWGN) channel, the channel capacity is

$$C = \frac{1}{2}\log_2\left(1+\frac{P}{\sigma_w^2}\right) \qquad bps / Hz$$



- Given channel bandwidth and SNR , provide an theoretical upper bound of data rate R.
- Energy Efficiency η = P/C (Joule/Bit)

Communication Energy Efficiency

■ Wireless communication performance under energy constraints

- Shannon-Von Neumann-Landauer Bound:

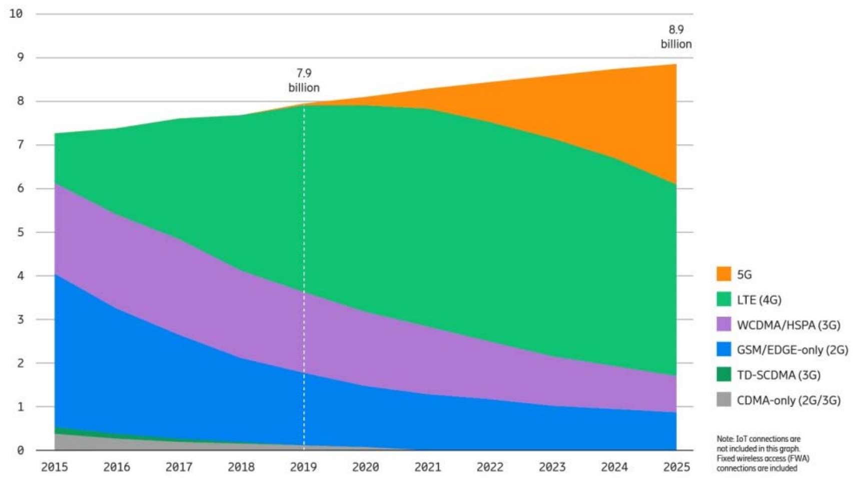
  Minimum energy/operation = $kTln2$ = 4×10^{-21} J/bit at 27°C

- Complexity-energy-performance trade-off

	Rate (Mb/s)	P_Rx (mW)	Rx (nJ/bit)	P_Tx (mW)	Tx (nJ/bit)
802.11g	22	140	6.4	450	20.4
802.11n	200	1000	5	1800	9.0
BT 2.0	0.7	45	64.3	62	88.6
BT EDR	2.2	48	21.8	65	29.5

Source: Wireless Net Designline

(Unit: Billions)

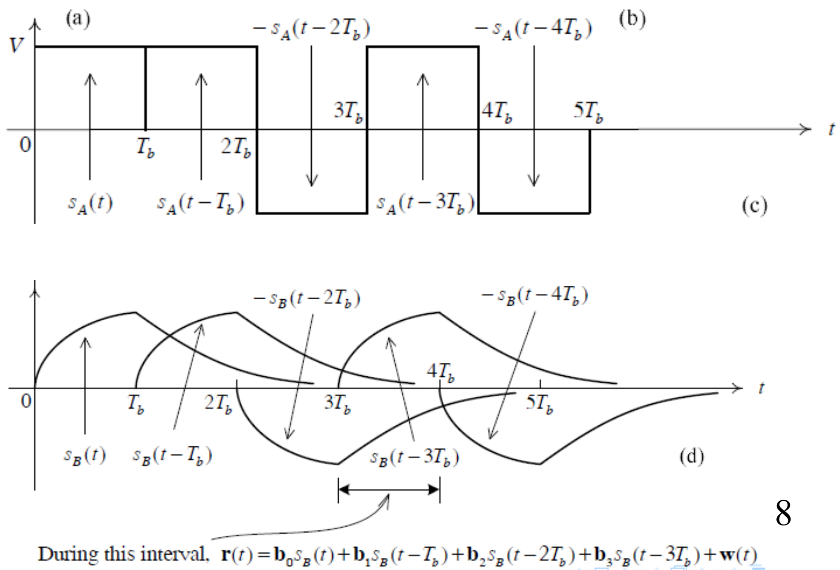


■ Energy efficiency under energy constraints

- Portable device/handset operations are always limited by the battery.
- Every mW saving in wireless transceiver represents MW's of saving for greener communications.

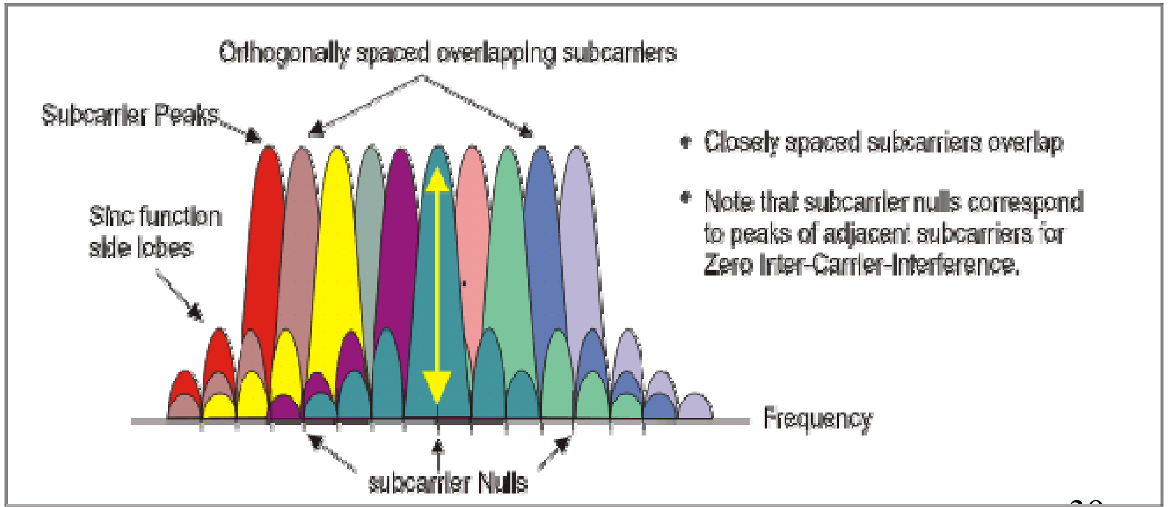
Ch. 9. Digital Communication through Band-limited Channels

- Signal design for band-limited channels
  - Ideal System without ISI -The Nyquist Criterion
  - System with controlled ISI
- Optimum Receiver for channels with ISI and AWGN
  - Maximum-Likelihood Sequence Detector (MLSD)
- Linear Equalization
  - Peak distortion criterion
  - ZF, MMSE equalizer
  - Decision feedback equalizer



Ch.11. Multichannel and Multicarrier Systems

- Multichannel digital communications in AWGN
  - M-ary Orthogonal Signals
- Multicarrier communications
  - Single carrier v.s. multicarrier modulation
  - OFDM
  - Implementation of OFDM with FFT
  - PAPR in OFDM

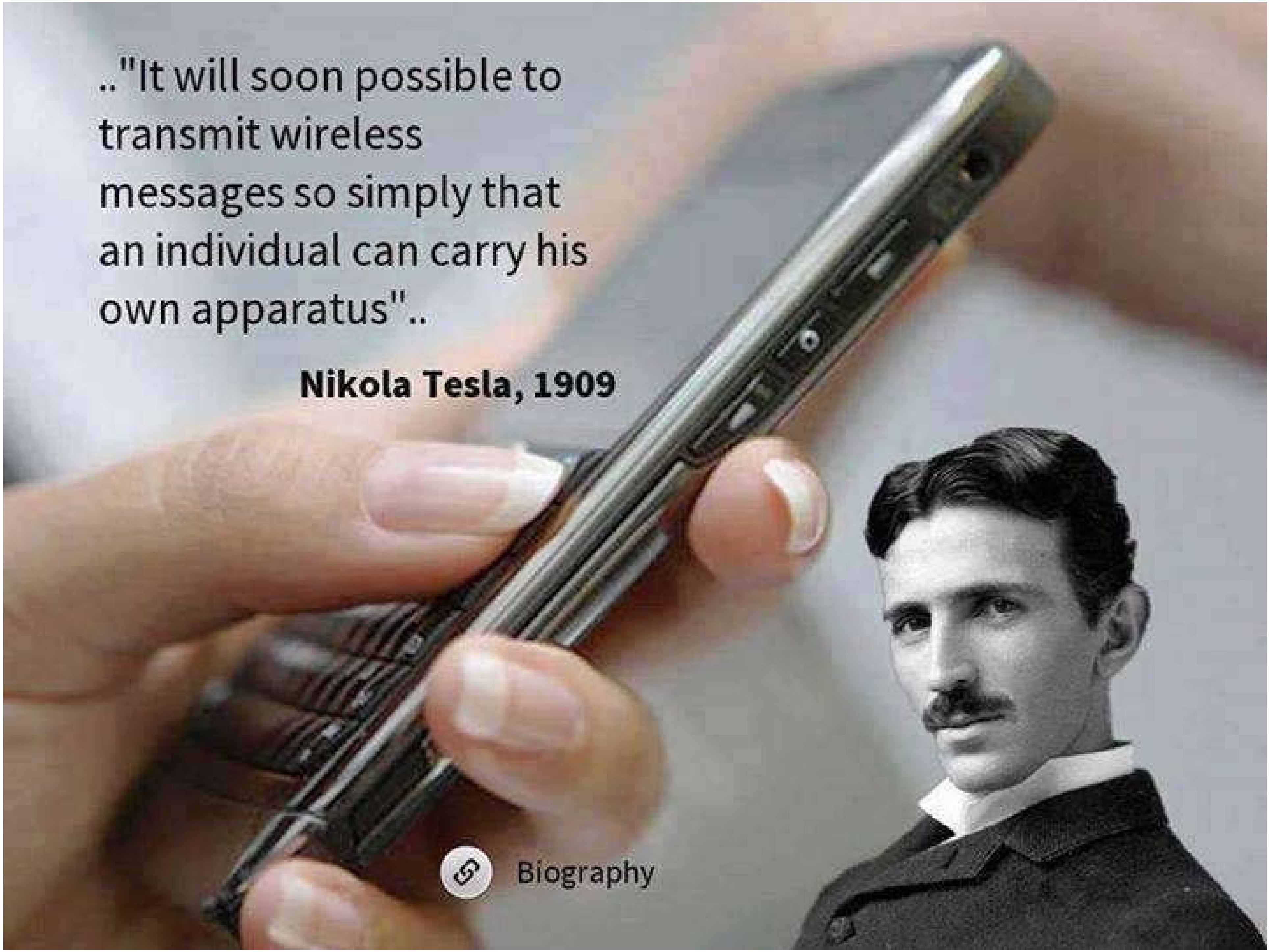


OFDM Signal Frequency Spectra

Ch. 15. Multiple-Antenna (MIMO) Systems

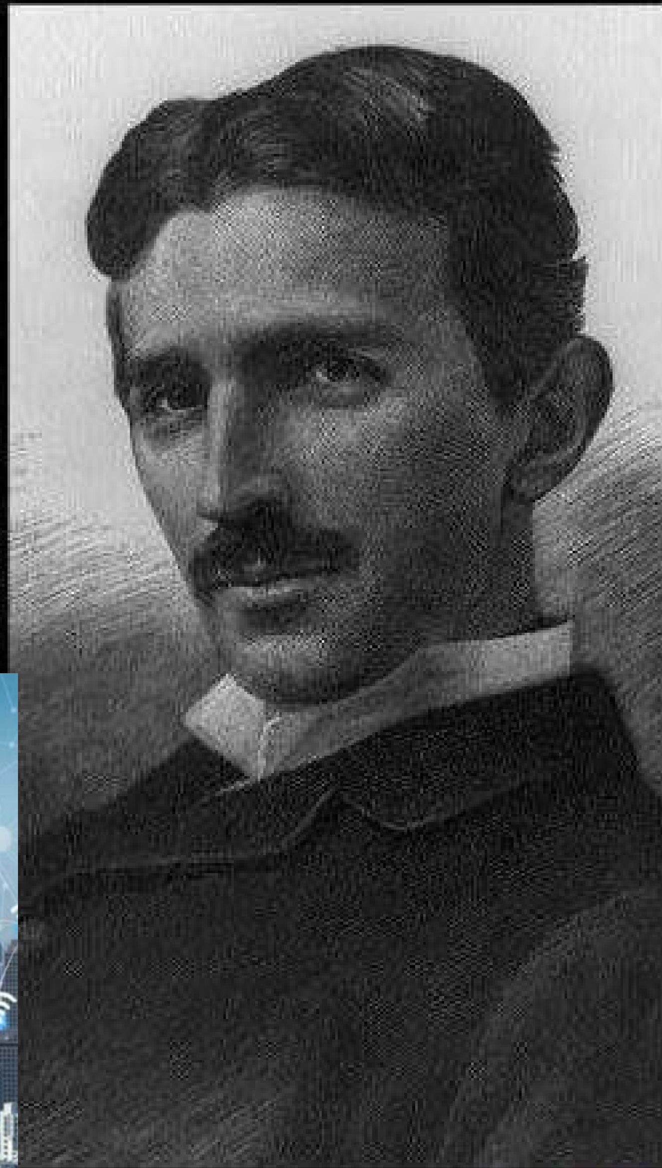
- Channel model of MIMO systems
- Capacity of MIMO channels
- Spread Spectrum Signals and multicode transmission
  - Multiplexing gain
  - Diversity gain
  - Multicode MIMO systems
- Coding for MIMO channels
  - Bit Interleaved Temporal Coding (BITC)
  - Space-Time Block Code (STBC)
  - Space-Time Trellis Code (STTC)

- This part to be offered if time allows.


.."It will soon possible to transmit wireless messages so simply that an individual can carry his own apparatus"..
Nikola Tesla, 1909
Biography

"All people everywhere should have free energy sources." [...] "Electric Power is everywhere present in unlimited quantities and can drive the world's machinery without the need for coal, oil or gas."

~ Nikola Tesla (1856-1943)



T.T.I.O.T.