Spectrum Sharing Theory and Practice

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ICTP School on Applications of Open Spectrum

and

White Spaces Technologies

Contents

- The history of wireless technology
  - from spectrum sharing to spectrum monopoly
- Modern wireless technology
  - Smart phones, OTT and the unconnected world need affordable wireless solutions
- Spectrum sharing for TV spectrum
  - a reminiscence of Marconi era with a delicate control in technologies and in governing
- Spectrum sharing pros & cons
- Available technologies
- 6Harmonics practice and solution

The History of Wireless Technology

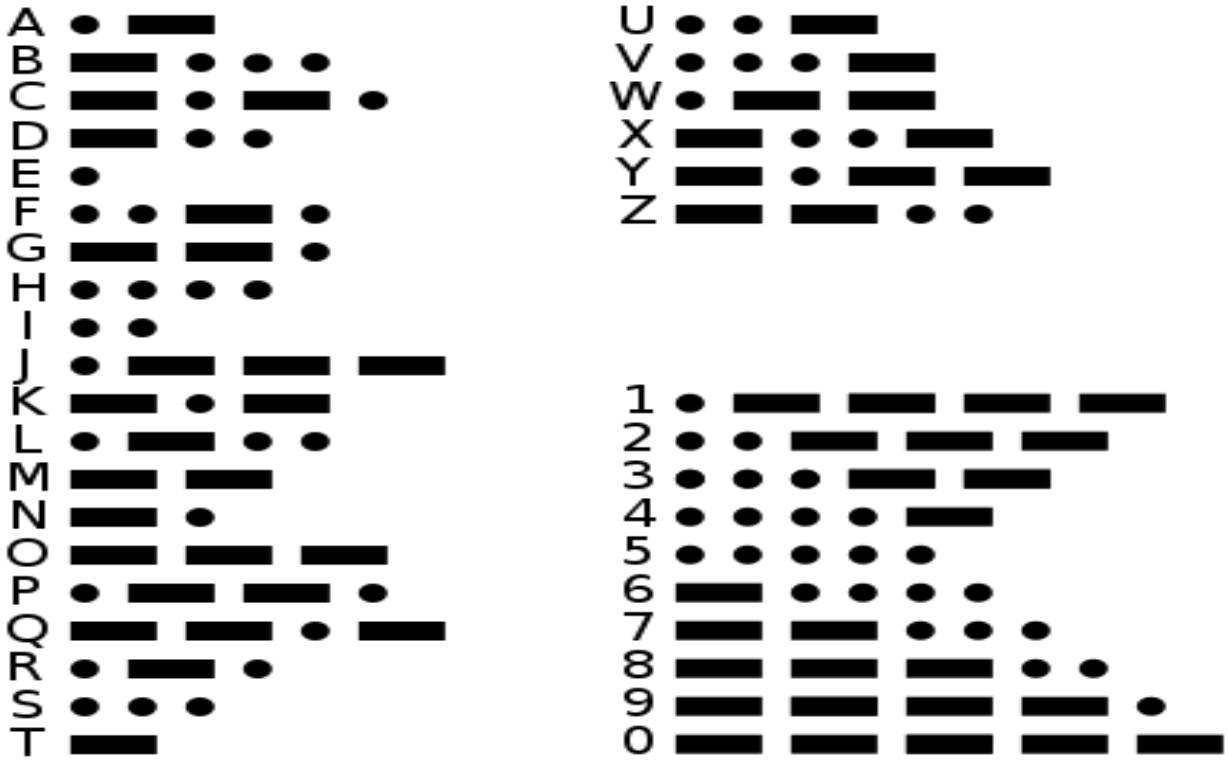
Communication in progress

- Sound
- Gesture
- Eye wave
- Fire
- Arrows
- Pigeon
- Message station
- Post
- Wire telegram
- Morse code
- Telephone
- Wireless telegram
- Cellphone
- Short message
- Internet
- Google, facebook, We-chat
- ◦ ◦ ◦

Morse code

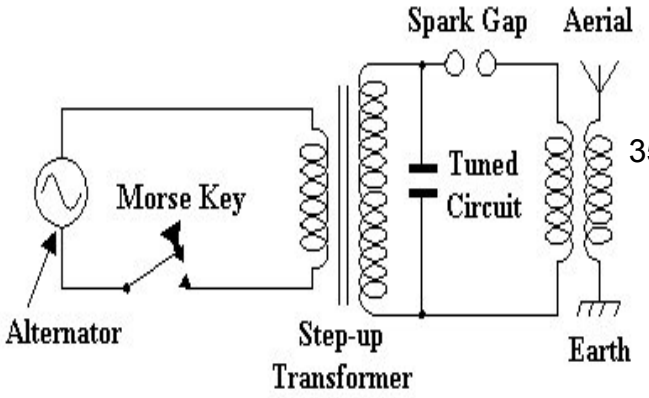
International Morse Code

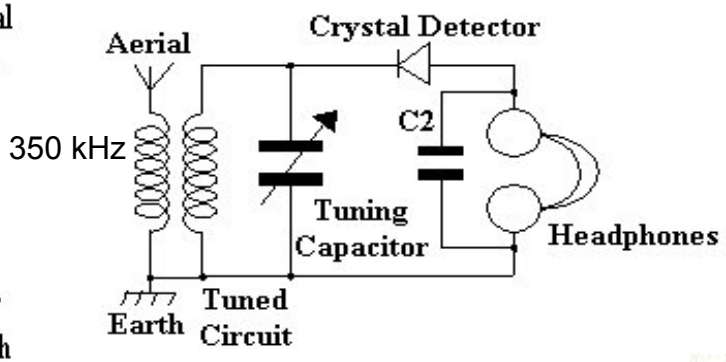
1. A dash is equal to three dots.
2. The space between parts of the same letter is equal to one dot.
3. The space between two letters is equal to three dots.
4. The space between two words is equal to seven dots.



Wireless telegram-spectrum shared

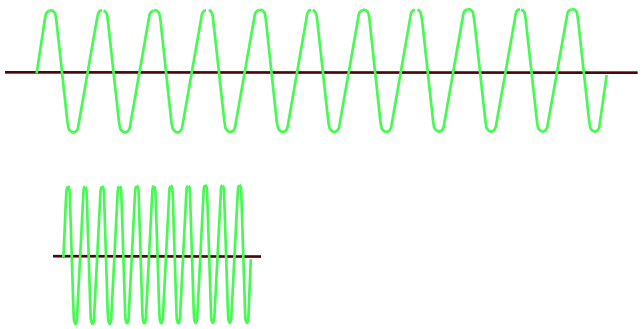
- Marconi, who had no degree, was intrigued by wireless communication at age 13（1887）, at age 23 he developed the sparkling device
- Maxwell hypothesized the propagation theory，Hertz did the experiments for wireless communication，Nicolas Tesla developed the 1st prototype and filed the 1st patent. Though it was Marconi who won the title of the “Wireless communications father” and the Nobel prize because he had made it practical and popular with his sparkling device

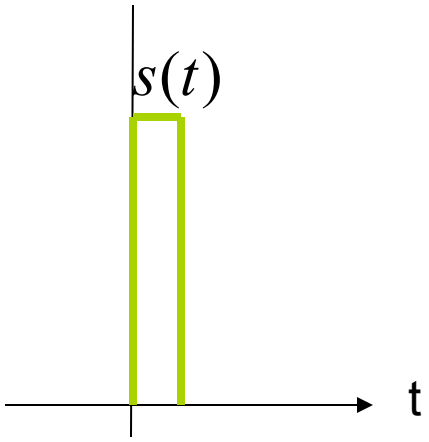




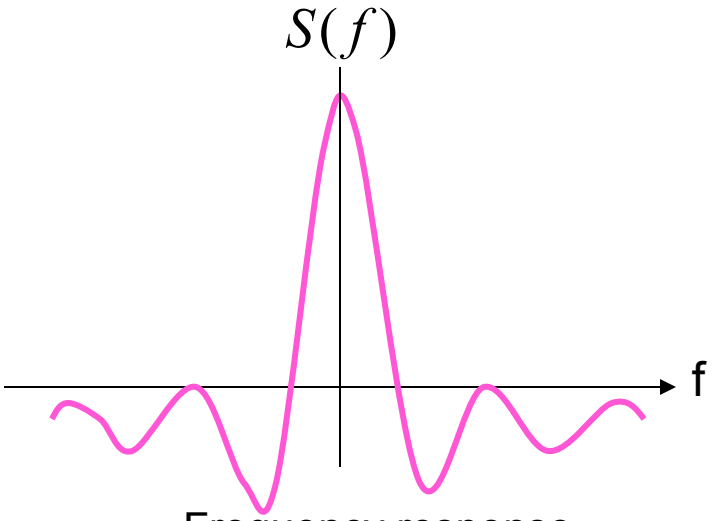
Wireless communication: a few milestones

- Hertz
- Maxwell
- Marconi
- Sinusoidal
- Fourier
- Shanno-Nyquist sampling





Time pulse



Frequency response

Maxwell Equations

Maxwell equation in vacuum

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

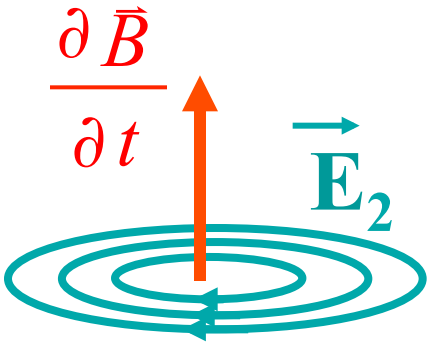
$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} + \varepsilon_0 \mu_0 \frac{\partial \boldsymbol{E}}{\partial t}$$

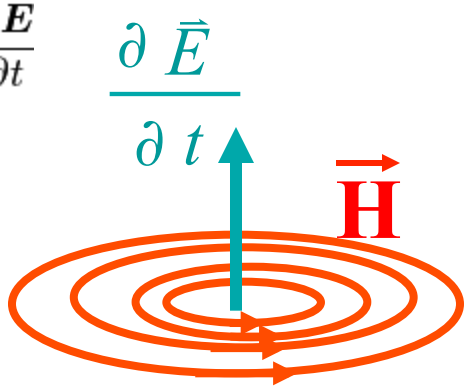
Static electrical field has a source

Magnetic field Has no source

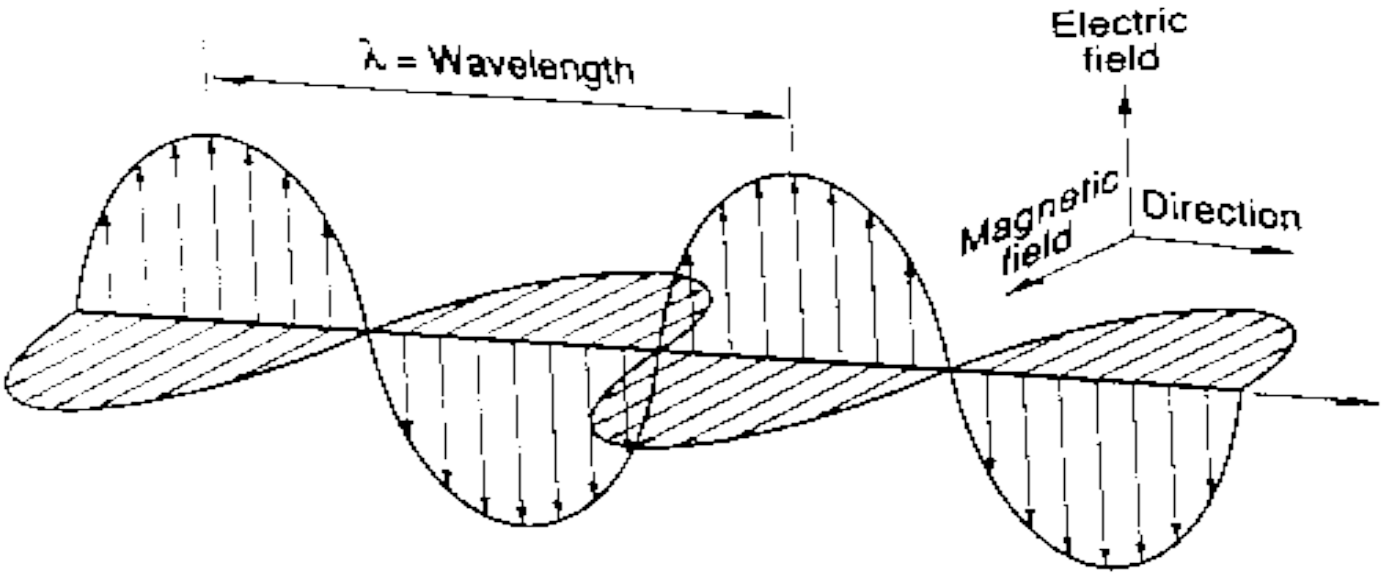
Magnetic field Change results Electrical field

Electrical field Change results Magnetic field change

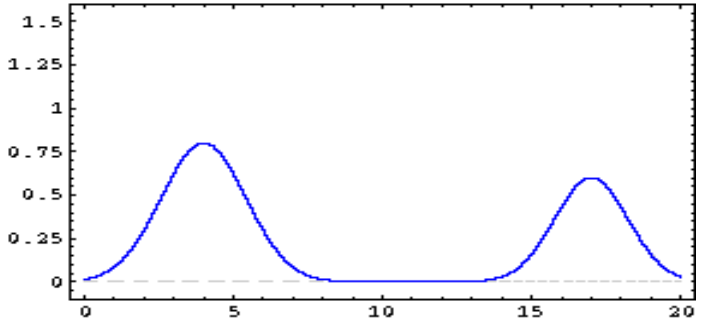




EM wave

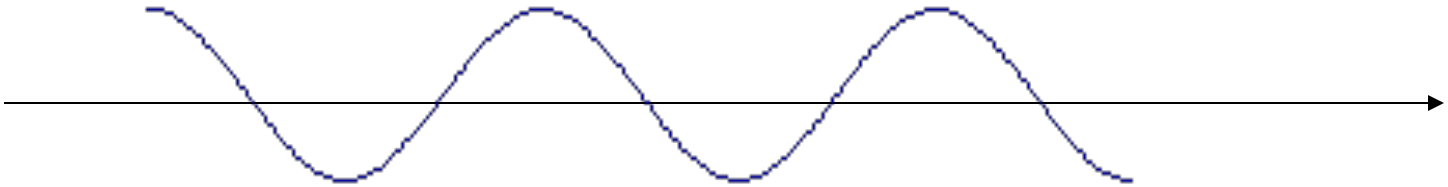


- EM wave behaves as wave and particles!
- As a waves：energy can be enhanced，cancel each other, or pass through each other
- As particles：particles can collide, smash，bounce back, cannot pass through each other
- How to visualize these?

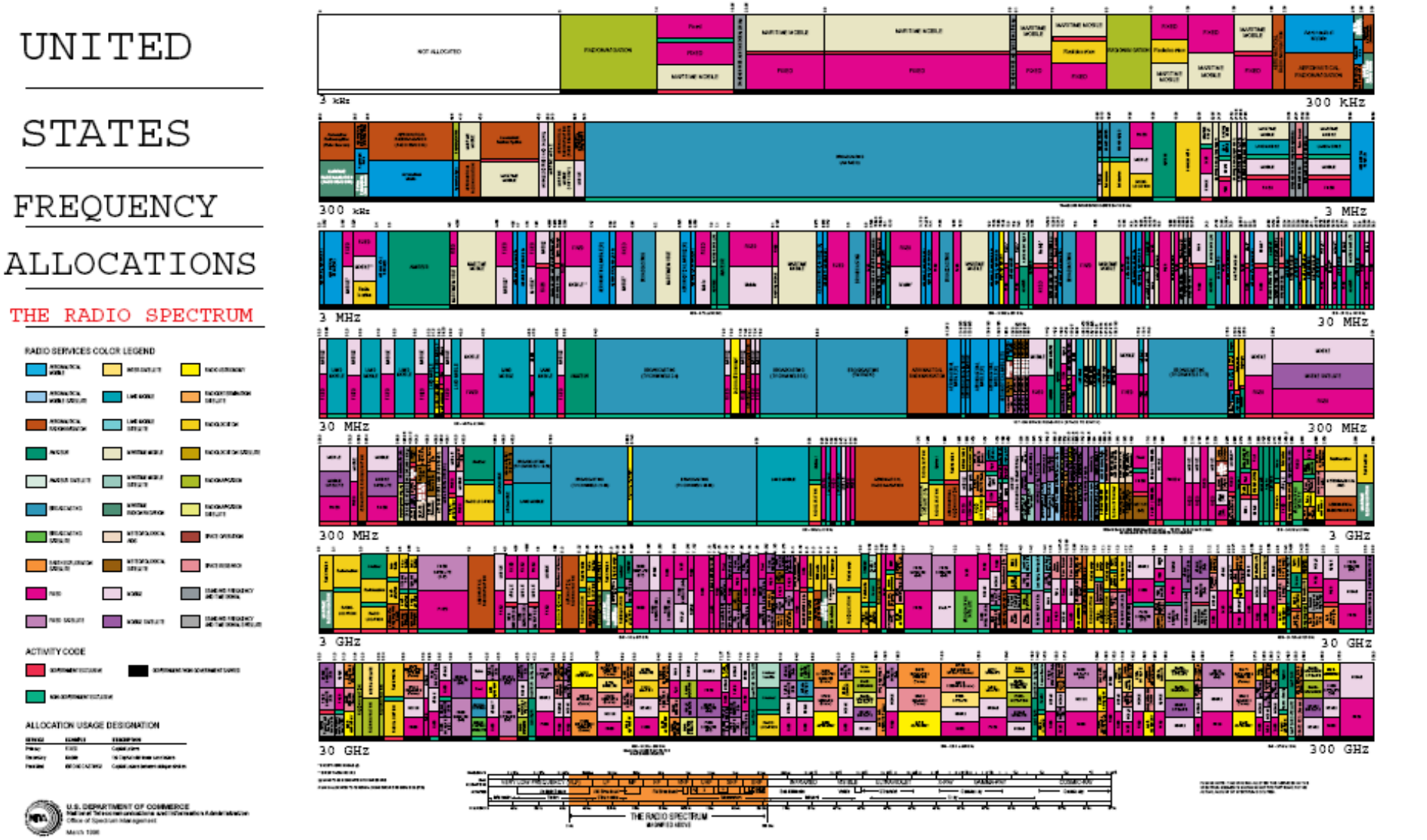


Ruling the waves – spectrum sharing has trouble & benefit!

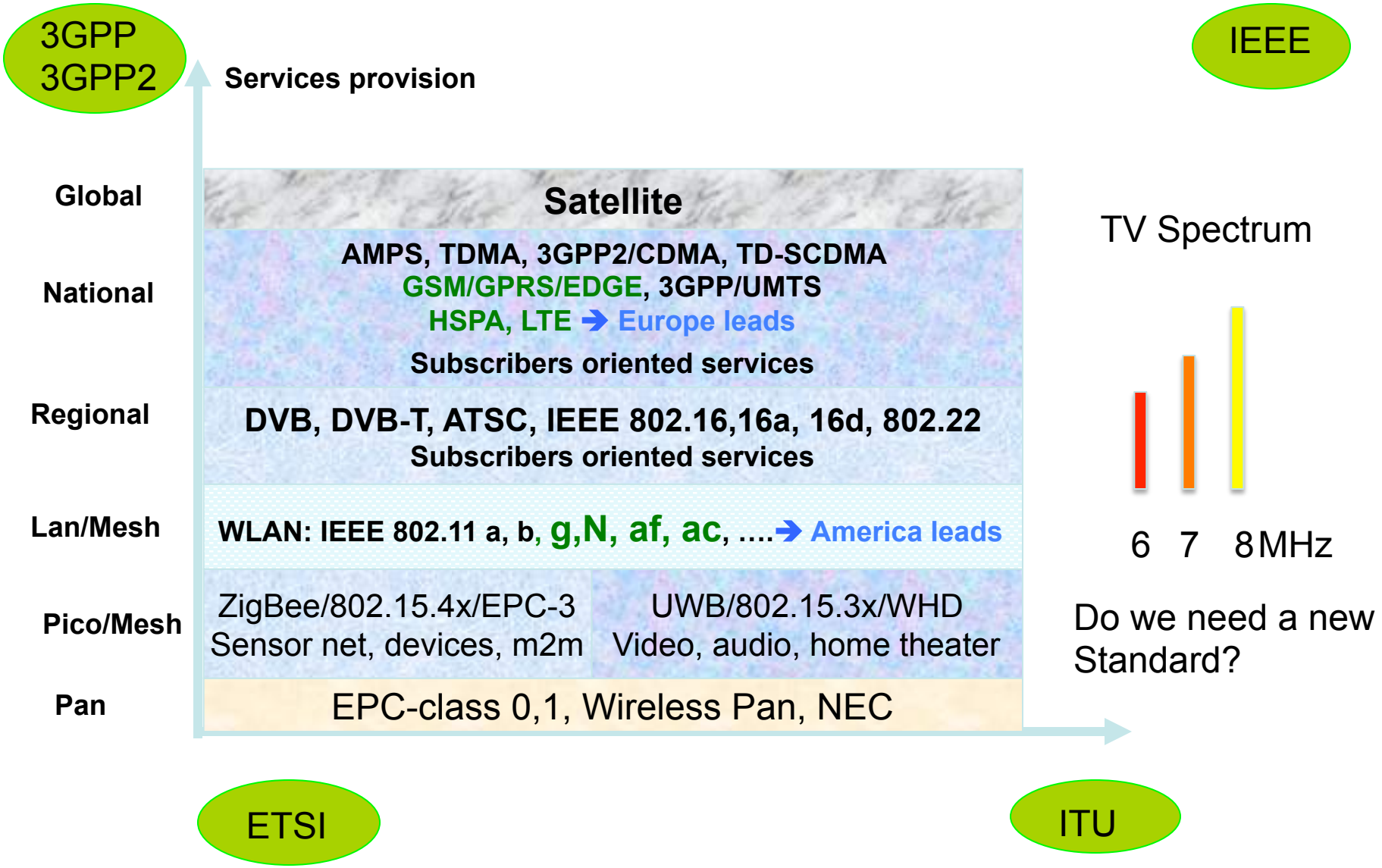
- Radios have experienced 4 phases
  1. Innovation
     - 1836 Morse codes and wired telegraph: on-off “sth” understood by recipients
     - 1896 Marconi extended to wireless
     - 1934 German Enigma machine, electro-mechanical rotor coding (broken by Henryk, Marian, Alan Turing)
  2. Commercialization
     - Marconi, GM, …
  3. Anarchy
     - Up to 1912, many radio stations, big and small, radio was very simple to make!
  4. Rules
     - 1927 Radio act
     - Private companies such as NBC, CBC wanted the ownership
     - Transition from broadcasting to voice
     - R.H. Coase’s article: Leave the spectrum allocation to the market, letting the demand for airwaves to determine who receive it and pay what price
     - recent FCC TVWS, Dr Juliet Knepp and his group and US 500 MHz plan!



Spectrum allocation – USA example



Wireless standards overview



Modern Wireless Communication

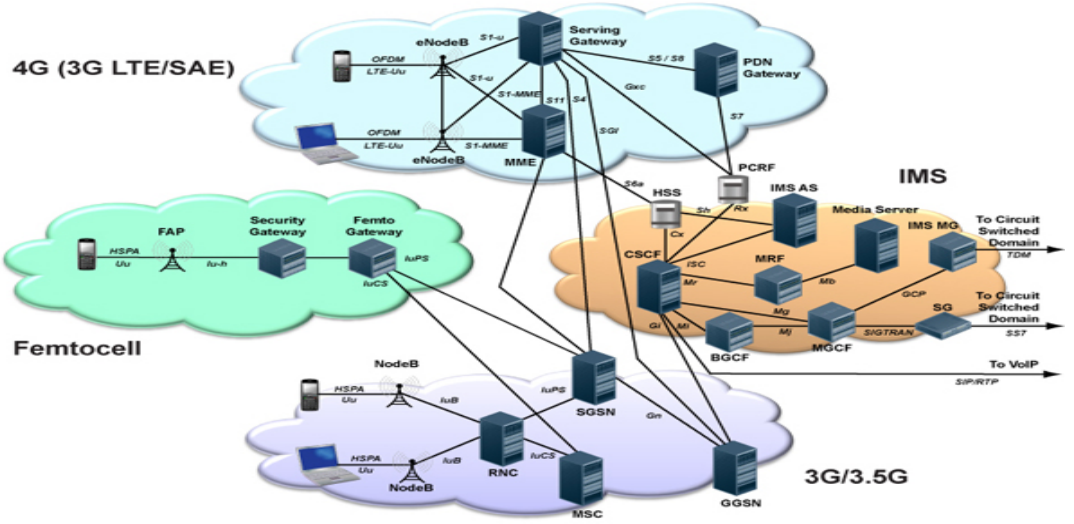
Wireless industry today (personal opinions)

- America leads LAN-WiFi & Evolution
- Europe leads WAN-GSM & Evolution

Converge to FFT + antennas

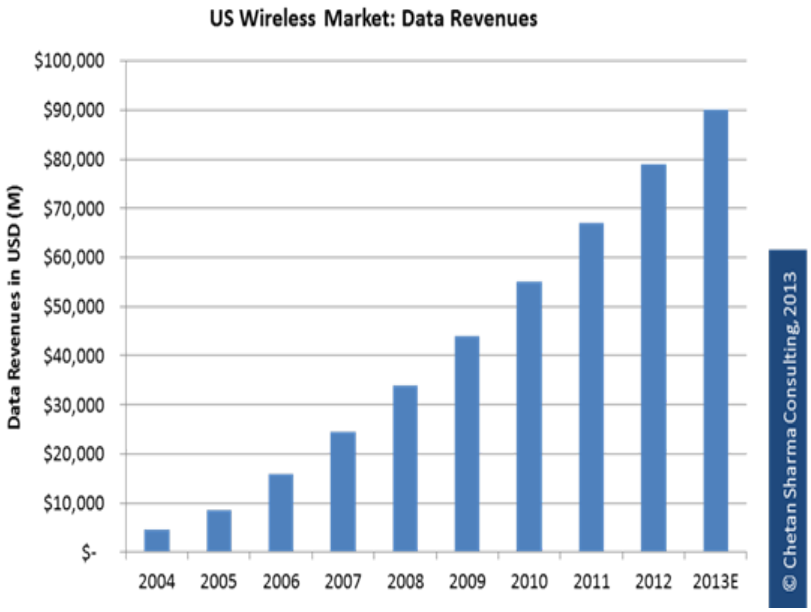
- Cellular Concept is 66 years old! Macro Cellular topology is not suitable for AAA (anyone, anytime, anywhere) IP broadband.
- Macro Cellular alone falls short of the hype for capacity demands.
- Macro cellular based wireless system for broadband needs to be re-planned for both performance and cost effectiveness
- LTE is too expensive and complicated for AAA (Anyone, Anytime, Anywhere!) for IP broadband and didn't consider iPhone-Galaxies actual capacity drivers.

Complicated,
expensive,
44 region bands,
Improper UL for video.



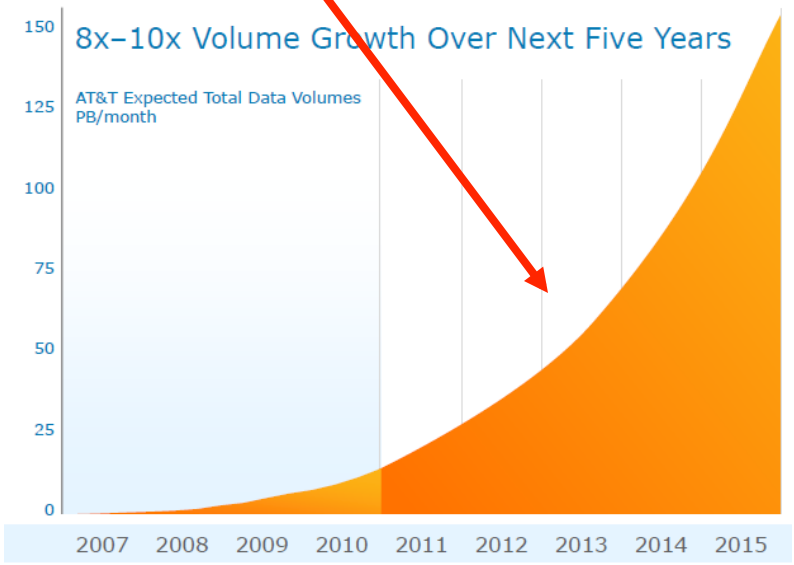
OTT* & massive data need to revolutionize 66 years old cellular

Data revenue grew 5% Q/Q and 15% Y/Y
2013 3rd Q reached 48% of total revenue



Next Q will hit cross-over point and will this trend results free voice call eventually?

Need economical solution to deliver this and Verizon Admits LTE Network Bogging Down in Cities.
http://www.eweek.com/networking/verizon-admits-lte-network-bogging-down-in-cities-report.html?kc=EWKNLNAV11142013STR4&dni=88608123&rni=23718418



AT&T published data

*Over-The-Top such as Google, Facebook, skype, wechat, youtube …

Bottlenecks in the connected world

Cellular

1. Over 66 years old, voice centric network topology which is inefficient and expensive to maintain.
2. Auctioned fragmented frequency bands in higher frequency spectrum result in high infrastructure and device costs.
3. Cannot keep up with exponential growth of data usage.
4. Not designed to support M2M and “Cloud”.

WiFi

1. Limited range and penetration making ubiquitous coverage very expensive if not impossible.
2. Congested spectrum and uncoordinated usage result in interference and unreliable communication.
3. Not designed for mobility, roaming and carrier grade services.
4. Not designed for M2M and wide area.

Spectrum monopoly starts to slow down innovation and economy

Connecting the unconnected world - economy

- UN estimated 4.4 billion of the world's 7.1 billion people remained unconnected at the end of 2013.
  http://www.broadband.com.au/blog/2013/10/15/un-report-reveals-most-of-the-world-remains-unconnected-to-internet/
- Most of the 1.033 billion people in Africa have no phone and no internet access.
- In the United States, 20% of libraries still using T1 link with a maximum speed 1.544 Mbps and 25% of the people go to libraries to surf internet.
- IoT (Internet of Things) and M2M (Machine to Machine) communication market is expected to grow $290.0 billion by 2017, CAGR of 30.1% from 2012 to 2017.
  http://www.researchandmarkets.com/reports/2228552/internet_of_things_iot_and_machinetomachine

Spectrum Sharing

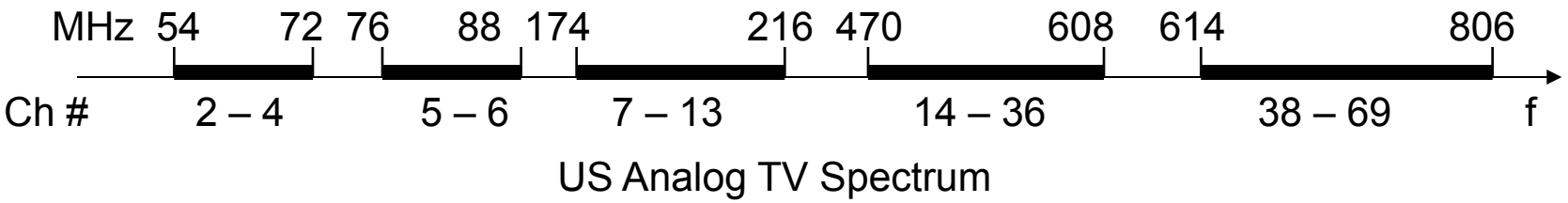
a reminiscence and essential differences

Dynamic spectrum sharing – can benefit more!

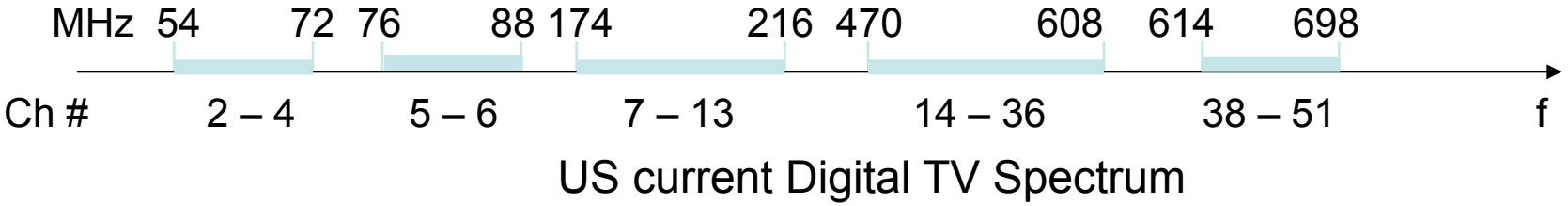
- With another decade, “ruling the wave” will be 100 years old
- Auctioned frequencies didn’t utilize such scarce resource efficiently
- Monopoly results slowness of technology innovation
- “evolution” cannot meet OTT demanding revolution
- Mobile operators are looking at re-farming of the licensed spectrum currently being occupied by legacy systems.
- FCC along with Microsoft and Google deserve the credit
- Spectrum below 1 GHz is relatively ‘clean and idle’ in many countries and is critical for data centric applications and mobile “cloud” thinking and computing.
- Innovative low cost Dynamic Spectrum Access technologies to efficiently use both licensed and unlicensed spectrum are needed.

In past few years, WiFi has well proved its capability for data transport. What you will do after you arrive a hotel or a coffee shop?

TVWS (TV White Space) – beginning of wireless revolution



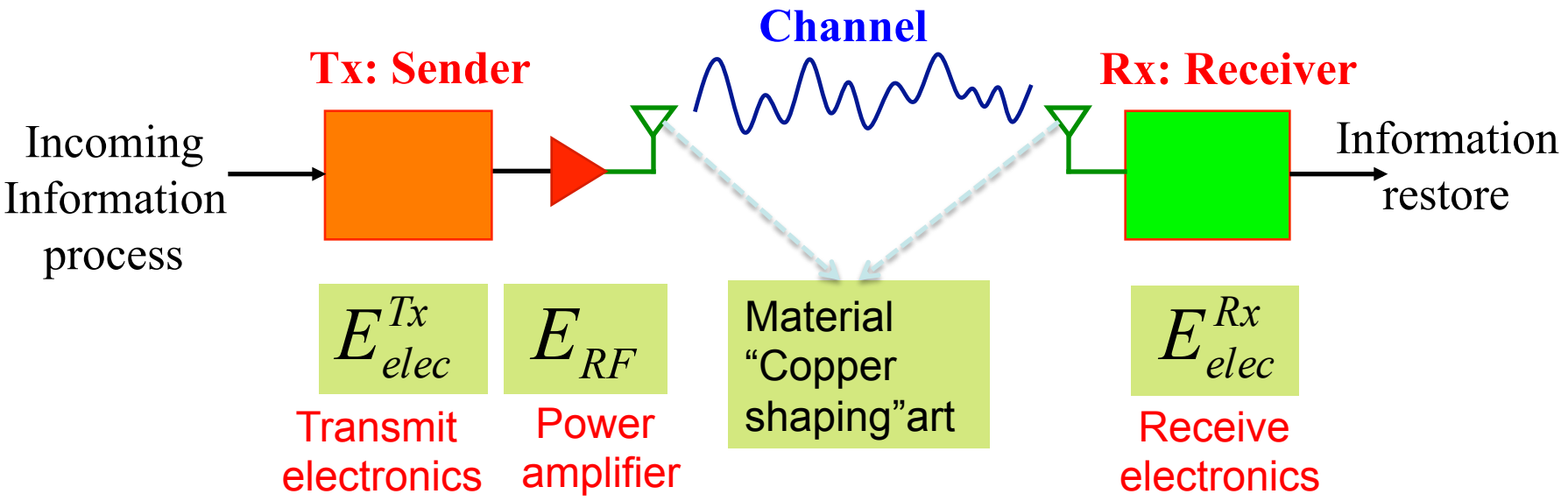
US Analog TV Spectrum



US current Digital TV Spectrum

- Between 54 MHz and 698 MHz, there are many idle TV channels .Unused TV spectrum is call TVWS. USA officially released this spectrum September 23, 2010 and started first commercial deployment December 2011.
- TVWS varies in different TV markets
- UtilizingTVWS must guarantee no interference to incumbent systems
  - Antenna design, RF design, spectrum management, coding/modulation are all significant design challenges.
- All other countries are following: Canada, UK, Singapore, African countries such as South Africa, Kenya, Tanzania, Ghana, ……

Spectrum sharing – gaming of energy distribution and conservation



- Wireless communication subsystem consists of four HW components with substantially different characteristics
- Their relative characteristics determine the distance between transmitter and receiver

Spectrum sharing – pros & cons

- Air Interface etiquette
  - Easy to distinguish
  - Easy to coexist
  - Easy to cooperate
  - Easy to manage
  - Easy to be courtesy
- MAC capability
  - Tolerate to Interferences and noise
  - High level mediation and intervene
  - Selves resolve when collisions
- Ecosystem
  - Mature and cost affordable
- Math, Physics & materials availability

- Antennas arts
  - Broadband
  - Gain
  - VSWR
  - Size
  - Weight
- To optimize these 5 parameters becomes a big challenge
- No good solution for CPE
- PA Art
- Tunable filters

Spectrum sharing – sensing and database

- FCC 2008 rules: sensing and database
- Sensing
  - Detect unused spectrum and then use
  - FCC TVWS requirements
    - ATSC signals: -114 dBm, averaged over 6 MHz
    - NTSC signals: -114 dBm, averaged over 100 kHz
    - Wireless Microphone signals: -114 dBm averaged over 200 kHz
- Protection area
  - is calculated using an FCC algorithm based on “F” curves. The resulting area does not guarantee TV reception nor does it preclude reception outside the area
    - Inside the contour, cannot use no matter TV signal being detected or not
    - Outside the contour, can be used whether TV signal being detected or not
- FCC 2010 rules: Database only
  - Check database before use and regularly check database and stop transmission if channel not available anymore

Spectrum sharing and re-farming problems

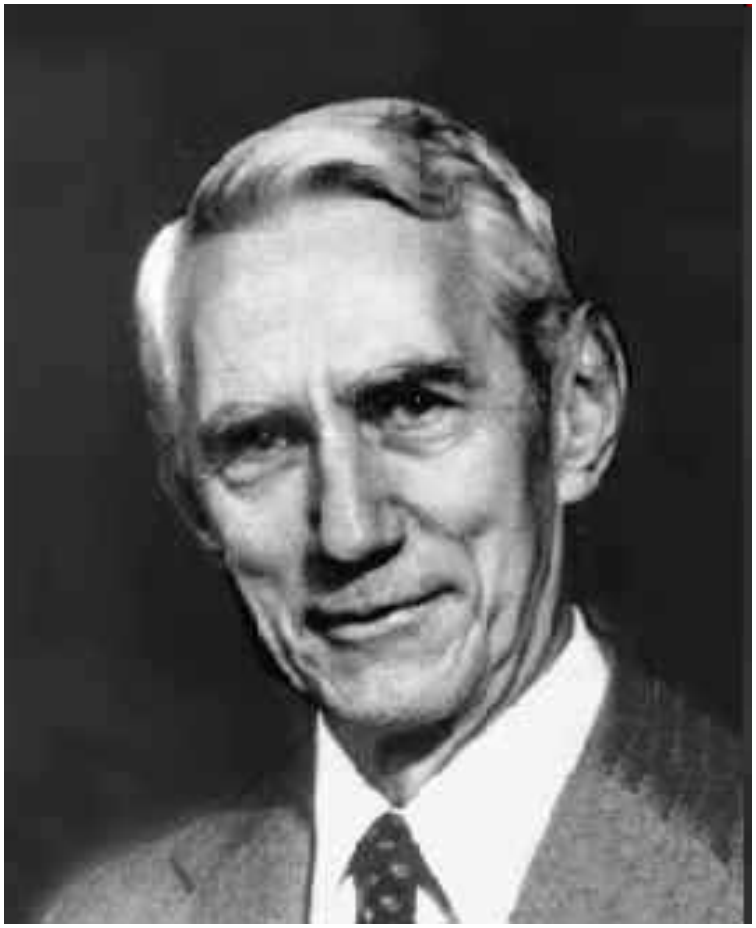
- Spectrum Sharing
  - Priority usage
  - 2nd usage
  - Rendez-vous based
  - Database oriented
  - Sensing based
  - Coexists in time, frequency, scale, code, spaces
    - PHY & MAC
  - Adaptive Radio Networks traffic modeling and capacity
    - “Voice becomes free”
- What is the appropriate white-space definition?
  - Unused spectrum
  - Can be used spectrum
  - Occupied spectrum and still can be used
  - ……

Spectrum sharing – early thoughts

- Spectrum sharing is nature and we share the the “voice spectrum” during everyday life
  - Biological organisms share lower frequencies!
- Wireless started with spectrum sharing
  - Marconi radios
- WiFi-Radar (802.11h)-sensing based seemed successful
  - The standard provides Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) to the 802.11a PHY
- Network Oriented Spectrum Sharing System-Rendez-vous based
  - US Patent 8170572 B2
  - WCDMA sharing spectrum with WiMax/OFDMA
- IEEE 802.22
- IEEE 1900.x, …

Available technologies for spectrum sharing

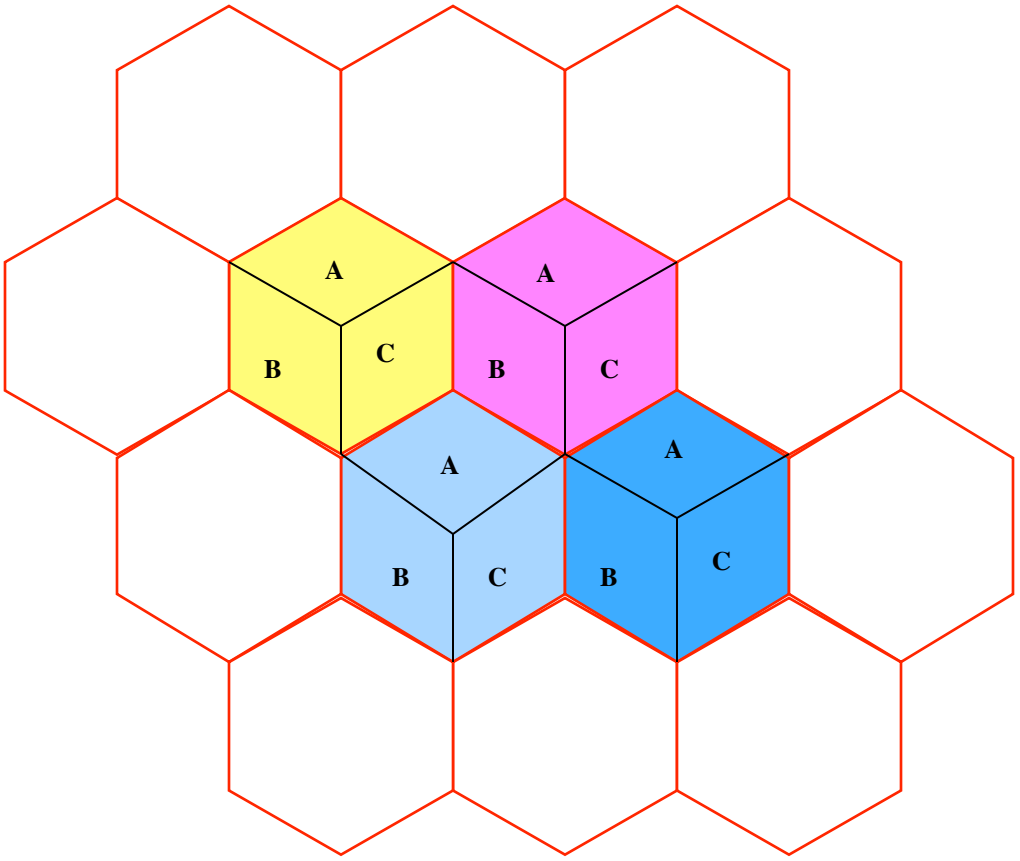
Shannon's channel capacity

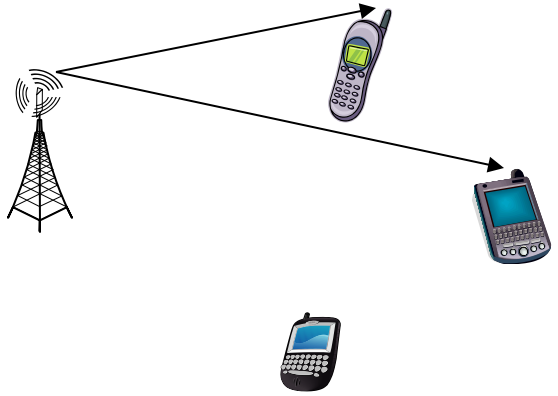


$$C = W \log\left(1 + \frac{P}{N_0 W}\right)$$

- Information highway capacity is linearly proportional to bandwidth, logarithmically proportional to SNR.
- Wireless engineer's duty is to balance W and P and deal with N0
- Such simple formula yet no one can solve it
- "Shannon deserves the title of father of information theory."
  - surely Kolmogrov
- He is a mathematician or an engineer?

Cellular Concept and frequency reuse: 1/3 frequency re-use cell site

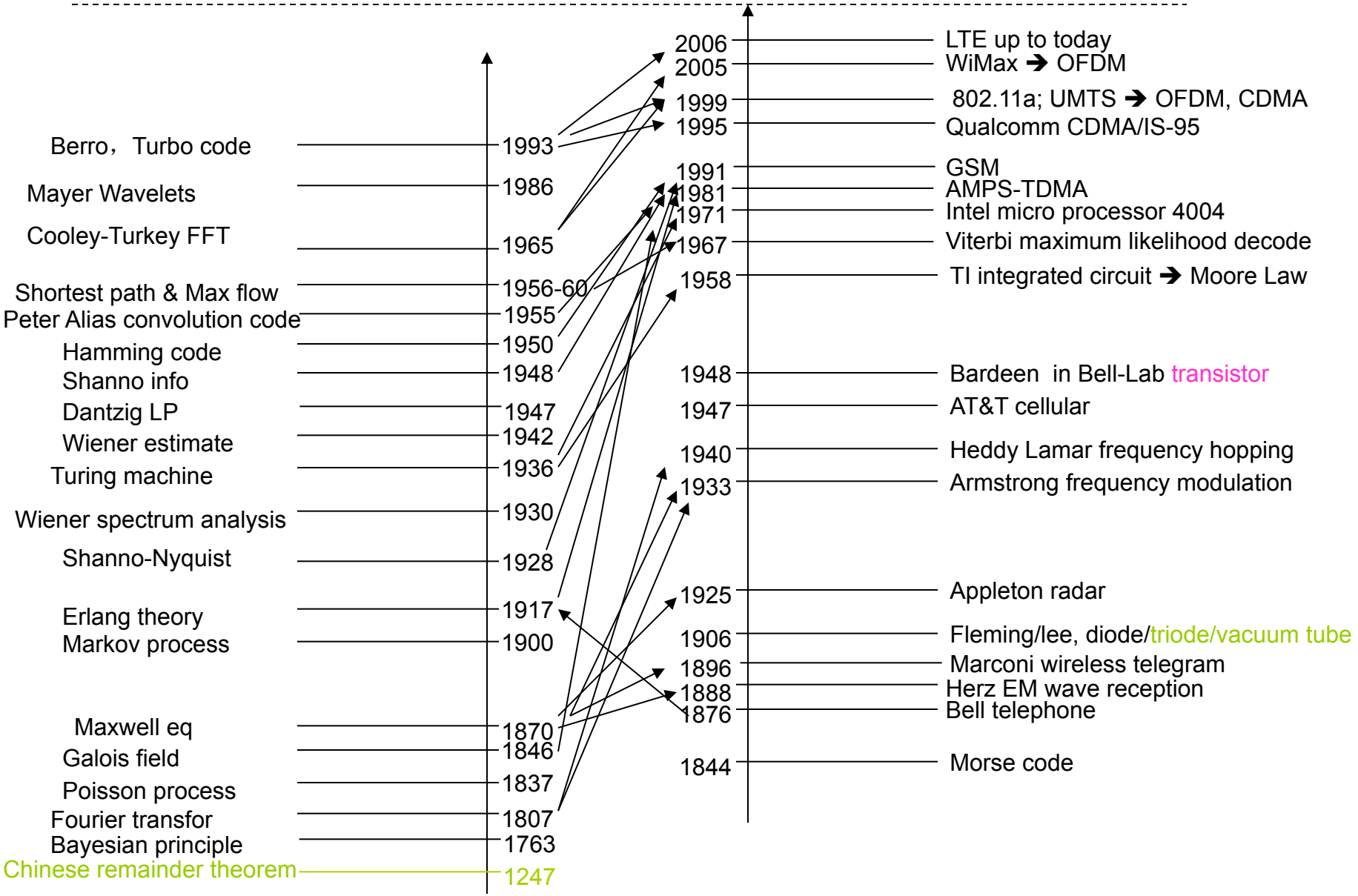




- Cell size?
- Interference
- Sensitivity
- QoS
- Environment imperfections
- Path-loss

Invented1948 in Bell Lab, mainly for guarantee voice call at cell edge.
If we forget all we developed in wireless and re-design a wireless system for today's applications，what it should be?

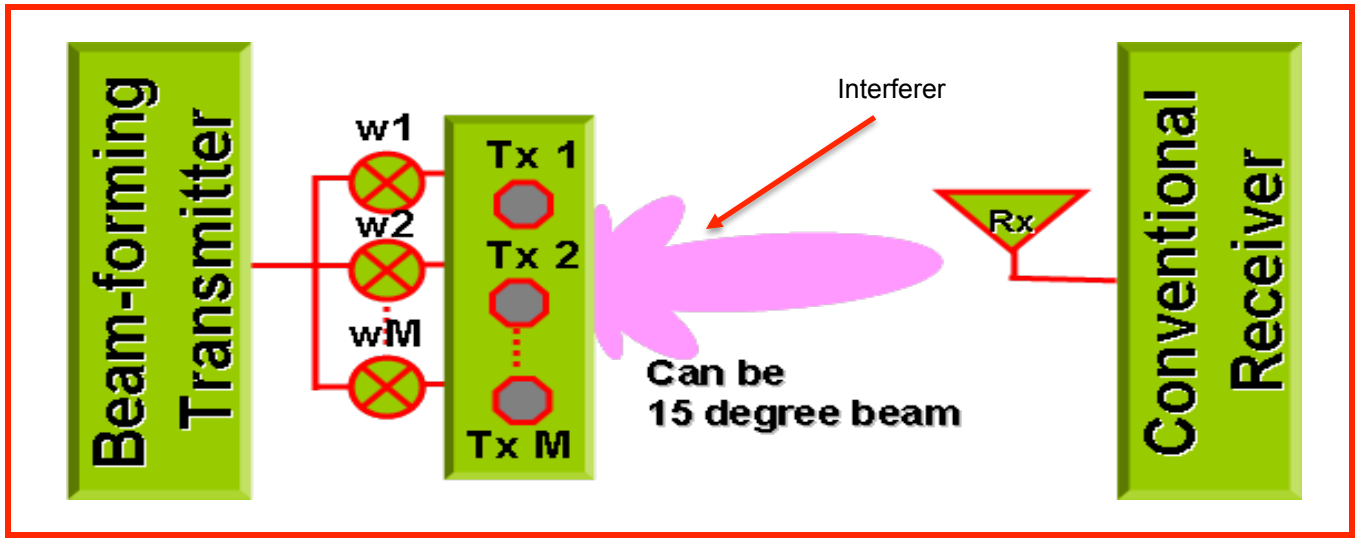
Mathematics, technologies and communication



Separation in signal domain – energy redistribution

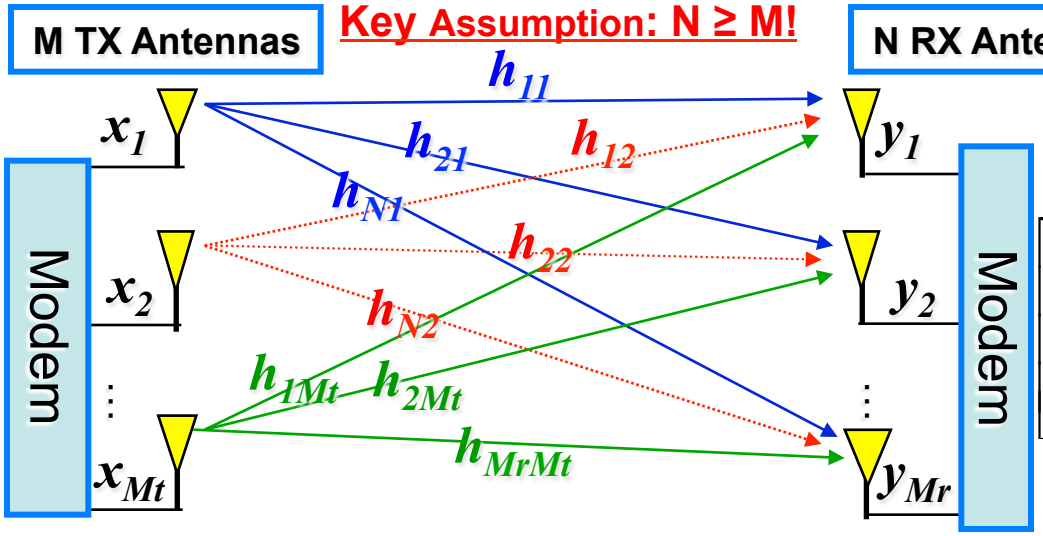
- Orthogonal transforms
  - FFT: N*log(N) versus WT: N
  - How to explore input data structure to save FFT computation ?
    - Refer to: Nearly optimal sparse FFT, MIT Haitham Hassanieh et al.
    - Beauty FFT: LUT + convolutional theorem
  - Hadamard Matrix
    - A matrix whose rows (or columns) are mutually orthogonal
  - How to retro-fit “wavelets transform (WT)” to have a convolutional type theorem
    - Beauty WT: fast and high compression ratio
    - Disadvantage: Convolutional Theorem doesn’t hold and irrational filters coefficients!
- Pseudo orthogonal
  - Random sequences: auto correlation has energy well concentrated in the middle while cross correlation has a mean value close to zero

Separation in space – energy redistribution



	Beam-forming
Capacity	Increases with log(M)
BTS Cost	Very expensive!
Terminal Cost	Low cost terminal
Performance	Poor in multi-path rich environments
Challenges	BTS antenna calibration, cabling, tower space, real estate

Separation in Eigen domain – energy redistribution



$$\begin{bmatrix} y_1 \\ \vdots \\ y_{M_R} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1M_T} \\ \vdots & \ddots & \vdots \\ h_{M_R1} & \cdots & h_{M_RM_T} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{M_T} \end{bmatrix} + \begin{bmatrix} N_1 \\ \vdots \\ N_{M_R} \end{bmatrix}, \qquad y = \sqrt{\frac{P}{M}} Hx + N$$

$$N \sim N(0, \sigma^2 I)$$

P: Total Power out of M antennas. n: Noise/Interference

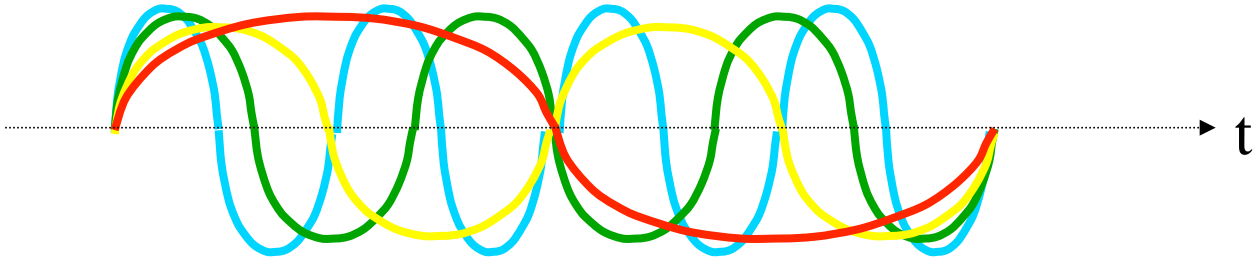
	MIMO
Capacity	Increases linearly with M Maximum M times
BTS Cost	Less expensive
Terminal Cost	Very expensive, good practice might be N=2 only!
Performance	Doesn't work in weak multi-path and Keyhole environments
Challenges	Terminal packaging, cabling, cost structure

OFDM fundamental

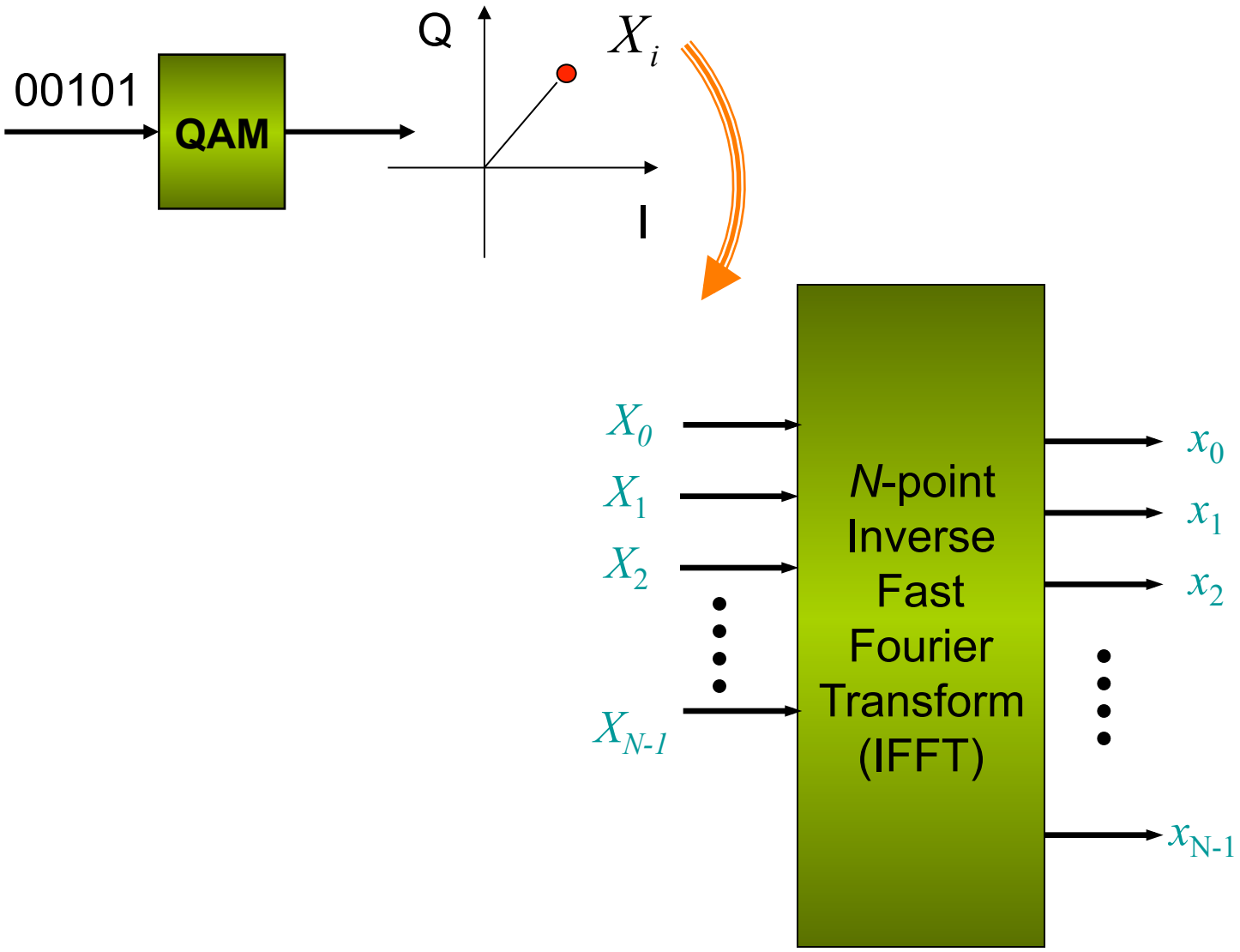
Jean Baptiste Joseph Fourier (1768-1830)

- Convolution Theorem

Suppose { x(n) | n = 0,1, …, N-1},
{y(n) | n = 0,1, …, N-1}, and
{z(n) | n = 0,1, …, N-1}
are 3 complex number sequences and
{ X(k) | k = 0,1, …, N-1},
{Y(k) | n = 0,1, …, N-1}, and
{Z(k) | n = 0,1, …, N-1} are their corresponding Fourier transforms.
Then Z(k) = X(k)Y(k), k = 0, 1, …,N-1
if and only if { z(n) | n = 0,1, …, N-1 }
is a cyclic convolution of
{ x(n) | n = 0,1, …, N-1}
and
{y(n) | n = 0,1, …, N-1}.



OFDM transmission

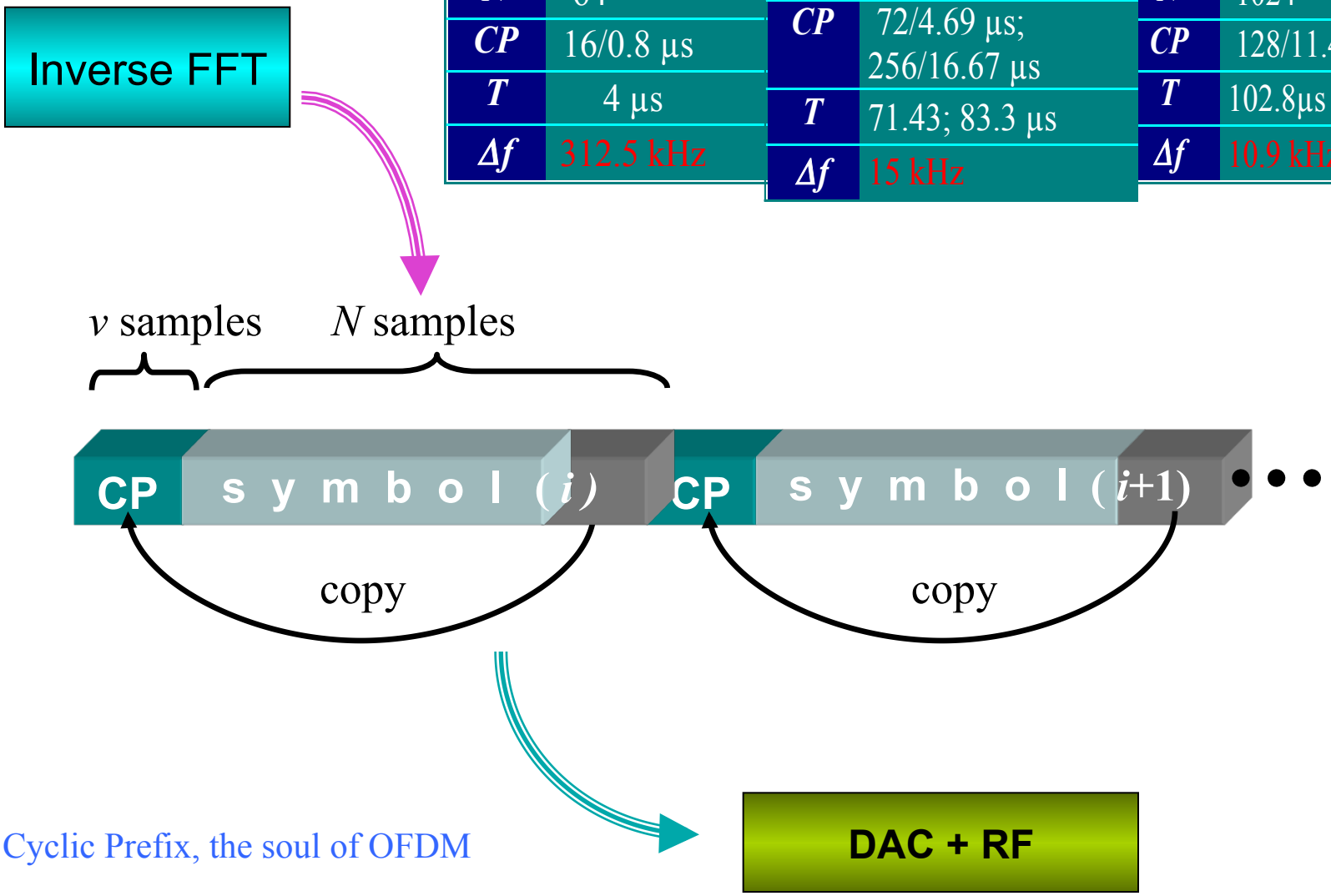


OFDM/OFDMA- best technique to handle multipath

802.11g, 20 MHz/64	
N	64
CP	16/0.8 μs
T	4 μs
Δf	312.5 kHz

LTE , 10 MHz, 15.36/1024	
N	1024
CP	72/4.69 μs; 256/16.67 μs
T	71.43; 83.3 μs
Δf	15 kHz

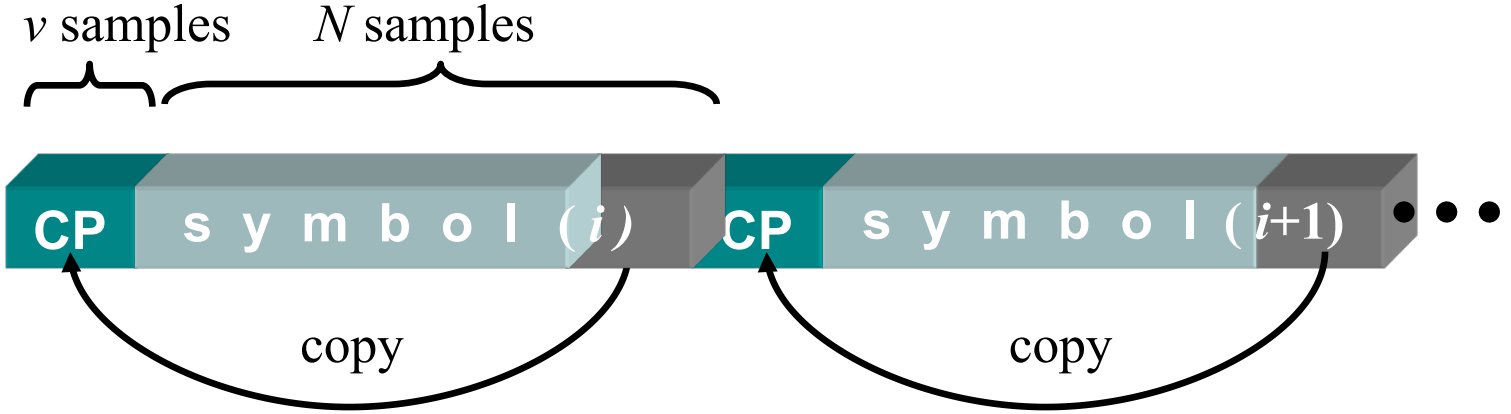
WiMax , 10 MHz, 11.2/1024	
N	1024
CP	128/11.4 μs
T	102.8μs
Δf	10.9 kHz



CP: Cyclic Prefix, the soul of OFDM

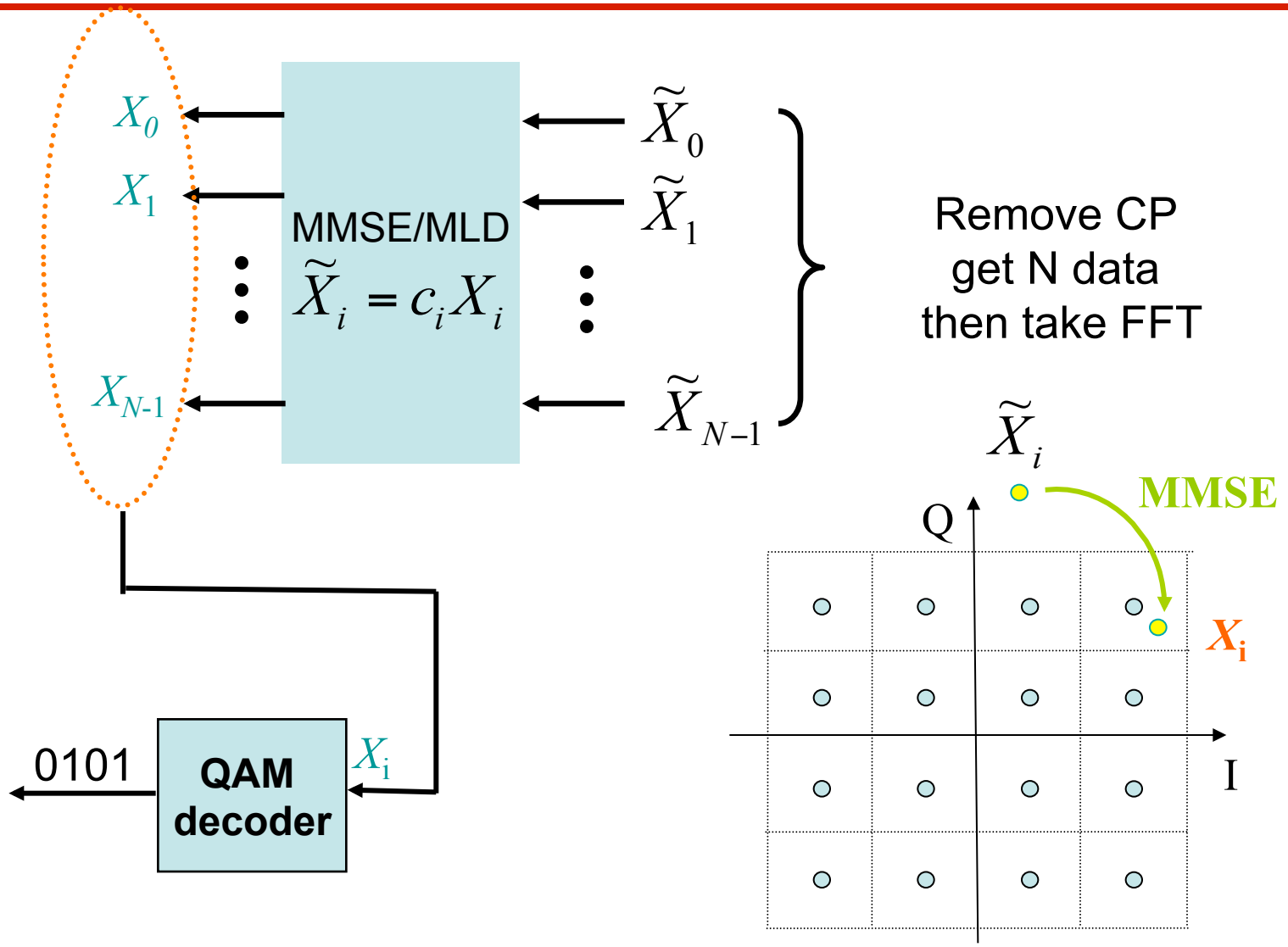
Why Cyclic Prefix (CP) is necessary

- Provide guard time between successive symbols
  - There isn't ISI if the multi-path channel delay spread is shorter than v samples
  - Guarantees integer cycles of all frequencies and therefore orthogonal sub-carriers
- Choose guard time samples to be a copy of the beginning of the symbol – Identical cyclic prefix ➔bandwidth waste!
  - Cyclic prefix converts linear convolution into circular convolution
  - Remember that only circular convolution has the property
  - symbol ⊗ channel ⇔ FFT(symbol) x FFT(channel)

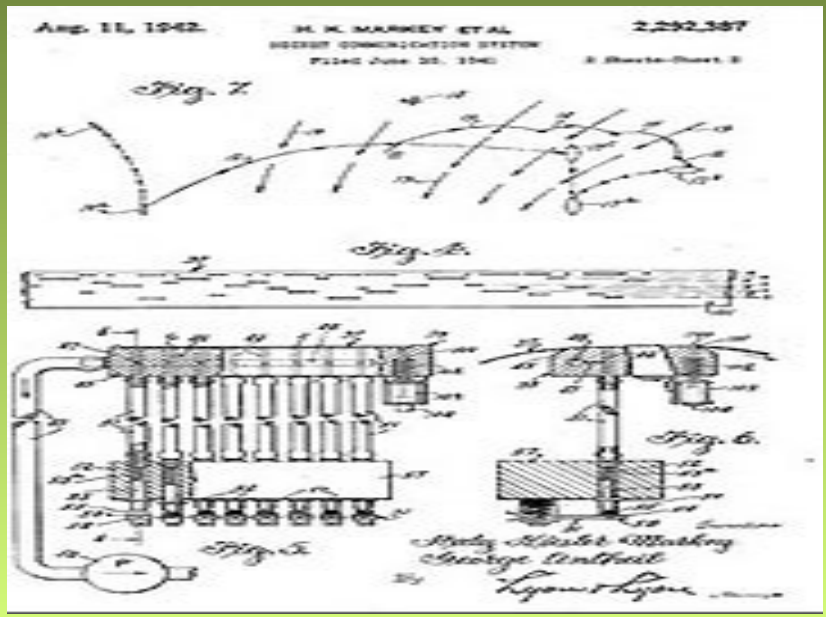


➔CP is the soul and corner stone of OFDM but CP is a spectrum waste, usually around 15%. WiFi = 25% and WiMax = 12.5% to 25%, LTE 7% ~ 25%!

After remove CP, OFDM receiver is very simple

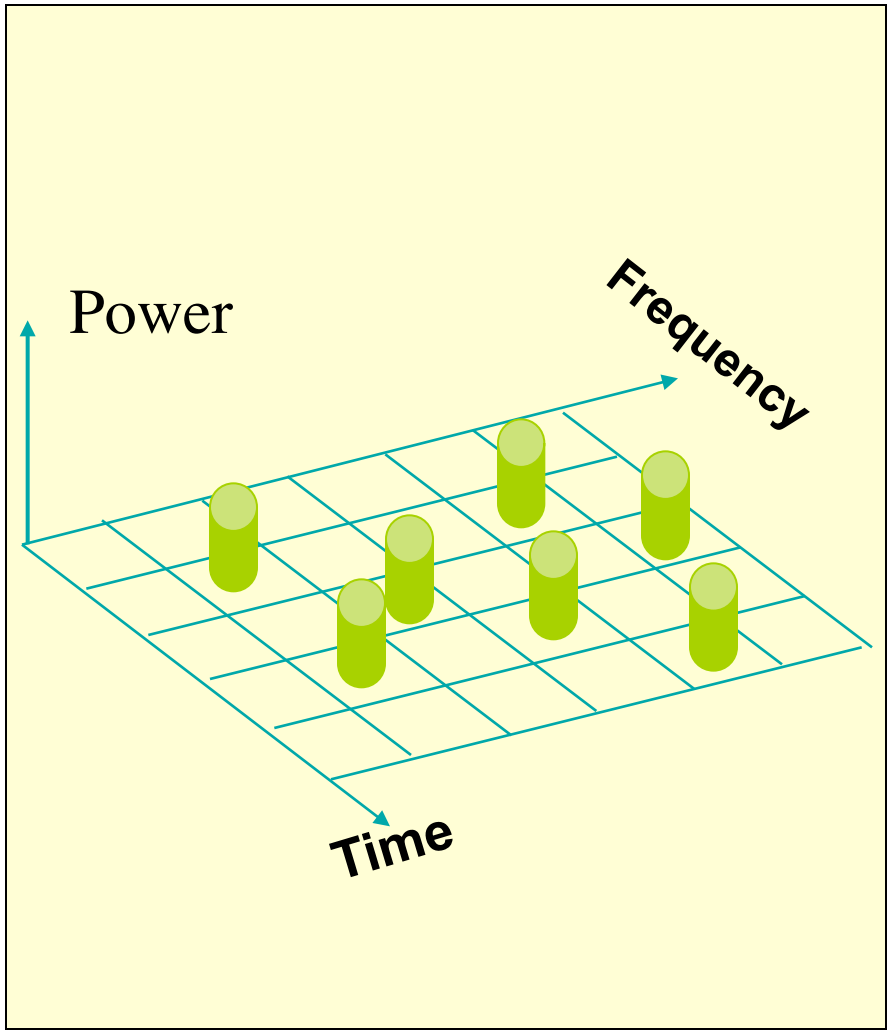


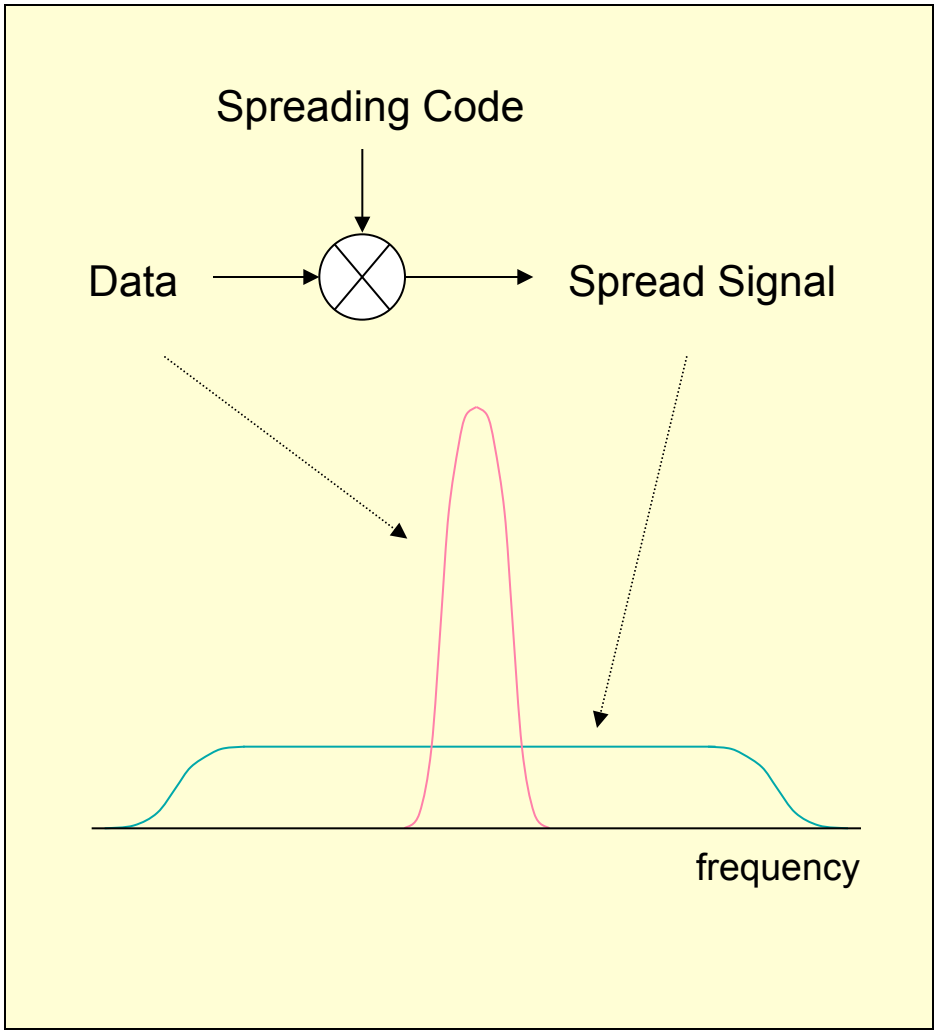
Beautiful Grand Mother Hedy Lamar invented " frequency hopping" in 1940 from harmonics observation



- US patent 2,292,387 in 1942 for the invention of frequency-hopped spread spectrum, co-inventor George Antheil, an composer.
- Frequency hopping – original version of spread spectrum
- Beauty always originated from harmonics!

Frequency hopping vs direct sequence spreading





Spectrum Sharing pros & cons again

- Physical layer coexistence*
  - CDMA behavior
  - OFDM/OFDMA flexibility
  - Wavelets compress
  - All 3 seamless combined
- Wide band radio
- Wide band antenna
- MAC
  - Enhanced CSMA/CA (carrier sense multiple access with collision avoidance)!
- Database governing and OMC optimization

* IEEE 802.19 is a coexistence standard

6Harmonics introduces ARN*

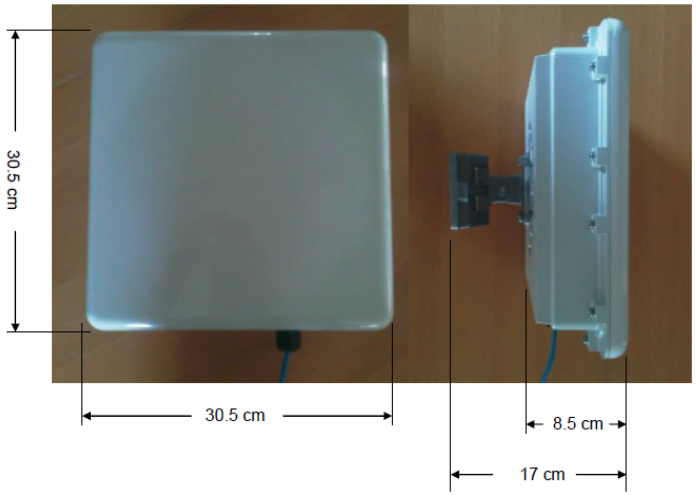
- Adaptive Radio Network (ARN*) Design Philosophy
  - WiFi throughput, wide area coverage and video oriented
  - Wide frequency-band tunable
  - Capability to reconfigure the transmitters and receivers to dynamically access available radio frequencies at any given time.
  - Ability to hop on preferred frequencies and reconfigure waveform properties
  - Ability to radiate sufficient power and to configure network topology and to optimize network performance and spectrum usage.
  - Self-configured Mesh networking and self healing capabilities.
  - effectively re-farm licensed spectrum for broadband wireless IP networking, cloud computing infrastructure and M2M backhaul

We selected WiFi as a base

- Cost
- Throughput
- Interference immunity
- Ecosystem
- Need to enhance its range and reliability
- Need to make it easy networking
- ……

6Harmonics products offering

Core Adaptive Radio (CAR*)

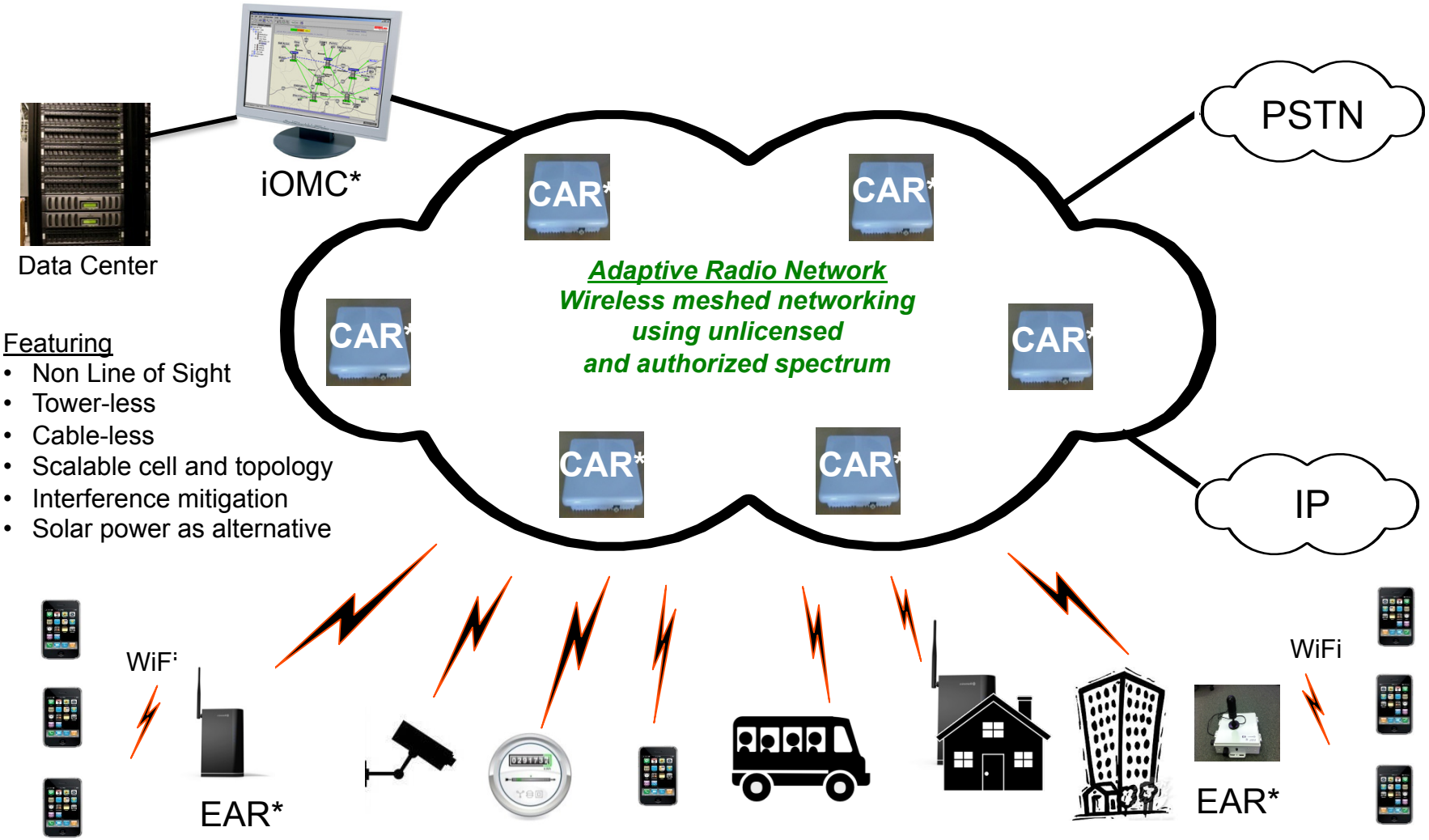


Broadband Antenna system

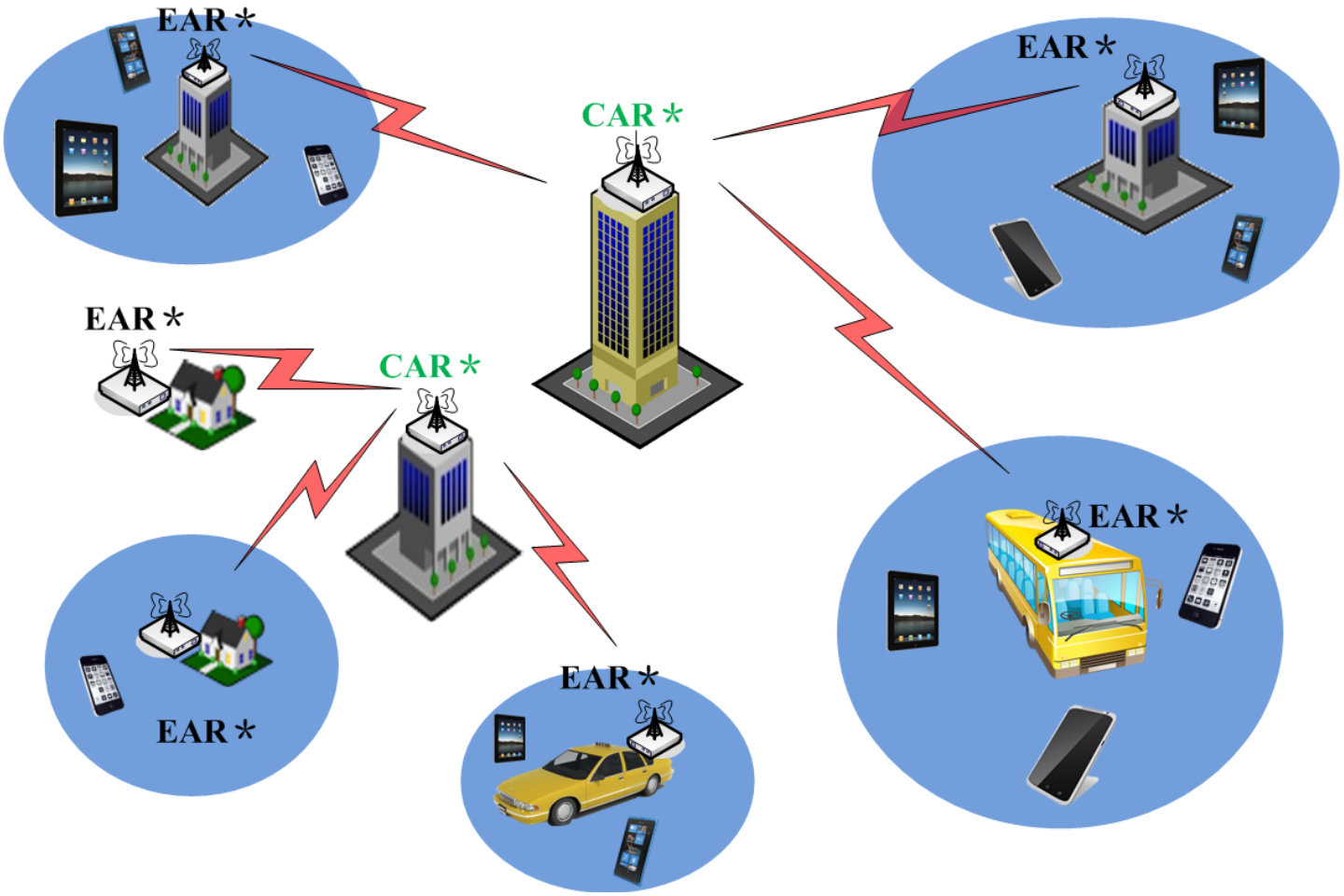
Edge Adaptive Radio (EAR*)

“Cloud” Management Center – iOMC*

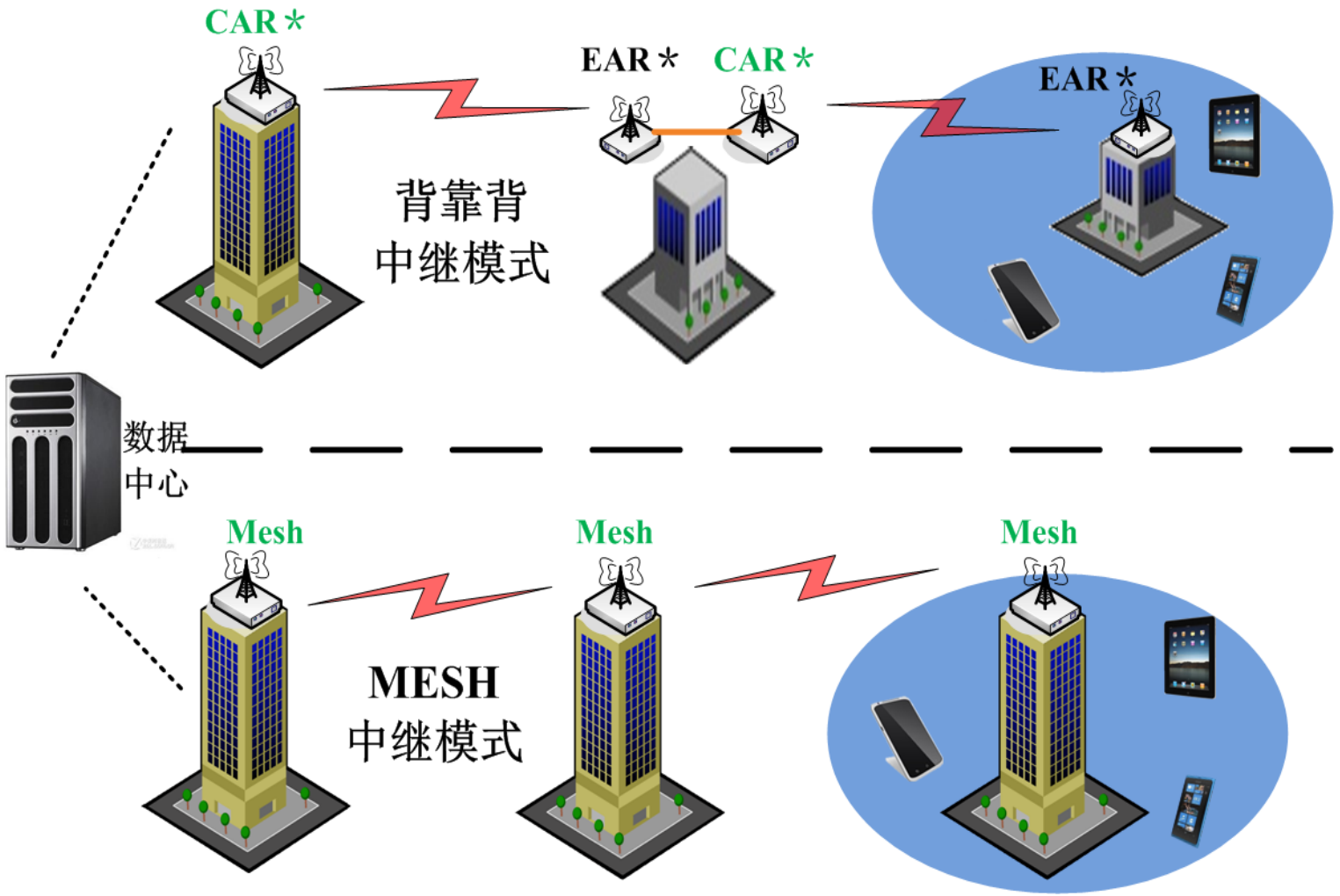
ARN* architecture - ideal for “Cloud” and M2M



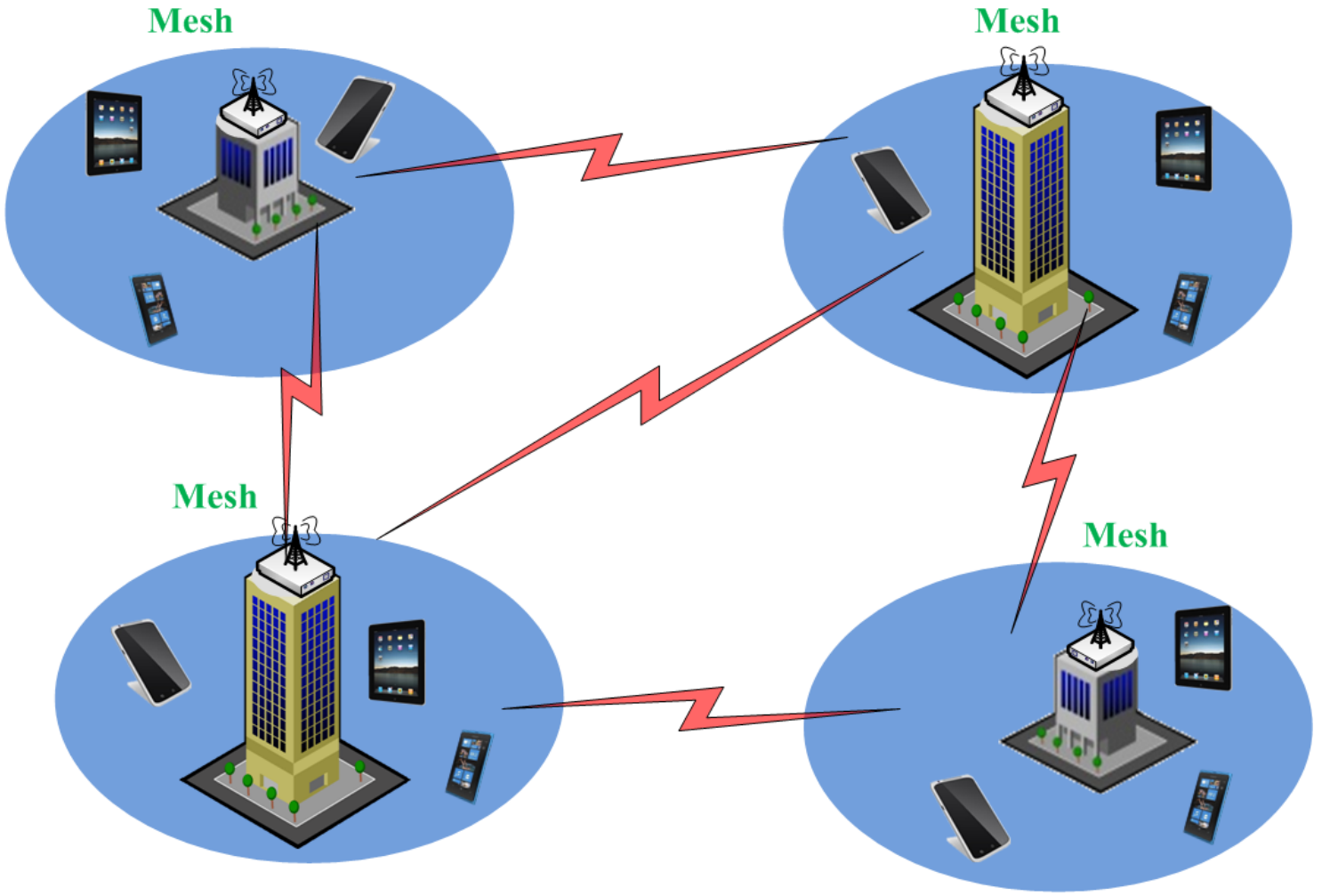
Point to multiple points



Point to point and relay



Mesh network



Typical applications

Flexible WiFi solutions for home and office

City and Remote wireless surveillance

Voice over IP with mobility

Wireless connection for IoT and M2M

Disaster communications recovery

LTE BTS and small cell backhaul, enterprise “cloud” infrastructure

Broadband for urban, mining sites, oil fields, highways and railways

Military communications

Evolution plans

Technology

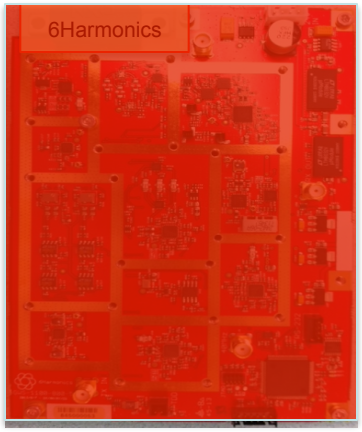
- Antenna technologies
  - 3 times spectrum efficiency
  - Broadband antenna sharing
  - Extended coverage
- Cloud Networking Platform
  - Dynamic topology
  - Self organizing
  - Speedy routing
  - Spectrum map
  - Interference mitigation
- ASIC

Product

- MIMO CAR* and EAR*
  - 3 times capacity
- Yuan-Yang phone
  - Wi-Fi call anywhere
- Small Cell backhaul
  - 600 Mbps down and 600 Mbps up for Carriers' small cell backhaul
- Cloud OMC - iOMC
  - Network management and optimization
  - Dynamic spectrum access
  - Maximize spectrum efficiency

ARN* schedule for economy scale

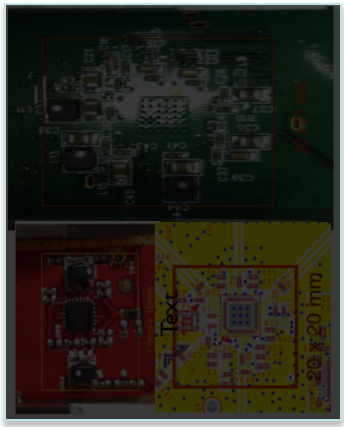
2013



17600mm2

Applications
- CAR* and EAR*
- Indoor and outdoor WiFi hotspots
- Backhaul

2014



1800mm2

Applications
- Laptops, tablets and PADs
- Mobile WiFi hotspots
- Cars and buses

2015

420mm2

Applications
- Cellular phones
- USB dongle
- M2M aggregation
- Smart grid

Network Node ➔ CPE ➔ Phones dial WiFi AAA

THANKS
Q&A