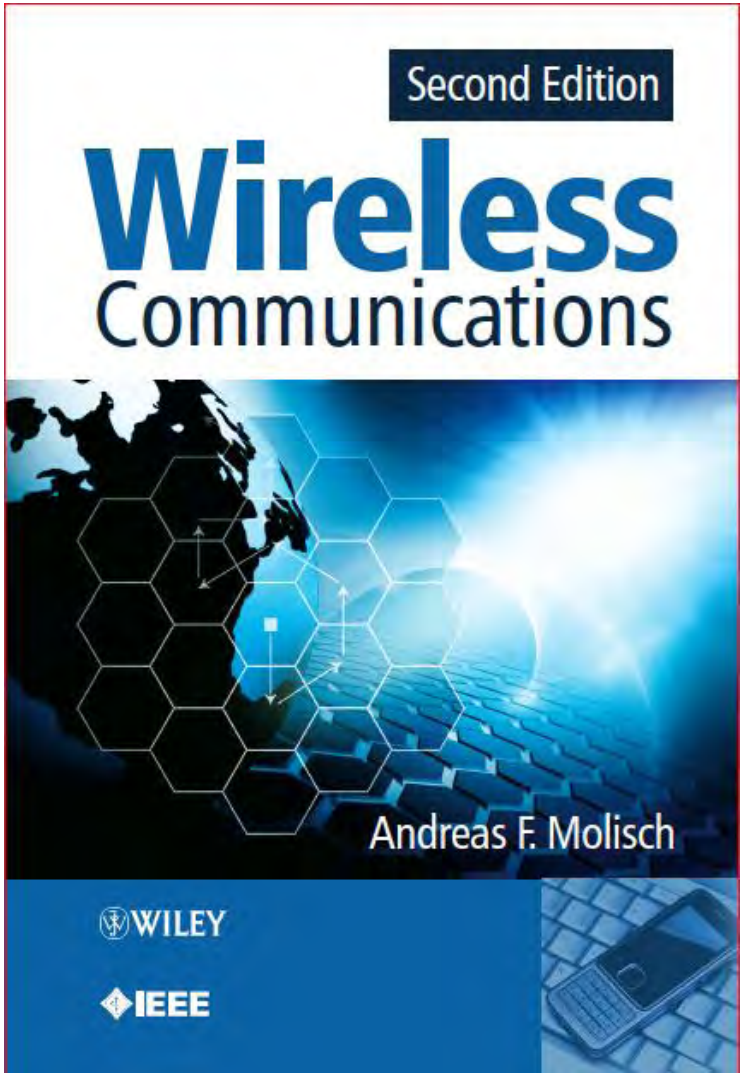
Lecture slides for courses based on the textbook by A. F. Molisch

Wireless Communications

2nd edition

Ove Edfors, Andreas F. Molisch, and Fredrik Tufvesson

Textbook


Second Edition
Wireless
Communications
Andreas F. Molisch
WILEY
IEEE

Contents

- What are radio systems?
- History of wireless systems
- Classifications
- Requirements for services
- Social and economic aspects

Radio system?

- From Merriam-Webster Dictionary
  - Radio:
    1 : of, relating to, or operated by radiant energy
    2 : of or relating to electric currents or phenomena (as electromagnetic radiation) of frequencies between about 15 kHz and 100 GHz
  - System:
    1 : a regularly interacting or interdependent group of items forming a unified whole
- ”Radio systems” can be used for many purposes, e.g.
  - Detection and ranging (Radar)
  - Astronomical observation (Radio telescope)
  - Heating food (Microwave oven)
  - Navigation (GPS, etc.)
  - Communication (Cellular telephony, etc.)

Some questions to ask

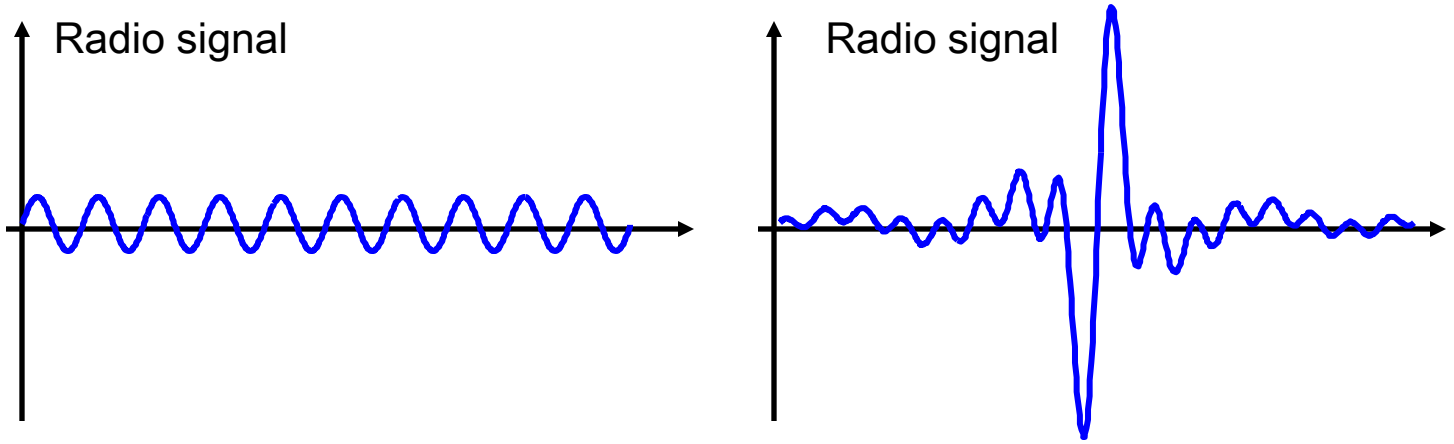
- What do we want to achieve with our system?
  - This gives us design constraints (system requirements)
- What frequency band should we use?
  - Properties of the radio channel changes with frequency
  - Radio spectrum is firmly regulated
- Which technology should we use?
  - Not all technologies can perform the task
  - Cost is important (design, production, deployment, etc.)

Example: Mobile telephony

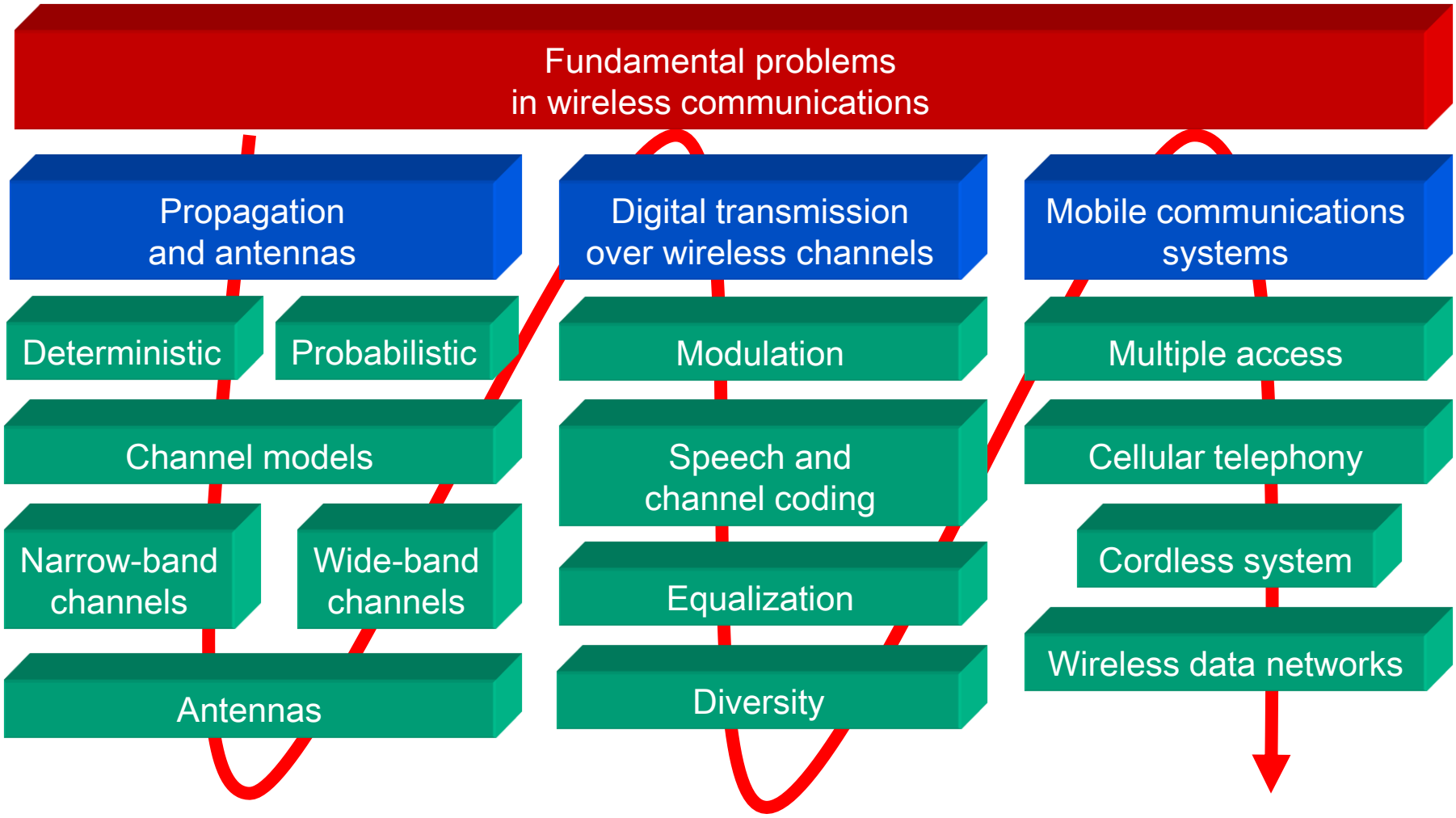
Amplifiers with low dynamic range can be made more power efficient than highly linear amplifiers.

Does this affect the choice of modulation technique?

Copyright: Sony-Ericsson



A rough breakdown into areas



HISTORY OF WIRELESS

History of wireless (1)

- Maxwell: theory
  original work was 20 differential equations in 20 unknowns later reworked by Oliver Heaviside into a vector notation creating just 4 vector differential equations in 2 unknowns that we use today.
- Hertz: fundamental experiments confirming Maxwell's theory
  using a spark gap driven by a Rumkorff coil, 26 years after Maxwell developed the complete theory of the electromagnetic field.
- 1890-1905: First experiments for wireless information transmission
  - Tesla, Bose, Marconi
- 1905-1946: First systems:
- 1947/1948: fundamental information theory (Shannon)

Shannon Capacity Formula: C = B log(1 + SNR) where log is base 2 and
C = channel capacity in bps, B = bandwidth in Hz, SNR = ratio of transmit power / noise power both in watts


LIFE MEMBERS FUND
MAXWELL'S EQUATIONS
1860
1871
$\nabla \cdot D = \rho$ $\nabla \cdot B = 0$ $\nabla \times E = -\frac{\partial B}{\partial t}$ $\nabla \times H = \frac{\partial D}{\partial t} + J$
IEEE
SUPPORTER

IEEE History Milestone - Maxwell's Equations, 1860-1871

Between 1860 and 1871, at his family home Glenlair and at King's College London, where he was Professor of Natural Philosophy, James Clerk Maxwell conceived and developed his unified theory of electricity, magnetism and light. Maxwell deduced that light was an electromagnetic wave, thus revolutionizing the fields of electrical science and electrical engineering. He pioneered the use of calculus in electromagnetic science and independently derived three of the four modern equations that now bear his name. These are Gauss' Law, Gauss' Law for Magnetism, Ampere's Law with Maxwell's correction and the fourth being the full-time-derivative version of Faraday's Law that he derived.

It was Oliver Heaviside who subsequently introduced the fourth modern Maxwell equation as a partial-time-derivative version of Faraday's Law, and re-cast the equations but acknowledged that it was Maxwell who did the original work. Albert Einstein specifically acknowledged the importance of Maxwell in his development of special relativity. It was apparently Einstein who originally referred to them as "Maxwell's Equations".

For more information on this and other IEEE History Milestones, please visit the IEEE Global History Network (www.ieeeghn.org)

Wireless Comes of Age

- Guglielmo Marconi invented the wireless telegraph in 1896
  - Communication by encoding alphanumeric characters in analog signal – continuous wave (CW)
  - Sent telegraphic signals across the Atlantic Ocean
  - "It is dangerous to put limits on Wireless" - Guglielmo Marconi, 1932
- Communications satellites launched in 1960s
- Advances in wireless technology
  - Radio, television, mobile telephone, communication satellites – initially RF based **analog** systems in the VHF/UHF spectrum
- More recently
  - Satellite communications, wireless networking, cellular technology – digital modulation schemes in the UHF/microwave spectrums
- Big Picture/Overall Viewpoint
  - Two types of wireless systems: WiFi (802.11) and Cellular (example 4G LTE) both of which provide access to the Internet

The History of Mobile Radio Communication (1/3)

- 1880: Hertz – Initial demonstration of practical radio communication
- 1897: Marconi – Radio transmission to a tugboat over an 18 mi path
- 1921: Detroit Police Department: -- Police car radio dispatch (2 MHz frequency band)
- 1933: FCC (Federal Communications Commission) – Authorized four channels in the 30 to 40 MHz range
- 1938: FCC – Ruled for regular service
- 1946: Bell Telephone Laboratories – 152 MHz (Simplex)
- 1956: FCC – 450 MHz (Simplex)
- 1959: Bell Telephone Laboratories – Suggested 32 MHz band for high capacity mobile radio communication
- 1964: FCC – 152 MHz (Full Duplex)
- 1964: Bell Telephone Laboratories – Active research at 800 MHz
- 1969: FCC – 450 MHz (Full Duplex)
- 1974: FCC – 40 MHz bandwidth allocation in the 800 to 900 MHz range
- 1981: FCC – Release of cellular land mobile phone service in the 40 MHz bandwidth in the 800 to 900 MHz range for commercial operation

The History of Mobile Radio Communication (2/3)

- 1981: AT&T and RCC (Radio Common Carrier) reach an agreement to split 40 MHz spectrum into two 20 MHz bands. Band A belongs to nonwireline operators (RCC), and Band B belongs to wireline operators (telephone companies). Each market has two operators.
- 1982: AT&T is divested, and seven RBOCs (Regional Bell Operating Companies) are formed to manage the cellular operations
- 1982: MFJ (Modified Final Judgment) is issued by the government DOJ. All the operators were prohibited to (1) operate long-distance business, (2) provide information services, and (3) do manufacturing business
- 1983: Ameritech system in operation in Chicago
- 1984: Most RBOC markets in operation
- 1986: FCC allocates 5 MHz in extended band
- 1987: FCC makes lottery on the small MSA and all RSA licenses
- 1988: TDMA (Time Division Multiple Access) voted as a digital cellular standard in North America
- 1992: GSM (Groupe Speciale Mobile) operable in Germany D2 system

The History of Mobile Radio Communication (3/3)

- 1993: CDMA (Code Division Multiple Access) voted as another digital cellular standard in North America
- 1994: American TDMA operable in Seattle, Washington
- 1994: PDC (Personal Digital Cellular) operable in Tokyo, Japan
- 1994: Two of six broadband PCS (Personal Communication Service) license bands in auction
- 1995: CDMA operable in Hong Kong
- 1996: US Congress passes Telecommunication Reform Act Bill
- 1996: The auction money for six broadband PCS licensed bands (120 MHz) almost reaches 20 billion US dollars
- 1997: Broadband CDMA considered as one of the third generation mobile communication technologies for UMTS (Universal Mobile Telecommunication Systems) during the UMTS workshop conference held in Korea
- 1999: ITU (International Telecommunication Union) decides the next generation mobile communication systems

  (e.g., W-CDMA, cdma2000, etc)

First Generation Cellular Systems and Services

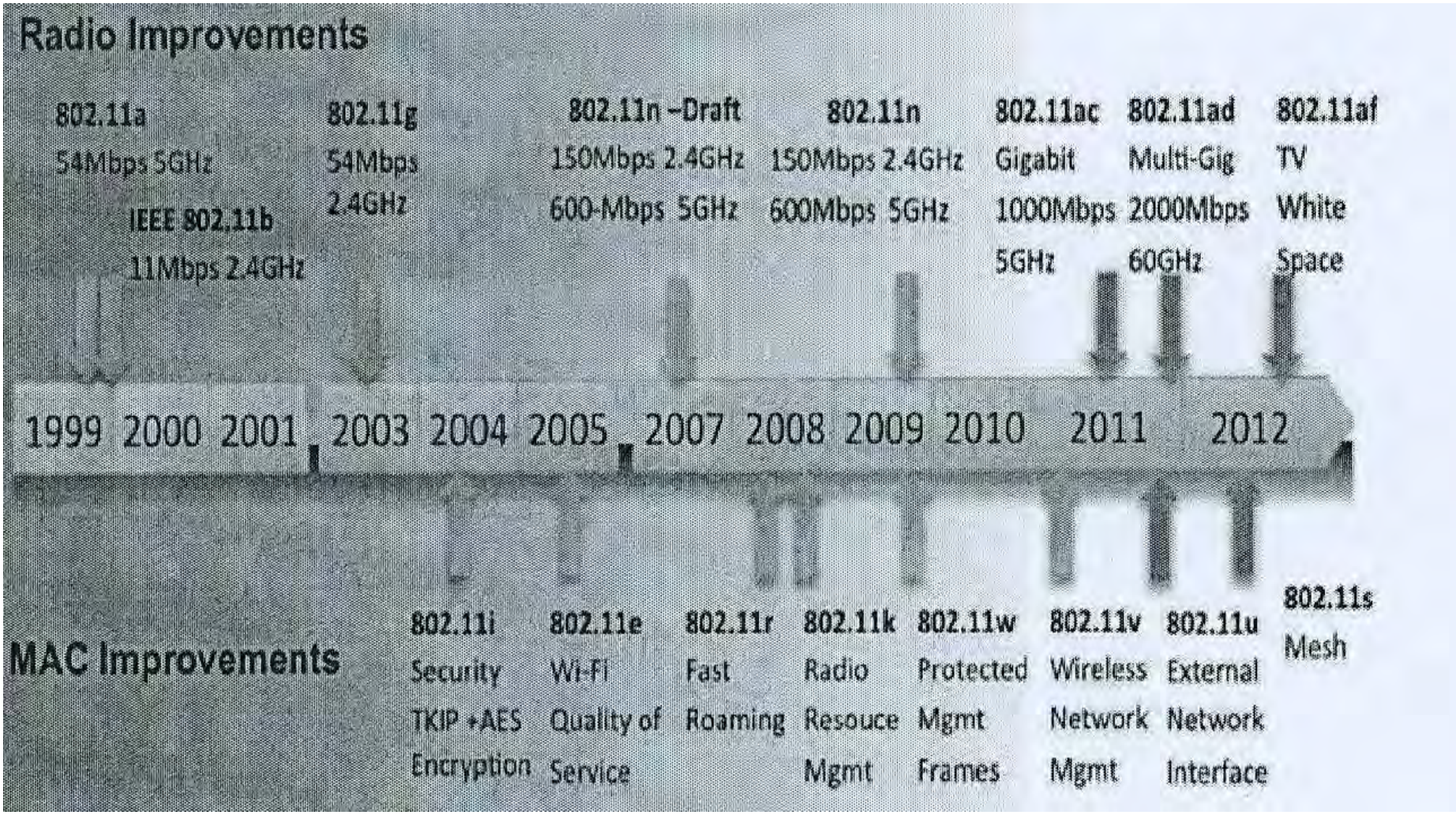
1970s	Developments of radio and computer technologies for 800/900 MHz mobile communications
1976	WARC (World Administrative Radio Conference) allocates spectrum for cellular radio
1979	NTT (Nippon Telephone & Telegraph) introduces the first cellular system in Japan
1981	NMT (Nordic Mobile Telephone) 900 system introduced by Ericsson Radio System AB and deployed in Scandinavia
1984	AMPS (Advanced Mobile Phone Service) introduced by AT&T in North America

Generational Cellular Systems

1G (1981) - Analog Voice (AMPS)
2G (1991) - Digital Voice (GSM, IS-95)
3G (2000) - Internet Data (WCDMA, CDMA2000)
4G (2008) - Broadband data (LTE, WiMax)
5G (2020) - ??? massive connectivity

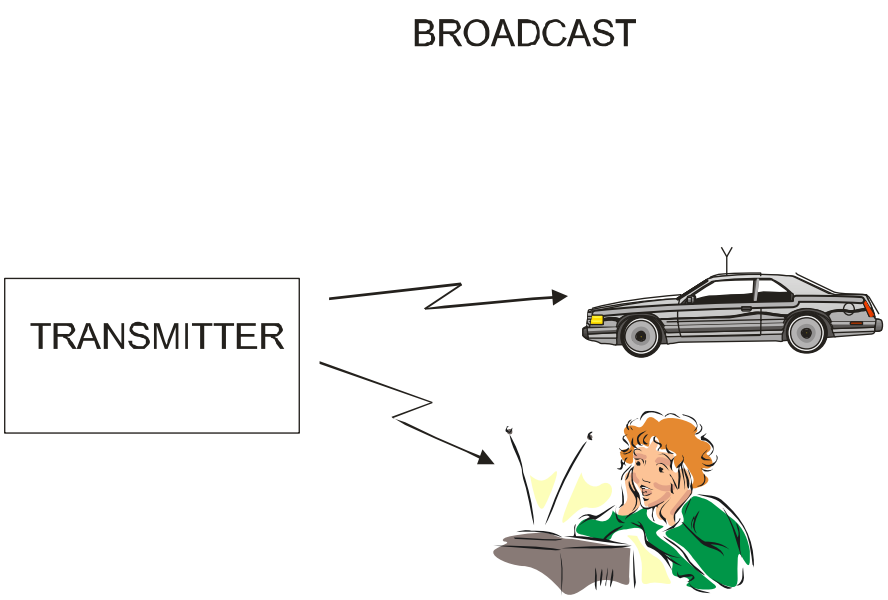
Wi-Fi (Radio) Communication Progress

Not Cellular Communication Systems

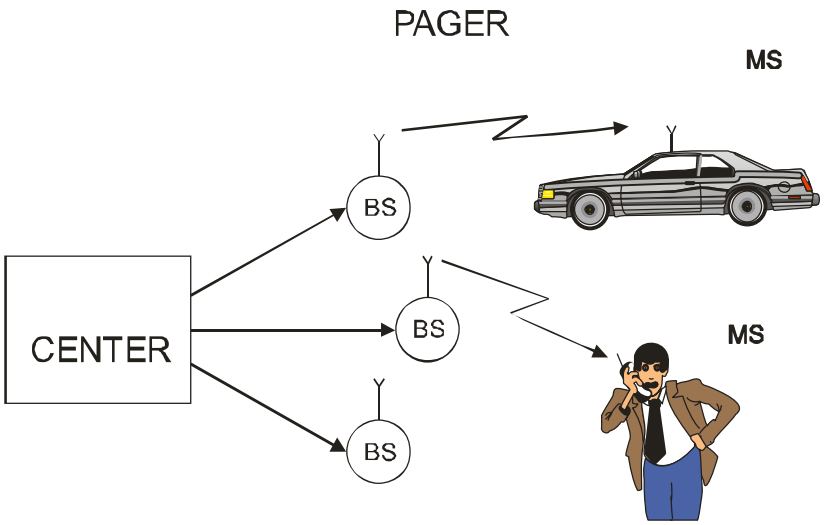


TYPES OF SERVICES

Broadcast



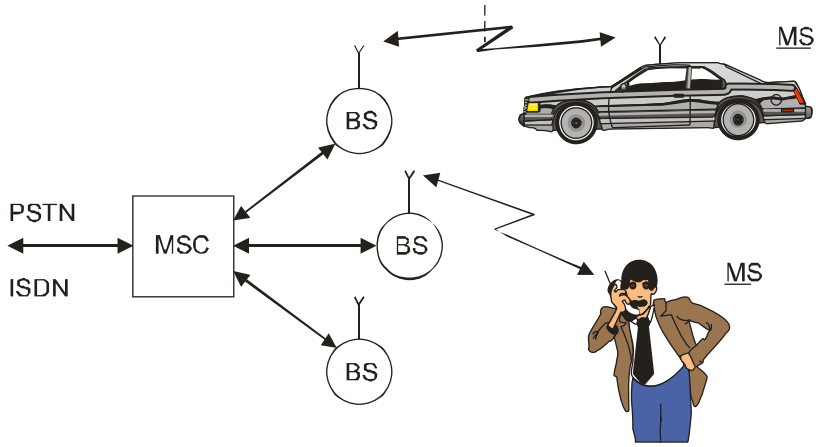
Paging



Medical personnel still use a pager system integrated into their cell phones

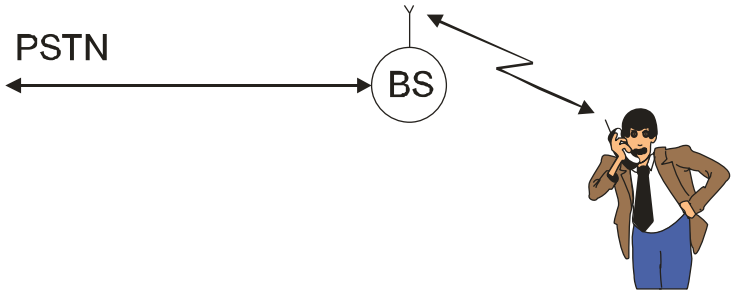
Cellular phones

Majority of the data load is carried
by hi-speed wired systems (fiber, copper)

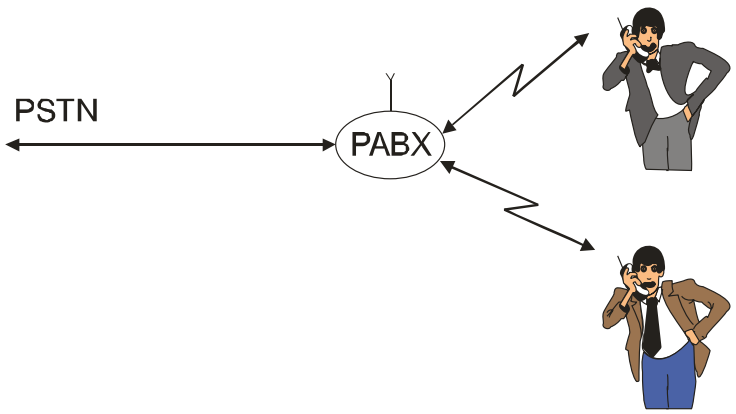


Cordless phones

CORDLESS PHONE



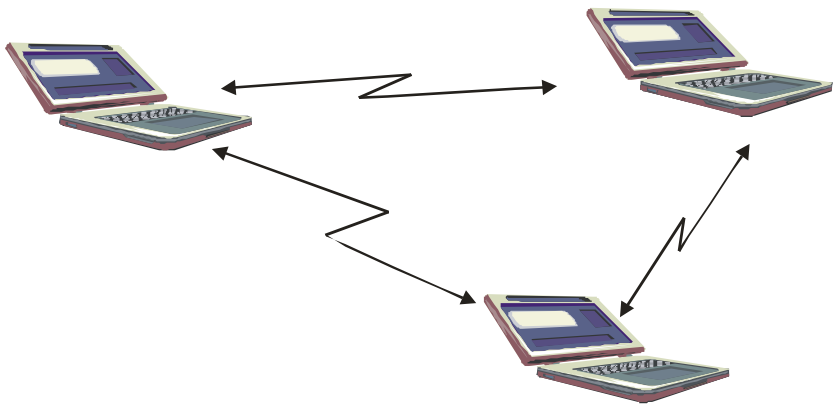
WIRELESS PABX



Wireless LANs and PANs

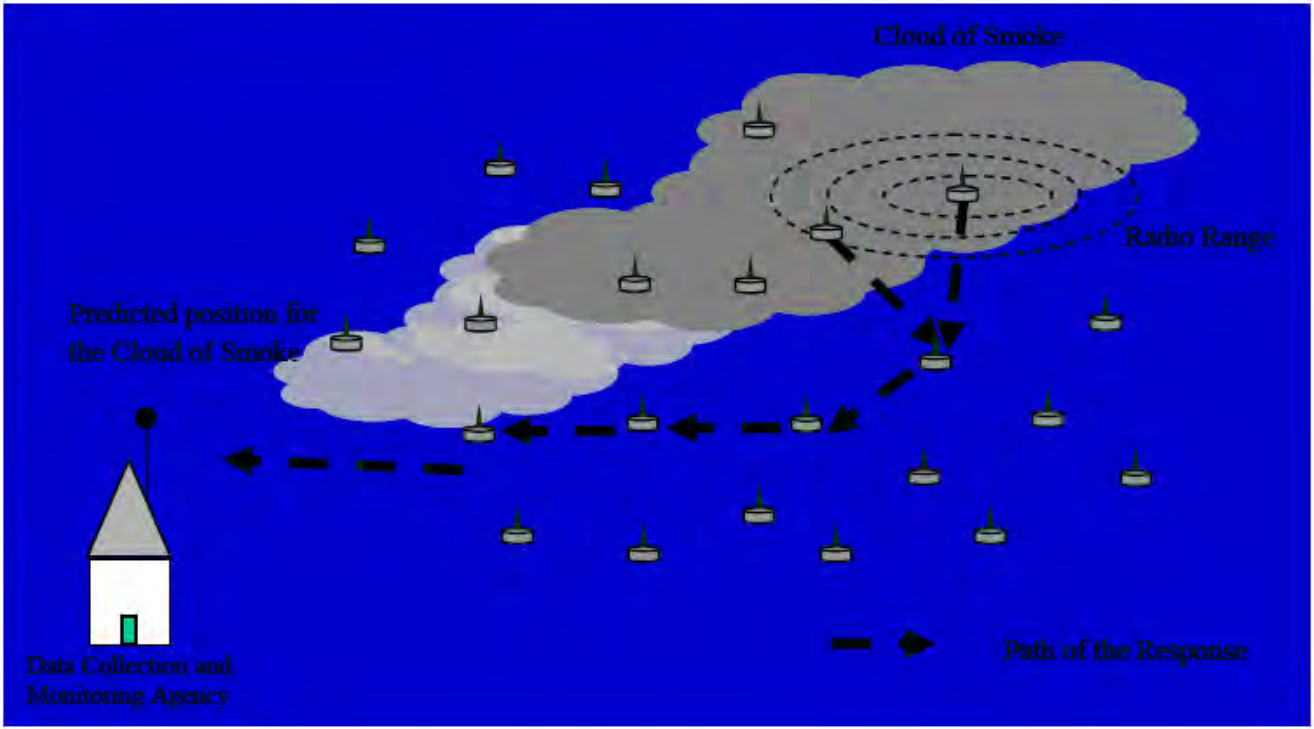
AD-HOC NETWORK (also P2P / peer-to-peer network)

Mesh Networks



Author needs to add WiFi/802.11 infrastructure networks which use routers for wired networks and access points (AP) for wireless networks. Note that the 802.11 standard does incorporate ad-hoc networks.

Wireless Sensor Networks



Fixed wireless and satellite

- Fixed wireless systems
  - Long distances between BS and MS
  - No mobility requirements
  - Typically high data rates, but can also be used for voice systems
  - WiMax standard (IEEE 802.16)
- Satellite systems
  - Cover very large area
  - No high density (Erlang/km^2)
  - Iridium system with LEO systems tried to get large user density, but progress considerably slower than anticipated (10 new satellites just launched in January 2017 by SpaceX with more to follow)

REQUIREMENTS FOR SERVICES

Data rate

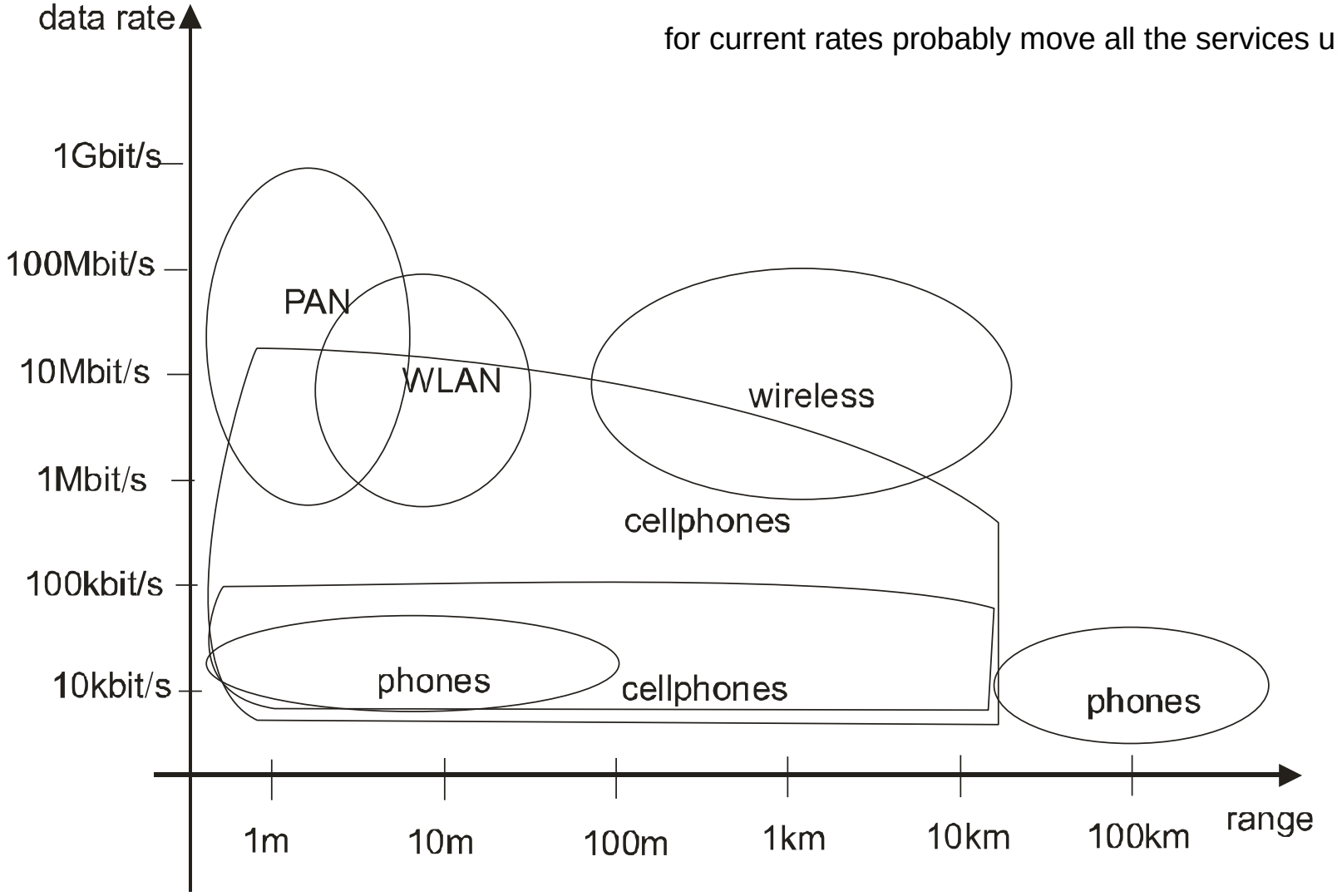
- Sensor networks: <1kbit/s; central nodes need up to 10 Mbit/s
- Speech communications: 5-64 kbit/s, depending in speech coder (vocoder) Nyquist Criterion
- Elementary data services: 10-100 kbit/s
- Communications between computer peripherals: 1 Mbit/s
- Wireless LANs: broadband internet speeds, 1-100 Mbit/s
- Personal Area Networks: >100 Mbit/s

Data rates 2 years old so already out of date USB3 is 4.8 GBPS for computer peripherals

cellular LTE 300 Mbps down/75 Mbps up

LTE Advanced 3 Gbps down/1.5 Gbps up

Tradeoff range vs. datarate



for current rates probably move all the services up

Mobility

- Fixed devices: stay in one location; temporal variations due to moving objects in surroundings
- Nomadic devices: MS placed at certain location, stays there for a while (WLANs)
- Low mobility: pedestrian speeds (cordless phones)
- High speed: cellphones in cars
- Extremely high speed: high-speed trains, planes, ….

Spectrum Usage - limited resource, cellular uses ISM 2.4 GHz and 5 GHz bands, 5G Systems will undoubtedly use millimeter frequencies

ECONOMIC AND SOCIAL IMPACT

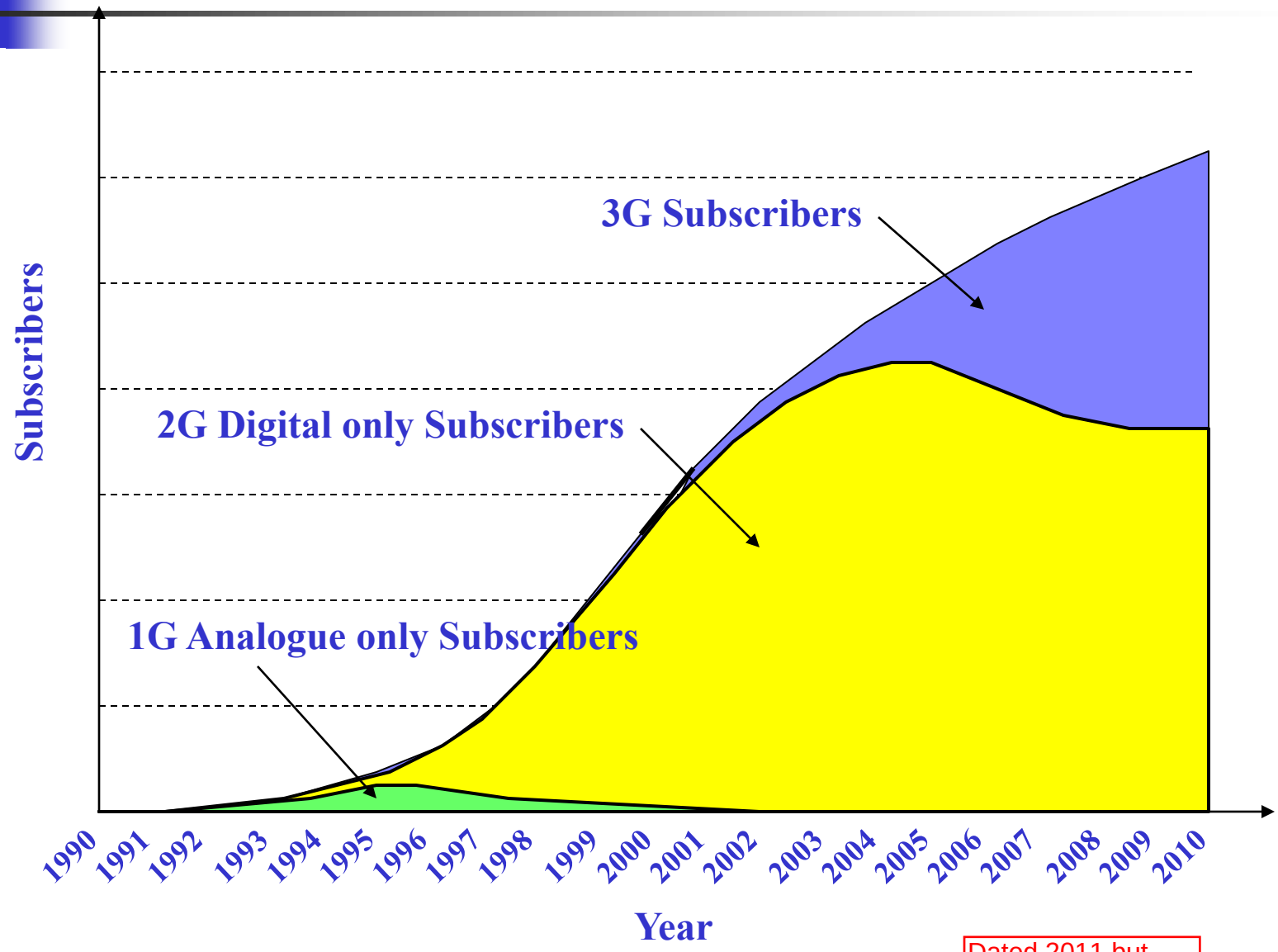
Economic requirements

- Systems where mobility is a value by itself
  - Cellphones, etc.
  - Can charge premium for service
- Systems that just are cable replacement
  - e.g., for fixed wireless access
  - Must be cheaper than cabled service
- In either case, quality has to be same as wired
- Systems should contain as many digital components as possible to reduce costs and allow the power of computers to be applied to the problems

Behavioral impact

- Communications are now with a person, not with a location
- Allows more flexibility for private/business life, but can also become electronic “ball and chain”
- Cellphone etiquette: generally underdeveloped
- Phoning while driving is dangerous
- Each cellphone has an OFF button

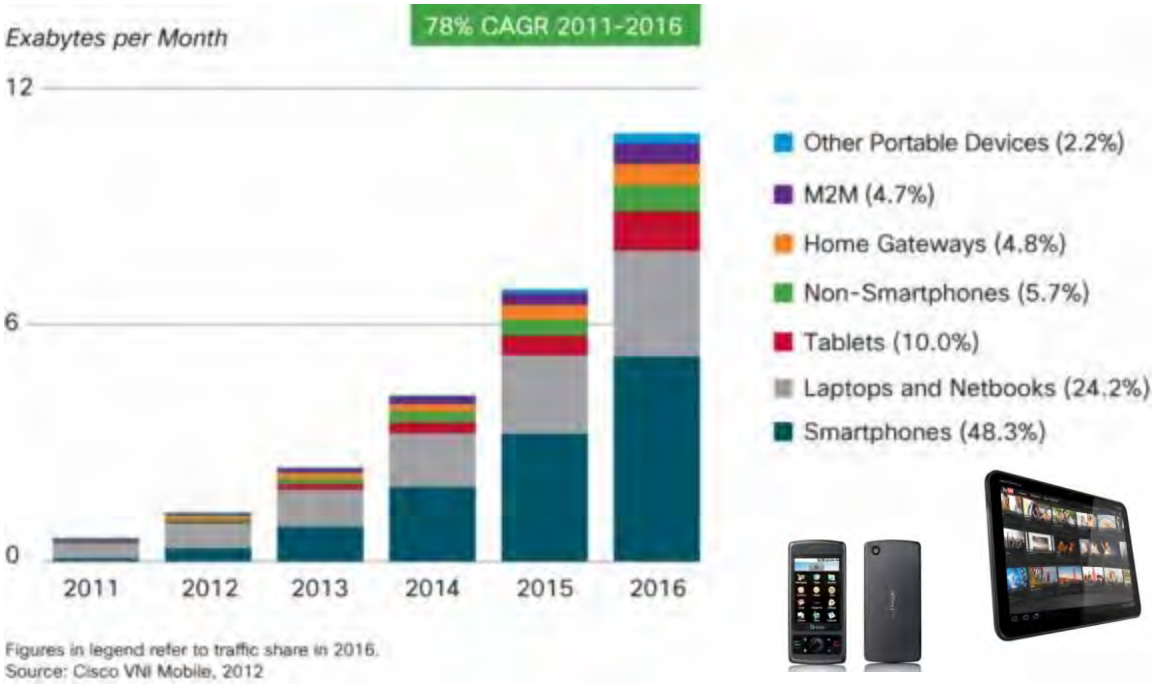
Subscriber Growth



Dated 2011 but where is 4G?

Mobile Device Internet Usage Accelerating

- Mobile broadband usage growing rapidly
  - New subscribers to broadband services
  - Quad core smartphones
  - Laptops and tablets
  - M2M
- Network intensive applications
  - Video



- Mobile data 2011-2016 78% CAGR compound annual growth rate *(Source:* Cisco VNI Mobile, 2012*)*
  - Mobile video traffic exceeded 50 percent for the first time in 2011
  - Average smartphone usage nearly tripled in 2011
    - 150 MB per month (up from 55 MB per month in 2010)
    - average smartphone will generate 2.6 GB of traffic per month in 2016 (17x 2011)

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Changes Since Yesterday (2013)

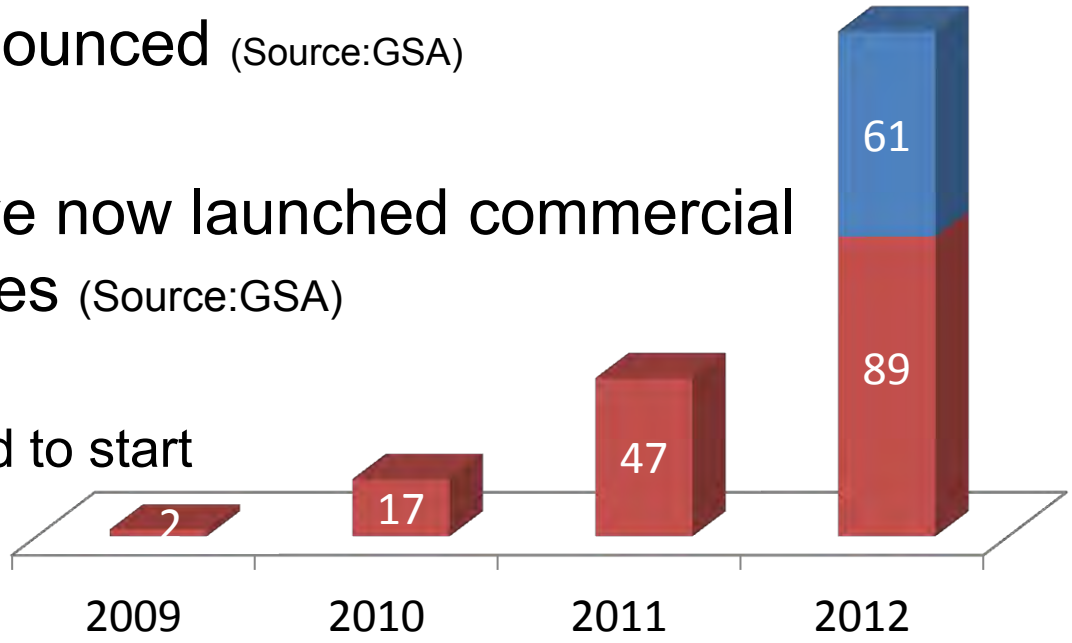
- The mobile data tsunami is driving the need for diverse, distributed network deployments.
- 4G LTE (Long Term Evolution) is the advertised solution in the US. This is an **engineering** solution based on four main features: a modulation technique Orthogonal frequency-division multiplexing (OFDM), multiple input/multiple output (MIMO) technologies (from 802.11n), highly efficient error correction techniques (Turbo Codes) and real-time network adaptability to user loads. LTE is a packet-switched network only (vs circuit-switched networks like GSM and CDMA)
- LTE (note the word Evolution) will continue to evolve as computer processing capabilities continue to improve (Moore's Law, muticore processors, etc.)
- Heterogeneous network deployments provide higher data rates and QoS (Quality of Service) for users at affordable CAPEX (capital investment) & OPEX (operational expenses) for service providers.
- Companies are providing complete, scalable hardware & software solutions from femto (< 15 users) to macro cell in order to build wireless communications networks from a large entity (company, conference, Flash Mobs, etc.) to a personal residence communications network for the wireless devices in a house.

LTE Is Significant Step Forward

- LTE provides **2 to 5 times greater spectral efficiency** than most advanced 3G networks
  - Lower cost per bit
- Faster downloads
  - Up to 100 Mbit/s initially
  - Better user experience
- Reduced OPEX and CAPEX (operational & capital expenditures)
  - LTE base station cost <1/5 HSPA cost per user per month (based on 10 Gbit/s per month)
  - Energy efficient

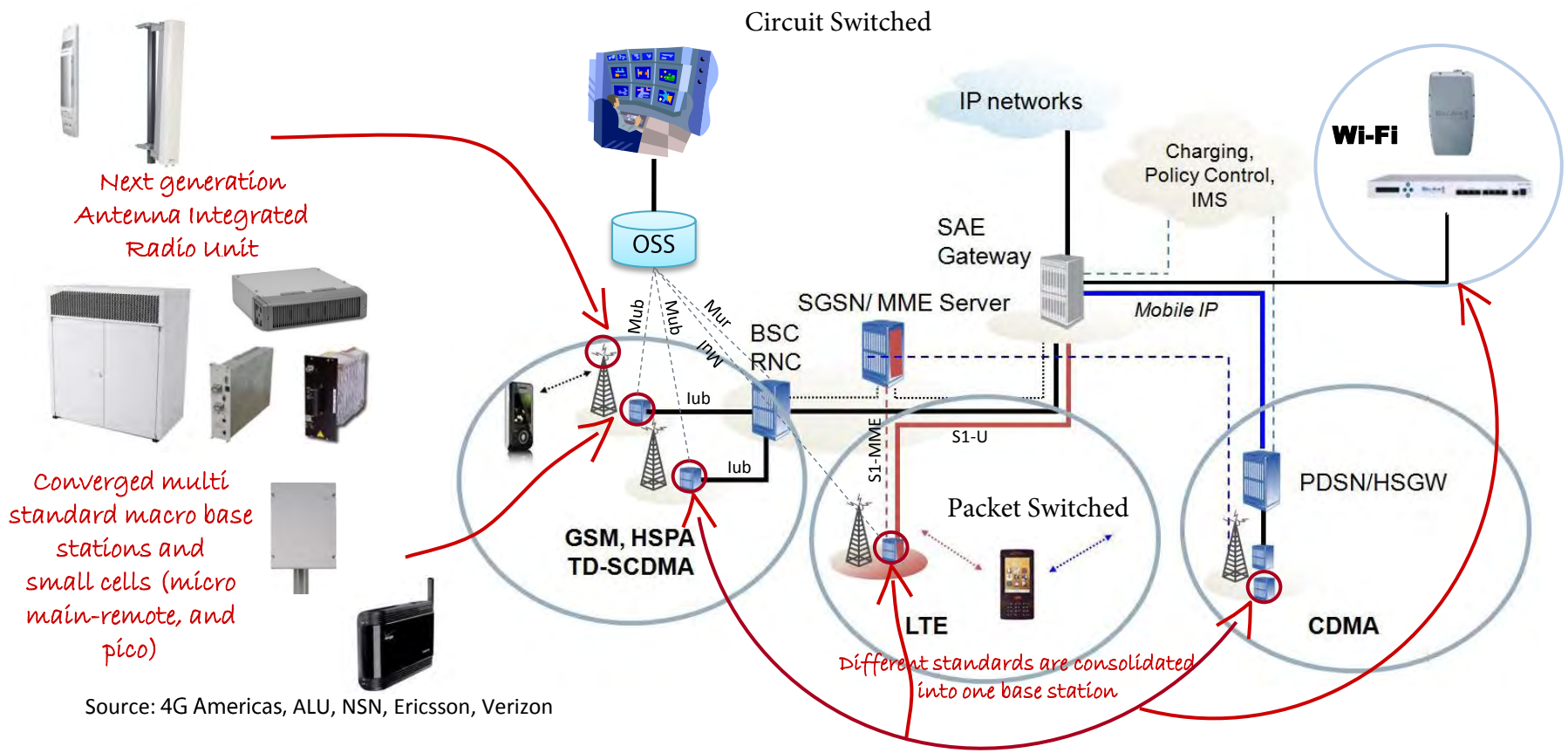
LTE Market Rollout

- 592 Million LTE Subscriptions by 2016 (Source: Pyramid Research)
- 4G LTE Revenues Projected to Exceed $265 Billion Globally in 2016 (Source: Juniper Research)
- 417 LTE Devices Announced (Source:GSA)
  - From 67 companies
- 89 LTE operators have now launched commercial services in 45 countries (Source:GSA)
  - 80 FDD, 9 TDD
  - Additional 61 expected to start services during 2012



Source: GSA Evolution to LTE report July 11, 2012

Evolving Multi standard Radio Access Networks (cellular connectivity diagramed)



Source: 4G Americas, ALU, NSN, Ericsson, Verizon

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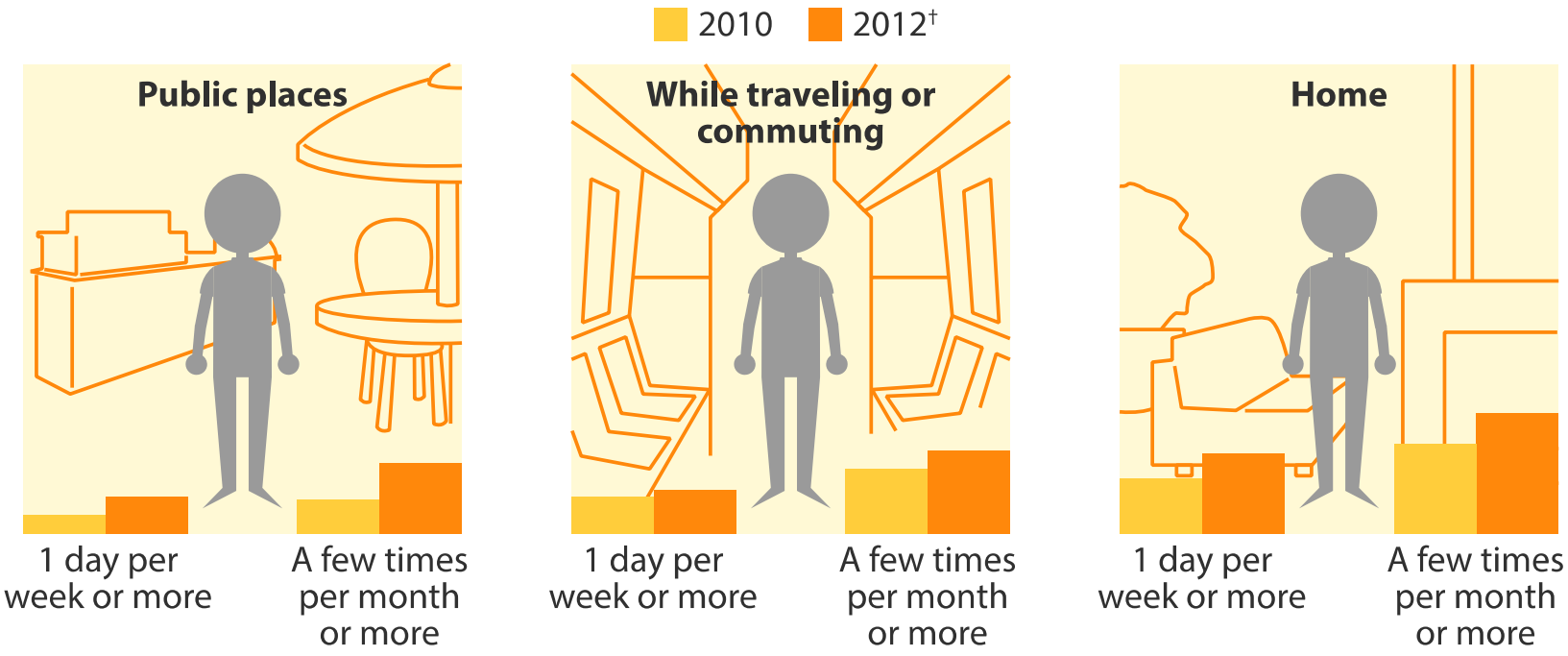
Employees at all levels are more autonomous and mobile than ever

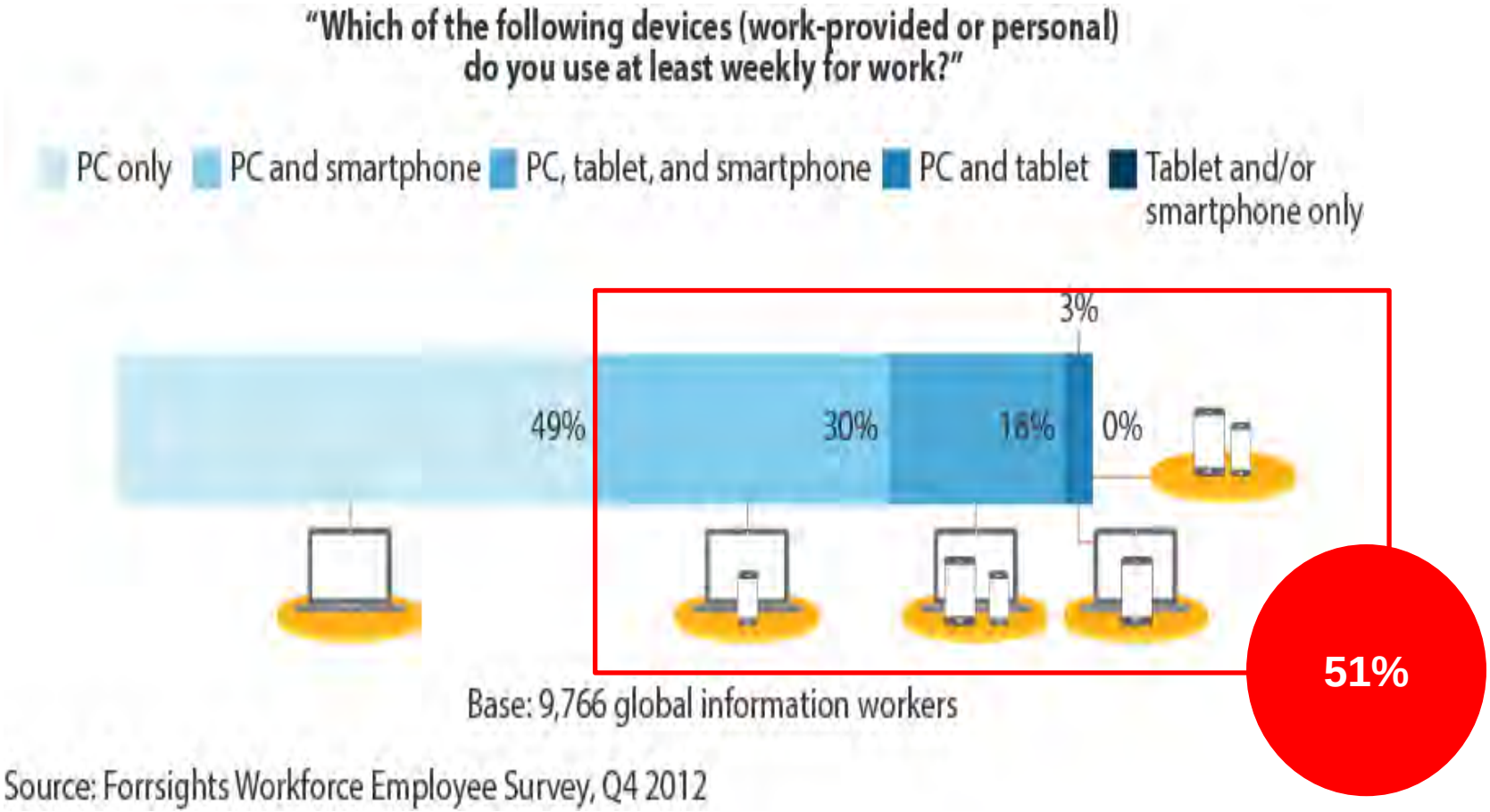


Employees use multiple devices to complete work activities

Mobile OS market continues to diversify

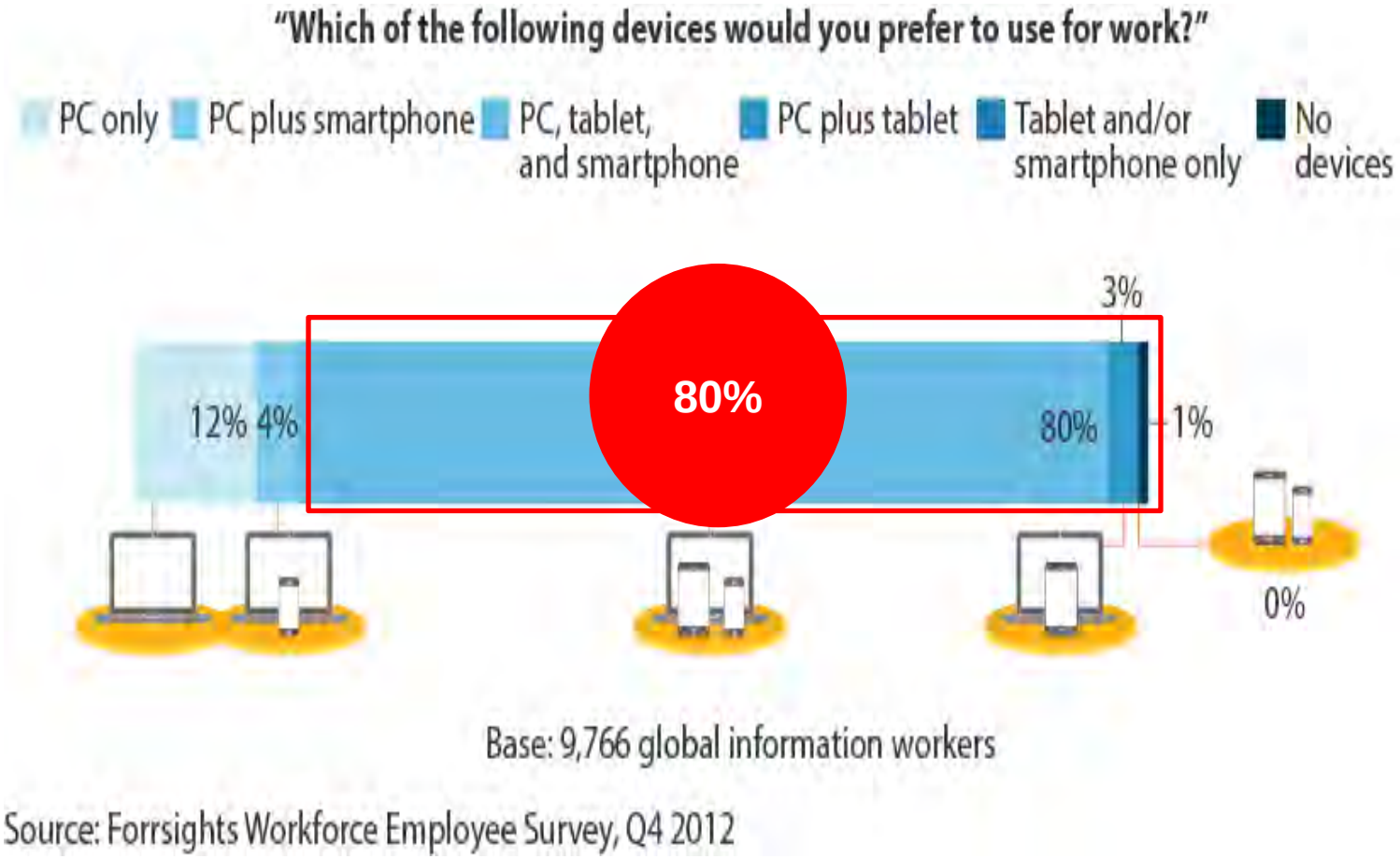
	Smartphones 2012†	Smartphones 2011*	Tablets 2012†	Tablets 2011*
Android	37%	26%	23%	25%
iOS	34%	23%	58%	47%
BlackBerry	15%	24%	2%	3%
Windows	5%	6%	11%	15%
Other	2%	2%	1%	1%

Workers have quickly added smartphones and tablets to their repertoire of devices…



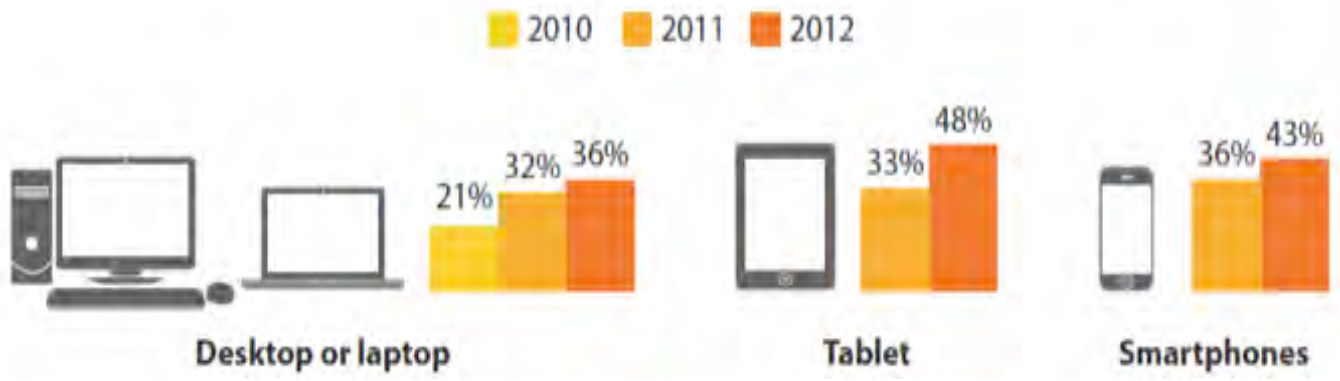
Source: Forrsights Workforce Employee Survey, Q4 2012

… but they <u>want</u> the trifecta: PC, tablet, and smartphone – some 80% of workers!

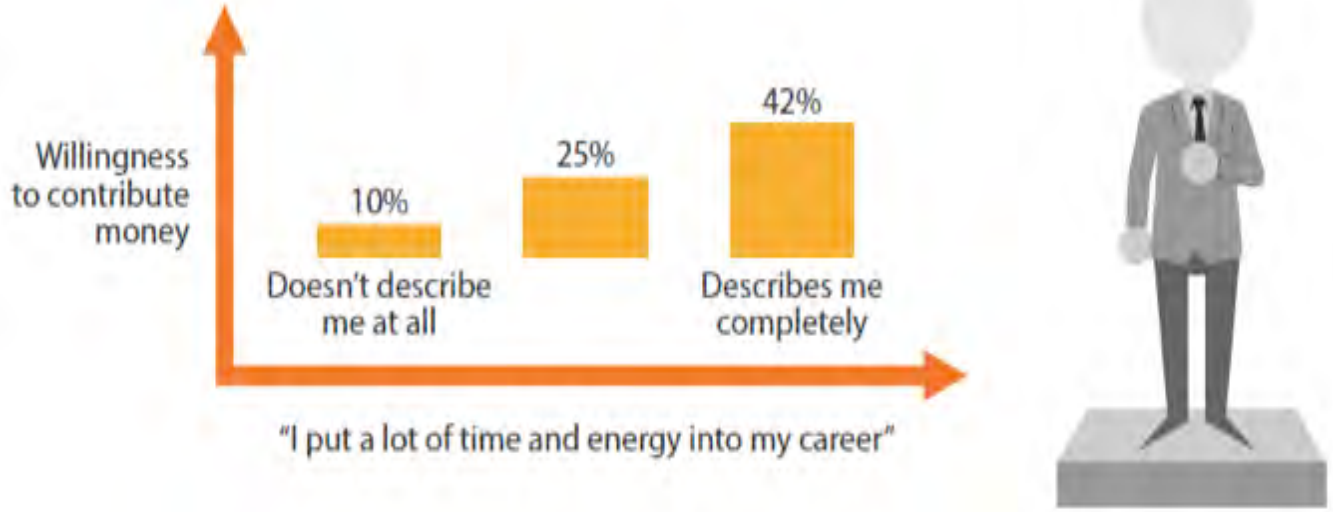


Source: Forrsights Workforce Employee Survey, Q4 2012

Employees are Willing to Pay More to Choose Their Tools Each Year



CAREER-FOCUSED EMPLOYEES ARE 4x MORE WILLING TO PAY TO CHOOSE!



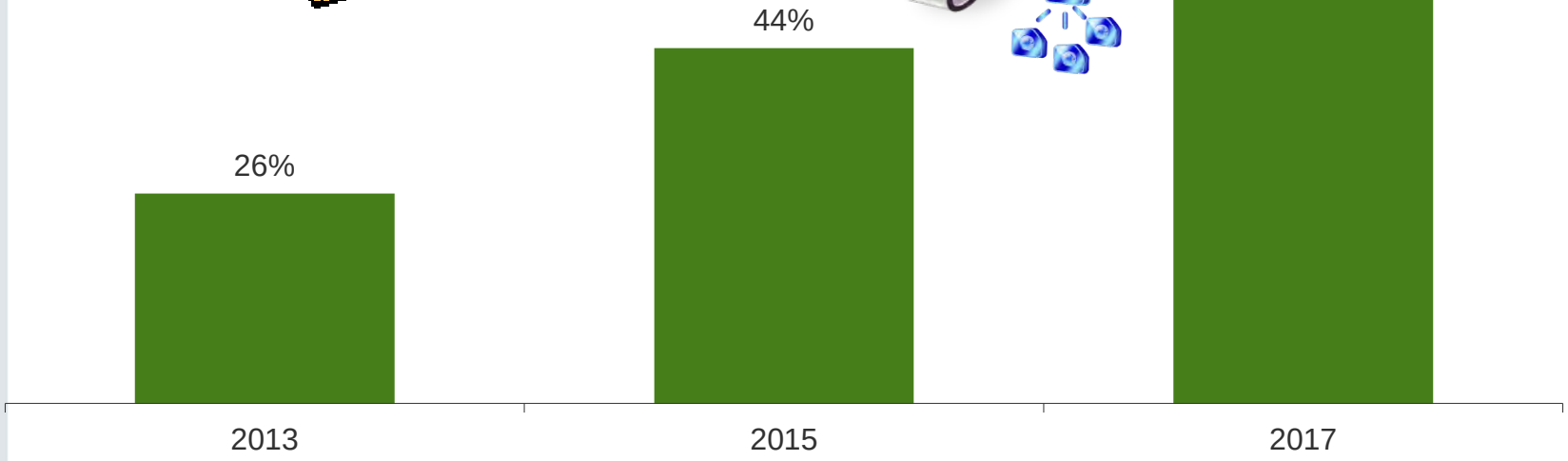
Source: Forrsights Workforce Employee Survey, Q3 2010, Q3 2011 and Q3 2012

The empowered era will create new variables not experienced on the wired side

"What is the amount of network traffic will cross over wireless?" (50% or more of traffic)

Internet 91%
Email 89%
Social Media 70%

Hi def video 62%
VDI 61%
Virtual Desktop Infrastructure - desktop on a virtual machine that lives on a server in a data center
UC and Collaboration 58%
unified communcations

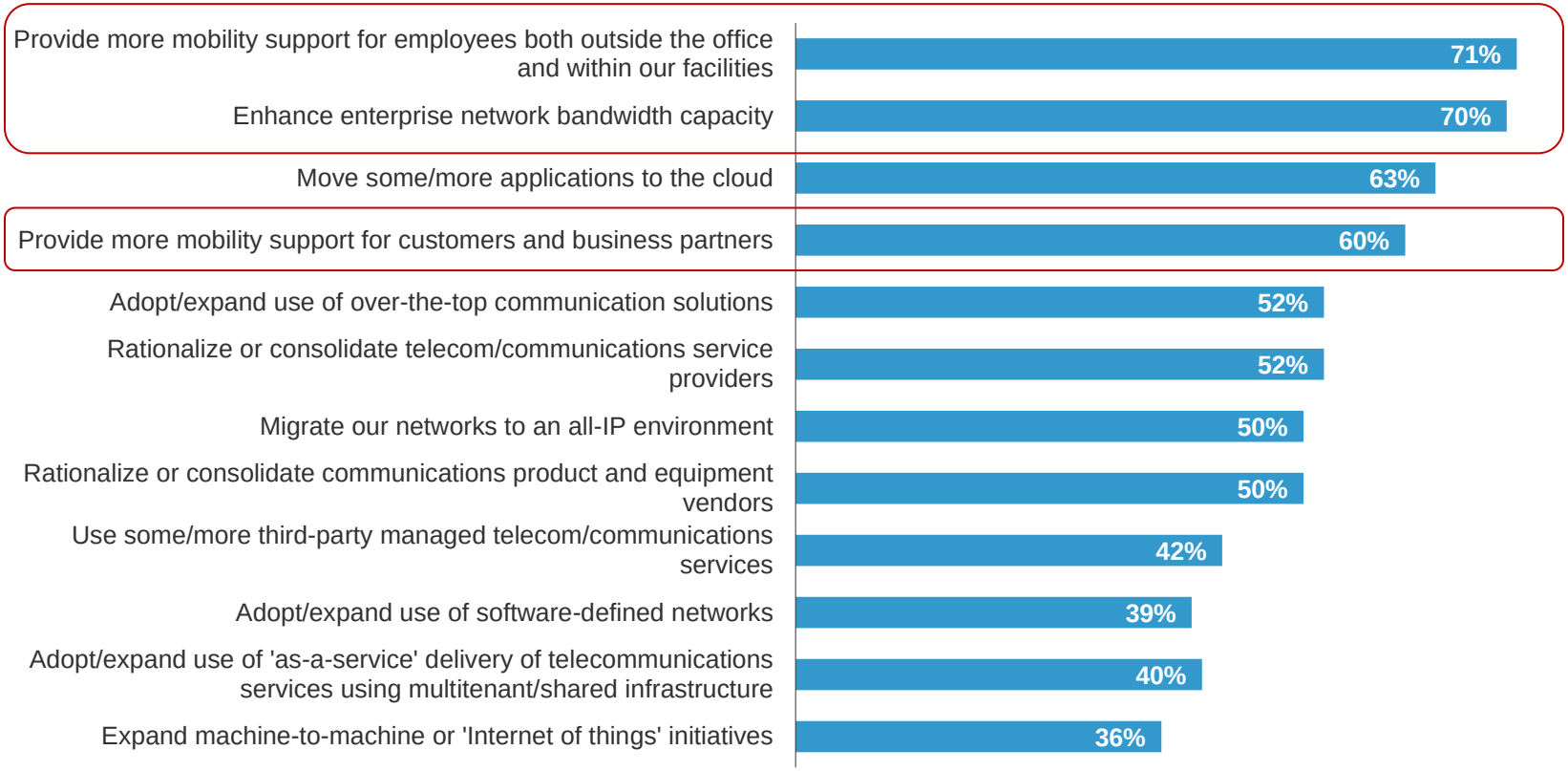


Base: 2258 Mobile telecommunication decision makers
Source: Forrsights Mobility Survey, Q2 2013

Mobility and device diversity shift attention back to the network

“Which of the following initiatives are likely to be your firm's top strategic network and telecommunications priorities during the next 12 months?”

(Respondents selecting High or Critical priority)

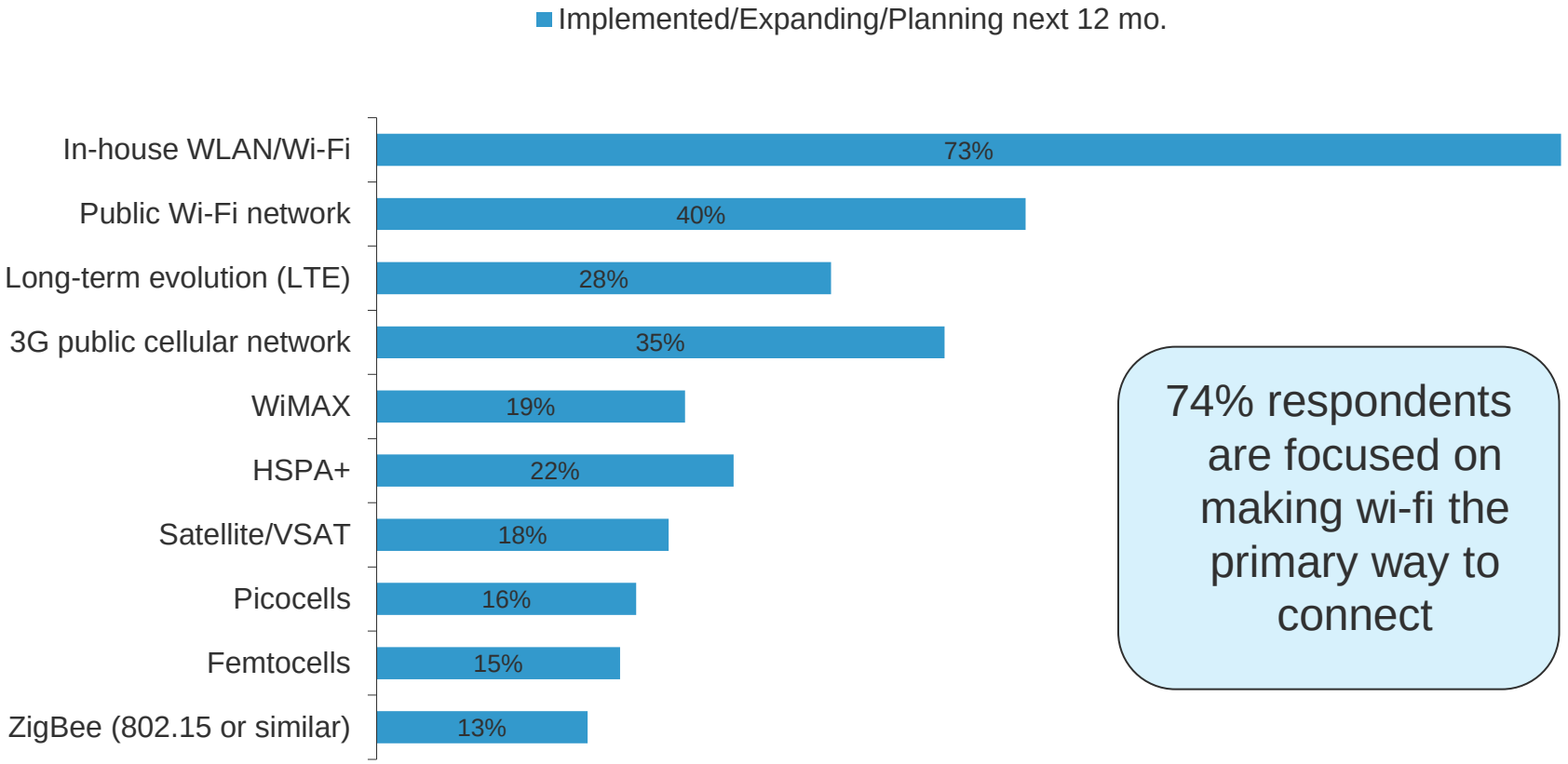


Base: 2144 IT decision makers

Source: Forrsights Networks And Telecommunications Survey, Q1 2013

…and Wi-Fi will be the dominant way to connect

“What are your firm's plans to adopt the following mobile and wireless network technologies/services?”

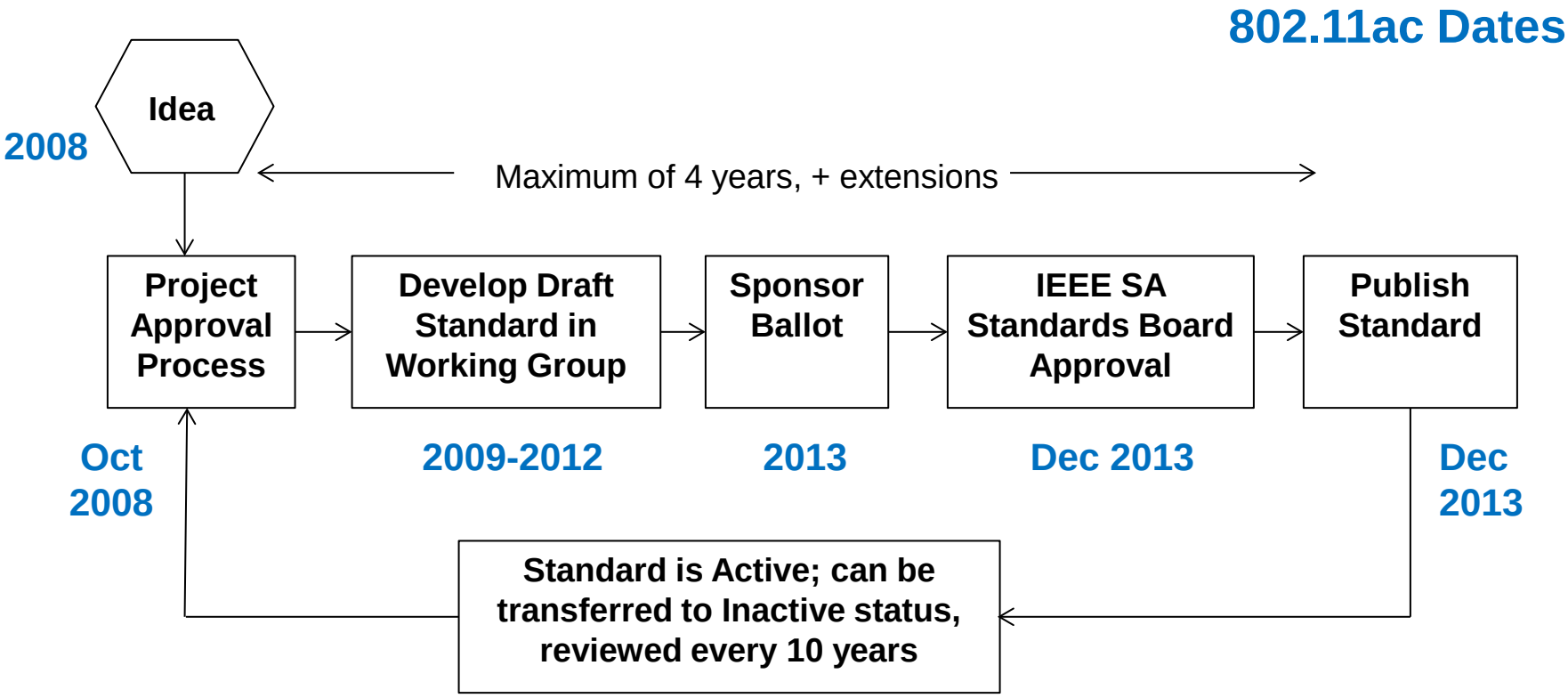


74% respondents are focused on making wi-fi the primary way to connect

Base: (Variable) mobile telecommunication decision makers in companies with more than 20 employees

Source: Forrsights Mobility Survey, Q2 2013

IEEE Standards Development: Process Flow – 802.11ac

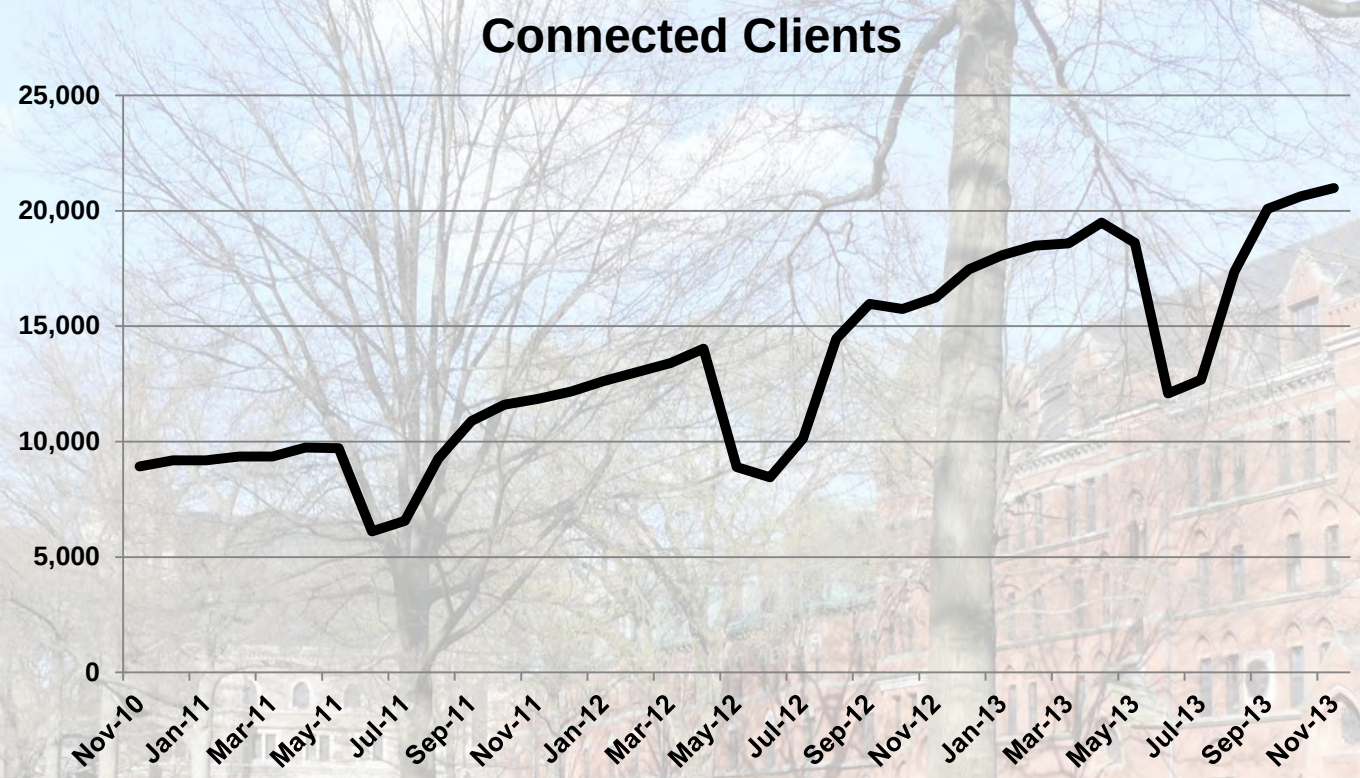


Source: https://mentor.ieee.org/802.11/dcn/10/11-10-0617-01-0000-ieee-standards-process-overview.ppt and http://www.ieee802.org/11/Reports/802.11_Timelines.htm, http://standards.ieee.org/develop/policies/opman/sb_om.pdf

Wi-Fi Alliance Interoperability Certification

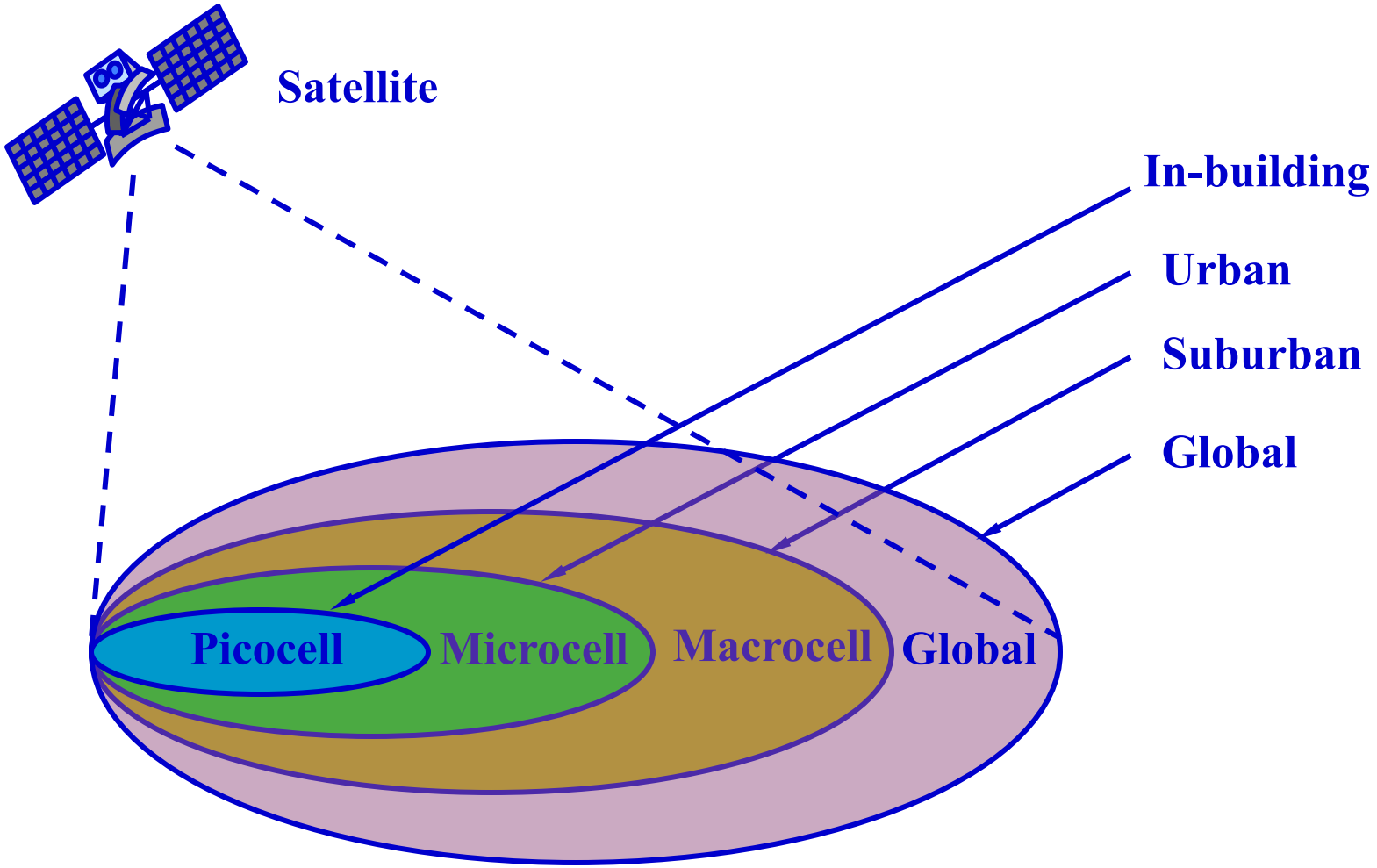
- Wi-Fi CERTIFIED™ ac certification is now available
  - Launched June 2013
  - 229 products certified to date, see https://www.wi-fi.org/wi-fi-certified%E2%84%A2-products
  - Based on IEEE 802.11ac draft 5.0
- Expect a “Final ac” certification in 2-3 years
  - Wi-Fi Alliance to update the program to include additional features and ensure backward compatibility with previously certified devices
  - Additional optional features to be added, as with 11n
  - Availability 2015/2016

Growth in Connected Devices at Yale University

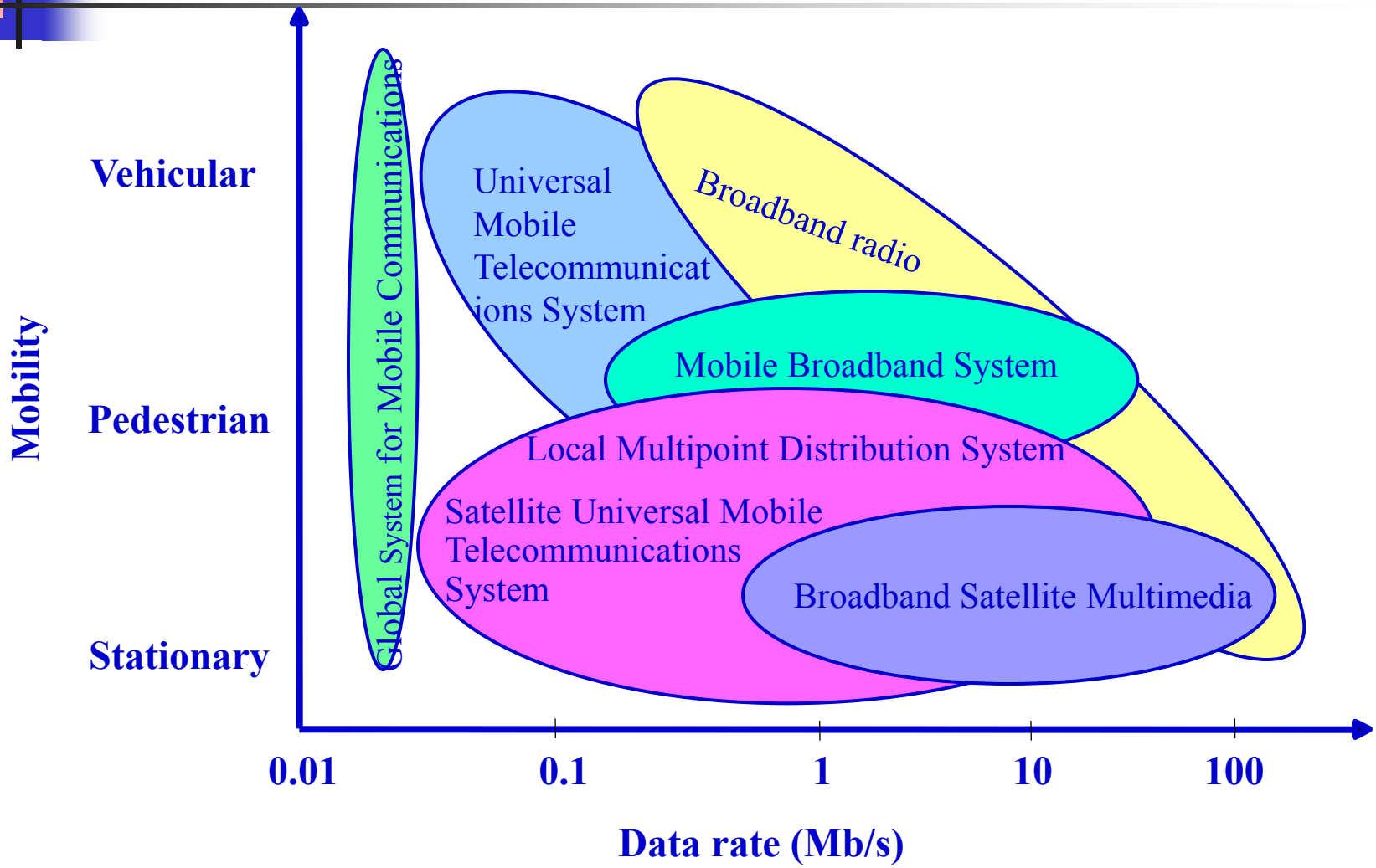


- >30% annual growth in devices on campus past 3 years
- Since deploying 802.11ac Access Points, seeing over 5% of devices are 802.11ac

Coverage Aspect of Next Generation Mobile Communication Systems



Transmission Capacity



Transmission capacity as a function of mobility in some radio access systems

Wireless Technology and Associated Characteristics

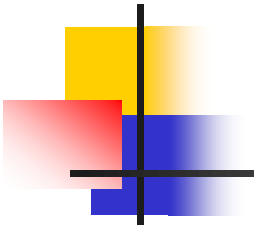
- Cellular
- Wireless LAN/PAN
- GPS
- Satellite Based GPS
- Home Networking
- Mesh and Ad Hoc Networks
- Sensor Networks
- Bluetooth

Satellite Systems

- Traditional Applications
  - Weather satellite
  - Radio and TV broadcasting
  - Military satellites
- Telecommunication Applications
  - Global telephone connections
  - Backbone for global network
  - GPS

Network Architectures and Protocols

- Systematic Signaling Steps for Information Exchange
- Open Systems Interconnections (OSI)
- Transmission Control Protocol (TCP)
- Internet Protocol (IP)
  - Internet Protocol Version 4 (IPv4)
  - Internet Protocol Version 6 (IPv6)
  - Mobile IP



Some Definitions

- Baseband – modulation techniques that do not use a sinusoidal carrier but encodes information directly as the amplitude, width of position of a pulse. PAM – pulse amplitude modulation PWM – pulse width modulation
- Bandpass – modulation techniques that encode information as the amplitude, frequency or phase of a sinusoidal carrier. FSK – frequency shift keying, PSK – phase shift keying, AM, FM

Broadband Wireless Technology

- Higher data rates obtainable with broadband wireless technology
  - Graphics, video, audio
- Shares same advantages of all wireless services: convenience and reduced cost
  - Service can be deployed faster than fixed service
  - No cost of cable plant
  - Service is mobile, deployed almost anywhere
- Ubiquitous Computing (*Mark Weiser/Xerox Parc*) – " The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."

Limitations and Difficulties of Wireless

- Mobility brings unique challenges of its own, has had a significant impact on lifestyles and society in the last five years.
- Too Big to Fail?
- Lack of an industry-wide standard, which should be a concern to the global community (but the global economy will mandate a solution)
- Device limitations
  - Power
  - Data Consumption
  - Throw away device, impacts of 2 year cellular contracts, electronics waste
- Security – Achilles heel of the technology
- RF Effects – long term effects on humans? Environment?
- Economics – industry in spite of its size is still impacted by the economy.

Why This Course?

- A very hot technology that has become a multi-billion industry with numerous job opportunties.
- Wireless is convenient and less expensive, low deployment costs, great for countries without a wired infrastructure.
- Already an integral part of business and our lifestyle.
- Data rates are improving significantly faster than anticipated and in time will no longer be a limitation, especially when wireless data rates reach the processing bandwidth of the human eye
- **Eventually <u>everything</u> will be wireless !!** Large Job Opportunties
- A communications technique that will become fully integrated with our bodies in terms of our clothes and maybe even our brain.

Why Not This Course?

- If it heats up quickly, it will also cool down just as fast (low specific heat)
- Course time limitations limit development of a fundamental set of 'knowledge' tools. Limited hands-on opportunities.
- Design, test and deployment is computer aided with new tools being introduced every day. **Very** difficult to stay 'current'.
- RF design is somewhat of a black art and not a large career field
- Governments are under pressure to open more spectrum for wireless applications (recent 108 MHz of analog TV channel spectrum available when digital TV became the standard) – all leading to a extremely dynamic landscape, probably unstable.
- What are the real job qualifications? Just about every engineering job will touch wireless communications in some manner.
- Conclusions - Flexibility is the keynote of life. No substitute for experience.