ELG4179: Wireless Communication Fundamentals (in-person)

Instructor: Dr. Sergey Loyka (CBY A608)

Course web page: http://www.site.uottawa.ca/~sloyka/ (most of the course material, including lecture slides, assignments will be posted there; download everything - do not assume it will be available online forever – network outages do occur).

Lectures: Monday 13:00-14:20 (LMX 221), Wednesday 11:30-12:50 (FTX 232). **1st Lecture**: Wed. Sep. 6, 11:30-12:50.

Tutorials: begin on Sep. 13, Wed. 8:30 – 9:50 (SMD224). No tutorials first week.

Labs: begin on Sep. 19, Tue. 19:00-21:50, CBY B02.

Office hours: You are encouraged to ask questions during lectures (additionally, time will be allocated at the end of each lecture).

Teaching assistant(s): TBD

Assignments: about 6.

Marking scheme:

Assignments +quizzes	10%
Labs	10%
Midterm Examination	20%
Final Examination	60%

Lots of bonus points to everybody who takes active part in the course!

Midterm exam: Wed. Oct. 18, 11:30-12:50, regular lecture time/place. Includes everything covered in the class before the midterm; closed book; 1 letter-sized page of reference material is allowed.

Final Exam: to be scheduled by the University**.** Includes everything covered in the class (including labs and tutorials), not just after midterm; closed book; 2 letter-sized pages of reference material are allowed. It is for evaluation purposes only and will not be returned to the students.

Exam marks are determined by academic performance only, not by bargaining abilities, and will not be negotiated

Everybody must do the exams individually, no group work/collaboration/consultation is allowed. The regular plagiarism policy applies and will be enforced (see below).

Important Notes:

- All the course components (lectures, tutorials, labs, assignments) are mandatory. Miss at your own risk. Attendance is also mandatory.
- If you do not finish any of the lab experiments, you will receive the incomplete grade for this course.
- Marking scheme is final and will not be changed/negotiated.
- Marks are determined by academic performance only (not by bargaining abilities).
- Marks will not be negotiated.
- All questions are to be answered during the semester (no guarantee afterwards).

Absence: valid if medical certificate (from the University medical authority)

Pre-requisites:

ELG3175. Basic knowledge of communication systems

ELG3126. Probability theory.

ELG4176 is highly desirable (but not required).

Plagiarism: copying solutions to assignments, quizzes, exams and lab reports from anywhere is a serious academic fraud that carries a significant penalty. Plagiarism is absolutely not acceptable.

While working in groups on assignments is not a plagiarism, submitting identical or nearly identical solutions is and will be severely penalized. Every student is expected to submit his own **individual solutions**.

If two (or more) identical or almost identical sets of solutions are found, each student involved receives 0 (zero) for that particular assignment. If this happens twice, the students involved receive 0 (zero) for the entire assignment component of the course in the marking scheme and the case will be send to the Dean's office for further investigation.

From the past experience, the students who copy assignments/labs, do **poorly in exams**.

Required textbook:

T.S. Rappaport, Wireless Communications: Principles and Practice, Prentice Hall, New Jersey, 2002. (2nd Edition) (available at amazon.com(ca)).

Additional texts:

- B.A. Black et al, Introduction to Wireless Systems, Prentice Hall, Boston, 2008.
- J.W. Mark, W. Zhuang, Wireless Communications and Networking, Prentice Hall, 2003.
- T.S. Rappaport et al, Millimeter Wave Wireless Communications, Prentice Hall, 2015.

The following 3 books are mostly undergraduate communications textbooks:

- R.E. Ziemer, W.H. Tranter, Principles of Communications, Wiley, New York, 2009.
- L.W. Couch II, Digital and Analog Communication Systems, Prentice Hall, 2013.
- J.M. Wozencraft, I.M. Jacobs, Principles of communication engineering, Wiley: New York, 1965.

The following 3 books are mostly graduate-level textbooks:

- A. Molish, Wireless Communications, Wiley, 2011.
- G.L. Stuber, Principles of Mobile Communications, Kluwer, Boston, 2011.
- D. Tse, P. Viswanath, Fundamentals of Wireless Communications, Cambridge, 2005.

The following 3 books deal with simulation issues:

- M.C. Jeruchim et al, Simulation of Communication Systems: Modeling, Methodology, and Techniques, Kluwer, New York, 2000.
- J.G. Proakis et al, Contemporary Communication Systems Using MATLAB and Simulink, Thomson & Books/Cole, 2004.
- W.H. Tranter et al., Principles of Communication Systems Simulation, Prentice Hall, 2004.

Practical Systems (cellular):

- E. Dahlman et al, 5G NR: The Next Generation Wireless Access Technology, Academic Press, 2020.
- A. Ghosh et al, Fundamentals of LTE, Prentice Hall, 2011.

Math handbooks (to refresh your math skills):

- G.A. Korn, T.M. Korn, Mathematical Handbook for Scientists and Engineers, Dover, 2000.
- I.N. Bronshtein et al, Handbook of Mathematics, Springer, 2004.
- E. Zeidler, Oxford User's Guide to Mathematics, Oxford University Press, 2004.

If you need some physics:

- W. Benenson et al (Ed.), Handbook of Physics, Springer, 2002.

Purpose of the course: to introduce basic principles and techniques of modern wireless communication systems.

Contents (tentative):

- Introduction. Brief overview. Historical perspective. Modern systems.
- Link budget analysis and wireless (radio) propagation channel. Impact of antennas.
- Free space propagation. Two-ray model. Path loss exponent. Okumura-Hata & other empirical models. Diffraction and Fresnel zones. 3 main factors & propagation mechanisms.
- Large-scale fading (shadowing), lognormal distribution. Small-scale (multipath) fading, Rayleigh/Rice distributions. Outage probability.
- Doppler effect & spread, coherence time. Delay spread and coherence bandwidth, power delay profile.
- Digital modulation techniques for wireless systems. Performance analysis. Impact of fading. Error floors. Information-theoretic limits & designs of modern systems.
- Diversity techniques. Combining methods. Performance improvement.
- Interference cancellation/management. Smart antennas and MIMO systems.
- Multi-user systems and multiple access methods. Orthogonal (FDMA, TDMA, CDMA, SDMA) and random (ALOHA, CSMA).
- The cellular concept. Frequency re-use and spectral efficiency. System design fundamentals.

How to Study: Learning Efficiency Pyramid

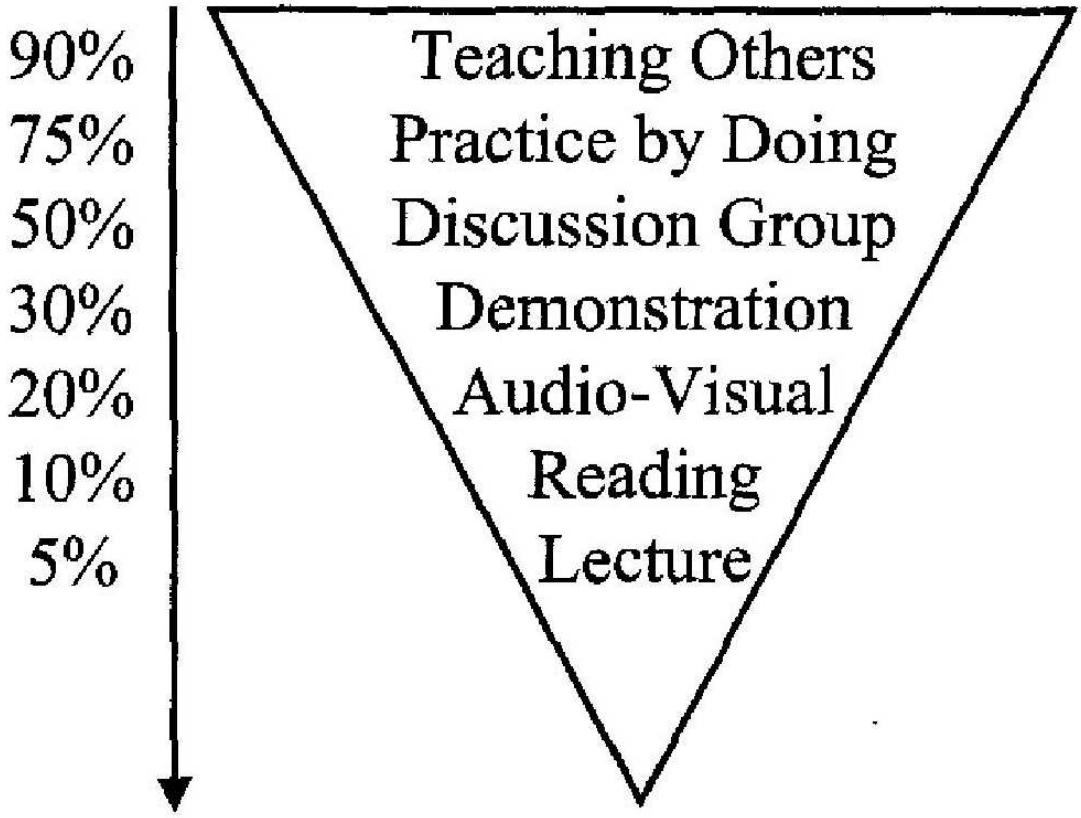


Figure 1. The Learning Pyramid, adapted from David Sousa, *How the Brain Learns*, Reston, VA, The National Association of Secondary School Principals, 1995, ISBN 0-88210-301-6.

"Tell me and I'll forget; show me and I may remember; involve me and I'll understand." – old Chinese proverb.

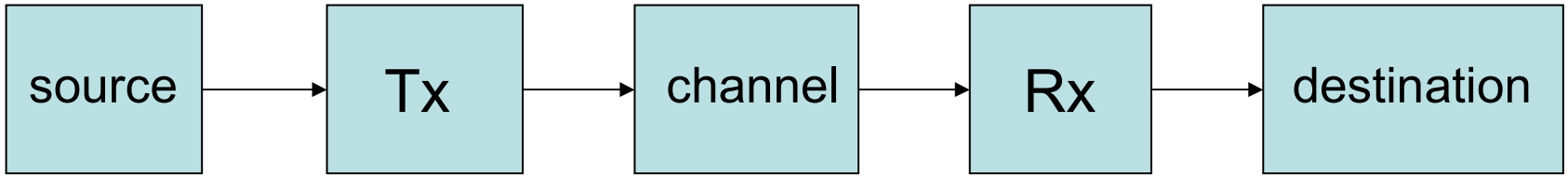
Another version: "I hear, I forget; I see, I remember; I do, I understand".

How to Study

"*Education is the accumulation of understanding, not just an accumulation of facts*" [D. Pozar]

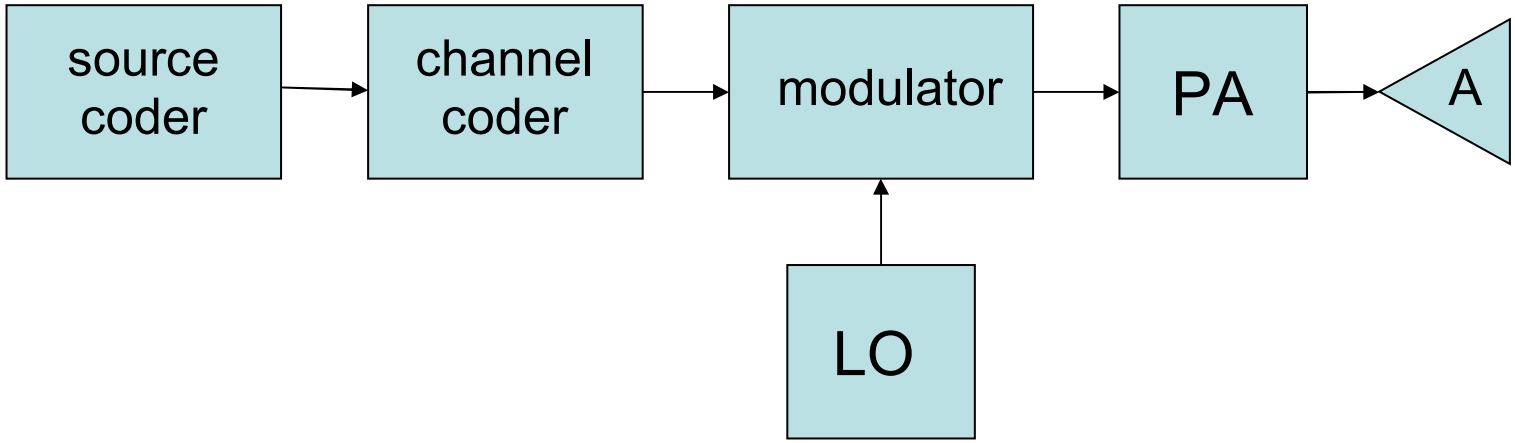
- Learning efficiency pyramid is a good guideline
- Reading is necessary, but taken alone is not efficient
- Solving problems ("practice by doing")
  - is much more efficient
  - examples, assignments, end-of-chapter problems
  - "*Remember that very little is gained by reading the solution to a problem before seriously attempting to solve it.*" W. Briggs, Ants, Bikes and Clocks: Problem Solving for Undergraduates, 2005.
- Group discussions
  - help provided you contribute something
- Systematic study during the semester
  - is a key to a success.
  - do not leave everything to the last day/night before exams!
  - 1 class hour = 1 hour of individual studies
- Lectures
  - should be supplemented by the items above
  - take notes in the class!

Block Diagram of a Communication System



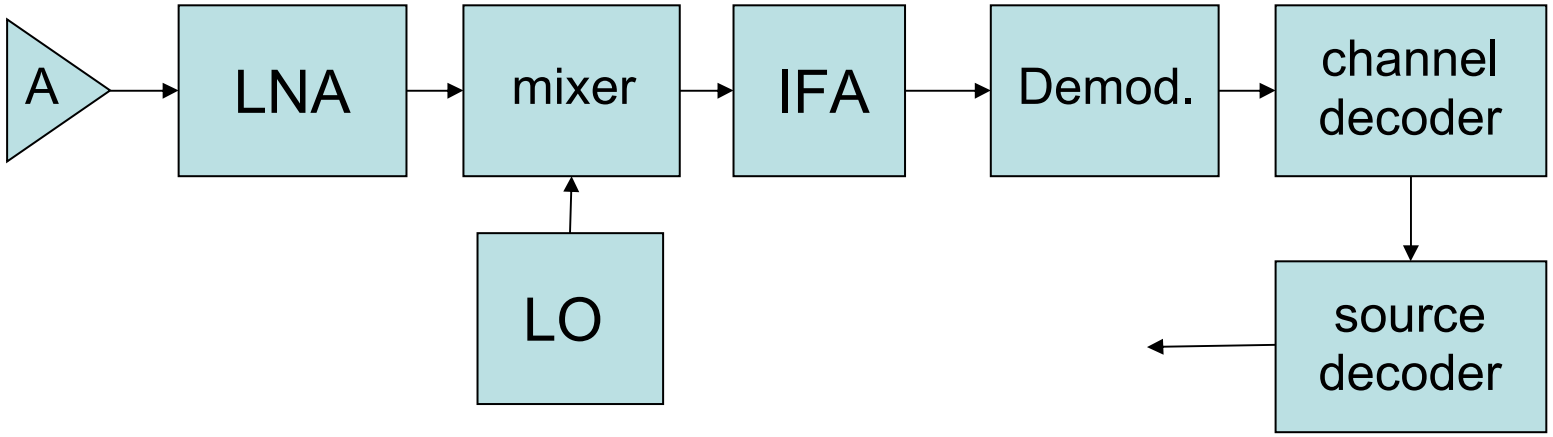
- Source – a source of information (e.g. voice, data file, YouTube video)
- Tx – a transmitter
- Channel – a path (link) from the Tx to the Rx (e.g. cable, wireless medium, etc.)
- Rx – a receiver
- Destination – a place where the information has to be delivered

Transmitter (Tx)



- Source coder – encodes the message to remove redundancy
- Channel coder – encodes the input to protect against errors introduced by the channel
- Local oscillator (LO) – generates the carrier
- Modulator – modulates the carrier using the encoded message
- Power amplifier (PA) – amplifies the modulated signal to required power level
- Antenna (A) – radiates the modulated signal as an electromagnetic wave

Receiver (Rx)



- Source decoder – decodes the source-encoded message
- Channel decoder – decodes the channel code
- Local oscillator (LO) – generates the carrier
- Mixer – down-converts the RF signal to IF frequencies
- IF amplifier (IFA): amplifies the IF signal significantly (up to 10^6) and rejects adjacent channel signals and interference (frequency selectivity). Its bandwidth is the same as the signal bandwidth.
- Demodulator: demodulates the modulated signal
- Low-noise amplifier (LNA): amplifies a weak RF signal coming out of the antenna. Rejects the image frequency. Bandwidth: much wider than the signal bandwidth.
- Antenna (A) – receives an incoming electromagnetic wave carrying the message

Introduction To Wireless

Various terms: “wireless”, “mobile”, “portable”, “radio”, “personal” communications (additionally: “digital”). Major differences and similarities.

There are few essential principles that make mobile/wireless communications special.

Differences between: “mobile” and “fixed wireless/radio”; “wireless” and “wired” etc.

Examples

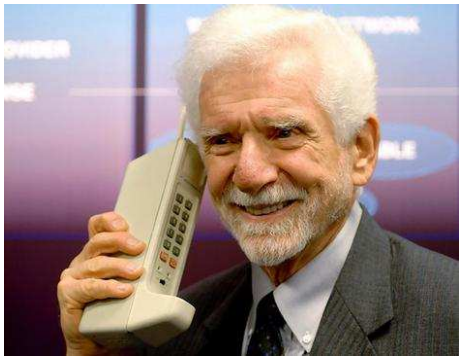
- WiFi (wireless Internet access, WLAN)
- Cell/cordless phones
- Remote control
- Bluetooth
- Radio/TV broadcast (incl. satellite)
- Navigation (GPS, radar)

Historical Perspective

- 1844: invention of telegraph by Morse
- 1876: invention of telephone by Bell
- 1895/96: invention of radio by Popov/Marconi
- early 1900s: 1st use of radio
- 1900: 1st transatlantic transmission by Marconi
- 1933: invention of FM by Amstrong
- 1936: 1st TV broadcast by BBC
- 1947: transistor is invented in Bell lab

- 1948: Shannon discovers information theory
- 1957: Sputnik is launched by USSR
- 1973: 1st cell phone call (by Martin Cooper of Motorola to his rival at AT&T; the phone weighted 1kg and cost approximately $4000)
- 1981: IBM PC is introduced.
- 1990s: launch of Internet.
- 2000s: launch of WiFi
- 2007: launch of iPhone
- 2010: launch of iPad
- 1998-2008: Google, Youtube, Facebook, Twitter, etc.

Cellular Systems (cell phones)



Martin Cooper of Motorola made the first publicized handheld mobile phone call on a prototype DynaTAC model on April 4, 1973. This is a reenactment in 2007. (https://en.wikipedia.org/wiki/Mobile_phone)

Cell Phones

https://en.wikipedia.org/wiki/Mobile_phone

1st com. cell phone, 1984

Cell phone evolution…

…and today…

Cellular System: 1 to 5G (generations)

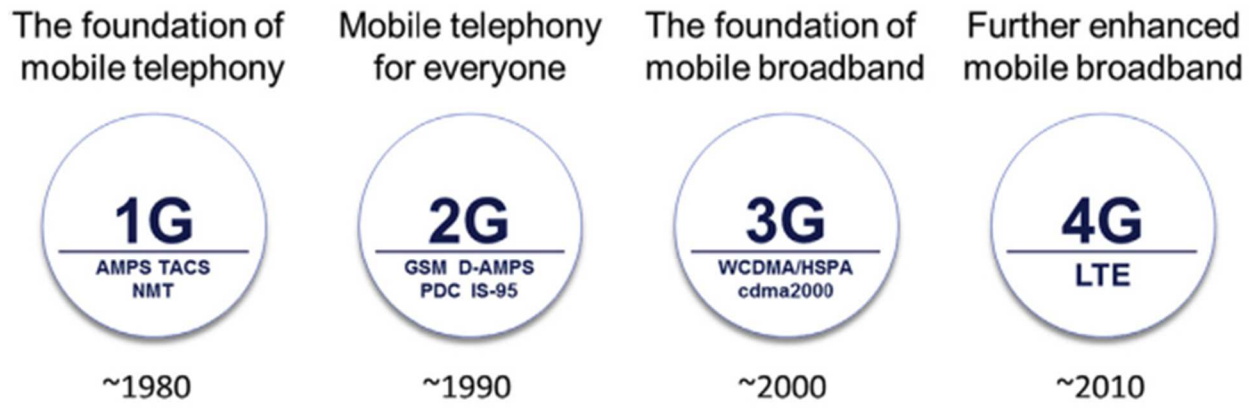


FIGURE 1.1

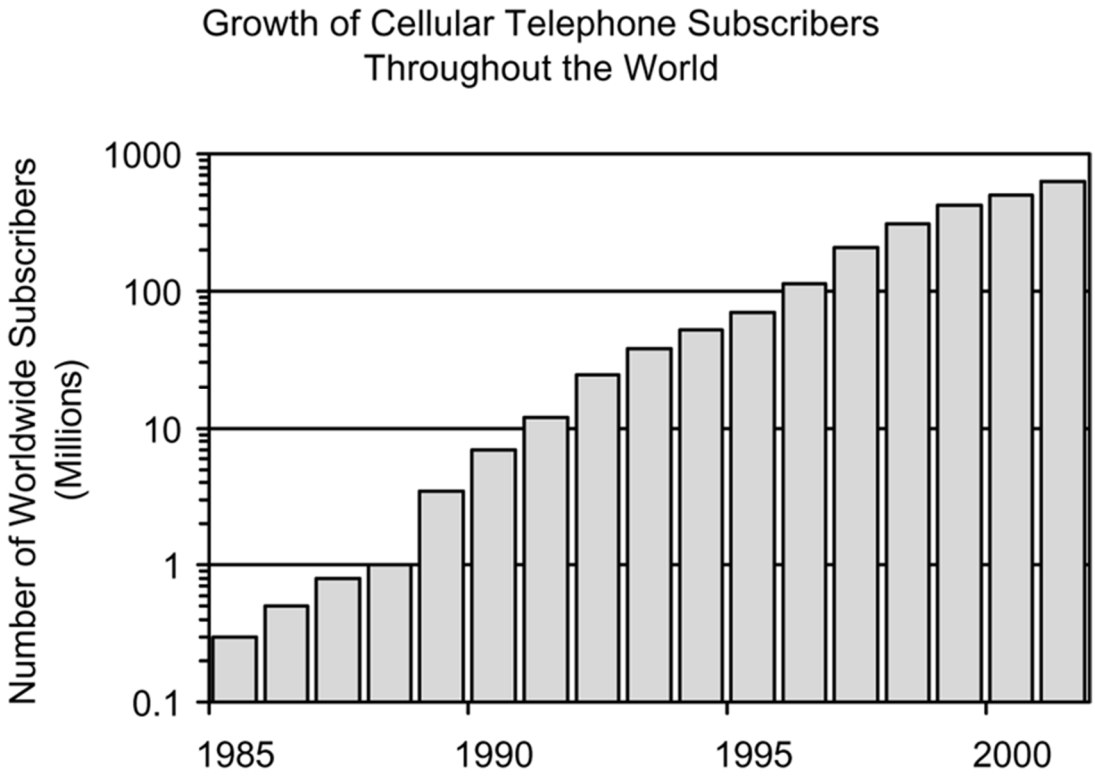
The different generations of mobile communication.

E. Dahlman et al, 5G NR: The Next Generation Wireless Access Technology, Academic Press, 2020.

1G to 5G Road

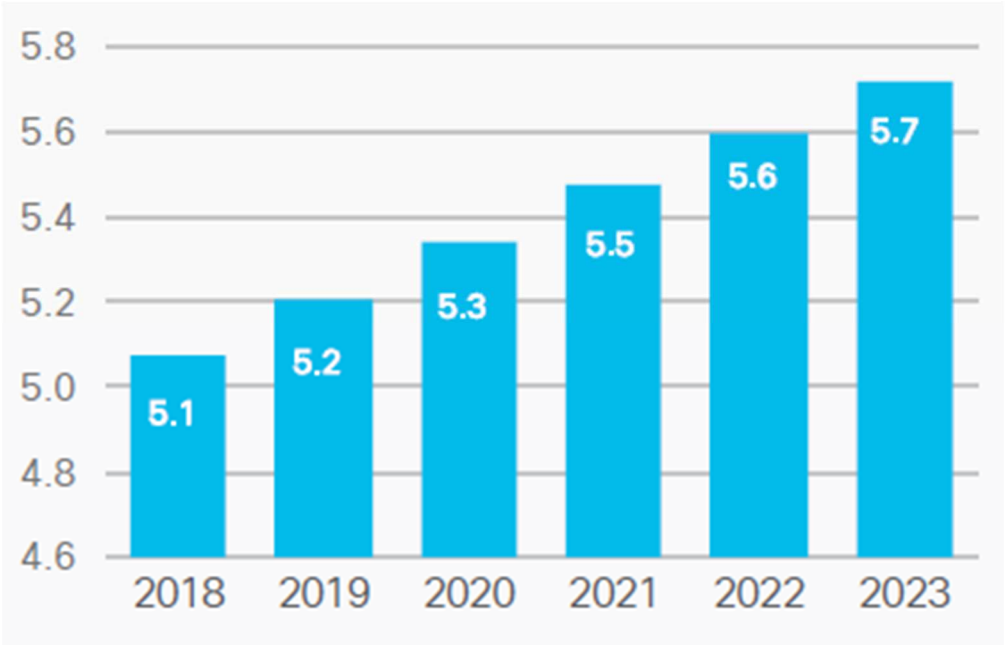
Standard	Year	Service	Data rate	Multiple access	Modulation	Bandwidth	Carrier
1G	1980s	voice	n/a	FDMA	Analog FM	30 kHz	450-900 MHz
2-2.5G	1990s	voice, data	9.6-300 kb/s	TDMA, FDMA, CDMA	BPSK, QPSK, GMSK	30 kHz – 1 MHz	0.7-2 GHz
3-3.75G	2000s	voice, Internet	0.1-20 Mb/s	W-CDMA	up to 64-QAM	1-5 MHz	0.7-2 GHz
4G	2010s	Internet	15-300 Mb/s	OFDMA, SDMA	up to 64-QAM	1-20 MHz	0.7-2.7GHz
5G	2020	Internet	50 Mb/s - 10 Gb/s	OFDMA, SDMA, NOMA	up to 256-QAM	5 - 400 MHz	0.4-6, 24-70 GHz

Some time ago (when the course textbook was published)

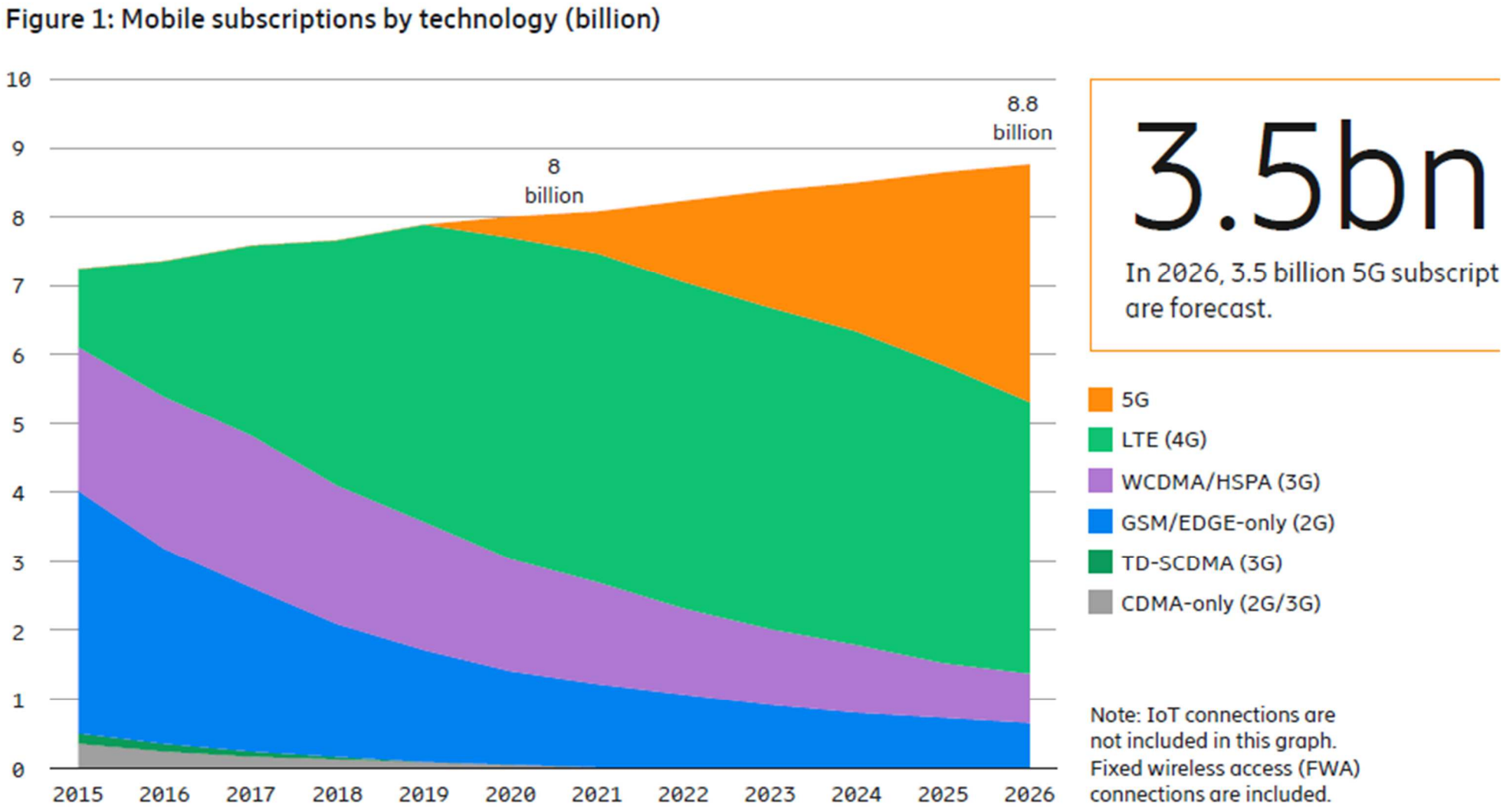


T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

and now...[billions]..

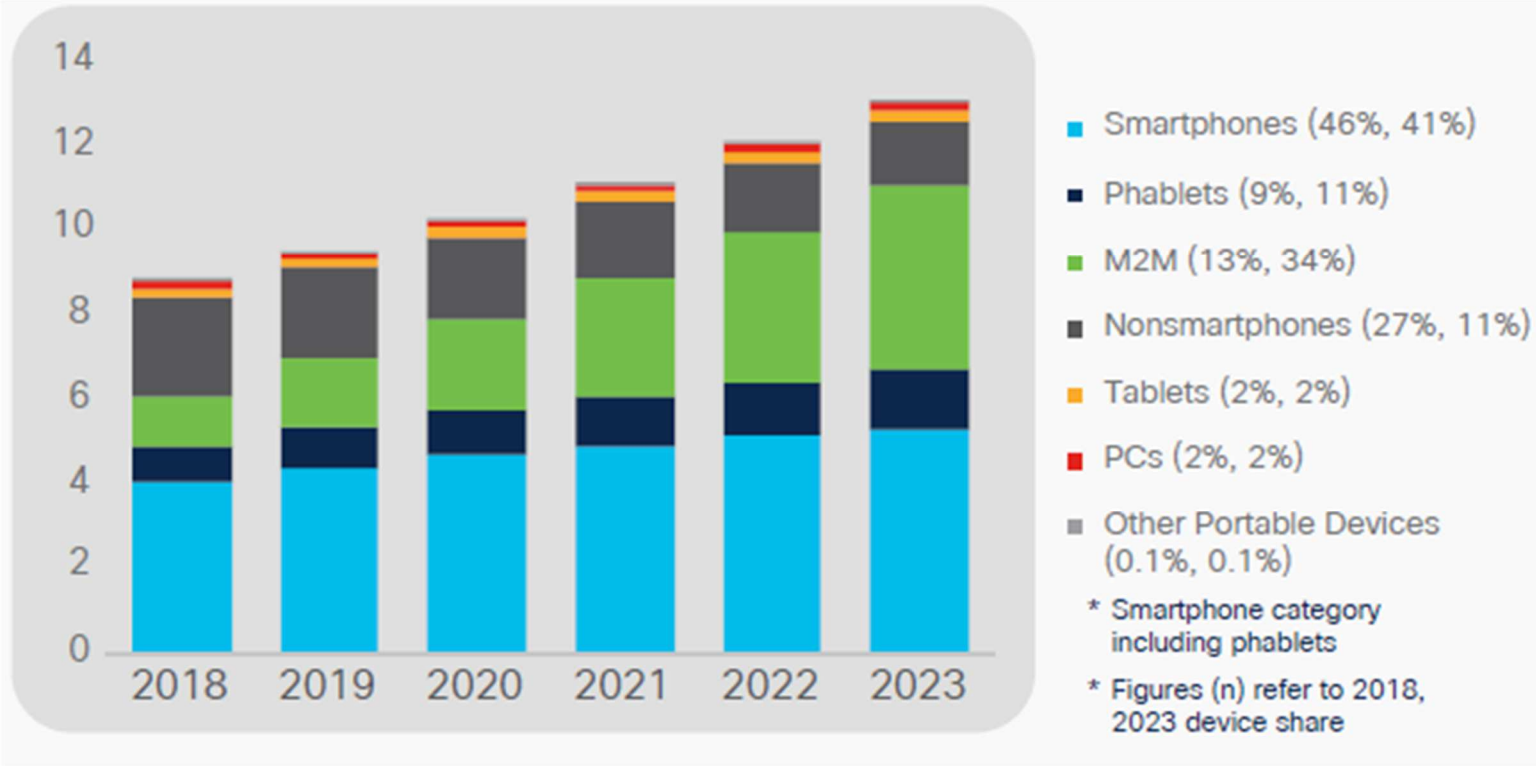


Cisco Annual Internet Report, 2018–2023



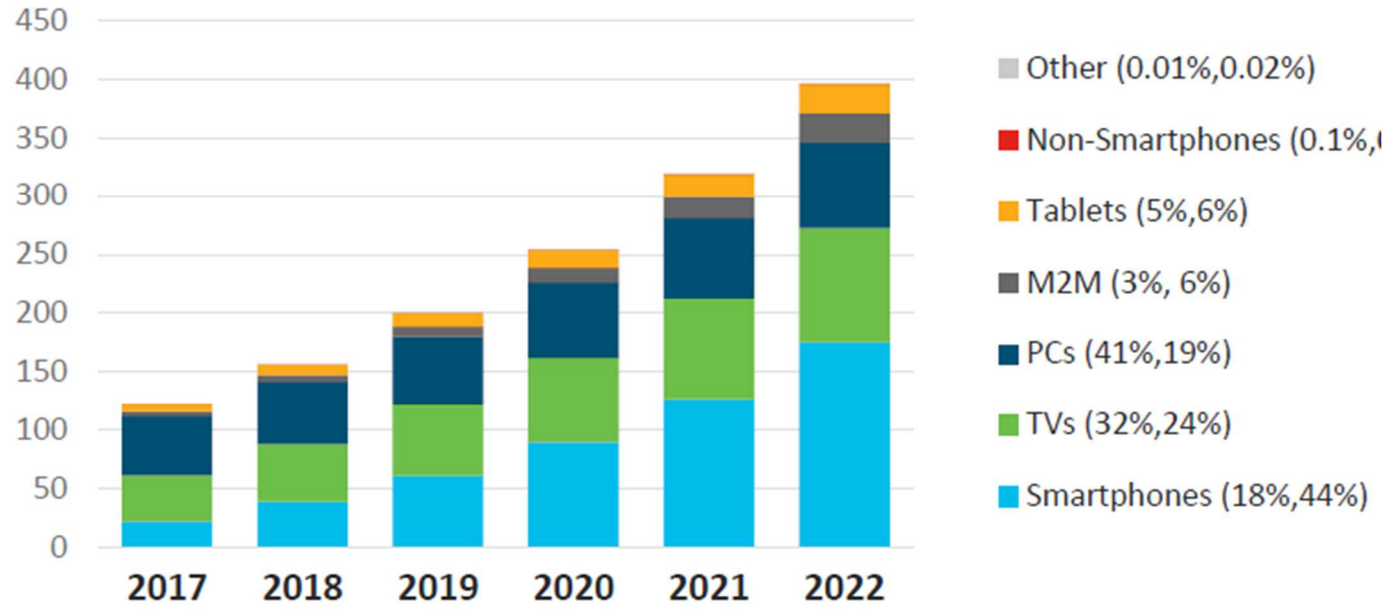
Ericsson Mobility Report, June 2021.

Global mobile devices [billions]

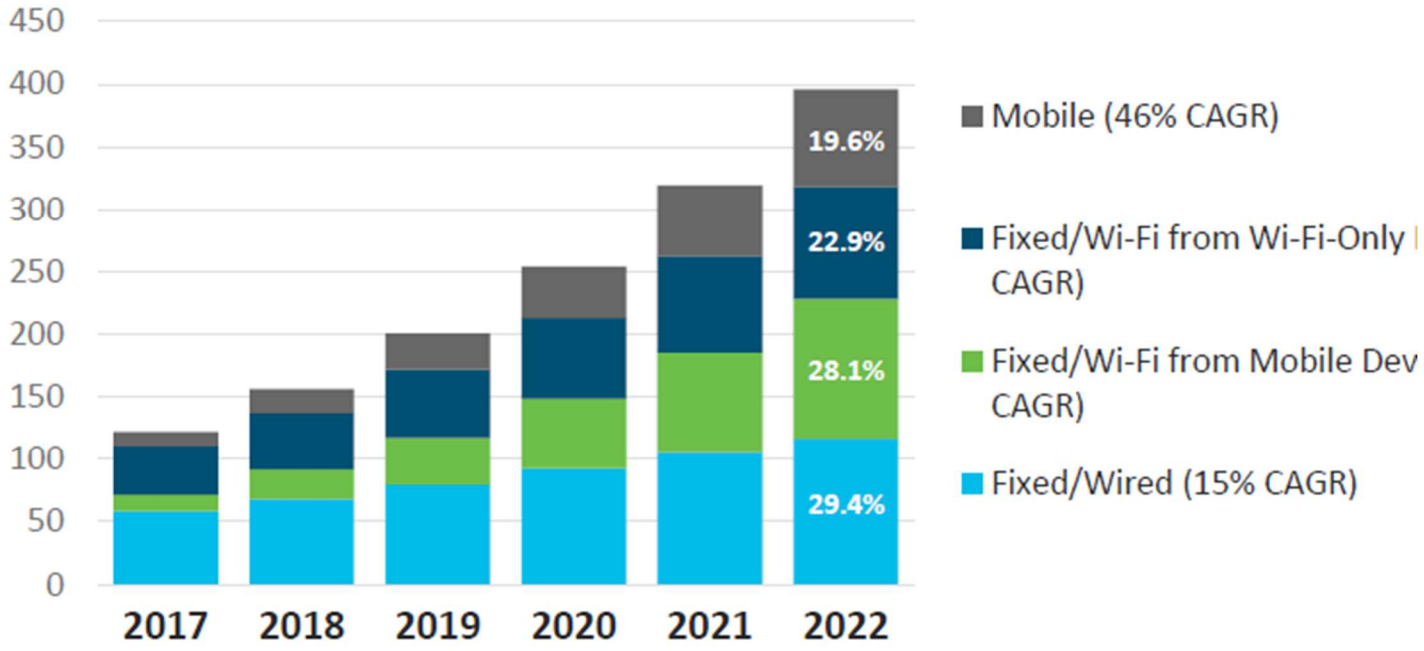


Cisco Annual Internet Report, 2018–2023

Global IP Traffic [Exabytes per Month]



By 2022, 71% of total IP traffic will be wireless (cellular + WiFi)



Cisco VNI Global IP Traffic Forecast, 2017–2022

Table 1. The Cisco VNI forecast: historical Internet context

Year	Global internet traffic
1992	100 GB per day
1997	100 GB per hour
2002	100 GB per second
2007	2,000 GB per second
2017	46,600 GB per second
2022	150,700 GB per second

Source: Cisco VNI, 2018.

Cellular System Standards

- **1st generation (1G)**: FDMA + Analog FM. Developed in early 1980s. Japan-NTT (1979), Europe-NMT-900 (1981), US-AMPS (AT&T), 1983

  $\Rightarrow$Narrowband, low-quality, voice, no additional services.

- **2nd generation (2G)**: Various systems

- Europe: GSM (TDMA, low-rate data services (up to 9.6 kb/s), deployed in 1992), uses GMSK; 800-900MHz, $\Delta f = 200KHz$, 8 users/channel.

- North America: IS-54/136 and IS-95 (TDMA and CDMA), DQPSK for IS-54/136 (IS-54/136: 800/1800/1900 MHz, DQPSK, $\Delta f = 30KHz$, 4 users/channel), and PN-CDMA for IS-95, adopted and deployed in 1990-1992 ($\Delta f = 1.25MHz$, 64 users, 800/900MHz, 1900/ 1900MHz BPSK)

- Japan: PDC (Personal Digital Cellular) similar to IS-54/136. Important—MS antenna diversity is possible.

All of them support up to **9.6kb/s** data.

- **2.5G system**: improvement of 2G system to allow for better data services (faster, email, internet). 2G systems were developed before internet - do not fit in well.
  - IS-95B for 2.5G CDMA: medium data rate, up to **115.2kb/s** (in practice, up to **64kb/s**)

3G systems:

- Evolution of 2G, with enhanced data services: Internet access, voice over IP (VoIP), higher link capacity.
- Two major standards: UMTS and CDMA2000.
- Downlink rate: 0.3-2 Mb/s; uplink: 200kb/s

4G systems:

- Data rates: 10 x 3G (peak at 50-100 Mb/s, less in practice, e.g. average 5-10 Mb/s)
- Fully-integrated Internet/data services

5G systems:

- latest generation on the market (but not everywhere and not fully operational)
- still under development
- significant improvement over 4G (when fully operational)

6G systems:

- "beyond" 5G: extensive research activities

4G systems:

Optimized for high-speed data service (Internet), VoIP.

Two major standards: LTE (Long Term Evolution) and WiMax (Worldwide Interoperability for Microwave Access).

LTE Standard

Modulation: OFDM + QPSK/16QAM/64QAM, up to 20MHz bandwidth.

Rates: see below.

Table 1. LTE (FDD) downlink and uplink peak data rates from TR 25.912 V7.2.0 Tables 13.1 and 13.1a

FDD downlink peak data rates (64QAM)			
Antenna configuration	SISO	2x2 MIMO	4x4 MIMO
Peak data rate Mbps	100	172.8	326.4
FDD uplink peak data rates (single antenna)			
Modulation depth	QPSK	16QAM	64QAM
Peak data rate Mbps	50	57.6	86.4

3GPP Long Term Evolution: System Overview, Product Development, and Test Challenges. Application Note, Agilent.

Note: MIMO = multiple-input multiple-output, or multi-antenna system.

SISO = single-input single-output, or single-antenna system.

5G Systems (still under development)

- 5G: the latest wireless system standard (cellular), already on the market[1]
- Still under development
- Significant improvement over 4G (current)
  - significantly higher data rates (peak: 10 Gb/s, cell edge 100 Mb/s, almost everywhere 10Mb/s)
  - better QoS (latency < 1ms, high reliability)
  - more services
- Several key new technologies:

Millimeter waves
Hybrid networks, small cells, aggressive frequency re-use
Massive MIMO (multi-antenna)[2]

---

[1] J. G. Andrews et al, What Will 5G Be?, IEEE JSAC, vol. 32, no. 6, Jun. 2014.

* M. Shafi et al, 5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice, IEEE JSAC, Part I & II, v. 35, N.6 & 7, Jun. & Aug. 2017.

* E. Dahlman et al, 5G NR: The Next Generation Wireless Access Technology, Academic Press, 2020.

* https://en.wikipedia.org/wiki/5G

[2] Special Issue on Large-Scale Multiple Antenna Wireless Systems, IEEE JSAC, vol. 31, no. 2, Feb. 2013.

* E. G. Larsson et al, Massive MIMO for Next Generation Wireless Systems, IEEE Communications Magazine, vol. 52, no. 2, pp. 186-195, Feb. 2014.

6G Systems

- extensive research activities [3]
- not developed/implemented yet
- many uncertainties
- significant improvement over 5G (predicted)
- new application areas (predicted)
- new technologies (predicted)

[3] W. Jiang et al, The Road Towards 6G: A Comprehensive Survey, IEEE Open Journal of the Communications Society, Feb. 2021.

* H. Viswanathan, P.E. Mogensen, Communications in the 6G Era. IEEE Access, Mar. 2020.

* W. Saad et al, A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems, IEEE Network, Oct. 2019.

* Z. Zhang et al, 6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies, IEEE Veh. Tech. Magazine, July 2019.

* https://en.wikipedia.org/wiki/6G_(network)

Wireless Local Area Networks (WLANs) – WiFi

IEEE 802.11.a(b,g,n); 2.4/5 GHz

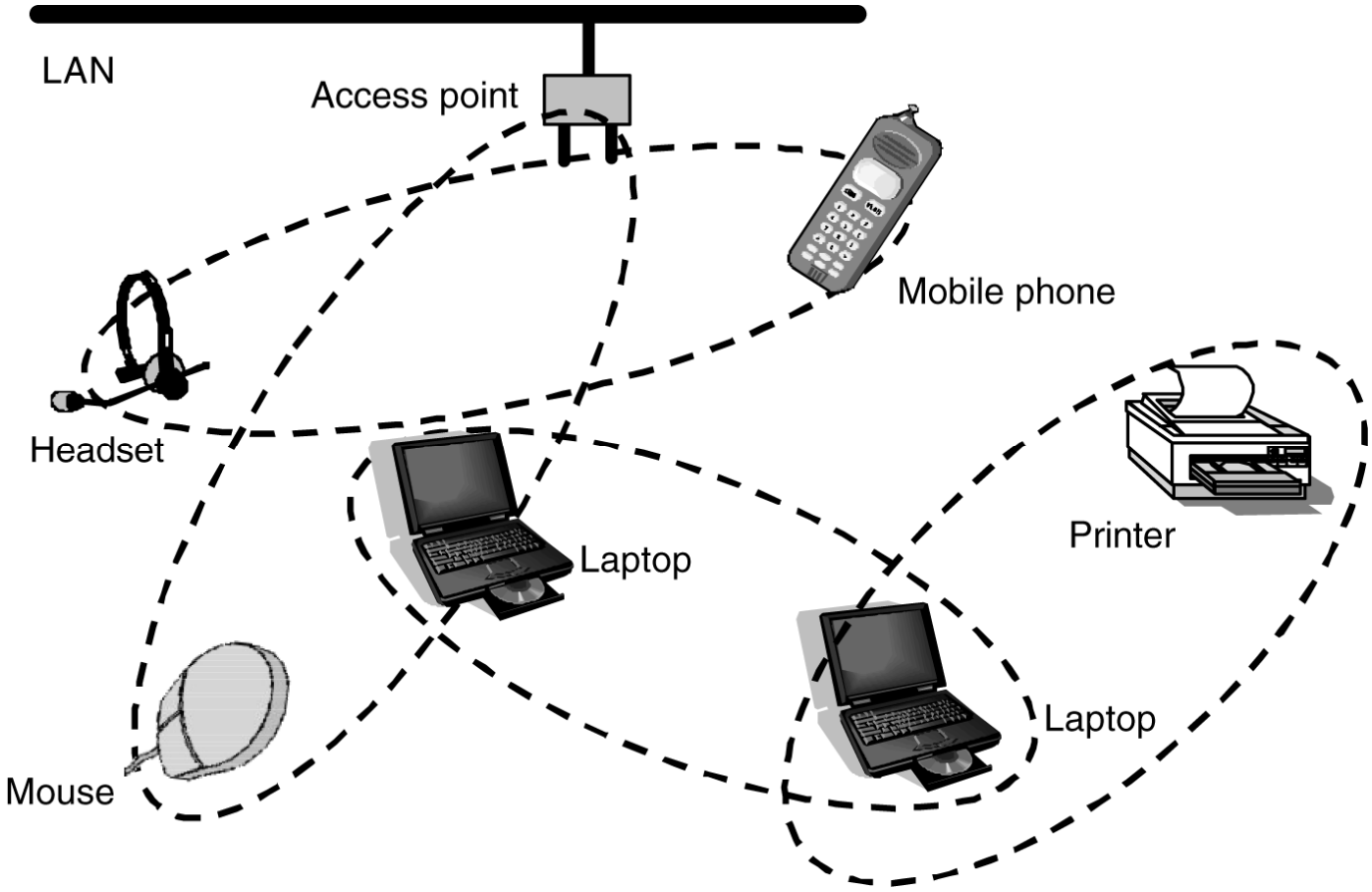
Popular WiFi Equipment

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Popular WiFi (WLAN) Equipment

- BLUETOOTH/IEEE 802.15: ad-hoc networking within 10 meter range, 2.4GHz, up to 1Mb/s
- IMT-2000: family of standard approved by ITU.

Personal Area Network – Bluetooth Standard



T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

TABLE 8–17 WIFI STANDARDS

Item	802.11a	802.11b	802.11g	802.11n
Band	5.0 GHz	2.4 GHz	2.4 GHz	2.4 GHz
Max data rate	54 Mb/s	11 Mb/s	54 Mb/s	120 MB/s
Modulation	OFDM	DSSS	OFDM	DSSS & OFDM
Bandwidth (typical)	20 MHz	20 MHz	20 MHz	20 MHz
Diversity	None	None	None	MIMO
Range (max)	500 ft	500 ft	500 ft	1,500 ft
Compatible with		802.11a	802.11b	802.11b, 802.11g

DSSS = Direct-sequence spread spectrum

MIMO = Multiple input and multiple output

Leon W. Couch II, Digital and Analog Communication Systems, Eighth Edition, Pearson Education, 2013.

IEEE 802.11n Wi-Fi (WLAN) standard

MCS Index	Type	Coding Rate	Spatial Streams	Data Rate (Mbps) with 20 MHz CH		Data Rate (Mbps) with 40 MHz CH	
				800 ns	400 ns (SGI)	800 ns	400 ns (SGI)
0	BPSK	1 / 2	1	6.50	7.20	13.50	15.00
1	QPSK	1 / 2	1	13.00	14.40	27.00	30.00
2	QPSK	3 / 4	1	19.50	21.70	40.50	45.00
3	16-QAM	1 / 2	1	26.00	28.90	54.00	60.00
4	16-QAM	3 / 4	1	39.00	43.30	81.00	90.00
5	64-QAM	2 / 3	1	52.00	57.80	108.00	120.00
6	64-QAM	3 / 4	1	58.50	65.00	121.50	135.00
7	64-QAM	5 / 6	1	65.00	72.20	135.00	150.00
8	BPSK	1 / 2	2	13.00	14.40	27.00	30.00
9	QPSK	1 / 2	2	26.00	28.90	54.00	60.00
10	QPSK	3 / 4	2	39.00	43.30	81.00	90.00
11	16-QAM	1 / 2	2	52.00	57.80	108.00	120.00
12	16-QAM	3 / 4	2	78.00	86.70	162.00	180.00
13	64-QAM	2 / 3	2	104.00	115.60	216.00	240.00
14	64-QAM	3 / 4	2	117.00	130.00	243.00	270.00
15	64-QAM	5 / 6	2	130.00	144.40	270.00	300.00
16	BPSK	1 / 2	3	19.50	21.70	40.50	45.00
...	...	...	...	...	...	...	...
31	64-QAM	5 / 6	4	260.00	288.90	540.00	600.00

802.11n Primer, Whitepaper, AirMagnet, August 05, 2008.

(n+1)G systems:

3G system rate=10*(2G rate)

4G rate=10*(3G rate).

Compatible with Internet (IP, Mobile IP, QoS).

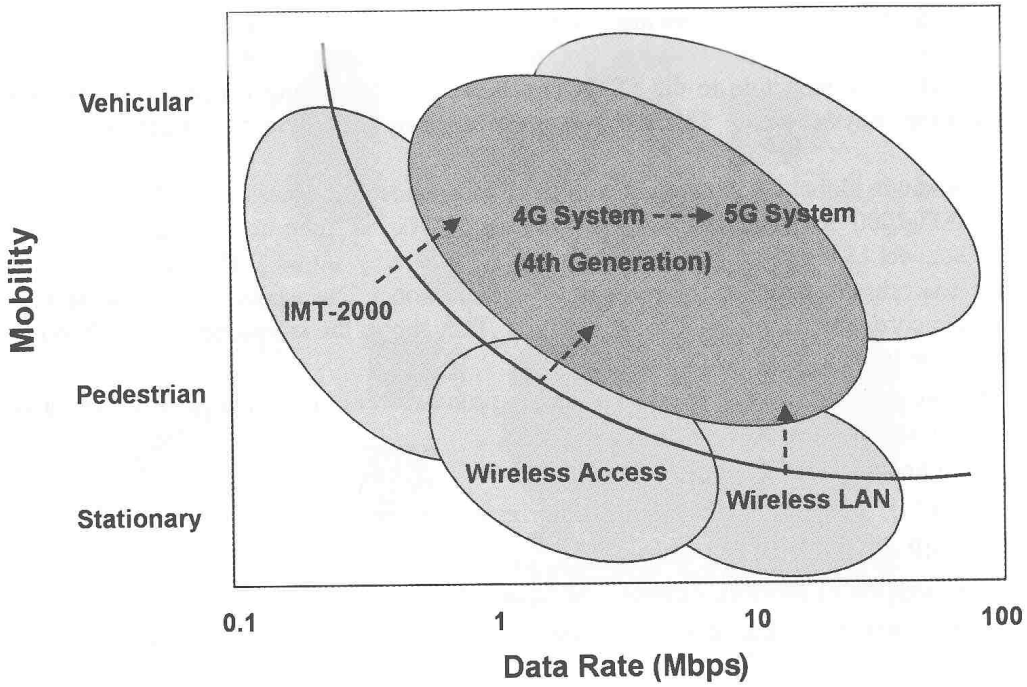


FIGURE 1.3 Mobility and bit rate perspective of 4G systems.

M. Shafi et al. Wireless Communications in the 21st Centurv. IEEE & Wilev. 2002.

A View of the Wireless World

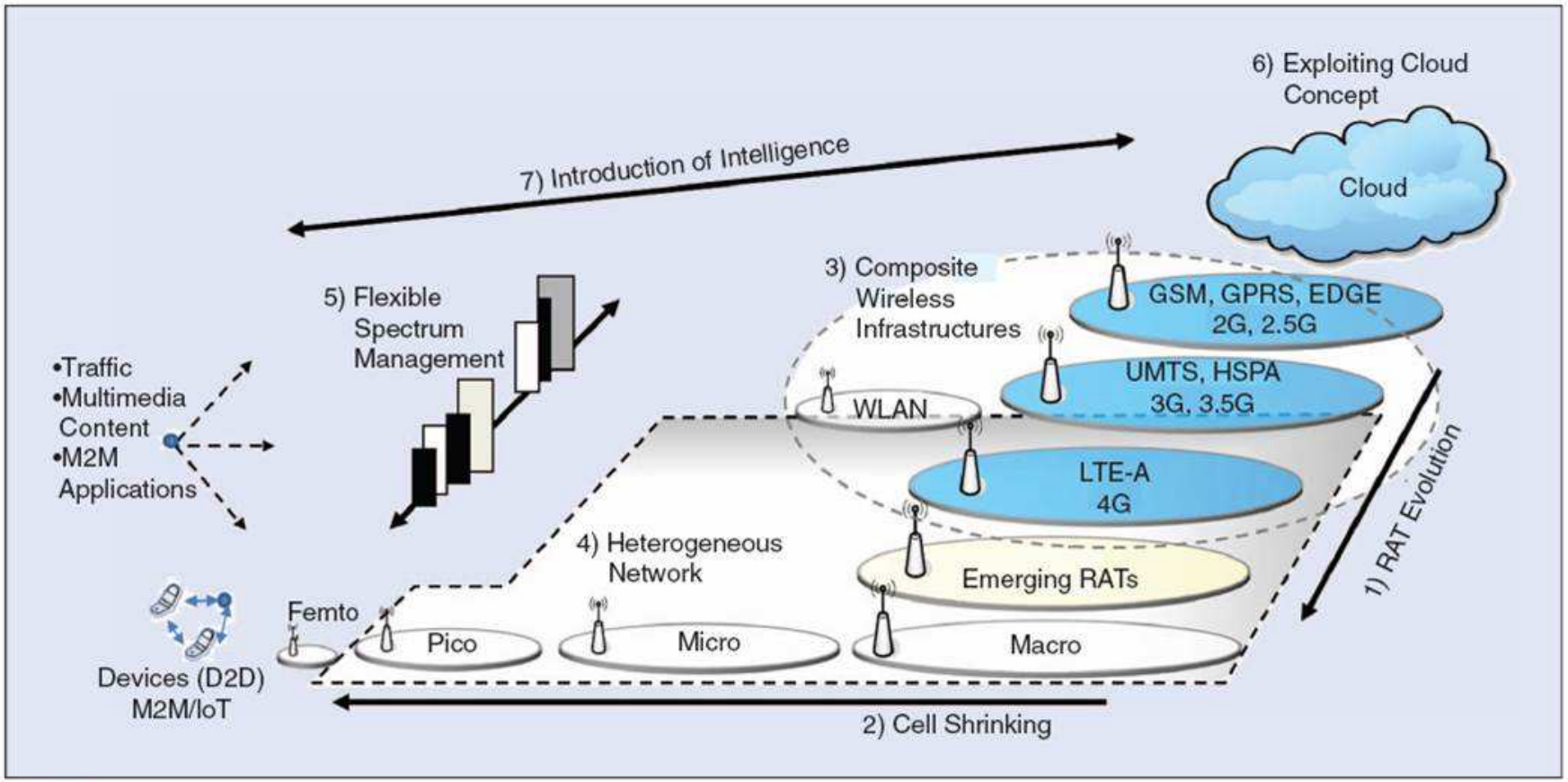


FIGURE 1 A view of the wireless world; seven technical directions aiming at the proper application provisioning, cost-efficient resource provisioning, and at the augmentation of the wireless world's intelligence. GSM: global system for mobile communications. GPRS: general packet radio service. EDGE: enhanced data rates for GSM evolution. UMTS: universal mobile telecommunications system. HSPA: high-speed packet access.

P. Demestichas et al, 5G on the Horizon, IEEE Vehicular Technology Magazine, Sep. 2013.

Wireless Networks of 21st Century

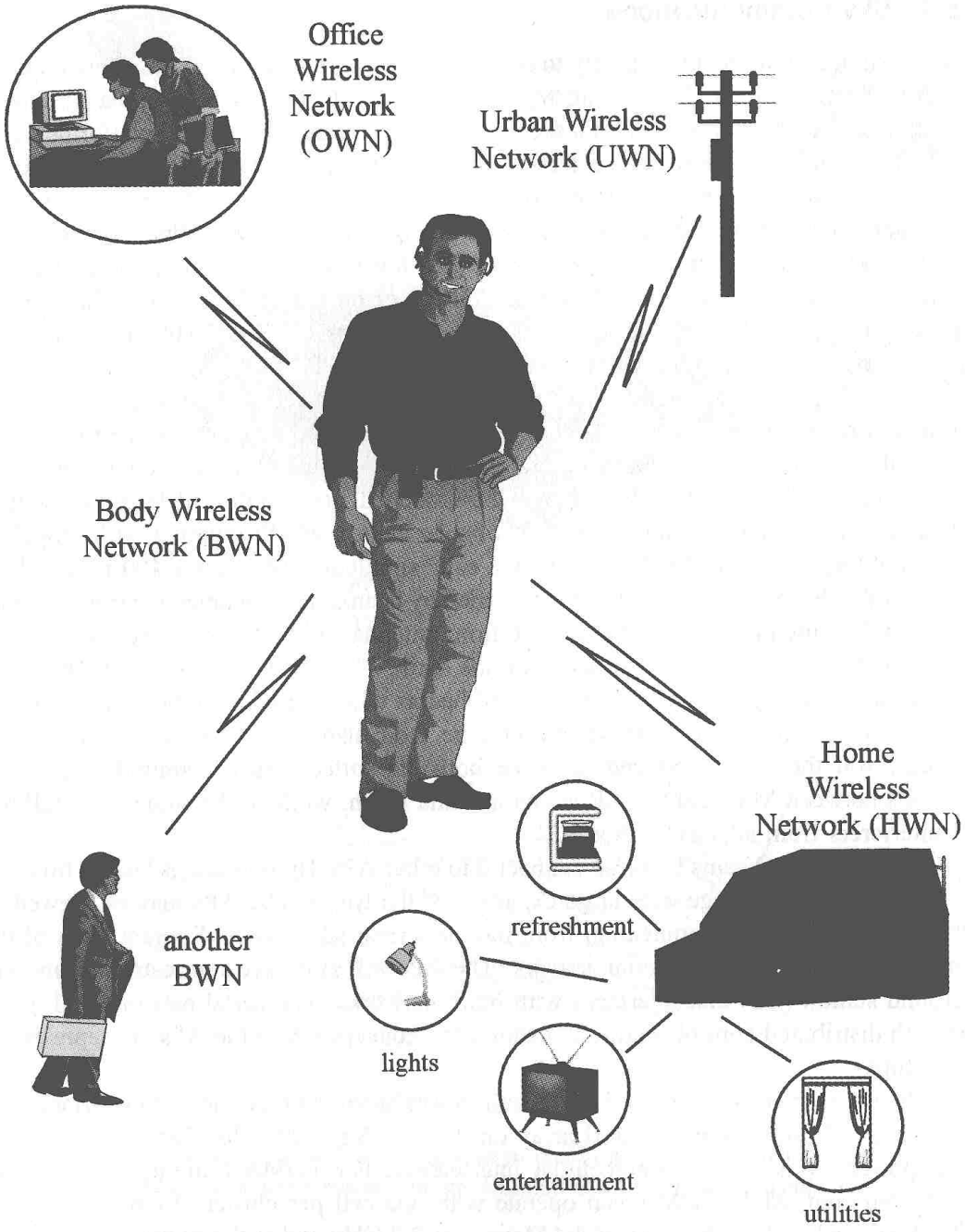


FIGURE 2.2 Some of the wireless networks of the 21st century.

M. Shafi et al. Wireless Communications in the 21st Century. IEEE & Wiley. 2002.

Cellular system

Major system components:

1) Mobile station (MS), or subscriber unit (SU), or mobile unit (MU) → e.g. a cell phone.
2) Base station (BS) (cellular operator equipment, with an antenna typically installed on a rooftop).
3) Mobile switching center (MSC) or mobile telephone switching office (MTSO) (controls multiple base stations).

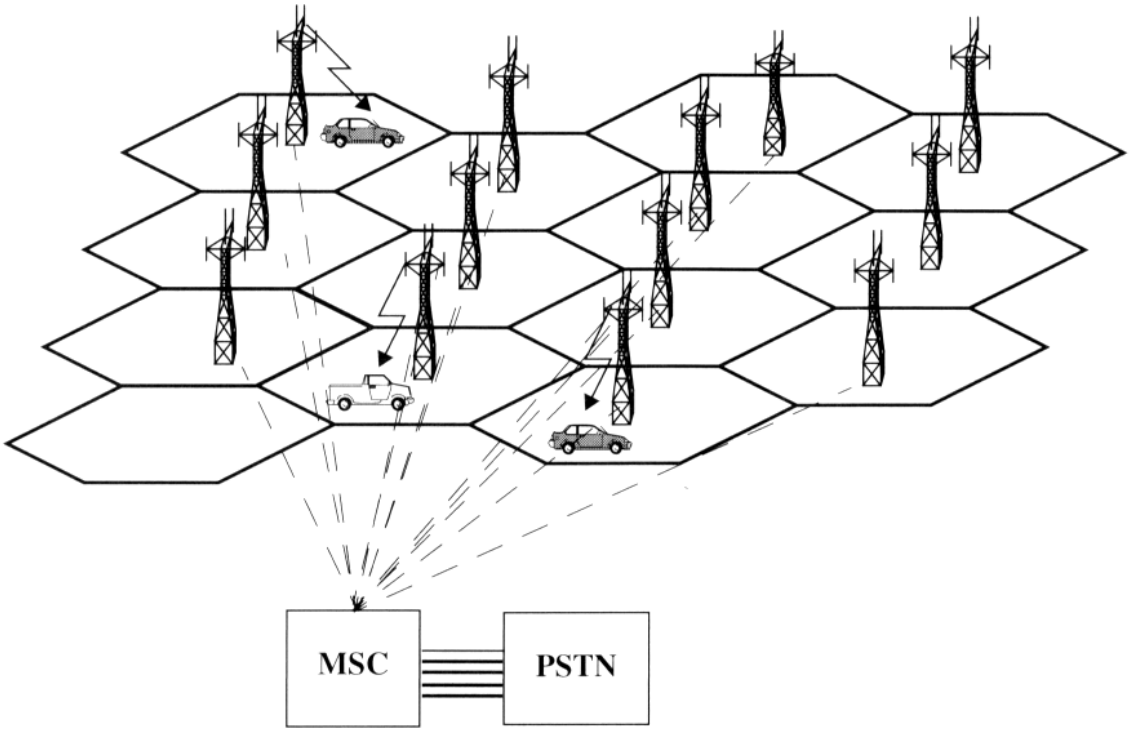


Figure 1.5 A cellular system. The towers represent base stations which provide radio access between mobile users and the mobile switching center (MSC).

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Basic terminology

- Cell: an area covered by a single base station.
- Control channel: channel used for call request, initiation, setup etc….
- Forward channel/link (downlink): a link from BS to MS.
- Reverse channel/link (uplink): a link from MS to BS.
- Simplex system: one-way communication system.
- Half-duplex system: two-way communication, but not at the same time.
- Full-duplex system: two-way communication at the same time.
- Mobile station (unit): is carried by a user.
- Base station: installed at the cell center, collects calls from all MSs in the cell.
- Mobile switching center: all BSs in a given region are connected to it. It coordinates all the BSs (hand-off) and directs calls to PSTN.
- Hand-off: transferring a MS from one BS to another.
- Roamer(ing): MS operates in a service area other than from where it was subscribed.
- Transceiver: transmitter (Tx) + receiver (Rx)
- FDD/TDD: frequency/time division duplex

Summary

- Examples of wireless communication systems
- Historical background
- 1G, 2G, 2.5G, 3G, 4G and 5G systems.
- Different standards. Examples.
- Cellular systems. Basic terminology.

Reading/References

- Rappaport, Ch. 1-3.
- Your ELG3175/ELG4176 textbook
- Other books (see the reference list).

Note: Do not forget to do end-of-chapter problems. Remember the learning efficiency pyramid!