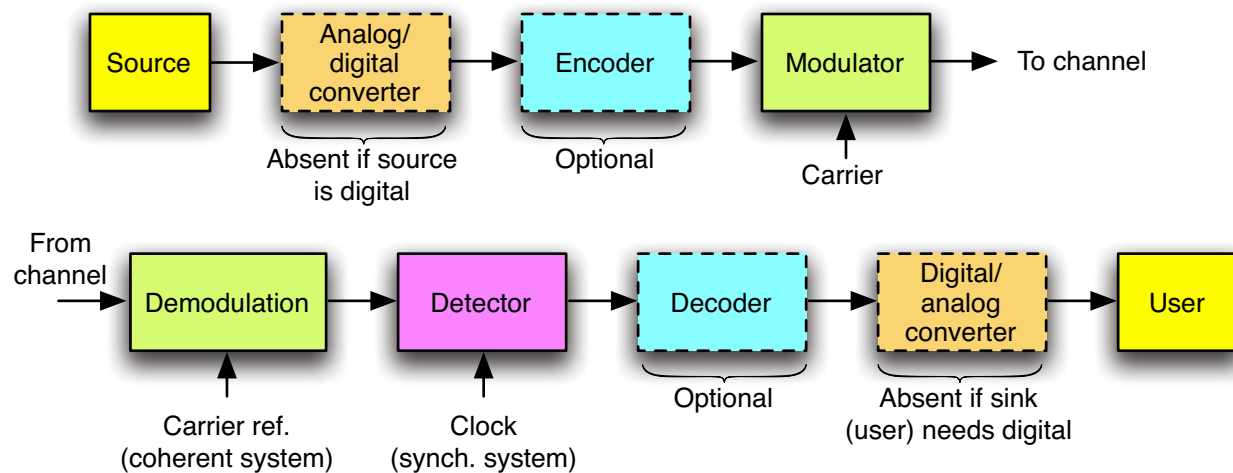


Communication Systems II

ECE 5630/4630 Lecture Notes Fall 2021



Chapter 1

Course Introduction/Overview

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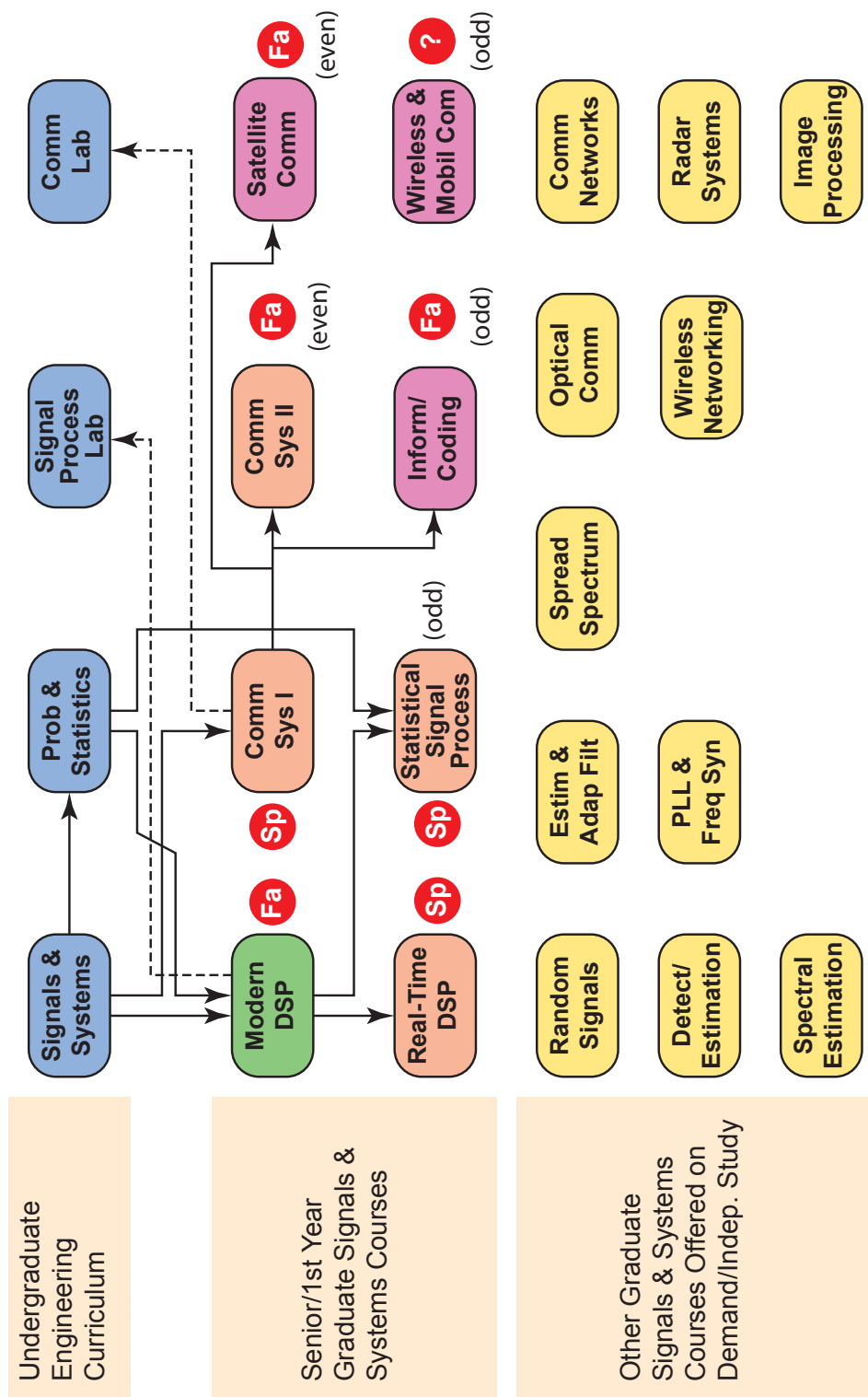
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1.1 Introduction

- Where are we in the ugrad and grad curriculum?
- Course topics
- Course Syllabus
- Instructor policies
- Software tools
- Hardware demos/hardware lab?
- Digital communications systems overview

1.2 Course Perspective in Comm/DSP Area ECE



1.3 Comm II Course Topics

- A lot can be said on the topic of digital communications theory and application
- This being an introductory course on digital comm, the desire is to cover many topics; of necessity the depth will be limited on any one topic
 - To get started you will be taken through a review of probability and random variables, and then a short trip through random processes
 - The waveform aspects of digital comm bring digital signal processing (DSP) to the forefront; simulate/implement
 - There are non-waveform topics such as coding and information theory and protocols for multiple access
 - Wave propagation theory is important for mobile radio communications including statistical channel models to work into the overall modeling scene
- There are many digital comm texts to choose from; Z&T is chosen to keep costs down and allow the optional purchase of the Rice or other text as a supplement
 - Note the Rice text features DSP implementation details of digital comm and is quite detailed on carrier phase and symbol synchronization

- With the advent of low-cost software defined radio (SDR) platforms, such as the RTL-SDR, a computer project using live I/Q captures is possible
- Likewise real-time processing using the `pyaudio_helper` module of `scikit-dsp-comm` is possible at I/Q sampling rates of 48 kHz
 - Interactive control of real-time algorithms is possible in the Jupyter notebook or Jupyter Lab using the Jupyter widgets¹

¹http://conference.scipy.org/proceedings/scipy2018/mark_wickert_250.html

1.4 Course Syllabus

ECE 5630/4630

Communication Systems II

Fall Semester 2021: Columbine 216, 8:00–10:40 AM

- Instructor:** Dr. Mark Wickert **Office:** EN292 **Phone:** 255-3500
 mwickert@uccs.edu **Fax:** 255-3589
<http://ece.uccs.edu/~mwickert/ece5630/>
- Office Hrs:** Mon. 10:40-11:30 am, others by appointment, including *Daily*, *Teams*, or *Zoom*.
- Required Text:** R. Ziemer and W. Tranter, *Principles of Communications*, seventh edition, Wiley, 2014 (ISBN-13: 978-1118078914). Full course notes available on the course Web Site with password.
- Optional Text:** M. Rice, *Digital Communications A Discrete-Time Approach*, Prentice Hall, 2009 (ISBN 978-0-13-030497-1). Used for emphasis on DSP implementation.
- Optional Software:** Scientific Python via the Jupyter notebook (installed with <https://anaconda.org/anaconda/python>). Julia with Pluto notebook is very nice. Mathematica?
- Grading:**
- 1.) Graded homework assignments, including the use of Python (or MATLAB or Mathematica OK too) in problem solutions + Python project 1; 25%.
 - 2.) Final Python computer project worth 20%/15%. Grade option with final.
 - 3.) Two "Hour" exams at 15% each, 30% total. One take-home likely.
 - 4.) Final exam worth 25%/30%. A take-home likely.

Topics	Text Sections
1. Introduction and course overview	1.1–1.5
2. Review of Probability and Random Variables	6.1–6.4
3. Introduction to Random Processes	7.1–7.5
4. Principles of Baseband Digital Data Transmission	5.1–5.8
5. Principles of Data Transmission in Noise	9.1–9.9
6. Advanced Data Communications (includes wireless comm and the mobile radio channel)	10.1–10.6
7. Information Theory and Coding	12.1–12.8

Important Deadlines: Review the Fall 2021 deadlines: <https://www.uccs.edu/registrar/course-deadlines/fall-2021>. Performance histograms (HW, Quiz, & Exams) will be discussed in class prior to the last day to drop, Friday October 29. Use this to decide on continuing or dropping the course – the deadline for dropping without ECE Chair signature (**NOT the Dean as stated in the link above**) is October 29. Only under **extenuating circumstances** will a late drop be considered.

Learning Outcomes

The expected learning outcomes of this course are a continuation of ECE4625/5625. In this course the learning experience will focus on a quick review of probability and random variables; an introduction to random processes, with an emphasis on continuous-time modeling; various forms of digital modulation and demodulation; adaptive equalization; error correcting code performance in noise; introduction to spread spectrum and mobile radio. Simulation in general and specifically waveform level simulation of digital communication systems.

Covid 19 & Face Coverings

All students are expected to wear face coverings while inside all UCCS buildings/facilities. Guidance and exceptions to wearing a face covering can be [read in the full executive order](#). Students may be asked to leave the class if they are not wearing a face covering and additional disciplinary action may result in accordance with the Student Code of Conduct.

Installing Scientific Python & scikit-dsp-comm

Download and Install the Anaconda Python ≥ 3.8 Distribution: <https://anaconda.org/anaconda/python>. Do not choose the defaults! I recommend you have Anaconda configure paths to the tools. This is not the default. Jupyter Notebook, QT Console, and Jupyter Lab will be installed with the Anaconda distribution, but more formation can be found at: <http://ipython.org/>. You will then Conda or PIP install scikit-dsp-comm, i.e., from your terminal (say Powershell) type

```
> conda install scikit-dsp-comm or
> pip install scikit-dsp-comm
```

Note: Jupyter notebook is the perfect place to write code, document code, write text using markdown, import figures, and typeset math equations using LaTeX syntax. The latest version of Jupyter Lab includes a debugged right Web browser environment. Very nice!

Optionally Download and Install a code development environment that also integrates git version control such as Visual Studio Code (VS Code): <https://code.visualstudio.com/> or PyCharm Community Edition IDE for Python: <https://www.jetbrains.com/pycharm/>.

Notebook to markdown, edit, PDF print

Install Typora: The markdown editor is at: <https://typora.io/>. Now you can export Jupyter notebooks as *.md and then open the file in Typora and save to PDF directly. You can also do some nice file editing if need be. Custom Header/footer, page numbers, etc. If need be **install Pandoc** for file conversion to LaTeX and other formats: <https://pandoc.org/index.html>.

- Alternative scientific Python installs are possible: [miniconda](#) and virtual environments (my favorite); install [Thonny](#) and use it's visual package manager to install scientific Python packages (I have used on Windows and Ubuntu Linux OK)
- For Julia I have used [Chocolatey](#) on Windows and [Homebrew](#) on Mac OS; both of these make upgrading versions easy

1.5 Instructor Policies

- Homework papers are due at the start of class
- If business travel or similar activities prevent you from attending class and turning in your homework, please inform me beforehand
- Grading is done on a straight 90, 80, 70, ... scale with curving below these thresholds if needed
- Homework solutions will be placed on the course Web site in PDF format with security password required; hints pages may also be provided

1.6 Software Tools

A combination of open-source and some commercial tools will be used in the course. The emphasis will be on the use of open-source tools.

- System Modeling & Analysis Aids
 - The tool emphasized in this course is open-source Python (the Scipy *stack* and the Jupyter Notebook/Jupyter Lab) see www.ipython.org
 - The use of `scipy.stats` will prove useful in the early parts of the course, as well as symbolic Python, via `sympy`
 - A great new open source alternative is Julia with Pluto notebook; with the `PyCall` and `Conda` packages you can bring Python nicely inside Julia (watch for demos in class)
 - Commercial software such as MATLAB and Mathematica are also very helpful, and at least for now still integrated into the course notes
- Transceiver with Channel Model System Simulation
 - The use of Python is again convenient, especially with the addition of the modules found in `scikits-dsp-comm`²
 - Considerably faster execution time is possible using Julia so this may be utilized if a large number of bits/symbols must be simulated
 - For even greater execution speed one may consider C/C++

²<http://scikit-dsp-comm.readthedocs.io/en/latest/?badge=latest>

1.7 A Digital Comm Lab Experiment?

- Exposure to digital communications hardware is also possible
 - The [RTL-SDR](#) implements a low-cost (\$25) software defined radio (SDR) receiver
 - See [ECE 4670 lab experiment #6](#) written for ECE 4670 makes use of the RTL-SDR
 - The Analog devices [Pluto](#) is an SDR transceiver (\$200)
 - RT-Logic (Kratos) donated a *channel simulator* which is capable of introducing common signal impairments;
- Besides 6 GHz Keysight FieldFox spectrum and network analyzers, the lab is equipped with a vector signal generator (Rohde-Schwarz SMIQ) with full digital modulation capability
- The RTL-SDR can be configured to receive digital comm signals from the SMIQ or the Pluto
- In this line we see how the Pluto was used in the [Final exam for ECE 4675/5675](#), Spring 2020
- In the above the `scikit-dsp-comm` module synchronization was used for its carrier and symbol timing synchronization algorithms

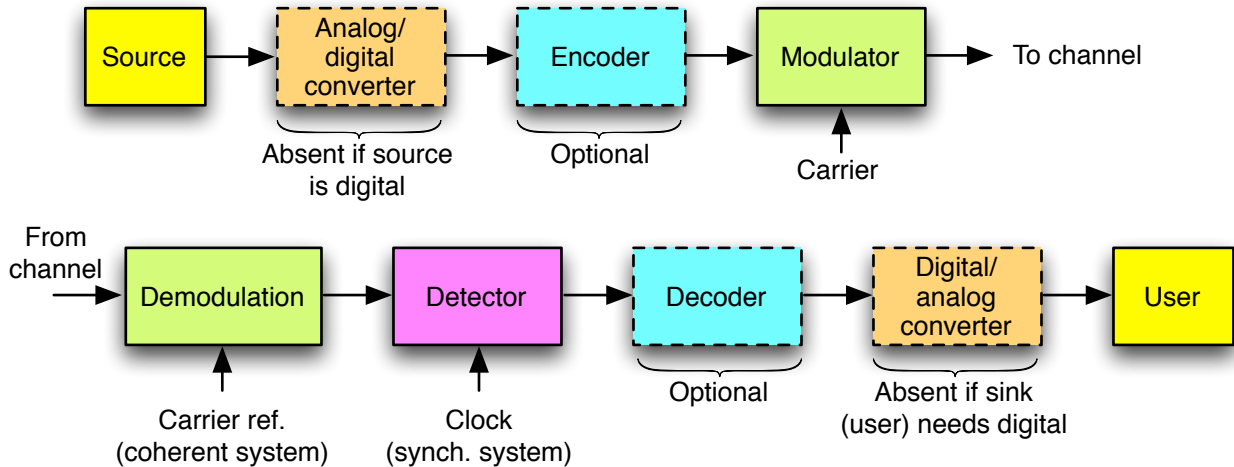
1.8 Course Introduction and Overview

- “The theory of systems for the conveyance of information”
- Communication systems must deal with uncertainty (noise and interference)
- Probability, random variables, and random processes based modeling will be used in this course
- Digital communications is the emphasis of this course
- Some important dates with respect to digital communications are:

1977	Fiber optic communication systems
1988	Asymmetric digital subscriber lines (ADSL) developed
1993	Invention of Turbo coding allows approach to Shannon limit
mid-1990's	Second generation (2G) cellular systems fielded
1996	All-digital phone systems result in modem with 56k download speed
late-1990's	Widespread usage of Internet for commercial apps
2001	Fielding of 3G cellular begins. WiFi begins
2000s	Wireless sensor networks begin to find a place in civilian applications
2002	RIM introduces Blackberry <i>smartphone</i> optimized for wireless e-mail
2007	Apple introduces iPhone & the <i>App Store</i> in 2008

1.9 A Block Diagram

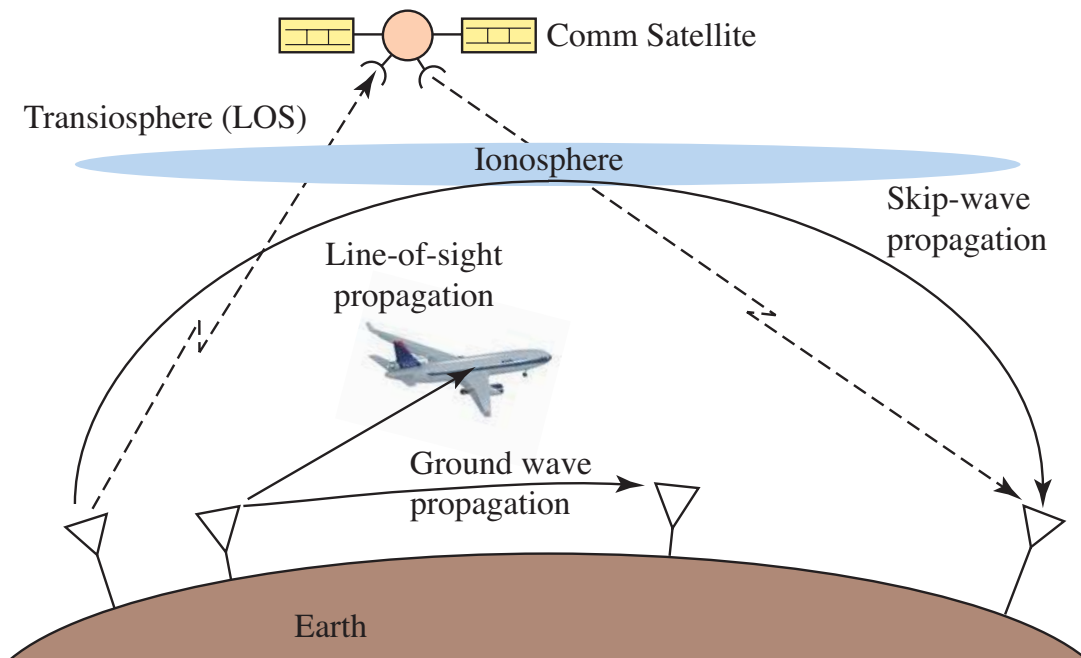
- A high level communication systems are typically described using a block diagram



- There is an information source as the input and an information sink to receive the output
- The block diagram shown above is very general
 - The source may be digital or analog
 - The transmission may be at baseband or on a radio frequency (RF) carrier as depicted here
 - The channel can take on many possible forms
 - * The channel adds noise and interference
 - * The channel may also impart multiplicative effects and be time varying

1.10 Channel Types

1.10.1 Electromagnetic-wave (EM-wave) propagation



- When you think wireless communications this is the channel type most utilized
- The electromagnetic spectrum is a natural resource
- The above figure depicts several propagation modes
 - Lower frequencies/long wavelengths tend to follow the earth's surface
 - Higher frequencies/short wavelengths tend to propagate in straight lines
- Reflection of radio waves by the ionosphere occurs for frequencies below about 100 MHz (more so at night)

Frequency Bands and Their Designations (Z&T)

Frequency band	Name
3–30 kHz	Very low frequency (VLF)
30–300 kHz	Low frequency (LF)
300–3000 kHz	Medium frequency (MF)
3–30 MHz	High frequency (HF)
30–300 MHz	Very high frequency (VHF)
0.3–3 GHz	Ultrahigh frequency (UHF)
3–30 GHz	Superhigh frequency (SHF)
30–300 GHz	Extremely high frequency (EHF)
43–430 THz	Infrared ($0.7\text{--}7\text{ }\mu\text{m}$)
430–750 THz	Visible light ($0.4\text{--}0.7\text{ }\mu\text{m}$)
750–3000 THz	Ultraviolet ($0.1\text{--}0.4\text{ }\mu\text{m}$)

Microwave band (GHz)	Letter designation	
	Old	Current
0.5–1.0		C
1.0–2.0	L	D
2.0–3.0	S	E
3.0–4.0	S	F
4.0–6.0	C	G
6.0–8.0	C	H
8.0–10.0	X	I
10.0–12.4	X	J
12.4–18.0	Ku	J
18.0–20.0	K	J
20.0–26.5	K	K
26.5–40.0	Ka	K

- There is a hierarchy of organizations that regulate how the available spectrum is allocated
 - Worldwide there is the *International Telecommunications Union* (ITU), which convenes regional and worldwide *Administrative Radio Conferences* (RARC & WARC)
 - Within the United States we have the *Federal Communications Commission* (FCC) and the National Telecommunications and Information Administration (NTIA)

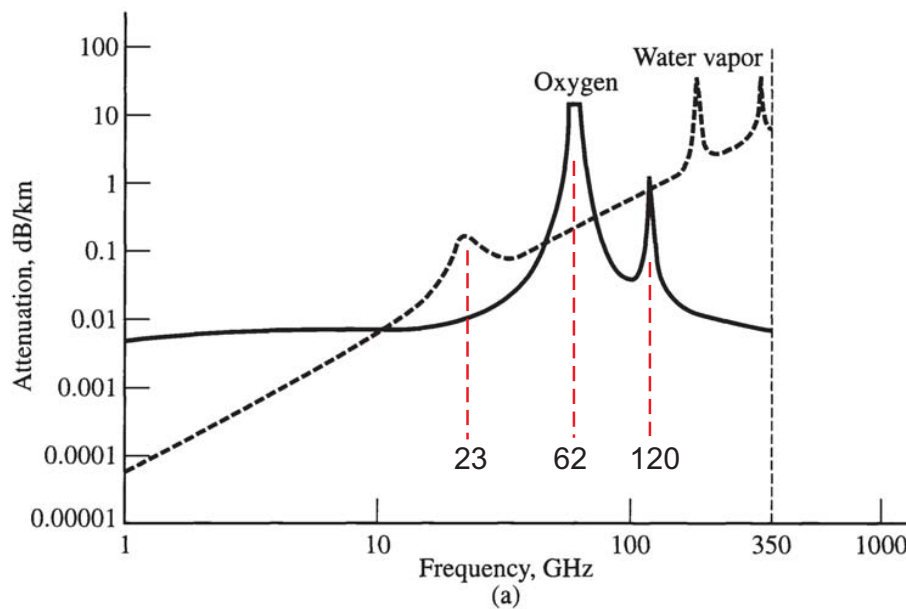
<http://www.ntia.doc.gov/osmhome/osmhome.html>

<http://www.ntia.doc.gov/osmhome/allochrt.html>

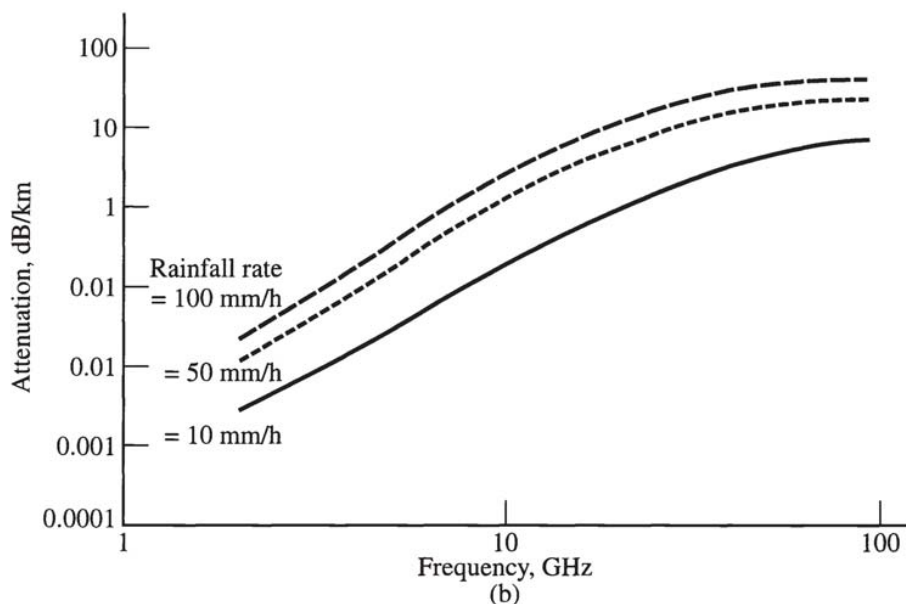
Use		Frequency
Omega navigation		10–14 kHz
Worldwide submarine communication		30 kHz
Loran C navigation		100 kHz
Standard (AM) broadcast		540–1600 kHz
ISM band	Industrial heaters; welders	40.66–40.7 MHz
Television:	Channels 2–4	54–72 MHz
	Channels 5–6	76–88 MHz
FM broadcast		88–108 MHz
Television	Channels 7–13	174–216 MHz
	Channels 14–83	420–890 MHz
	(In the United States, channels 2–36 and 38–51 will be used for digital TV broadcast; others will be reallocated.)	
Cellular mobile radio (plus other bands in the vicinity of 900 MHz)	Mobile to base station	824–849 MHz
	Base station to mobile	869–894 MHz
ISM band	Microwave ovens; medical	902–928 MHz
Global Positioning System		1227.6, 1575.4 MHz
Point-to-point microwave		2.11–2.13 GHz
Personal communication services	CDMA cellular in North America	1.8–2.0 GHz
Point-to-point microwave	Interconnecting base stations	2.16–2.18 GHz
ISM band	Microwave ovens; unlicensed spread spectrum; medical	2.4–2.4835 GHz
		23.6–24 GHz
		122–123 GHz
		244–246 GHz

Oxygen and Water Vapor Absorption

- At frequencies above 1–2 GHz oxygen and water vapor absorb and scatter radio waves
- Satellite communications, which use the microwave frequency bands, must account for this in what is known as the *link power budget*



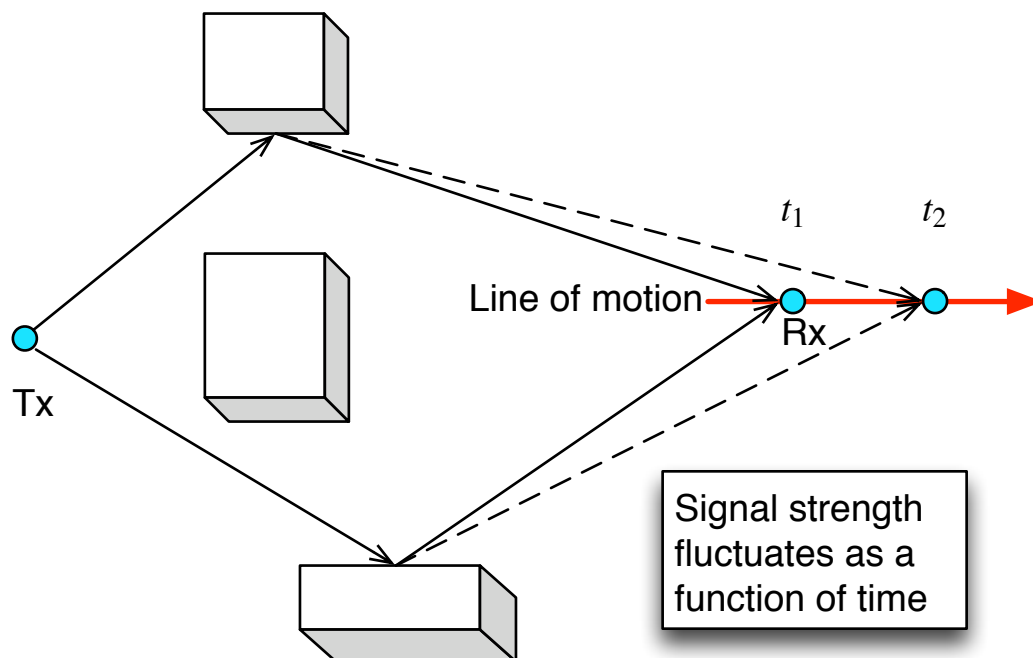
Water vapor
and oxygen
attenuation



Rainfall rate
attenuation

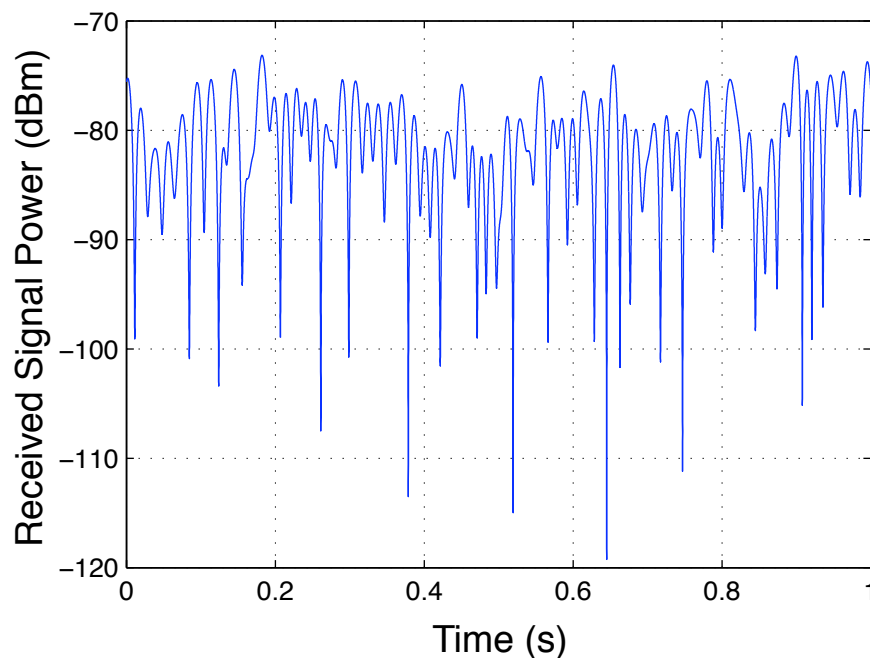
1.10.2 Mobile Radio Channel

- A very important channel model associated with free-space EM propagation is that of mobile radio, i.e., cellular telephony and wireless internet
- The free-space propagation model works well for satellite communications, but is not appropriate for terrestrial communications
- Near the surface of the earth there are many obstructions, reflectors, diffractors, and refractors that create multipath
- Physical model analysis can become quite complex, e.g., the use of ray-tracing models for a particular geometry scenario



- When talking on your cell phone or using WiFi, how often can you see the base station antenna?

- Beyond simple physical models, the complexity grows and statistical models are often employed
 - With the statistical approach an empirical model is generated based on measurements for certain environments classes, e.g., *urban*, *suburban* and *rural*
 - There are typically two parts to the model: (1) *median path loss* , (2) *local variations*



1.10.3 Guided EM-wave propagation

- Communication using transmission lines such as twisted-pair and coax cable

1.10.4 Magnetic recording channel

- Disk drives, fixed (at one time flexible too)

- Video and audio

1.10.5 Optical channel

- Free-space
- Fiber-optic
- CD, DVD, Blu-ray, etc.

1.11 Digital Communications Overview

- Digital communications is used in many different application areas
- This course will stick with the basic concepts
- In the commercial world we think *wireless* and are head begins to spin as we think of all the possible applications
- In the government and military sector we think of all the systems deployed for national security
- Consider the recent (May 2010) text by Du and Swamy³, which covers the following topics in one 950+ page text:
 - Channel and propagation
 - Cellular and multiple-user systems
 - Diversity
 - Channel estimation and equalization
 - Modulation and detection
 - Spread spectrum communications
 - Orthogonal frequency division multiplexing
 - Antennas*
 - RF and microwave subsystems*
 - A/D and D/A conversions*
 - Signals and signal processing*

³Ke-Lin Du and M.N.S. Swamy, *Wireless Communications Systems*, Cambridge University Press, 2010. ISBN-13: 9780521114035

- Fundamentals of information theory
- Channel coding
- Source coding 1: speech and audio coding
- Source coding 2: Image and video coding
- Multiple antennas: smart antenna systems
- Multiple antennas: MIMO (multiple-input/multiple-output) systems
- Ultra wideband communications
- Cognitive radios
- Wireless ad hoc and sensor networks

*Unusual coverage for a traditional digital communications text

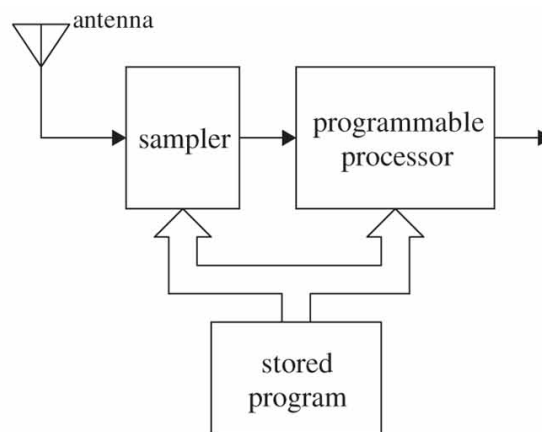
1.11.1 Digital Signal Processing Motivation

- Discrete-time signal processing is the *modern* implementation means for most digital communication systems⁴
- Note that discrete-time signal processing can be used for both analog and digital modulation/demodulation
- The transmitter requires a digital-to-analog converter (DAC) and the receiver requires an analog-to-digital converter (ADC)
- As long as the sampling theorem can be satisfied, discrete-time processing can be utilized

⁴Rice, 2008

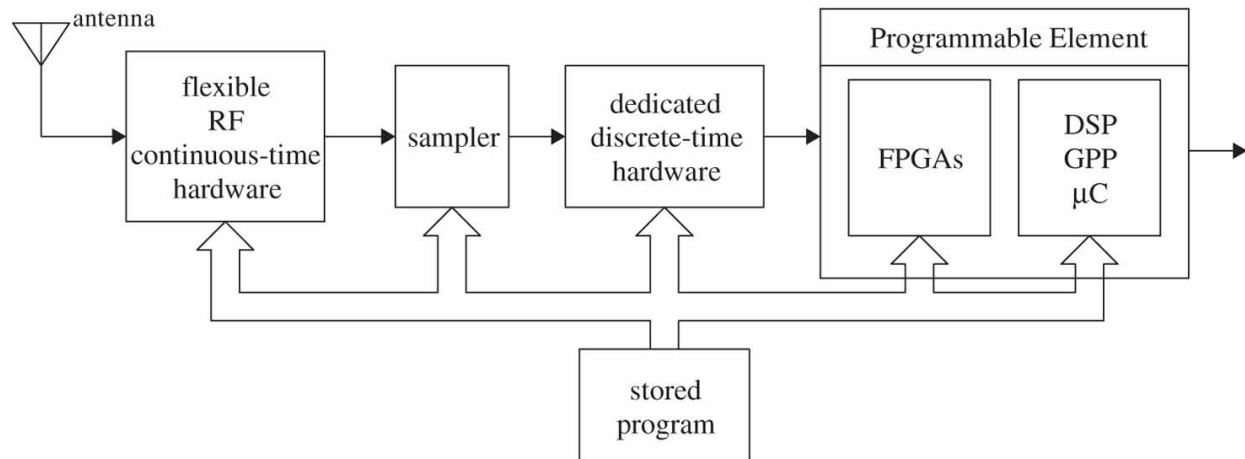
- **Advantages:**

- Improved design cycle
 - Improved manufacturing
 - Advanced signal processing techniques
 - Flexibility
- Shortened design cycles and multi-functionality are particularly true when the discrete-time processing is programmable and under software control



The Ideal *software defined radio*

- A more practical form of the software defined radio contains flexible analog (continuous-time) processing as well as dedicated discrete-time processing plus programmable processing

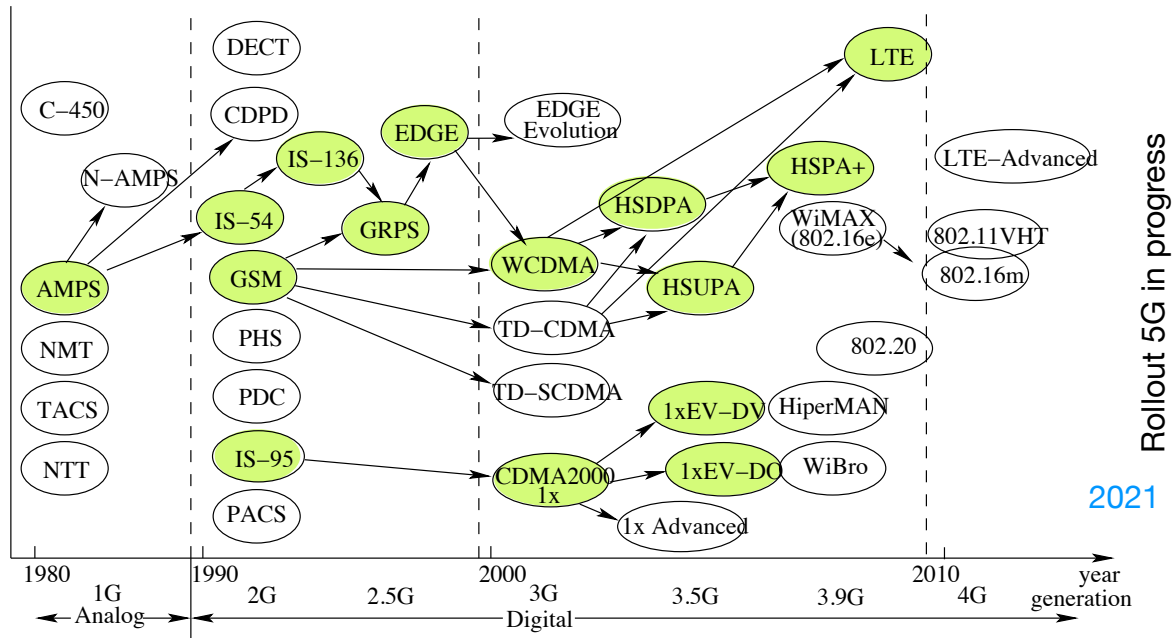


Practical/typical software defined radio

Example 1.1: Cellular Communications Roadmap⁵

- The history of world-wide cellular communications is depicted in the figure below
- The green shaded ellipses track approximately the development in the U.S.
- The ITU-R (ITU's Radio Comm. Sector) formulated 3G standards under the heading UMTS or *Universal Mobile Telecommunications System* (also known as IMT-2000), with the general requirements of 2 Mbps at stationary mobiles, 384 kbps at pedestrian speeds, and 144 kbps for moving vehicles

⁵Du and Swamy, Cambridge University Press, 2010.



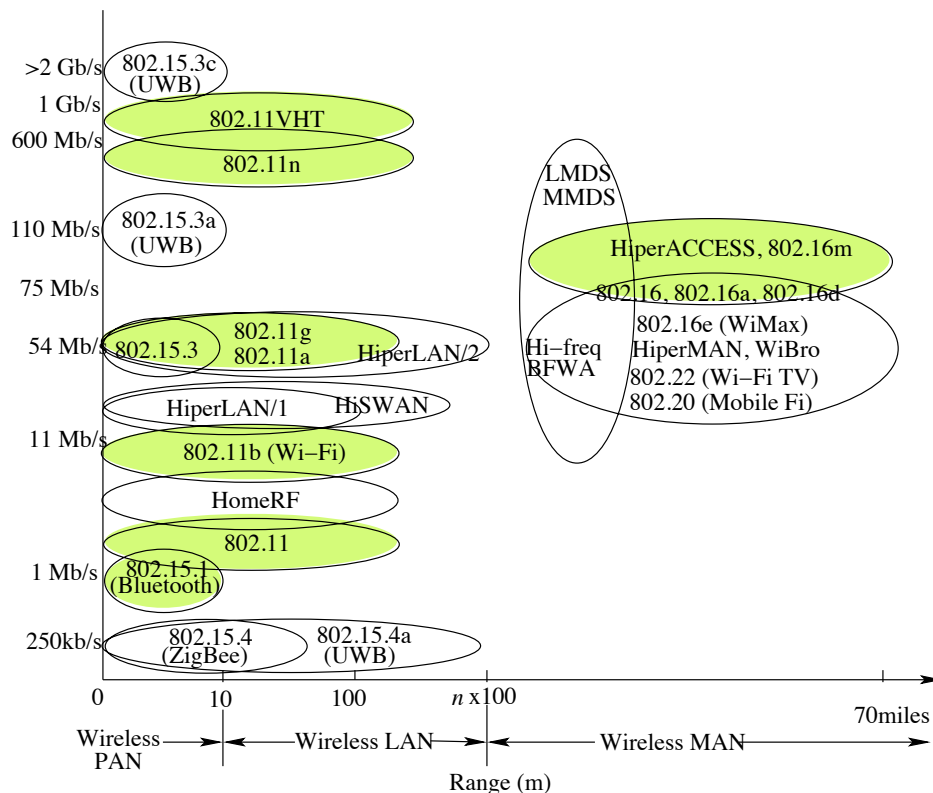
System	Description	System	Description
AMPS	Advanced mobile phone system (analog-based, 30 kHz BW)	WCDMA	Wideband CDMA also known as UTRA or UMTS Terrestrial Radio Access, (5 MHz BW, 3.84 Mcps, can support legacy GSM, up/down up to 2.3 Mbps data rates)
IS-54/ IS-136	North American Digital Cellular (TDMA, $\pi/4$ DQPSK, 30 kHz BW, 48.6 kbps, over 3 users)	CDMA 2000	Multiple carrier CDMA which evolved from IS-95, initially up to 3 carriers using BPSK, QPSK, or 8PSK, 6, 12, or 12 in future for 1.288N Mcps
GSM	Global system for Mobile Comm. TDMA with GMSK, 200 kHz BW, 270.833 kbps over 8 users)	HSPDA HSUPA (HSPA)	High-Speed Download Packet Access and High-Speed Uplink Packet Access, together High-Speed Packet Access (down: OFDM with 16QAM, up to 14.4 Mbps and up: QPSK up to 5.76 Mbps)
IS-95	Single carrier code division multiple access (CDMA) with OQPSK (1.2288 MHz BW, IS-95B provides 64 kbps)	1xEV-DO 1xEV-DV	CDMA2000 1x (phase 1) Evolution, Data Optimized, followed by Evolution, Data and Voice, together IS-856 of EIA/TIA
EDGE Evolution	Enhanced data for GSM evolution (8-PSK in same bandwidth as GSM, 384 kbps)	LTE & UMB	3GPP Long Term Evolution or E-UTRA (evolved UTRA), uses OFDM and MIMO over a 1.25 to 20 MHz BW; 3GPP2 Ultra Mobile Broadband, uses OFDMA/OFDM/CDMA/TDMA, 1.25 to 20 MHz BW, also MIMO and SDMA

- WCDMA and CDMA2000 are the mainstream 3G standards
 - 3GPP (3rd gen partnership proj.) and 3GPP2 (3rd gen partnership proj. 2) administer respectively
- UTRA + HSPA has lead to HSPA+ (or 3.9G)
 - WCDMA began deployment in 2003
 - HSPDA began deployment in 2006
 - HSUPA began deployment in 2007
- LTE in a 5 MHz band achieves 43.2 Mbps downlink and 21.6 Mbps uplink using QPSK, 16QAM, or 64QAM within an OFDM scheme
- 3GPP2 evolves CDMA2000 to N xEV-DO and provides a peak forward link speed of $N \times 4.9$ Mbps and a reverse line data rate of $N \times 1.8$ Mbps (published in 2006)
- The 3GPP2's UMB is an all-IP network with forward data rates up to 288 Mbps and a reverse link data rate of 75 Mbps
- The move to 4G systems intends to move the spectral efficiency of 1 bit/s/Hz of bandwidth in 2G systems, 1–3 bits/s/Hz of 3G systems, to a goal of 10 bits/s/Hz
- The ITU-R is working on 4G with targets of 100 Mbps highly mobile access (up to 250 km/hr) and 1 Gbps for low mobility pedestrian or fixed users
 - *Ubiquitous, mobile, and seamless communications*
 - IPv6

- Quality of service (QoS)-driven
 - Smart spectrum with dynamic spectrum allocation (cognitive radio) within 3 to 10 GHz
 - MIMO and the use of multiple antennas permits high spectral efficiency
 - Adaptive modulation and coding (AMC)
 - Hybrid-ARQ (HARQ) to increase throughput via automatic repeat request and channel coding
- Wireless networking ideas and standards are also permeating 4G
 - IEEE extensions to 802.11 and in particular 802.16m (*WiMAX* evolved) support multi-hop relays to achieve high data rate over a wide area
 - IEEE 802.11 VHT (very high throughput) for data rates up to 1 Gbps stationary or pedestrian
 - IEEE 802.21 defines link layer services to enable handovers between different air interfaces
 - Combining IEEE 802.11 VHT and 802.16m with 802.21 produces the IEEE's IMT-Advanced proposal (early 2010)
 - Need to update for 5G and current [rollout](#) status
-

Example 1.2: Wireless Networking Roadmap⁶

- Digital communications is essential to wireless networking as we know it today



- As consumers we are most familiar with 802.11 (WiFi) and 802.15.1 (Bluetooth), both in the 2.4 GHz band
- Bluetooth is now at version 4.0 (Dec 2009)
 - Version 1.2 supports up to 780 kbps
 - Version 2.0 up to 2 Mbps
 - Version 3 up to 24 Mbps

⁶Du and Swamy, Cambridge University Press, 2010.

- Version 4 features very low power (coin-cell for several years) small data packets up to 1 Mbps
 - WiFi continues to evolve:
 - 802.11g achieves 54 Mbps using 64QAM
 - 802.11n, ratified September 11 2009, achieves up to 300 Mbps using multiple antennas
 - 802.11 VHT, described in part earlier, operates in the 6 and 60 GHz bands
 - Other extensions include ‘e’ for QoS, ‘i’ for security, ‘r’ for secure fast roaming, and ‘u’ interworking with non-802.11 networks
 - For wider area coverage there are wireless metropolitan area networks (WMAN)
 - IEEE 802.16e-2005 (*WiMAX* or *mobile WiMAX*) is the current standard operating in 2–11 GHz bands, but may also operate in the re-licensed UHF TV bands around 700 MHz
 - WiMAX uses a scalable OFMDA (SOFMDA) with a peak data rate of 75 Mbps and a range of 70 miles at speeds up to 70 km/h; note there is a trade between these two in a practical link
 - WiMAX can be used to connect WiFi hotspots and is found in cellular devices such as the *EVO 4G* from Sprint Wireless
-

Example 1.3: Digital Comm in Government/Military Systems

- Government/military systems use a wide variety of digital communication schemes
 - Applications range from telemetry links (satellites, missiles, etc.), data links, digital voice links, navigation (GPS), a variety of command and control functions, and others
 - Depending upon the application, early generation digital communications might be frequency-shift keying (FSK) based and use noncoherent demodulation
 - Deep space communications where power efficiency is important use coherent communications such as phase-shift keying (PSK), e.g., BPSK and QPSK
 - Detailed scenario modeling, e.g., particular channel types and or jamming, makes these applications challenging
-

Example 1.4: Other Systems⁷

- Other application areas that are popular are (1) paging systems, (2) digital broadcasting, and (3) RF identification
- **Paging Systems:**
 - Pagers are not as popular as they once were due to cell phones, but the systems still exist

⁷Du and Swamy, Cambridge University Press, 2010.

* Consider also restaurant pagers

- Today, pagers mainly support the “critical messaging” markets, such as emergency services and medical personnel⁸
- In the early days proprietary systems were developed by companies such as Motorola, NEC, and Ericsson
- For example in the late 1970s the British Post Office created POCSAG (Post Office Code Standard Advisory Group) which used FSK at 512 bps
- The newer FLEX system introduced in the USA in 1993, supports 6400 bps via FSK and 4FSK and operates at 900 MHz

- **Digital Broadcasting:**

- AM radio, analog TV and FM radio are all based on analog communications
- Increased reception quality and bandwidth efficiency are possible with digital broadcasting
- Analog TV has now been shut down in the USA
- We have satellite radio (2.3 and 1.4 GHz)) which uses digital modulation and source compression, (similar to MPEG-4 AAC?)
- *HD Radio* is available from both FM and AM broadcasting stations⁹
- In both cases the digital broadcast can coexist with the existing analog broadcast

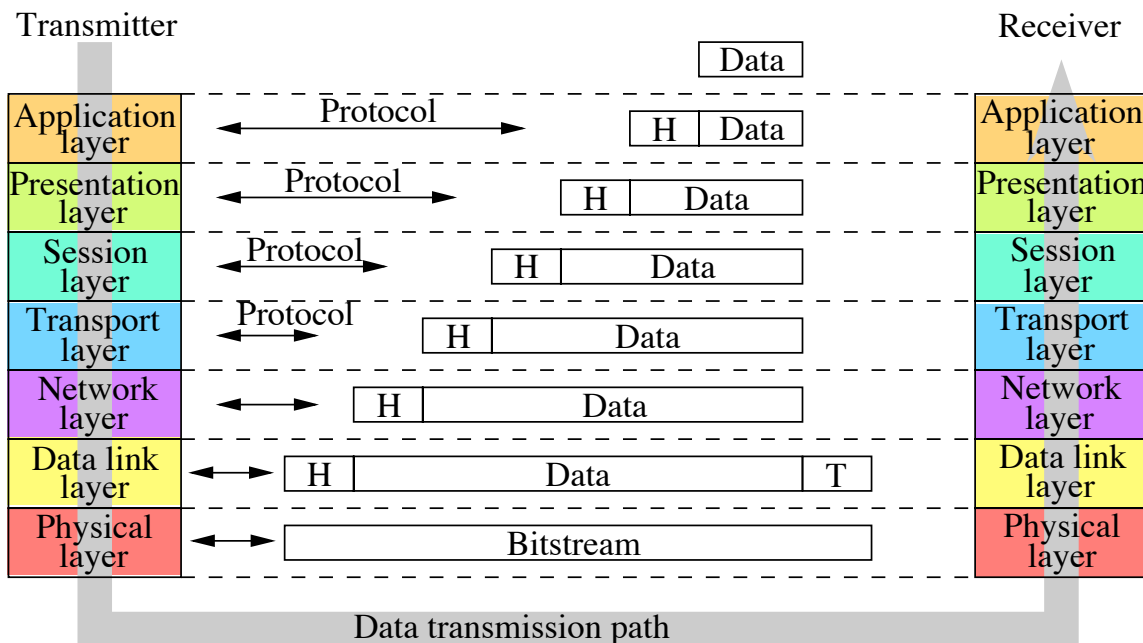
⁸<http://en.wikipedia.org/wiki/Pager>

⁹http://en.wikipedia.org/wiki/HD_Radio

- HD FM and AM use COFDM, with the bit rate lower in the case of the AM channel, thus enforcing more compression and a lower quality signal recovered at the receiver
 - HDTV in the USA serves as a total replacement for analog (NTSC) TV; Europe has their own digital video broadcast standards
- **RFIDs:**
 - Small tags placed on objects in order to track their position/location; also used in *smart cards* for personnel access control in buildings
 - Three frequency bands are in use: Low (125 kHz), Medium (13.56 MHz), and High (868 MHz, 2.4 GHz)
 - At the lower frequencies inductive coupling can be used to power up a purely passive tag to read and set data stored on the tag; the down side is a short reading range
 - The high frequency tags use EM wave coupling and thus have a much greater reading range
 - Digital modulation schemes employed include amplitude shift keying (ASK) and FSK
-

Example 1.5: Open Systems Interconnect (OSI) Model¹⁰

- Digital communications as presented in this course, will focus primarily on the physical layer, as depicted in the open system interconnect (OSI) model shown below

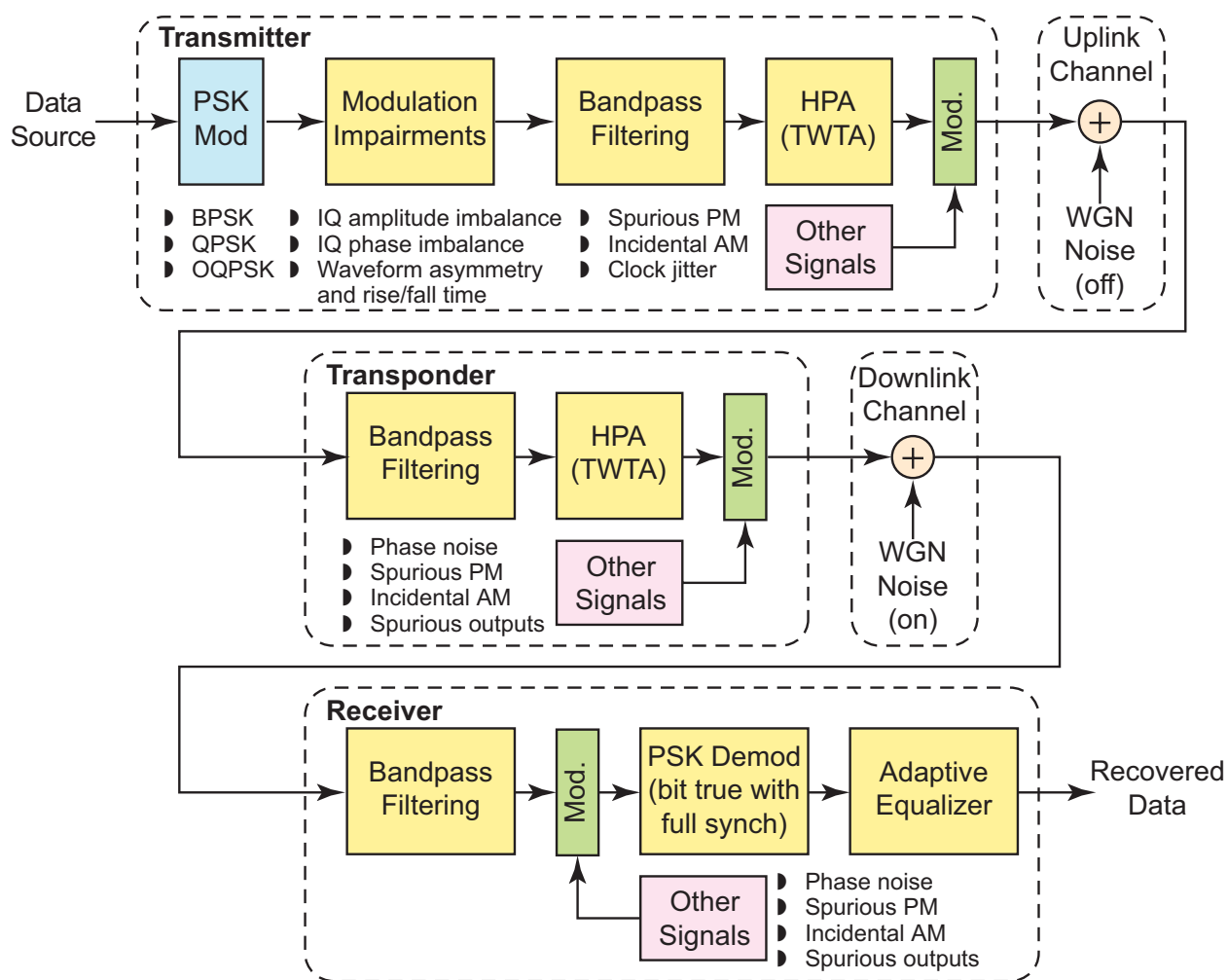


- From this figure we see that the transmitted data that begins at the application layer, is prefixed with a layer header as it is passed downward in the stack; at the receiver the process is reversed
- In modern digital communication systems, it is becoming more common place to consider *cross-layer* design/adaptation
- The intent of the cross-layer design is to improve performance in some way

¹⁰Du and Swamy, Cambridge University Press, 2010.

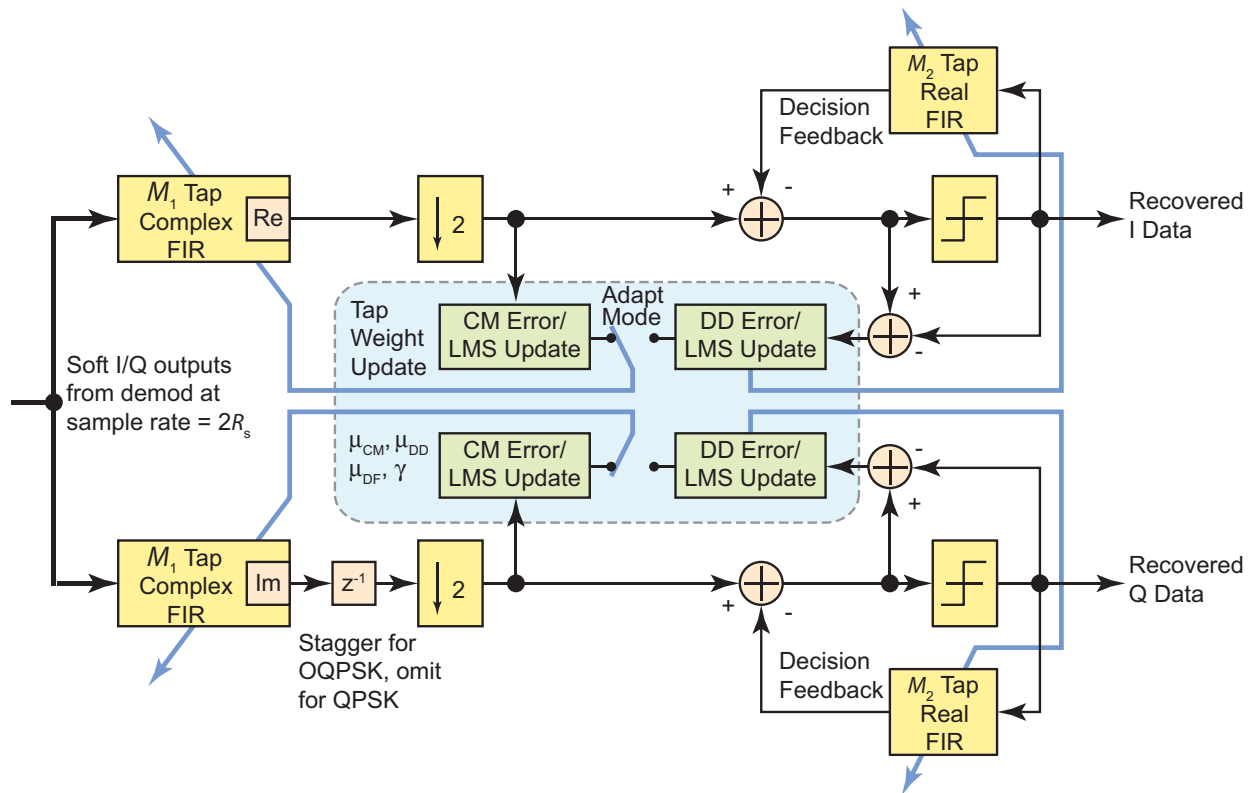
Example 1.6: A High Fidelity Sat-Comm Simulation

- Wideband satellite communication channels are subject to both linear and non-linear distortion



Wideband Sat-Comm simulation model

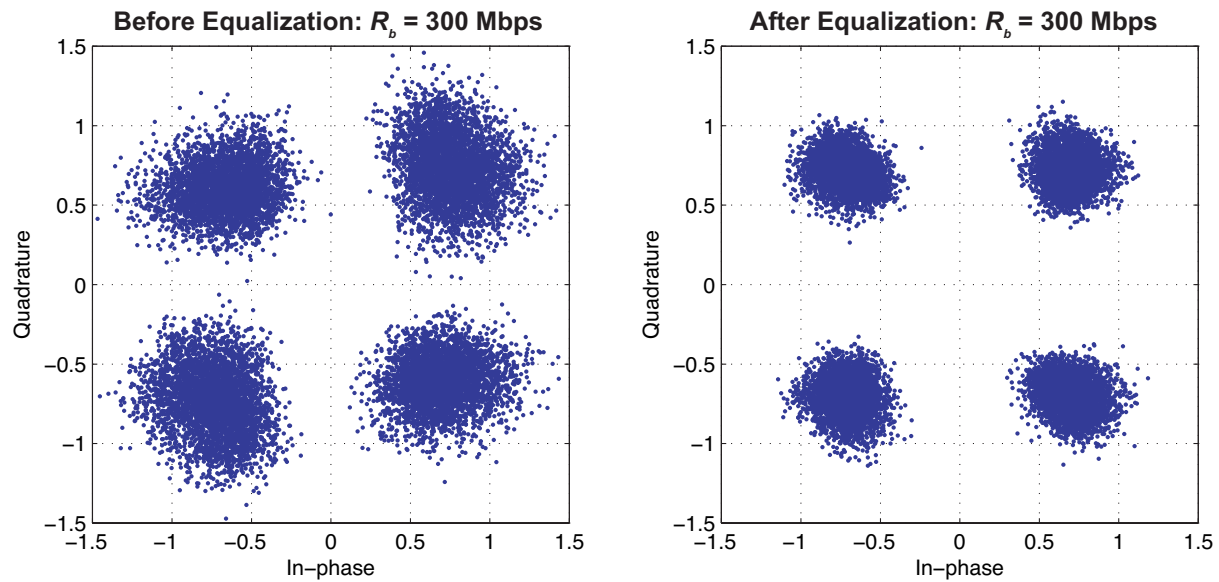
- An adaptive filter can be used to estimate the channel distortion, for example a technique known as *decision feedback equalization*



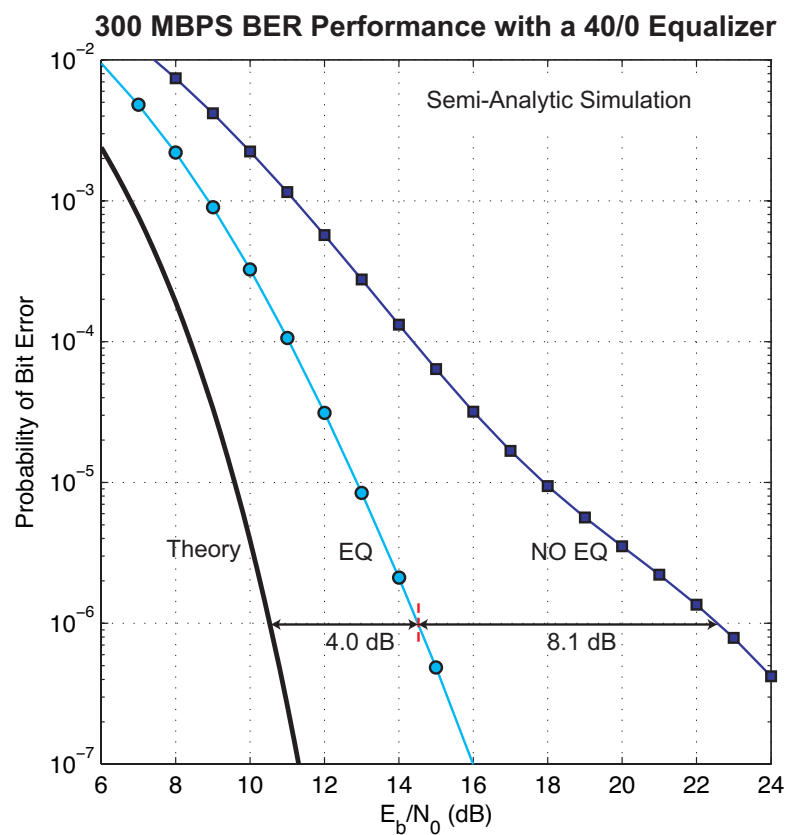
An adaptive baseband equalizer implemented in FPGA¹¹

- Since the distortion is both linear (bandlimiting) and nonlinear (amplifiers and other interference), the distortion cannot be completely eliminated
- The following two figures show first the modulation 4-phase signal points with and with out the equalizer, and then the bit error probability (BEP) versus received energy per bit to noise power spectral density ratio (E_b/N_0)

¹¹Mark Wickert, Shaheen Samad, and Bryan Butler. "An Adaptive Baseband Equalizer for High Data Rate Bandlimited Channels," *Proceedings 2006 International Telemetry Conference*, Session 5, paper 06-5-03.



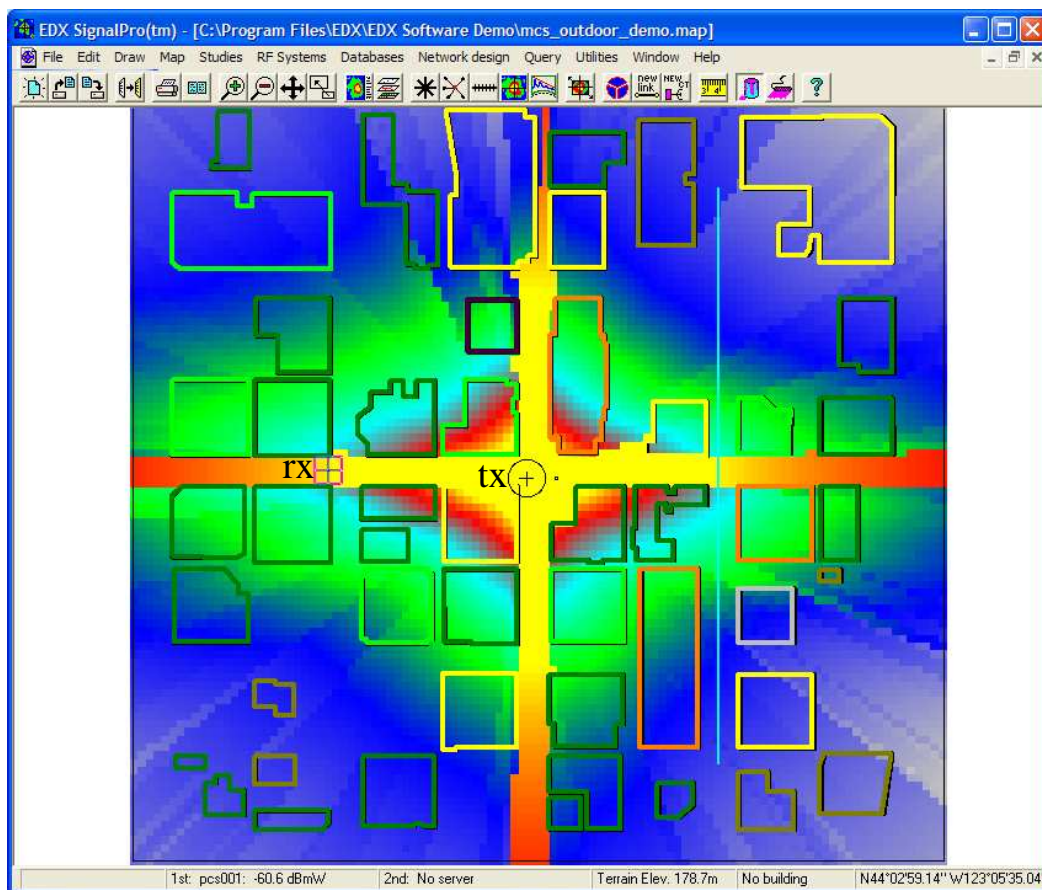
OQPSK scatter plots with and without the equalizer



BEP versus E_b/N_0 in dB

Example 1.7: PCS Urban Study at 1900 MHz In this study a downtown area is considered where the transmitter is located at 6m elevation at the crossing of two main streets. The brighter colors indicate higher signal levels.

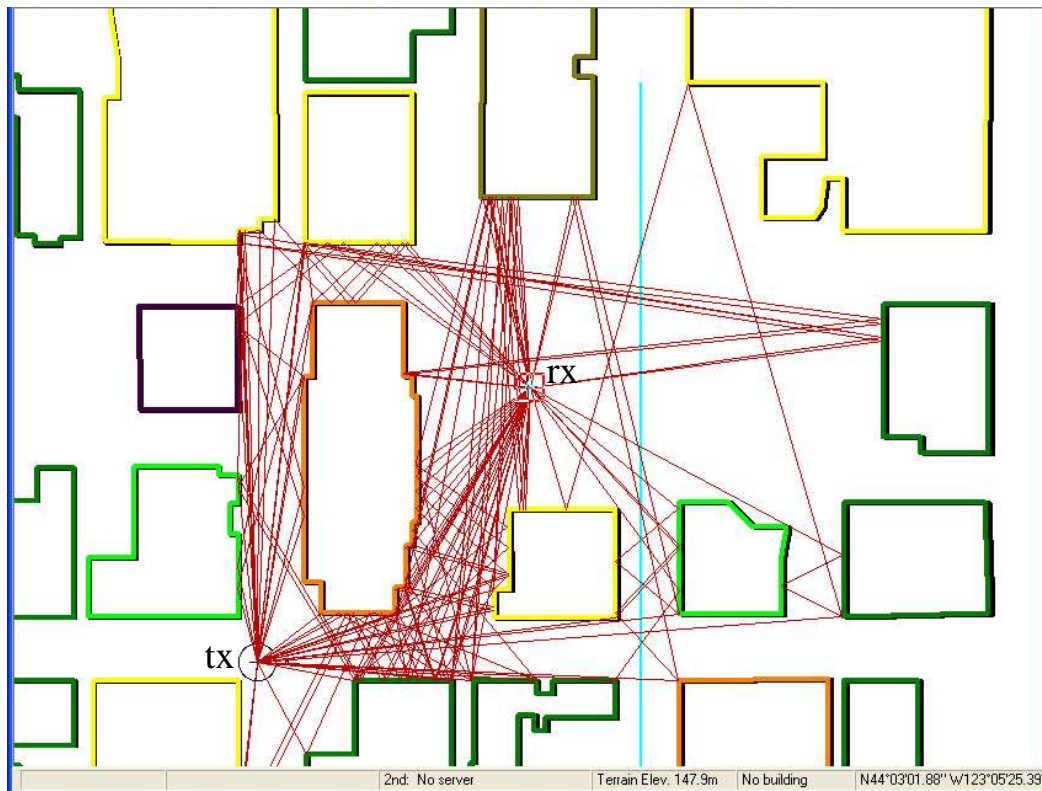
- First an *area study* using the *Walfish-Ikegami* model is performed
- This model utilizes elevation data as measurement points are taken radially from the transmitter



1900 MHz PCS area study via Walfisch-Ikegami model

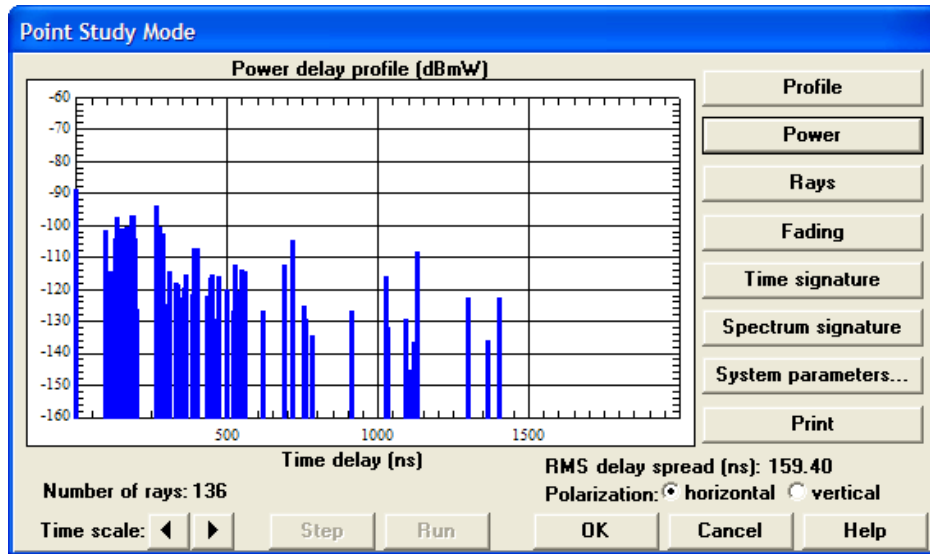
Next 2D ray tracing is used to perform a *point study* at a location without line-of-sight to the transmitter.

- Here a 3-bounce maximum 2D model provides rapid simulation

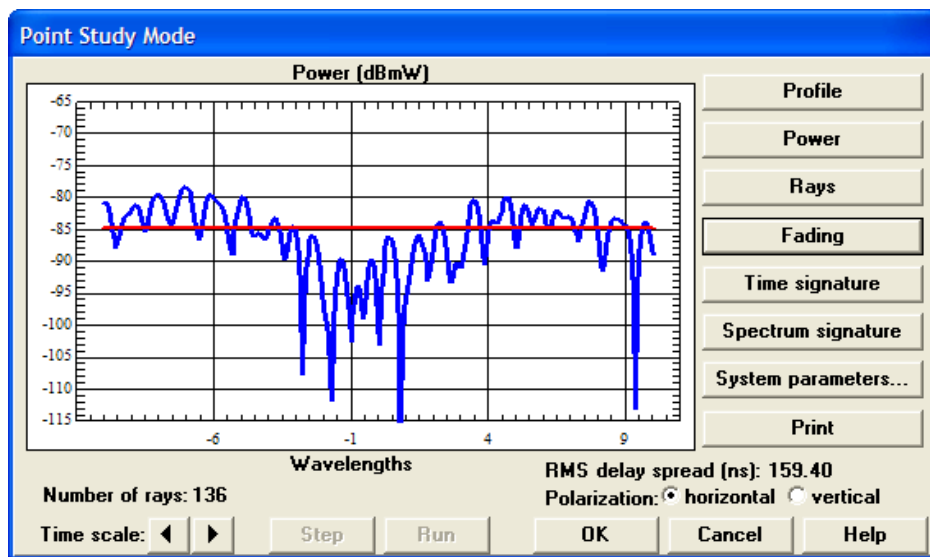


1900 MHz PCS point study using 2D ray-tracing

- Using the rays, the simulation tool builds a power delay profile plot and fading pattern plot versus wavelength shifts about the current receiver location

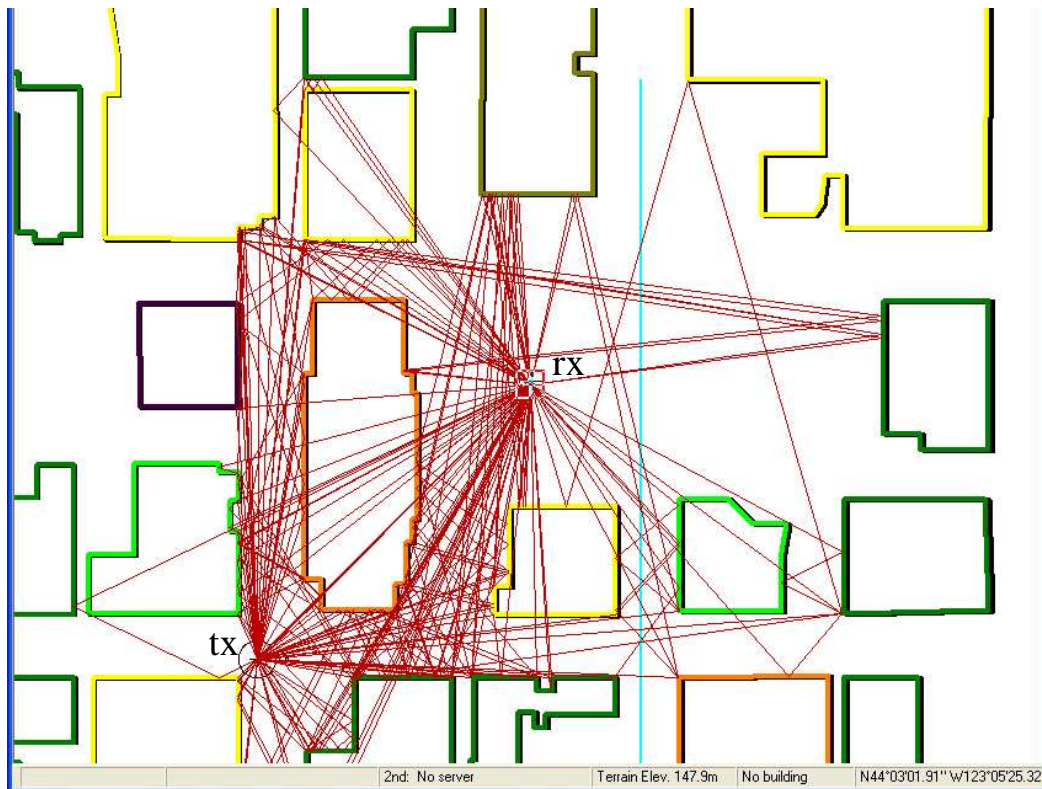


Power delay profile for the above point study
(rms delay spread = 159 ns)



Fading vs wavelength for the above point study

The present urban point study is now enhanced by including wall scattering and transmission.



2D ray-tracing with wall scattering and transmission

