Chapter 1: Introduction
History of Antennas and Propagation

Timeline

- 1870  Maxwell’s Equations
- 80  Heinrich Hertz’s Loop Experiment (1886)
- 90
- 1900  Guglielmo Marconi (1901) Transatlantic Transmission
- 10  Spark gap telegraphy
- 20  Audio broadcasting
- 30
- 40  WWII: Microwave sources Radar
- 1950  MTS system in USA
- 60  Computers, Numerical CEM
- 70  Analog Cellular
- 80  GPS satellites launched
- 90  Digital cellular, wireless LAN
- 2000  Advanced integrated devices/MIMO
- 10  ???
History of Antennas and Propagation

Timeline

1870  Maxwell’s Equations
80    Heinrich Hertz’s Loop Experiment (1886)
90    
1900  Guglielmo Marconi (1901) Transatlantic Transmission
10    Spark gap telegraphy
20    Audio broadcasting
30    
40    WWII: Microwave sources Radar
1950  MTS system in USA
60    Computers, Numerical CEM
70    Analog Cellular
80    GPS satellites launched
90    Digital cellular, wireless LAN
2000  Advanced integrated devices, MIMO
10    ???

\[ \nabla \cdot \vec{D} = \rho_v \]
\[ \nabla \cdot \vec{B} = 0 \]
\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]
\[ \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \]
# History of Antennas and Propagation

## Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>Maxwell's Equations</td>
</tr>
<tr>
<td>80</td>
<td>Heinrich Hertz's Loop Experiment (1886)</td>
</tr>
<tr>
<td>90</td>
<td>Spark gap telegraphy</td>
</tr>
<tr>
<td>1900</td>
<td>Guglielmo Marconi (1901) Transatlantic Transmission</td>
</tr>
<tr>
<td>20</td>
<td>Audio broadcasting</td>
</tr>
<tr>
<td>30</td>
<td>WWII: Microwave sources Radar</td>
</tr>
<tr>
<td>1950</td>
<td>MTS system in USA</td>
</tr>
<tr>
<td>60</td>
<td>Computers, Numerical CEM</td>
</tr>
<tr>
<td>70</td>
<td>Analog Cellular</td>
</tr>
<tr>
<td>80</td>
<td>GPS satellites launched</td>
</tr>
<tr>
<td>90</td>
<td>Digital cellular, wireless LAN</td>
</tr>
<tr>
<td>2000</td>
<td>Advanced integrated devices, MIMO</td>
</tr>
<tr>
<td>10</td>
<td>???</td>
</tr>
</tbody>
</table>
History of Antennas and Propagation

Timeline

1870  Maxwell’s Equations
80    Heinrich Hertz’s Loop Experiment (1886)
90
1900  **Guglielmo Marconi (1901) Transatlantic Transmission**
10    Spark gap telegraphy
20    Audio broadcasting
30
40    WWII: Microwave sources Radar
1950  MTS system in USA
60    Computers, Numerical CEM
70
80
90
2000
20
History of Antennas and Propagation

Timeline

- 1870: Maxwell’s Equations
- 80: Heinrich Hertz’s Loop Experiment (1886)
- 90: Guglielmo Marconi (1901) Transatlantic Transmission
- 10: Spark gap telegraphy
- 20: Audio broadcasting
- 30: WWII: Microwave sources Radar
- 1950: MTS system in USA
- 60: Computers, Numerical CEM
- 70: Analog Cellular
- 80: GPS satellites launched
- 90: Digital cellular, wireless LAN
- 2000: Advanced integrated devices/MIMO
- 10: ???
History of Antennas and Propagation

Timeline

1870  Maxwell’s Equations
80    Heinrich Hertz’s Loop Experiment (1886)
90
1900  Guglielmo Marconi (1901) Transatlantic Trans
10    Spark gap telegraphy
20    Audio broadcasting
30
40    WWII: Microwave sources Radar
1950  MTS system in USA
60    Computers, Numerical CEM
70    Analog Cellular
80    GPS satellites
90    Digital cellular
2000  Advanced integrated devices/MIMO
10    ???
## History of Antennas and Propagation

### Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>Maxwell’s Equations</td>
</tr>
<tr>
<td>80</td>
<td>Heinrich Hertz’s Loop Experiment (1886)</td>
</tr>
<tr>
<td>90</td>
<td>Spark gap telegraphy</td>
</tr>
<tr>
<td>1900</td>
<td>Guglielmo Marconi (1901) Transatlantic Transmission</td>
</tr>
<tr>
<td>20</td>
<td>Audio broadcasting</td>
</tr>
<tr>
<td>30</td>
<td>WWII: Microwave sources Radar</td>
</tr>
<tr>
<td>40</td>
<td>MTS system in USA</td>
</tr>
<tr>
<td>60</td>
<td>Computers, Numerical CEM</td>
</tr>
<tr>
<td>70</td>
<td>Analog Cellular</td>
</tr>
<tr>
<td>80</td>
<td>GPS satellites launched</td>
</tr>
<tr>
<td>90</td>
<td>Digital cellular, wireless LAN</td>
</tr>
<tr>
<td>2000</td>
<td>Advanced integrated devices/MIMO</td>
</tr>
<tr>
<td>10</td>
<td>???</td>
</tr>
</tbody>
</table>
History of Antennas and Propagation

Timeline

1870  Maxwell’s Equations
80  Heinrich Hertz’s Loop Experiment (1886)
90
1900  Guglielmo Marconi (1901) Transatlantic Transmission
10  Spark gap telegraphy
20  Audio broadcasting
30
40  WWII: Microwave sources Radar
1950  MTS system in USA
60  Computers, Numerical CEM
70  Analog Cellular
80  GPS satellites launched
90  Digital cellular, wireless LAN
2000  Advanced integrated devices/MIMO
10  ???
History of Antennas and Propagation

Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>Maxwell’s Equations</td>
</tr>
<tr>
<td>80</td>
<td>Heinrich Hertz’s Loop Experiment (1886)</td>
</tr>
<tr>
<td>90</td>
<td>Heinrich Hertz’s Loop Experiment (1886)</td>
</tr>
<tr>
<td>1900</td>
<td>Guglielmo Marconi (1901) Transatlantic Transmission</td>
</tr>
<tr>
<td>10</td>
<td>Spark gap telegraphy</td>
</tr>
<tr>
<td>20</td>
<td>Audio broadcasting</td>
</tr>
<tr>
<td>30</td>
<td>MTS system in USA</td>
</tr>
<tr>
<td>40</td>
<td>WWII: Microwave sources Radar</td>
</tr>
<tr>
<td>60</td>
<td>Computers, Numerical CEM</td>
</tr>
<tr>
<td>70</td>
<td>Analog Cellular</td>
</tr>
<tr>
<td>80</td>
<td>GPS satellites launched</td>
</tr>
<tr>
<td>90</td>
<td>Digital cellular, wireless LAN</td>
</tr>
<tr>
<td>2000</td>
<td>Advanced integrated devices/MIMO</td>
</tr>
<tr>
<td>10</td>
<td>???</td>
</tr>
</tbody>
</table>
History of Antennas and Propagation

Timeline

1870  Maxwell’s Equations
80   Heinrich Hertz’s Loop Experiment (1886)
90
1900  Guglielmo Marconi (1901) Transatlantic Transmission
10   Spark gap telegraphy
20   Audio broadcasting
30
40   WWII: Microwave sources Radar
1950  MTS system in USA
60   Computers, Numerical CEM
70  **Analog Cellular**
80   GPS satellites launched
90   Digital cellular, wireless LAN
2000  Advanced integrated devices/MIMO
10   ???
History of Antennas and Propagation

Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>Maxwell’s Equations</td>
</tr>
<tr>
<td>80</td>
<td>Heinrich Hertz’s Loop Experiment (1886)</td>
</tr>
<tr>
<td>90</td>
<td>Guglielmo Marconi (1901) Transatlantic Transmission</td>
</tr>
<tr>
<td>10</td>
<td>Spark gap telegraphy</td>
</tr>
<tr>
<td>20</td>
<td>Audio broadcasting</td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>WWII: Microwave sources Radar</td>
</tr>
<tr>
<td>1950</td>
<td>MTS system in USA</td>
</tr>
<tr>
<td>60</td>
<td>Computers, Numerical CEM</td>
</tr>
<tr>
<td>70</td>
<td>Analog Cellular</td>
</tr>
<tr>
<td>80</td>
<td><strong>GPS satellites launched</strong></td>
</tr>
<tr>
<td>90</td>
<td>Digital cellular, wireless LAN</td>
</tr>
<tr>
<td>2000</td>
<td>Advanced integrated devices/MIMO</td>
</tr>
<tr>
<td>10</td>
<td>???</td>
</tr>
</tbody>
</table>
History of Antennas and Propagation

Timeline

1870   Maxwell’s Equations
80     Heinrich Hertz’s Loop Experiment (1886)
90     Spark gap telegraphy
1900   Guglielmo Marconi (1901) Transatlantic Transmission
10     Audio broadcasting
20     WWII: Microwave sources Radar
30     MTS system in USA
40     Computers, Numerical CEM
50     Analog Cellular
60     GPS satellites launched
90     Digital cellular, wireless LAN
2000   Advanced integrated devices/MIMO
10     ???
History of Antennas and Propagation

Timeline

1870    Maxwell’s Equations
80      Heinrich Hertz’s Loop Experiment (1886)
90
1900    Guglielmo Marconi (1901) Transatlantic Transmission
10      Spark gap telegraphy
20      Audio broadcasting
30
40      WWII: Microwave sources Radar
1950    MTS system in USA
60      Computers, Numerical CEM
70      Analog Cellular
80      GPS satellites launched
90      Digital cellular, wireless LAN
2000    Advanced integrated devices/MIMO
10      ???
# History of Antennas and Propagation

## Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>Maxwell’s Equations</td>
</tr>
<tr>
<td>1886</td>
<td>Heinrich Hertz’s Loop Experiment</td>
</tr>
<tr>
<td>1900</td>
<td>Guglielmo Marconi (1901) Transatlantic Transmission</td>
</tr>
<tr>
<td>1910</td>
<td>Spark gap telegraphy</td>
</tr>
<tr>
<td>1920</td>
<td>Audio broadcasting</td>
</tr>
<tr>
<td>1930</td>
<td>WWII: Microwave sources Radar</td>
</tr>
<tr>
<td>1950</td>
<td>MTS system in USA</td>
</tr>
<tr>
<td>1960</td>
<td>Computers, Numerical CEM</td>
</tr>
<tr>
<td>1970</td>
<td>Analog Cellular</td>
</tr>
<tr>
<td>1980</td>
<td>GPS satellites launched</td>
</tr>
<tr>
<td>1990</td>
<td>Digital cellular, wireless LAN</td>
</tr>
<tr>
<td>2000</td>
<td>Advanced integrated devices/MIMO</td>
</tr>
<tr>
<td>2020</td>
<td>???</td>
</tr>
</tbody>
</table>
Antennas

Definition
Antennas are *transducers* that convert electrical signals into propagating electromagnetic waves and vice versa.

Analogy
Sound: Speakers, Microphones
Basic Antenna System (1)

Source

Equivalent circuit that generates signals
E.g. DSP, D/A converter, microwave oscillator, mixer

$V_g$: Generator voltage

$Z_g$: Generator input impedance
Basic Antenna System (2)

Transmission Line
- Carries signals from source to antenna
- E.g. coaxial cable, waveguide, circuit board trace
- Propagating, standing waves can be present
Basic Antenna System (3)

Antenna (Load)
- $R_L$ Power dissipated in the antenna, ohmic losses
- $R_r$ Radiation resistance.  Good loss!
- $X_A$ Reactance of antenna.  Stored energy.  Can make matching more difficult.

Matching
- Important to ensure nearly all available power delivered to antenna.
Antenna Design

Goals

Should be low-loss = high efficiency
Matched to a convenient impedance
Radiate (or receive) power in right “directions” and polarizations
Be as compact as possible
Operate over required bandwidth

Propagation aspects

Right “directions” depends on environment
User/nearby objects affect antenna operation
Importance of Good Antenna Design

Analogy: Camera

Antenna is like lens, camera optics
Possible impairments:
  - Dirt/scratches on lens
  - Improper focus
  - Inadequate lighting
DSP techniques can enhance image
But ... impossible to restore lost information

Well-designed antennas

Provide huge improvement to later DSP algorithms and operations
Can ease system constraints (e.g. filtering)
Often must consider *propagation* environment for optimal solution
Antenna Types: Wire Antennas

Wire Antennas

- Dipole
- Monopole
- Loop

Properties

- Simple
- Low cost (a bent wire!)
- Efficient
- Single frequency
Antenna Types: Microstrip Antennas

Microstrip Antennas

- Patch
- Spiral

Properties

- Planar (low profile)
- Rigid / Robust
- Can be low cost (integrated with PC board)
- Versatile
Antenna Types: Aperture Antennas

Aperture Antennas

- Horn
- Vivaldi
- Waveguide

Properties

- Rigid (especially horn)
- Wideband operation
- Useful for aerospace applications
- antenna measurements
- But, can be bulky / heavy
Antenna Types: Conformal

Conformal Antennas

Cone

Properties

Surface is a degree of freedom to optimize pattern

Or, given an existing surface, can use for antenna

Example: airplane wing, window, etc.

Design / fabrication more involved
Antenna Types: Reflector Antennas

Reflector Antennas
- Parabolic Dish
- Corner Reflector

Properties
- Very narrow beam (high gain) possible
- Bandwidth only limited by feed and size of reflector
- But, can be bulky, expensive
Antenna Types: Antenna Arrays

Antenna Arrays

Patch Array (WLAN)

Properties

- Gain enhancement over a single element
- Dynamic/electronic steering of beam
- Spatial diversity / multiplexing

NRAO VLA
Antenna Operational Principles

1. Resonant Antennas
   Designed to operate at one frequency. Analogy: guitar string.
   Dipoles, loops, patches

2. Waveguide type antennas
   Smooth transition from waveguide to free-space. Analogy: speaker
   Very wide operational bandwidth
   Horn antennas

Reflectors / Arrays
   Can be considered method of modifying/focusing pattern of other
   basic antenna types
Propagation

Free Space
Through air or vacuum
Simple to describe mathematically
Line-of-sight, space channels
(scatterers not in main path)

Ionosphere
Looks conductive at many uW frequencies = loss!
Faraday (polarization) rotation

Multipath Propagation
Multiple paths from TX to RX create fading of signal

Human Body Interactions
Course Organization
1. Electromagnetic (EM) Analysis (2 weeks)

Transmission Lines (review)
Vector Potentials / Wave Equation
   Derive waves generated by source currents in an arbitrary antenna

Far-field Radiation
   Exact computation of fields can be costly
   Often we are interested in fields far from antenna (radar, comm)
   Far-field expressions usually much simpler

Duality/Reciprocity
   Extremely useful properties of EM fields

Motivation
   Fundamental mathematical tools to predict antenna behavior
Course Organization
2. Antenna Parameters (1 week)

Standard Antenna Terms and Parameters
- Patterns
- Gain
- Bandwidth
- Polarization
- Input Impedance
- Coupling

Motivation
Language to describe / compare antenna operation
Course Organization
3. Antenna Types (2 weeks)

Basic Antenna Types
- Show at least one example of each antenna type
  - Wire Antennas: Dipoles and loops
  - Planar Antennas: Patches
  - Aperture Antennas, Reflectors
  - Broadband, frequency-independent antennas

Motivation
- See techniques (tricks) to analyze most antennas
- Gain intuition: “see” how antennas work
Element/Array Factor
   Separate effect of individual elements, array

Mutual coupling
   For closely-spaced antennas, fields interact

Beamforming, Nulling
   Most basic and useful applications of arrays
   Enhance signals of interest, suppress interference

Motivation
   Array processing used in most advanced modern systems
   Overcomes deficiencies of single elements
Course Organization
5. Propagation (3 weeks)

Channel Modeling
- Power laws (radar range equation)
- Multipath: rays and clusters
- Fading: Rayleigh, Rician, Shadowing

MIMO Modeling/Analysis
- Random matrix models
- Channel covariance
- Diversity techniques
- Channel capacity

Motivation
- Understand how channel influences communications
- Learn most important terms for research in this area
Course Organization
6. Applications / Research (2 weeks)

MIMO
  Space-Time Coding
  Alamouti Scheme, VBLAST

Reconfigurable Antennas
  Antennas whose properties can be dynamically changed / tuned

Radio Frequency Identification (RFID)

Ultra-Wideband Systems (UWB)

Motivation
  See recent advances / uses of antennas
  Get better picture of complete system
Conclusion

Antennas and Propagation

Still an important area of research / development
Course gives basic tools to be proficient in this area