KI4: SIGNAL TRANSMISSION IN A RADIO SYSTEM

Power Supply & Management

Antenna & Propagation

RF Frontend

Baseband Backend

A/D and D/A Converters and Filters

Video I/O

Audio I/O

storage

BPF
PA
Mixer
Amp

LO

LNA
Mixer
Amp

BPF

Antenna
Diplexer

Colorado State University

NSF
• Pre-amp (332)
• Carrier frequency in radio systems (312)
• Modulation techniques (up conversion) (312)
• CMOS drivers for power amplifiers in radio transmission path (332)
• Band-pass filters (BPF) and their transfer function in the Laplacian domain (312)
• Passive vs. active BPFs (332/312)
• RF power amplifiers and its efficiency illustrated as a CMOS driver plus a BPF (332/342)
• Antennas and radiation in radio systems (342)
• Antenna size as a function of carrier frequency (342)
A DEMO SYSTEM – SILICON LAB SINGLE CHIP TRANSMITTER

[Diagram showing the integrated circuit and its components]

- Si4010
- LDO REGULATOR
- FSK
- DIVIDER
- PA
- OOK
- INTEGRATED 8051 MCU
- LOOP ANTENNA
- VDD
- CR2032 COIN CELL
- 1.8 – 3.6 V
- GND
- LED
- TXP
- TXM
- GPIO
- 4/8
- I/O INTERFACE
- RAM
- ROM
- NVM 8 Kbyte
- EEPROM 128-bit

[Text on the diagram]

- Application of diff. amp. circuits
- Modulation (up conversion)
- Linearity & power efficiency
- Output spectrum tuning (passive & active)

[Transfer functions of components in the Laplace domain to show baseband vs. RF characteristics]

- Pre-amp
- Carrier signal
- RF power amp
- Oscillator design using LC circuits
- BPF
- Antenna & radiation, EM wave & propagation vs. carrier freq.

[Logo of Colorado State University]
RADIO SPECTRUM ALLOCATION

Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gases (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.

Atmospheric opacity

Wavelength

1  10^3  10^6  10^9  10^{12}  10^{15}  10^{18}  10^{21}  f[Hz]
radio waves  microwaves  terahertz  infrared  ultraviolet  X-rays  cosmic rays

\( \lambda_0[\text{m}] \)
# Electromagnetic Spectrum

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Free-space wavelength</th>
<th>Band</th>
<th>Selected applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 3 Hz</td>
<td>&gt; 100 Mm</td>
<td>Extremely low frequency (ELF)</td>
<td>Geophysical sensing</td>
</tr>
<tr>
<td>3–30 Hz</td>
<td>10–100 Mm</td>
<td>Super low frequency (SLF)</td>
<td>Detection of buried metallic objects</td>
</tr>
<tr>
<td>30–300 Hz</td>
<td>1–10 Mm</td>
<td>Ultra low frequency (ULF)</td>
<td>Electric power distribution (50 or 60 Hz), submarine communications, ionospheric sensing</td>
</tr>
<tr>
<td>0.3–3 kHz</td>
<td>0.1–1 Mm</td>
<td>Very low frequency (VLF)</td>
<td>Telephone, audio systems, geomagnetic sensing</td>
</tr>
<tr>
<td>3–30 kHz</td>
<td>10–100 km</td>
<td>Low frequency (LF)</td>
<td>Navigation, positioning, ship/submarine comm.</td>
</tr>
<tr>
<td>30–300 kHz</td>
<td>1–10 km</td>
<td>Medium frequency (MF)</td>
<td>Long-wave broadcasting, radio beacons, navigation</td>
</tr>
<tr>
<td>0.3–3 MHz</td>
<td>0.1–1 km</td>
<td>High frequency (HF)</td>
<td>AM radio broadcasting (0.535–1.605 MHz)</td>
</tr>
<tr>
<td>3–30 MHz</td>
<td>10–100 m</td>
<td>Very high frequency (VHF)</td>
<td>Short-wave broadcasting, amateur radio</td>
</tr>
<tr>
<td>30–300 MHz</td>
<td>1–10 m</td>
<td>TV channels 2–4 (54–72 MHz)</td>
<td>TV broadcasting (all TV channels have a 6-MHz bandwidth), FM radio broadcasting, mobile radio communication, air traffic control, navigation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TV channels 5–6 (76–88 MHz)</td>
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<tr>
<td></td>
<td></td>
<td>FM radio (88–108 MHz)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>TV chann. 7–13 (174–216 MHz)</td>
<td></td>
</tr>
<tr>
<td>0.3–3 GHz</td>
<td>0.1–1 m</td>
<td>Ultra high frequency (UHF)</td>
<td>Radar, TV broadcasting, cellular telephone, personal communication service (PCS), global positioning system – GPS (1.23 and 1.58 GHz), microwave cooking (2.45 GHz), satellite radio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TV chann. 14–69 (470–806 MHz)</td>
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<tr>
<td></td>
<td></td>
<td>Cellular (824–894 MHz)</td>
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<tr>
<td></td>
<td></td>
<td>PCS (1850–1990 MHz)</td>
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<tr>
<td></td>
<td></td>
<td>L-band (1–2 GHz)</td>
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<td></td>
<td></td>
<td>S-band (2–4 GHz)</td>
<td></td>
</tr>
<tr>
<td>3–30 GHz</td>
<td>1–10 cm</td>
<td>Super high frequency (SHF)</td>
<td>Radar, satellite communications, direct TV, wireless communication systems, wireless networks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C-band (4–8 GHz)</td>
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<td></td>
<td></td>
<td>X-band (8–12 GHz)</td>
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<td></td>
<td></td>
<td>K_{u}-band (12–18 GHz)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>K-band (18–27 GHz)</td>
<td></td>
</tr>
</tbody>
</table>
# ELECTROMAGNETIC SPECTRUM

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Wavelength</th>
<th>Region</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>30–300 GHz</td>
<td>1–10 mm</td>
<td>Extremely high frequency (EHF)</td>
<td>Radar, remote sensing, radio astronomy, satellite communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kₐ-band (27–40 GHz)</td>
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<tr>
<td></td>
<td></td>
<td>V-band (40–75 GHz)</td>
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<tr>
<td></td>
<td></td>
<td>W-band (75–110 GHz)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Millimeter-wave (110–300 GHz)</td>
<td></td>
</tr>
<tr>
<td>0.3–3 THz</td>
<td>0.1–1 mm</td>
<td>Submillimeter wave or terahertz</td>
<td>Meteorology, sensors, imaging, astronomy</td>
</tr>
<tr>
<td>3–400 THz</td>
<td>0.75–100 μm</td>
<td>Infrared (IR)</td>
<td>IR heating, night vision, optical communications</td>
</tr>
<tr>
<td>400–789 THz</td>
<td>380–750 nm</td>
<td>Visible light</td>
<td>Vision, optical devices and systems, lasers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Red (620–750 nm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Orange (590–620 nm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yellow (570–590 nm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Green (495–570 nm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blue (450–495 nm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Violet (380–450 nm)</td>
<td></td>
</tr>
<tr>
<td>10^{15}–10^{18} Hz</td>
<td>0.3–300 nm</td>
<td>Ultraviolet (UV)</td>
<td>UV sterilization, lasers, semiconductor processing</td>
</tr>
<tr>
<td>10^{17}–10^{21} Hz</td>
<td>0.3 pm–3 nm</td>
<td>X-rays</td>
<td>Medical diagnostics</td>
</tr>
<tr>
<td>10^{19}–10^{22} Hz</td>
<td>0.03–30 pm</td>
<td>γ-rays</td>
<td>Radiation medical therapy, astrophysics</td>
</tr>
<tr>
<td>&gt; 10^{22} Hz</td>
<td>&lt; 0.03 pm</td>
<td>Cosmic rays</td>
<td>Astrophysics</td>
</tr>
</tbody>
</table>
ANTENNA EXAMPLES

- GPS IFA Antenna
- Diversity Cell Antenna
- Feed
- Shorting Pin
- Transmit/Receive Antenna (Dual Band IFA)
- High-Band Arm 1800 MHz
- Low-Band Arm of IFA (900 MHz)
ANTENNA EXAMPLES

iPhone 4 GSM

iPhone 4 CDMA
ANTENNA EXAMPLES
DIPOLE ANTENNA RADIATION PATTERN
LOCAL OSCILLATOR

Ideal LC Tank

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

Real LC Tank

$$Q_L = \frac{\omega_0 L_1}{R_1}$$

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} \sqrt{1 - \frac{R_1^2 C_1}{L_1}}$$

$e^{\alpha t} \cos \omega_0 t$
LOCAL OSCILATOR

- Tuning is provided by the programmable capacitor
- Tuning range:
  - 902MHz – 928MHz
  - Able to compensate for 5% process variation
  - Able to compensate for 2% inductance variation
- $L = 17\text{nH}$, $Q = 30$
- Output swing 1Vp-p
- $I_{bias} = 200 – 300\text{uA}$
MIXER USING SQUARE LAW

\[ v_o = V_o \cos(\omega_0 t) \Leftarrow \text{LO signal,} \]

\( V_o \) is set not to put the FET in cutoff

Square Law: \( I_D = \frac{k' W}{2L} (V_{gs} - V_t)^2 (1 + \lambda V_{ds}) \)

\[ = \frac{k' W}{2L} (V_Q + V_o \cos(\omega_0 t) - V_t)^2 (1 + \lambda V_{ds}) \]

\( V_Q + V_o \cos(\omega_0 t) > V_t \Rightarrow V_Q - V_o > V_t \) or \( V_o < V_Q - V_t \)

Expand the square term:

\[ I_D \propto \left( (V_Q - V_t)^2 + V_o \cos^2(\omega_0 t) + 2(V_Q - V_t)V_o \cos(\omega_0 t) \right) \]
MIXER USING SQUARE LAW

- The DC current from the previous equation:

\[ I_{D,DC} = \frac{k'}{2L} \left( V_Q - V_t \right)^2 \left( 1 + \lambda V_{ds} \right) \]

- Further expand the \( \cos^2(\omega_0 t) \) term:

\[ \cos^2(\omega_0 t) = \cos(\omega_0 t) \cdot \cos(\omega_0 t) = \frac{1}{2} \left[ 1 + \cos(2\omega_0 t) \right] \]

\[ I_D = \frac{k'}{2L} \left( (V_Q - V_t)^2 + V_o \cos^2(\omega_0 t) + 2(V_Q - V_t)V_o \cos(\omega_0 t) \right) \]

\[ = I_{D,DC} + \frac{k'}{2L} \left( V_o^2 \cos^2(\omega_0 t) + 2(V_Q - V_t)V_o \cos(\omega_0 t) \right) \]

\[ = I_{D,DC} + k' \frac{W}{L} \left( \frac{V_o^2}{4} + (V_Q - V_t)V_o \cos(\omega_0 t) + \frac{V_o^2}{4} \cos(2\omega_0 t) \right) \]

bias point shift  LO modulation  2\textsuperscript{nd}-order harmonics. ignore
MIXER USING SQUARE LAW

- MOSFET transconductance under large signal LO input signal:
  
  \[ g(t) = \frac{\partial I_D}{\partial V_{gs}} = k' \frac{W}{L} (V_{gs} - V_t)(1 + \lambda V_{ds}) \]

- If \( V_{gs} \) follows the LO signal, then \( I_d \) also follows LO signal.

  \[ V_{gs}(t) = V_Q + V_o \cos(\omega_0 t) \]

  \[ \therefore g(t) = k' \frac{W}{L} (V_Q - V_t + V_o \cos(\omega_0 t))(1 + \lambda V_{ds}) \]

  \[ = g_{mQ} \left(1 + \frac{V_o}{V_Q - V_t} \cos(\omega_0 t)\right)(1 + \lambda V_{ds}) \]
**Mixer Using Square Law**

- Add LO and the signal at the input, we have a mixer.

\[ i_o(t) = g(t)v_s = g_{mQ} \left( 1 + \frac{V_o}{V_Q - V_t} \cos(\omega_0 t) \right) \times V_s \cos(\omega_s t) \]

\[ i_0(t)_{IF} = \frac{g_{mQ} V_o}{2} \frac{V_s}{V_G - V_t} \cos(\omega_0 \pm \omega_s) t \]

\[ g_c(t) = \frac{i_0(t)_{IF}}{V_s} = \frac{g_{mQ} V_o}{2} \frac{V_s}{V_G - V_t} \]

\[ k' \frac{W}{L} \left( V_G - V_t \right) = \frac{V_o}{2} \frac{V_o}{V_G - V_t} = k' \frac{W}{2L} V_o \]

- The LC tuning network at the load will only select (i.e. resonate) the desired IF signal and pass it on to the output load. All the other frequencies will be shorted by the tuning network.
MIXER USING SQUARE LAW
MIXER USING SQUARE LAW

• Real modulation using sine function:

\[
\text{Fourier}\{\sin(\omega_0 t) f(t)\} = \int_{-\infty}^{\infty} f(t) \left[ \frac{e^{j\omega_0 t} - e^{-j\omega_0 t}}{2j} \right] e^{-j\omega t} dt
\]

\[
= \frac{1}{2j} F(\omega - \omega_0) - \frac{1}{2j} F(\omega + \omega_0)
\]

\[
= \frac{j}{2j^2} F(\omega - \omega_0) - \frac{j}{2j^2} F(\omega + \omega_0)
\]

\[
= -\frac{j}{2} F(\omega - \omega_0) + \frac{j}{2} F(\omega + \omega_0)
\]

– Sine function modulation results in a negative lower band shift and a positive upper band shift
SIGNAL COMBINERS
SIGNAL COMBINERS

![Signal Combiner Diagram](Image)

- **V_{IN1}, V_{IN2}, V_{IN3}** are the input signals.
- **U1-a** is the operational amplifier (LM3900).
- **R1, R2, R3, R4, R5** are resistors with values 4.7K, 10K, and 100K.
- **C1, C2, C3, C4, C5** are capacitors with values of 4.7uF.
- **+12VDC, -12VDC** are the power supplies.

SeekIC.com

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ACTIVE LOW-PASS FILTERS
ACTIVE HIGH-PASS FILTERS

\[ A_v = 1 + \frac{R_2}{R_1} \]

\[ f_c = \frac{1}{2\pi \sqrt{R_3 C_3 C_1}} \]
ACTIVE BAND-PASS FILTERS

Diagram showing the circuit and frequency response of an active band-pass filter.
MONO-CHANNEL VS. STEREO TRANSMISSION

- To recover the stereo signal:

\[
L\_\text{channel} = \frac{(L+R)+(L-R)}{2} \\
R\_\text{channel} = \frac{(L+R)-(L-R)}{2}
\]
KI5: SIGNAL RECEIVER IN A RADIO SYSTEM
DETAILED RECEIVING CHANNEL IN A RADIO SYSTEM

- Roles of the front-end BPF in radio receiving path (selectivity, signal blocking) (312, 332)
- BPF with LC ladders (312/332)
- Frequency characteristics of amplifiers (312/332)
- Modulation techniques (down conversion) (312)
- Feedback topologies in frequency synthesizers (332)
- Design of baseband LPF/BPF with RC circuits and imperfect amplifiers (312/332)
- Design and characterization of receiver antenna
- Design and characterization of interface between antenna and circuits (matching and transmission line modeling) (342)
- Roles of discrete time signal processing (Z-transform) on future software-defined radio (312)
A DEMO SYSTEM – SILICON LAB SINGLE CHIP RECEIVER
**QUESTIONS**

1. What signals does the receiver antenna “see”?

2. Assuming the receiver antenna is a dipole antenna for 433MHz signal, what should the dimension of the antenna be?

3. What is the purpose of the first BPF?

4. How would you build a simple BPF using either passive or active (Op-amps) components?
RECEIVING ANTENNA
SIGNAL FLOW IN A GENERIC RECEIVER

Diagram showing the flow of signals in a generic receiver, including components such as LNA, VGA, and ADC, with power and frequency axes.
FILTER BASICS

4 basic filter types

Ideal low-pass filter

Practical low-pass filter
**ACTIVE FILTERS**

\[
H(s) = -\frac{Z_f}{Z_i}
\]
ACTIVE FILTERS

**Low-pass filter**

\[
H(s) = -\frac{Z_f}{Z_i} = -\frac{\frac{R_f}{1+j\omega R_f C_f}}{\frac{R_1}{R_1}} = \frac{-\frac{R_f}{R_1}}{1+j\omega R_f C_f}
\]

\[
P_{\text{filter}} = \frac{1}{R_f C_f}
\]

Bode plot
ACTIVE FILTERS

**Band-Pass Filter**

\[ H(s) = -\frac{R_f}{Z_i} - \frac{Z_f}{1 + j\omega R_f C_f} \]

\[ = \frac{-j\omega R_f C_1}{(1 + j\omega R_1 C_1)(1 + j\omega R_f C_f)} \]

Bode plot

Colorado State University
ACTIVE FILTERS

Now, think about the op-amp has a dominant pole at \( p_{op} \), and assume the op-amp has a finite gain and infinite bandwidth

\[
H(s) = -\frac{Z_f}{Z_i} \frac{1}{1 + \frac{2}{A}} \quad A \Rightarrow \frac{A}{1 + \frac{s}{p_{op}}}
\]

\[
\frac{1}{1 + \frac{2}{A}} = \frac{A}{A + 2} = \frac{A}{1 + \frac{s}{p_{op}}} + 2 = \frac{1}{1 + \frac{A}{2p_{op}}}
\]

**LPF**: \( H(s) = -\frac{Z_f}{Z_i} \times \frac{1}{1 + \frac{s}{p_{filter}}} \times \frac{1}{1 + \frac{A}{2p_{op}}} \)
ACTIVE FILTERS

Now, we know we want high DC gain!

\[ A_v = g_m R_{out} = \frac{1}{2} g_m r_o = \frac{I_{ds}}{V_{sat}} \frac{1}{\lambda I_{ds}} = \frac{1}{V_{sat}} \times f(L) \]

\[ \omega_{p1} = \frac{1}{R_{in} C_{in\_equivalent}} \approx \frac{1}{R_{in} C_{gs}} = \frac{1}{R_{in} \cdot \frac{2}{3} \cdot W \cdot L \cdot C_{ox}} \]

\[ g_m = \mu C_{ox} \frac{W}{L} V_{sat} \quad \text{and} \quad a_{v0} = g_m R_o \]

\[ \therefore \omega_{p1} = \frac{3}{4} \frac{\mu}{L^2} \cdot \frac{r_o}{a_{v0} R_{in}} \cdot V_{sat} \]

\[ V_{sat} \text{ is a crucial parameter for trading off gain, BW, and swing.} \]
ACTIVE FILTERS

Or, you can attack them individually!

\[ A_v = g_m R_{out} \]

- W/L
- Ids
- folding
- Cascoding
- Ids
- L
AMPLIFIER DESIGN PLAN

\[ I_{ds} = k \cdot \frac{W}{L} \left( V_{gs} - V_t \right)^2 = k \cdot \frac{W}{L} V_{sat}^2 \]

\[ g_m = 2k \cdot \frac{W}{L} V_{sat} = 2 \sqrt{k \cdot \frac{W}{L} I_{ds}} = \frac{2I_{ds}}{V_{sat}} \]

4 design variables \((I_{ds}, V_{sat}, g_m, W/L)\) and 2 equations!

- Design for \(g_m\) and DC gain: Need to pick \(V_{sat}\) and \(I_{ds}\) first!
**AMPLIFIER DESIGN PLAN**

Now, add swing constraint:

\[
I_{ds} = k \cdot \frac{W}{L} \left( V_{gs} - V_{t} \right)^2 = k \cdot \frac{W}{L} V_{sat}^2
\]

\[
g_m = 2k \cdot \frac{W}{L} V_{sat} = 2 \sqrt{k \cdot \frac{W}{L} I_{ds}} = \frac{2I_{ds}}{V_{sat}}
\]

\[
V_{swing} = V_{dd} - 2V_{sat}
\]

5 design variables (\(I_{ds}, V_{sat}, g_m, W/L, V_{swing}\)) and 3 equations!

- **Design for \(g_m\) and DC gain:** Still need to pick \(V_{sat}\) and \(I_{ds}\) first!
QUESTIONS

5. How does the mixer perform signal down-conversion?

6. Can the same mixer used for up-conversion perform down-conversion?

7. What is the function of the baseband amplifier?

8. What is the function of the LPF at the end?
**LOCAL OSCILLATOR**

Ideal LC Tank

\[ \omega_0 = \frac{1}{\sqrt{LC}} \]

Real LC Tank

\[ \omega_0 = \frac{1}{\sqrt{L_1 C_1}} \sqrt{1 - \frac{R_1^2 C_1}{L_1}} \]

\[ Q_L = \frac{\omega_0 L_1}{R_1} \]
LOCAL OSCILLATOR

- Tuning is provided by the programmable capacitor
- Tuning range:
  - 902MHz – 928MHz
  - Able to compensate for 5% process variation
  - Able to compensate for 2% inductance variation
- \( L = 17\text{nH}, \ Q = 30 \)
- Output swing 1Vp-p
- \( I_{bias} = 200 – 300\text{uA} \)
LOCAL OSCILLATOR – USE MOS VARACTOR FOR TUNING

MOS varactor

MOS varactor

CV-characteristic

Tuning range
ACTIVE LOW-PASS FILTERS

[Diagrams showing active low-pass filter configurations and their frequency response graphs, including components like resistors (R), capacitors (C), and operational amplifiers (op-amps).]
ACTIVE HIGH-PASS FILTERS

\[ A_v = 1 + \frac{R_2}{R_1} \]

\[ f_c = \frac{1}{2\pi \sqrt{R_1 C_1 C_2}} \]
ACTIVE BAND-PASS FILTERS
KI6: WRAPPING UP: THE POWER OF SMARTPHONES

Smart office!?
KI6: WHAT ENABLES THE POWER OF SMARTPHONES?

Devices/Circuits
- antennas
- sensors
- signal transmission
- converters
- amplifiers
- drivers
- displays
- transistors

Platforms
- analog
- computation
- protocols
- digital
- networking

Systems
- apps
- signal processing
- security
- operating systems
- networking
KI6: WHAT ENABLES THE POWER OF SMARTPHONES?

- ECE311/312
- ECE331/332
- ECE341/342
- ECE451
KI6: WHAT ENABLES THE POWER OF SMARTPHONES?

But the advances have been mainly driven by semiconductors and signal processing.
KI6: WHAT ENABLES THE POWER OF SMARTPHONES?

Moore’s Law Scaling and Exponential Increase in Functionality
KI6: WHAT ENABLES THE POWER OF SMARTPHONES?

Moore’s Law Scaling and Exponential Increase in Functionality
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

A lot of storage for the exponential amount of garbage we want to keep with us.
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

A lot of graphics capabilities

Qualcomm Snapdragon 820 Mobile SOC
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

Global Mobile Data Traffic Growth / Top-Line
Global Mobile Data Traffic will Increase 8-Fold from 2015–2020

Source: Cisco VNI Global Mobile Data Traffic Forecast, 2015–2020
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KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

- Increase connectivity through innovations in modulation technology

![Graphs showing different modulation techniques:](image)

- a. Unmodulated
- b. Amplitude
- c. Frequency
- d. Phase

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KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

- AM or FM is simple but is inefficient for frequency spectrum usage

![Diagram of AM transmission system]

- The oscillator is used to generate carrier signal
- The simplest AM method uses a MOSFET to turn the carrier signal “on” or “off”
- The receiver uses the band-pass filter to tune to the carrier frequency.
- The diode is the simplest way for AM detection.
- If the load is a light (a simple earphone), the receiver doesn’t really need power supply as the received signal energy can drive the load directly
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

• Limitations of AM:
  – AM signals are more susceptible to noise, especially weather related noise
  – An AM channel only emits one signal channel (can’t do stereo)
  – The receiver has poor selectivity, particularly when the carrier frequency is reasonably high.
    » Hard to control the bandwidth shape (narrow) when the center frequency is increased
  – Starting from the 1920s, the vacuum tubes were used to amplify the received signal to improve receiver sensitivity. However, selectivity is still the major obstacle at the time
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

- FM:
  - It doesn’t rely on varying amplitudes, it doesn’t get as much noise interference
  - An FM channel potentially allow for the source to emit two sub-channels of information simultaneously, allowing for left and right audio channels, perfect for stereo quality, if the carrier frequency is sufficiently high
  - Short transmission distance (< 50 miles)
  - Both AM and FM are analog mode of communication. They are very inefficient in the use of limited frequency spectrum.
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

- To improve spectrum efficiency:
  - Modern communication relies on digital signals in the form of symbols.
  - The signal bandwidth for a digital communications channel depends on the symbol rate as opposed to the bit rate.
    \[ \text{bit rate} = \text{symbol rate} \times \text{bits per symbol} \]
  - Phase modulation is more suited for digital signal communication
    » Binary phase shift keying (BPSK): 1 bit per symbol
    » Quadrature phase shift keying (QPSK): The four symbols are +45°, +135°, -45°, and -135°.
      - 2 bits per symbol
      - Change in one of the bits \(\rightarrow\) 90 degree shift
      - Change in both bits \(\rightarrow\) 180 degree shift

![constellation diagram](image)
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

• To improve spectrum efficiency:
  – Phase modulation is more suited for digital signal communication
    » Differential $\pi/4$ quadrature phase shift keying ($\pi/4$ DQPSK):
      • Allow only $\pm \pi/4$ and $\pm 3\pi/4$ for each bit change
      • Can be viewed as superimposing two QPSK signal constellations offset by 45°
      • To reduce complexity, during each symbol period, a phase angle from one of the QPSK constellations is transmitted. The two constellations are used alternately to transmit every pair of bits. ➔ the output demodulation rate is doubled compared to QPSK ➔ think about pipelining
      • One additional (differential) bit codes which QPSK constellation ➔ giving effective 3bits/symbol
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

- Problems with the conventional PSK schemes
  - Abrupt changes in carrier signal due to phase change

These abrupt changes cause harmonics extending to infinity

Produce an RF spectrum of considerable bandwidth

Not efficient for limited spectrum usage!
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

- To improve spectrum efficiency:
  - Minimum shift keying (MSK)
    - Continuous phase modulation scheme where the modulated carrier contains no phase discontinuities and frequency changes occur at the carrier zero crossings.
    - The difference between the frequency of a logical zero and a logical one is always equal to half the data rate
      - For example, a 1200 bit per second baseband MSK data signal could be composed of 1200 Hz and 1800 Hz frequencies for a logical one and zero respectively
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

• Problems with MSK:
  – MSK is great for transmitting data where the data rate is relatively low compared to the channel BW
    » i.e. for high data rates, it still occupy too wide of a BW for the need of current RF applications, even though it is a lot better than BPSK/QPSK.
    » The spectrum energy outside the required BW mainly comes from the data source, especially when data rates are going up!
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

- Gaussian MSK:
  - One solution is to forcefully reduce the spectrum energy outside the defined band (say 200KHz) by using a pre-modulation filter
    - Gaussian filter is a good candidate
    - This leads to GMSK (Gaussian MSK)
KI6: WITH “FREE” TRANSISTORS, WHAT ADVANCES WERE MADE?

- 4G/LTE:
  - Need more performance (data rate) per channel
  - 16 QAM (Quadrature Amplitude Modulation) → 4-bit/symbol → combination of amplitude and phase modulations.
# KI6: CELLPHONE COMMUNICATION STANDARD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>E-GSM900</th>
<th>DCS1800</th>
<th>IS-136</th>
<th>IS-95</th>
<th>PDC</th>
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<tbody>
<tr>
<td>Tx (MHz)</td>
<td>880-915</td>
<td>1710-1785</td>
<td>824-849</td>
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<td></td>
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<td>1850-1910</td>
<td></td>
<td>1477-1501</td>
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<tr>
<td>Rx (MHz)</td>
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<td>1805-1880</td>
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<td>1930-1990</td>
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<td>1429-1453</td>
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<td>TDMA</td>
<td>TDMA</td>
<td>CDMA</td>
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<td>(\pi/4)-DQPSK</td>
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<td>(\pi/4)-DQPSK</td>
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<tr>
<td>Carrier spacing (kHz)</td>
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<td>200</td>
<td>30</td>
<td>1250</td>
<td>25</td>
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<td>Duplex</td>
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<td>FDD</td>
<td>FDD</td>
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</tbody>
</table>
KI6: CELLPHONE COMMUNICATION STANDARD

- TDMA (Time Division Multiple Access) used on GSM phones

\[
\sum \begin{cases} 
\text{User 1} \\
\text{User 2} \\
\text{User 3}
\end{cases}
\]

Composite (\(\sum\))

\(time\)
KI6: WHAT ABOUT NOISE?

- At the end of the receive, the quality of the signal depends on the noise level
  - Carrier-to-noise ratio decreases through the receiver
  - The minimum detectable signal (MDS) is when C/N ratio reaches zero.
KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?
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Source-degenerated Common-source LNA

Antenna & Propagation

RF Frontend

Baseband Backend

Power Supply

Antenna

Diplexer

BPF

PA

Mixer

LO

LNA

Mixer

BPF

Vin

ω₁

ω₂

Ls

M₁

Vₛ

id

storage

A/D
KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?
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- R-String DAC
- Flash ADC

Antenna & Propagation
RF Frontend
Baseband Backend
KI6: WHAT DO AMPLIFIERS HAVE TO DO WITH ALL OF THESE?
KI6: FUTURE OF SMARTPHONE?
LOCAL OSCILLATOR

Ideal LC Tank
\[ \omega_0 = \frac{1}{\sqrt{LC}} \]

Real LC Tank
\[ \omega_0 = \frac{1}{\sqrt{L_1 C_1}} \sqrt{1 - \frac{R_1^2 C_1}{L_1}} \]

\[ Q_L = \frac{\omega_0 L_1}{R_1} \]
LOCAL OSCILLATOR

- Tuning is provided by the programmable capacitor
- Tuning range:
  - 902MHz – 928MHz
  - Able to compensate for 5% process variation
  - Able to compensate for 2% inductance variation
- L = 17nH, Q = 30
- Output swing 1Vp-p
- Ibias = 200 – 300uA
LOCAL OSCILLATOR – USE MOS VARACTOR FOR TUNING

MOS varactor

MOS varactor

CV-characteristic

Tuning range
NOISE

- Thermal noise
- Shot noise
- Noise 1/f
- Burst noise
- Transit time noise

Thermal noise

Produced by current fluctuations due to thermal energy in electrons. It is reduced by cooling the circuit even down to LN temperatures

\[ v_{\text{rms}} = \sqrt{4 k_B T R f} \]
NOISE

Shot noise

Occurs when electrons have to flow across a barrier (diode). Electrons arrive individually and provoke a random fluctuation in the current. The rms value of the shot noise is given by the Schottky formula

$$i_n = \sqrt{i I q f}$$

1/f noise

It occurs in almost all electronic devices. It is the consequence of a variety of phenomena like impurities in a conductive channel, or recombination in a transistor due to base current. This kind of noise is typically overshadow in electronic devices at high frequencies. The distribution is approximately Gaussian.
BURST OR “POPCORN” NOISE

Burst or “popcorn” noise
Step-like transitions between two or more discrete voltage or current levels, as high as several hundred of microvolts. It is produced by periodic trapping of carriers in impurities or in defect interfaces in the bulk. These defects can be provoked by manufacturing processes as ion implantation. Whether or not popcorn noise is a real problem, depends on your application, but when you work with small signals and low frequencies (or even DC), it is often a practical issue.

http://www.advsolned.com/example_popcorn_noise.html
TRANSIT-TIME NOISE

When the time taken by electrons to travel from emitter to collector is comparable to the period of the signal. It is important at high frequencies and dominates over other terms.
COUPLED NOISE

This is noise captured in the electronic circuits by inductive or capacitive coupling. The sources are various:

- Crosstalk: signal in one channel leaks onto the signal in other channel
- Static noise: produced by atmospheric or natural disturbances like lightning
- Industrial noise: automobiles, ignition of electric motors, HV wires...
- Solar noise: generated in the solar corona. These electrical disturbances generated in the Sun reaches the Earth as random EM signals
- Cosmic noise: produced by stars. It is smaller than the solar noise (because the distance) but collectively (high number) can have apretiable effects
REDUCTION OF EM NOISE INFLUENCE

When building a circuit we want to avoid noises to have the true output of our circuit. Different techniques and strategies can be used to reduce the noise influence in the circuits

- **Faraday cage**: it is an enclosure that shields the circuit from external EM noise. A Faraday cage is a grounded conductive enclosure.

- **Avoid ground loops**: ground loops generate a voltage difference between two ground nodes. Bring all ground wires to the same potential in a ground bus.

- **Wiring**: using coaxial cables can reduce noise influence (the mesh acts as a Faraday cage). Also twisted pairs decreases the loop sizes randomizing the noise picking and reducing the overall noise signal.

- **Filtering**
NOISE: FARADAY CAGES
FFEWS AND WINDOWING - TIME DOMAIN WAVEFORMS

```matlab
>> clear
>> t = [0:255];
>> om = 0.2;
>> y = cos(om*t);
>> stem(t,y)
>> title('Original Waveform')
```
WINDOW FUNCTIONS

```matlab
>> win1 = window(@triang,256).';
>> stem(t,win1)
>> title('Triangular Window')

>> win2 = hann(256).';
>> stem(t,win2)
>> title('Hanning Window')
```
WINDOWED WAVEFORMS

>> stem(t,y.*win1)
>> title('Triangular Windowed Waveform')

>> stem(t,y.*win2)
>> title('Hanning Windowed Waveform')
FFT AND WINDOWING

>> k = [0:255];
>> omg = 2*pi*k/256;
>> stem(omg,abs(fft(y)))
>> title('Original FFT')
FFT AND WINDOWING

>> stem(omg,abs(fft(y.*win1)))
>> title('FFT with Triangular Window')

>> stem(omg,abs(fft(y.*win2)))
>> title('FFT with Hanning Window')
COMPARISON BETWEEN FILTERS

ord = 4;

[zb,pb,kb] = butter(ord,1000,'s');
[zc,pc,kc] = cheby1(ord,3,1000,'s');
[ze,pe,ke] = ellip(ord,3,100,1000,'s');

filtb = zpk(zb,pb,kb);
filtc = zpk(zc,pc,kc);
filte = zpk(ze,pe,ke);

bode(filtb,filtc,filte)
legend('Butterworth','Chebyshev','Elliptic')
4\textsuperscript{TH} ORDER FILTERS

Bode Diagram

- Magnitude (dB)
- Phase (deg)

Frequency (rad/s)

Butterworth
Chebyshev
Elliptic

Bode Diagram

- Magnitude (dB)
- Phase (deg)

Frequency (rad/s)

Butterworth
Chebyshev
Elliptic
8TH ORDER FILTERS
FILTER COMPLEXITY – 4TH ORDER

```matlab
>> filtb
filtb =
    1e+12
------------------------------------------
(s^2 + 1848s + 1e06) (s^2 + 765.4s + 1e06)
Continuous-time zero/pole/gain model.

>> tf(filtb)
ans =
    1e12
-------------------------------------------------
 s^4 + 2613 s^3 + 3.414e06 s^2 + 2.613e09 s + 1e12
Continuous-time transfer function.

>> filte
filte =
    1e-05 (s^2 + 4.687e07) (s^2 + 2.707e08)
---------------------------------------------------
(s^2 + 412.7s + 1.982e05) (s^2 + 168.5s + 9.044e05)
Continuous-time zero/pole/gain model.

>> tf(filte)
ans =
    1e-05 s^4 + 1.783e-19 s^3 + 3176 s^2 + 1.356e-10 s + 1.269e11
-------------------------------------------------------------
 s^4 + 581.3 s^3 + 1.172e06 s^2 + 4.067e08 s + 1.792e11
Continuous-time transfer function.
```
FILTER COMPLEXITY – 4th ORDER

2nd order Butterworth LPF

4th order Butterworth LPF
FILTER COMPLEXITY – 4TH ORDER

>> filtb
filtb =

1e+24

(s^2 + 1962s + 1e06) (s^2 + 1663s + 1e06) (s^2 + 1111s + 1e06) (s^2 + 390.2s + 1e06)
Continuous-time zero/pole/gain model.

>> tf(filtb)
ans =

1e24

(s^8 + 5126 s^7 + 1.314e07 s^6 + 2.185e10 s^5 + 2.569e13 s^4 + 2.185e16 s^3 + 1.314e19 s^2 + 5.126e21 s + 1e24
Continuous-time transfer function.

>> filte
filte =

1e-05 (s^2 + 2.183e06) (s^2 - 6.821e-13s + 2.808e06) (s^2 + 6.821e-13s + 5.595e06) (s^2 + 4.158e07)
(s^2 + 248.5s + 6.769e04) (s^2 + 183.9s + 3.948e05) (s^2 + 101.8s + 7.679e05) (s^2 + 4.158e07)
Continuous-time zero/pole/gain model.
>> tf(filte)

ans =

1e-05 s^8 - 1.954e-19 s^7 + 521.7 s^6 - 4.348e-11 s^5 + 4.742e09 s^4 - 0.001027 s^3 + 1.45e16 s^2 - 2084 s + 1.426e22
(s^8 + 565.5 s^7 + 2.318e06 s^6 + 1.06e09 s^5 + 1.739e12 s^4 + 5.862e14 s^3 + 4.436e17 s^2 + 8.663e19 s + 2.014e22
Continuous-time transfer function.
FILTER COMPLEXITY – 8\textsuperscript{TH} ORDER

4\textsuperscript{nd} order Butterworth LPF

8\textsuperscript{nd} order Butterworth LPF