HW1

1. Many simple antennas, such as a dipole, are most efficient when they are a significant fraction of the wavelength (quarter or half). (a) For operation at 900 MHz, what is the half-wave dipole length? (b) At 2.4 GHz? (c) At 10 MHz? (d) Explain the choice of carrier frequency based on this information for portable wireless devices. (e) (Bonus) What is the downside of a very short antenna (l ≪ λ)?

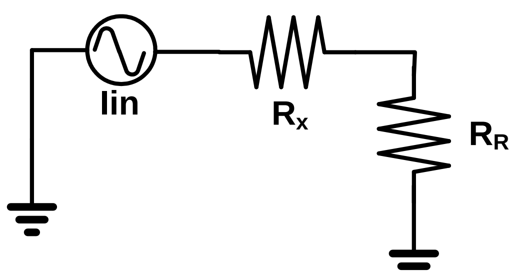
Half wavelength at 900MHz: $\frac{1}{2}\lambda = \frac{1}{2} \times \frac{c}{f} = \frac{1}{2} \times \frac{3 \times 10^8 m/s}{900MHz} = 16.67cm$

Half wavelength at 2.4GHz: $\frac{1}{2}\lambda = \frac{1}{2} \times \frac{c}{f} = \frac{1}{2} \times \frac{3 \times 10^8 m/s}{2.4GHz} = 6.25cm$

Half wavelength at 10MHz: $\frac{1}{2}\lambda = \frac{1}{2} \times \frac{c}{f} = \frac{1}{2} \times \frac{3 \times 10^8 m/s}{10MHz} = 15m$

A practical size of stand-alone antenna in portable wireless devices ranges from 1cm to several 10s cm. This translates to a carrier frequency from several 100s MHz to 15GHz.

An antenna is an energy transformation system which converts driving current into EM radiation. It can be modeled by a simple schematic as shown below. Resistor R_X refers to the energy loss in the form of heat caused within the antenna conductor. R_R is called radiation resistance which is defined as the total EM power radiated in all directions divided by the square of the driving current. The radiation resistance increases with antenna dimension and thus the efficiency of the antenna is increased. Antennas with very small dimension have small radiation resistance, often comparable to R_X, which results in poor efficiency.



2. **(a) What determines the minimum detectable signal for a receiver? (Hint: What do you hear on a radio when it's tuned to a channel without a station?) (b) What determines the largest signal? (Hint: Consider an audio amplifier that is driven with a signal that is too large for it to handle? Radio receivers also employ amplifiers that exhibit the same behavior.)**

Signal at the receiver output needs to meet a certain SNR (signal-to-noise ratio) so that the information it carries can be retrieved at a satisfactory BER (bit error rate). The extra noise added by electronic devices (transistors, resistors, diodes…) in the circuits deteriorates SNR as signal moves along the receiver. As such, there's a minimum requirement on the input signal strength that makes sure a worst-case SNR still be met.

On the other hand, as signal strength increases, the ratio of output signal to input signal will deviate from the linear relationship and start to experience "compression" or "expansion" due to nonlinearity of the circuits. The output signal is no more a faithful amplified copy of the original input but much distorted. The distortion grows so much that it overwhelms the signal at receiver output. Thus “distortion” determines the largest signal a receiver can operate on.

3. **(a) What’s the typical received signal strength of a cellular phone? (b) What voltage does that impart onto the antenna? (c) How about for WLAN (Wi-Fi)? (Hint: Use the signal strength indicator of your WLAN utility or a program such as iStumbler on a Mac.)**

Cellular network may have a Receiver Signal Strength (RSS) ranging from -40dBm to -110dBm. By properly designing the network cell size and enforcing power management between the base station and the mobile terminal, operating cell phones at these extreme scenarios rarely occurs. In a rural environment, for instance, a typical GSM receiving signal strength is -60dBm to -80dBm.
Assume -70dBm signal strength at 50Ω antenna:

$$V = \sqrt{2*50*1mW*10^{-70dBm/10}} = 100uV$$

RSS in WLAN has less variation than in cellular network because of shorter distance. Typical RSS range is -30dBm to -60dBm. The picture below shows a snapshot of RSS in a 802.11b environment. The green/yellow/red curves indicate peak/instantaneous/average RSS, respectively. 802.11b signal occupies around 2.4GHz and has a bell-shape spectrum in which there’re usually 1-5 peak instantaneous tones.
Assume -45dBm signal strength at 50Ω antenna:

$$V = \sqrt{2*50*1mW*10^{-45dBm/10}} = 1.8mV$$

4. (a) What is the typical loss of a coaxial cable at 1 GHz? (b) What determines the maximum power that we may transmit into a cable? (c) Assuming a minimum detectable signal of -90 dBm (75Ω), what is the maximum distance we can communication over a cable? To answer this question, use the results of part (b).

(a) Typical loss of a coaxial cable at 1GHz is from 0.15dB/meter to 0.4dB/meter.

(b) The max transmitter power is limited by 2 factors. One is the max current density that the inner conductor in a coaxial cable can carry. The other is the max electric field that the dielectric materials can sustain before it starts to conduct current between the inner conductor and outer ground shell.

(c) The maximum communication distance over a cable is determined by:

$$\frac{\text{max allowable signal strength at transmitter - min detectable signal at receiver}}{\text{loss per distance}}$$

As mentioned in part (b), the maximum power transmitted is limited by either current or electric filed. A typical max voltage in a coaxial cable is on the order of several thousand volt. We use 5000V as an example here.

$$\frac{10*\log\left(\dfrac{5000V^2}{2*75\Omega*1mW}\right)-(-90dBm)}{0.15dB/meter} = 1.148km$$

$$\frac{10*\log\left(\frac{5000V^2}{2*75\Omega*1mW}\right)-(-90dBm)}{0.4dB/meter}=430m$$

5. How do we increase the communication distance beyond the limits imposed in the previous problem? Why can we not do this indefinitely?

From 4, the communication distance can be increased by 1. increase transmitter power, 2. lower minimum detectable signal strength (called sensitivity), and 3. reduce cable loss. Thermal noise sets an ultimate limit in 2 and 3 because of electron vibration at any temperature other than zero K degree. On the other hand, electro-migration and dielectric breakdown sets the limit on the max current and max voltage that can be put out into the cable. Therefore the cable transmission distance can not be increased indefinitely.

6. Why are cables terminated? Termination is the process of adding a resistance to the end of a cable transmission line equal in value to the characteristic resistance of the line (or designing the input stage of the receiver to have the same impedance as the line).

Termination at the end of the cables is needed in order to prevent the incoming signal from bouncing back to the source. This makes sure most signal energy is conveyed into the receiver. The amount of reflection is determined by the termination impedance, the length of the cable and the cable characteristic resistance. In the case where impedance is same as transmission line impedance, there is no reflection regardless of the length of the cable which eases the distribution of the signal.

7. A given communication link is tested over the ocean and found to have a range of 10 km. However when the same link is tested in downtown SF, the range is only 1 km. (a) Why? (Hint: Putting the transmitter at the top of a building helps, but does not completely solve the problem). (b) It is found that the signal quality varies dramatically if one walks a few meters around a given location. Explain.

(a) Wireless communication over the ocean is near line-of-sight propagation because there're no terrain obstacles. So it can transmit at a longer distance. In a densely populated city like SF, very often the radio propagation is reflected or deflected by many buildings. The transmitted signal finds different paths to arrive at the destination at different time instant. This is called multi-path effect. Multi-path increases the difficulty of recovering the information successfully. Therefore for the same transmission rate, the transmission distance drops at rural area.

(b) As explained in (a), poor signal quality is due to different path of signal arriving in different phase. Therefore signal strength varies when the phase change is significant which means a movement close to wavelength in space will vary the signal quality. In the case of RF signal at ~100MHz range, it only takes order of meter.

8. In a quiet cafe in downtown Berkeley your Wi-Fi connection is very strong and you can transmit at maximum throughput. However, as more people come in and turn on their laptops, you find your throughput decreasing. (a) Why? (b) How is the bandwidth shared in this scenario?

Radio spectrum is a government regulated resource. Wi-Fi communication is constrained in an ISM band (Industrial, Scientific and Medical) around 2.4GHz due to FCC regulation. All laptop users in the café share the same fixed bandwidth. As more people turn on their WLAN adapter, the bandwidth available to each user drops. The following picture shows the RSS at max download speed. Notice a wider bandwidth (wider bell shape and more peak tones) is allocated to in order to achieve higher speed.

The second cause for reduced throughput is the interference from adjacent users. The more laptops turns on nearby, the more intermodulation distortion (IM) created by them. Intermodulation distortion degrades the bit error rate at the receiver output and slows down the speed.

9. A “jammer” is a device you can buy (illegal) which is used to drop all mobile calls within a certain radius. Can you explain how this device works?

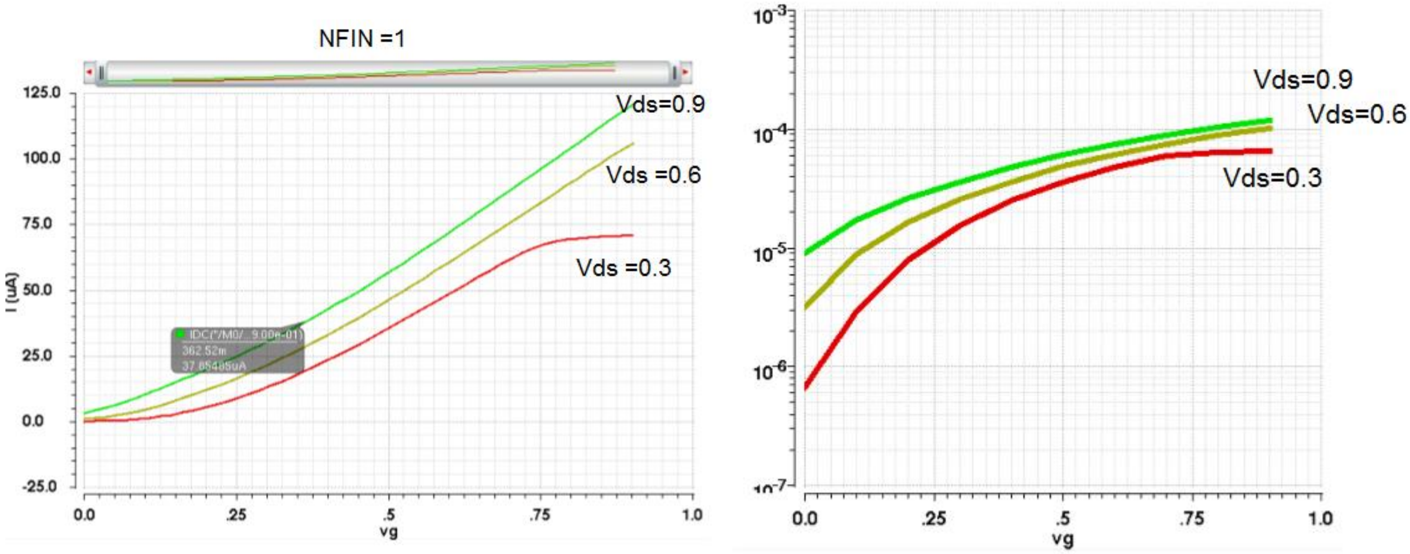
Mobile jammer sends out radio waves at the same frequencies that cellular phones use. This causes enough interference with the communication between cell phones and towers. Strong jamming signal provides big distortion and can saturate the cellular phone receiver to disable its functionality.

10. Suppose that you setup a WiFi network in your house on channel 1 and everything is working great and your maximum throughput is 54 Mbps. A few days later, your neighbor moves in and even though he’s on channel 6 (note only 3 WiFi channels are non-overlapping), your throughput has dropped. Why?

Though the neighbor is using a non-overlapping channel, due to the non-ideality of the filters, there is still some signal power leaking to my channel as noise or interference, reducing the signal to noise ratio (SNR) and lower my throughput.

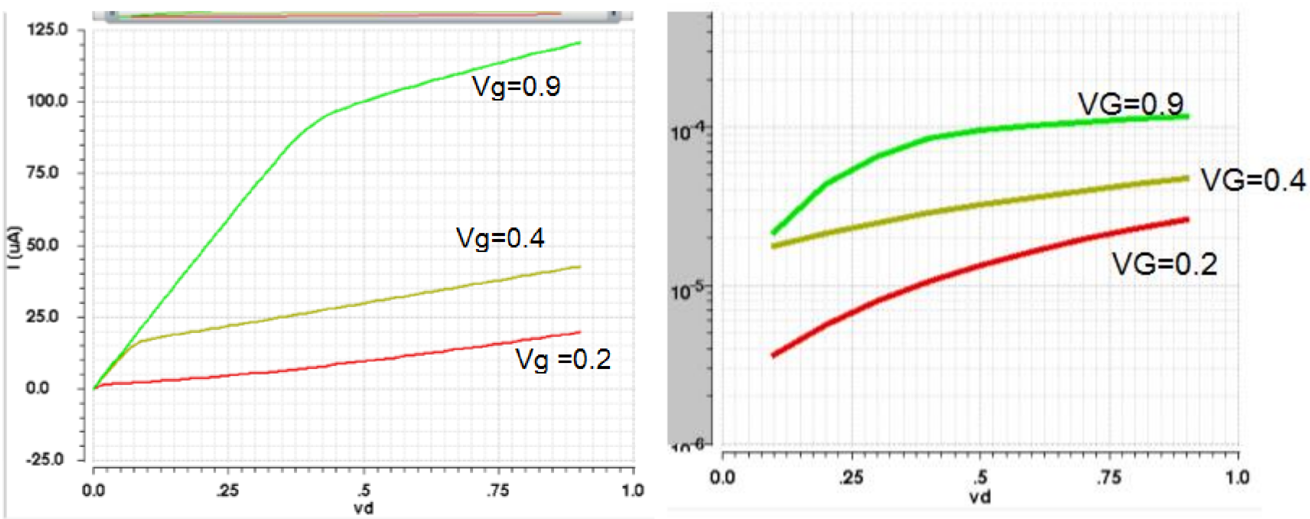
11. 242M Required, 142 optional: Using the Predictive Transistor Model (PTM) (http://ptm.asu.edu/) 7nm MG HPNMOS model, create the following plots. For this technology, VDD = 0.9V, Lmin = 7nm. Note these are FinFET devices so that you can specify the number of fins. Select enough fins to realize a device that can deliver a peak current of 100μA. For other fin parameters, use the param.inc file. To generate the plots, pick three operating points for Vgs and Vds. When sweeping Vds, use three values of Vgs, one below “threshold”, a little above “threshold”, and Vgs = VDD. For Vgs sweeps, pick a Vds point below saturation, around the knee of saturation, and Vds = VDD.

(a) Plot the I-V curves, sweeping both Vgs an Vds and plotting the drain current on a linear and log scale. What can you learn from these graphs? How do they deviate from square law?



ID-VGS

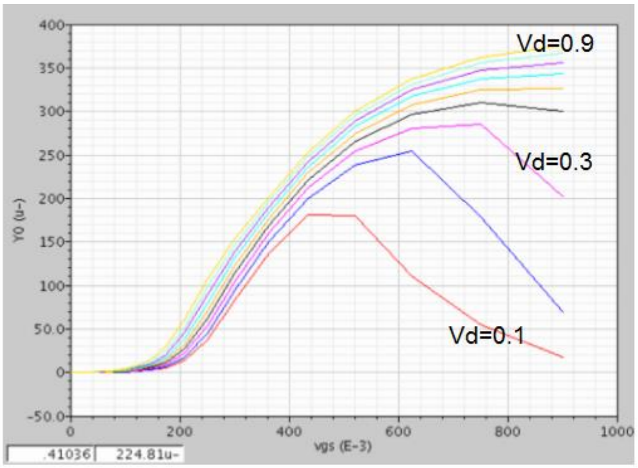
The square law relation does not hold. For low VGS (sub-threshold region), the curve appears exponential. For VGS above sub-threshold, the ID-VGS characteristics are nearly linear (velocity saturation), and do not follow square law.



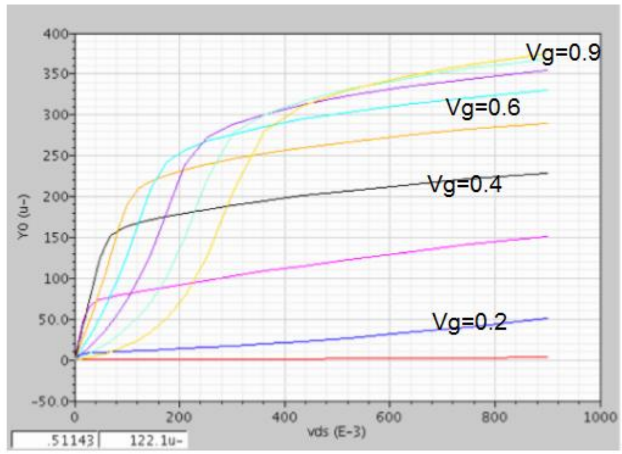
ID-VDS

(b) Plot gm versus Vgs and Vds. Explain qualitatively the behavior of these plots. Why does gm increase/decrease as a function of bias?

GM-VGS

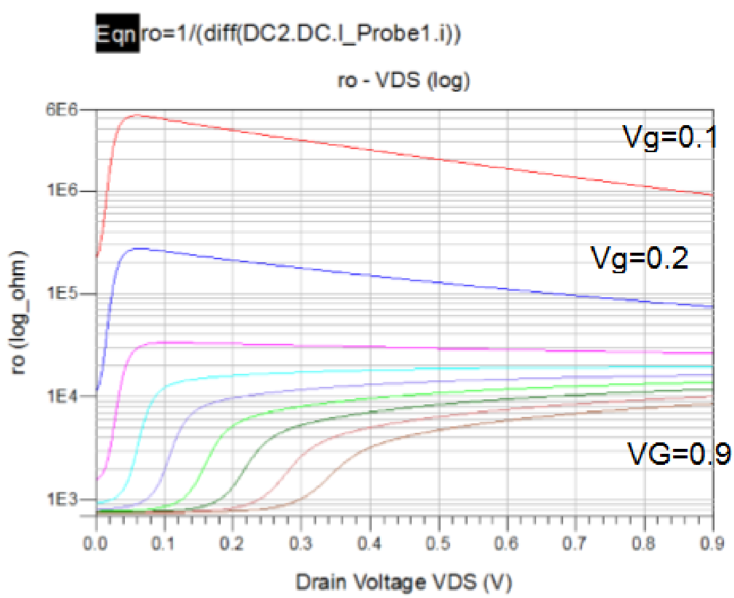


GM-VDS



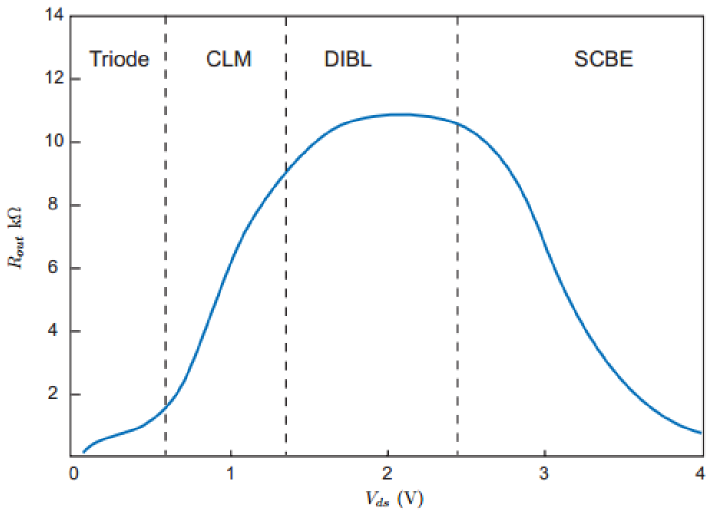
GM-VGS:
After saturation, gm will increase a little with Vds due to the reducing in Vth caused by DIBL.
As VGS goes higher with a low VDS (here, 0.3 V), the transistor comes into in triode (linear) region and Gm drops with VGS **(vertical mobility degradation must be taken into account!!).**
GM-VDS:
At high Vds, GM is quite a constant versus Vds.
It is found that at low Vds (linear) region, Gm goes lower with a lower Vg, this can also be explained by **vertical mobility degradation.**

(c) Plot ro versus Vds. Explain qualitatively the behavior of these plots. Why does ro increase/decrease as a function of bias?

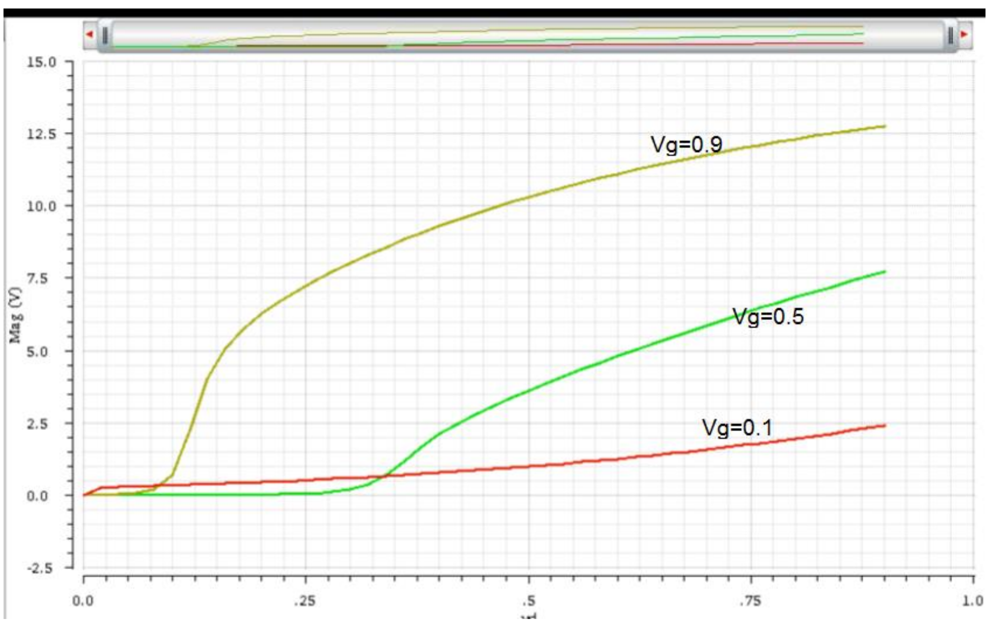


With a high Vds, ro is constant and dominated by CLM. ro ~ VA/ID and is higher for a low Vgs.
ro is lower in triode region.

The typical ro response is shown below.

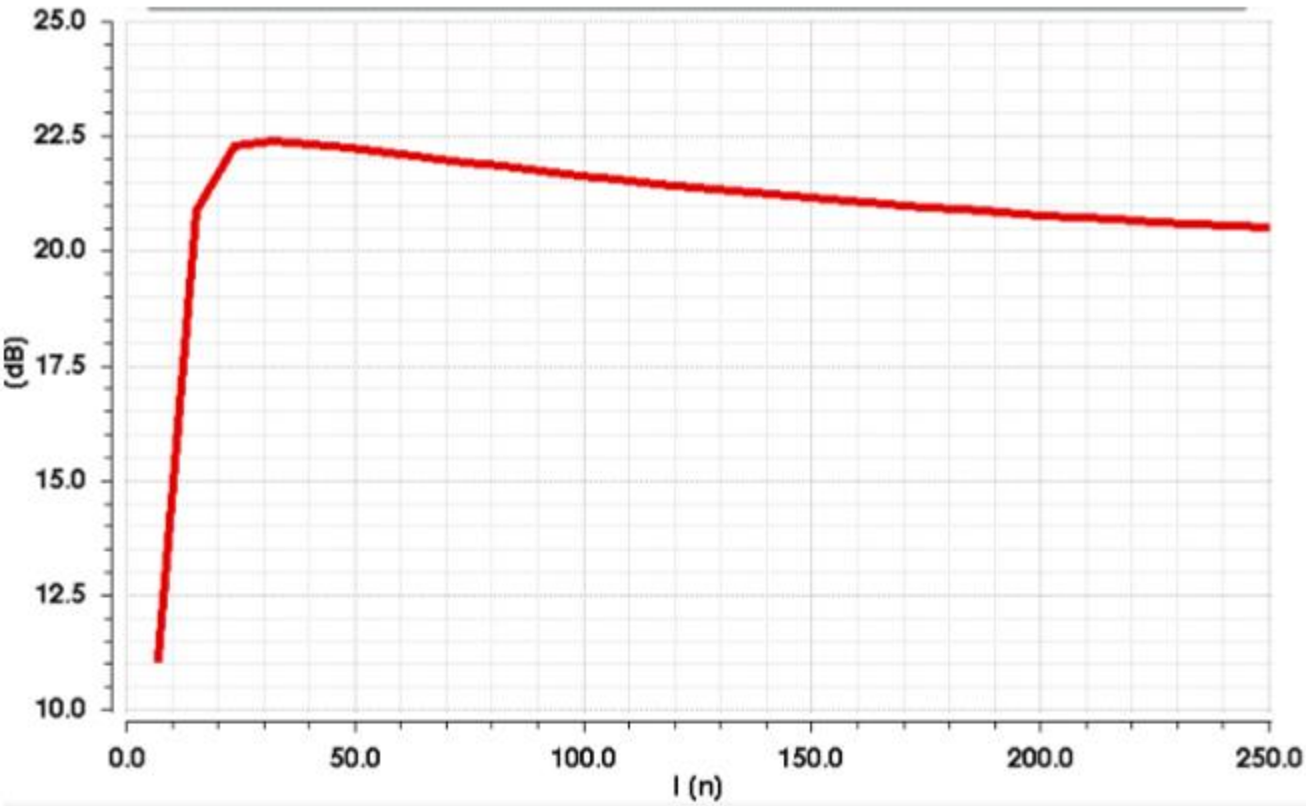


(d) Plot Av (maximum voltage gain) versus Vds.



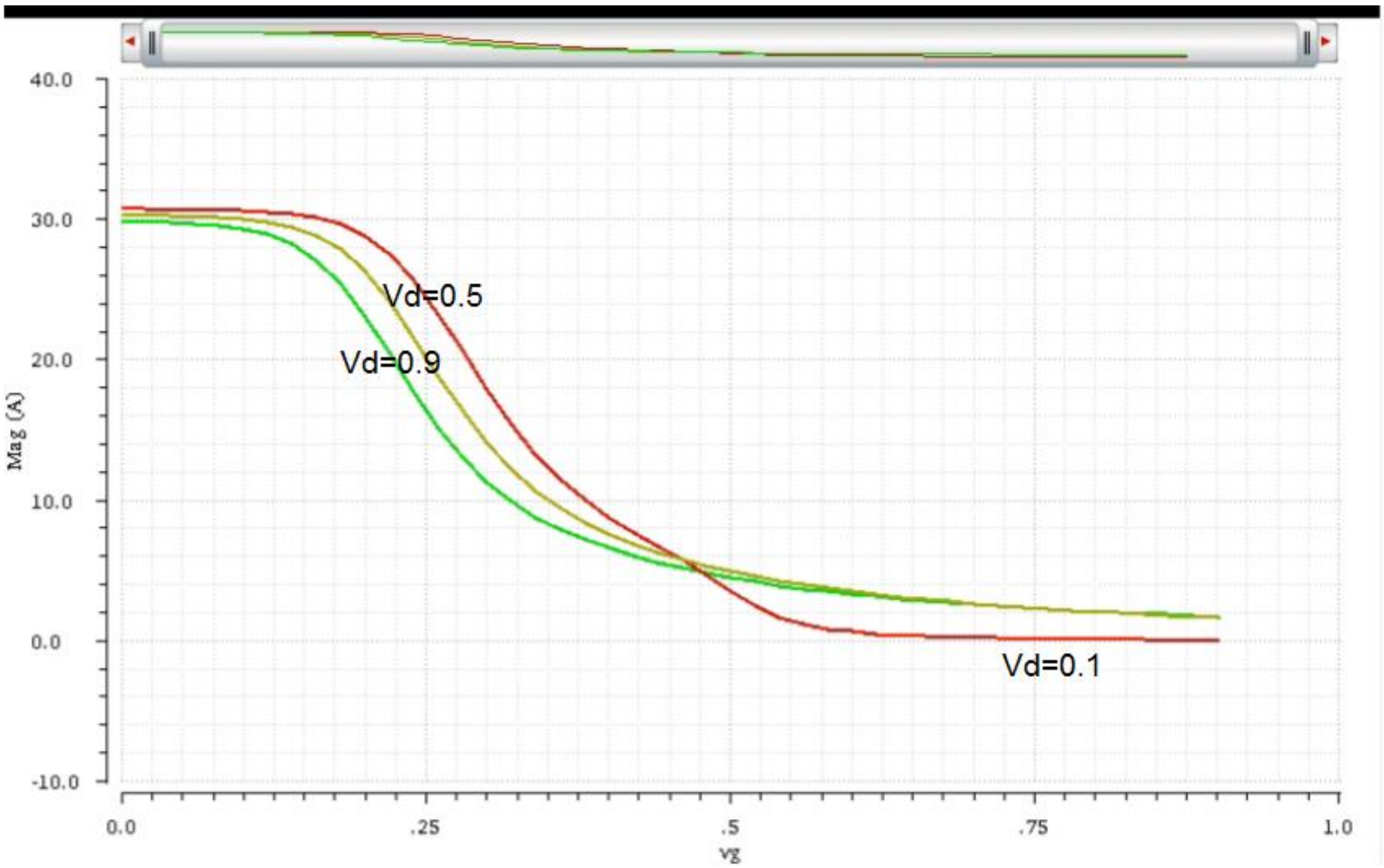
Gain in saturation region (higher VDS) is substantially higher than that in triode region due to higher ro.

(e) Plot Av versus the cannel length L from minimum to 0.25µm. Pick a value of Vgs = Vds = VDD.



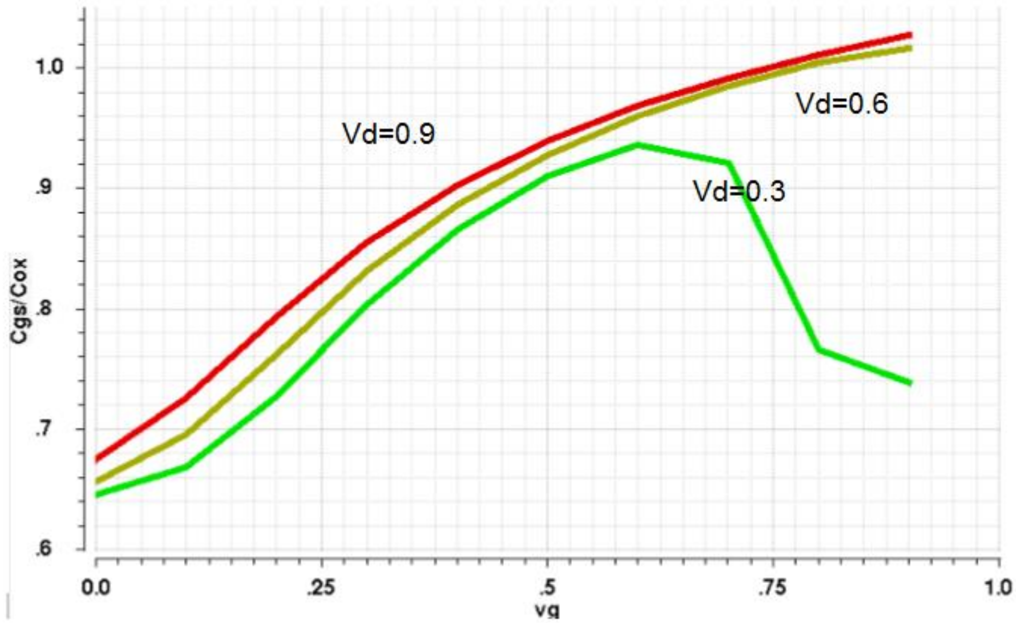
CMOS is running out of steam because the DC gain per device is dropping with smaller L. This makes design very difficult, especially since the DC gain drops with supply voltage

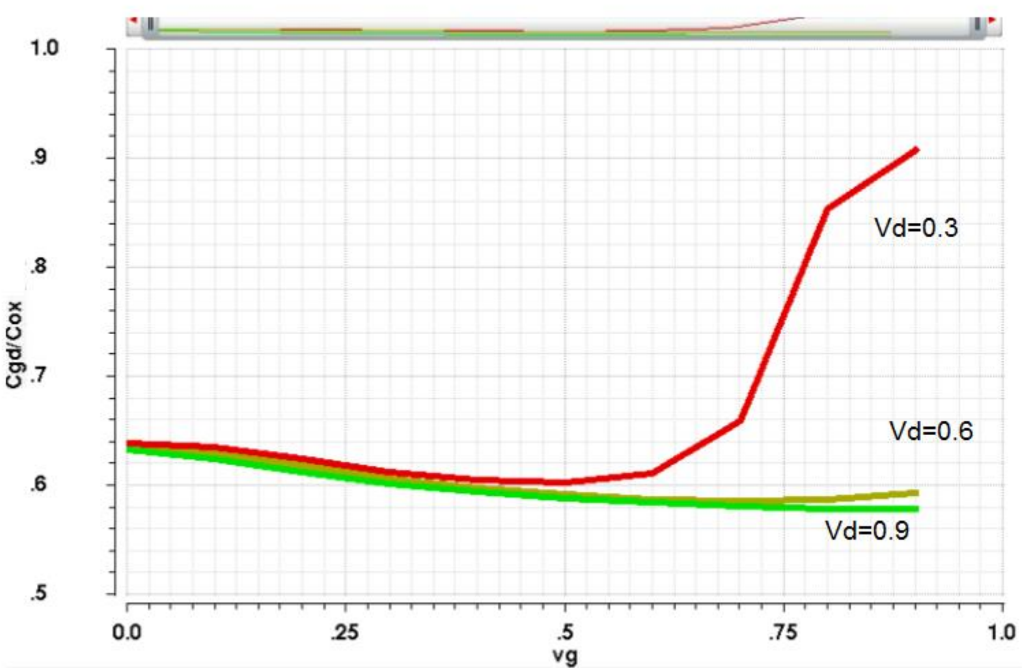
(f) Plot gm/Ids, or the transconductor efficiency, versus Vgs and Vds. Explain qualitatively the behavior of these plots. Why does gm/I increase/decrease as a function of bias? What is the optimal bias point in terms of efficiency? What are the downsides to operating at the optimal point? (Hint: See next bullet.)



Transconductor efficiency is higher with a low VGS, but it is not a desirable region of operation because the gm is too low.

(g) Plot Cgs, Cgd, and Cds while sweeping both Vgs and Vds. Normalize the plots to Cox.

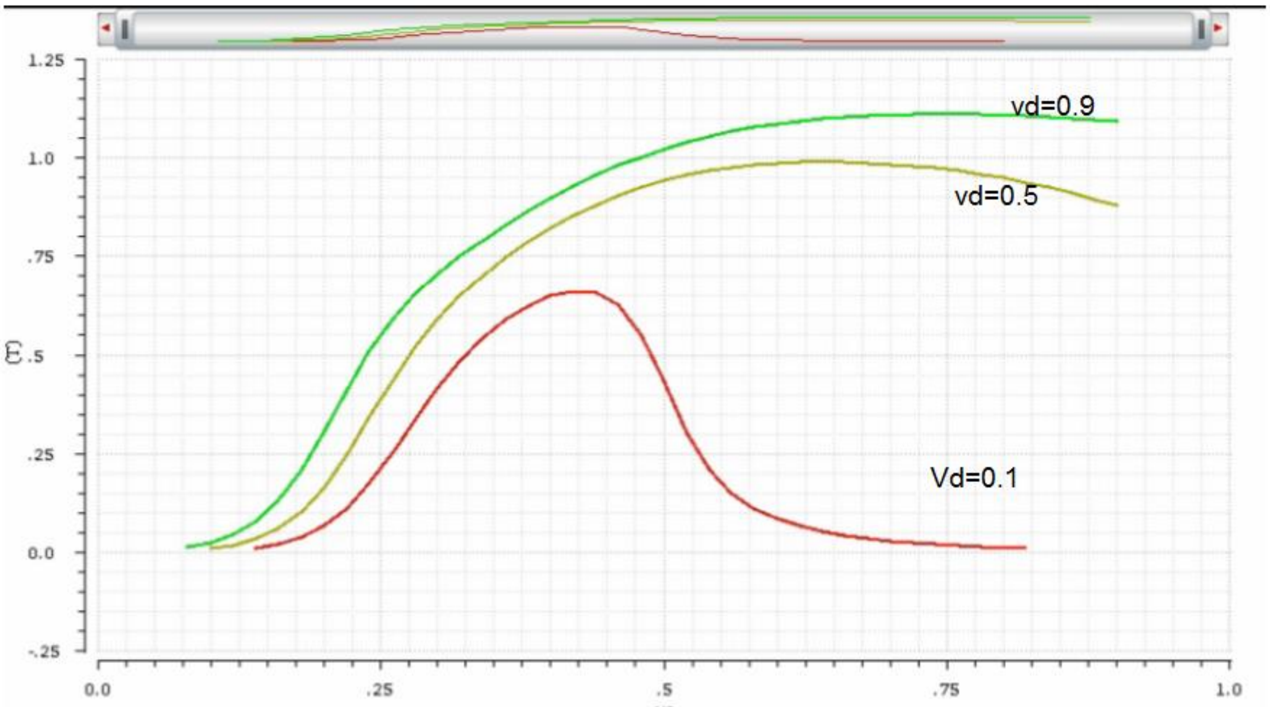




(h) Plot of fT, or the unity gain frequency, versus Vgs and Vds. Explain qualitatively the behavior of these plots. What is the optimal bias point?

Vd=VG=VDD has the highest fT. Basically it is dominated by Gm.

fT-Vg



fT-Vd