Project

- XC pro-rated friday 9AM → Monday 9AM
- leakage : source/body, gate-drain
- SAR B7 → B6 transition

Noise

Environmental

thermal

1/f

My ADC works great, I'm adding bits!

My PGA works great, I can amplify anything

What sets lower limit?

e.g. - mK temp resolution

- strain gauge sensor amplifier nV, ≈ DC
- μV, 2,45 ± 1 MHz

Lower limit set by noise

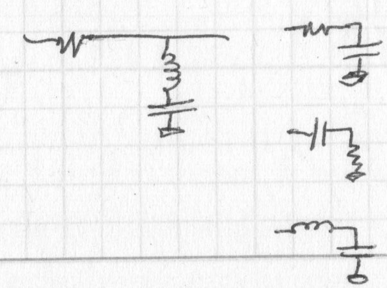
Environmental noise

60 Hz

power line, power supply noise

RF : cell, wifi, μwave ovens

solutions: filtering



Shielding

co-axial

twisted pair

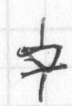
Intrinsic noise

shot noise

thermal noise

1/f noise

Shot noise - uncorrelated carriers over a barrier, e.g. diode

I ↓  If my current is 6 pA

$$1.6\times10^{-12}\frac{C}{s} = \frac{(1.6\times10^{-12})(6\times10^{18}\frac{e}{C})}{1.6\times10^{-19}\frac{C}{e}} \approx 10^{7}\frac{e}{s}$$

$I = 1.6\,pA$ do they arrive once per $0.1\mu s$?

In a ~~resistor~~ low-R wire, yes. (-ish. see below)

In a diode, no.

$\bar{I}$ = average current

actual current is noisey, $I + \bar{I}_n$

$\bar{I}_n^2 = 2 q I \Delta f$

$\bar{I}_n = \sqrt{2 q I \Delta f}$ e.g. $\sqrt{2q(10^7 \frac{e}{s})(5\,Hz)}$

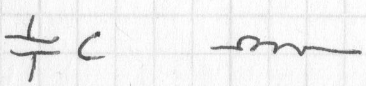
$= 10^4 \frac{e}{s}$ in a 1 Hz BW

$K_B T = (1.38 \times 10^{-23} \frac{J}{K})(300K) = 4 \times 10^{-21}$ J

$1\,J = 1\,Ws = 1\,W/Hz$

$K_B T = 4 \times 10^{-21} \frac{W}{Hz}$ → at room temp

<u>Equipartition</u>



$E = \frac{1}{2} C V^2$ $E = \frac{1}{2} L i^2$

$\bar{E}_n = \frac{1}{2} K_B T = \frac{1}{2} C \bar{V}_n^2$ say $C = 1pF$

$\bar{V}_n^2 = \frac{K_B T}{C} = \frac{4 \times 10^{-21} J}{1pF} = 4 \times 10^{-9} V^2 \approx 60\mu V$

avg. energy

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thermal noise - random motion due to temperature

Brownian motion

Johnson noise

white noise

2 Key theorems

1) equipartition $\bar{E}_n = \frac{1}{2} K_B T$

every storage mode has, on average $\frac{1}{2} K_B T$

2) fluctuation/dissipation $\bar{P}_N = 4 K_B T \Delta f$

every dissipative element causes fluctuation

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fluctuation/dissipation

$\bar{P}_N = 4 K_B T \Delta f = \bar{V}_n^2 / R$

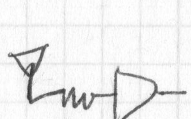
$\bar{V}_n^2 = 4 K_B T R \Delta f$ say $R = 1k\Omega$

$\bar{V}_n = \sqrt{4 (4 \times 10^{-21} \frac{W}{Hz}) 10^3 \Omega \,\Delta f}$

$= 4nV/\sqrt{Hz}\,\sqrt{\Delta f}$

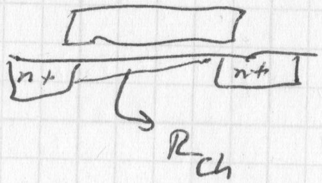
say RF amp for 2.4 GHz ± 1 MHz

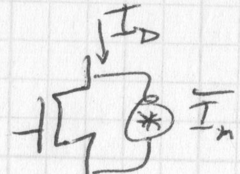
$\Delta f = 2 MHz$

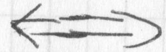


$\bar{V}_n = (\frac{4nV}{\sqrt{Hz}})(\sqrt{10^6}) = 4\mu V$

sets minimum detectable signal voltage/power what about the amplifier?



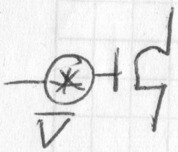




thevenin/norton

$\overline{I}_n = \frac{V_n}{R}$

$$\overline{I}_n^2 = \frac{4k_BT}{R_{ch}}\Delta f$$



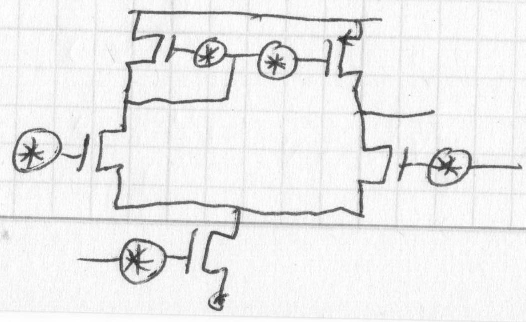
$$\overline{V}_{gn} = \sqrt{4k_bT\left(\frac{2}{3}\frac{1}{g_m}\right)\Delta f}$$

$g_m = 1mS \quad \frac{1}{g_m} = 1K\Omega$

$$\overline{V}_{gn} \simeq 4nV/\sqrt{Hz}\,\sqrt{\Delta f}\,\sqrt{\tfrac{2}{3}}$$

every transistor has this noise!

Impact?



maybe!

$R_{ch} \simeq \left(\frac{3}{2}\right)\left(\frac{1}{g_m}\right)$ for noise calculations

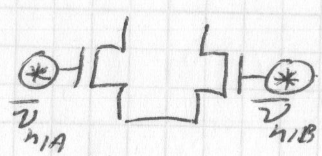
what is the equivalent gate noise that would give me that channel noise?

$$i = g_m v_g \Rightarrow \overline{V}_{g,n}^2 = \frac{\overline{I}_n^2}{g_m^2}$$

$$= \frac{4k_BT\left(\frac{2}{3}g_m\right)\Delta f}{g_m^2}$$

all noise sources are uncorrelated so their powers add, not magnitudes.

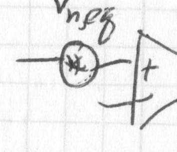
Input pair impact on output



$$\overline{V}_{n,out}^2 = \left(A_V\overline{v}_{n1A}\right)^2 + \left(A_V\overline{v}_{n1B}\right)^2$$

$$\overline{V}_{n,eq}^2 = \frac{\overline{V}_{n,out}^2}{A_V^2}$$

$$= 2\,\overline{v}_{n1}^2$$



$$\overline{V}_{n,eq} = \sqrt{2}\,\overline{v}_{n1}$$

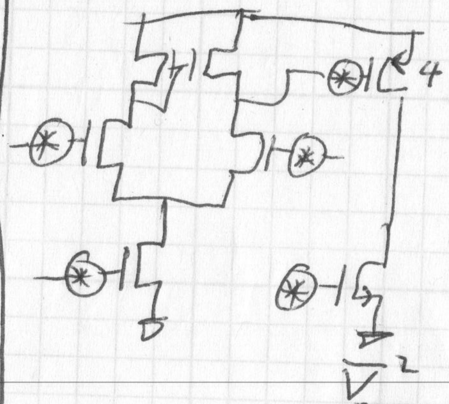
current mirror $\overline{V}^2_{n,out} = 2(g_{m2} R_o \overline{v}_{n2o})^2$

$$\overline{V}^2_{n,eq\,mirror} = \frac{2(g_{m2} R_o)^2 \overline{v}^2_{n2}}{(g_{m1} R_o)^2}$$

effect of mirror noise can be reduced by reducing gain to output, i.e. reduce g_{m2} relative to g_{m1}

both have same I_d, so change $V_{OVP} > V_{OVN}$

what about 2 stage?



forward gain for $\overline{v}_{n4}$ is A_{v2}

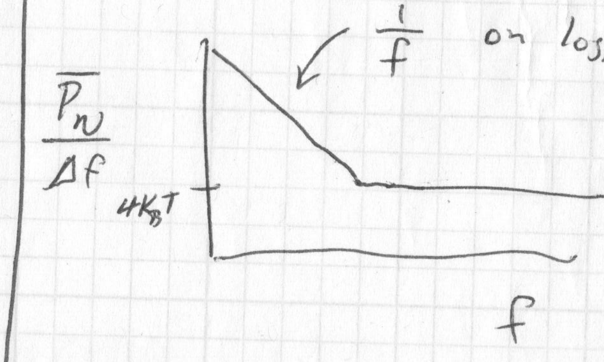
to reflect back to input

$$\overline{V}^2_{n,eq\,m4} = \frac{(A_{v2} v_{n4})^2}{(A_{v1} A_{v2})^2} = \frac{\overline{v}^2_{n4}}{A^2_{v1}}$$

forward gain for m3 is <u>small</u>

LNA - low noise amplifier

at the beginning of an analog chain, take particular care to get low noise and <u>some</u> gain. After that, it doesn't matter as much.



$\frac{1}{f}$ on log/log plot

charge trapping under gate?