EE194-EE290C

28 nm SoC for IoT

Acknowledgement: Wayne Stark EE455 Lecture Notes, University of Michigan
Noise

• Unwanted electric signals come from a variety of sources, both from
  – Naturally occurring noise (Atmospheric disturbances, extraterrestrial radiation, random electron motion)
  – Human interference. (Other communication systems, Lighting, ignition etc.)

• One unavoidable electrical noise is the thermal motion of electrons in conducting media
  – Modeled as white noise, a useful model in communication. (AWGN channel)

When a resistance $R$ at a temperature $T$, random electron motion produces a noise voltage $v(t)$ at the open terminals. Consistent with the central-limit theorem, $v(t)$ has a Gaussian distribution with zero mean and variance:

$$
\overline{v^2} = \sigma_v^2 = \frac{2(\pi k T)^2}{3 h} R \quad \text{Units: } V^2
$$
Noise

\[ \bar{v}^2 = \sigma_v^2 = \frac{2(\pi kT)^2}{3h} R \quad \text{Units: V}^2 \]

For all practical purposes, the mean square voltage spectral density of thermal noise is constant at:

\[ G_v(f) = 2RkT \quad \text{Units: V}^2/\text{Hz} \]

\[ P_a = \frac{\langle [v_s(t)/2]^2 \rangle}{R_s} = \frac{\langle v_s^2(t) \rangle}{4R_s} \]

\[ G_a(f) = \frac{G_v(f)}{4R} = \frac{kT}{2} = \frac{N_o}{2} \quad \text{Units: W/Hz} \]

All frequency components in equal proportion and is therefore called white noise.
Noise Figure (NF)

Noise figure (NF) measure the degradation of Signal-to-Noise ratio (SNR) caused by components in a signal chain.

\[ F = \frac{SNR_{in}}{SNR_{out}} \quad \text{Units: Dimensionless} \]

\[ NF = 10 \log_{10} \left( F \right) = 10 \log_{10} \left( \frac{SNR_{in}}{SNR_{out}} \right) = SNR_{in, dB} - SNR_{out, dB} \quad \text{Units: Dimensionless} \]

It is a number by which the performance of a radio receiver can be specified. Lower the better.
Link Budget

Friis Equation:

\[
\frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4 \pi R} \right)^2
\]

\[
P_r = P_t + G_t + G_r + 20 \log_{10} \left( \frac{\lambda}{4 \pi R} \right)
\]

Gain has units of dB and power has units of dBm or dBW.
# Example Link Budget

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_t$ (Transmit power)</td>
<td>-5 dBm (316.2μW)</td>
</tr>
<tr>
<td>$G_t$ (Transmit antenna Gain)</td>
<td>0 dB</td>
</tr>
<tr>
<td>$G_r$ (Receive antenna Gain)</td>
<td>0 dB</td>
</tr>
<tr>
<td>$\lambda$ (2.45 GHz)</td>
<td>0.12491 m</td>
</tr>
<tr>
<td>$P_r$ (Received power)</td>
<td>-75 dBm (31.6pW)</td>
</tr>
<tr>
<td>Link Margin</td>
<td>70 dB</td>
</tr>
<tr>
<td>Distance (d)</td>
<td>~17 m</td>
</tr>
</tbody>
</table>

\[ NF < R_{ss} - SNR_{min} + 174 - 10 \log_{10}(BW) \]
Receiver NF

\[ NF < R_{ss} - SNR_{\text{min}} + 174 - 10 \log_{10}(BW) \]

For BLE: \( P_e = 0.1\% = 10^{-3} \)

\[ SNR = \frac{\text{Signal}}{\text{Noise}} = \frac{E_b \times R}{N_o \times B} = \frac{E_b}{N_o} \]

\( E_b/N_o \) depends on the type of modulation and demodulator.
Matlab Signal & Noise Modeling

According to the sampling theorem we can represent $x(t)$ by samples at rate $2f_{\text{max}}$.

In addition, assume that $x(t)$ is causal so that $x(t) = 0$ for $t < 0$.

The Fourier transform of $x(t)$ is given by

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft} dt$$

Notice that when $x(t)$ is real then $X(-f) = X^*(f)$. 
Matlab Signal & Noise Modeling

The inverse Fourier transform is

\[ x(t) = \int_{-\infty}^{\infty} X(f) e^{j2\pi ft} df \]

\[ = \int_{-f_{\text{max}}}^{f_{\text{max}}} X(f) e^{j2\pi ft} df \]

Now we can approximate these integrals with finite sums.
Matlab Signal & Noise Modeling

- Since the highest frequency is $f_{\text{max}}$ we sample at a rate $2f_{\text{max}}$.
- Thus the samples are separated in time by $\Delta t = 1/(2f_{\text{max}})$.
- Suppose we have $N$ samples in the time domain.
- We can reconstruct these $N$ samples in the time domain with just $N$ samples in the frequency domain.
- The spacing in the frequency domain is $\Delta f = 2f_{\text{max}}/N$.
- Since $\Delta t = 1/(2f_{\text{max}})$ and $\Delta f = 2f_{\text{max}}/N$

$$\Delta f \Delta t = \frac{1}{N}$$

- That is, we are dividing the interval of the frequency response from $-f_{\text{max}}$ to $f_{\text{max}}$ into $N$ discrete frequencies and we are dividing time from 0 to $(N-1)\Delta t$ into $N$ discrete time samples.
Matlab Signal & Noise Modeling

Then for $|f| < f_{\text{max}}$

$$X(f) = \int_{0}^{\infty} x(t) e^{-j2\pi ft} \, dt$$

$$\approx \sum_{l=0}^{N-1} x(l\Delta t) e^{-j2\pi fl\Delta t} \Delta t$$

$$X_m = X(m\Delta f) = \Delta t \sum_{l=0}^{N-1} x(l\Delta t) e^{-j2\pi m\Delta f l\Delta t}$$

$$= \Delta t \sum_{l=0}^{N-1} x(l\Delta t) e^{-j2\pi ml/N}$$
Matlab Signal & Noise Modeling

• Thus the above expression for $X_m$ is valid for $0 \leq |m| \leq N/2$.
• Notice that $X_{-m} = X_{N-m}$.
• In MATLAB the operation FFT takes an input vector (indexed from 1 to $N$) and produces an output vector (indexed from 1 to $N$).
• The input-output relation is

$$X_k = \sum_{n=1}^{N} x_n e^{-j2\pi(k-1)(n-1)/N} \quad k = 1, \ldots, N$$

The input should correspond to the samples starting at time 0 up to time $(N - 1)\Delta t$. Notice that in order to get the correct magnitude of the frequency response we must multiply what MATLAB produces by $\Delta t$. 
The output samples from 1 to N/2 (when normalized appropriately) correspond to the frequency response $X(0), X(\Delta f), ..., X((N/2)\Delta f) = X(f_{\text{max}} - \Delta f)$.

The samples from N/2 + 2 to N correspond to the frequency response from $X(-f_{\text{max}} + \Delta f), ..., X(-\Delta f)$.

The order can be reversed into the logical order with the MATLAB command `fftshift`.
# Matlab Signal & Noise Modeling

<table>
<thead>
<tr>
<th>Matlab Index</th>
<th>Frequency</th>
<th>Matlab Index</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>N/2+1</td>
<td>-f_{\text{max}}</td>
</tr>
<tr>
<td>2</td>
<td>\Delta f</td>
<td>N/2+2</td>
<td>-f_{\text{max}}+\Delta f</td>
</tr>
<tr>
<td>3</td>
<td>2\Delta f</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>N/2+k</td>
<td>-f_{\text{max}}+(k-1) \Delta f</td>
</tr>
<tr>
<td>m</td>
<td>(m-1) \Delta f</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>N/2+(f_{\text{max}}-f_2)/\Delta f +1</td>
<td>-f_2</td>
</tr>
<tr>
<td>(f_1/\Delta f)+1</td>
<td>f_1</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>N-1</td>
<td>-2\Delta f</td>
</tr>
<tr>
<td>N/2</td>
<td>f_{\text{max}}-\Delta f</td>
<td>N</td>
<td>-\Delta f</td>
</tr>
</tbody>
</table>
Matlab Signal & Noise Modeling

N/2+1  N  1  2  N/2

-f_{max}  \quad -f_2  \quad -\Delta f  \quad 0  \quad -\Delta f  \quad -f_1  \quad f_{max}  \quad -\Delta f
Matlab FFT Caveat

\[ x(t) \xrightarrow{\text{Sample}} x_l = x((l - 1)\Delta t), \quad l = 1, \ldots, N \]

\[ X(f) \xrightarrow{\text{Fourier Transform}} \]

\[ (\text{fft} \ast \Delta t) \]

\[ x_l = x((l - 1)\Delta t), \quad l = 1, \ldots, N \]

\[ X(f) \xrightarrow{\text{Inverse Fourier Transform}} \]

\[ (\text{ifft} / \Delta t) \]

\[ X_k = X((k - 1)\Delta f), \quad k = 1, \ldots, N/2 \]

\[ X_k = X((k - 1 - N)\Delta f), \quad k = N/2 + 1, \ldots, N \]
Simulating Noise

- In a computer simulation of a communication system we represent a continuous time signal with samples according to the sampling theorem.
- A signal can be represented if the highest frequency content is less than half the sampling rate.
- Thus if \( f_s \) represents the sampling rate the simulation bandwidth is \( f_s/2 \).
- If we consider white Gaussian noise the noise has equal power at all frequencies up to the simulation bandwidth.
Simulating Noise

• Thus the power spectral density of the noise in the simulation is

\[ S_n(f) = \frac{N_0}{2} \quad -\frac{f_s}{2} < f < \frac{f_s}{2} \]

• The noise samples (with this finite bandwidth) have variance

\[ \sigma^2 = \int_{-\frac{f_s}{2}}^{\frac{f_s}{2}} S_n(f) \, df = \int_{-\frac{f_s}{2}}^{\frac{f_s}{2}} \frac{N_0}{2} \, df = N_0 f_{max} \]
Digital Baseband Block Diagram

Nordic: nRF52840 Datasheet.
Power Management

1.5V-0.9V

DC/DC Converter

RF LDO
0.8V
250μA

Digital LDO
0.8V
500μA

Analog LDO
0.8V
200μA

PTAT IRef
10μA±15%
1μA±15%
10nA±15%

BG Vref
0.8V±20%
Tunable

Temp. Sensor
To ADC

POR BDet.
Reset Signals

Nordic: nRF52840 Datasheet.
Rx Signal Flow

IL: -1dB
Gain: 15dB
NF: 1-2dB

Band Select Filter
LNA
LO
LPF
PGA
Channel Select Filter
ADC

2400-2483 MHz

\[ F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots \]
Matching Network

RF LO

2f₀

÷ 2

I

Q

Passive

IF

MIXERS

Gain

BPF

Filter

IF

Gain

N-bit

ADC

Gaussian

Pulse Shaping

Tx Data

from RISC V

Power Management

Bandgap Vref

Temp. sensor

PTAT Iref

Power-on-Reset (POR)

LDO

Timing

Relaxation oscillator

clock generation

Power Management

Clock &

Data Recovery

Rx Data

Clk

Image

Rejection

Channel

Filter

RISC V