

date: 2024-03-22

TFE4188 - Lecture 10

Low Power Radio

Goal

Let's make a radio (or at least, let's **pretend**)

Problem statement:

Make the best radio ICs for gaming mice

What do we need to know?

- Data Rate
- Carrier Frequency & Range
- Power supply

Data Rate

Data

Rate

Assume 1 ms update rate

What	Bits	Why
X displacement	8	
Y displacement	8	
CRC	4	Bit errors
Buttons	16	One-hot coding. Most mice have buttons
Preamble	8	Synchronization
Address	32	Unique identifier
Total	76	

Data Rate

Application Data Rate $> 76 \text{ bits/ms} = 76 \text{ kbps}$

Assume 30 % packet loss

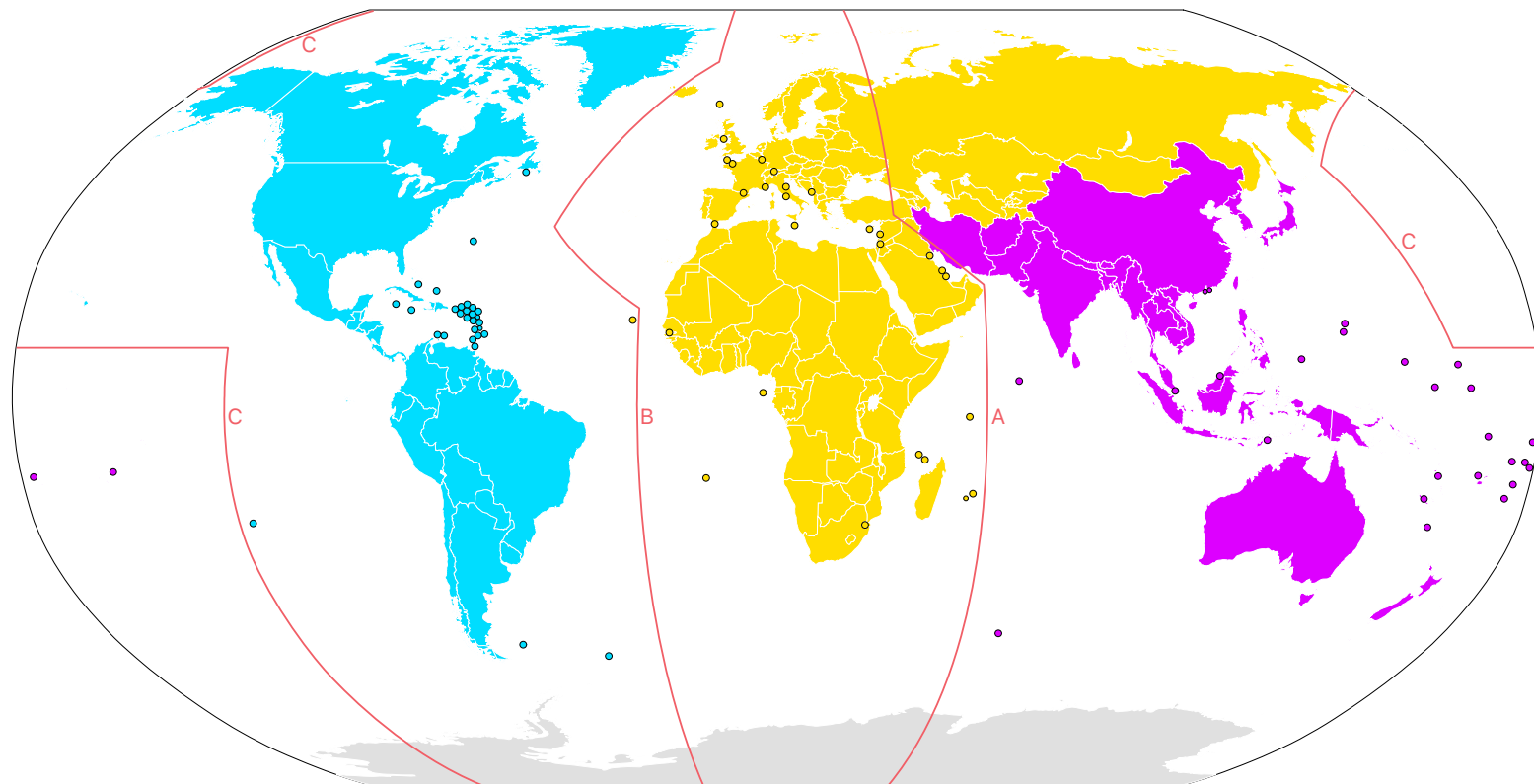
Raw Data Rate $> 228 \text{ kbps}$

Multiply by $\pi > 716 \text{ kbps}$

Round to nearest nice number = 1Mbps

Carrier Frequency & Range

ISM (industrial, scientific and medical) bands



- Yellow: Region 1
- Blue: Region 2
- Pink: Region 3

Flow	Fhigh	Bandwidth	Description
40.66 MHz	40.7 MHz	40 kHz	Worldwide
433.05 MHz	434.79 MHz	1.74 MHz	Region 1
902 MHz	928 MHz	26 MHz	Region 2
2.4 GHz	2.5 GHz	100 MHz	Worldwide
5.725 GHz	5.875 GHz	150 MHz	Worldwide
24 GHz	24.25 GHz	250 MHz	Worldwide
61 GHz	61.5 GHz	500 MHz	Subject to local acceptance

Antenna

assume $\lambda/4$ is an OK antenna size ($\lambda = c/f$)

ISM band		Unit	OK/NOK
40.68 MHz	1.8	m	✗
433.92 MHz	17	cm	✗
915 MHz	8.2	cm	
2450 MHz	3.06	cm	✓
5800 MHz	1.29	cm	✓
24.125 GHz	3.1	mm	✓
61.25 GHz	1.2	mm	✓

Range (Friis)

Assume no antenna gain, power density p at distance D is

$$p = \frac{P_{TX}}{4\pi D^2}$$

Assume receiver antenna has no gain, then the effective aperture is

$$A_e = \frac{\lambda^2}{4\pi}$$

Power received is then

$$P_{RX} = \frac{P_{TX}}{D^2} \left[\frac{\lambda}{4\pi} \right]^2$$

Or in terms of distance

$$D = 10^{\frac{P_{TX} - P_{RX} + 20 \log_{10} \left(\frac{c}{4\pi f} \right)}{20}}$$




Range (Free space)

Assume TX = 0 dBm, assume RX sensitivity is -80 dBm

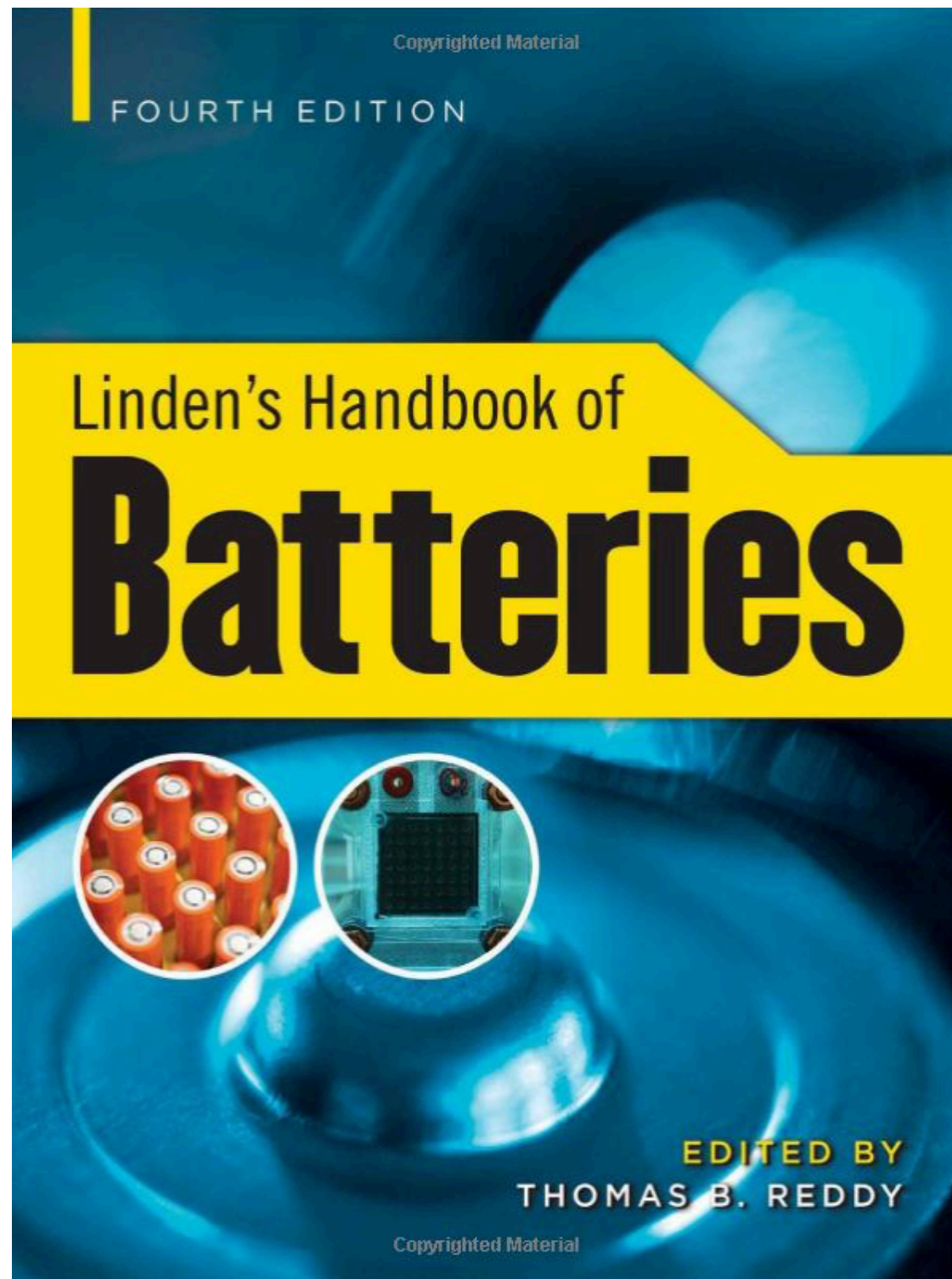
Freq [dB]			D [m]	OK/NOK
915 MHz	-31.7		260.9	✓
2.45 GHz	-40.2		97.4	✓
5.80 GHz	-47.7		41.2	✓
24.12 GHz	-60.1		9.9	✗
61.25 GHz	-68.2		3.9	✗
160 GHz	-76.52		1.5	✗

Range (Real world)

path loss factor, $n \in [1.6, 6]$, $D = 10^{\frac{P_{TX} - P_{RX} + 20 \log_{10} \left(\frac{c}{4\pi f} \right)}{n \times 10}}$

Freq [dB]		D@n=2 [m]	D@n=6 [m]	OK/NOK
2.45 GHz	-40.2	97.4	4.6	
5.80 GHz	-47.7	41.2	3.45	
24.12 GHz	-60.1	9.9	2.1	

Power supply



Battery

Mouse is maybe AA, 3000 mAh

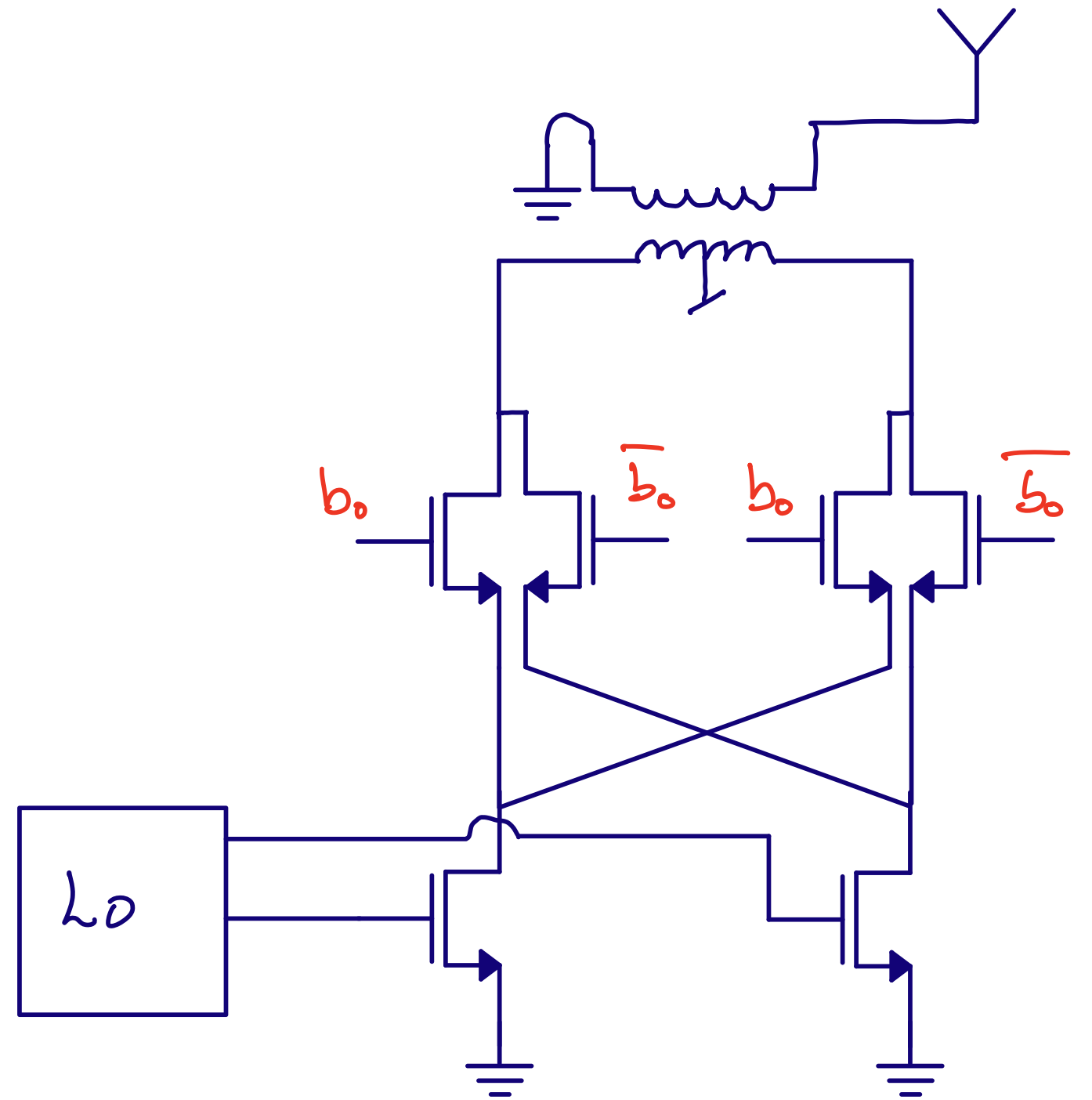
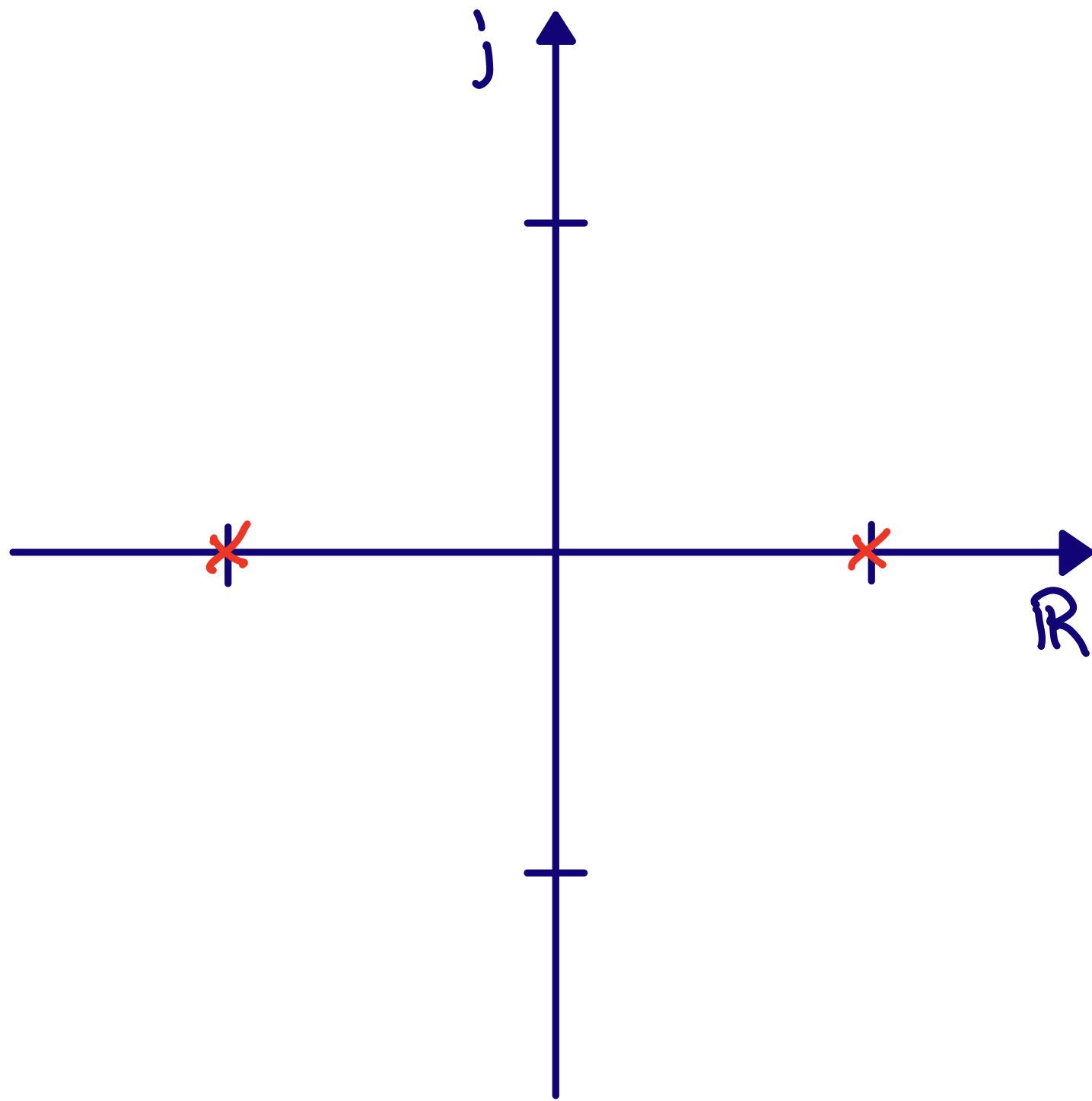
Cell	Chemistry	Voltage (V)	Capacity (Ah)
AA	LiFeS2	1.0 - 1.8	3
	2xAA	LiFeS2	2.0 - 3.6
AA	Zn/Alk/ MnO2	0.8 - 1.6	3
2xAA	Zn/Alk/ MnO2	1.6 - 3.2	3

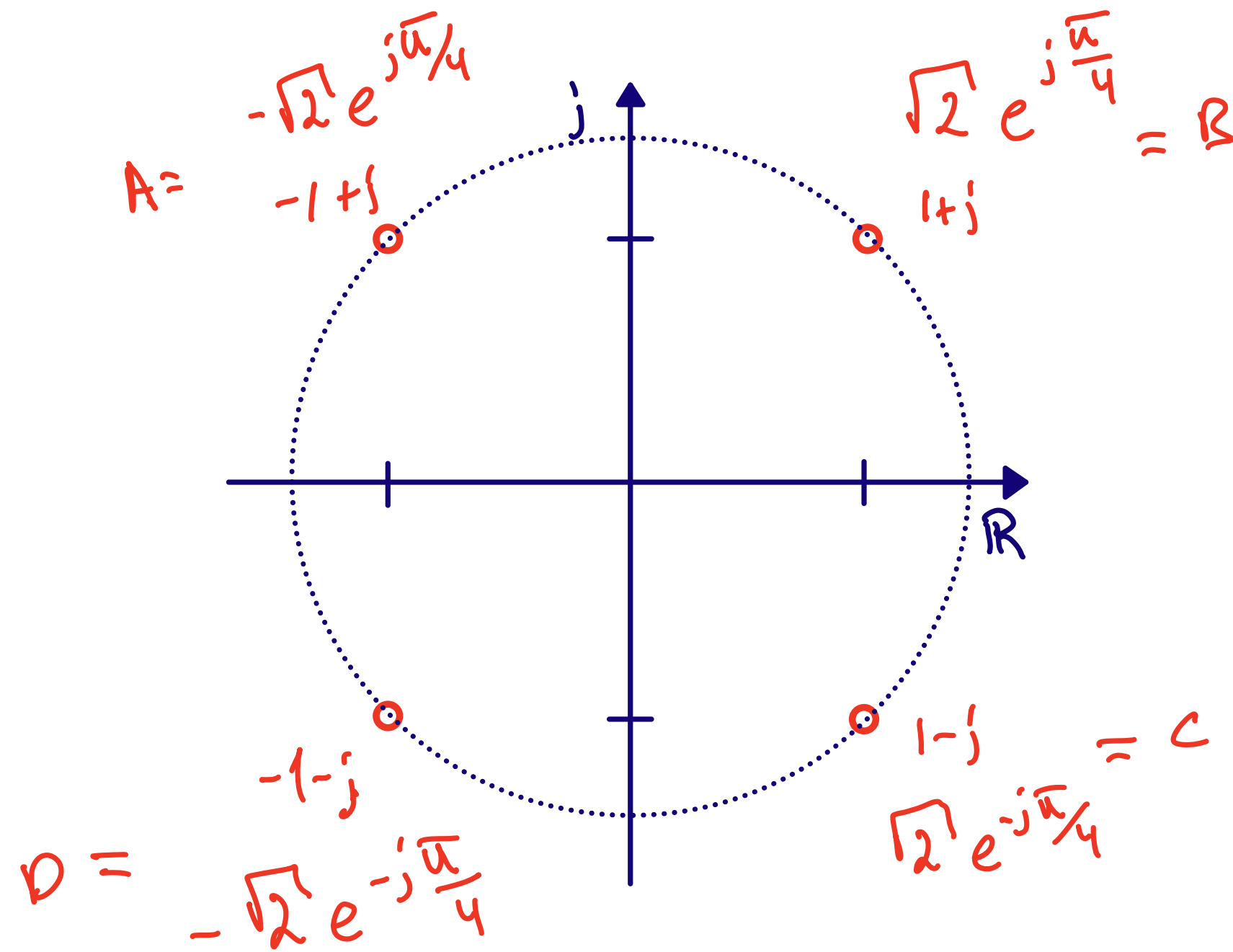
Decisions

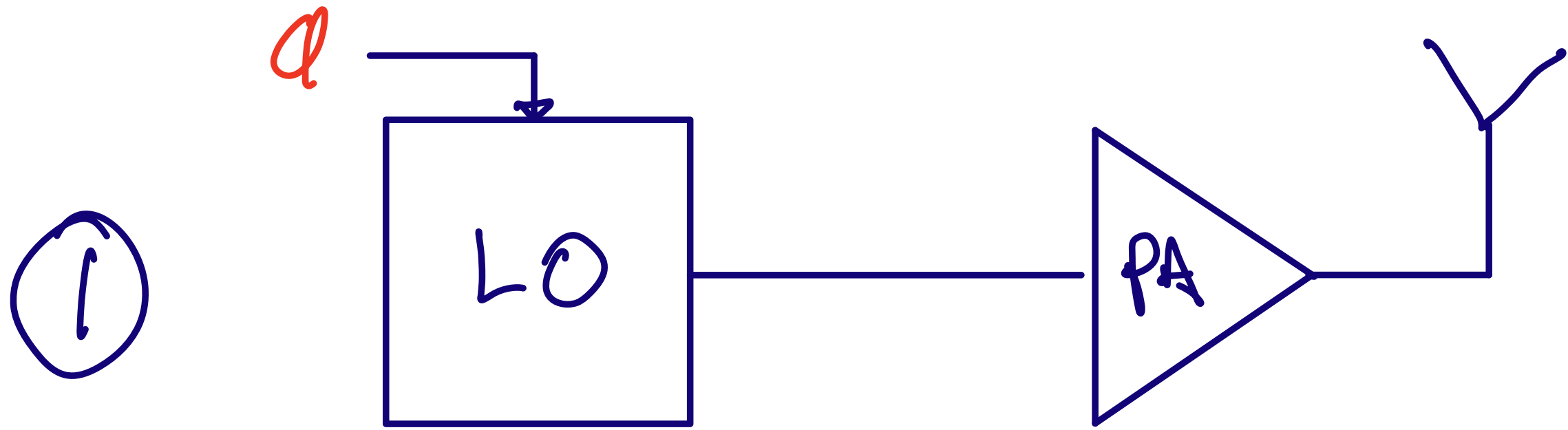
Modulation

$$A_m(t) \times \cos(2\pi f_{carrier}(t)t + \phi_m(t))$$

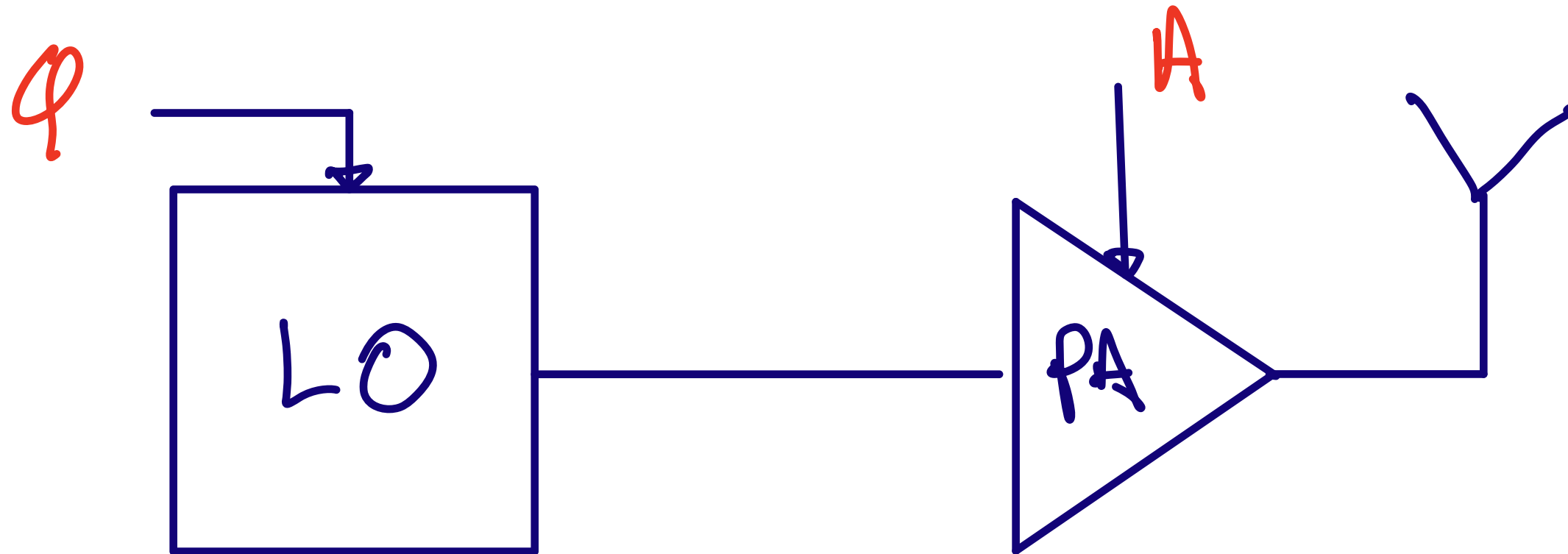
Scheme	Acronym	Pro	Con
Binary phase shift keying	BPSK	Simple	Not constant envelope
Quadrature phase-shift keying	QPSK	2bits/symbol	Not constant envelope
Offset QPSK	OQPSK	2bits/symbol	Constant envelope with half-sine pulse shaping
Gaussian Frequency Shift Keying	GFSK	1 bit/symbol	Constant envelope
Quadrature amplitude modulation	QAM	> 1024 bits/symbol	Really non-constant envelope



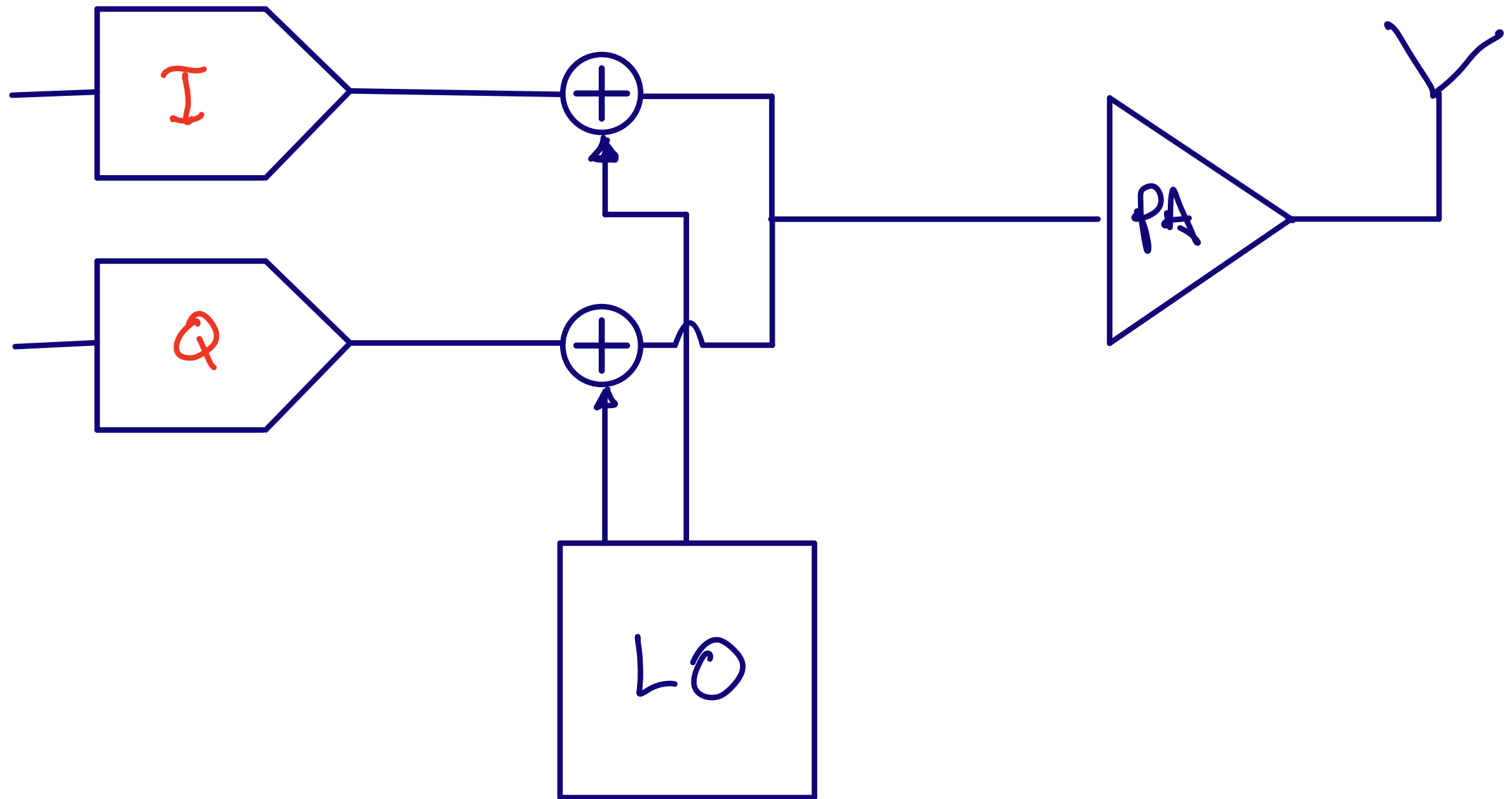


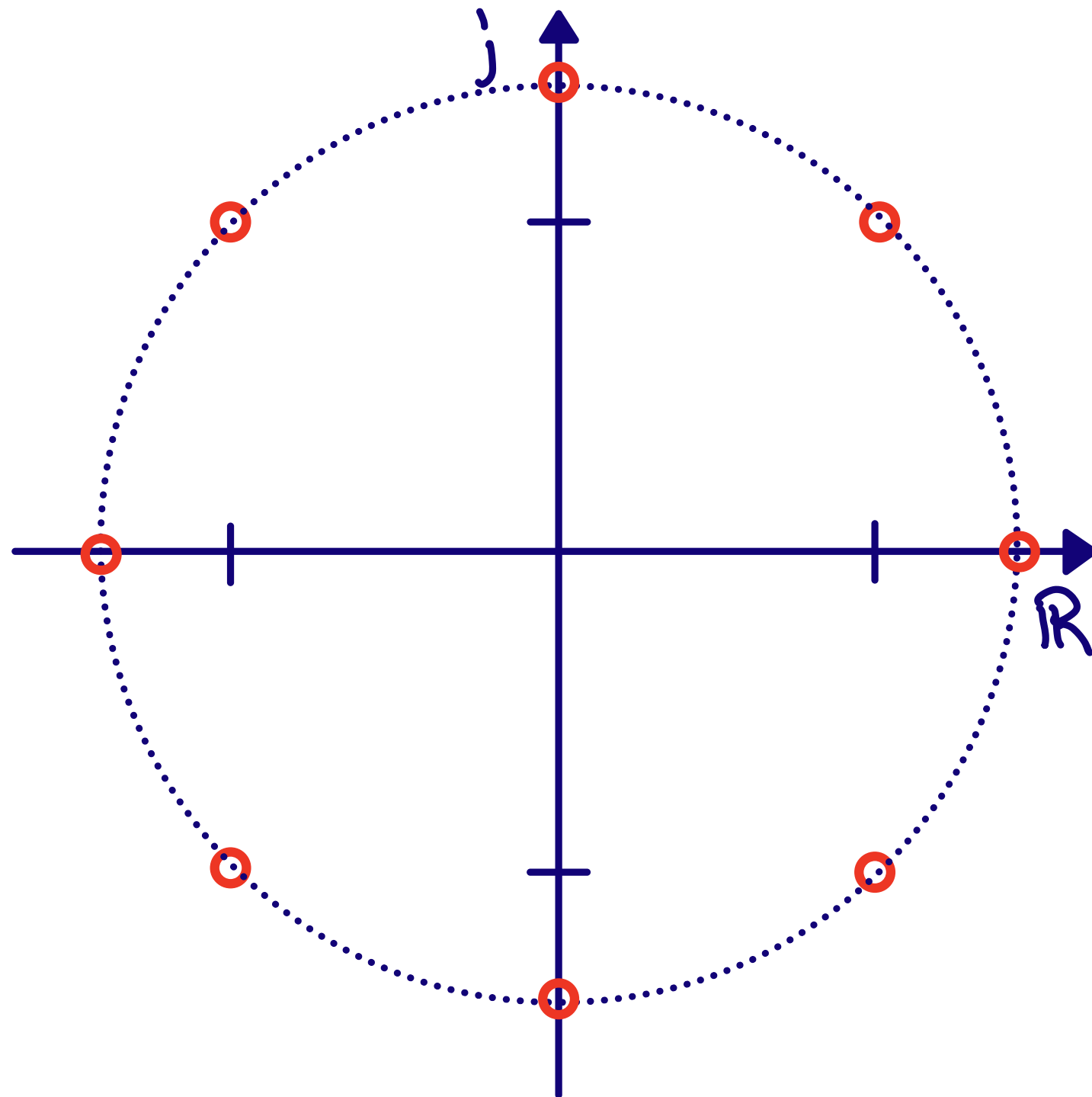


②



3





GFSK modulation mode, whereas the subsequent synchronization sequence, payload, and trailer sequence are transmitted using the Enhanced Data Rate PSK modulation mode.

3.2.1 Modulation characteristics

During access code and packet header transmission the Basic Rate GFSK modulation mode shall be used. During the transmission of the synchronization sequence, payload, and trailer sequence a PSK type of modulation with a data rate of 2 Mb/s or optionally 3 Mb/s shall be used. The following subsections specify the PSK modulation for this transmission.

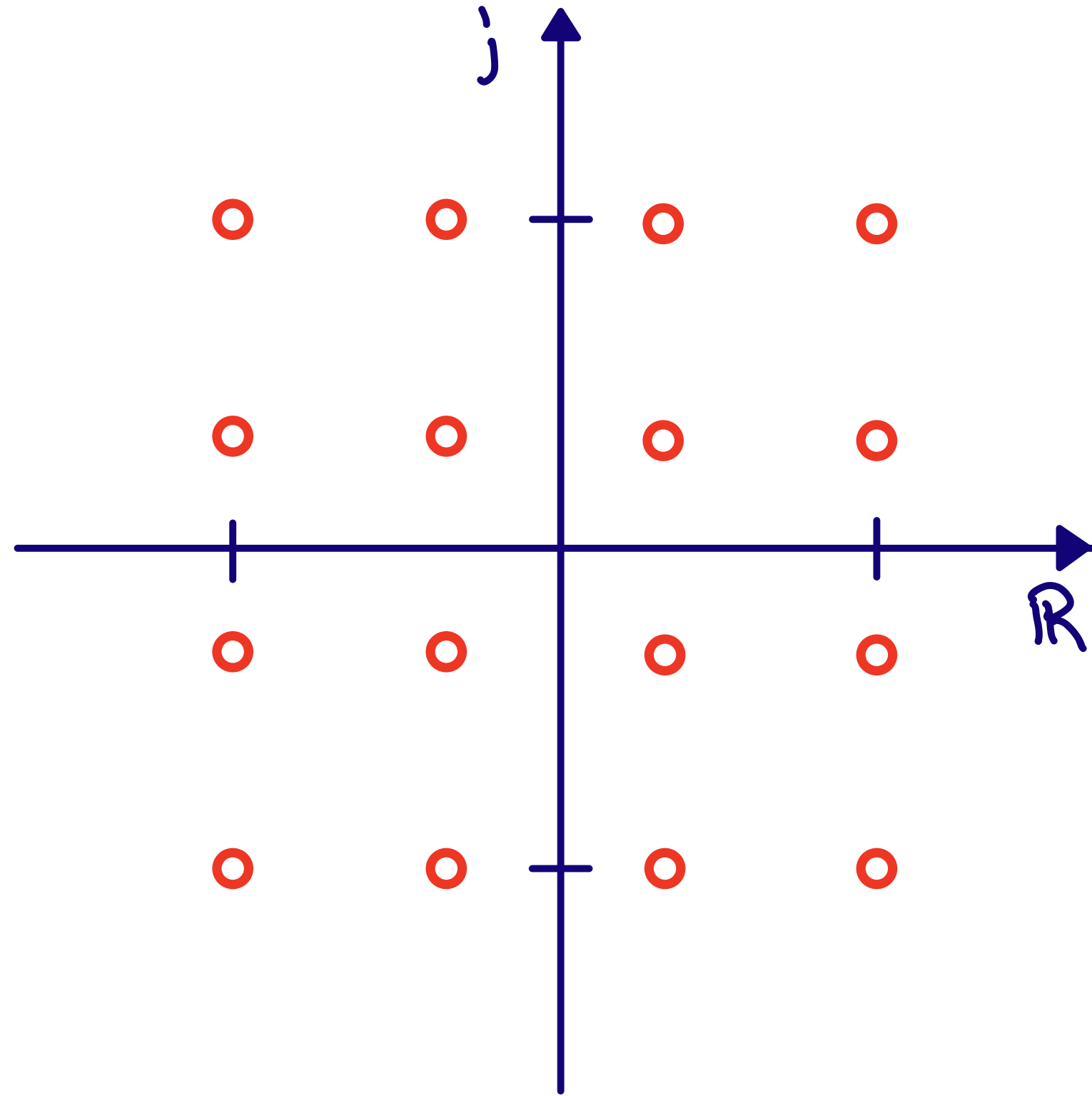
3.2.1.1 Modulation method overview

The PSK modulation format defined for the 2 Mb/s transmission shall be $\pi/4$ rotated differential encoded quaternary phase shift keying ($\pi/4$ -DQPSK).

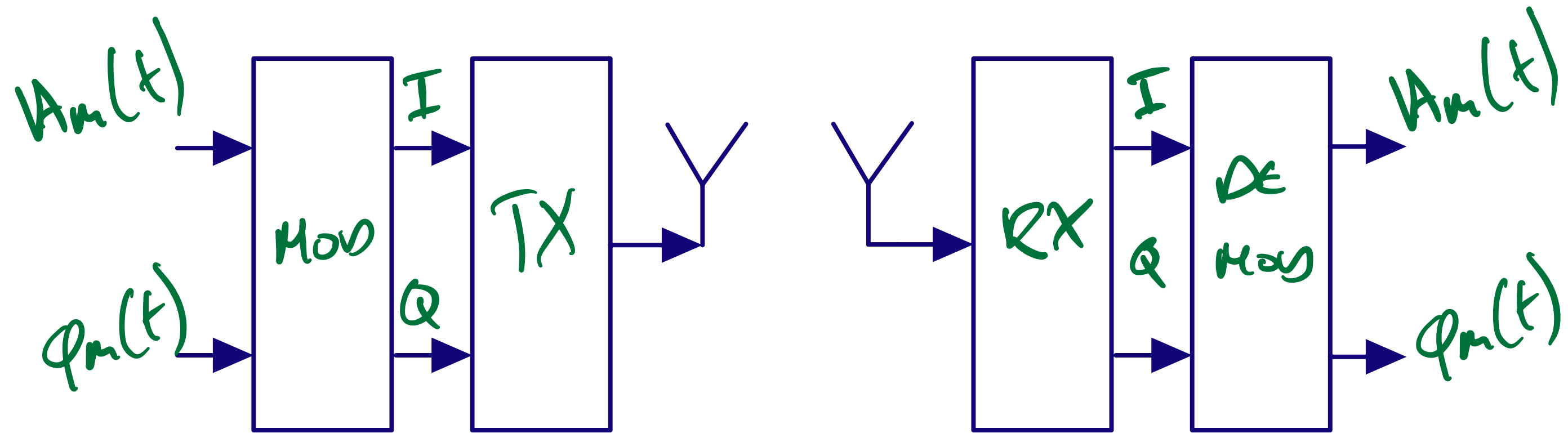
The PSK modulation format defined for the 3 Mb/s transmission shall be differential encoded 8-ary phase shift keying (8DPSK).

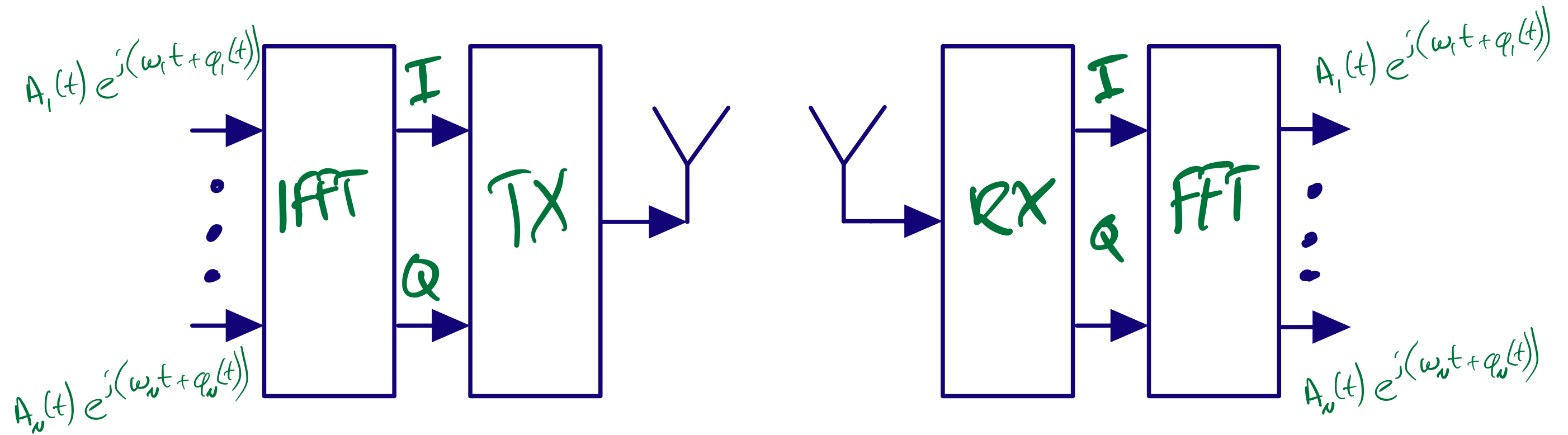
The modulation shall employ square-root raised cosine pulse shaping to generate the equivalent lowpass information-bearing signal $v(t)$. The output of the transmitter shall be a bandpass signal that can be represented as

$$S(t) = Re[v(t)e^{j2\pi F_c t}] \tag{EQ 1}$$



Single carrier, or multi carrier?





Let's make the best, highest data rate radio!

*#race*toidle

Use a Software Defined Radio

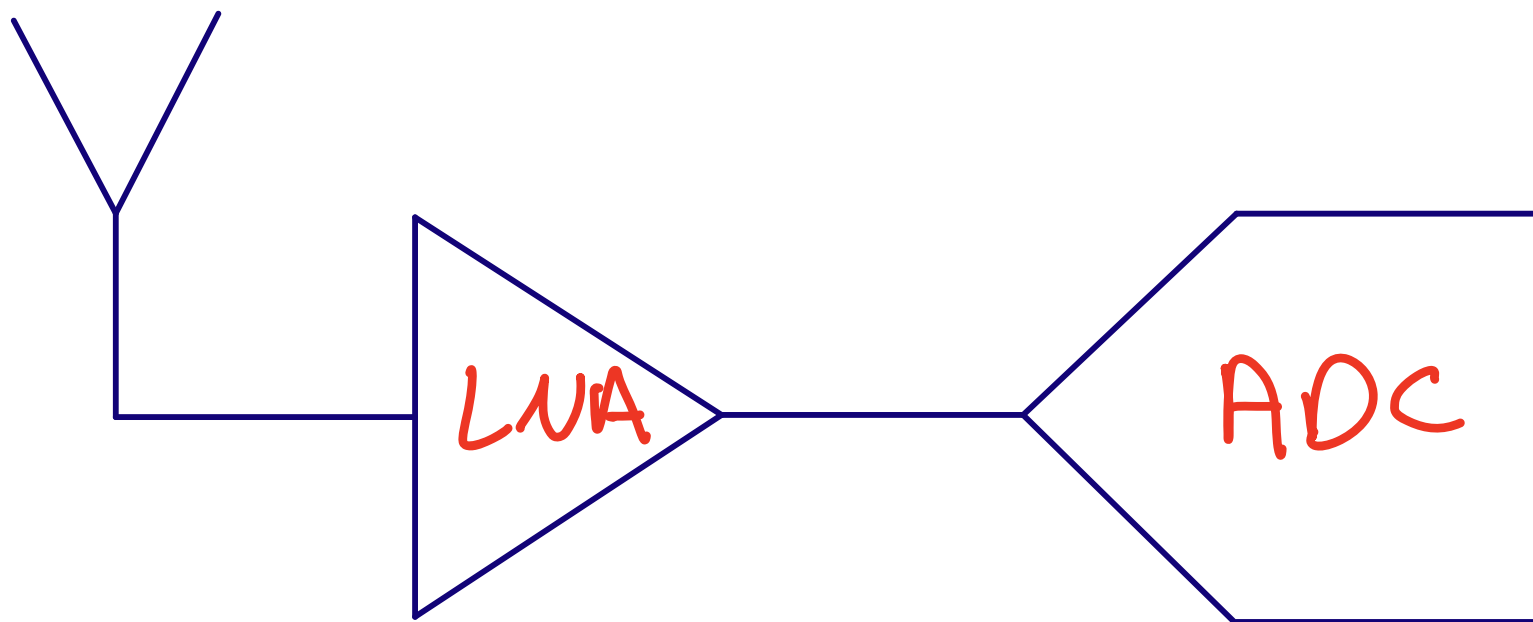
$$\text{ADC FOM} = \frac{P}{2BW2^n}$$

State of the art FOM ≈ 5 fJ/step

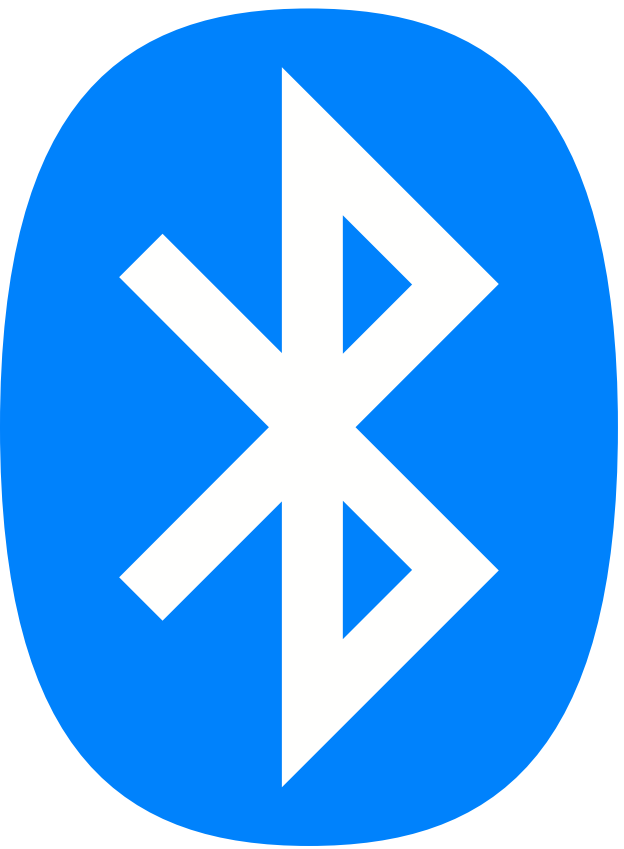
$$BW = 2.5 \text{ GHz}$$

$$DR = 100 \text{ dB} = (96 - 1.76)/6.02 \approx 16 \text{ bit}$$

$$P = 5 \text{ fF} \times 5 \text{ GHz} \times 2^{16} = 1.6 \text{ W}$$



Crap, complex!
Crap, too high power!



Bluetooth[®]

Bluetooth

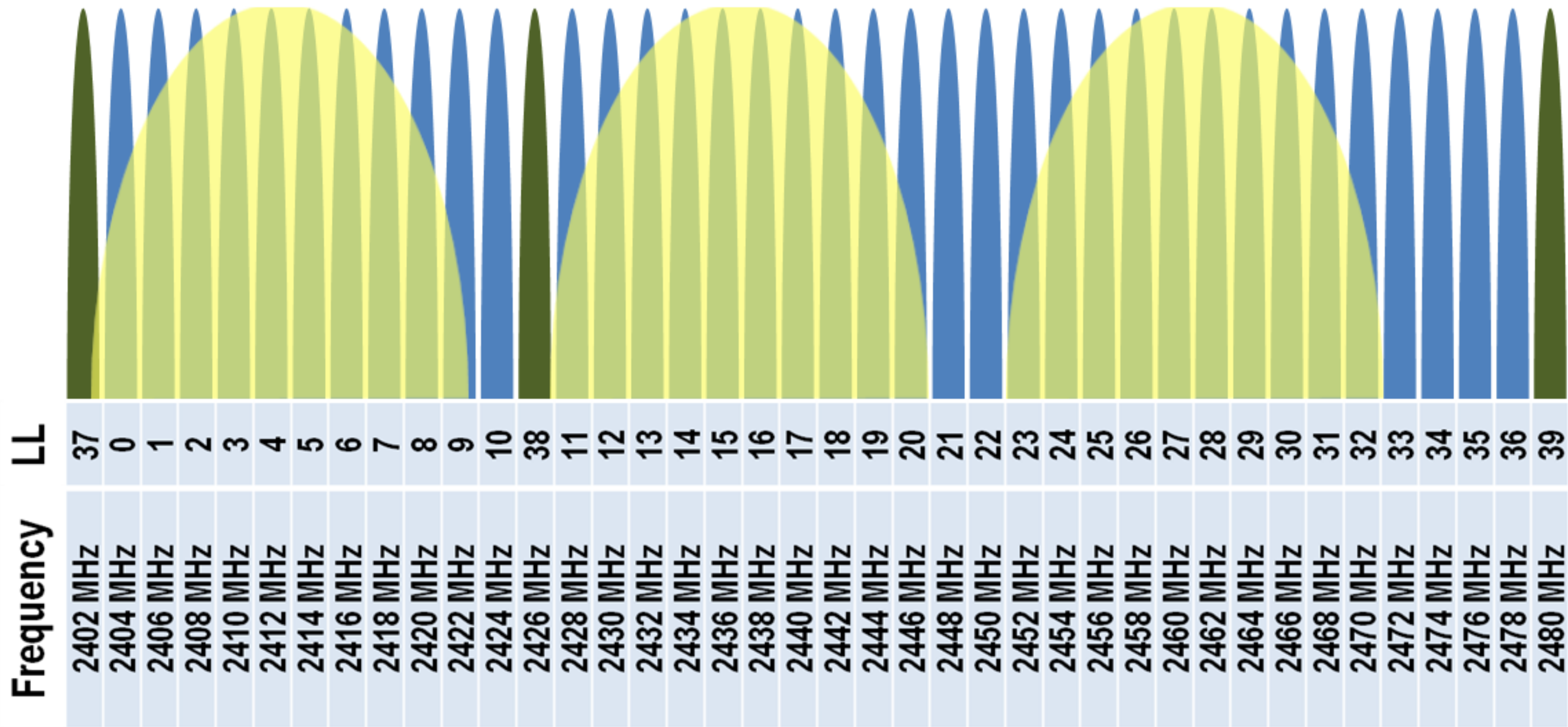
- Compromise between speed, power and cost
- "Simple" to use
- "Simple" to implement

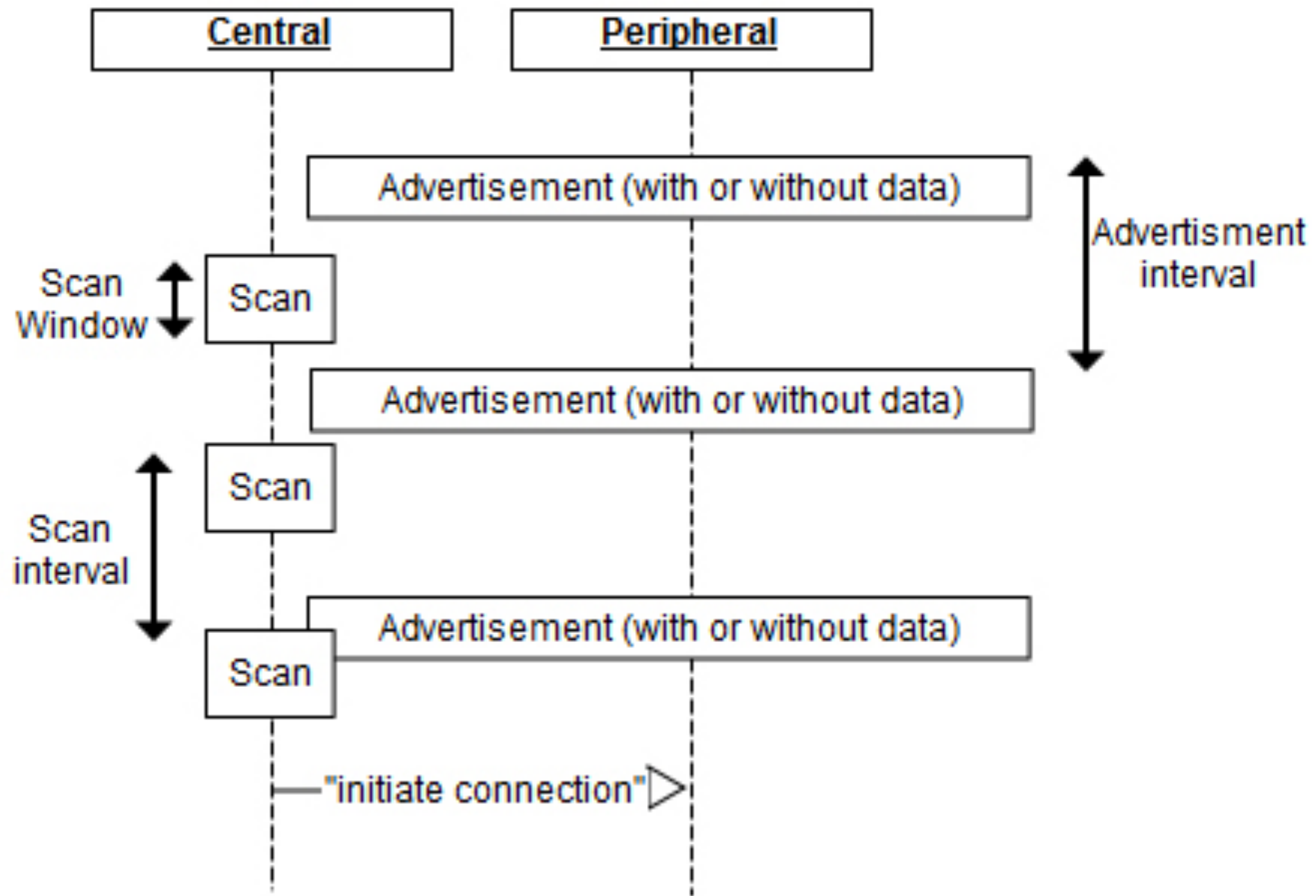
Bluetooth Basic Rate/Extended Data rate

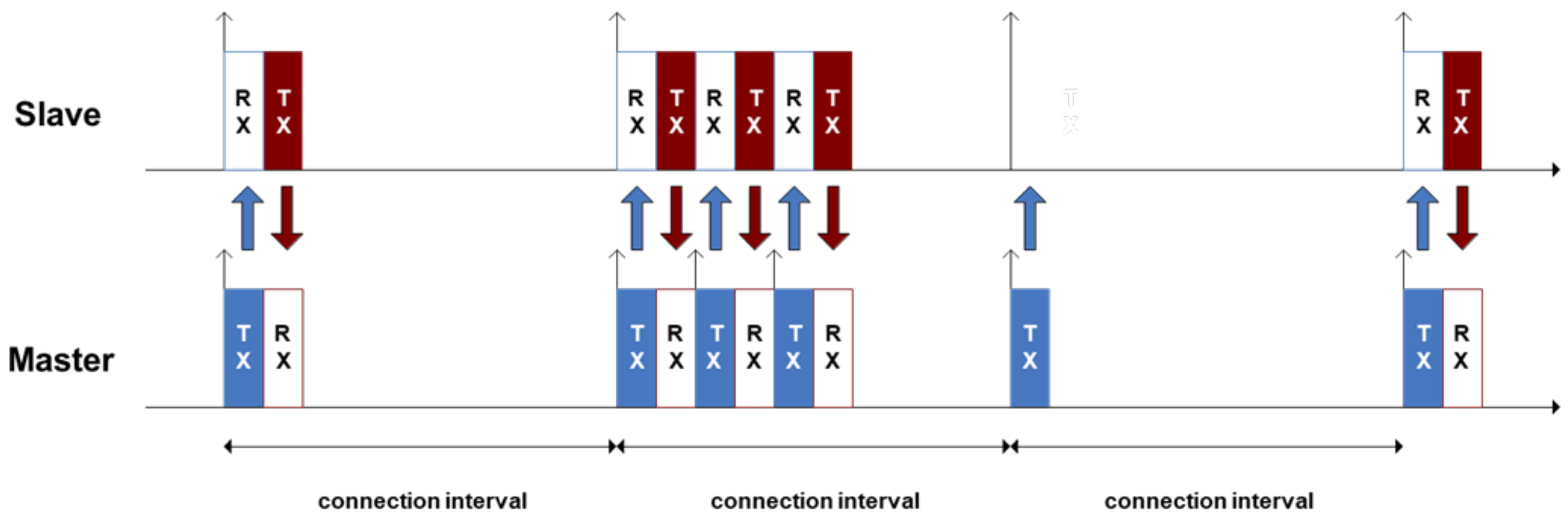
- 2.400 GHz to 2.4835 GHz
- 1 MHz channel spacing
- 78 Channels
- Up to 20 dBm
- Minimum -70 dBm sensitivity (1 Mbps)
- 1 MHz GFSK (1 Mbps), pi/4-DQPSK (2 Mbps), 8DPSK (3 Mbps)

Bluetooth Low Energy

- 2.400 GHz to 2.480 GHz
- 2 MHz channel spacing
- 40 Channels (3 primary advertising channels)
- Up to 20 dBm
- Minimum -70 dBm sensitivity (1 Mbps)
- 1 MHz GFSK (1 Mbps, 500 kbps, 125 kbps), 2 MHz GFSK (2 Mbps)







For further information [Building a Bluetooth application on nRF Connect SDK](#)

Bluetooth Specifications in Development



Bluetooth LE in Higher Frequency Bands

A specification development project is currently underway to define the operation of Bluetooth Low Energy (LE) in additional unlicensed mid-band spectrum, including the 6 GHz frequency band. With over 5 billion products shipping each year, Bluetooth technology is the most widely deployed wireless standard in the world. A core reason for its unmatched adoption and success is the continual evolution of the technology in key areas, including higher data throughput, lower latency, and greater positioning accuracy. The new spectrum expansion project will help ensure that these Bluetooth performance enhancements can continue well into the future, paving the way for the next generation of Bluetooth innovation.

This project currently includes [enhancements being made to the Bluetooth Core Specification](#) taking place within the [Core Specification Working Group](#). Employees of all Bluetooth SIG member companies are welcome to join the subgroup to participate in the project.



Higher Data Throughput

Added to Bluetooth® wireless technology in 2016, the [LE 2M PHY](#) doubled the data rate that could be achieved between Bluetooth Low Energy (LE) devices from the original LE 1M PHY. The LE 2M PHY was introduced to address a number of market opportunities, including enhancing data transfer performance for the growing number of IoT devices consumers were connecting to their smartphones.

Today, an increasing number of these connected devices are looking for even greater performance, as well as support for streaming larger media, and could benefit from an even higher data rate Bluetooth LE PHY. The Higher Data Throughput project was established to address that growing market need and intends to support data rates up to 8 Mbps.

This project currently includes [enhancements being made to the Bluetooth Core Specification](#) taking place within the [Core Specification Working Group](#).



High Accuracy Distance Measurement

Adding to the growing set of device positioning capabilities of Bluetooth® wireless technology – which currently includes Advertising (for presence), RSSI (for basic distance measurement) and [Direction Finding](#) (for high accuracy direction) – a specification development project is currently underway to enable high-accuracy distance measurement between two Bluetooth enabled devices. This feature is expected to enable the creation of locating systems that can provide even higher levels of accuracy.

This project currently includes:

- [Enhancements being made to the Bluetooth Core Specification](#) taking place within the [Core Specification Working Group](#)
- A [new profile specification](#) being developed within the [Direction Finding Working Group](#)



Ultra Low Latency HID

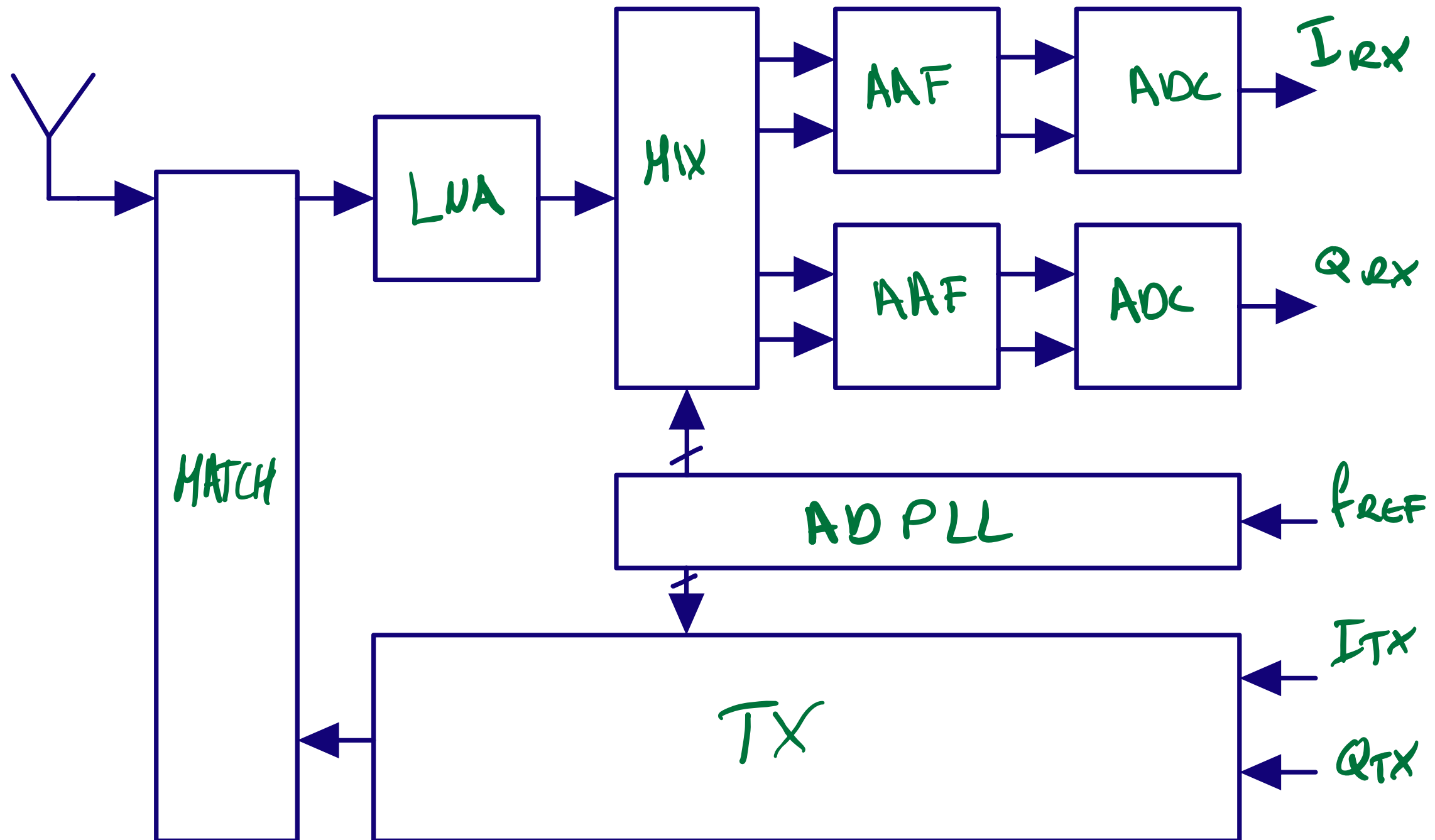
The ultra-low latency (ULL) Human Interface Device (HID) enhancement project aims to make Bluetooth gaming controllers as responsive as those using USB-wired or proprietary wireless communications. This enhancement, which is intending to provide polling rates as high as 1000 Hz, could also be used to improve the user experience for other latency-sensitive devices such as controllers and sensors for augmented, virtual, or mixed reality (AR/VR/MR) scenarios.

This project currently includes [enhancements being made to the HID over GATT Profile Specification](#) being developed within the [Human Interface Device \(HID\) Working Group](#).

Low Power Receivers

Algorithm to design state-of-the-art LE radio

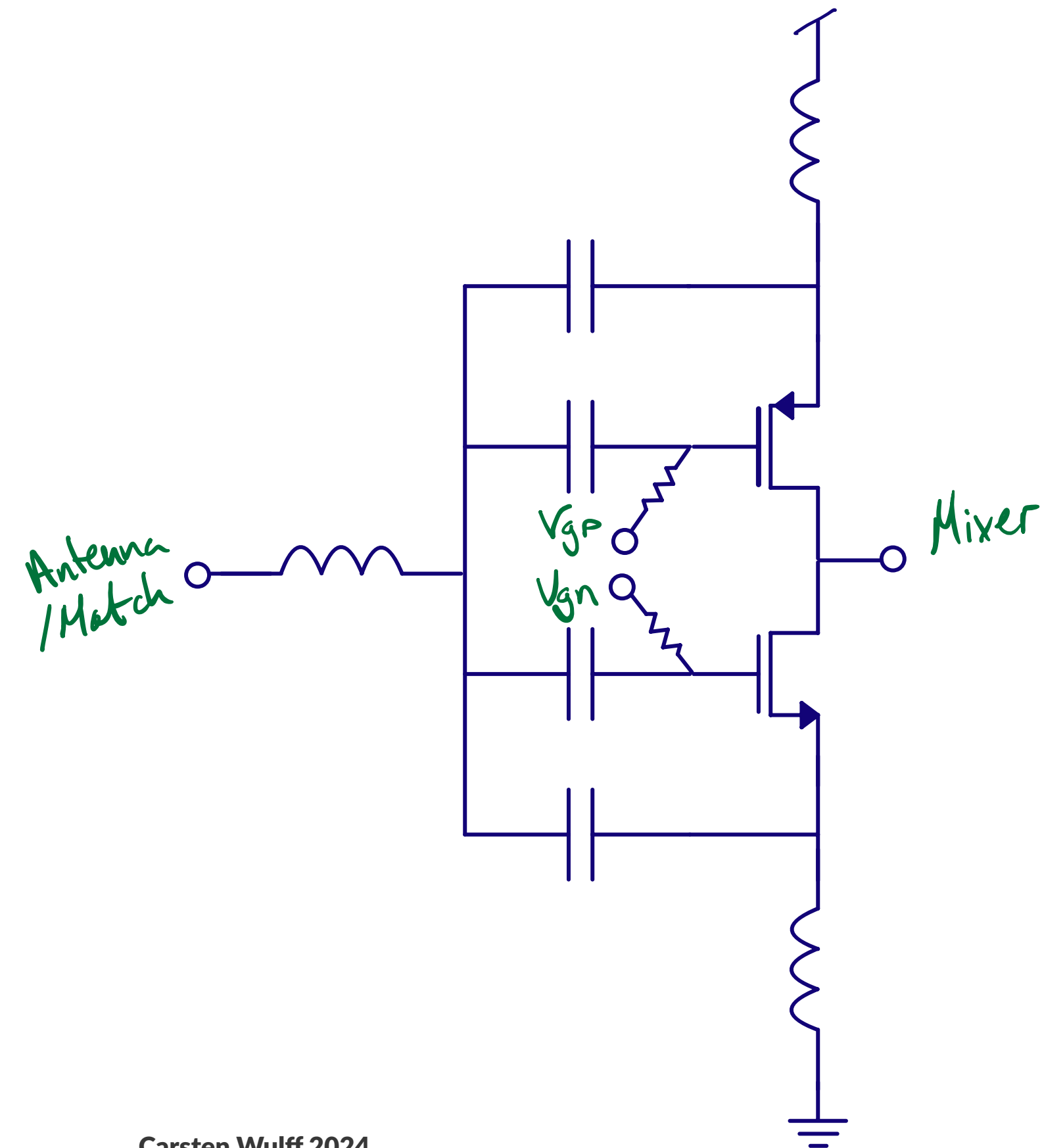
- Find most recent digest from International Solid State Circuit Conference (ISSCC)
- Find Bluetooth low energy papers
- Pick the best blocks from each paper



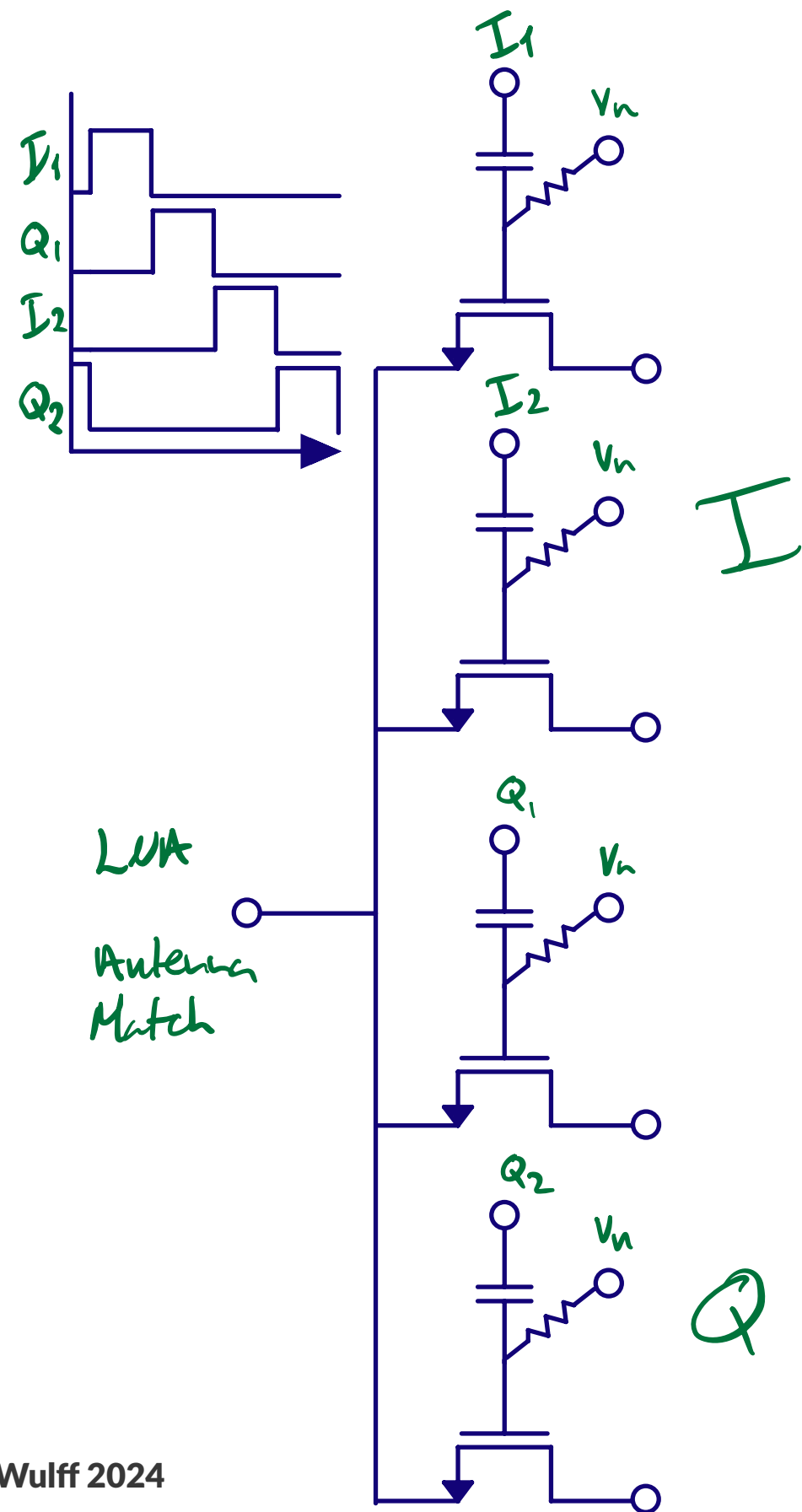
Blocks	Key parameter	Architecture	Complexity (nr people)
Antenna	Gain, impedance	$\lambda/4$	<1
RF match	loss, input impedance	PI-match	<1
Low noise amp	NF, current, linearity	LNTA	1
Mixer	NF, current, linearity	Passive	1
Anti-alias filter	NF, current, linearity	Active-RC	1
ADC	Sample rate, dynamic range, linearity	NS-SAR	1 - 2
PLL	Phase noise, current	AD-PLL	2-3
Baseband	E_b/N_0 , gate count, current.	SystemVerilog	> 10

L N T A

30.5 A 0.5V BLE Transceiver with a
1.9mW RX Achieving -96.4dBm Sensitivity
and 4.1dB Adjacent Channel Rejection at
1MHz Offset in 22nm FDSOI

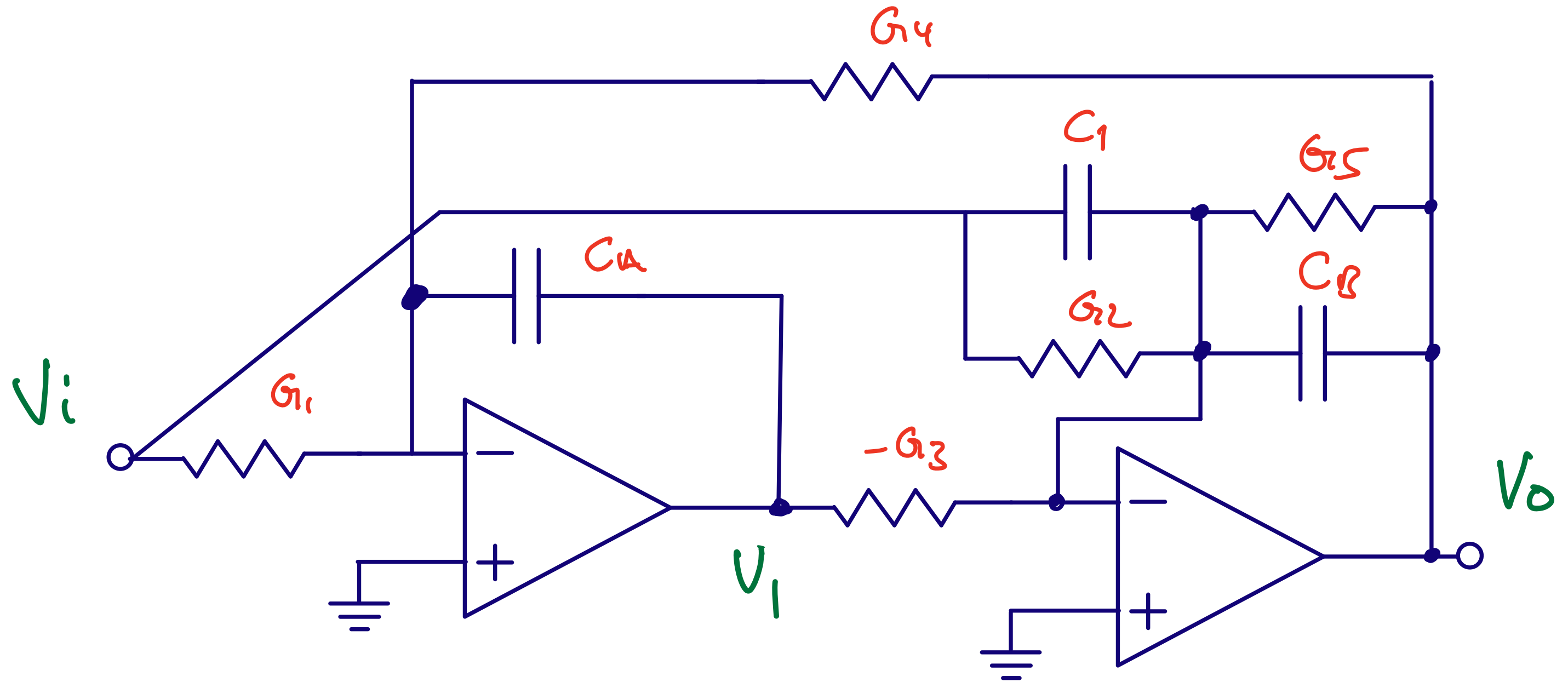


MIXER

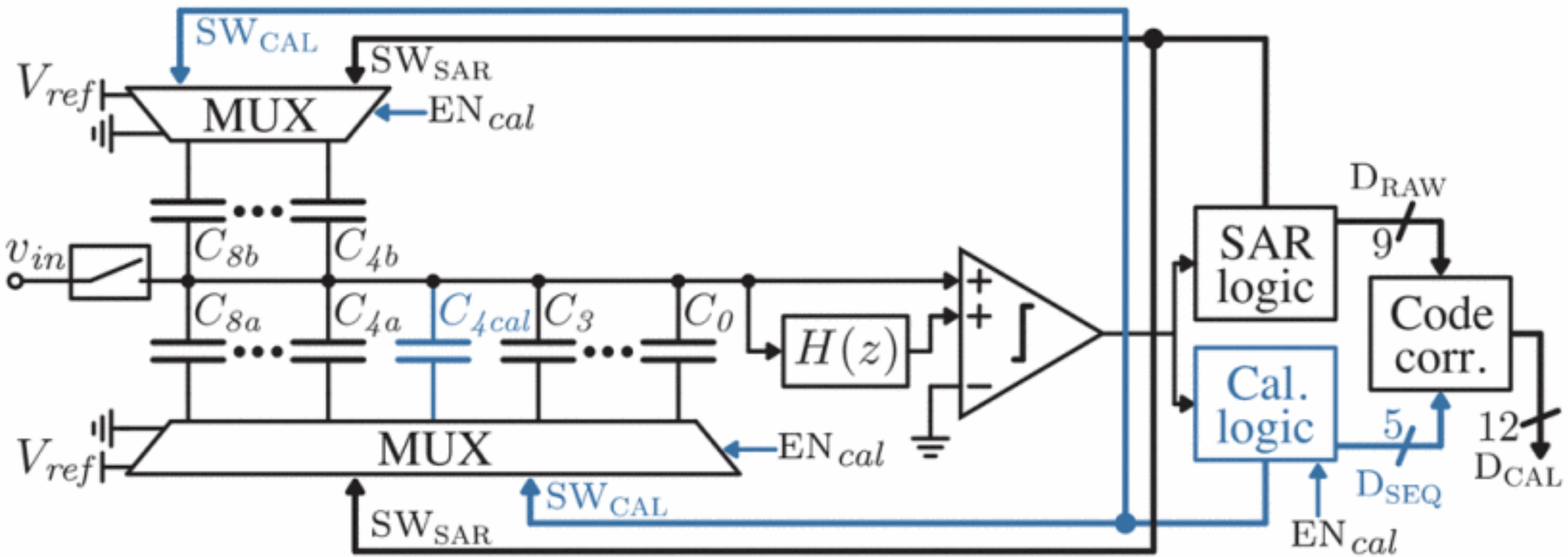


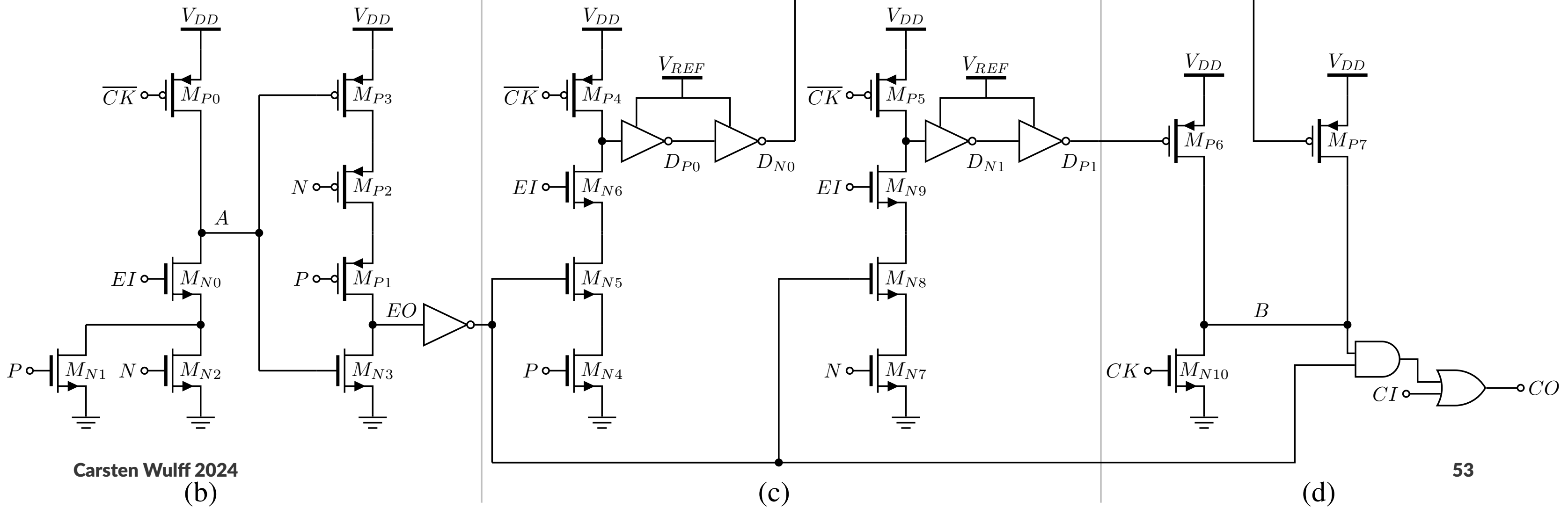
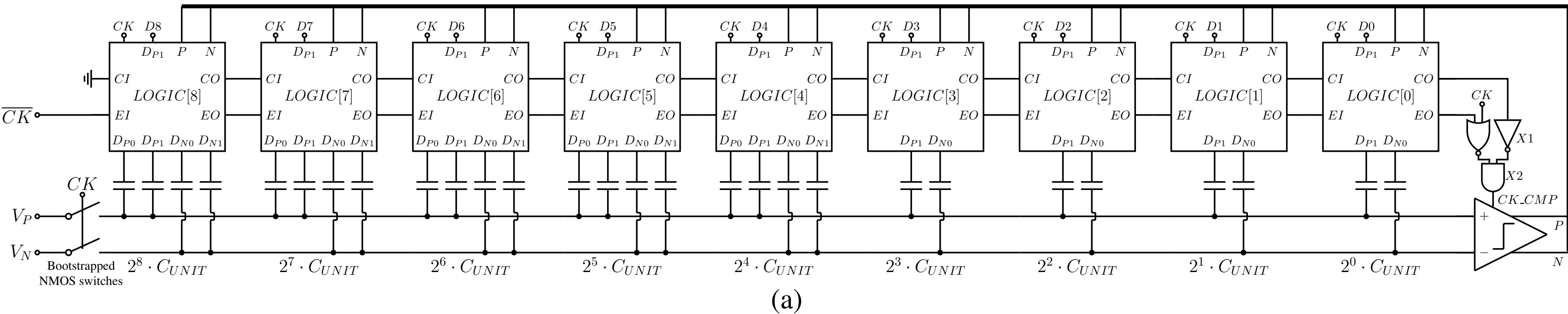
Complex signal processing is not complex
 A 370uW 5.5dB-NF BLE/BT5.0/IEEE
 802.15.4-Compliant Receiver with >63dB
 Adjacent Channel Rejection at >2
 Channels Offset in 22nm FDSOI

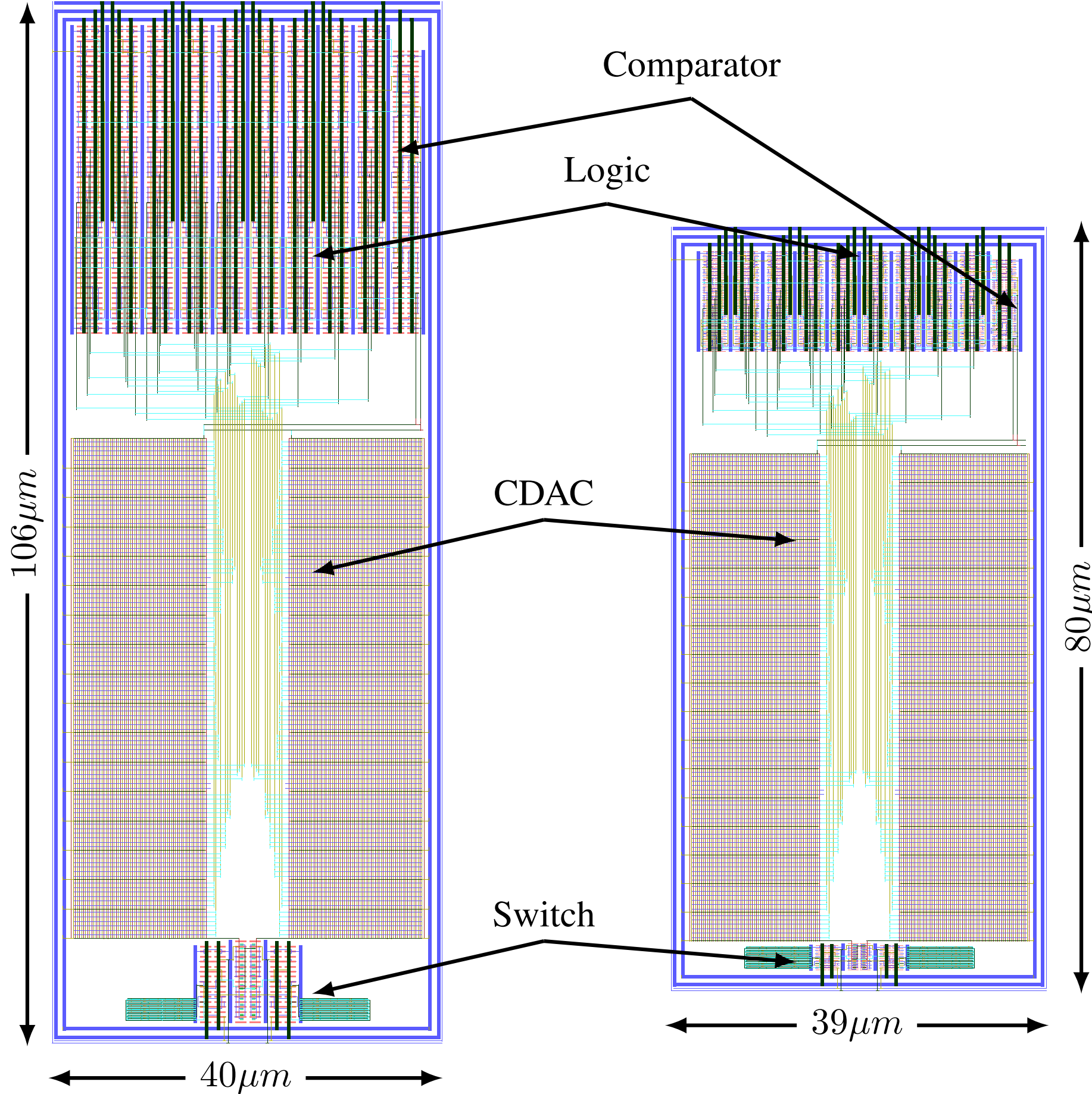
A A F



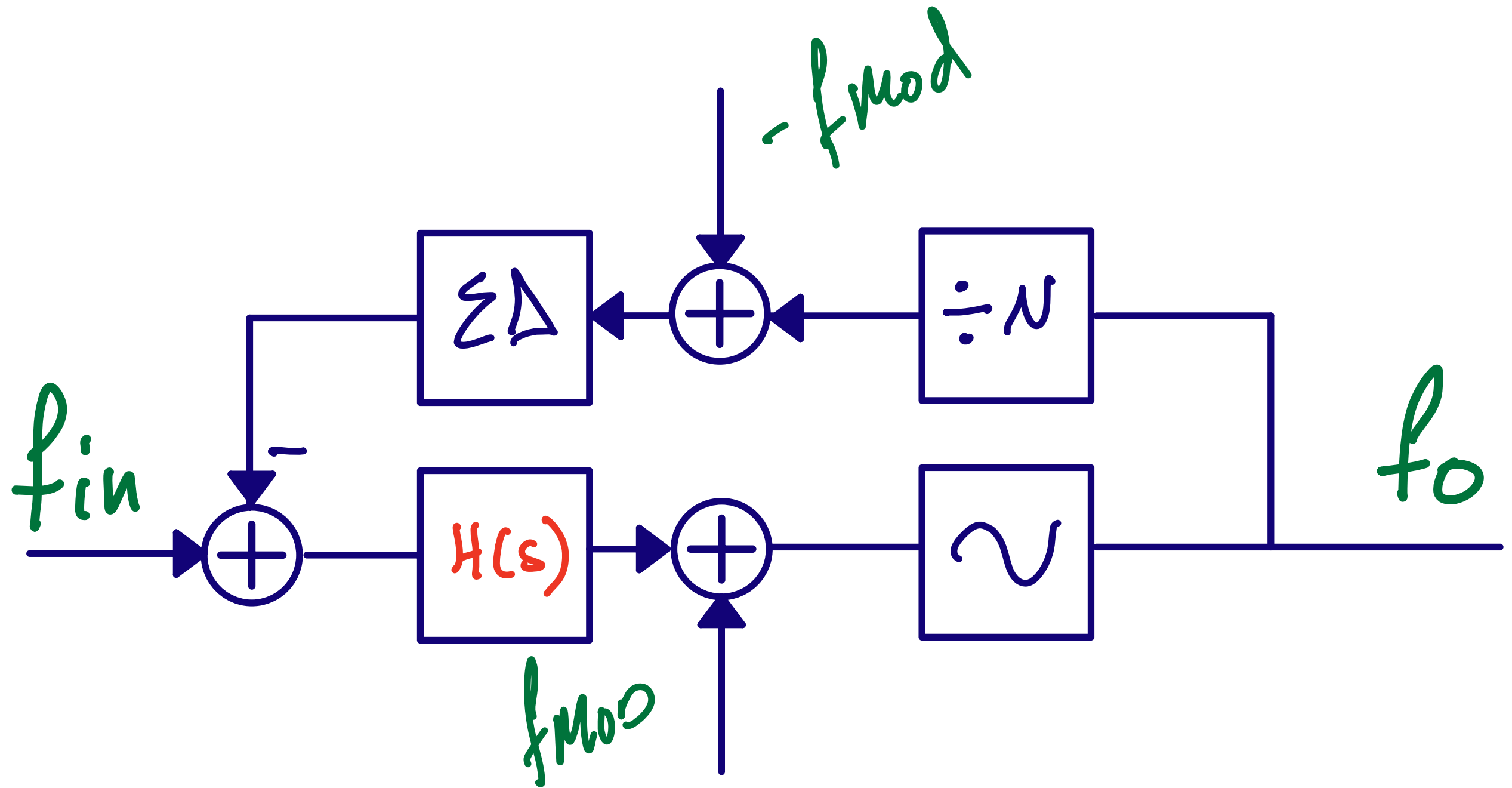
A D C



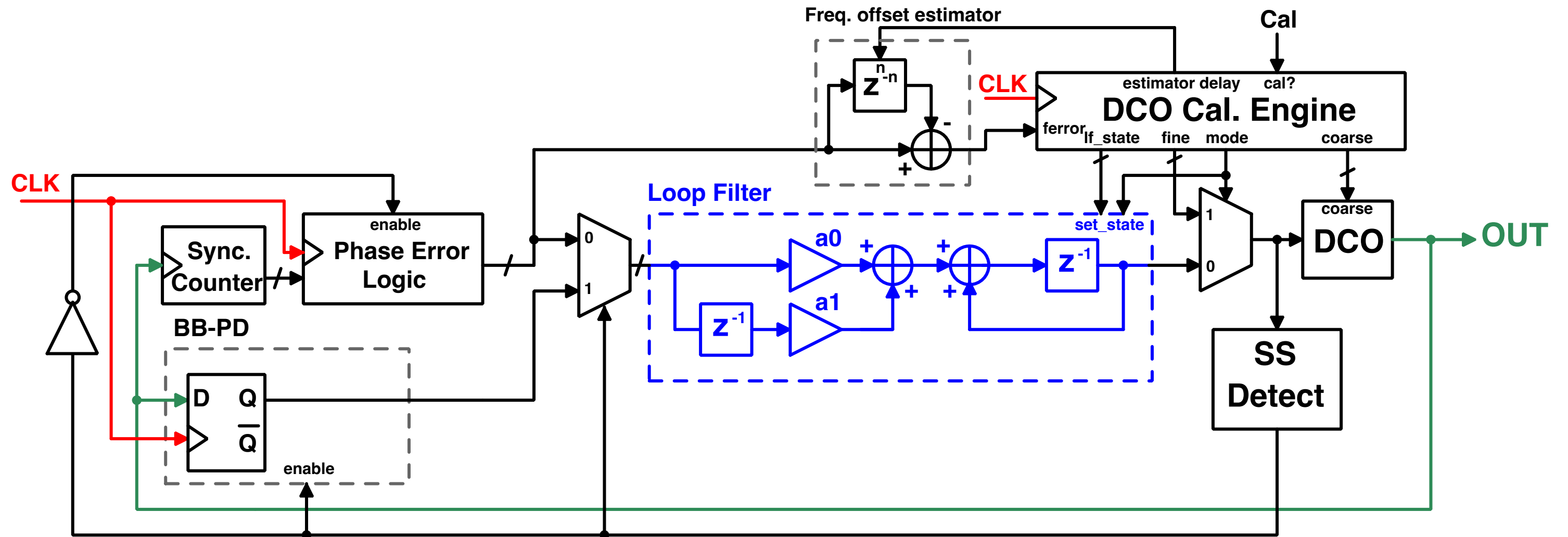




AD-PLL



AD-PLL with Bang-Bang phase detector for steady-state



Baseband

Baseband block

Why

Mixer?

If we're using low intermediate frequency to avoid DC offset problems and flicker noise

Channel filters?

If the AAF is insufficient for adjacent channel

Power detection

To be able to control the gain of the radio

Phase extraction

Assuming we're using FSK

Timing recovery

Figure out when to slice the symbol

Bit detection

single slice, multi-bit slice, correlators etc

Address detection

Is the packet for us?

Header detection

What does the packet contain

CRC

Does the packet have bit errors

Payload de-crypt

Most links are encrypted by AES

Memory access

Payload need to be stored until CPU can do something

What do we really want, in the end?

$$P_{RX_{sens}} = -174dBm + 10 \times \log_{10}(DR) + NF + Eb/N0$$

for example, for nRF5340

$$P_{RX_{sens}} + 174 - 60 = NF + Eb/N0 = 17dB$$

- *Bluetooth*[®] 5.1, IEEE 802.15.4-2006, 2.4 GHz transceiver
 - -97.5 dBm sensitivity in 1 Mbps Bluetooth low energy mode
 - -20 to +3 dBm configurable TX power
 - On-air compatible with nRF52, nRF51, nRF24L, and nRF24AP Series
 - Supported data rates:
 - *Bluetooth* 5.1: 2 Mbps, 1 Mbps, 500 kbps, and 125 kbps
 - IEEE 802.15.4-2006: 250 kbps
 - Proprietary 2.4 GHz: 2 Mbps, 1 Mbps
 - Single-ended antenna output (on-chip balun)
 - 128-bit AES/ECB/CCM/AAR co-processor (on-the-fly packet encryption)
 - 3.2 mA run current in TX (0 dBm)
 - 2.6 mA run current in RX
 - RSSI (1 dB resolution)

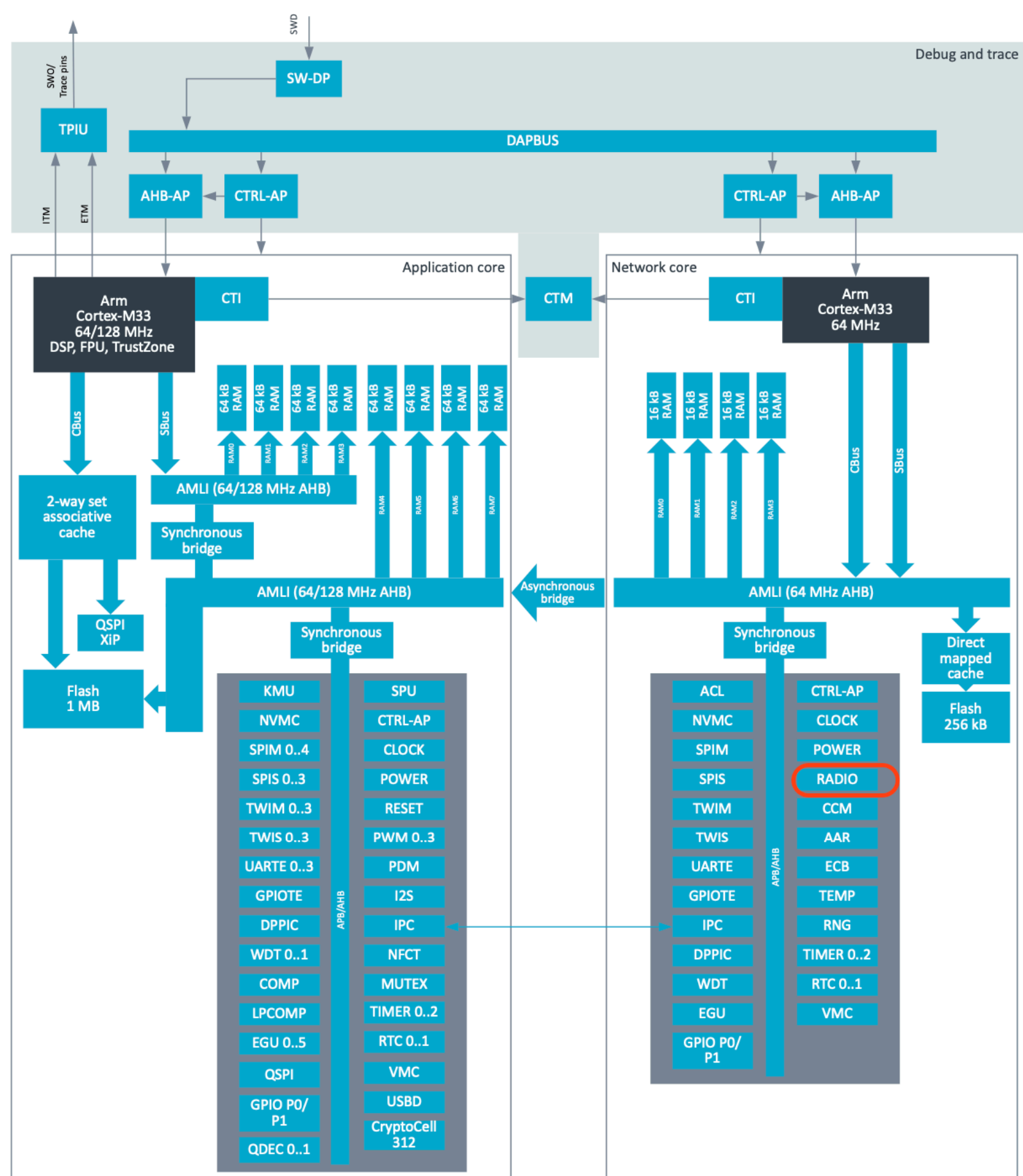
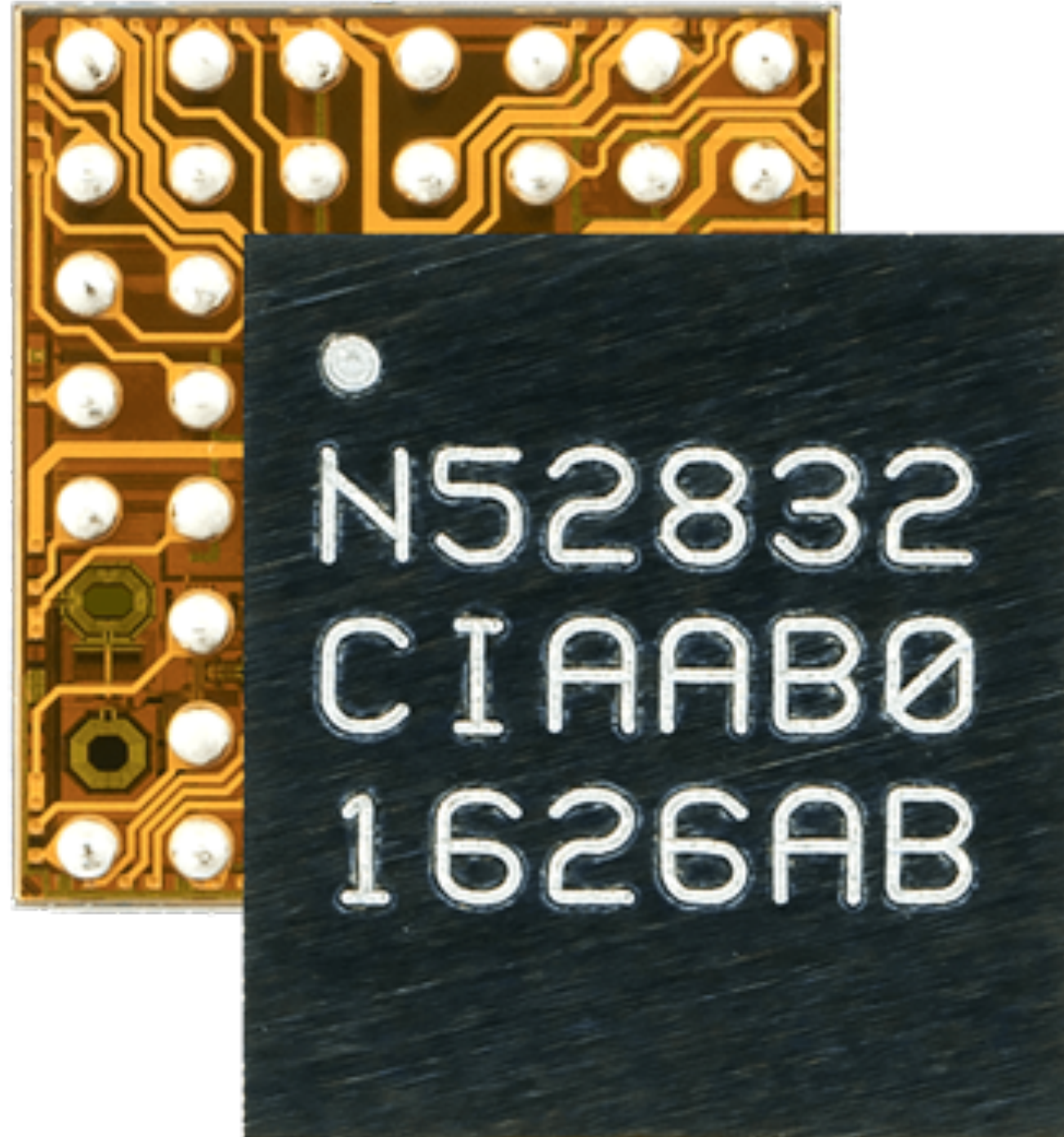


Figure 1: Simplified block diagram



Thanks!

References

[A 0.5V BLE Transceiver with a 1.9mW RX Achieving -96.4dBm Sensitivity and 4.1dB Adjacent Channel Rejection at 1MHz Offset in 22nm FDSOI](#), M. Tamura, Sony Semiconductor Solutions, Atsugi, Japan, 30.5, ISSCC 2020

[A 370uW 5.5dB-NF BLE/BT5.0/IEEE 802.15.4-Compliant Receiver with >63dB Adjacent Channel Rejection at >2 Channels Offset in 22nm FDSOI](#), B. J. Thijssen, University of Twente, Enschede, The Netherlands

[A 68 dB SNDR Compiled Noise-Shaping SAR ADC With On-Chip CDAC Calibration](#), H. Garvik, C. Wulff, T. Ytterdal

[A Compiled 9-bit 20-MS/s 3.5-fJ/conv.step SAR ADC in 28-nm FDSOI for Bluetooth Low Energy Receivers](#), C. Wulff, T. Ytterdal

Cole Nielsen, https://github.com/nielscol/thesis_presentations

"Python Framework for Design and Simulation of Integer-N ADPLLs", Cole Nielsen, <https://github.com/nielscol/tfe4580-report/blob/master/report.pdf>

[Design of CMOS Phase-Locked Loops](#), Behzad Razavi, University of California, Los Angeles