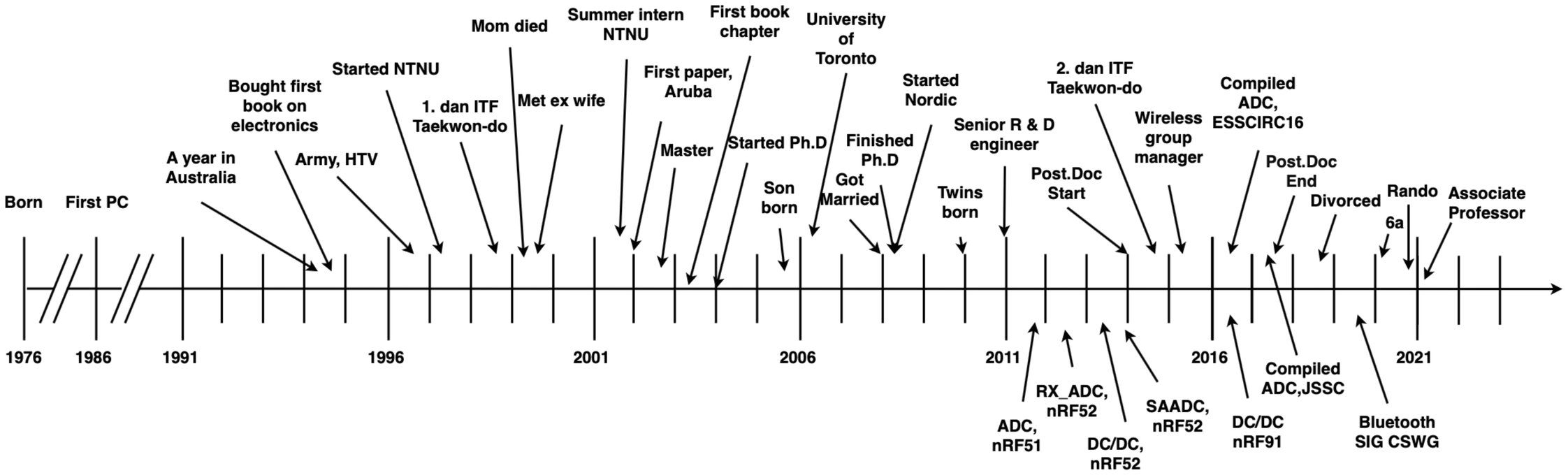
TFE4188 - Introduction to Lecture 10

Low Power Radio

Carsten Wulff



Goal

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

Introduce Bluetooth

Introduce Low Power Recievers

Make the best radio ICs for gaming mice

What do we need to know?

- Data Rate
- Carrier Frequency & Range
- Power supply

Data Rate

Data

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

Rate

Assume 1 ms update rate

Data Rate

Application Data Rate > 76 bits/ms = 76 kbps

Assume 30 % packet loss

Raw Data Rate > 228 kbps

Multiply by π > 716 kbps

Round to nearest nice number = 1Mbps

Carrier Frequency & Range

ISM (industrial, scientific and medical) bands

6 765-6 795 kHz	(centre frequency 6 780 kHz)	FN 5.138
13 553-13 567 kHz	(centre frequency 13 560 kHz)*	FN 5.150
26 957-27 283 kHz	(centre frequency 27 120 kHz)	FN 5.150
40.66-40.70 MHz	(centre frequency 40.68 MHz)	FN 5.150
433.05-434.79 MHz	(centre frequency 433.92 MHz)in Region1**	FN 5.138
902-928 MHz	(centre frequency 915 MHz) in Region 2	FN 5.150
2 400-2 500 MHz	(centre frequency 2 450 MHz)	FN 5.150
5 725-5 875 MHz	(centre frequency 5 800 MHz)	FN 5.150
24-24.25 GHz	(centre frequency 24.125 GHz)	FN 5.150
61-61.5 GHz	(centre frequency 61.25 GHz)	FN 5.138
122-123 GHz	(centre frequency 122.5 GHz)	FN 5.138
244-246 GHz	(centre frequency 245 GHz)	FN 5.138

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 reciever antenna has no gain, then the effective apature is

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

Power recieved is then

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

Or in terms of distance

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

Range (Free space)

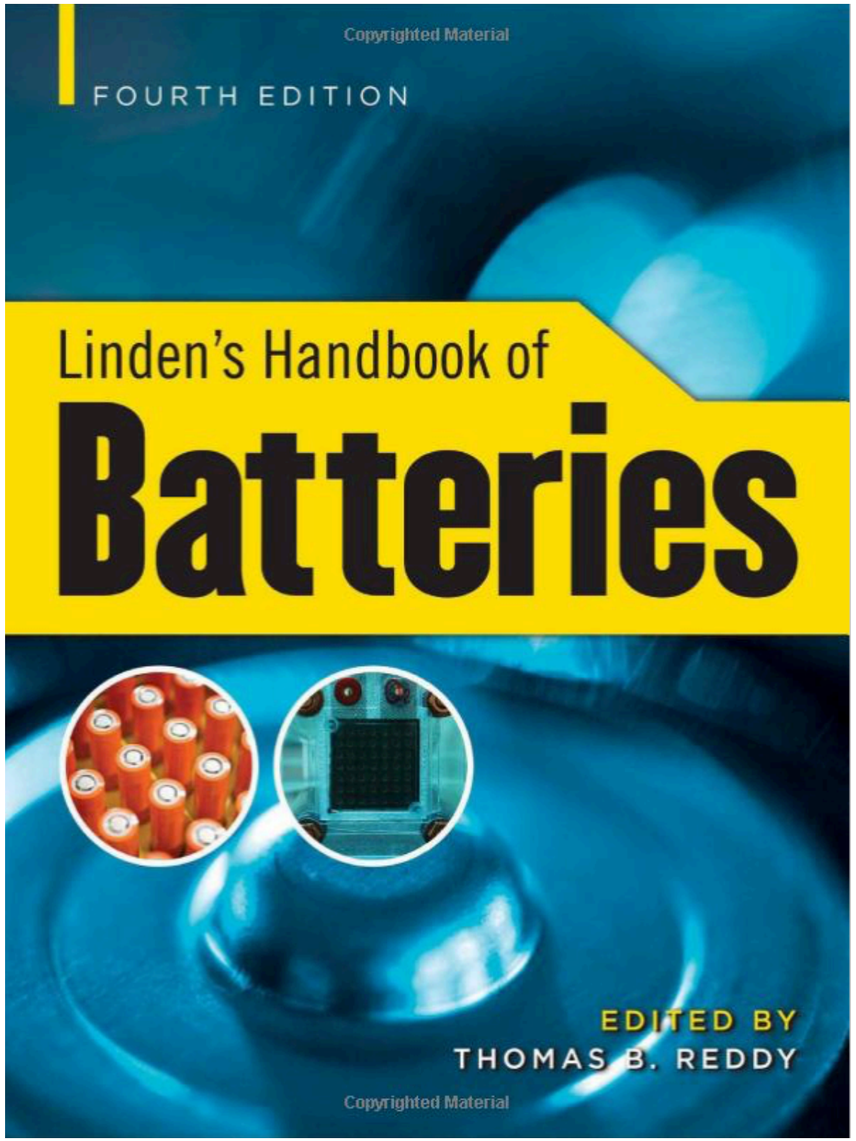
Assume TX = 0 dBm, assume RX sensitivity is -80 dBm

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	❌

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

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	3
AA	Zn/Alk/ MnO2	0.8 - 1.6	3
2xAA	Zn/Alk/ MnO2	1.6 - 3.2	3

Decisions we must make

Modulation scheme

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

Single carrier, or multi carrier?

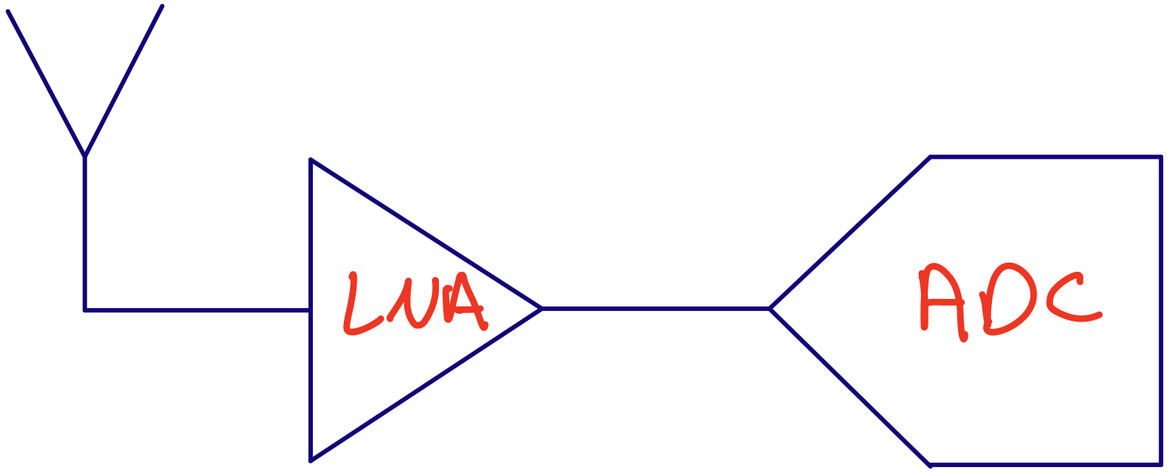
Bluetooth, 802.15.4, ANT all use one carrier
- Simple TX, constant envelope

WiFi, LTE ++ all use Ortogonal frequency division multiplexing (OFDM)
- Complex TX, non-constant envelope

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

#racetoidle

Use a Software Defined Radio



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

State of the art FOM $\approx 5\ \text{fJ/step}$

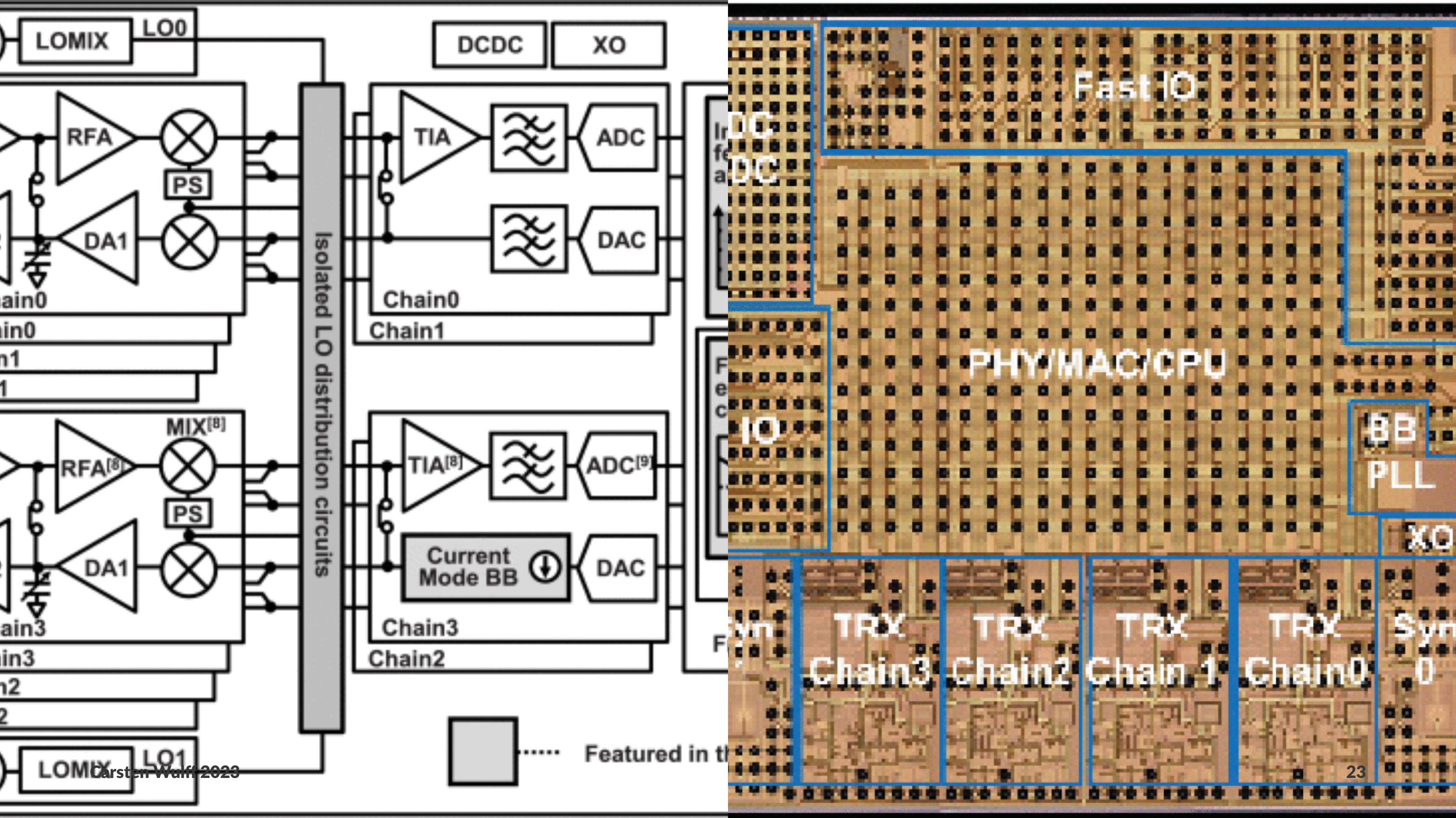
$$BW = 2.5\ \text{GHz}$$

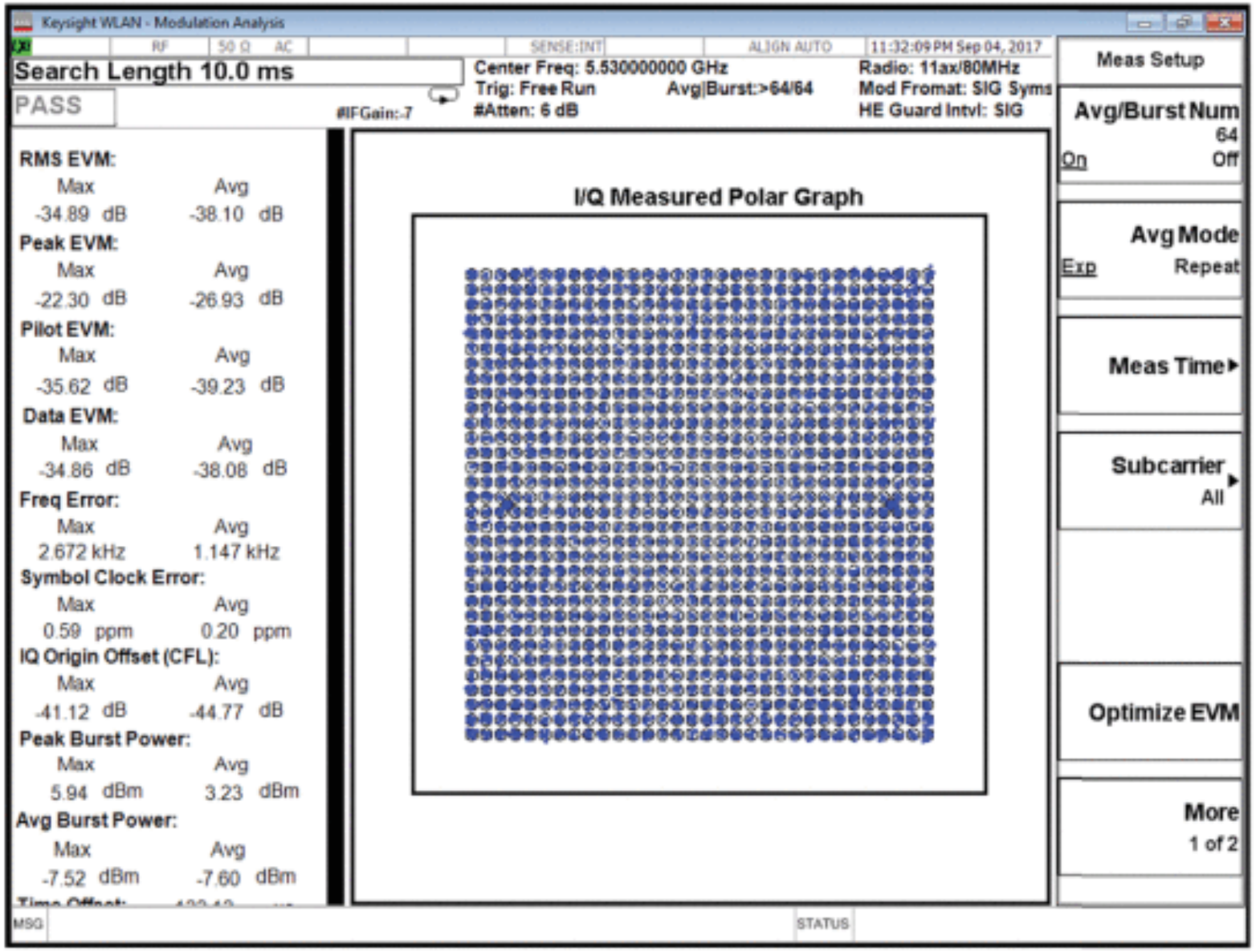
$$DR = 100\ \text{dB} = (96 - 1.76)/6.02 \approx 16\ \text{bit}$$

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

WiFi 6

An 802.11ax 4 × 4 High-Efficiency WLAN AP Transceiver SoC Supporting 1024-QAM With Frequency-Dependent IQ Calibration and Integrated Interference Analyzer


LOMIX
LO0
DCDC
XO
RFA
PS
DA1
TIA
ADC
DAC
Chain0
Chain1
Isolated LO distribution circuits
MIX[8]
RFA[8]
TIA[8]
ADC[9]
Current Mode BB
Chain3
Chain2
LOMIX
LO1
Fast IO
PHY/MAC/CPU
BB PLL
XO
IO
TRX Chain3
TRX Chain2
TRX Chain 1
TRX Chain0


Keysight WLAN - Modulation Analysis
RF
50 Ω AC
SENSE:INT
ALIGN AUTO
11:32:09 PM Sep 04, 2017
Search Length 10.0 ms
PASS
#IFGain:-7
Center Freq: 5.530000000 GHz
Trig: Free Run
Avg|Burst:>64/64
#Atten: 6 dB
Radio: 11ax/80MHz
Mod Fromat: SIG Syms
HE Guard Intvl: SIG
RMS EVM:
Max
-34.89 dB
Avg
-38.10 dB
Peak EVM:
Max
-22.30 dB
Avg
-26.93 dB
Pilot EVM:
Max
-35.62 dB
Avg
-39.23 dB
Data EVM:
Max
-34.86 dB
Avg
-38.08 dB
Freq Error:
Max
2.672 kHz
Avg
1.147 kHz
Symbol Clock Error:
Max
0.59 ppm
Avg
0.20 ppm
IQ Origin Offset (CFL):
Max
-41.12 dB
Avg
-44.77 dB
Peak Burst Power:
Max
5.94 dBm
Avg
3.23 dBm
Avg Burst Power:
Max
-7.52 dBm
Avg
-7.60 dBm
I/Q Measured Polar Graph
Meas Setup
Avg/Burst Num
64
On
Off
Avg Mode
Exp
Repeat
Meas Time
Subcarrier
All
Optimize EVM
More
1 of 2
MSG
STATUS

		This work	ISSCC2017[4]	JSSC2017[6]	CICC2015[3]	RFIC2014[5]	ISSCC2014[7]
WLAN standards		4x4 11abgn/ac/ax	4x4 11abgn/ac	2x2 11abgn/ac	1x1 11abgn/ac	2x2 11abgn/ac	3x3 11abgn/ac
Process [nm]		28	40	40	55	55	40
TX EVM [dB]	2.4G	-42.1(n,64QAM*3,-5dBm) -42.5(ax,40M,1KQAM*1,-5dBm)	NA	-40 (20M, Floor)	NA	-38(20M, Floor)	-41 (HT40, -5dBm)
	5G	-38.4(ac,80M,256QAM*2,-5dBm) -38.1(ax,80M,1KQAM*1,-5dBm)	-36.5(ac,80M,MCS9, Floor)	-38 (20M,Floor)	-37.8(80MHz, Floor)	-37.5(ac, 80M, Floor)	-37 (-5dBm)
RX sensitivity [dBm]	2.4G	-78.4(g,54M) -64.2(ax,40M,1KQAM*1)	-77(LG,54M)	-78.3(54Mbps)	-77.5(LG,54M)	-77.5(LG, 54M)	NA
	5G	-65.4(ac,80M,256QAM*2) -57.7(ax,80M,1KQAM*1)	-62(ac,80M,MCS9)	-66(MCS9)	-63.5(80M, MCS9)	-62.5 (ac, 80M, MCS9)	NA
RX NF [dB]	2.4G	2.9	N/A	2.9	3	3.8	3.0
	5G	3.2	N/A	4.5	3.7	4	4.3
RF power consumption [mW]	TX 2.4G	844(4SS+1LO, -5dBm)	3863 (4SS+1LO,21dBm)	1460 (2SS+1LO,20dBm)	705(1SS+1LO, 20.5dBm)	1588 (2SS+1LO, 20dBm)	1080*4 (3SS+1LO)
	TX 5G	832(4SS+2LO, -5dBm)	4164 (2SS+2LO,22dBm)	1750 (2SS+1LO,18dBm)	996 (2SS+1LO, 18.5dBm)	1722 (2SS+1LO, 17.5dBm	1520*4 (3SS+1LO)
	RX 2.4G	354(4SS+1LO)	297(4SS+1LO)	179 (2SS+1LO)	84 (1SS+1LO)	303 (2SS+1LO)	1170*4 (3SS+1LO)
	RX 5G	447(4SS+2LO)	474(2SS+2LO)	243 (2SS+1LO)	156 (1SS+1LO)	317 (2SS+1LO)	2080*4 (3SS+1LO)
Image rejection ratio after cal. [dB]		-53(RX, Ave. over 80M) -58(RX, at 5MHz) -61(TX, Ave. over 80M) -64(TX, at 5MHz)	-61(TX,at 5MHz)	NA	-45(RX)	-45(RX)	NA
RF chip area[mm^2]		12.0	11.4	8.6	3.4*6	7.7	21.5*5
1K QAM		Yes	No	No	No	No	No
FD-IQ amp. mismatch calibration		Yes	No	No	No	No	No
Non-contiguous		Yes	Yes	No	No	No	No
Integrated interference analyzer		Yes	No	No	No	No	No

*1 Modulation and coding scheme is MCS11 *2 Modulation and coding scheme is MCS9 *3 Modulation and coding scheme is MCS7 *4 SoC power *5 SoC area *6 Including BT RF area

Crap, complex!
Crap, too high power!

Bluetooth®

Bluetooth

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

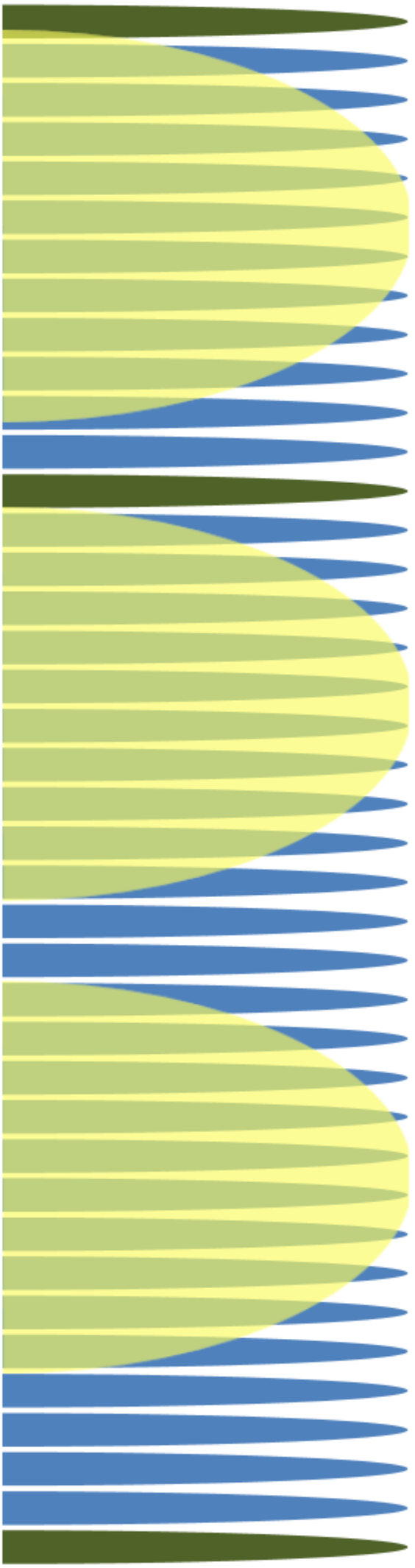
Bluetooth Basic Rate/Extended Data rate

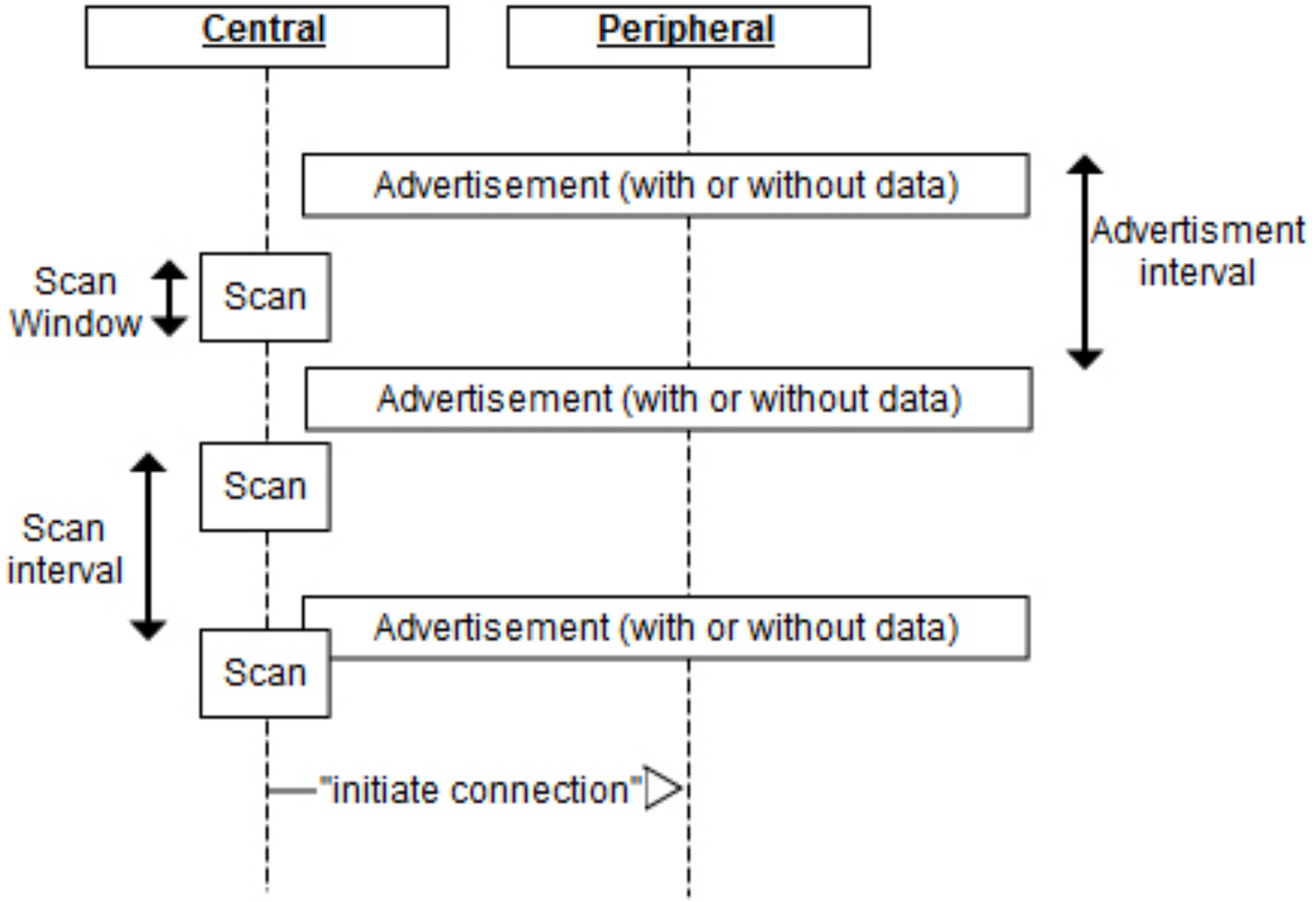
- 2.400 GHz to 2.4835 GHz
- 1 MHz channel spacing
- 78 Channels
- Up to 20 dBm
- Minimum -70 dBm sensitivity (1 Mbps)
- 1 MHz GFSK (1 Mbps), pi/4-DQPSK (2 Mbps), 8DPSK (3 Mbps)

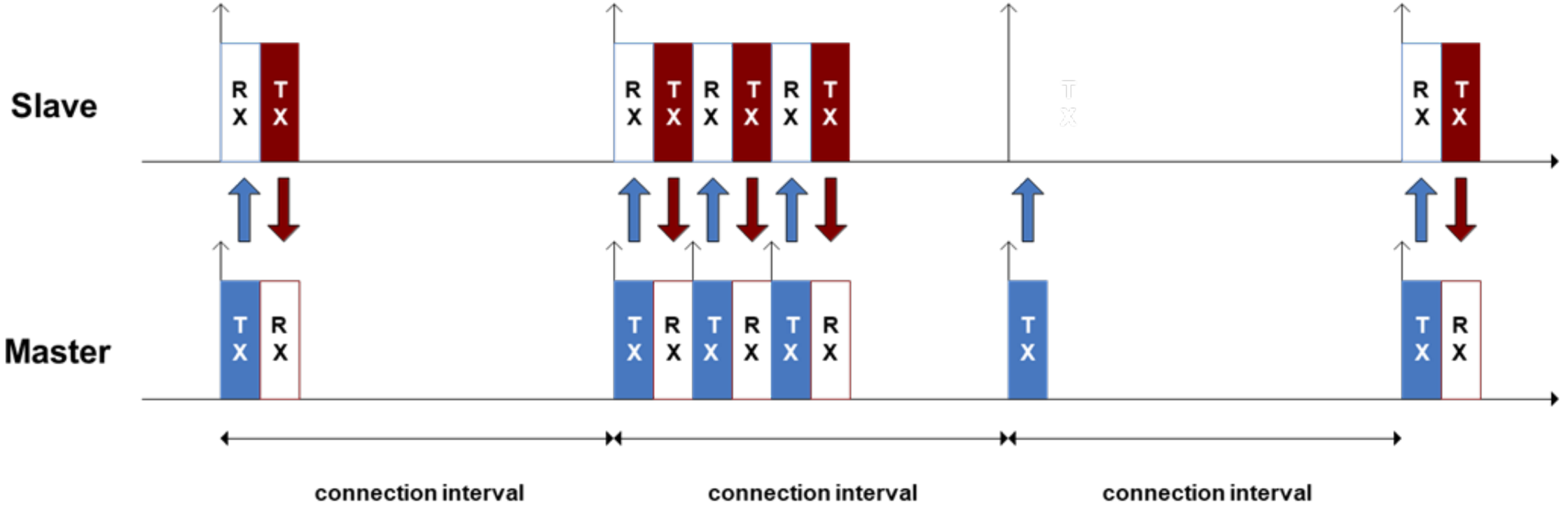
Bluetooth Low Energy

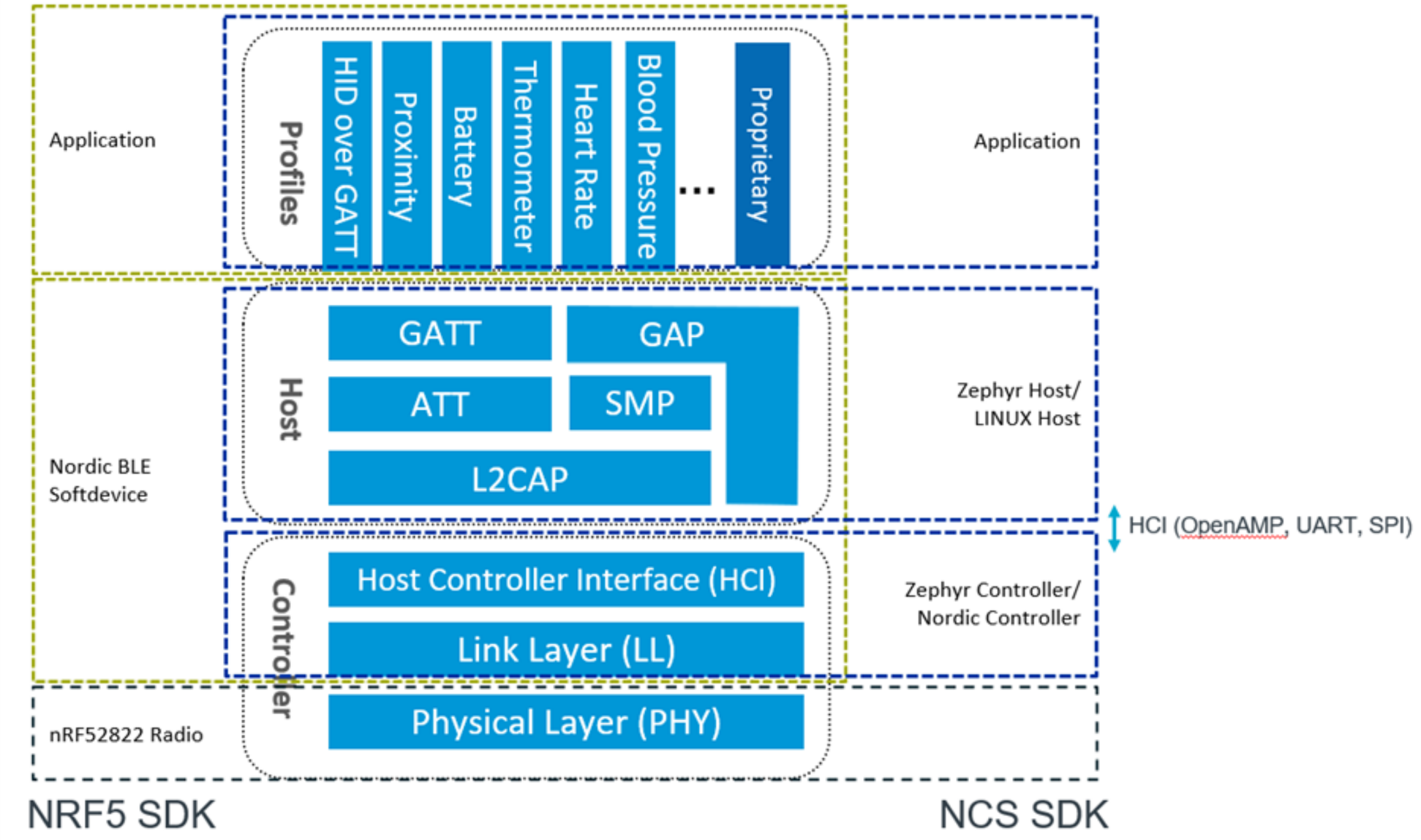
- 2.400 GHz to 2.480 GHz
- 2 MHz channel spacing
- 40 Channels (3 primary advertizing channels)
- Up to 20 dBm
- Minimum -70 dBm sensitivity (1 Mbps)
- 1 MHz GFSK (1 Mbps, 500 kbps, 125 kbps), 2 MHz GFSK (2 Mbps)

Frequency	LL
2402 MHz	37
2404 MHz	0
2406 MHz	1
2408 MHz	2
2410 MHz	3
2412 MHz	4
2414 MHz	5
2416 MHz	6
2418 MHz	7
2420 MHz	8
2422 MHz	9
2424 MHz	10
2426 MHz	38
2428 MHz	11
2430 MHz	12
2432 MHz	13
2434 MHz	14
2436 MHz	15
2438 MHz	16
2440 MHz	17
2442 MHz	18
2444 MHz	19
2446 MHz	20
2448 MHz	21
2450 MHz	22
2452 MHz	23
2454 MHz	24
2456 MHz	25
2458 MHz	26
2460 MHz	27
2462 MHz	28
2464 MHz	29
2466 MHz	30
2468 MHz	31
2470 MHz	32
2472 MHz	33
2474 MHz	34
2476 MHz	35
2478 MHz	36
2480 MHz	39



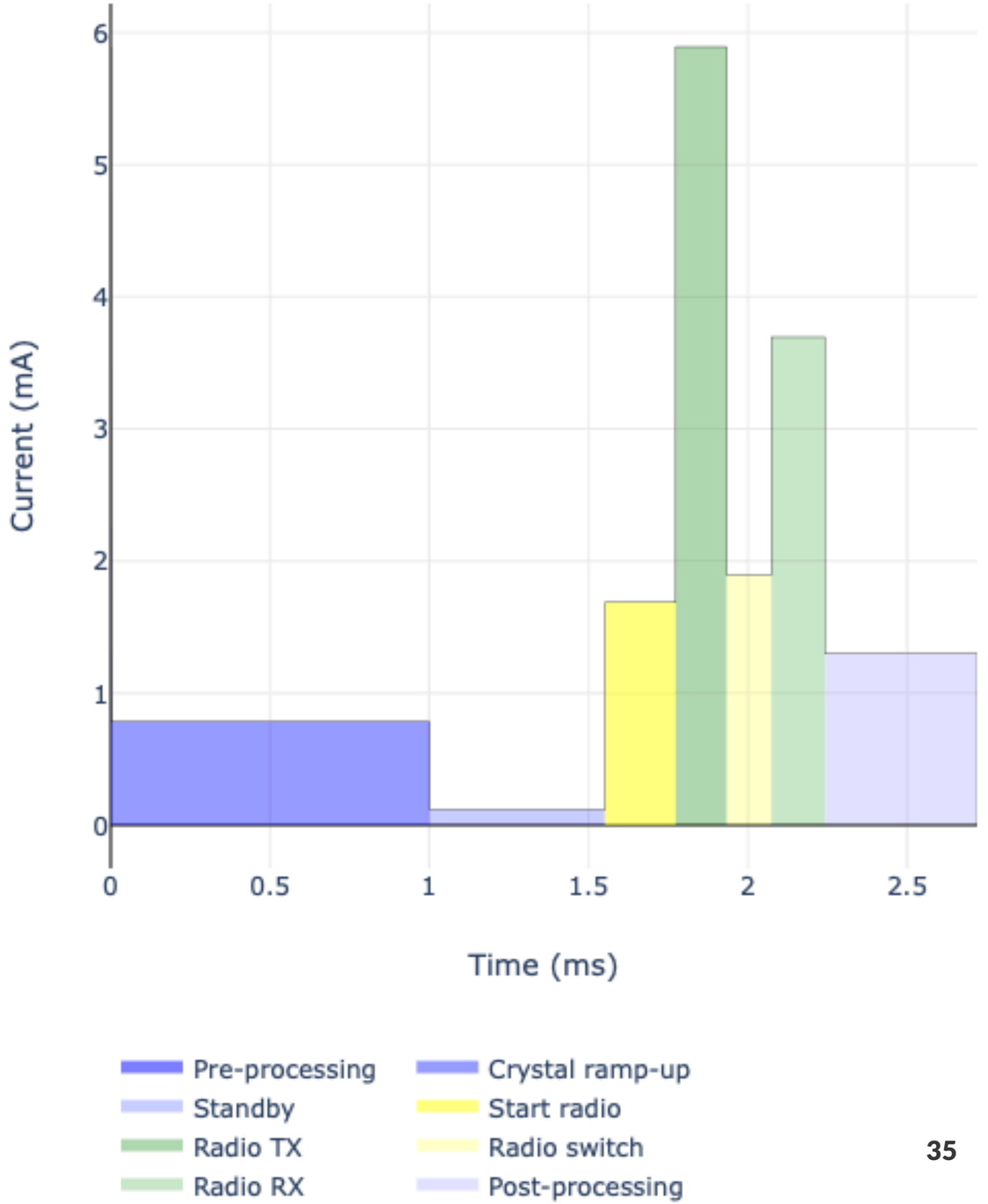

Central
Peripheral
Advertisement (with or without data)
Advertisment interval
Scan Window
Scan
Advertisement (with or without data)
Scan
Scan interval
Advertisement (with or without data)
Scan
"initiate connection"


Slave
Master
RX
TX
connection interval
connection interval
connection interval


Application
Profiles
HID over GATT
Proximity
Battery
Thermometer
Heart Rate
Blood Pressure
...
Proprietary
Application
Nordic BLE
Softdevice
Host
GATT
GAP
ATT
SMP
L2CAP
Zephyr Host/
LINUX Host
HCI (OpenAMP, UART, SPI)
Controller
Host Controller Interface (HCI)
Link Layer (LL)
Physical Layer (PHY)
Zephyr Controller/
Nordic Controller
nRF52822 Radio
NRF5 SDK
NCS SDK

Test setup	
Voltage	3.0 V
Regulator	DCDC
Application RAM	512 kB
Network RAM	64 kB
BLE event details	
Interval	7.50 ms
Length	2.72 ms
Number of packets	1
Master sleep clock accuracy	20 ppm
Slave sleep clock accuracy	20 ppm
Data transmission	
LL PDU size	27 Byte
TX payload per event	10 Byte
TX LL throughput	10.67 kbps
RX payload per event	10 Byte
RX LL throughput	10.67 kbps
On air data rate	1 Mbps

Current consumption	
BLE event total charge	6.06 µC
Idle current	3.1 µA
Total average current	811 µA



For further information Building a Bluetooth application on nRF Connect SDK

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 Higher Bands for LE Subgroup 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 data transfer 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.

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:

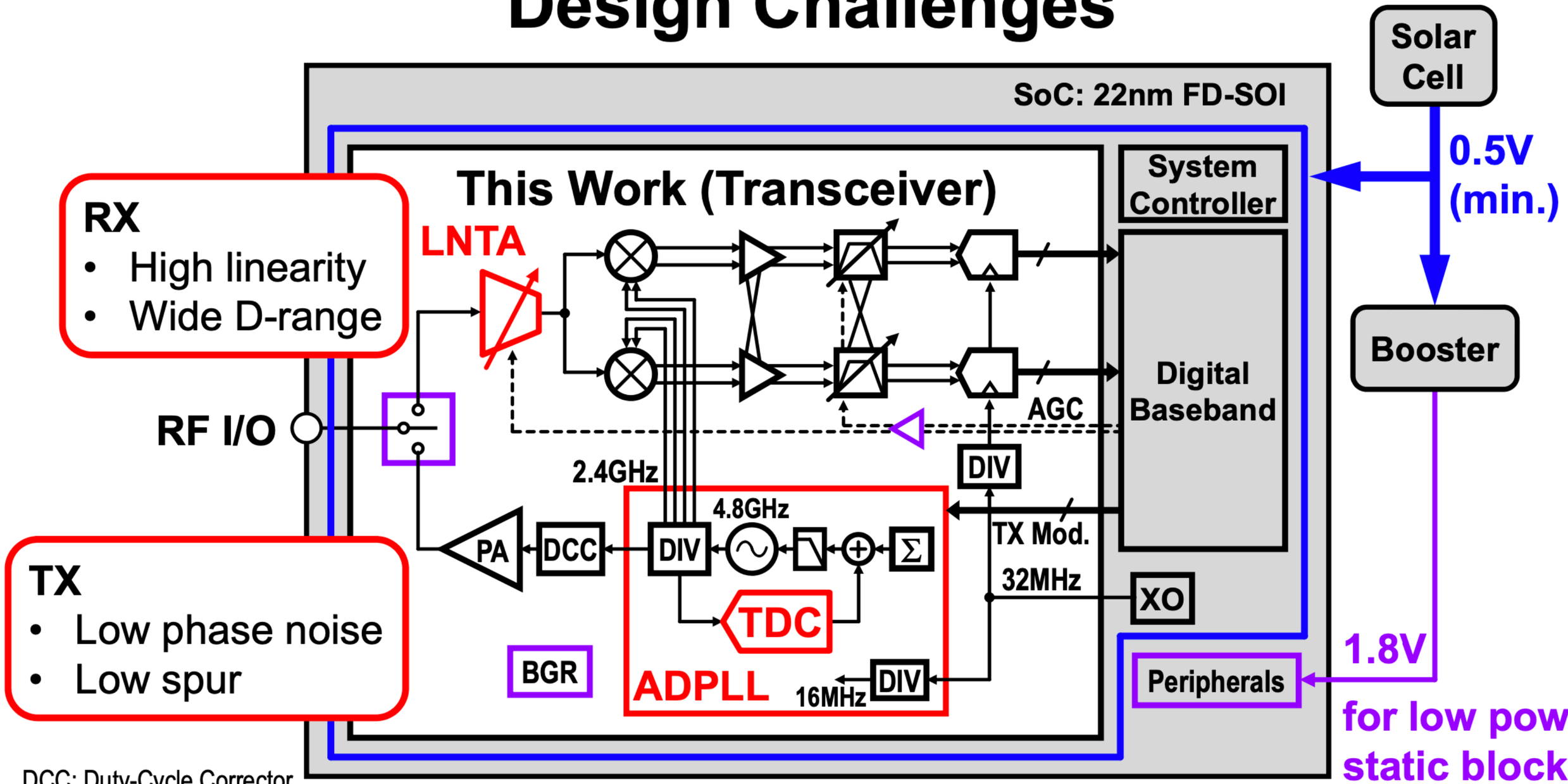
- Enhancements being made to the Bluetooth Core Specification taking place within the Core Specification Working Group
- A new profile specification being developed within the Direction Finding Working Group

Low Power Recievers

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

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

Design Challenges

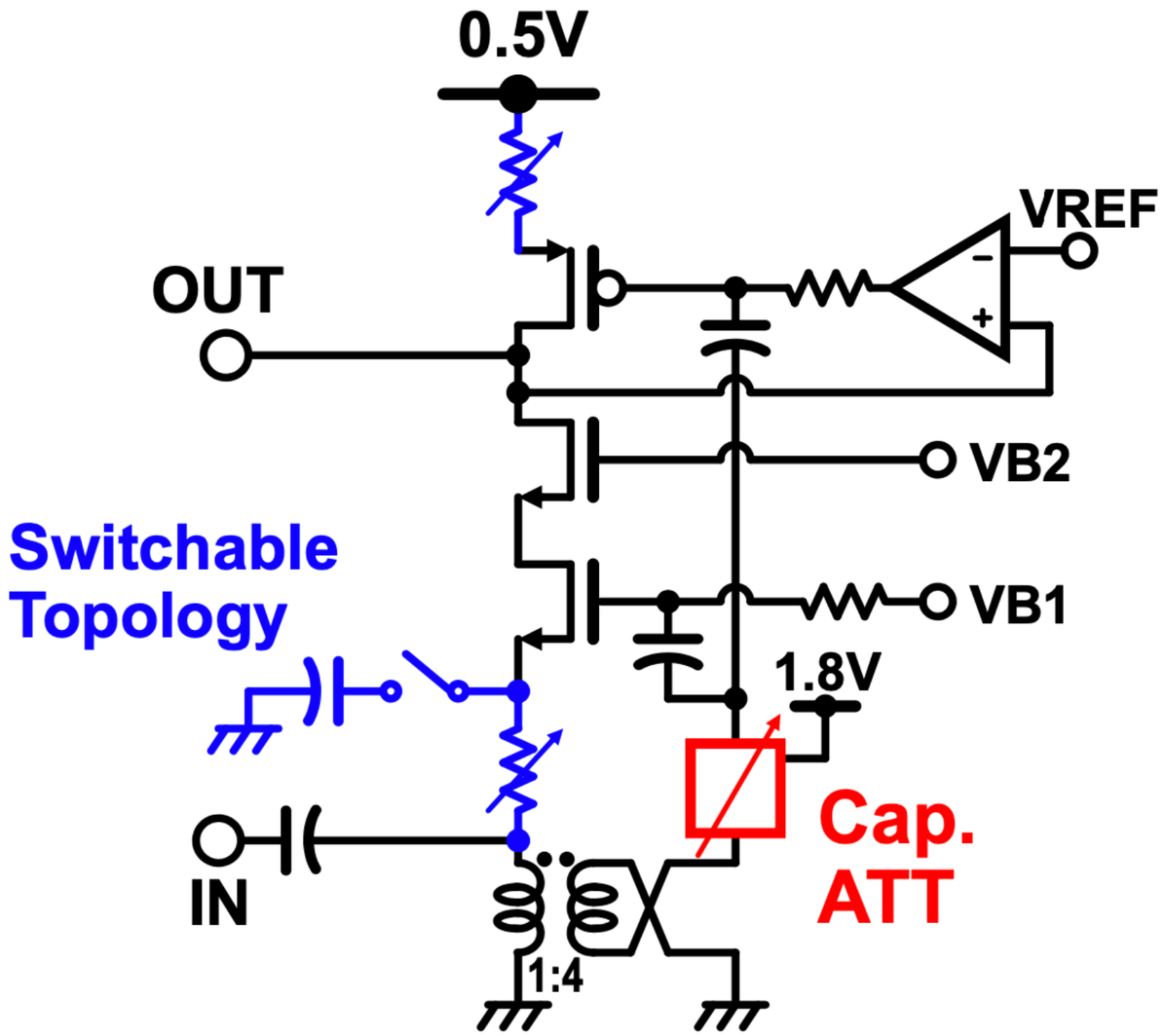


DCC: Duty-Cycle Corrector

Blocks	Key parameter	Architecture	Complexity (nr people)
Antenna	Gain, impedance	??	<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, linearity	TIA + AFIR	1
ADC	Sample rate, dynamic range, linearity	NS-SAR	1 - 2
PLL	Freq accuracy, phase noise, current	AD-PLL	2-3
Baseband	Eb/N0, gate count, current	Verilog, but first Matlab	> 10


LNTA

0.5V Programmable-Gain LNTA



- Low voltage bias design with DC feedback circuit [3]
- Switchable topology
  - High-Gain: Common-Gate
  - Low-Gain: Common-Source
  - Mid-Gain: Mixed operation
- Capacitive attenuator
  - IIP3 improves proportional to the attenuation factor

[3] K. Yamamoto, ISSCC ’16

MIXER

LNTA and Mixer

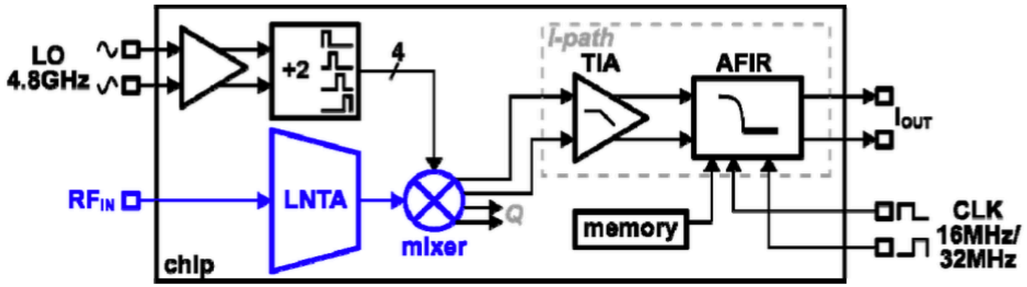
LNTA

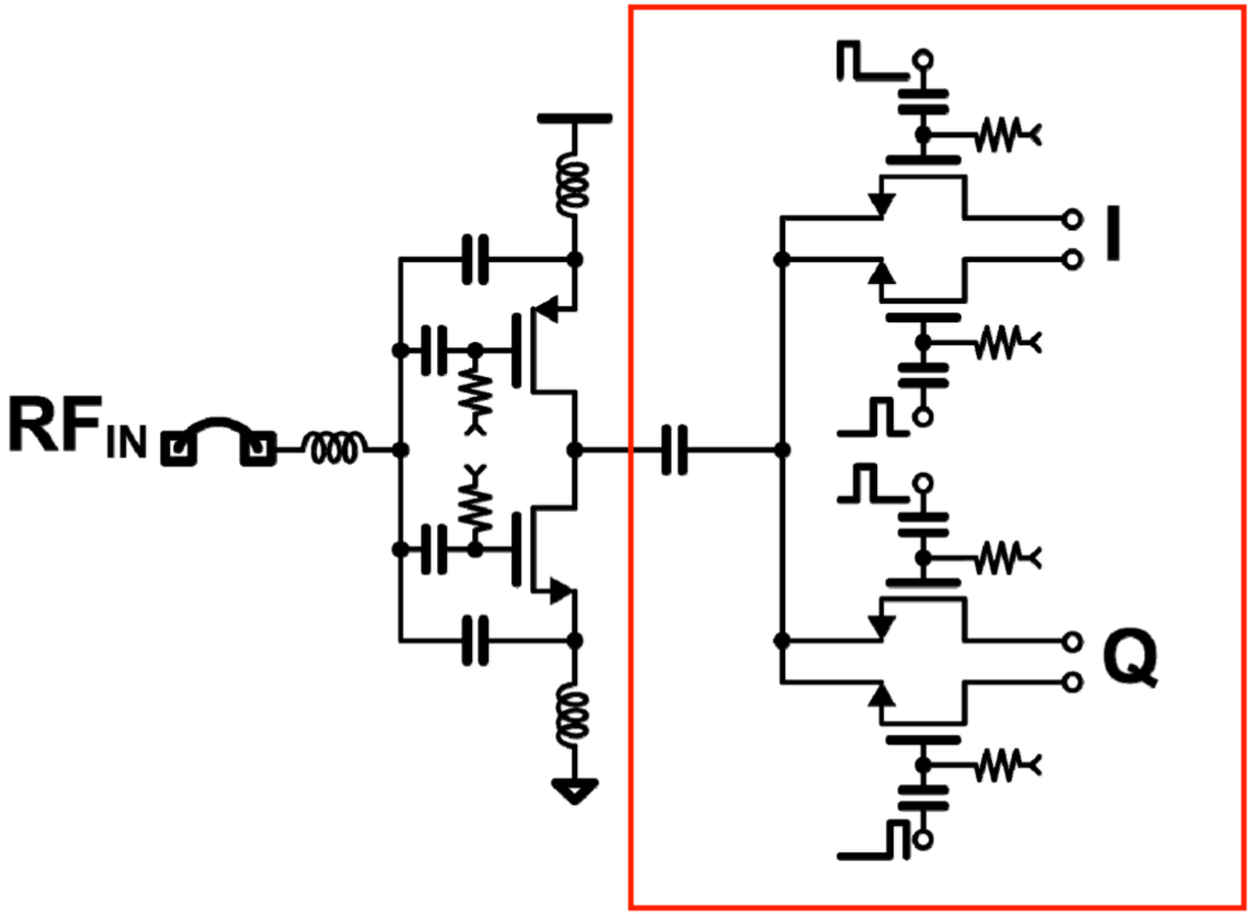
- Push-Pull
- Inductive degeneration

[Jiang, CICC'18]

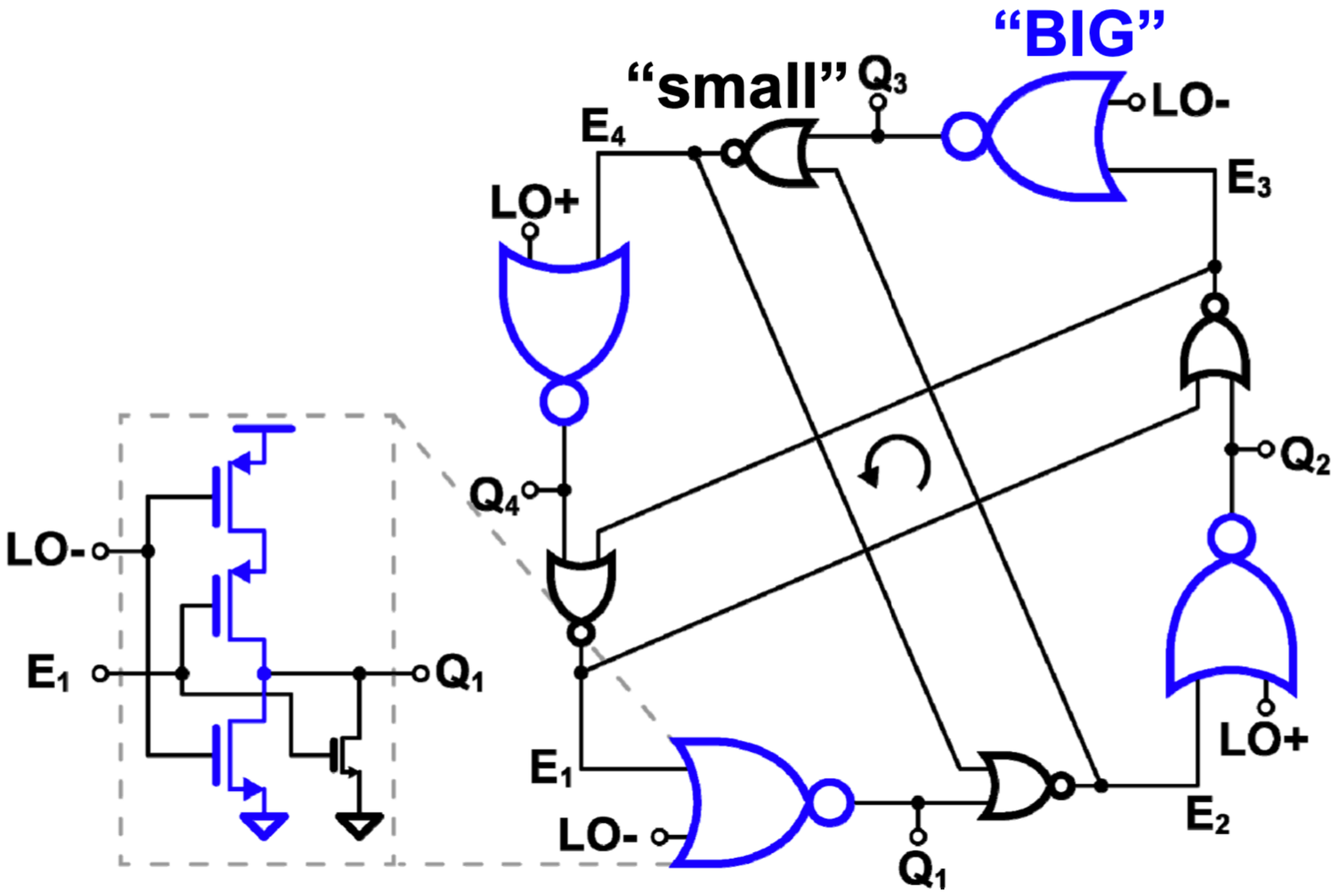
Mixer

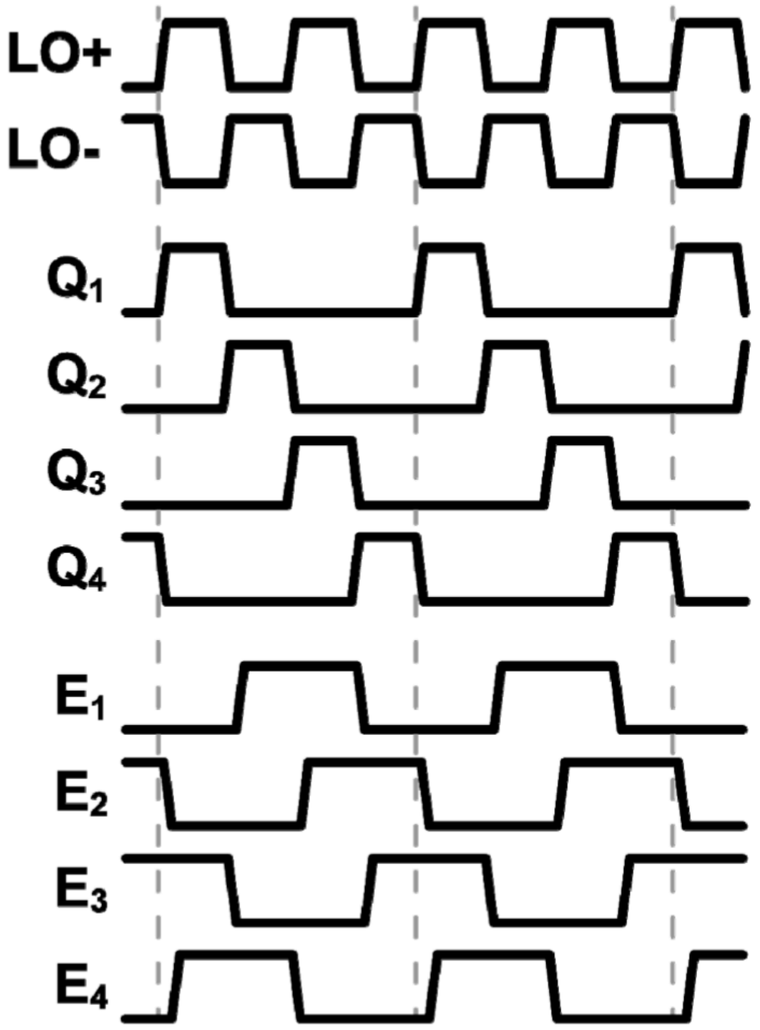
- Passive
- 25% duty-cycle clocks





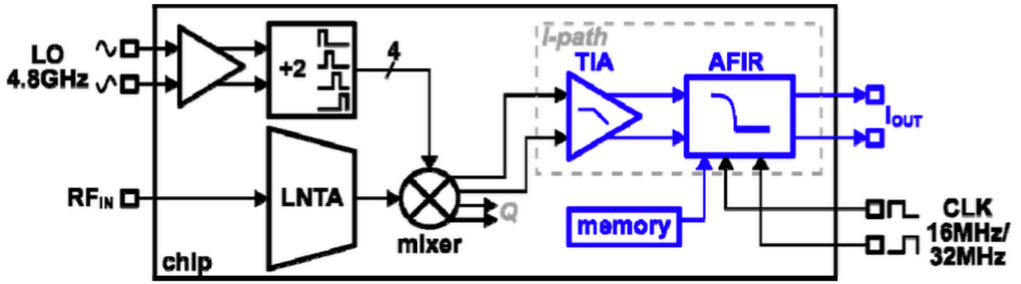
Combining and Sizing

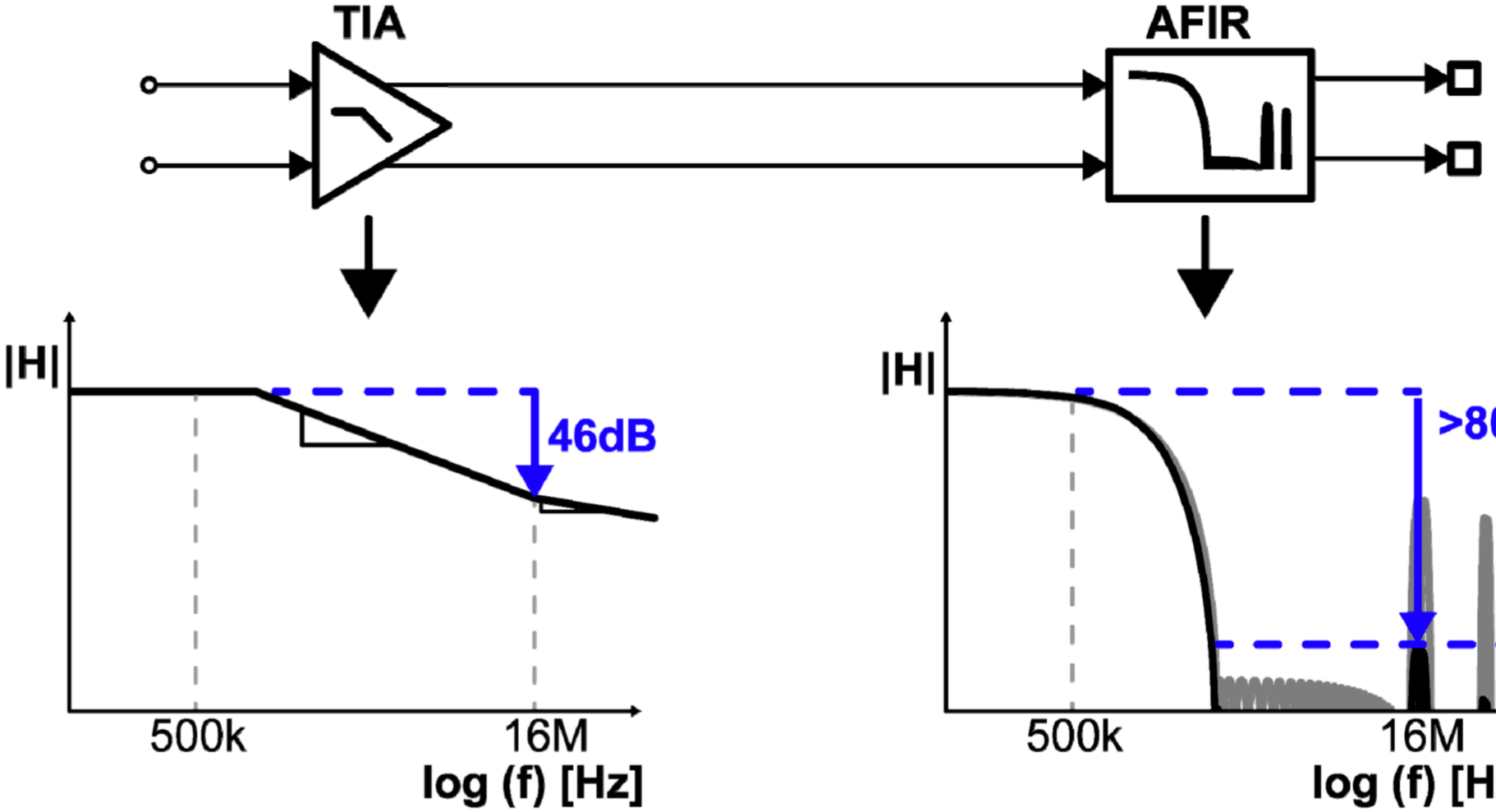


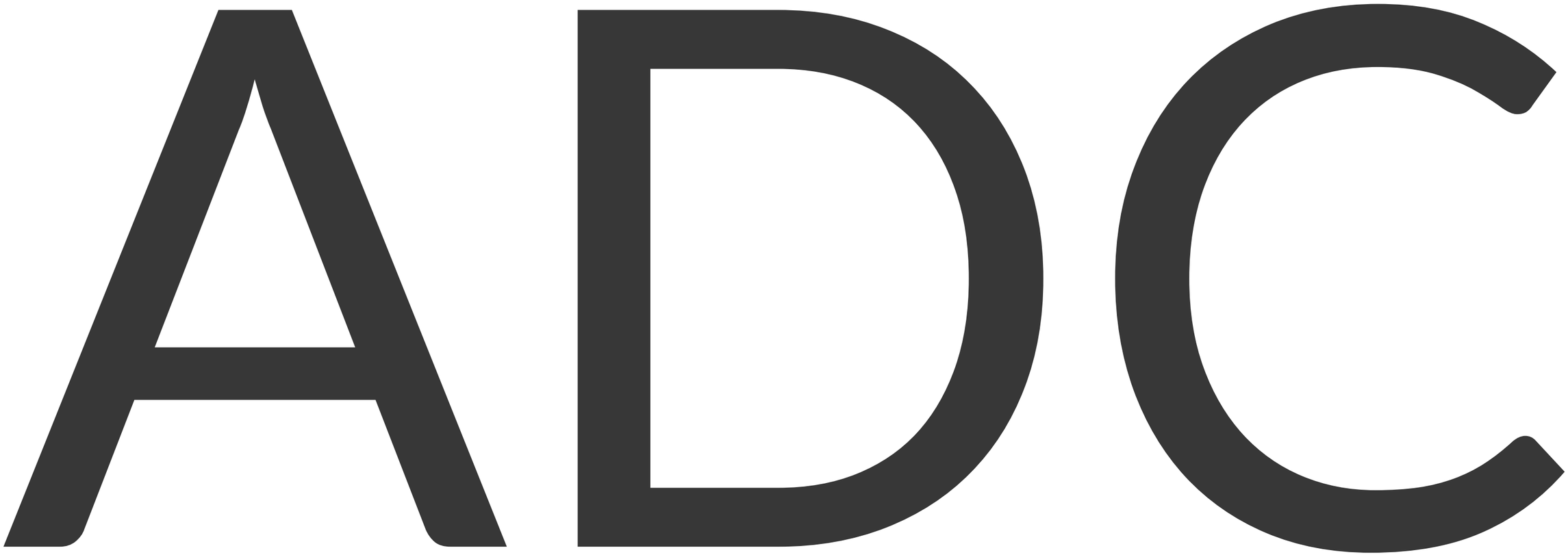



AAF

Baseband Architecture






ADC

A Compiled 9-bit 20-MS/s 3.5-fJ/conv.step SAR ADC in 28-nm FDSOI for Bluetooth Low Energy Receivers

Carsten Wulff, *Member, IEEE*, and Trond Ytterdal, *Senior Member, IEEE*

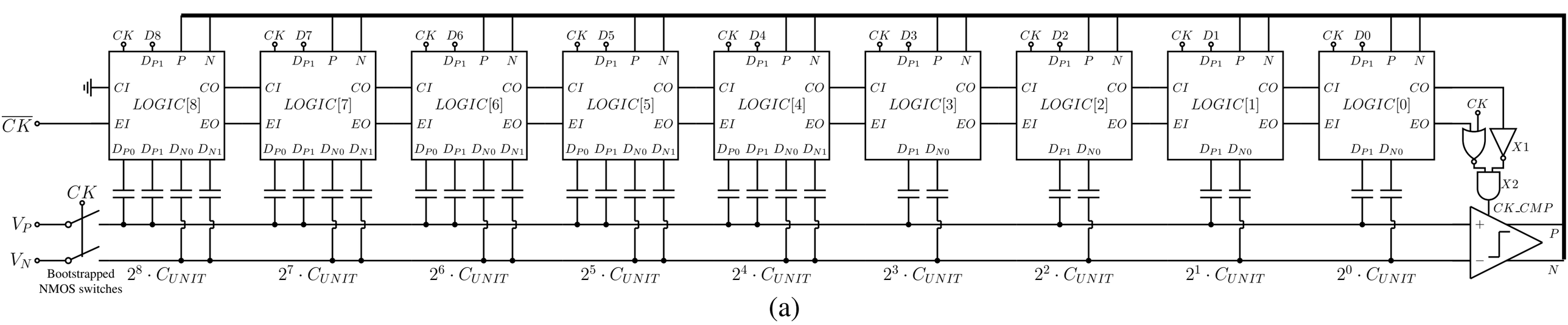
***Abstract*— This paper presents a low-power 9-bit compiled successive-approximation register (SAR) analog-to-digital converter (ADC) for Bluetooth low energy receivers. The ADC is compiled from a SPICE netlist, a technology rule file, and an object definition file into a design rule check and layout versus schematic clean layout and schematic in 28-nm FDSOI. The compiled SAR ADC reduces the design time necessary to port to a new technology, and to demonstrate technology porting the same SAR ADC architecture is compiled in 28-nm FDSOI with Input/Output (IO) transistors. This paper also includes a comparator clock generation loop that uses the bottom plate of the capacitive digital-to-analog converter. The proposed compiled core transistor SAR ADC achieves the state-of-the-art Figure of Merit (FoM) of 2.7 fJ/conv.step at 2 MS/s, and 3.5 fJ/conv.step at 20 MS/s with an area of 0.00312 mm^2.**

***Index Terms*— Analog layout, analog layout synthesis, analog-to-digital conversion, analog-to-digital converter (ADC), Bluetooth low energy, Fully-depleted Silicon-on-insulator (FDSOI), low power, successive approximation.**

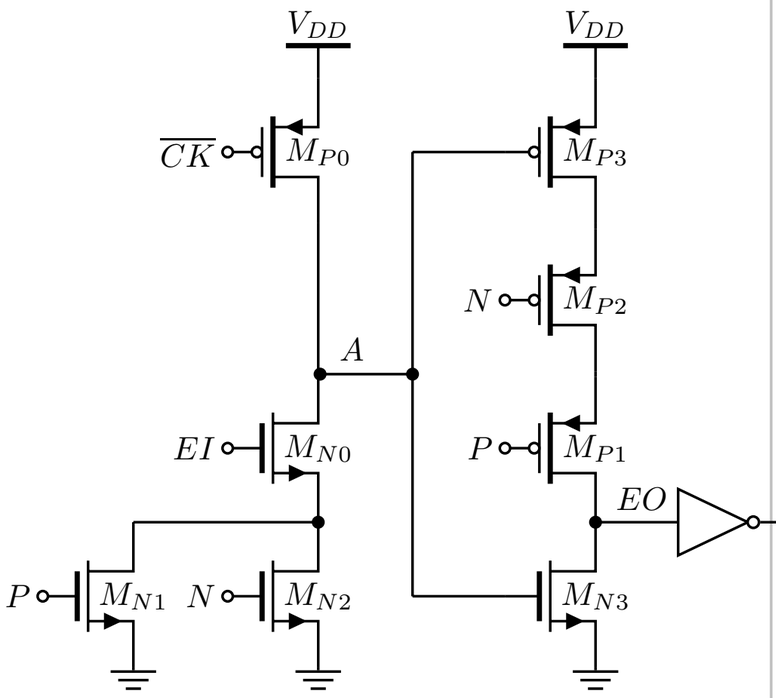
layout. For example, the schematic does not contain placement information for layout, since the optimum layout placement might be different from optimal schematic placement.

Analog layout generation has a long history with works from the previous century [2], [3], but the state-of-the-art analog layout generation, as reviewed in [4], is not widely adopted. More promising research avenues avoid the challenge of analog layout generation from schematics, by not having a schematic. Recently, ADCs have been compiled in a digital flow [5], [6], and although the Effective Number of Bits (ENOB) was less than 6 bit, it is an interesting approach. A similar approach has been used successfully for all-digital Phase Locked Loops [7].

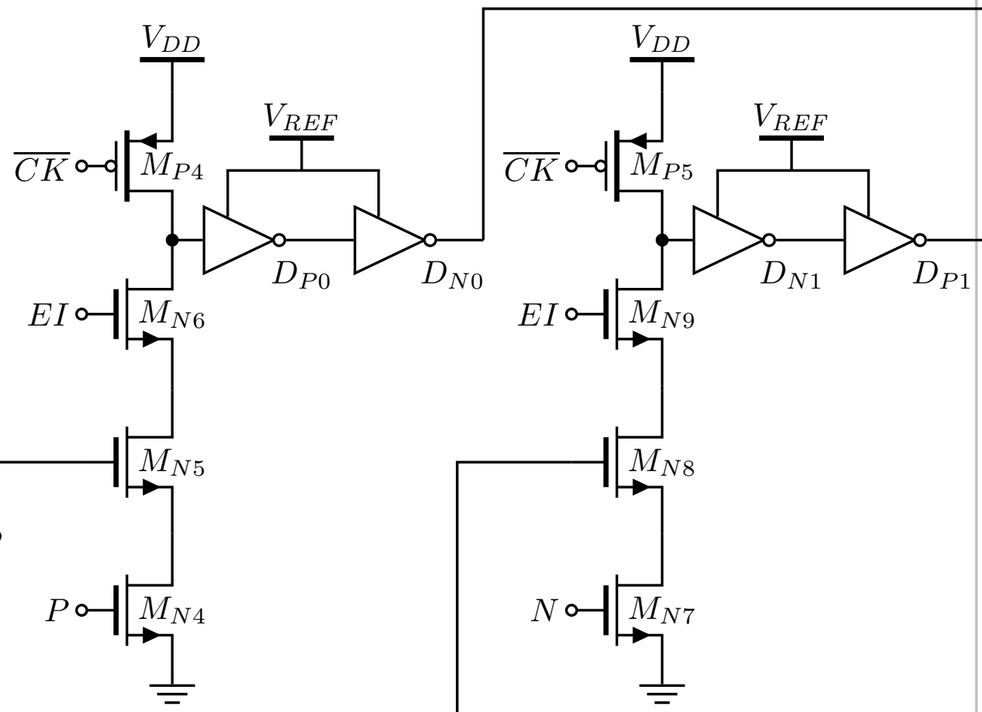
This paper, first introduced at a conference [8], presents a method where the layout is not generated based on drawn schematics. The ADC is described using an approach borrowed from object oriented programming. A custom compiler


CK D8
CK D7
CK D6
CK D5
CK D4
CK D3
CK D2
CK D1
CK D0
LOGIC[8]
LOGIC[7]
LOGIC[6]
LOGIC[5]
LOGIC[4]
LOGIC[3]
LOGIC[2]
LOGIC[1]
LOGIC[0]
CI CO EI EO
X1
X2
CK_CMP
P
N
Bootstrapped NMOS switches
$2^8 \cdot C_{UNIT}$
$2^7 \cdot C_{UNIT}$
$2^6 \cdot C_{UNIT}$
$2^5 \cdot C_{UNIT}$
$2^4 \cdot C_{UNIT}$
$2^3 \cdot C_{UNIT}$
$2^2 \cdot C_{UNIT}$
$2^1 \cdot C_{UNIT}$
$2^0 \cdot C_{UNIT}$

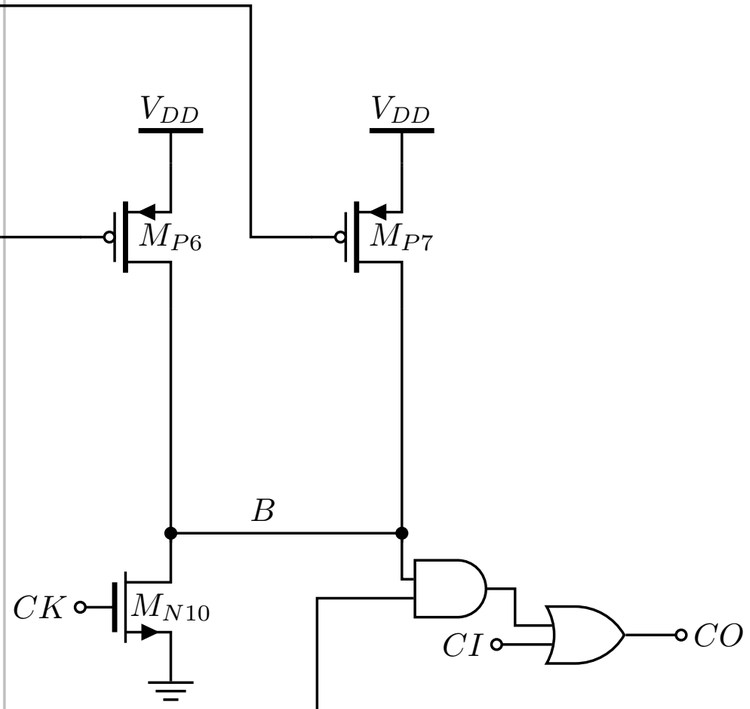
(a)


V_{DD}
$\overline{CK}$
M_{P0}
M_{P3}
N
M_{P2}
A
EI
M_{N0}
P
M_{P1}
EO
P
M_{N1}
N
M_{N2}
M_{N3}

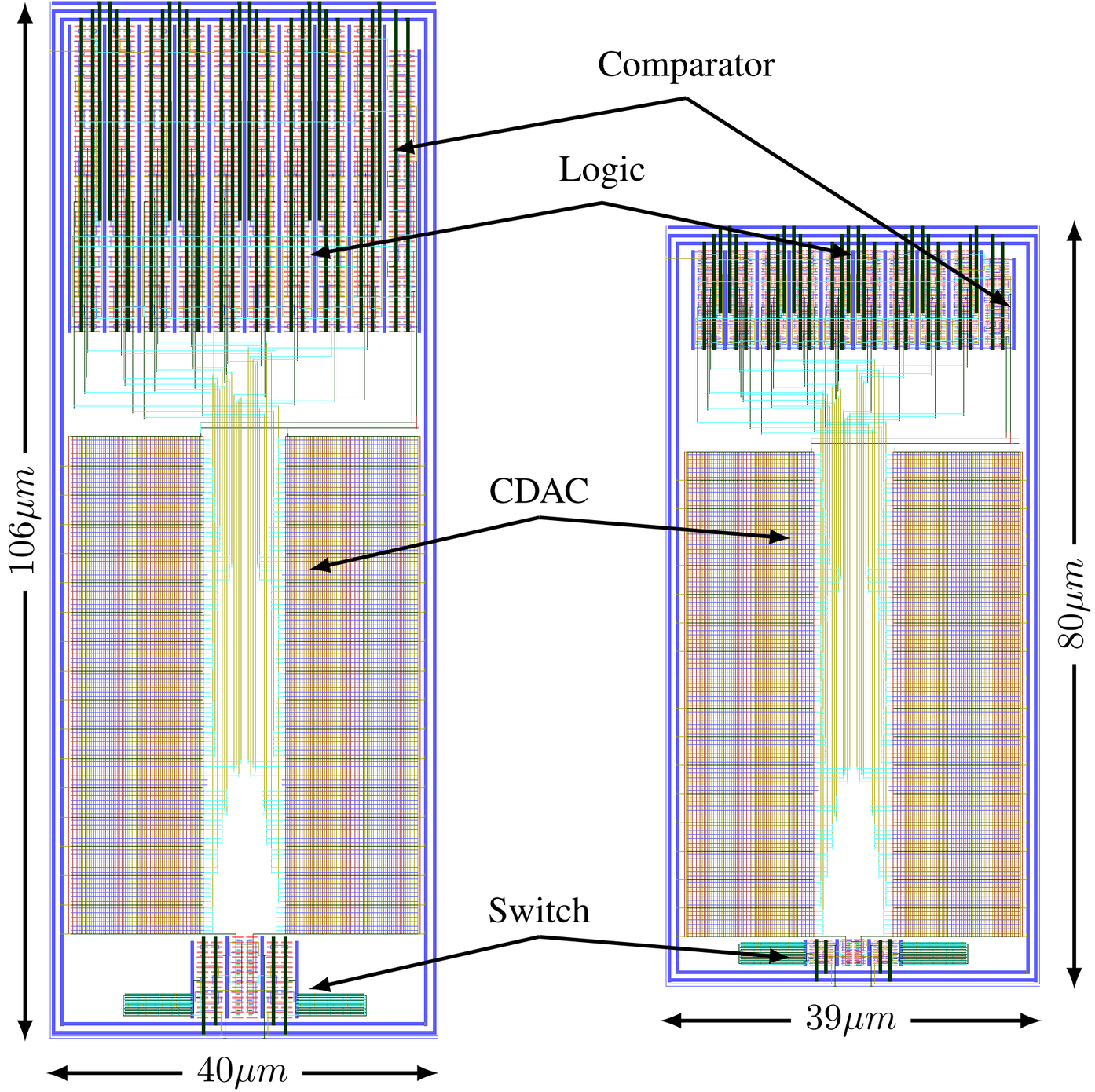
(b)


V_{DD}
V_{REF}
$\overline{CK}$
M_{P4}
D_{P0}
D_{N0}
EI
M_{N6}
M_{N5}
P
M_{N4}
M_{P5}
D_{N1}
D_{P1}
M_{N9}
M_{N8}
N
M_{N7}

(c)


V_{DD}
M_{P6}
M_{P7}
B
CK
M_{N10}
CI
CO

(d)


Comparator
Logic
CDAC
Switch
106μm
40μm
80μm
39μm
(a)
(b)

A 68 dB SNDR Compiled Noise-Shaping SAR ADC With On-Chip CDAC Calibration

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***Abstract*—This paper presents a noise-shaping SAR ADC with an on-chip, foreground capacitive DAC calibration system. At start-up, the ADC uses the smallest DAC capacitors to measure and digitize the errors of the largest ones. A synthesized digital module accumulates the noise-shaped measurements, computes calibration coefficients, and corrects ADC codes at run-time. The loop filter implements two optimal zeros and two poles, and achieves 27.8 dB in-band attenuation at an oversampling rate of 4. The prototype implemented in 28 nm FDSOI achieves 68.2 dB SNDR at 5 MHz bandwidth while using 108.7 µW. The Walden figure-of-merit is 5.2 fJ/conv.-step. The layout of the ADC is compiled from a netlist, a rule file, and an object definition file.**

***Index Terms*—Noise-shaping, SAR ADC, CDAC calibration, analog layout synthesis.**

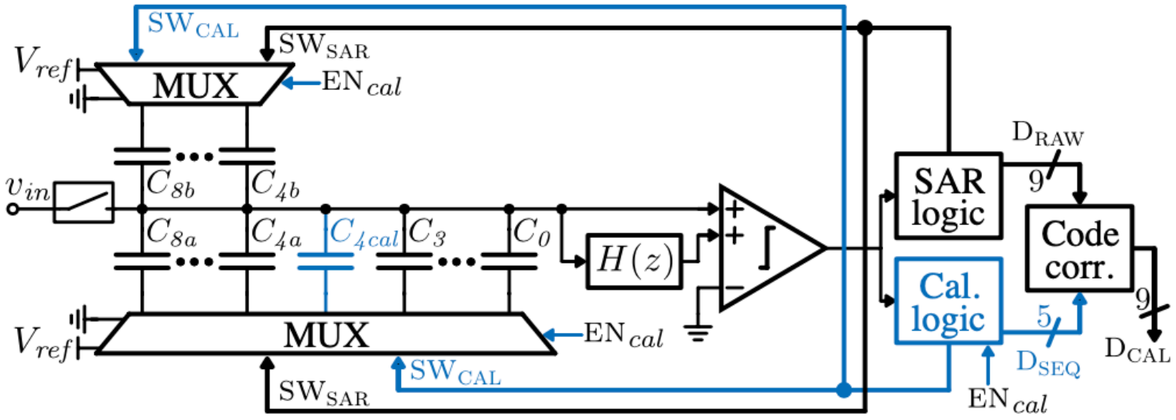


Fig. 1. Proposed noise-shaping SAR architecture. Blue blocks and paths are only active in calibration mode.

AD-PLL

Phase Locked loops

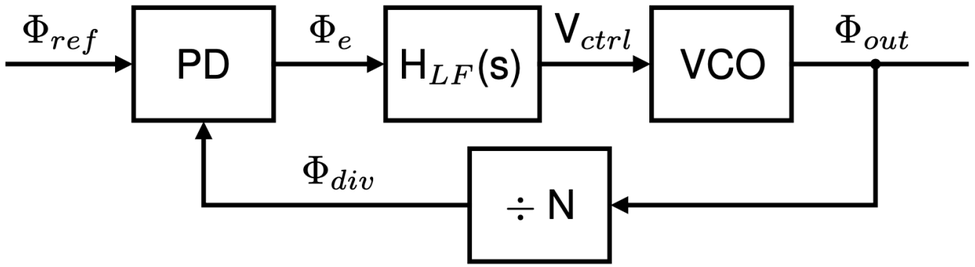
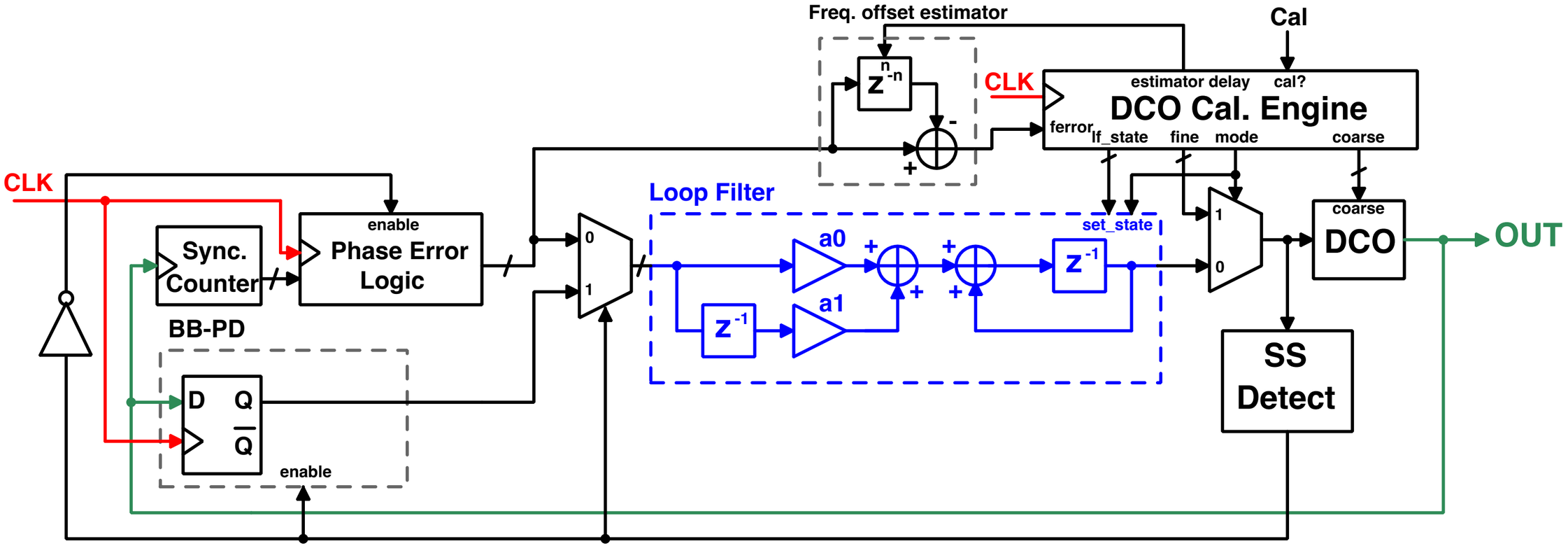


Figure 2: Basic PLL.

- Read Razavi's PLL book [7]

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

AD-PLL with Bang-Bang phase detector for steady-state [5]



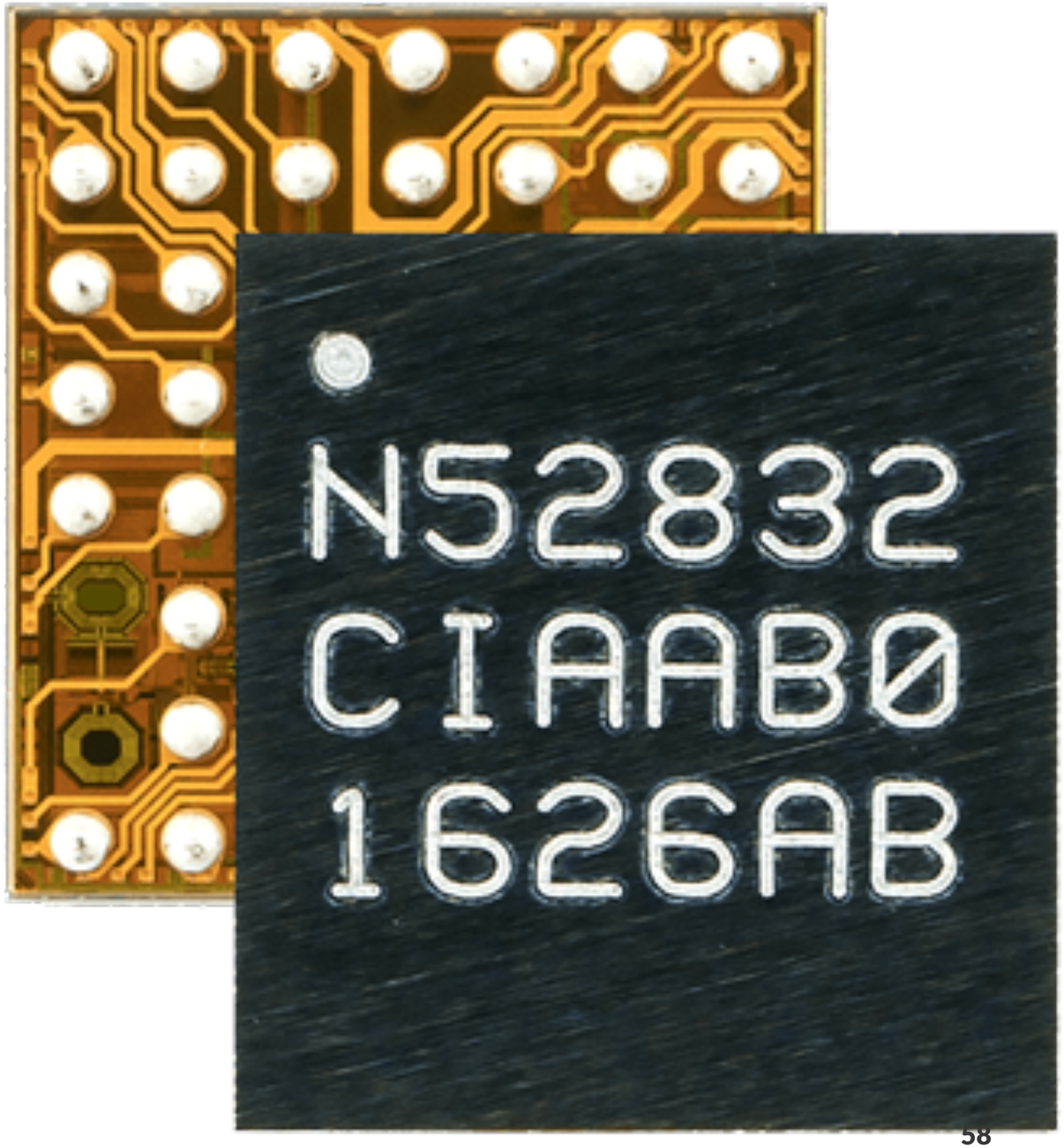
[5] Cole Nielsen, https://github.com/nielscol/thesis_presentations

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 adjaecent 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, see
Address detection	Is the packet for us?
Header detection	What does the packet contain
CRC	Does the packet have bit errors
Payload decrypt	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?

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



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