1 Introduction

An analog-to-digital converter (ADC) translates an analog quantity, typically a voltage, into a digital word. A digital-to-analog converter (DAC) translates a digital word into an analog quantity, typically a voltage.

1.1 State of the Art A/D and D/A Conversion Speeds

Typical commercial devices
Typical conversions speed of commercial analog-to digital converters (ADCs) that we use in the lab deliver data rates of some 500 kilo samples per second (KSPS) to 1 mega samples per second (MSPS). Commercially available high-speed ADCs offer sample rates of some giga sample per second (GSPS): Analog Devices "250+" MSPS [2], Texas Instruments "up to 10.4 GSPS" [3], [10], and Maxim Integrated "over 2 Gsps" [4].

Totorials on fundamentals of high speed A/D conversion can be found e.g. at [11], [12].

1.2 Examples That Need High Conversion Speeds

1.2.1 Software Defined Radio (SDR)

Mitola's Idea of Software Defined Radio (SDR)

Facing the problem of interfacing more than 100 different communication standards Mitola [1] created the idea of software defined radio (SDR): Digitalize all other parts than A/D and D/A conversion and do signal processing on the software side. According to Nyquist and Shannon, the sampling frequency must be at least twice the sampled frequency, i.e. for sampling a 2.5GHz carrier signal we need a 5GHz sampler or even a 10-GHz sampler for a quadrature amplitude modulated signal.
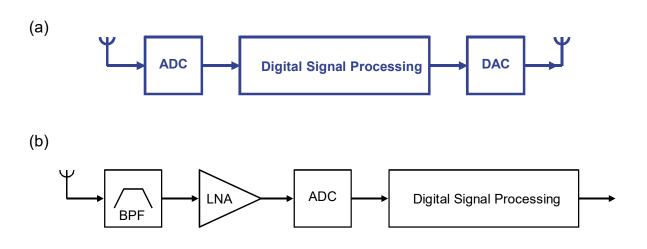

Fig. 1: Mitola's vision of SDR: **(a)** ideal, **(b)** real (LNA=Low-Noise Amplifier, BPF=Band-Pass Filter)

State of the art commercial devices:
March 2021: ADC Captures 1Gsps [8],
March 2021: AD9081, *Quad, 16-Bit, 12 GSPS RF DAC and Quad, 12-Bit, 4 GSPS RF ADC*, [9].
2023 TI: ADC12DJ5200RF, 2 x 5.2 GSPS Interleaved ADC [10].

Question: How many wireless communication standards do you know?

Some examples in alphabetic order: BGAN (Broadband Global Area Network), BT (Bluetooth), DECT (Digital Enhanced Cordless Telecommunication), EDGE (Enhanced Data Rates for GSM Evolution), GPRS (General Packet Radio Service), GSM (Global System for Mobile communication), IMT-A (International Mobile Telecommunications– Advanced), UMTS (Universal Mobile Telecommunications System), WiFi, WiBro (Wireless Broadband), WiMax (Worldwide Interoperability for Microwave Access)...

1.2.2 Radio Frequency Spectra
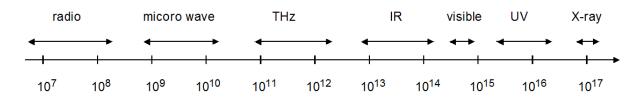
1.2.2.1 RF Spectra Overview

Fig 1.2.2.1: RF spectra

This chapter illustrates required A/D conversion rates for direct RF sampling, which has to be at least twice the frequency sampled. The RF radio frequency (RF) band addresses typically the range of some 6 MHz – 2.4 GHz. For frequencies of 6 GHz and more we need a line of sight (LoS) between transmitter and receiver. Terahertz (THz) radiation is absorbed by water, metals and other materials, its applications are limited and it is difficult to generate, as frequency is too high for oscillators and too low for light.

1.2.2.2 Industrial, Scientific Medical (ISM) Bands

ISM bands [5] are ruled worldwide by ITU-R [6] and are distinguished in A and B types, where A requires admission of local authorities while B can be used free up to a certain power level.

From	To	Type	Comment
6.765 MHz	6,795 MHz	A	SRD (Short Range Devices)
13.553 MHz	13,567 MHz	B	SRD
26.957 MHz	27,283 MHz	B	SRD
40.66 MHz	40,70 MHz	B	SRD
433,05 MHz	434,79 MHz	A	SRD, region 1 only (Europe, Africa, Russia, Mongolia)
902 MHz	928 MHz	B	Region 2 only (Nord- and South Amerika)
2.400 GHz	2,500 GHz	B	
5.725 GHz	5,875 GHz	B	
24 GHz	24,25 GHz	B	
61 GHz	61,5 GHz	A	
122 GHz	123 GHz	A	
244 GHz	246 GHz	A	

1.2.3 Example Modulation Technique

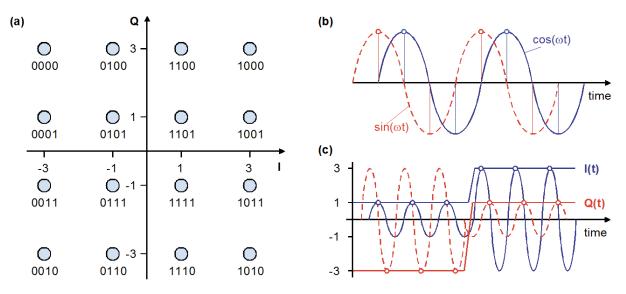### 1.2.3.1 Quadrature Amplitude Modulation (QAM)

Fig. 1.2.3.1: QAM16 scheme. **(a)** Coding, **(b)** direct sampling, **(c)** nested sin & cos functions

Quadrature Amplitude Modulation signal is defined as [7]

$$S_{QAM}(t) = I(t)\, cos(\omega_c t) + Q(t)\, sin(\omega_c t)$$

sometimes plotted as complex signal $S_{QAM}(t) = I(t)\, cos(\omega_c t) + j\, Q(t)\, sin(\omega_c t)$ with

ω_c RF carrier frequency
$I(t)$ In-phase signal, envelope $I(t)$,
$Q(t)$ Quadrature-phase signal, envelope $Q(t)$,
BER Bit Error Rate, most important figure of merit.

Demodulation of a QAM signal can be performed in two different ways:

1. Analog mixing: Multiplication with $cos(\omega_c t)$ and $sin(\omega_c t)$
After synchronization (typically by a phase-locked loop or PLL) to the carrier-oscillation of the input signal we take advantage of the trigonometric relationships [10], p. 157

$sin(x)\, sin(x) = \frac{1}{2}\, (1 - cos(2x))$ $\rightarrow \frac{1}{2}$ after low-pass filtering
$cos(x)\, cos(x) = \frac{1}{2}\, (1 + cos(2x))$ $\rightarrow \frac{1}{2}$ after low-pass filtering
$sin(x)\, cos(x) = \frac{1}{2}\, sin(2x)$ $\rightarrow 0$ after low-pass filtering

delivers
$s_{QAM}\, cos(\omega_c t)$ $\rightarrow$ subsequent lowpass filtering obtains   **$\frac{1}{2}\, I(t)$**.
$s_{QAM}\, sin(\omega_c t)$ $\rightarrow$ subsequent lowpass filtering obtains   **$\frac{1}{2}\, Q(t)$**.

2. RF direct sampling: When sampling the $s_{QAM}(t)$ sum signal at time points where $cos(\omega_c t)$ or $sin(\omega_c t)$ has an extremum, then the contribution of the other signal is zero. Accurate samplers required.
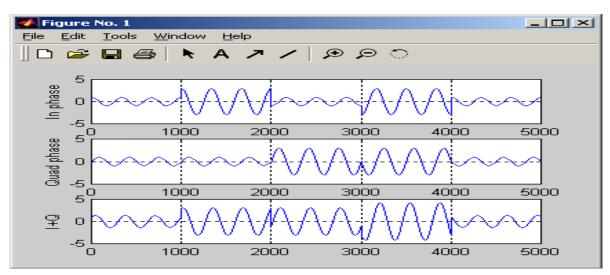
Rectangular QAM16 as Example

QAM16 allows to represent 16 different values at a time by 4 different *I*- and 4 different *Q*-signals: Amplitude steps for QAM16 signals: Q/A_{min}, $I/A_{min} = \pm 1, \pm 3$ multiplied with minimum amplitude A_{min} being e.g. U_{min} or I_{min}.

Exercise:

QAM64 signals allow to represent . . . . . . different values at a time by . . . . . different *I*-

and . . . . different *Q*-values: $\boldsymbol{Q/A_{min}}$, $\boldsymbol{I/A_{min}} = $ . . . .

Exercise : QAM-Modulation

The figure above gives you reference oscillations for $Q=I=1$ within the time 0…10000. Conclude from the waveforms the other values of Q and I.

Time Axis	Amplitude A_I	Amplitude A_Q	coded value	
0000...1000	1	1	1101	
1000...2000				
2000...3000				
3000...4000				
4000...5000				

Solutions see → next page.

Solutions:

QAM64 signals allow to represent `..64..` different values at a time by `...8...` different I- and `...8...` different Q-values:
Q/A_{min}, I/A_{min} = `±1, ±3, ± 5, ± 7` .

Time Axis	Amplitude AI	Amplitude AQ	coded value	
0000...1000	1	1	1101	
1000...2000	3	1	1001	
2000...3000	−1	3	0100	
3000...4000	−3	−3	0010	
4000...5000	1	−1	1111	

1.3 References

[1]   Mitola, "The Software Radio Architecture", IEEE Comm. Magazine, Mai 1995.

[2]   Analog Devices, Available: http://www.analog.com/en/products/analog-to-digital-converters.html, Apr. 2020.

[3]   Texas Instruments, Available in Apr. 2020: : http://www.ti.com/data-converters/adc-circuit/overview.html?keyMatch=ADC%20SPEED&tisearch=Search-EN-everything

[4]   Maxim Integrated, Available: https://www.maximintegrated.com/en/products/analog/data-converters/analog-to-digital-converters/high-speed-adcs.html, Apr. 2020

[5]   Available: https://de.wikipedia.org/wiki/ISM-Band, Oct. 2017.

[6]   Available: https://en.wikipedia.org/wiki/ITU-R, Oct 2017.

[7]   Available https://en.wikipedia.org/wiki/Quadrature_amplitude_modulation, Oct. 2017.

[8]   Maxim APPLICATION NOTE 642, *ADC Captures 1Gsps*, available: https://www.maximintegrated.com/en/design/technical-documents/app-notes/6/642.html.

[9]   Analog Devices, AD9081, *Quad, 16-Bit, 12 GSPS RF DAC and Quad, 12-Bit, 4 GSPS RF ADC, available* March 2021: https://www.analog.com/media/en/technical-documentation/data-sheets/AD9081.pdf

[10] Texas Instruments, ADC12DJ5200RF product website, available June 2023: https://www.ti.com/product/de-de/ADC12DJ5200RF.

[11] Texas Instruments, "High Speed, Analog to Digital Converter Basics", available June 2023: https://www.ti.com/lit/an/slaa510/slaa510.pdf.

[12] Texas Instruments, "High speed data converter fundamentals", available June 2023: https://www.ti.com/video/series/high-speed-data-converter-fundamentals.html.