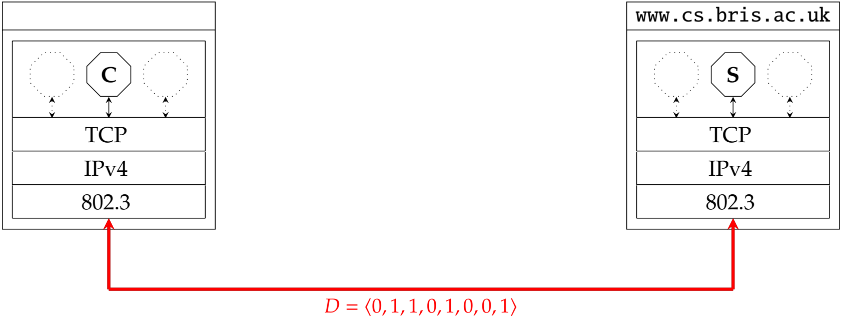
- Goal: investigate the **physical layer**, e.g.,
  1. communication media and signals,
  2. encoding and/or modulation, and
  3. efficiency metrics (and limits)

  st. we can transmit (unstructured) **bit-sequences** along a physical connection between two end-points.



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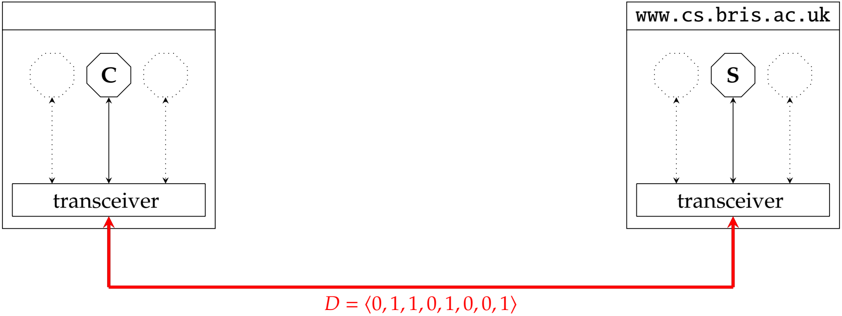

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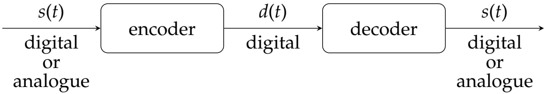
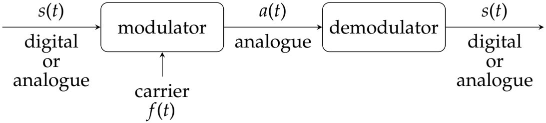
  st. we can transmit (unstructured) **bit-sequences** along a physical connection between two end-points.

- **Idea**:
  - we have some digital input (i.e., our data), so can
    1. directly **encode** it, i.e.,

       via a digital signalling scheme, or
    2. use it to **modulate** a **carrier signal**, i.e.,

       via an analogue signalling scheme

    to produce an (digital or analogue) output signal,
  - so can then transmit that signal along a communication medium (e.g., a wire), and
  - the resulting behaviour has a clear theoretical basis.

Definition

The sinusoidal function

$$s(t) = A \cdot \sin(2\pi \cdot f \cdot t + \varphi)$$

is periodic, and parameterised by

1. an **amplitude** A (which is the maximum deviation of $s(t)$ from 0),
2. a **frequency** f (which is inversely proportional to the period, which is normally termed the **wavelength** λ), and
3. a **phase** (or offset) φ (which basically dictates where in the cycle the wave is at time $t = 0$).

"Communication Theory in 10 minutes" (1)

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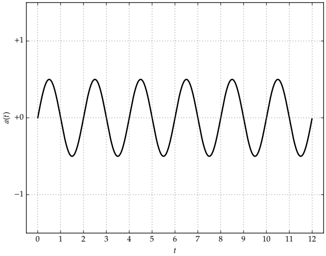
By evaluating over a time period (i.e., over a range of t), such a wave can be visualised as a **waveform**, e.g.,



where $A = 0.5, f = 0.5, \varphi = 0$.

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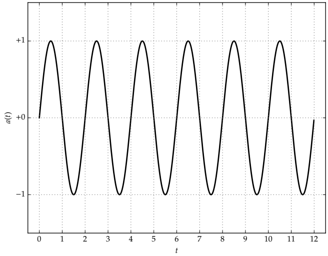

where $A = 1.0, f = 0.5, \varphi = 0$.

Definition

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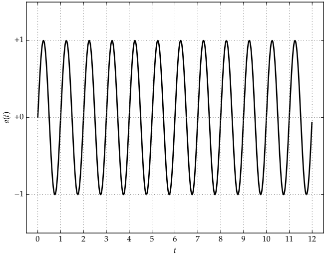

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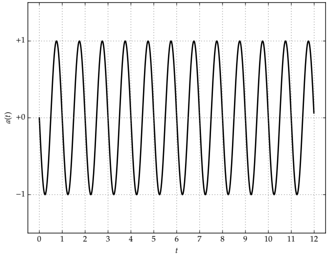


where $A = 1.0, f = 1.0, \varphi = \pi$.

Definition

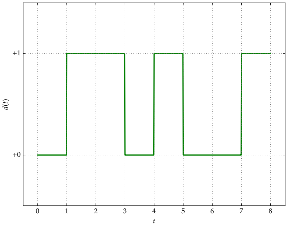
Fourier analysis allows us to represent a signal as an (infinite) sum of sinusoids:

$$s(t) \sim \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cdot \cos(2\pi \cdot f \cdot t \cdot n) + b_n \cdot \sin(2\pi \cdot f \cdot t \cdot n)$$

The resulting **Fourier series** (or **Fourier expansion**) $s(t)$ typically makes use of **Fourier coefficients** a_n and b_n for $1 \leq n < N$ wrt. some (finite) bound N.

“Communication Theory in 10 minutes” (4)

- Eh?!



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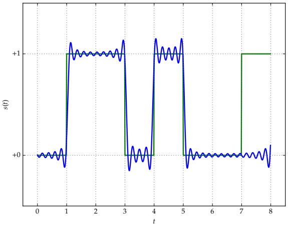

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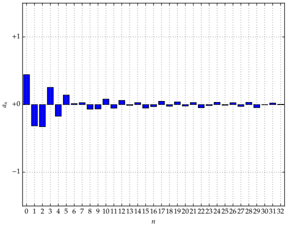

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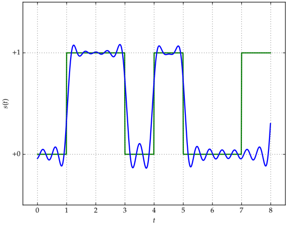

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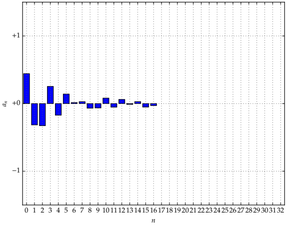

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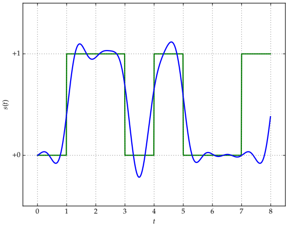

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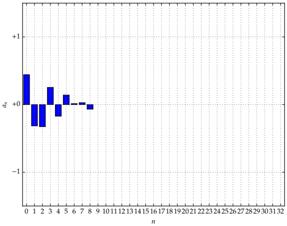

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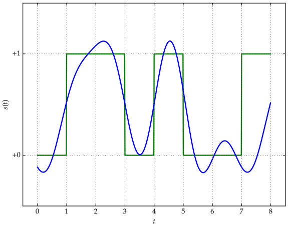

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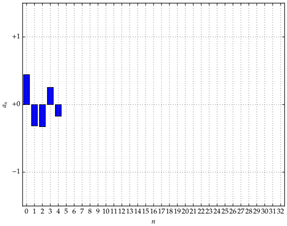

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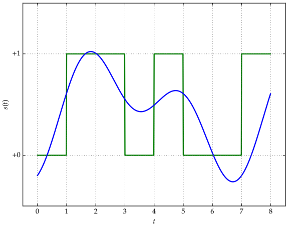

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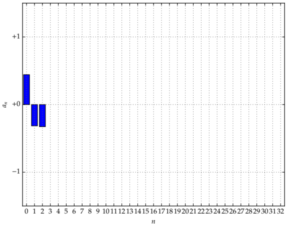

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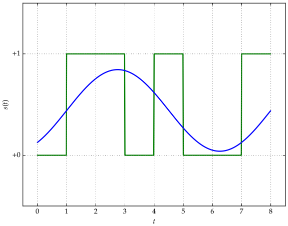

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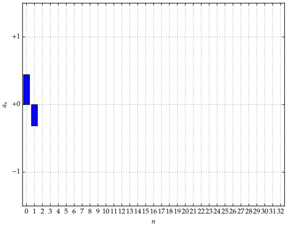

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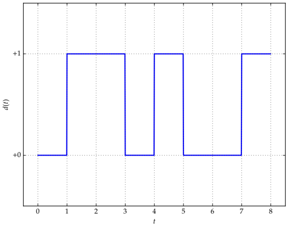

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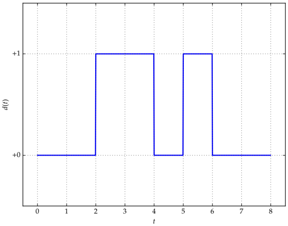

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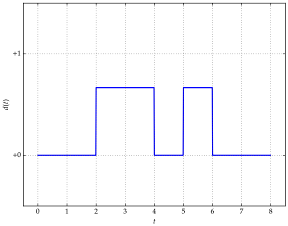

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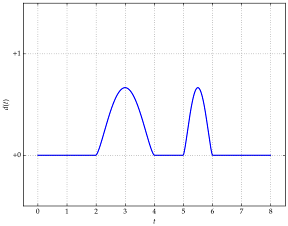

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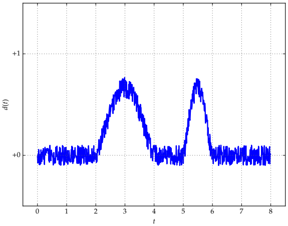

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Definition

The **signalling rate** (or **symbol rate**, or **baud rate**) of a channel measures how many symbols it can transmit per unit of time. The associated **data signalling rate** (or just **data rate**, or **gross bit rate**) measures this in bits per second.

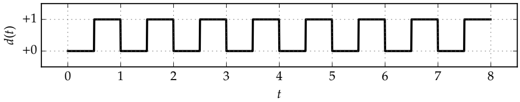
Definition

The **modulation rate** measures how quickly (i.e., how often per unit of time) the channel can change (or transition, which may be termed a **signalling event**) between signalling levels; this of course determines the (minimum) **symbol period**.

Definition

When sampled at a given instance in time, a signal will take one of l **signalling levels**; this means each **symbol** transmitted will take one of l values. Note that $l > 2$ implies the ability to transmit *more* than 1 bit of information per symbol.

Encoding/Modulation (1) – Digital signalling

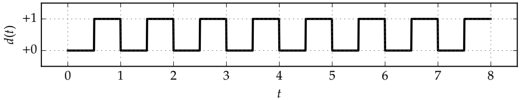
Original data	0 1 1 0 1 0 0 1
Clock signal	

Encoding/Modulation (1) – Digital signalling

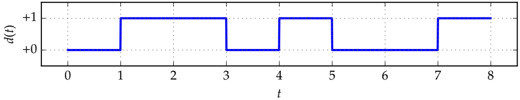
Original data

0 1 1 0 1 0 0 1

Clock signal



Non-Return to Zero (NRZ)

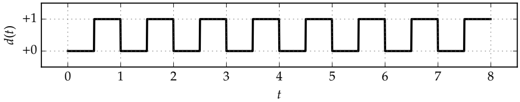


Encoding/Modulation (1) – Digital signalling

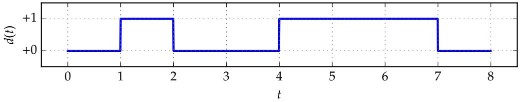
Original data

0 1 1 0 1 0 0 1

Clock signal



Non-Return to Zero Inverted (NRZ-I)

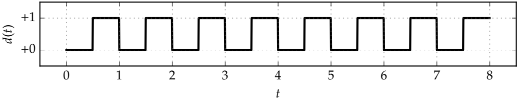


Encoding/Modulation (1) – Digital signalling

Original data

0 1 1 0 1 0 0 1

Clock signal



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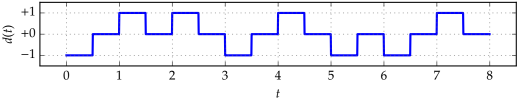

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Original data

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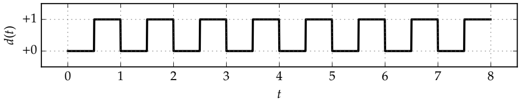
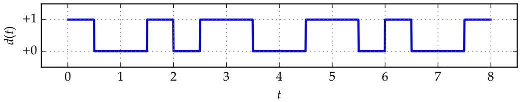
Clock signal



Manchester (per 802.3)



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Original data

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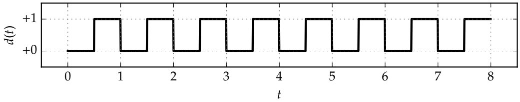
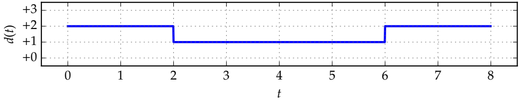


l-ary (for $l = 4$)

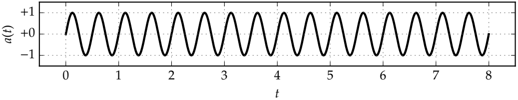


Encoding/Modulation (2) – Digital signalling

- ... or, to summarise, we have something like the following

Scheme	Signalling levels	Modulation rate	Self clocked?	Differential ?	Runs of $x \in X$
NRZ	2	r	$\times$	$\times$	$X = \{0, 1\}$
NRZ-I	2	r	$\times$	$\checkmark$	$X = \{0\}$
RZ	2(ish)	$r \cdot 2$	$\checkmark$	$\times$	$X = \emptyset$
Manchester	2	$r \cdot 2$	$\checkmark$	$\times$	$X = \emptyset$
l-ary	l	$r / \log_2(l)$	$\times$	$\times$	$X = \{0, 1, \ldots, n-1\}$

Encoding/Modulation (5) – Analogue signalling

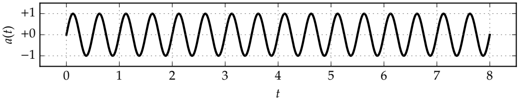
Original data	0 1 1 0 1 0 0 1
Carrier signal	

Encoding/Modulation (5) – Analogue signalling

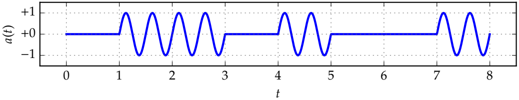
Original data

0 1 1 0 1 0 0 1

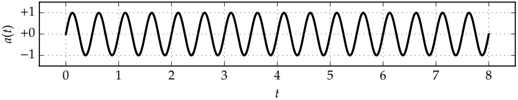
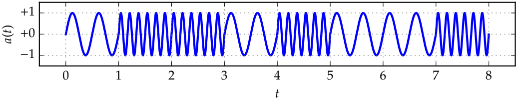
Carrier signal



Amplitude-Shift Keying (ASK)



Encoding/Modulation (5) – Analogue signalling

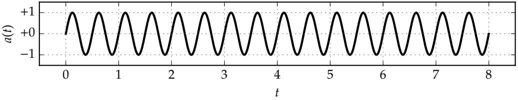
Original data	0 1 1 0 1 0 0 1
Carrier signal	
Frequency-Shift Keying (FSK)	

Encoding/Modulation (5) – Analogue signalling

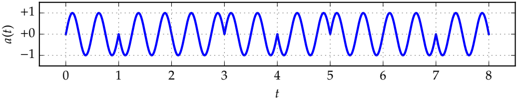
Original data

0 1 1 0 1 0 0 1

Carrier signal



Phase-Shift Keying (PSK)



Metrics (2)

Definition

The **bandwidth** of a communication channel is the number of symbols which can be transmitted per unit of time; this is sometimes referred to as the **channel capacity**, and often measured in bits per second (which is then the **bit rate**).

It is common to contrast total available bandwidth, with that achievable in practice; the latter is termed **throughput**, st.

$$\text{bandwidth} \geq \text{throughput} + \text{overhead}.$$

Metrics (2)

Definition

The **latency** of a connection relates to the (total) time required to transmit data between two end-points (e.g., between $\mathcal{H}_0$ and $\mathcal{H}_1$). This is typically expressed as $n/r + d$, where

- n/r is the **transmission delay**, and
- d is the **propagation delay**

given n symbols and a bandwidth of r symbols per unit of time. Note that

- **One-Way Delay (OWD)** measures the latency of $\mathcal{H}_0$ transmitting data to $\mathcal{H}_1$, whereas
- **Round-Trip Time (RTT)** measures the latency of $\mathcal{H}_0$ transmitting data to $\mathcal{H}_1$, *plus* the latency of $\mathcal{H}_1$ transmitting an associated response back to $\mathcal{H}_0$.

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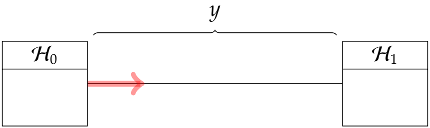

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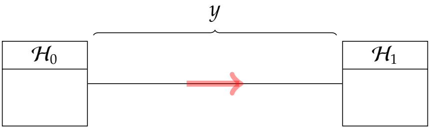

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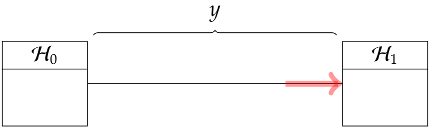

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$$\text{st. latency} = x + y = \text{transmission delay} + \text{propagation delay}.$$

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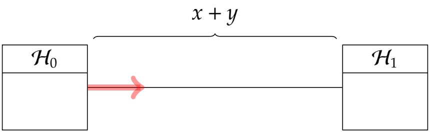

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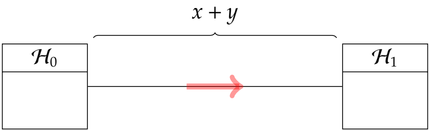

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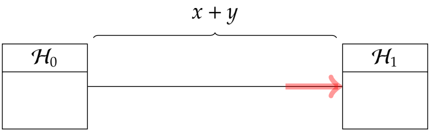

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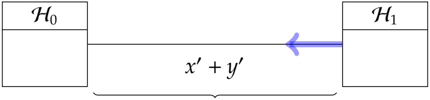

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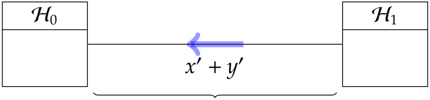

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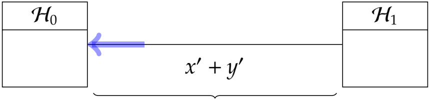

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st. $\text{RTT} \;=\; (x+y)+(x'+y') \;\geq\; 2\cdot\text{OWD}.$

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Imagine that a given channel is a pipe, whose diameter is defined by bandwidth and length by latency. The "volume" of the pipe is termed the **bandwidth-latency product** (or **bandwidth-delay product**), and captures the amount of data "in-flight".

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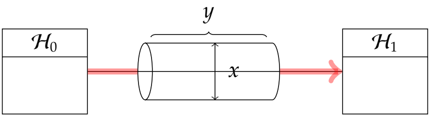

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st. bandwidth-latency product $= x \cdot y =$ bandwidth $\cdot$ latency

Conclusions

- Take away points:
  - Digital and analogue signal processing is a *big* topic; this is a light-weight introduction only!
  - There are *many* of possible ways to address the initial goal, but keep in mind that
    1. a given approach is often underpinned by theory, but
    2. choices are often made with lower-level, Engineering requirements in mind,
    3. we can only make *good* choices by understanding how the channel is used.

Additional Reading

- *Wikipedia: Physical layer*. URL: http://en.wikipedia.org/wiki/Physical_layer.
- W. Stallings. "Chapter 4: Data transmission". In: *Data and Computer Communications*. 9th ed. Pearson, 2010.
- W. Stallings. "Chapter 5: Transmission media". In: *Data and Computer Communications*. 9th ed. Pearson, 2010.
- W. Stallings. "Chapter 6: Signal encoding techniques". In: *Data and Computer Communications*. 9th ed. Pearson, 2010.

References

[1] *Wikipedia: Physical layer*. URL: http://en.wikipedia.org/wiki/Physical_layer (see p. 60).

[2] W. Stallings. "Chapter 4: Data transmission". In: *Data and Computer Communications*. 9th ed. Pearson, 2010 (see p. 60).

[3] W. Stallings. "Chapter 5: Transmission media". In: *Data and Computer Communications*. 9th ed. Pearson, 2010 (see p. 60).

[4] W. Stallings. "Chapter 6: Signal encoding techniques". In: *Data and Computer Communications*. 9th ed. Pearson, 2010 (see p. 60).

[5] H. Nyquist. "Certain topics in telegraph transmission theory". In: *Transactions of the AIEE* 47 (1928), pp. 617–644.

[6] C.E. Shannon. "Communication in the presence of noise". In: *Proceedings of the IRE* 37.1 (1949), pp. 10–21.