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Badji Mokhtar Annaba University
Faculty of Technology

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وزارة التعليم العالي و البحث العلمي
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Department of Electronics

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Course intended for third-year Telecommunications students

Academic year: 2024/2025

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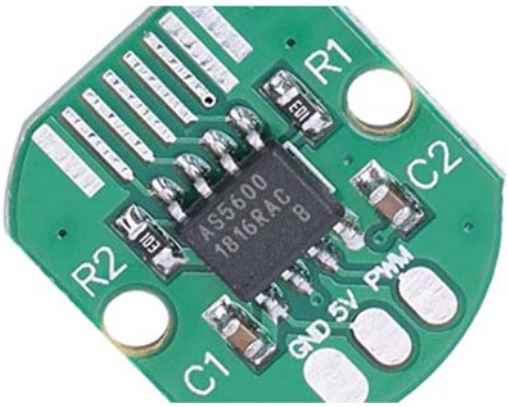
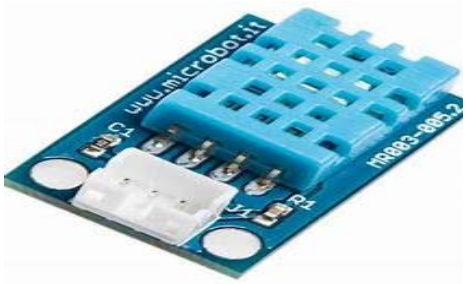
Department of Electronics



Educational Handbook

Sensors and Measurements Chains in Telecommunications

- Course -



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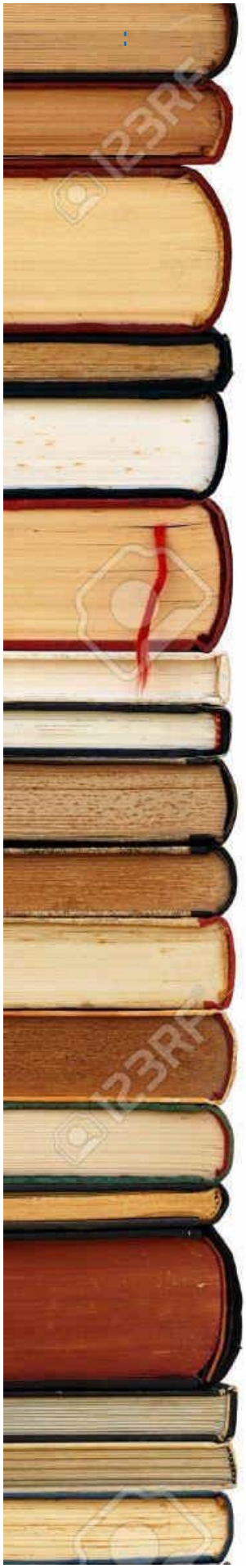
This manuscript has been prepared in accordance with the officially approved and validated program by the CPNDST..

-Target Audience:

- Third-year Bachelor's in Telecommunications.
- Third-year Bachelor's in Electronics.

Academic year 2024/2025

Déclaration



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Preface

This handout is a course material for the "***Sensors and Measurements Chains in Telecommunications***" module and is in line with the official national program of higher education and scientific research. This handout develops a course on sensors and measurements in telecommunications for the transversal teaching unit, primarily aimed at third-year Telecommunications students in the LMD (Bachelor-Master-Doctorate) training system, but it can also be useful for other technical specializations.

This course is the result of several years of teaching in this subject, and it represents a very rich and up-to-date practical resource that allows students to grasp the fundamental concepts. The aim of this document is to raise students to a level of knowledge and skills in the field of sensors in telecommunications, with the theoretical and practical knowledge acquired serving as a springboard for immediate integration into the professional environment.

The content of this handout covers the official program taught in the Department of Electronics at Badji Mokhtar Annaba University. The handout methodically and in detail describes the program, which is structured into six chapters, and has been slightly reorganized from the original framework. The expected weekly time allocation is one course.

This course material has been created from numerous bibliographic references for educational purposes.

In this module, students will learn the basics of measurement systems used primarily in telecommunications, as well as the different sensors and their characteristics. The goal is to understand the fundamentals of measurement systems and the sensors used in this field. It is written in the form of detailed lessons with solved exercises and presented in a very simple style to enable students to understand the concepts quickly.

This document is intended for those with prior knowledge in fundamental telecommunications, electronics, analog communication, and telecommunications applications. It is especially suitable for students with a background in electronics and telecommunications. I hope this material will be useful and serve as a reference for anyone interested in the study of sensors and measurements chains in telecommunications.

Dr. N. ZERMI

I would like to express my sincere gratitude to all those who, to varying degrees, contributed to the publication of this handout. I hope that this manual will be beneficial and serve as a reference for anyone interested in the study of sensors and measurements in telecommunications. I wish for this modest course to be a valuable addition to our university's educational resources and to serve as a valuable course material for our students.

Dr ZERMI Narima

General Introduction

"This world is permeated with applications of measurement; any knowledge that is not measurable is subject to a judgment of depreciation. The name 'science' is increasingly being denied to any knowledge that cannot be translated into numbers." — Paul Valéry, 1871-1945

This statement by Paul Valéry is more relevant than ever. Our world is, and will increasingly be, permeated by applications of measurement. And nothing will be achieved without the "sensor," which is at the very foundation of the "measurement" structure.

Scientific knowledge has developed through a dual effort:

1. ✔ On one hand, reflection on the mechanisms, i.e., on the nature of the interactions between physical quantities related to phenomena; this reflection is materialized through mathematical tools by the laws of physics, which are abstract relationships between physical quantities.
2. ✔ On the other hand, experimentation relies on measuring physical quantities, and by associating them with a numerical value, it allows us to quantitatively define the properties of objects, numerically verify physical laws, or empirically establish their form.

In scientific research laboratories and industrial facilities, one of the main tasks of researchers and technicians is to measure various physical quantities that determine their experiments or condition the smooth running of their production processes. For a measurement operation to be successful, it is generally necessary for the collected information to be transmitted from the point of capture, protected against alterations due to parasitic phenomena, amplified, and then processed in different ways: displayed, recorded, or processed by a computer. Electronics offers various powerful means for this.

To make the best use of measurements of all kinds of physical quantities, as well as their processing and exploitation, it is advisable to immediately convert each relevant physical quantity into an electrical signal. This is the role of the sensor, which ensures the duplication of information by transferring, at the very point of measurement, the physical (non-electrical) quantity associated with it onto an electrical quantity: current, voltage, charge, or impedance.

A sensor is a device that converts a physical quantity (temperature, pressure, position, concentration, etc.) into a signal (often electrical) that provides information about this quantity. For example, the pressure exerted by air on a pressure gauge positions the needle on the scale corresponding to the measurement of that pressure. The sensor differs from the measuring instrument in that it is merely an interface between a physical process and a manipulable piece of information. In contrast, a measuring instrument is a self-contained device that functions independently, with a display or data storage system. The sensor lacks such a system. There are many different types of sensors, which vary in the physical quantity they measure and the device that creates the signal. For example, chemical concentration can be measured with a piezoelectric transducer or a microcalorimeter. Similarly, a piezoelectric device can be used to measure pressure or the concentration of biological compounds.

This course material aims to bring together the essential concepts to understand the fundamentals of measurement systems mainly used in telecommunications, as well as the different sensors and their characteristics.

- ☑ **Chapter 1**: Characteristics of a Measurement System, General introduction to measurement and the measurement chain, with a special focus on the different components and metrological characteristics of this chain, including accuracy, resolution, response time, measurement range, linearity, physical quantities, sensors...
- ☑ **Chapter 2**: Classification of sensors in telecommunications according to their operating principles (active or passive) and classification of signal conditioning circuits.
- ☑ **Chapter 3**: Examples of sensors, their operating principles, and their application domains, including microphones, CCD sensors, RF field sensors, digital software sensors for frames...
- ☑ **Chapter 4**: Static Measurements in Telecommunications; The importance of measurements in telecommunications, and an overview of the instruments used for these measurements such as multimeters, spectrum analyzers, reflectometers, optical fiber testers.
- ☑ **Chapter 5**: Dynamic Measurements in Telecommunications; The importance of measurements in telecommunications, the distinction between static and dynamic measurements, and an overview of the instruments used for these measurements such as link testers, frame analyzers, protocol analyzers.

- ✅**Chapter 6**: Case Study: Examples of measurements for mobile telephony or IP network telephony.

This document is designed to provide a comprehensive and useful reference for anyone interested in the study of sensors and measurements in telecommunications. The course is available through the online platform (Moodle e-learning), where students can consolidate their knowledge and access course materials in PDF format, PowerPoint presentations, and videos with examples and applications.

I - Generalities:

In many fields (industry, scientific research, services, leisure, etc.), there is a need to monitor various physical parameters (temperature, force, position, speed, luminosity, etc.). The sensor is the essential component for measuring these physical quantities.

In technical systems, many physical quantities (temperature, pressure, light intensity, position, displacement, etc.) need to be measured and recorded. It was necessary to develop technical devices to acquire these physical quantities, transform them, and transmit usable information to processing units. This technical device is defined by: measurement system (measurement chain, metrological system). [1]

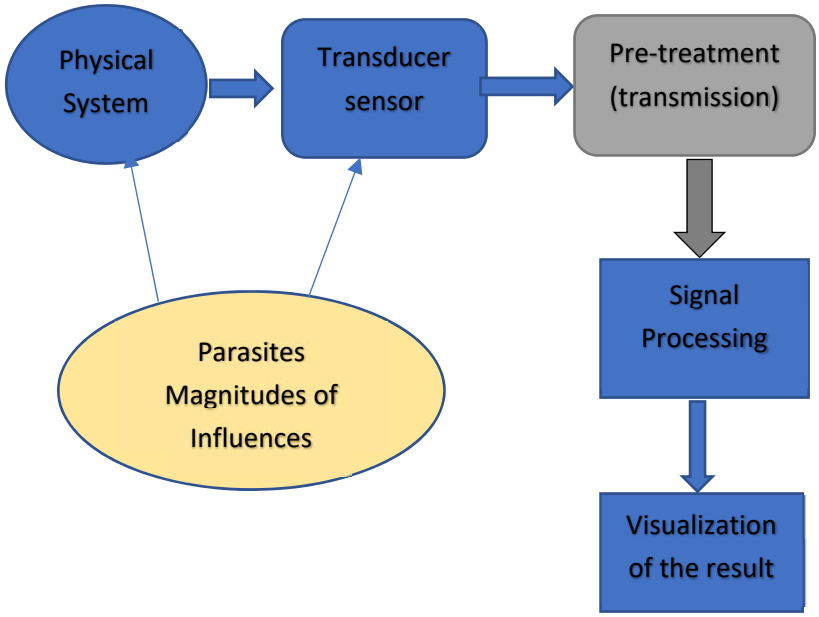


Figure I.1: Schematic representation of a measurement system

II - Fundamental Concepts of Measurement:

II.1 Some Definitions:

What is measurement? Measurement refers to the expression of any given quantity, typically represented by a number followed by a symbol: the number indicates the value of the measured quantity, and the symbol denotes its nature.

For example: 10 kg/cm²: 10 expresses the value of a pressure measured in kg/cm², where kg/cm² is the symbol indicating that it is a pressure.

✅**Metrology:** In its etymological sense, metrology means the science of measurement. In everyday language among "metrologists," it is often said that measuring is comparing!

✅**Unit of Measurement:** A specific quantity, defined and adopted by convention, to which other quantities of the same type are compared in order to express them quantitatively (value) relative to this unit.

✅**Measuring:** The set of operations aimed at determining the value of a quantity.

✅**Measurand:** The particular quantity subject to measurement.

✅**Measurement Uncertainty:** A parameter associated with the result of a measurement, characterizing the dispersion of values that could reasonably be attributed to the measurand.

✅**Standard of Measurement:** In metrology, a standard is a device that is relied upon to control the accuracy of results provided by a measuring instrument. [1]

II-2 Purpose of Measurement:

The results of measurements are used to make decisions:

- ✅Acceptance of a product (measurement of characteristics, performance, compliance with requirements)
- ✅Adjustment of a measuring instrument, validation of a process
- ✅Adjustment of a parameter within a manufacturing process control
- ✅Validation of a hypothesis
- ✅Definition of safety conditions for a product or system [2]

A measurement result is written as: **X = {X} [X]**

Where: X: The name of the physical quantity

[X]: The unit

{X}: The numerical value of the quantity expressed in the chosen unit.

II-3 Principle of Measurement:

To measure any physical quantity, one of the following three methods will be used:

- ☑ **Direct Method:**

A measurement is called direct when the variable to be measured is evaluated by comparing it with a known quantity of the same value. Example: Measuring a length with a standard meter, caliper, etc.

- ☑ **Indirect Method:**

A measurement is called indirect when the variable is evaluated by comparing it with a known quantity of a different nature, and through a known law, the value of the variable is determined.

Examples:

The distance E between two cities A and B. To do this, the time t taken to cover E at a constant speed v is measured, and by the law E = vt, E is determined.

- ☑ **Opposition Method:**

In this case, a known quantity is opposed to the variable to be measured such that their difference is null.

Examples: Double-pan balance: Place the quantity to be measured on one pan and weights on the other. Once equilibrium is achieved, knowing the value of the added weights, the measured quantity can be determined.

Note:

A measurement by opposition can be either direct or indirect.

- ☑ ***Example***: In the case of the Roberval balance, the method is direct by opposition because the value of the weights gives the value to be measured.

- ✅ ***Example:*** In the case of measuring temperature with a thermocouple, a known electromotive force is opposed to the electromotive force of the couple, and applying the law relating temperature to electromotive force determines the temperature; here the method is indirect by opposition. [2]

III - Measurement Errors:

III-1 Introduction:

No measurement is perfect. Regardless of the care taken in its implementation, the precision of the device, the competence of the operator, adherence to manipulation rules, and strict control of all influencing parameters, there will always remain uncertainty in the measurement. All efforts in instrumentation aim to reduce this uncertainty to a value as low as possible, knowing that it will never be possible to eliminate it. That is why any measurement, to be complete, must include both the measured value and the limits of the possible error on that value.

III-2 Classification of Errors:

Based on their causes, there are two types of errors:

III-2.1 Systematic Errors:

These are errors caused by a known or knowable factor. They can result from:

- **III-2.1.1 Measurement Method:**

Sometimes, the chosen measurement method leads to a disturbance in the quantity being measured (for example: when measuring resistance or power, there is a choice between series and parallel configurations).

- **III-2.1.2 Operator:**

Sometimes, during a measurement, the needle or the light spot rests between two scale marks, which forces the operator to estimate a fraction of a division of the scale, resulting in an inevitable error.

- **III-2.1.3 Measuring Instrument:**

The accuracy class of a measuring instrument depends on manufacturing tolerances, calibration, and design. The more careful the manufacturing, the smaller the error. Additionally, the error depends on zero adjustment (electrical or mechanical) and the calibration curve of the instrument. [3]

Note:

Systematic errors can be corrected by proper zero adjustment, accurate calibration, and estimation of fractional divisions, taking method errors into account in the measurement and calculating them.

III-2.2 Random Errors:

These are errors that do not follow any known law when taken from a single result. However, they follow statistical laws when the number of results becomes very large. They can arise from :

- **III-2.2.1 The Operator:**

For analog multimeters with several complex scales and ambiguously graduated on the same dial, the operator may make mistakes in choosing the scale. Additionally, the parallax error is made when reading "off-angle," as the needle is always slightly offset from the scale.

- **III-2.2.2 The Instrument:**

External influences such as position, temperature, air humidity, or magnetic and electrical interference can cause the instrument to distort a measurement.

✔ ***Examples:*** Magnetic interference may prevent measurement by induction near a transformer. Also, the position (horizontal or vertical) of the measuring instruments is decisive. These instruments must be used according to the position indicated on the dial.

- **III-2.2.3 The Setup:**

Bad contacts, such as tightening parts, surface condition, connection wires, and poor insulation, can lead to errors.

Note:

To reduce random errors, ensure that setups are clear and well-maintained, and that the parameters involved are well understood and controlled. For instance, using a good oscilloscope with adjustments to eliminate beam rotation can help. One can also reduce these errors by making a series of measurements and calculating the arithmetic mean.

Based on the expression of the measurement, there are two types of errors:

- ☑ Absolute error
- ☑ Relative error

III-3Absolute Error, Absolute Uncertainty:

Let:

☑ **X**: The measured value of the quantity

☑ **Xe**: The theoretical exact value of the same quantity

The absolute error, denoted δX, is the difference between the measured value and the exact theoretical value expressed in the same unit.

$$\boxed{\checkmark}\ \delta X = X - Xe \quad \text{.....(I.1)}$$

Since the exact value of the quantity to be measured is unknown, an upper limit of the absolute error must be evaluated, which is the absolute uncertainty, denoted:

$$\boxed{\checkmark}\ \Delta X = \sup(|\delta X|) \quad \text{.....(I.2)}$$

III-4 Relative Error, Relative Uncertainty:

The relative error is the ratio of the absolute error to the exact value.

$$\boxed{\checkmark}\ \varepsilon_r = \frac{\delta X}{X_e} = \frac{X - X_e}{X_e} \quad \text{.....(I.3)}$$

Since it is a dimensionless number (no unit), it is generally expressed as a percentage:

$$\boxed{\checkmark}\ \varepsilon_r\% = \frac{\delta X}{X_e} \times 100 = \frac{X - X_e}{X_e} \times 100 \quad \text{.....(I.4)}$$

If the exact value of the quantity is inaccessible, the upper limit of the relative error, which is the relative uncertainty, is used: $\frac{\Delta X}{X_e}$

It can also be expressed as a percentage: $\frac{\Delta X}{X_e} \times 100$

Note: Errors can have any sign (positive or negative).

III-5 Expression of the Result:

The result can be expressed in two ways:

III-5.1. First way:

The adopted value equals the measured value followed by the evaluation of the absolute uncertainty:

☑ **Xe = X ± ΔX [unit]…….(I.5)**

III-5.2. Second way:

The adopted value equals the measured value followed by the evaluation of the relative uncertainty:

☑ $X_e = X\ [unité]\ \pm \left(\frac{\Delta X}{X}\right)\%$.....(I.6)

Examples:

☑ R = 10 Ω ± 5% or R = (10.0 ± 0.5) Ω

III-6 Calculating Uncertainty for Basic Operations:

In general, the value of the quantity to be measured (Xe) is obtained through a mathematical relationship: Xe = f(a, b, c, ...). Therefore, the "differential calculation" method can be used to determine uncertainties:

The absolute uncertainty is expressed as follows:

- ☑ $\Delta X = \left|\frac{\partial f}{\partial a}\right|_{b,c=cte} . \Delta a + \left|\frac{\partial f}{\partial b}\right|_{a,c=cte} . \Delta b + \left|\frac{\partial f}{\partial c}\right|_{a,b=cte} . \Delta c$.....(I.7)

The relative uncertainty is expressed as:

- ☑ $\frac{\Delta X}{X} = \left|\frac{\partial f}{\partial a}\right|_{b,c=cte} . \frac{\Delta a}{X} + \left|\frac{\partial f}{\partial b}\right|_{a,c=cte} . \frac{\Delta b}{X} + \left|\frac{\partial f}{\partial c}\right|_{a,b=cte} . \frac{\Delta c}{X}$.....(I.8)

Let's apply these two formulas to determine the absolute and relative uncertainties for basic operations:

III-6.1 Sum:

For a series combination of resistance boxes:

☑ R = R1 + R2 + R3…….(I.9)

↳ We get: : ☑ $\Delta R = \Delta R_1 + \Delta R_2 + \Delta R_3$ or $\frac{\Delta R}{R} = \frac{\Delta R_1 + \Delta R_2 + \Delta R_3}{R_1 + R_2 + R_3}$……(I.10)

III-6.2 Difference

Let: **I = I1 − I2**……**(I.11)**

We obtain: **ΔI = ΔI1 + ΔI2** or equivalently**:** $\frac{\Delta I}{I} = \frac{\Delta I_1 + \Delta I_2}{I_1 - I_2}$……**(I.12)**

III-6.3 Product

Case of Energy: W= U· I · t……(I.13)

We obtain: **ΔW= It ΔU + Ut ΔI + UI Δt** ……**(I.14)**

or equivalently**:** $\frac{\Delta W}{W} = \frac{\Delta U}{U} + \frac{\Delta I}{I} + \frac{\Delta t}{t}$……**(I.15)**

III-6.4 Quotient

Let: $X = \frac{a}{b}$……**(1.16)**

We obtain: $\Delta X = \frac{\Delta a}{b} + \frac{a}{b^2}\Delta b$ ……...(I.17)

or equivalently: $\frac{\Delta X}{X} = \frac{\Delta a}{a} + \frac{\Delta b}{b}$……**(I.18)**

III-7 PRACTICAL CALCULATION OF UNCERTAINTY

III-7.1 Case of Analog (or Deflection) Instruments

This type of instrument operates by providing a needle deflection on a graduated scale proportional to the value of the measured quantity. Thus, the measured value is given by the following equation: $X = \frac{C \times L}{E}$ ……..**(I.19)**

Where:

- ☑C: the selected range [unit]
- ☑L: the reading (number of graduations read on the scale)

- ✅E: the scale (total number of graduations on the scale)

A deflection measuring instrument is characterized by its accuracy class index, which results in:

✅**Class uncertainty:**

$$\Delta X_c = \frac{Cl \times C}{100} = \frac{Classe \times Calibre}{100} \text{ .....(I.20)}$$

Moreover, the operator is not perfect and may make a reading error, leading to:

✅**Reading uncertainty:**

If we denote by ΔL the fraction of a graduation error committed (also called the estimated division fraction during measurement), the reading uncertainty is given by:

$$\Delta X_L = \frac{C \times \Delta L}{E}, \text{.....(I.21)}$$

✅**Total uncertainty:**

The method used is also a source of uncertainty to be evaluated (denoted as ΔXmethod).

Thus, the total uncertainty associated with a measurement using an analog instrument is the sum of the class uncertainty, the reading uncertainty, and the method uncertainty (if applicable):

$$\Delta X = \Delta X_c + \Delta X_L + \Delta X_{méthode}, \text{.....(I.22)}$$

III-7.2 Case of Digital Instruments

For digital display instruments, manufacturers provide a precision indication that allows the total measurement uncertainty to be calculated. Precision is generally given as a percentage of the reading for each range and can be expressed in two ways:

✅**First method:**

$$\Delta X = \pm(x\%Lecture + y\%Gamme) \text{.....(I.23)}$$

We obtain:

$$\Delta X = \frac{x.L}{100} + \frac{y.G}{100}, \ldots\ldots\ldots\

Table I.1: Base Units of the International System (SI).

Quantity	Base Unit	Symbol
Time	Second	s
Length	Meter	m
Mass	Kilogram	kg
Electric current	Ampere	A
Temperature	Kelvin	K
Amount of substance	Mole	mol
Luminous intensity	Candela	cd

After years of meticulous work, most units in use have been reduced to functions of seven base units (Figure I.1). These base units are independent of each other. Their notation is provided in Table I.1.

Note: Apart from thermodynamic temperature (symbol: T), expressed in kelvins, the Celsius temperature (symbol: °C) is also used. It is defined by the equation:

$$C = T - T_O \text{ Where: } T_O = 273,15^{O}K \text{ by definition}$$

Figure I.2: The Seven Base Units.

IV-2 Derived Units

Derived units are formed consistently from the base units. Some derived units have been given a special name, which can in turn be used to form other unit names. The table below lists some of the derived units (Table 1.2).

Table I.2: List of Some Derived Units.

Quantity	Derived Unit	Symbol
Area	Square meter	m^2
Volume	Cubic meter	m^3
Speed	Meter per second	m/s
Acceleration	Meter per second squared	m/s^2
Density	Kilogram per cubic meter	kg/m^3
Force	Newton	N
Work/Energy	Joule	J
Power	Watt	W
Pressure	Pascal	Pa
Frequency	Hertz	Hz
Voltage	Volt	V
Electric charge	Coulomb	C
Electrical capacitance	Farad	F
Magnetic induction	Tesla	T
Magnetic flux	Weber	Wb

IV-3 Non-SI Units

Non-SI units are used for practical reasons related to magnitude (such as hours, minutes, and liters) and for cultural purposes. These practical units can be categorized into three groups:

1. **Units Compatible with SI:**
   - ✅ **Time unit:** 1 min = 60 s
   - ✅ **Volume unit:** 1 L = 1 dm^3
   - ✅ **Mass unit:** 1 t (ton) = 10^3 kg
2. **Temporarily Compatible Units with SI:**
   - ✅ **Distance unit:** Angstrom (A^O) = $10^{-10} m$ (atomic radius).
   - ✅ **Land area units:**
     - ✅ Are: 1 are = $10^2 m^2$
     - ✅ Hectare: 1 ha = $10^4 m^2$

3. **Incompatible Units with SI:**
    - **CGS System (centimeter-gram-second).**
    - **Anglo-Saxon units:**
        - ☑ **Distance:**
            - Inch: 1 in = 2.54 cm
            - Foot: 1 ft = 12 in = 30.48 cm
            - Mile: 1 mile = 5280 ft = 1.609 km
        - ☑ **Volume:**
            - Pint: 1 pint ≈ 0.94 L 1 m^3 = 1000 L
            - 1 dm^3 = 1 L

IV-3.1 Multiples and Submultiples

In engineering, to simplify calculations, certain powers of 10 are commonly used, generally as multiples or submultiples of 1000 (Table 1.3).

Table I.3: List of Multiples and submultiples

Symbol	Name	Factor	Symbol	Name	Factor
Y	**Yotta**	10^{24}	y	**yokto**	10^{-24}
Z	**Zetta**	10^{21}	z	**zepto**	10^{-21}
E	**Exa**	10^{18}	a	**atto**	10^{-18}
P	**Peta**	10^{15}	f	**femto**	10^{-15}
T	**Tera**	10^{12}	p	**pico**	10^{-12}
G	**Giga**	10^{9}	n	**nano**	10^{-9}
M	**Mega**	10^{6}	μ	**micro**	10^{-6}
K	**Kilo**	10^{3}	m	**milli**	10^{-3}
h	**hicto**	10^{2}	c	**centi**	10^{-2}
da	**deca**	10^{1}	d	**deci**	10^{-1}

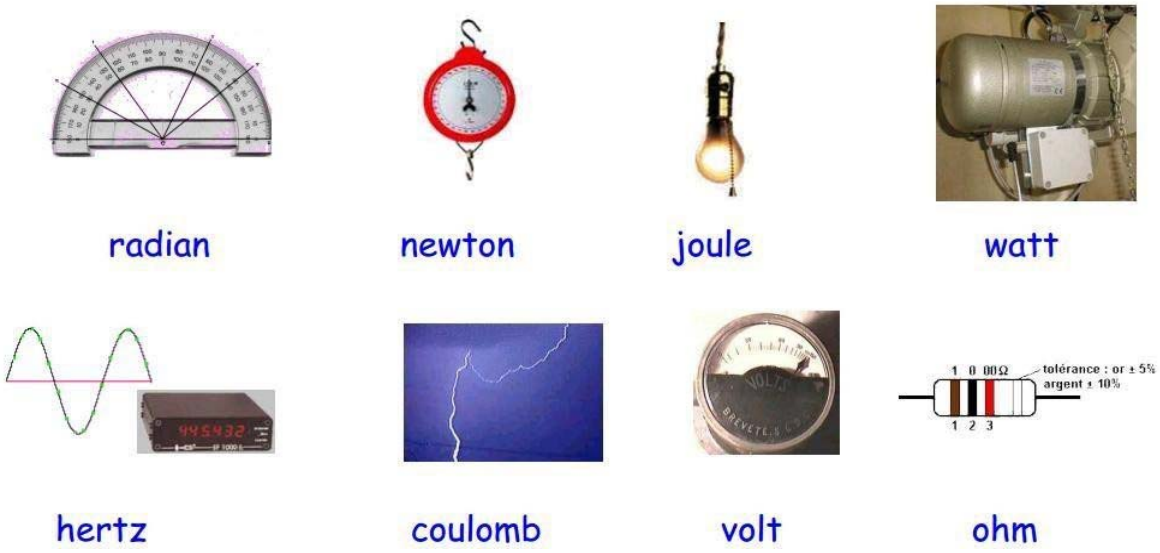


Figure I.3 : Derived Units

V. EXERCISE 01:

✅ We consider the Wheatstone bridge shown in Figure I.4.

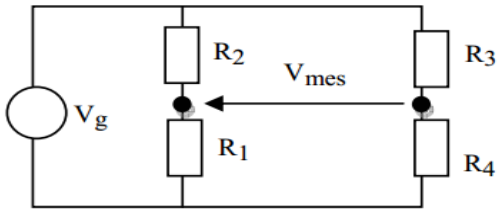


Figure I.4: Wheatstone Bridge Circuit

1. Show that the measured voltage V_{mes} can be expressed as follows:

$$V_{mes} = \left(\frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) . V_g$$

2. At equilibrium, the value of V_{mes} is equal to zero. Deduce a relationship between R1 and the other resistances.
3. Suppose that resistances R_3 and R_4 are equal, and that $R_1=2\times R_2$. Determine the relative error in V_{mes}, knowing that the error in V_g is 1%.

V. EXERCISE 02:

✅ The measurement of the voltage across a resistive sensor in a potentiometric circuit (Figure I.5) is based on the following setup:

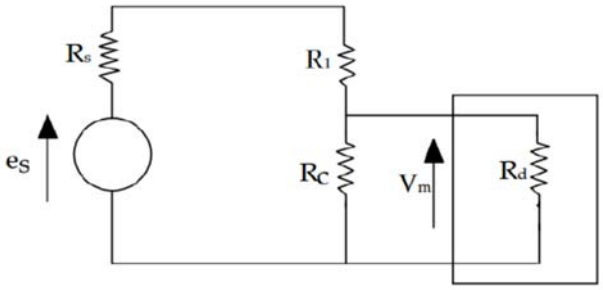


Figure I.5: Potentiometric Circuit

The voltage is given by the following equation:

$$V_m = e_s \cdot \frac{R_C}{R_C + R_1 + R_s}$$

If the error in the resistances is 1% and the error in ese is 2%, calculate the relative error in V_m for: $R_C = R_1 = R_S = 50\ \Omega$.

I.Introduction

A sensor is a device that converts a physical quantity (such as temperature, pressure, position, concentration, etc.) into a signal (often electrical) that provides information about that quantity. For example, the pressure exerted by air on a needle gauge positions the needle on the scale corresponding to the measurement of this pressure.

A sensor differs from a measuring instrument in that it is merely an interface between a physical process and usable information. In contrast, a measuring instrument is a standalone device with a display or a data storage system, whereas a sensor lacks these features.

There are many different types of sensors, varying in the physical quantity they measure and the mechanism used to generate the signal. For example, a chemical concentration can be measured using a piezoelectric transducer, a microcalorimeter, or an ISFET. Similarly, a piezoelectric device can be used to measure pressure or the concentration of biological compounds. [4]

II. Metrology

Metrology is the science of measurement. It defines the principles and methods necessary to ensure and maintain confidence in the measurements resulting from measurement processes. It is a cross-disciplinary science applied in all fields where quantitative measurements are performed.

For better understanding, metrology can be artificially divided into different aspects:

☑ ***Fundamental or scientific metrology***, which aims to create, develop, and maintain recognized reference standards.

☑ ***Industrial metrology***, the most common type, ensures measurement accuracy, for example, in a manufacturing process, often as part of quality control within a quality management system.

☑ ***Legal metrology,*** which applies to measurements subject to regulatory requirements.

In addition to traditional quantitative metrology, some refer to "soft metrology" for measurements without physical dimensions and qualitative assessments. This appears to be a misuse of terminology; it would be more appropriate to consider them as specific quality controls. Currently, no authoritative reference recognizes the term "soft metrology."[4]

III. Elements of Metrology (Definitions)

- ✅**Measurement Process:** The set of operations aimed at determining the value of a quantity.
- ✅**Measurement (x):** The evaluation of a quantity by comparison with another quantity of the same nature, taken as a unit. *Example*: 2 meters, 400 grams, 6 seconds.
- ✅**Quantity (X):** A parameter that must be controlled during the development or transfer of a product. Example: pressure, temperature, level. Measurements are taken to determine the instantaneous value and evolution of certain quantities, providing information on the state and progression of a physical, chemical, or industrial phenomenon.
- ✅**Measurand:** What we aim to measure, whereas the measured quantity is what we can measure. It is the object of measurement or, simply, the quantity to be measured.
- ✅**Uncertainty (dx):** The measurement result **x** of a quantity **X** is not fully defined by a single number. It must at least be characterized by a pair (**x, dx**) and a unit of measurement. **dx** represents the uncertainty of **x**.
- Uncertainties arise from various measurement errors. Thus, we have:
- **x - dx < X < x + dx** *Example:* 3 cm ±10% or 3 cm ± 3 mm.
- ✅**Absolute Error (e):** The difference between a measurement result and the true value of the measurand. An absolute error is expressed in the unit of measurement.
- **e = x – X** *Example*: A 10 cm error in a distance measurement.
- ✅**Relative Error (er):** The ratio of the measurement error to the true value of the measurand. A relative error is generally expressed as a percentage of the measured quantity. **er = e/X ; er% = 100 × er**

Example: A 10% error in a distance measurement (10% of the actual distance).

Different Types of Errors

- ✅**Systematic Errors:** These are reproducible errors related to their cause by a physical law, making them possible to eliminate through appropriate corrections.
- ✅**Random Errors:** These are non-reproducible errors that follow statistical laws.
- ✅**Accidental Errors:** These result from mishandling, improper use, or malfunction of the device. They are generally not considered when determining a measurement.

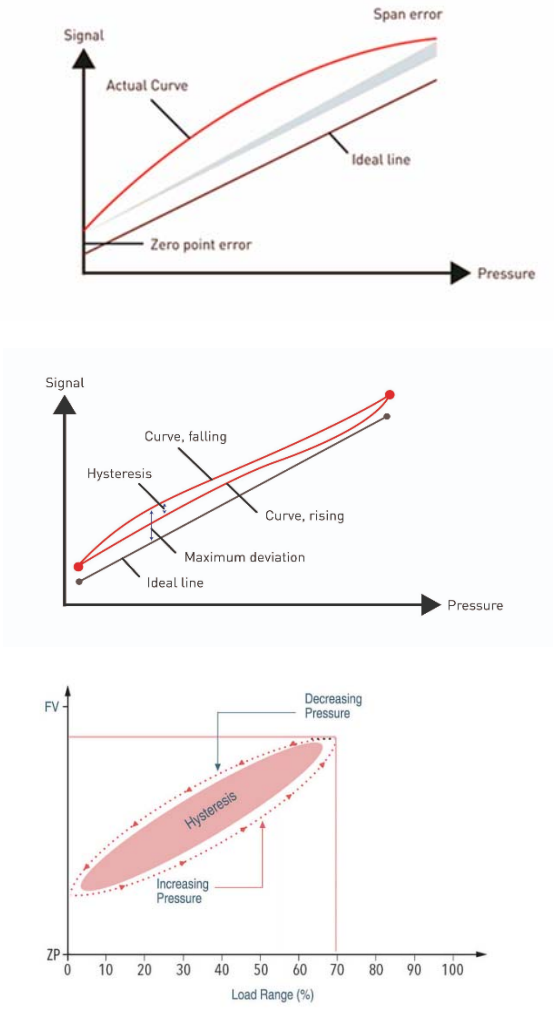


Figure II.1 Sensos errors

IV. Principles of Sensors

A sensor is a device that collects information by converting a physical quantity into another physical quantity of a different nature (most often electrical). This representative

quantity of the measured parameter is used for measurement or control purposes (see Figure II.2).

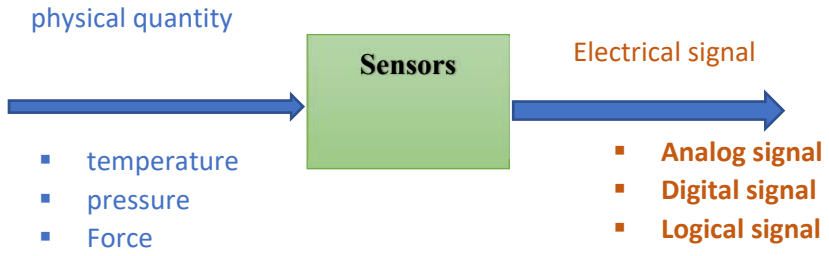


Figure II.2: Measurement Chain

The sensor, as the first element of the measurement chain, is the primary source of the electrical signal that the rest of the system must process and utilize. A sensor transforms a physical quantity (temperature, speed, force, etc.) into an exploitable electrical quantity (resistance, voltage, current, etc.), which accurately represents the measured parameter.

In other words, a sensor is a device that allows the measurement of a physical or chemical parameter. It provides an electrical output that represents the measured value as accurately as possible. Generally, this electrical output varies proportionally with the measured parameter. Thus, for a variation **Δm** in the measured quantity, the output quantity varies by **Δs** such that**:** **S Δm =Δs** (Equation II.1)

Where **S** is the sensitivity of the sensor. Ideally, **S** should be as independent as possible from aging and environmental influences (i.e., variations in other quantities).

To facilitate sensor utilization, it is preferable to design it in such a way that it delivers a **linear** relationship:

Δs/Δm = S = constante ,..... (II.1)

The adaptation between the sensor and the measurement chain ensures that the latter does not introduce additional uncertainties or limitations beyond those inherent to the sensor itself.

The **quality of the sensor** determines two key factors:

1. ☑ The degree of concordance between the measured value and the true value of the measurand.

2. ☑ The limits of uncertainty in the measured value.

A sensor is a device whose physical characteristics respond to a measurand. When exposed to this measurand, it provides an output in the form of an exploitable physical quantity, usually electrical.

The following diagram summarizes the concept of a sensor:

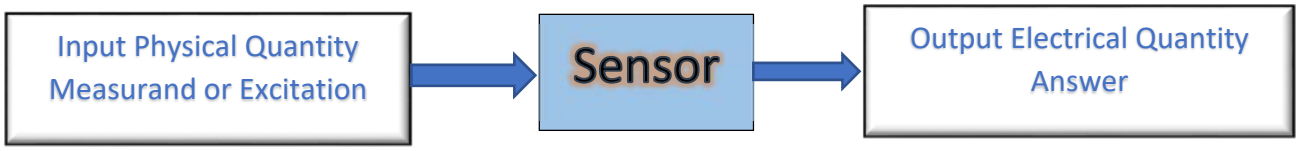
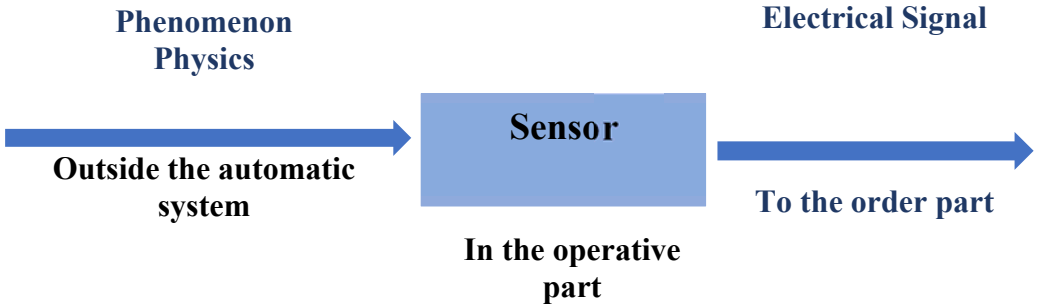


Figure II.3: Sensor Diagram

A mathematical relationship, derived from physical laws, must exist between the input quantity and the output quantity. This relationship, linking the measurand **m** and the output **s** (s = f(m)), is known as the **sensor calibration curve**.

- ☑ A sensor is **linear** if the calibration curve is a straight line.
- ☑ Otherwise, the sensor is considered **nonlinear**.



Objective of This Chapter

This chapter aims to provide an overview of the **12 most common types of sensors**, highlighting their characteristics, functions, and applications. Additionally, we will explore the fundamental principles of sensor technology and discuss key factors to consider when selecting and using sensors for specific applications. [5]

V. Types of Sensors

Sensors can be classified based on the physical quantity they measure. Here is a list of the 12 most common types of sensors used in various applications:

- ☑ ***Temperature Sensors***: Measure the temperature of an object or environment.
- ☑ ***Pressure Sensors***: Measure the force applied to a given surface.
- ☑ ***Level Sensors:*** Measure the level of a liquid or solid in a tank.
- ☑ ***Flow Sensors:*** Measure the volume of a fluid passing through a given cross-section per unit of time.
- ☑ ***Light Sensors***: Measure the intensity, wavelength, or frequency of light.
- ☑ ***Proximity Sensors***: Detect the presence of an object without physical contact.

- ☑ ***Temperature Sensors***

Portable model

Non-Contact Pyrometer

Industrial measuring rod

Electronic thermistor

☑ ***Pressure Sensors***

Mechanical display

Electronic sensors

Industrial Sensors

☑ ***Level Sensors***

☑ ***Flow Sensors***

Gaz

Portable model

Automotive Sensor

industrial sensors

Liquids

Laboratory

☑ ***Light Sensors***

• ☑ ***Proximity Sensors***

Proximity Sensors

V-1. Temperature Sensors

Temperature sensors measure the heat of an object or environment. They are used in various applications, including temperature control, industrial process monitoring, meteorology, and medicine. Temperature sensors can be classified based on their operating principle, which includes:

- ☑ ***Thermocouples:*** Generate a voltage proportional to the temperature difference between two different metals.

- ☑ ***Thermistors:*** Are resistors whose value changes depending on temperature.

- ☑ ***Platinum Resistance Temperature Detectors (RTDs):*** Use a platinum resistance whose value changes linearly with temperature.

- ☑ ***Infrared Sensors***: Measure the heat radiated by an object.

V-2. Pressure Sensors

Pressure sensors measure the force exerted by a fluid on a given surface. They are used in various applications, including monitoring hydraulic and pneumatic systems, meteorology, aviation, and medicine. Pressure sensors can be classified based on their operating principle, which includes:

- ☑ ***Strain Gauge Sensors***: Measure the deformation of a membrane or diaphragm caused by pressure.

- ☑ ***Piezoelectric Sensors:*** Generate a voltage proportional to the applied force.

• ☑ ***Capacitive Sensors:*** Measure changes in capacitance resulting from membrane or diaphragm deformation due to pressure.

• ☑ ***Variable Resistance Sensors:*** Use a resistive element whose resistance changes according to pressure.

V-3. Level Sensors

Level sensors measure the height of a liquid or granular solid in a tank or container. They are used in various applications, including industrial process control, wastewater management, fuel tank monitoring, and liquid level monitoring in buildings. Level sensors can be classified based on their operating principle, which includes:

• ☑ ***Float Sensors:*** Use a float that moves according to the liquid level and transmits a position to a sensor.

• ☑ ***Ultrasonic Sensors:*** Emit sound waves and measure return time to determine liquid level.

• ☑ Differential Pressure Sensors: Measure the pressure difference between the bottom of the tank and the liquid surface.

• ☑ ***Capacitive Sensors:*** Measure changes in capacitance resulting from liquid level variation.

V-4. Flow Sensors

Flow sensors measure the amount of fluid passing through a given cross-section per unit of time. They are essential in various applications, including industrial process monitoring, water management, heating, ventilation, and air conditioning (HVAC) control, and gas distribution system monitoring. Flow sensors can be classified based on their operating principle, which includes:

• ☑ ***Volumetric Sensors***: Measure the volume of fluid passing through a given cross-section per unit of time.

• ☑ ***Mass Flow Sensors:*** Measure the mass of fluid passing through a given cross-section per unit of time.[6]

- ☑ ***Doppler Effect Sensors:*** Use the Doppler effect to measure fluid velocity and calculate flow rate.

- ☑ ***Paddle Wheel Sensors***: Use a paddle wheel that rotates based on fluid flow.

V-5. Light Sensors

Light sensors, also known as photodetectors, are designed to detect and measure light. They convert light energy into an electrical signal proportional to the received light intensity. Light sensors are used in various fields, including photography, medical imaging, remote sensing, industrial monitoring, and automation systems. The most common types of light sensors include:

- ☑ ***Photodiodes:*** Convert light into electrical current.

- ☑ ***Phototransistors:*** Amplify the current generated by light.

- ☑ ***Photomultipliers:*** Amplify the light signal for low-intensity detection.

- ☑ ***CCD and CMOS Sensors***: Used in digital cameras and video cameras.

V-6. Proximity Sensors

Proximity sensors detect the presence of an object without physical contact. They operate by emitting an electromagnetic field or a light beam and detecting changes in this field when an object approach. These sensors are widely used in industrial automation systems, robotics, machine tools, and security applications. The most common types of proximity sensors include:

- ☑ ***Inductive Sensors***: Detect metals by generating a magnetic field.

- ☑ ***Capacitive Sensors***: Detect conductive and non-conductive materials by measuring changes in capacitance.

- ☑ ***Optical Sensors***: Detect the presence of objects using a light beam.

- ☑ ***Ultrasonic Sensors:*** Emit sound waves and detect echoes reflected by objects.

V-7. Position Sensors

Position sensors measure the linear or angular position of an object. They are used in a wide range of applications, including motion control systems, robotics, machine tools, and navigation systems. The most common types of position sensors include:

- ☑ ***Potentiometric Sensors:*** Measure position based on the resistance of a potentiometer.
- ☑ ***Hall Effect Sensors***: Detect the position of a magnet using the Hall effect.
- ☑ ***Optical Sensors:*** Measure position using light beams.
- ☑ ***Rotary Encoders:*** Measure the rotation angle of a shaft.
- ☑ ***Linear Encoders***: Measure the linear position of an object.

V-8. Speed Sensors

Speed sensors measure the speed of a moving object. They are widely used in motion control systems, vehicles, machine tools, and sports applications. The most common types of speed sensors include:

- ☑ Tachometric Sensors: Measure the rotational speed of a shaft using an electrical generator.
- ☑ Doppler Effect Sensors: Measure an object's speed using the Doppler effect.
- ☑ Optical Sensors: Measure an object's speed using light beams.
- ☑ Ultrasonic Sensors: Measure an object's speed using sound waves.
- ☑ Accelerometers: Measure an object's acceleration, which can be integrated to obtain speed.

V-9. Acceleration Sensors

Acceleration sensors measure the linear or angular acceleration of an object. They are used in various applications, including vehicle safety systems, wearable fitness tracking devices, navigation systems, and motion control systems. The most common types of acceleration sensors include:

- ☑ ***Piezoelectric Accelerometers***: Convert acceleration into an electrical signal using the piezoelectric effect.

- ☑ ***Capacitive Accelerometers***: Measure changes in capacitance resulting from acceleration.

- ☑ ***Semiconductor Accelerometers***: Use micro-mechanical structures to detect acceleration. [6]

V-10. Force Sensors

Force sensors measure the force applied to an object. They are used in various applications, including robotics, industrial machinery, medical equipment, and weighing systems. The most common types of force sensors include:

- ☑ ***Piezoelectric Force Sensors:*** Convert force into an electrical signal using the piezoelectric effect.

- ☑ ***Strain Gauge Force Sensors:*** Measure resistance changes resulting from material deformation due to force.

- ☑ ***Capacitive Force Sensors:*** Measure capacitance changes resulting from material deformation due to force.

V-11. Torque Sensors

Torque sensors measure the torque applied to a rotating shaft. They are used in various applications, including motors, robotics, machine tools, and medical equipment. The most common types of torque sensors include:

• ☑***Strain Gauge Torque Sensors***: Measure resistance changes resulting from material deformation due to torque.

• ☑***Hall Effect Torque Sensors:*** Measure the magnetic field generated by a current in a conductor subjected to torque.

• ☑***Piezoelectric Torque Sensors:*** Convert torque into an electrical signal using the piezoelectric effect.

V-12. Sound Sensors

Sound sensors, also known as microphones, convert sound waves into electrical signals. They are widely used in audio systems, communication, surveillance, and control applications. The most common types of sound sensors include:

• ☑***Condenser Microphones:*** Use a thin membrane that vibrates in response to sound waves, modifying a capacitor's capacitance.

• ☑***Dynamic Microphones:*** Use a moving coil that displaces within a magnetic field in response to sound waves, inducing an electric current.

• ☑***Electret Microphones:*** Are condenser microphones using an electret material to create a permanent electric field.

VI. Sensor Characteristics

Sensor characteristics describe their performance and capabilities. They are essential for selecting the appropriate sensor for a specific application. Here are some key characteristics:

- ☑**Accuracy**: Indicates how close the sensor's measurement is to the true value. It is usually expressed as a percentage of full scale or in measurement units.
- ☑**Precision**: Describes the systematic deviation between the sensor's measurement and the true value. It is often expressed in measurement units.
- ☑**Sensitivity**: Represents the change in the sensor's output relative to a change in the measured quantity. It is typically expressed in output units per unit of the measured quantity.[7]

VI-1. Accuracy

The accuracy of a sensor reflects its ability to provide consistent and repeatable measurements. It quantifies the spread of measurements around the average value obtained for a constant physical quantity. Accuracy is often expressed as a percentage of full scale or in measurement units. For example, a temperature sensor with an accuracy of ±0.5°C means that the measurements will fall within a range of 0.5°C around the true value. High accuracy is essential for applications requiring precise and reliable measurements, such as medical monitoring or industrial processes.

VI-2. Precision

The precision of a sensor measures its ability to provide measurements close to the true value of the measured physical quantity. It is defined as the difference between the measured value and the true value, expressed as a percentage of full scale or in measurement units. A sensor with high precision minimizes systematic error, ensuring that measurements are close to reality. Precision is crucial for applications where measurement accuracy is paramount, such as instrument calibration or industrial process control.

VI-3. Sensitivity

The sensitivity of a sensor represents its ability to detect small changes in the measured physical quantity. It is defined as the ratio of the change in the sensor's output to the corresponding change in the input physical quantity. High sensitivity indicates that the sensor can detect subtle changes, which is critical for applications requiring high measurement resolution. Sensitivity is typically expressed in output units per input unit, for example, in volts per degree Celsius for a temperature sensor.

VI-4. Response

The response of a sensor describes its temporal behavior when subjected to a change in the measured physical quantity. It includes two main aspects: response time and dynamics. Response time represents the delay between the application of a stimulus and the sensor's stable output. Dynamics, on the other hand, characterizes the sensor's ability to follow rapid changes in the measured quantity. A fast response is essential for applications requiring real-time monitoring, while high dynamics are important for measuring rapidly changing signals.

VI-5. Bandwidth

The bandwidth of a sensor represents the range of frequencies of signals it can accurately detect and transmit. It is defined as the difference between the upper and lower frequencies at which the sensor's response is greater than 70.7% of its maximum value. A wide bandwidth is essential for applications requiring the measurement of high-frequency signals, such as vibrations or sound waves. Conversely, a narrow bandwidth is more suitable for applications involving low-frequency signals, such as temperature or atmospheric pressure.

VI-6. Measurement Range

The measurement range of a sensor represents the interval of physical values it can detect and convert into an electrical signal. It is defined by the minimum and maximum values that the sensor can measure accurately. The measurement range is a critical parameter for selecting the right sensor for a specific application. A sensor with too narrow a range will not detect extreme values, while a sensor with too wide a range may result in low resolution and reduced accuracy within the actual measured range.

VI-7. Reliability

The reliability of a sensor is its ability to provide accurate and consistent measurements over an extended period under various operating conditions. It is typically defined by the failure rate, which represents the probability of a sensor failing within a given time frame. Reliability is a crucial factor in critical applications, where sensor failure could lead to serious consequences. To improve sensor reliability, manufacturers use high-quality materials, rigorous manufacturing processes, and thorough validation testing.

VI-8. Robustness

The robustness of a sensor refers to its ability to withstand harsh environmental conditions and mechanical stresses. Robust sensors are designed to operate reliably in hostile environments, such as extreme temperatures, vibrations, shocks, high pressures, and high humidity levels. They are typically made from corrosion- and wear-resistant materials, and their internal components are protected by sealed enclosures or protective coatings. Robustness is essential for industrial applications, where sensors are often exposed to challenging conditions.

VII. Functions of Sensors

Sensors play a crucial role in many systems and applications by providing information about the state of the environment or a process. Their main functions can be summarized into five categories: measurement, control, monitoring, diagnostics, and automation. Measurement involves acquiring data about a physical quantity, such as temperature, pressure, or speed. Control uses the measured data to adjust a process or system to achieve a specific objective. Monitoring involves tracking the evolution of a physical quantity over time and alerting when predefined limits are exceeded. Diagnostics use sensor data to identify issues or anomalies in a system. Automation uses sensor data to automatically control processes or systems.

VII-1. Measurement

The primary function of a sensor is measurement. It involves converting a physical quantity into a proportional electrical signal. For example, a temperature sensor converts temperature into an electrical voltage, a pressure sensor converts pressure into resistance, and a light sensor converts light intensity into an electrical current. The accuracy of the measurement depends on the sensor's sensitivity, resolution, and measurement range. Sensitivity represents the change in the output signal for a given change in the measured physical quantity. Resolution corresponds to the smallest variation in the physical quantity that the sensor can detect. The measurement range defines the limits of the physical quantity that the sensor can measure accurately.

VII-2. Control

Sensors play a critical role in control systems, enabling the regulation and adjustment of processes based on measured data. By receiving information about the state of a system, sensors transmit this data to a controller, which, based on predefined algorithms, adjusts the system's parameters to maintain a desired output. For example, a temperature sensor in an oven sends information about the current temperature to a controller, which adjusts the heating power to maintain the oven at the desired temperature. Control sensors are essential in many fields, including industrial automation, robotics, heating and cooling systems, and autonomous vehicles.

VIII. Classification of Sensors

Sensors can be classified in several ways:

- ✅By the physical quantity they measure (position, temperature, pressure, etc.).
- ✅By their role in the industrial process (finished product control, safety, etc.).
- ✅By the output signal they provide, which can be digital or analog.
- ✅By their principle of converting the physical quantity (resistive, piezoelectric, etc.).
- ✅By their operating principle: active or passive sensors.

All these classifications provide an overview of sensors, and of course, none of the classification methods is better than the others, as each has its advantages and disadvantages. In the continuation of our course, we have decided to classify sensors by the physical quantity they measure. We could have chosen another method, but this one seemed the most advantageous for us.

Although we have decided to classify sensors by the physical quantity they measure, it is important to understand what an active or passive sensor is, as well as to have some knowledge of metrology.

VIII-1. Active Sensors

This type of sensor functions as a generator; as soon as it is subjected to the action of a physical quantity, it converts it into a directly usable form of energy, namely electrical energy.

The following table lists the most commonly used physical principles based on the measured quantity:

Table II.1 Most commonly used physical principles based on the measurand

Measurand	Inherent Energy of the Measurand	Physical Principle	Output Quantity
Temperature	Thermal energy	Thermoelectric effect, Pyroelectric effect	Voltage, Charge
Light flux	Electromagnetic energy	Photoemissive effect, Photovoltaic effect, Photoelectric effect	Current, Voltage, Voltage
Force	Mechanical energy	Piezoelectric effect	Charge
Pressure	Mechanical energy	Piezoelectric effect	Charge
Acceleration	Mechanical energy	Piezoelectric effect	Charge
Velocity	Mechanical energy	Electromagnetic induction effect	Voltage
Position	Mechanical energy	Hall effect	Voltage

VIII-2 Passive Sensors

A passive sensor is considered an impedance, one of whose parameters is sensitive to the measurand. This impedance must then be integrated into a circuit to obtain an electrical output. The setup enabling this is called a *conditioner*. There are several types of conditioners, such as potentiometric setups, Wheatstone bridges, oscillating circuits, or operational amplifiers.

The following table lists different passive sensors:

Table II.2 Different passive sensors.

Measurand	Sensitive Electrical Characteristics	Types of Materials Used
Temperature	Resistivity, Dielectric constant	Metals: platinum, nickel, copper; Glasses
Very low temperature	Resistivity, Dielectric constant	Metals: platinum, nickel, copper; Glasses
Light flux	Resistivity	Semiconductors

Strain	Resistivity, Magnetic permeability	Nickel alloys, doped silicon; Ferromagnetic alloys
Position	Resistivity	Magneto-resistive materials: bismuth, indium antimonide
Humidity	Resistivity, Dielectric constant	Lithium chloride; Alumina, polymers
Level	Dielectric constant	Insulating liquids

VIII-3 Composite Sensors

A composite sensor consists of a *proof body* and an active or passive sensor. The proof body, when subjected to the measurand, produces a non-electrical physical quantity called a *secondary measurand*, which is then converted into an electrical quantity by a sensor. The schematic of a composite sensor is as follows:

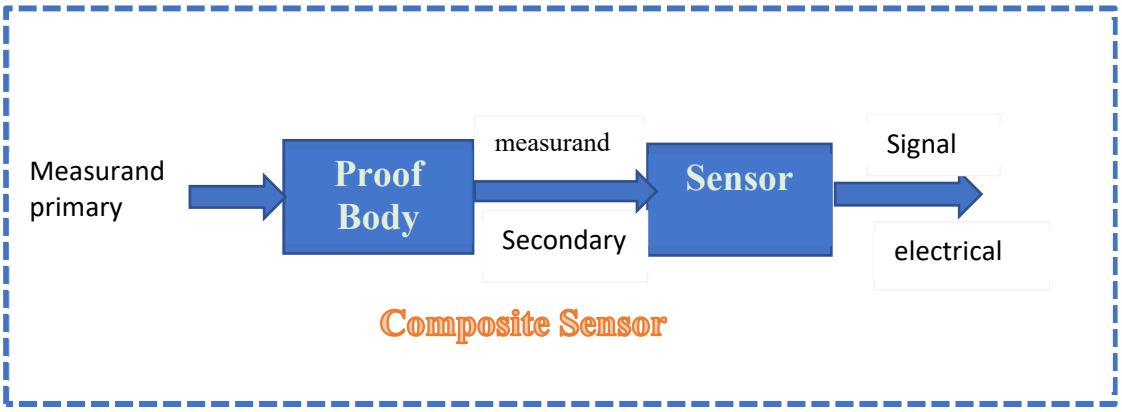


Figure II.4 Schematic of a composite sensor.

Examples of composite sensors:

- ☑Measuring force using a displacement sensor. In this case, the proof body is a spring that translates the force (primary measurand) into elongation (secondary measurand), which is then converted into an electrical signal by a displacement sensor.
- ☑Measuring acceleration using a force sensor. The proof body is a seismic mass that translates acceleration (primary measurand) into force (secondary measurand), which is then converted into an electrical signal by a force sensor.
-

VIII-4 Integrated Sensors

An integrated sensor utilizes microelectronics. It consists of a silicon wafer on which the sensor, the proof body (if needed), and other electronic components (such as linearizers, amplifiers, or current-to-voltage converters) are mounted. This type of sensor is highly useful as it provides a linear signal with high sensitivity, miniaturization, and low cost.

IX. Errors and Uncertainties

To choose a sensor properly, it is important to understand its metrological characteristics. These characteristics help determine which sensor to use, its measurement range, the accuracy of the results, and many other details that are crucial for sensor selection. However, before examining these characteristics, it is important to understand the errors that occur during measurement.

IX-1 Measurement Errors

Reference standards are the only measurands for which the true value is known, unlike other measurands whose values can only be determined after processing by a measurement chain. The true value of the measurand determines the sensor's excitation, but the user only has access to the measurement chain's response, called the *measured value*. The difference between the true value and the measured value is called the *measurement error*. Since the true value of the measurand cannot be known, the measurement error can only be estimated. There are several types of errors, which we will detail below.

IX-1.1 Systematic Errors

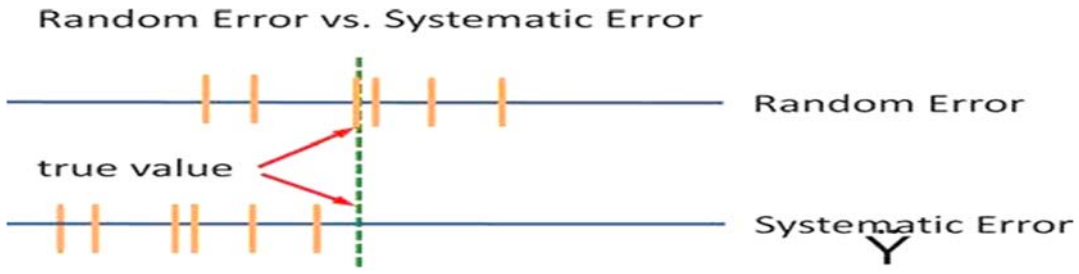


Figure II.5 Illustration of a systematic error.

For a given value of the measurand, a systematic error is either constant or varies slowly relative to the measurement duration. There is thus a discrepancy between the true value and the measured value. This error can be easily corrected depending on the type of systematic error.

For an error in the value of a reference quantity (e.g., zero offset), the error can be easily fixed by carefully checking the associated equipment or by calibrating the device. An error in the sensor's characteristics, such as sensitivity error, can be corrected by recalibrating the sensor. An error due to operating conditions, such as a speed error, can be reduced by waiting for the system to stabilize before taking the measurement.

IX-1.2 Random Errors

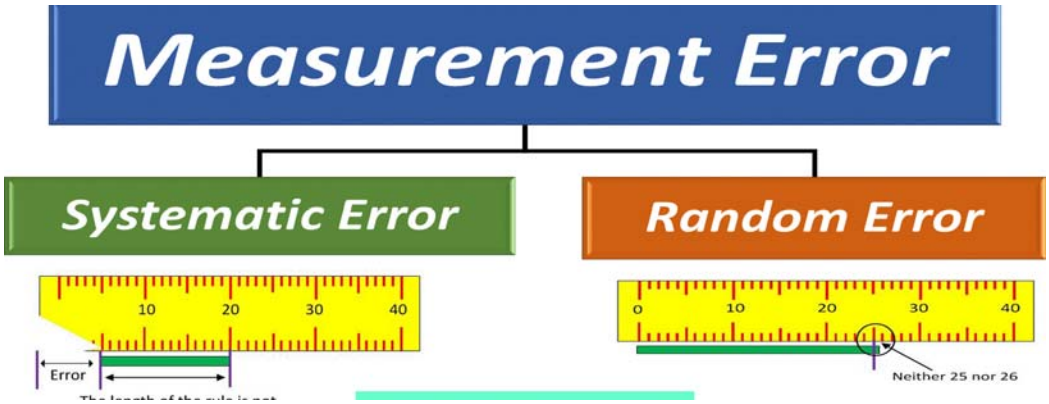


Figure II.6 Illustration of a random error.

Random errors can occur on either side of the true value. Several types of random errors can be defined, such as mobility error, reading error, hysteresis error, quantization error in an analog-to-digital converter, background noise, drift, etc. Although these errors are difficult to determine, solutions exist to reduce them, such as taking multiple measurements so that the average value centers around the true value, or preventing drift by shielding the measurement chain from external environmental factors.

X. Metrological Characteristics

Now that you are familiar with the various errors that can occur during the measurement of a quantity, it is useful to define some metrological characteristics related to sensors. These characteristics can be very helpful in selecting the right sensor for a specific measurement.

X-1 Operating Limits and Measurement Range

Changes in the properties and characteristics of a sensor may occur if it is subjected to influencing quantities such as temperature, mechanical stress, or electrical stress. As shown in the diagram, there are four operating domains for a sensor, which can more or less affect its characteristics:

- ✅The **nominal operating domain** corresponds to the normal conditions of use for the sensor.
- ✅When the values of the measurand or influencing quantities enter the **non-deterioration domain**, the metrological characteristics may be altered, but this change is reversible, and the sensor can return to its normal characteristics once it is back in its nominal operating domain.
- ✅If the sensor is used in the **non-destruction domain**, the alterations will be irreversible, and only recalibration will allow measurements to be taken again in the nominal operating domain.
- ✅Finally, if the sensor is used in the **destruction domain**, it will no longer be usable, and even calibration will not restore it. The only solution is to purchase a new sensor.

The **measurement range** is defined as the difference between the extreme values of the measurand range within which the sensor operates according to given specifications. Most often, the measurement range corresponds to the nominal operating domain.

X-2 Sensitivity

The sensitivity S*S*, for a given value of the measurand, determines the change in the sensor's output quantity relative to the input quantity.

X-3 Resolution

The resolution is the smallest variation in the measurand that the sensor can detect. Resolution is crucial when measuring a quantity, as it determines the accuracy of the result. For example, if you want to measure a temperature of around 1°C, do not use a sensor with a resolution of 0.5°C. However, if you are measuring a temperature of around 10°C, such a sensor would be suitable.

Caution: Errors can occur when reading digital displays, as some displays show more significant digits than the resolution allows. It is therefore essential to know the resolution of the entire measurement chain before using a result, to avoid obtaining non-significant digits.

X-4 Finesse

Finesse allows the user to estimate the influence of the sensor's presence on the value of the measurand. For example, in temperature measurement, the sensor must have a low heat capacity to avoid disturbing the system. Sensitivity and finesse are generally antagonistic and require a compromise.

X-5 Repeatability - Trueness - Precision

These three terms are often confused by users and in technical documents, so it is essential to understand the differences between them.

- ✅***Repeatability*** is the ability of a sensor to provide consistent and repetitive measurements for the same value of the measured quantity. The repeatability error corresponds to the standard deviation obtained from a series of measurements for a constant measurand.
- ✅***Trueness*** is the ability of a sensor to provide a response close to the true value, independent of repeatability. It is related to the average value obtained from a large number of measurements compared to the true value.
- ✅***Precision*** (or accuracy) is defined by the percentage deviation between the true value and the value obtained at the sensor's output. Precision is often given as a percentage of the measurement range. A precise sensor is both true and repeatable.

To better visualize these terms, a diagram in the form of a target has been created, with the center representing the true value we aim to achieve. [8]

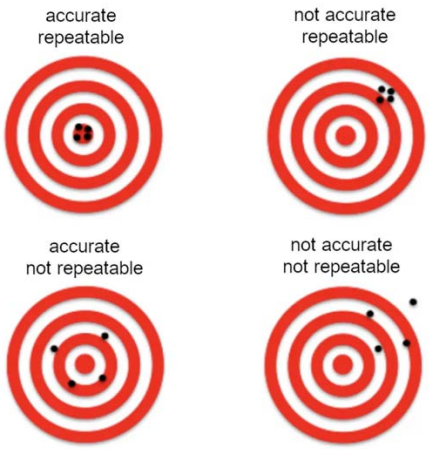


Figure II.7 Illustration of trueness, repeatability, and precision.

X-6 Hysteresis or Reversibility

Hysteresis characterizes the ability of a sensor to provide the same indication when a given value of the measurand is reached, whether by increasing or decreasing variation. Hysteresis is the maximum difference between the two output quantities obtained for the same measurand. It is often expressed as a percentage of the measurement range.

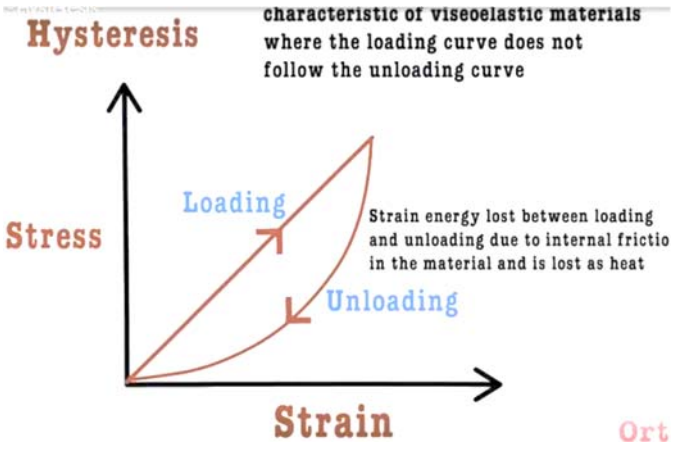


Figure II.8 Hysteresis curves.

An example of hysteresis is temperature measurement using a sensor with a plastic casing, such as thermistors or molded Pt100 sensors. Heat exchange occurs between the external environment, the casing, and the sensor itself, causing hysteresis. If you conduct a temperature study with a Pt100, you will obtain different results for increasing and decreasing temperature measurements.

X-7 Reproducibility or Repeatability

These two terms are often confused, so we will define the difference between them.

- ✅**Repeatability** is the measurement of the same sample using the same method, in the same laboratory, by the same person, and with the same equipment.
- ✅**Reproducibility** is the measurement of the same sample using the same method but in a different laboratory, by different people, and with different equipment.

The standard deviation quantifies these two concepts. In these cases, we speak of repeatability or reproducibility standard deviation. The standard deviation shows the dispersion of values around the mean, indicating whether repeated measurements result in excessive dispersion. A low standard deviation means that performing two measurements yields values close to the expected result, and the sensor is said to be repeatable or reproducible. Knowing these standard deviations helps estimate uncertainties. Of course, only an analysis based on technical documents and experiments can provide a global uncertainty that is as close to reality as possible.

X-8 Response Time

The response time of a sensor is the time interval that elapses after a sudden change in the measurand until the sensor's output variation differs by less than a conventionally fixed limit. This is always provided with the corresponding.

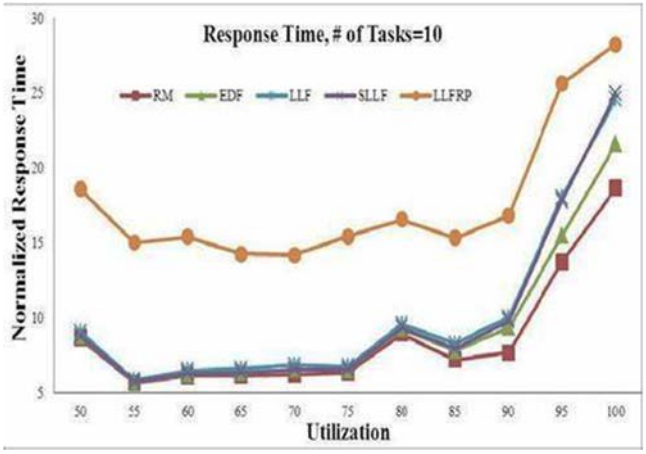


Figure II.9 Response Time

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II. Exercise N°1

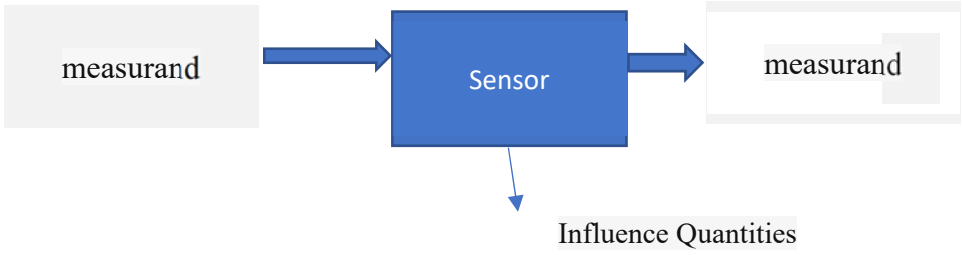


Figure II.10 *Operation of a sensor.*

1. ☑ What is the function performed by this sensor?
2. ☑ What is a measurand?
3. ☑ a. What does the influencing quantity represent?
4. b. How should its contribution to the output signal be?
5. c. Can a sensor be used to measure an influencing quantity? If yes, provide an example.

II.Exercise N°2: Hall Effect

When a material, typically a semiconductor in the form of a wafer, is subjected to a current I and a magnetic induction B at an angle θ with the current, a voltage VH perpendicular to the current and induction appears. This voltage is given by the following relation:

$$\mathbf{VH = KH \times I \times B \times Sin\theta}$$

where K_H is a constant.

For values of θ close to 0 ($tg\theta \approx \theta$), the errors are 2% on I, 1% on B, and 3% on θ. Calculate the possible error on V_H.

II.Exercise N°3

1. ☑ Define a conditioning circuit (in an electronic instrument) and provide an example.
2. ☑ Under what conditions can the Gaussian probability law be applied to a set of N measurements of a quantity X?

II.Exercise N°4

To measure the flow rate of a liquid in a tube, a turbine can be used. This type of sensor is calibrated in an environment at 20°C, and the characteristics "rotational speed/liquid flow rate" are summarized in the following table:

Table II.3 *Sensor characteristics at 20°C.*

Rotational speed (rd/s)	0 ,00	0,20	0,40	0,60	0,80	1,00
Liquid flow (Kg/s)	0,00	0,30	0,60	0,90	1,20	1,50

1. ☑ Explain the operating principle of this type of sensor.
2. ☑ Determine its sensitivity at 20°C.
3. ☑ The sensor is used to measure the flow rate of a liquid at 50°C. List the different errors that may occur and specify whether they are systematic or random.
4. ☑ The experiment conducted at 50°C shows that the turbine's characteristics change as follows:

Table II.4 *Sensor characteristics at 50°C.*

Rotational speed (rd/s)	0 ,00	0,20	0,40	0,60	0,80	1,00
Liquid flow (Kg/s)	0,10	0,35	0,64	0,85	1,10	1,60

Determine the sensitivity at 50°C.

II.Exercise N°5

The resistance of a thermistor at a temperature T is given by the following relation:

$$R = R_0 \exp \beta . (\frac{1}{T} - \frac{1}{T_0})$$

where:

- ☑ R_0 is the resistance value at temperature T_0 [K], R_0=5000 Ω at 23°C.

- ☑ β is a constant in the considered range.

A calibration is performed to determine the value of the constant β in the study range.

1. ☑ Explain the meaning of calibration and describe how to conduct such an experiment.
2. ☑ The experimental results obtained are illustrated in the following table:

📌 ***Table II.5 Temperature measurement results.***

T (°C)	23	30	35	40	45	50	55	60
R(T) (Ω)	5000	3950	3650	2890	2500	2150	1860	1630

Using linear regression (least squares method), determine the best estimate of β.

II.Exercise N°6

During the calibration of a device in the acquisition chain, the manufacturer records experimental points showing the relationship between the input and output signals.

Input	1	2	3	4	5	6	7	8	9	10
Output	0.4	1.06	1.37	2.01	2.56	3.12	3.42	3.85	4.49	5.12

a. ☑ Plot the graph defined by these points and draw the "best" line passing through them.

b. ☑ The nominal relationship between the input and output provided by the manufacturer is:

$$S = G_n \times E + S_{on}$$

where:

- Gn is the nominal gain, Gn=0.5044.
- Son is the nominal offset, Son=−0.0293.
- Justify these parameters.
- Calculate the maximum linearity error and the relative linearity error.

II.Exercise N°7

Consider a device A in the measurement chain (sensor, amplifier) with the following metrological characteristics:

- Gain uncertainty : $\pm 1 \times 10^{-3}$.
- Maximum linearity error: $\pm 0.2 \times 10^{-3}$.
- Cut off frequency : 20 kHz.
- Temperature coefficient of gain: $\alpha G = 0.3 \times 10^{-4} °C-1$.
- Thermal sensitivity of offset uncertainty: $0.1 \times 10^{-3} °C-1$.

Given that the high frequency of the measurand signal is fh=2kHz, the temperature variation range is ΔT=30°C, and the device's response is first-order:

1. ☑Calculate the maximum uncertainty introduced by the device.
2. ☑A temperature sensor is installed near this device to compensate for thermal drift errors. Given that the sensor's measurement range is 0–100°C and its accuracy is 2%, calculate the maximum uncertainty introduced by the device after thermal error compensation.

II.Exercise N°8

A sensor is calibrated in an environment at 21°C. The deflection/load characteristics are illustrated in the following table:

Table II.6 Deflection/load characteristics at 21°C.

Charge (kg)	0	50	100	150	200
Deflection (mm)	0.0	1.0	2.0	3.0	4.0

When used at 35°C, its characteristics change as follows:

Table II.7 Deflection/load characteristics at 35°C.

Charge (kg)	0	50	100	150	200
Déflection (mm)	0.2	1.3	2.4	3.5	4.6

1. Determine the sensor's sensitivity at 21°C and 35°C. What do you observe?
2. Calculate the zero offset and the sensitivity deviation at 35°C.

II.Exercise N°9

The sensitivity of a resistance thermometer (Pt100 probe), whose resistance is 100 Ω at 0°C, is approximately $3.9 \times 10-1 \Omega/°C$, assumed to be nearly constant with temperature (linear variation of resistance with temperature). Calculate the precision of the temperature

measurement if the probe's resistance is measured with an uncertainty of 0.1% near 100°C.

II.Exercise N°10

The cursor of a potentiometer is linked to a membrane or capsule so that the deformation of this proof body causes the cursor to move.

The potentiometer, with a total resistance *Rn*, is powered by an electromotive force *e.* What is the physical quantity for which this sensor is specifically designed?

1. ☑What is the electrical signal provided by this sensor?
2. a. ☑Give the expression for the voltage *Vm* between the cursor and one of its ends.

   b. If there is proportionality between:

   - The pressure *p* to be measured and the deformation of the proof body.
   - The deformation of the proof body and the displacement *x* of the cursor.
   - The displacement *x* of the cursor and the resistance *R*(*x*). How is *Vm* expressed?
3. ☑The amplitude of the output signal is on the order of volts. What is the advantage of having a high output signal?
4. ☑In your opinion, what are the disadvantages of this type of sensor?
5. ☑Propose the instrumentation associated with this sensor.

II.Exercise N°11

We want to measure the thermal stratification in a hot water storage tank. For this purpose, 10 PT100 temperature probes are placed at 15 cm intervals. For a PT100, the characteristic provided by the manufacturer is as follows:

$$R = R_0 [1 + 0{,}00385\ T]$$

where:

- *R* is the resistance in ohms.
- *T* is the temperature in °C.
- R_0 is the resistance value at 0°C, R_0=100Ω.

At a given time, the temperatures in the different layers of the tank are measured. The following table is obtained:

Table II.8 Temperature measurement results in different layers.

Layer	1	2	3	4	5	6	7	8	9	10
Resistance (Ω)	107,07	108,49	107,07	111,17	113,09	117,33	120,41	121,56	122,33	123,1

1. Determine the temperature values at each probe.
2. Plot the curve $T=f(Z)$. It is observed that the temperature shows an irregularity at probe N°5. A calibration is then performed, and the following table is obtained:

Table II.9 Calibration of probe N°5.

T [°C]	20	30	40	50	60
R (Ω)	106,15	110,25	114,30	118,35	122,45

3. Determine the characteristics of this probe. What can you conclude?
4. During a test, the water in the tank must be heated and well mixed until it reaches 60°C. The mixing must continue until the temperature difference between layer N°1 and layer N°10 is less than 0.5°C. What should be the resolution of the ohmmeter to achieve such precision?

I- Introduction

In our lives, various physical quantities such as speed, temperature, pressure, and displacement need to be measured and quantified. To achieve this, several types of sensors have been developed to digitize and facilitate the use of these quantities. These sensors are divided into several categories based on the quantity to be measured and the materials used in their construction. In this chapter, we will present some examples of sensors: microphone, CCD sensor, RF field sensor, and digital sensor. [9]

II- Microphone

The primary function of a microphone is to capture sound waves and convert them into an electrical signal called an audio signal. In this sense, a microphone is an energy transducer that transforms acoustic energy into electrical energy. There are several types of microphones, classified based on the system used for energy conversion, such as:

- Electret microphone
- Condenser microphone
- Dynamic microphone, etc.

The shape of the casing in which the microphone's transducer capsule is housed influences the preferred direction of sensitivity. This defines the acoustic type of the microphone: omnidirectional, unidirectional, cardioid, etc.

Electrotechnical Definition of a Microphone

The conversion of acoustic energy into electrical energy, and vice versa, does not occur directly. There is an intermediate stage where mechanical energy is stored in a solid that either moves or deforms. Acoustic waves primarily manifest through variations in pressure and velocity. In many cases, the acoustic field at a point results from the superposition of sound waves undergoing multiple reflections. Advances in sensor technology (miniaturization) and instrumentation now allow for the measurement of energy-related quantities.

In the simplest case, there are two types of waves: *plane progressive waves* and *general plane waves.*

For plane progressive waves, the physical description of a fluid relies on the law of mass conservation, the fundamental law of dynamics, and thermodynamic relationships or the equation of state.

For general plane waves, they can be generated by exciting a finite-length cylindrical tube using a vibrating piston along the x-axis (Ox). Reflection occurs at the tube's end, affecting the pressure field.

Two fundamental mechanical quantities associated with acoustic waves—*pressure* and *velocity*—must be measured. While pressure is relatively easy to measure, the velocity of fluid particles associated with acoustic waves is too low to be detected using conventional methods. Furthermore, characterizing a diffuse field based on velocity is extremely challenging.

Note:

The primary acoustic sensor is the pressure microphone.

When a coil moves near a magnet (or vice versa), an electric voltage appears at its terminals—this is the principle of magnetic induction.

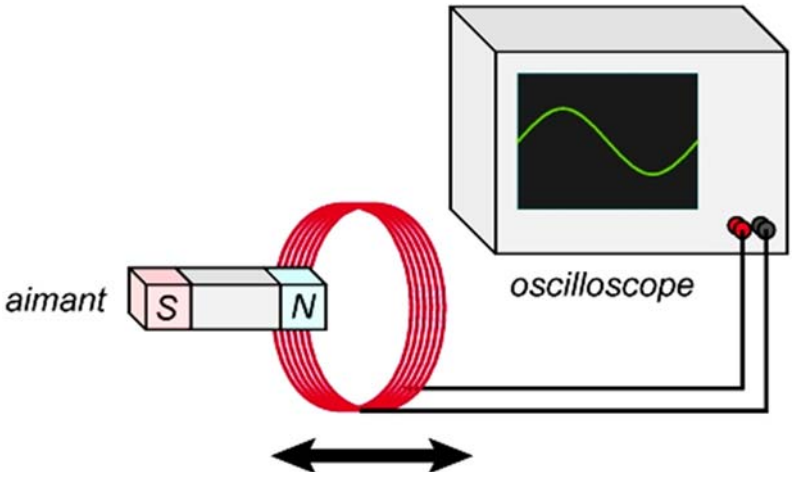


Figure III.1 : principle i Induction n a microphone

This phenomenon is utilized in dynamic microphones, which convert sound into an electrical signal. In this type of microphone, the sound wave passing through the grille causes a diaphragm to vibrate. This diaphragm is attached to a coil placed near permanent magnets. As the diaphragm moves, the coil also moves, generating an electrical voltage at its terminals. Consequently, the produced electrical signal is a direct representation of the received acoustic wave.

II-1 Principle of a Dynamic Microphone

The moving part (diaphragm + coil) is represented in red.

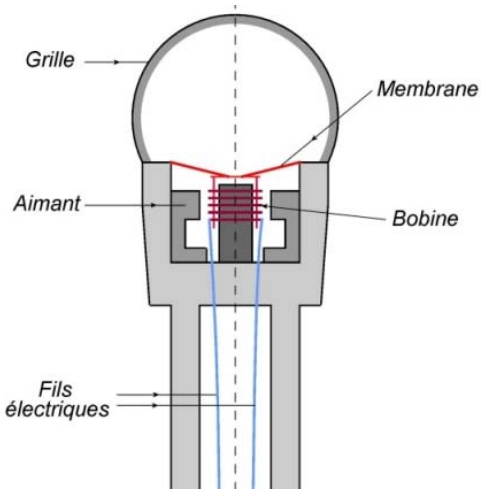


Figure III.2 : The microphone

The dynamic microphone is very common, but there are variations and other types based on different physical phenomena, such as the piezoelectric microphone. Piezoelectricity refers to the generation of an electrical voltage at the ends of a piezoelectric crystal when it undergoes mechanical stress, such as the action of a sound wave. The reverse is also true: applying an electrical voltage to the crystal causes it to deform.

II-1.1. The Loudspeaker

A coil is placed near a magnetic field produced by a permanent magnet. When an electrical voltage is applied to the coil, it generates its own magnetic field, causing it to be attracted or repelled by the magnet, depending on the polarity of the applied voltage. The resulting force responsible for this motion is called the Laplace force. In the diagram, the moving parts are shown in red.

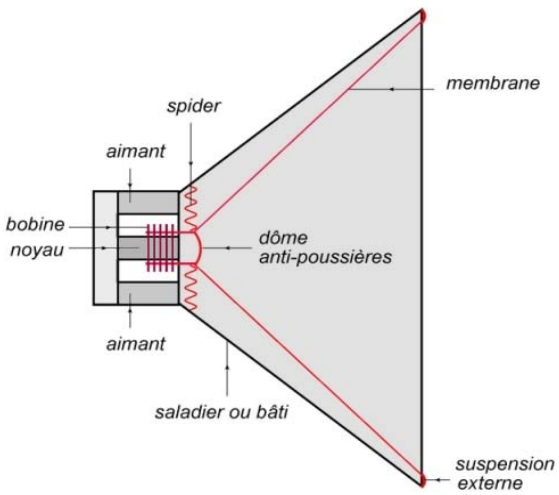


Figure III.3 : The Loudspeaker

Thanks to this force, a dynamic loudspeaker converts an electrical signal into an acoustic signal. In a speaker, a coil is placed near magnets. When the electrical signal is applied, the coil moves along the axis of the core (left/right axis in the diagram). The coil is attached to a diaphragm, which transmits the vibration to the surrounding air, producing a sound wave.

II-1.2. Acoustic Enclosures

A loudspeaker emits two sound waves: one moving forward (to the right in the diagram) and another backward. The backward wave can interfere with the forward wave, which is the desired output. To prevent this, in home Hi-Fi systems, the loudspeaker is enclosed in a wooden box, called an acoustic enclosure.

A single acoustic enclosure often contains multiple loudspeakers, each handling a specific frequency range. Typically, there are three loudspeakers, classified by their English names:

- ***Woofer (Boomer):*** Reproduces low frequencies between 20 Hz (the lowest audible frequency) and 500 Hz. The woofer is the largest of the three and has a large diaphragm surface.
- ***Midrange (Medium):*** Covers mid-range frequencies, typically between 500 Hz and 5000 Hz.
- ***Tweeter:*** Handles the highest frequencies, from 2000 Hz to 20,000 Hz (the highest audible frequency). The tweeter is the smallest loudspeaker.

As with microphones, other types of loudspeakers exist beyond the dynamic model. For example, piezoelectric crystals can also be used to generate sound waves, particularly for tweeters or even ultrasound generation.

II-1.3. Headphones

The purpose of headphones is to produce sound that is theoretically heard only by the person wearing them. A standard headphone consists of one loudspeaker per ear, meaning each speaker must handle the entire frequency range.

In some applications, headphones provide sound isolation from surrounding noise, allowing users to hear the output more clearly. This is particularly important for submarine sonar operators, where headphones completely cover the ears.[10]

Other applications require a more compact and discreet design, such as MP3 player earphones. In this case, the headband found in traditional headphones is removed in favor of earbuds, which can be inserted into the ear or secured with a clip system. When stereo listening is unnecessary, a single earphone may be used, such as for telephone operators or TV presenters using an in-ear monitor.

II-2. Fidelity of an Electroacoustic Transducer

Regardless of the technology used, the human ear is the final acoustic receiver in the chain. Therefore, its characteristics must be considered. Since human perception of sound intensity is logarithmic, the concept of sound intensity level (L) in decibels (dB) is introduced. This level is associated with the acoustic intensity (I) of a sound, following the equation: $L = 10 \cdot \log(I / I_0)$. where $I_0 = 1{,}00 \cdot 10^{-12}\ \mathrm{W/m^2}$ is the reference acoustic intensity, defined as the threshold of audibility?

In electronics and electrical engineering, the decibel (dB) is also used to compare power levels (electrical, acoustic, etc.), which can vary by several orders of magnitude.

The gain (G) between two power levels P and P_0 is defined as: $G = 10\log(P / P_0)$ or $P / P_0 = 10^{G/10}$.

A **gain of 0 dB** means that the signal power **P** is equal to the reference power. A **gain of -5 dB** means that the signal power is attenuated by **5 dB** relative to the reference value.

Some Key Criteria:

- ***Bandwidth:*** Not all frequencies are processed with the same efficiency by an acoustic sensor or emitter. The frequency response curve of a microphone is a semi-logarithmic graph that shows gain as a function of frequency. For this type of device, the gain at 1000 Hz is typically chosen as the reference gain (0 dB).

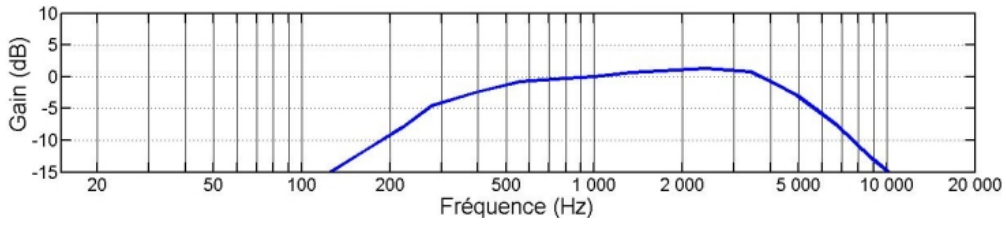


Figure III.4 : ***Response curve of a Microphone***

For **loudspeakers**, **sound intensity level** is often used instead of gain, but the principle remains the same (vertical axis in dB).

The curve defines a **frequency range** where the dB values are high enough to be meaningful. This is called the **bandwidth**, which indicates the range of **usable frequencies** for the transducer. The values given correspond to the **lower and upper limits** of the bandwidths for the three types of loudspeakers.

- **Directivity:** For a given frequency, a microphone does not always have the same efficiency depending on the **angle** at which it captures sound relative to its axis. Similarly, for a loudspeaker, the emitted sound does not always have the same power in all directions.

In such cases, we say that the device is **directional**. This characteristic is analyzed using a **directivity diagram**, which represents **gain as a function of the angle** at which sound is captured or emitted.

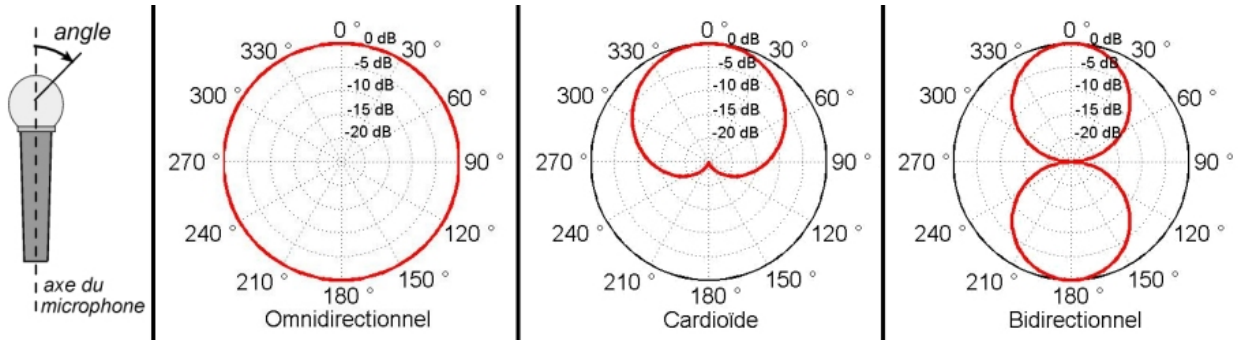


Figure III.5 : directivity diagram

The reference gain (0 dB) is defined for an angle of 0° (aligned with the axis of the microphone or loudspeaker). The graphs above illustrate common scenarios encountered with microphones. By definition, an omnidirectional transducer captures or emits sound equally in all directions.

Directivity is frequency-dependent. Professional directivity diagrams display multiple curves on the same graph, each corresponding to a different frequency.[10]

II-3 Main Characteristics of Microphones:

Microphones are considered, from an electrical perspective, as voltage generators that produce an electromotive force with their own internal resistance. We can add to the basic

circuit diagram a load resistance, which represents the amplifier to which the microphone will be connected.

- ***Frequency Response Curve***: Like any device in an acoustic chain, the frequency response curve is essential for assessing both linearity and the frequency range it can handle. For a microphone, it indicates the frequency range for which it delivers an electrical signal, but its linearity is equally important. Additionally, some microphones even feature a built-in switch to adjust the frequency response based on the microphone's position relative to the sound source.

Note:

The orientation of the microphone relative to the sound source, as well as the direction of incoming sound waves, has a significant impact on the quality of the microphone's output signal.

Three Main Types of Microphones:

- ***Pressure Microphone***: A transducer capsule enclosed in a fully sealed housing is sensitive to sound waves arriving from all directions. This type of microphone is omnidirectional, capturing sounds from all directions across all frequencies.

  The directivity diagram of a microphone illustrates its sensitivity based on the direction of incoming sound waves and frequency. While lower frequencies (a few kHz and below) are less affected, the microphone's housing can cause disparities in response at higher frequencies.

- ***Pressure Gradient Microphones***: The transducer capsule is housed in a casing with openings at the front and back of the diaphragm. This design makes the microphone more sensitive to sound waves coming from the front and back, while side sounds cancel out as they reach both sides of the diaphragm simultaneously. These are known as bidirectional microphones, and their directivity diagram takes the shape of a figure-eight (8 pattern).
- ***Hybrid Microphones:*** These combine both pressure and pressure gradient principles, allowing for more focused directivity patterns, particularly toward the front of the microphone. The resulting directivity diagrams are called cardioid or super-cardioid patterns. Some specialized microphones, known as "shotgun microphones," feature a

long tube in front of the transducer capsule, significantly increasing directionality. These are commonly used in studio settings where microphones need to stay out of a camera's frame.

Conclusion

Devices such as microphones and loudspeakers are referred to as electroacoustic transducers.

The dynamic microphone converts acoustic waves into electrical signals using the principle of magnetic induction. The dynamic loudspeaker performs the opposite conversion using the Laplace force. Acoustic enclosures (speaker cabinets) and headphones are two common applications of loudspeakers.

To evaluate the performance of a microphone or loudspeaker, two key factors are considered:

- *Bandwidth*, analyzed through the frequency response curve.
- *Directivity*, assessed using the directivity diagram. [11]

III. CCD SENSORS (Charge-Coupled Devices)

III-1. GENERAL OVERVIEW & OPERATING PRINCIPLE

The general public is familiar with **image sensors** or **electronic retinas** through multimedia products, where they have rapidly replaced older image capture tubes such as **vidicon**, **plumbicon**, and others. These sensors are commonly found in **camcorders**, **lightweight video cameras**, and have enabled the development of **digital photography** and **webcams**.

Beyond these consumer applications, where cost efficiency is a major factor, CCD image sensors are also used in a wide range of **industrial, scientific, and professional fields** where high performance is crucial. These include:

- Astronomy
- Microscopy
- Biology (fluorescence analysis)
- Radiography
- Spectrometry
- Nuclear physics
- Pattern recognition

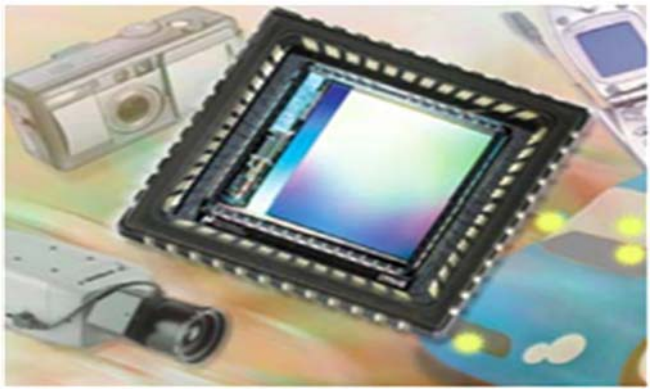


Figure III.6 :CCD Sensor

- Dimensional control
- Professional photography
- High-definition television
- Telecinema, and more.

III-2. CCD Sensor Structure

CCD image sensors or CCD retinas were invented by Boyle and Smith at AT&T laboratories in 1970. The term CCD (Charge-Coupled Device) refers to the way in which electrical charges accumulated in one semiconductor region are transferred (coupled) to an adjacent region. These charge storage regions are called potential wells, created when an electric field is applied to the semiconductor.

The basic structure of a CCD sensor (often compared to the human eye's retina) is a MOS capacitor (Metal Oxide Semiconductor). The electrodes (also called Gate) are just a few microns thick and are made from a highly conductive material, such as aluminum or polycrystalline silicon. The insulating layer, also a few microns thick, is made of silicon dioxide (SiO_2). The substrate (support), where the electrical charges move, consists of P-doped semiconductor material (e.g., P-type silicon). Under the gate, the entire structure behaves like a capacitor. Most CCD sensors also include a buried N-type semiconductor layer within the silicon, located beneath the oxide layer.[12]

III-3 Types of CCDs

A CCD (Charge-Coupled Device) consists of a matrix array of MOS capacitors. To obtain an image of a scene, it is necessary to count the number of electrons trapped in each potential well, which is proportional to the number of incident photons on each pixel.

To achieve this, the voltage of the gates in each MOS capacitor is controlled sequentially in sync with a clock signal. This process transfers electrons from one capacitor to its neighbor, a mechanism known as a shift register. After n transfers, the accumulated charges are converted into voltage in a capacitor, then amplified. Finally, they are digitally encoded using an analog-to-digital converter located outside the CCD matrix.

There are several CCD sensor architectures, each optimized for specific applications.

Full-frame transfer (FFT) and frame transfer (FT) CCDs are primarily used in scientific applications. Interline transfer CCDs are widely used in consumer cameras and professional television systems.

There are three main types of CCD sensors:

- Full-Frame Transfer CCDs (FFT CCD)
- Frame Transfer CCDs (FT CCD)
- Interline Transfer CCDs

III-3.1 FULL-FRAME TRANSFER CCD SENSOR

Full-frame transfer CCDs (FFT CCDs) follow the simplest architecture. The entire surface of the sensor is photosensitive and collects incident photons. The sensor is then read vertically, line by line, using a shift register. Each line, once transferred to the readout register, is then read horizontally to determine the value of each pixel.

This progressive readout process is slow, but full-frame CCD sensors are among the most sensitive on the market and can operate under various lighting conditions.

In full-frame technology (see Figure 3.7), the design is relatively simple:

The vertical CCD lines serve both as light detectors and as charge transmission channels. The CCD capacitor cells are photosensitive, but their efficiency is lower for shorter wavelengths due to the semi-transparent polycrystalline silicon electrodes. A key advantage of this design is its high overall efficiency—nearly the entire surface of the sensor is light-sensitive. The fill factor (the ratio of photosensitive area to the total integrated circuit area) is close to 100%. However, an external optical shutter is required to precisely control the integration time and prevent unwanted light exposure during the charge transfer process.

In this type of sensor, the vertical CCD lines are both photosensitive and responsible for charge transfer, ensuring a fill factor close to 100%. [13]

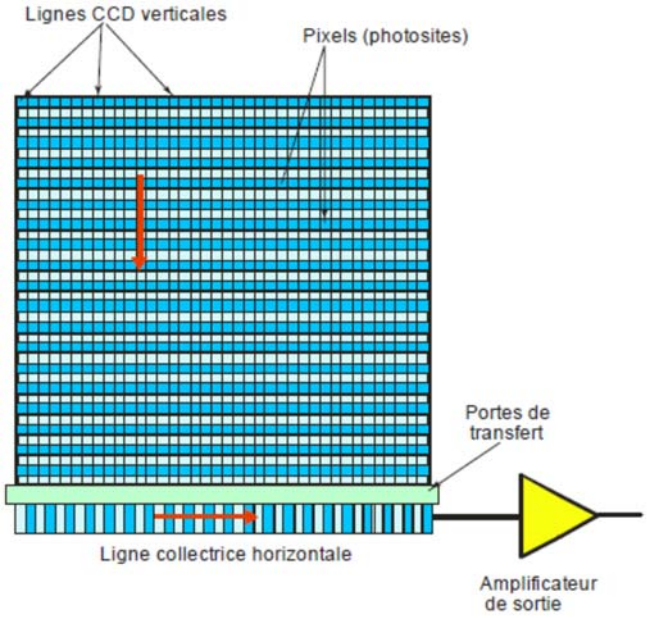


Figure III.7: Sensor CCD FFT (Full Frame Transfert)

III-3.2 FRAME TRANSFER CCD SENSOR

Frame Transfer CCDs (FT CCDs) use an architecture based on dividing the sensor's photosensitive area into two symmetrical parts of equal size. The first part collects incident photons in the usual manner. The second part, which is shielded from light, serves as a storage area for electron readout.

The captured electrons from the first part are rapidly transferred (within a few milliseconds) to the second, shielded part of the sensor. This allows the next image (n+1) to be acquired in the exposed part of the sensor while the previous image (n) is being read from the masked part.

This greatly increases the image acquisition speed compared to full-frame CCDs.

Advantages & Drawbacks:

✅ High fill factor, similar to full-frame CCDs.

✅ Faster image acquisition since exposure and readout occur simultaneously.

❌ More expensive, as the sensor size must be doubled to achieve the same active area as a full-frame CCD.

In frame transfer CCD technology (see Figure 3.8), an additional set of vertical CCD lines is used, which is masked by an opaque metal layer. At the end of the exposure time, the captured electronic image is quickly transferred from the photosensitive matrix to the shielded matrix. This enables a new image acquisition to begin while the stored image is being read out at a normal rate. The fill factor remains close to 100%, but only within the active area. As a result, the actual active matrix size is effectively halved compared to its total physical size. [14]

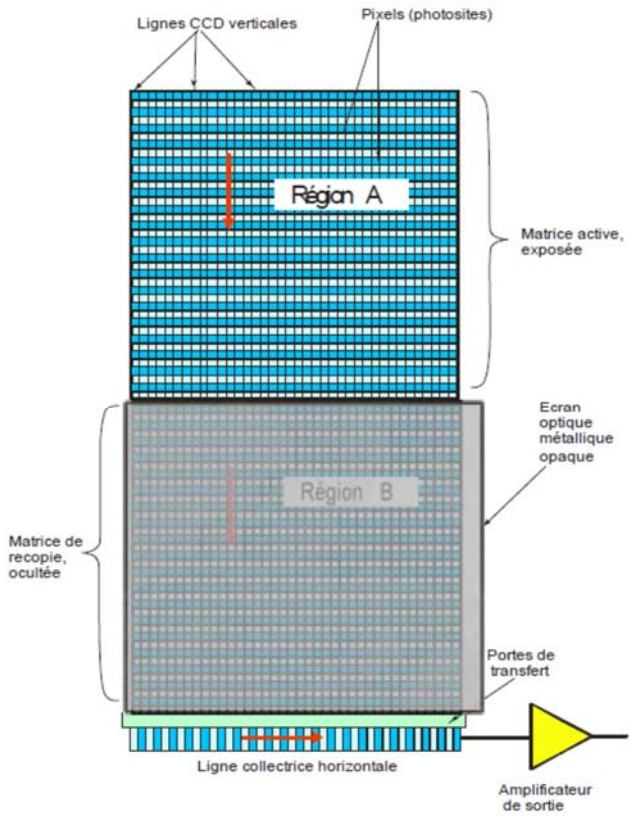


Figure III.8: Sensors CCD « Frame Transfer » (FT CCD)

III-3.3 INTERLINE TRANSFER CCD SENSOR

Interline Transfer CCDs (IT CCDs) incorporate a charge transfer channel (a vertical register shielded by a metallic optical cover) adjacent to each photodiode. This allows the accumulated charges to be rapidly transferred (within microseconds) as soon as the image acquisition is completed.

This design enables:

✅ Extremely short exposure times, preventing pixel saturation.

✅ No need for a mechanical shutter to block incident light.

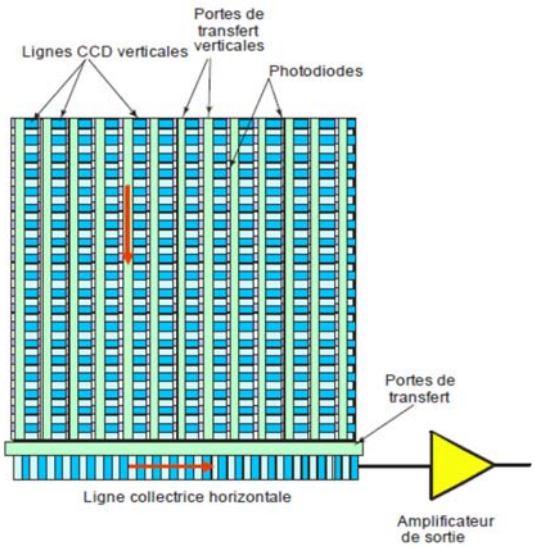
However, the shielding of vertical registers acts like Venetian blinds, reducing the sensor's photosensitive area compared to full-frame architectures.

To compensate for this limitation and increase the fill factor, microlens arrays can be used to focus incident light onto the photodiodes. However, when using wide-aperture lenses (wide-angle illumination), the overall sensitivity remains low.

In an interline CCD sensor (see Figure 3.9):

- The blind vertical CCD registers are not arranged in a compact matrix as in frame transfer technology, but are interleaved between vertically aligned photosensitive sites.
- Efficiency decreases, as the fill factor is significantly lower in this configuration.

One notable limitation of full-frame CCDs is that they do not support interlaced scanning, which is essential for standard television formats (ITU-R 601). Variations of interline CCDs are also used in linear image sensors. The charge transfer function is performed by vertical CCD lines placed between rows of photosensitive elements. While this significantly reduces the fill factor, it provides greater flexibility, allowing for multiple image resolutions. To improve light collection, micro lenses placed in front of each pixel can help mitigate the fill factor issue. [15]



📌 ***Figure III.9 : Sensor CCD « interligne ».***

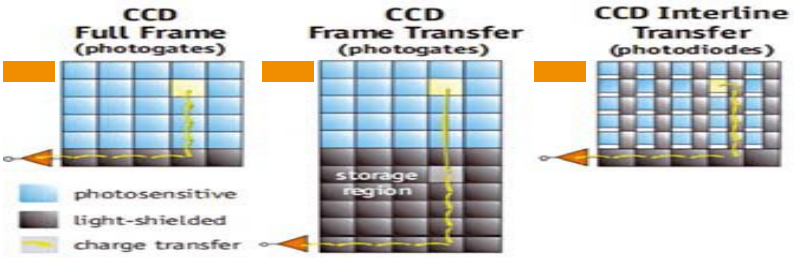


Figure III.10. Diagram of the different types of sensor architecture.

CCD SENSOR CHARACTERISTICS AND LIMITATIONS

Due to their architecture, CCD sensors have the advantage of a fill factor close to unity (>98%), meaning that the photosensitive area is nearly equal to the total sensor size.

The dynamic range of a CCD sensor is determined by the ratio between the quantum capacity of each photosite (which is proportional to the size of the photosensitive area) and the sum of dark noise (low in CCDs) and read noise. This results in a high dynamic range, given by:

$$Dynamic\ Range = 20\log(Dark\ Noise + Read\ Noise Capacity)$$

Additionally, sensitivity—defined as a pixel's ability to quickly reach saturation—is high in CCD sensors because they are continuously exposed to light.

Common Image Artifacts in CCD Sensors

However, CCD sensors also have notable limitations, mainly due to their continuous exposure and the need to transfer accumulated charges at the end of acquisition.

📌 Blooming:

- When a pixel receives too many photons (exceeding its charge capacity), it saturates and overflows into adjacent pixels, similar to an overfilled bucket spilling water.
- This phenomenon is known as blooming (see Figure 3.10).

📌 Smearing (Column Noise):

- When a pixel is saturated, it affects the entire column during readout through the shift register, causing vertical streaks in the image.
- This effect is called smearing or colonnage (see Figure III.10).

Addressing CCD Limitations

☑ Mechanical Shutter:

- To prevent unwanted exposure during image readout, a mechanical shutter may be required.

☑ Readout Speed Limitations :

- Despite advancements in CCD architectures to increase readout speeds, it is impossible to directly address individual pixels or select a region of interest (ROI).
- This limits the achievable frame rates, with the upper limit currently in the range of a few tens of kHz.

Figure III.11. Example of smearing and blooming on an image taken by a CCD sensor. Smearing results in a saturated vertical line. Blooming results in saturation of the nearest pixels.

III-4 How Do CMOS Sensors Work?

Digital image sensors are ubiquitous in our daily lives. From mobile phones and digital cameras to high-sensitivity scientific cameras and high-speed cameras, the sensor market has exploded in recent years. Given the ever-expanding range of applications and the vast diversity of products available, it is essential to go back to the fundamentals and identify the key questions one should ask when choosing the right technology and sensor type for a specific need. To that end, this section revisits the working principles and distinct characteristics of the two main types of image sensors: CCD and CMOS. [16]

III-4.1 Operation of a MOS Capacitor-Based Sensor

The fundamental technology behind both CCD and CMOS sensors is the MOS (Metal-Oxide-Semiconductor) capacitor. This structure consists of three thin-layer materials arranged in a sandwich-like formation:

- ✅ A metal gate (also called a "grille" or "gate"),
- ✅ An insulator (typically an oxide),
- ✅ A semiconductor substrate (usually P-doped, with two N-doped inclusions called the source and drain), as illustrated in Figure 3.12.

📌 Charge Generation & Storage : When a photon with energy greater than the semiconductor's bandgap is absorbed, it generates an electron-hole pair:

- An atom in the semiconductor lattice releases an electron, which moves from the valence band to the conduction band.
- This electron leaves behind a positively charged "hole".

📌 Charge Migration & Trapping:

- Due to the electric field applied by the gate (in the depletion zone), the electron migrates to the semiconductor-oxide interface, where it gets trapped in a potential well.
- Meanwhile, the hole migrates toward the ground electrode.
- The number of electrons that can be collected depends on the capacity of the potential well, which is determined by the surface area, the voltage applied to the gate, and the thickness of the oxide layer.

Although both CCD and CMOS sensors rely on this fundamental principle of charge generation and storage through photon absorption, they differ significantly in how the trapped charges are transferred from the pixel wells to the electronic circuitry that ultimately forms the image.

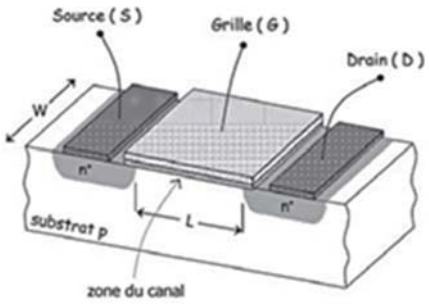


Figure III.12. Diagram of a MOS capability. The grid (G) represents the photosensitive zone while the source (S) and drain (D) electrodes trap electrons in the potential well located under each grid.

III-4.2 CMOS Sensors

A more recent technology that emerged in the 1990s, CMOS (Complementary Metal-Oxide-Semiconductor) sensors operate on the same principle of photon absorption and generation of current proportional to the incident light flux on each pixel. However, the key difference lies in how the charges are read.

Unlike CCD sensors, in CMOS technology, the charges are directly converted at the generation site through an amplifier integrated into each pixel (Figure 4). This design eliminates the need for multiple charge transfers, as required in CCD shift registers, thus significantly increasing the readout speed. While CMOS sensors are similar in size to CCDs, their spatial resolution is lower due to the presence of individual amplifiers for each pixel (similar to interline CCDs). However, as with CCDs, a microlens array can be added to partially compensate for this effect.

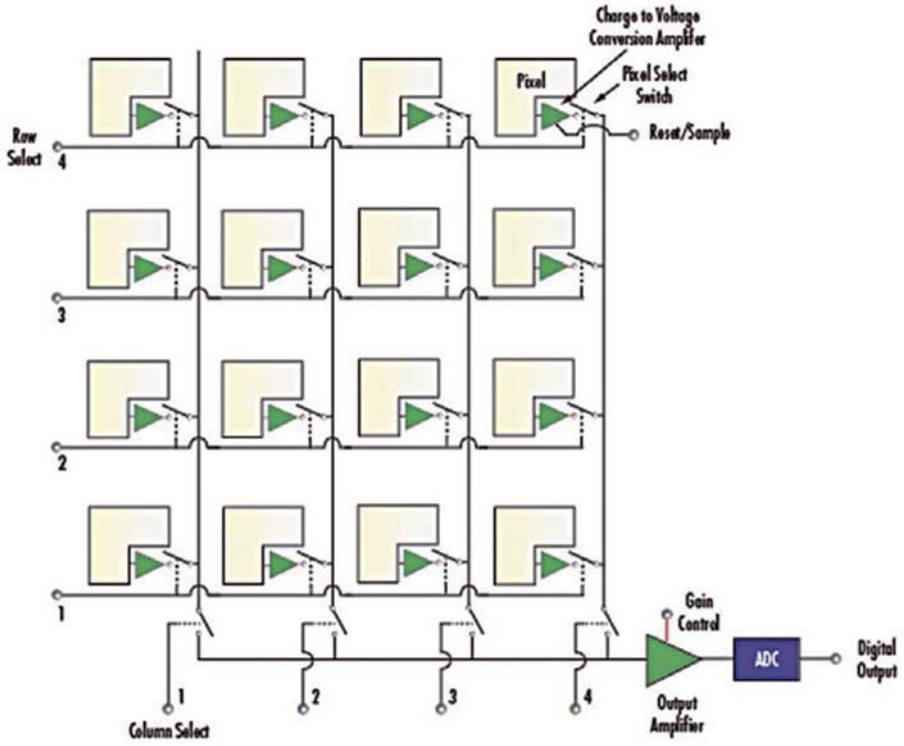


Figure III.13 – CMOS Sensor Architecture

Each photosite is equipped with its own amplifier, meaning that each pixel can be individually addressed and has an independent response from its neighbors.

Shutter Mechanisms: Global vs. Rolling Shutter

Another fundamental difference is how the image is captured:

- In CCD sensors, the entire sensor (and thus all pixels) is exposed simultaneously. Immediately after, the photosites are shuttered while the electron count is measured, creating the final image. This mode is known as global shutter (Figure 3.14).
- In CMOS sensors, although each photosite is exposed for the same duration, it does not capture light at the same moment. Instead, exposure occurs sequentially, line by line, starting from the top of the sensor. This method is called rolling shutter (Figure 3.15).

Advantages of CMOS Sensors

Selective Readout & Higher Frame Rates Since each pixel in a CMOS sensor can be individually accessed, it is possible to read only a portion of the sensor matrix. This region of interest (ROI) selection reduces readout time per image, allowing higher frame rates than interline CCD sensors.

📌 Pixel Correction & Noise Reduction CMOS technology enables the correction of individual pixel values using customized functions, which helps:

- Correct non-linearity effects,
- Compensate for fixed pattern noise (FPN)—a phenomenon where pixels respond non-uniformly to identical illumination or even in the absence of light.

📌 Cost-Effective Manufacturing Another advantage is that CMOS sensor fabrication is compatible with mass-production facilities for integrated circuits, making it significantly cheaper than CCD technology.

Disadvantages of CMOS Sensors

📌 Lower Fill Factor & Reduced Sensitivity: The presence of amplifiers within each pixel reduces the photosensitive area, leading to a much lower fill factor (< 30%) compared to CCD sensors. Without a microlens array, this greatly impacts sensitivity.

📌 Higher Susceptibility to Noise : CMOS sensors are more sensitive to noise sources (including readout noise and digitization noise), which degrades the signal-to-noise ratio (SNR) in the final image.

📌 Rolling Shutter Artifacts: The rolling shutter mechanism can cause motion artifacts if an object moves too quickly relative to the camera's frame rate:

- Horizontal motion distortion – The object may appear skewed due to the line-by-line readout.
- Non-uniform brightness – If the lighting fluctuates, image intensity may vary across the sensor.

These issues make global shutter CMOS sensors more desirable for applications requiring high-speed imaging or motion capture. [17]

Figure III.14: Operation of the CCD sensor in global shutter. The sensor is fully exposed and then closed for the time it takes to read the image.

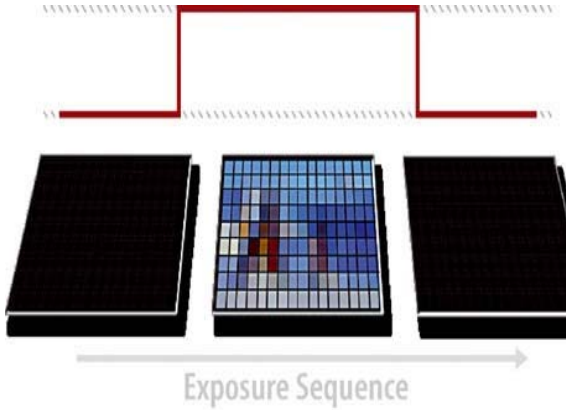
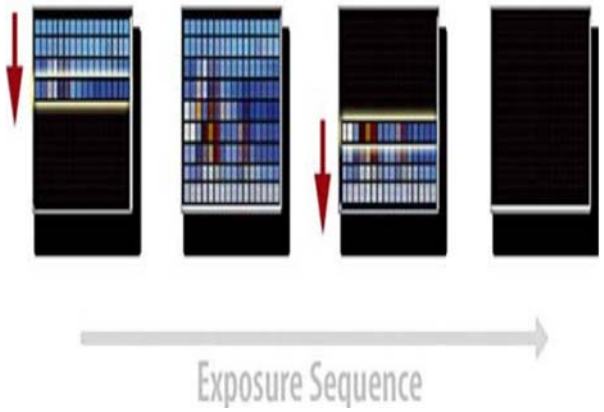


Figure III.15 : Rolling shutter operation of a CMOS sensor. The sensor is read sequentially, which can lead to representation defects if the phenomenon moves too quickly.



Comparison Table: CCD vs. CMOS

Table III.1 – CCD vs. CMOS Comparison

Feature	CCD	CMOS
Fill Factor	50% to 98%	30% to 50%
Light Sensitivity	High (0.1 lux)	Lower (10 lux)
UV & IR Sensitivity	Wide	Narrow
Response Time	Medium	Very fast (10 to 100× faster)
Power Consumption	High (2 to 4× more than CMOS)	Low
Dynamic Range	High	Medium
Sensor Uniformity	High (1 to 2% FPN*)	Low to moderate (5 to 20% FPN*)
Electronic Noise	Low	Medium to high (10× more than CCD)
Dark Current	Low	Medium
Region of Interest Selection	Very limited	High
Anti-Blooming	Absent *(except custom solutions)*	Present by default
Shuttering Speed	Fairly fast	Low
Biasing & Clocking	Multiple, high voltage	Single, low voltage

Conclusion: Both CCD and CMOS sensors are high-performance and complementary technologies. The choice of sensor depends on key factors required to produce a usable image for a given scene:

- If sensitivity and dynamic range are more important than frame rate, a full-frame CCD sensor is preferable.
- If frame rate and exposure time (to avoid saturation) are critical, then a CMOS sensor is the better option.

IV. Which Instruments Are Used to Measure Radio Frequency Fields?

Electromagnetic fields cannot be seen or heard, but there are ways to detect and measure them. Like many natural phenomena, electromagnetic fields can be measured directly. Just as the human nose detects odors in the air, a specialized "nose"—a probe—must be used to "sense" electromagnetic fields. This probe is connected to a measuring device, which determines the electromagnetic field strength at a given location.

The probe essentially acts as a receiving antenna that "captures" the electromagnetic field, while the measuring device processes the signal and provides the field value. Since radio frequency (RF) electromagnetic fields—particularly in the microwave range—have high frequencies, the appropriate measuring instrument and probe must be selected based on the specific frequency of the field being measured.

Figure III.16 : Low Frequency Electromagnetic Field Analyzer

Figure III.17 : High Frequency Electromagnetic Field Analyzer

IV-1 A Professional RF Meter

Radio frequency fields emitted by mobile network base stations (and mobile phones) range from 800 MHz to 2.6 GHz for 4G and 4.5G networks, while 5G networks operate in the

3.7 GHz and 26 GHz bands. Home Wi-Fi and public hotspots use 2.4 GHz and 5 GHz frequencies. Radio and TV broadcasters operate between 500 kHz and 750 MHz, while other radio services extend up to 900 MHz. For general RF measurement (excluding 5G), a measuring device should cover a frequency range of 700 MHz to 3.5 GHz.

At these frequencies, electromagnetic field wavelengths are relatively short, and measuring positions are generally in the far-field region, where only the electric field (E) needs to be measured. In the far-field, the magnetic field (H) and electric field (E) are related by a fixed constant. Thus, measuring only the E^2 component gives a close approximation of power density. However, at frequencies below 300 MHz, both electric (E) and magnetic (H) fields must be measured.

RF Signal Orientation & Measurement Units

Radio frequency (RF) signals have a spatial orientation. They can be vertically, horizontally, or circularly polarized. The orientation of the meter's antenna relative to the signal greatly affects measurement accuracy. If the antenna is properly aligned, it will detect the signal more effectively; otherwise, the reading will be lower. When multiple signals with different orientations are present, determining the correct antenna alignment can be challenging.

📌 Horizontal vs. Vertical Polarization (Left) & RF Measurement Units (Right)

For measuring low-level background RF radiation, small units like V/m (volts per meter) are used. For higher radiation levels, such as microwave oven emissions, larger units like mW/cm^2 (milliwatts per square centimeter) are used. The diagram above illustrates the relative sizes of different RF measurement units, where A/m (amperes per meter) is nearly 400 times larger than V/m, making it more suitable for measuring extremely strong radiation.

Legal RF Exposure Limits

Current legal limits for electric, magnetic, and electromagnetic fields generated by fixed high-frequency sources (100 kHz–300 GHz), such as mobile phone base stations, broadcasting, or television installations, are set by the Decree of the President of the Council of Ministers (July 8, 2003, published in Official Gazette No. 199, August 28, 2003). These regulations define exposure limits, precautionary values, and quality objectives based on the intended land use and type of emission system (e.g., mobile phones, radio, TV, etc.).

Since RF electric and magnetic fields are often proportional, exposure measurement typically focuses on the electric field (E), with a standard limit of 6 V/m for locations where people stay for more than four hours. However, in specific cases—such as near radio installations or sources operating below 300 MHz—separate electric and magnetic field measurements (in μT, microtesla) are necessary.

📌 Legal RF Limits in Daily Life

- Indoor & Residential Areas (e.g., homes, gardens, schools):
  - ✅ Electric Field: 6 V/m
  - ✅ Power Density: 100 mW/m²
- Outdoor Areas (short-term exposure):
  - ✅ Limits range from 20 to 60 V/m, depending on the source frequency.

RF exposure measurements must now be averaged over 24 hours, instead of the previous 6-minute standard.

Radiated Power of RF Sources

The power radiated by an RF source is often expressed in decibels relative to standard reference power levels:

- ✅ 1 mW (dBm)
- ✅ 1 W (dBW)

Typical power levels for different RF sources:

- ✅ Portable RF transmitters: <1 W (0 dBW)
- ✅ High-power systems (e.g., radar, VLF transmitters): 100 kW (50 dBW) or more
- ✅ Mobile phone base stations: 1–100 W
- ✅ Common mobile phones: 1–2 W

This overview highlights the importance of selecting the appropriate RF measuring instrument and considering exposure limits to ensure accurate and safe field measurements.

IV-2 Wideband and Narrowband Measurement Instruments

Electromagnetic field measurement instruments are mainly of two types:

- ✅ Wideband meters, which measure the total electromagnetic field value.
- ✅ Narrowband meters, which isolate and measure the electromagnetic field from a single source.

As a result, electromagnetic field measurements can be conducted in different ways, and when selecting a measuring instrument, it is crucial to have a clear understanding of what information is needed from the measurement.

Wideband meters measure total radiation by capturing all signals within a broad range of the electromagnetic spectrum. For example, if a certain area has a radio transmitter operating at 95 MHz and a mobile base station emitting in the microwave band, a wideband meter will provide a single field value that includes contributions from both sources. In contrast, a narrowband meter isolates and measures the field intensity of only one source.

IV-2.1 Examples of Wideband and Narrowband Meters

A wideband meter helps verify that the total electromagnetic field value across a wide frequency range does not exceed safety limits, as excessive exposure could be harmful to health. A narrowband meter, on the other hand, focuses on a specific source, isolating it from others, and ensures that no single source exceeds the regulatory limit set by applicable legislation.

The classification of a signal as "narrowband" or "wideband" (not to be confused with the instrument's bandwidth) is determined by the frequency spectrum occupied by the examined signal relative to the Resolution Bandwidth (RBW) of the measuring instrument.

- ✅ If the signal spectrum fits entirely within the intermediate frequency (IF) filter bandwidth, it is classified as narrowband.
- ✅ If it exceeds the filter bandwidth, it is considered wideband.

IV-2.2 Example of a Wideband Signal (Left) and a Narrowband Signal (Right)

In practice:

- ✅ A wideband meter provides a uniform response across a broad frequency range and does not require adjustments.
- ✅ A narrowband meter can also cover a broad range, but its reception bandwidth is reduced, and it must be tuned to the specific frequency of interest.

Both wideband and narrowband instruments have advantages and disadvantages, depending on the spectral environment and the type of measurements required.

IV-2.3 Guide to Selecting RF Measurement Instruments

Electromagnetic field detectors—used to measure the overall intensity of various electromagnetic fields—are now available with a wide range of sensitivities, frequency responses, and features.

For home, office, or open-area use, simple wideband meters are often sufficient for an initial assessment. To measure the most common radio frequencies, a wideband RF and microwave field meter is typically needed.

A wideband RF meter should be capable of measuring:

- ✅ Voltage gradient (in mV/m)
- ✅ Power density (in W/m^2)

Additionally, it should detect pulsed RF power from mobile phones, base stations, DECT cordless phones, and wireless networks, as well as the continuous RF power from simpler sources like radio and TV transmitters. Affordable examples of such meters can easily be found online.

For instance, one of the most popular and cost-effective RF electrometers is the PCE-EM 29, manufactured by PCE. This wideband device, measures RF electromagnetic fields in the range of 50 MHz to 3.5 GHz, using an isotropic electric field sensor (capable of simultaneous three-axis or single-axis measurements).

IV-2.4 The PCE-EM 29 in Action on a Mobile Phone

The PCE-EM 29 is an ideal budget-friendly instrument for measuring:

✅ High-frequency (RF) electromagnetic field intensity

✅ Power density radiated by mobile base station antennas

✅ Wireless communication applications (CW, TDMA, GSM, DECT)

✅ Wi-Fi signals (routers, WLAN, access points)

✅ Spy cameras and wireless bugs

✅ Safety levels of radiation emitted by mobile and cordless phones

✅ Potential microwave oven leaks

✅ Personal safety regarding electromagnetic fields in daily environments

In general, an RF meter should have a frequency range of 50 MHz to 3 GHz, or slightly higher.

- ✅RF meters (or microwave meters), which are particularly useful for mobile telephony, typically measure voltages in volts per meter (V/m).
- ✅For smaller ranges, measurements can be taken in millivolts per meter (mV/m).
- ✅Many RF meters also convert and display power density in watts per square meter (W/m^2) when needed.

IV-2.5 Field Measurement Near a Mobile Phone Antenna

Regarding measurements on Wi-Fi routers, it is important to note that newer models operate not only in the 2.4 GHz band but also in the 5 GHz band, which is beyond the range of many standard RF electrometers (such as the PCE-EM 29, which only covers up to 3.5 GHz). In such cases, it is advisable to use a wider-band radiometer, such as:

- ✅Cornet ED78S, which operates between 100 MHz and 8 GHz
- ✅Cornet ED88T Plus, a slightly more expensive model that, unlike the ED78S, is not only a high-quality RF radiometer but also measures low-frequency electric and magnetic fields (like the TriField meter) in the 50 Hz – 10 kHz range (ideal for detecting

"dirty electricity"). Additionally, the ED88T Plus can display the exposure frequency, although only in the 100 MHz – 2.7 GHz range.

This frequency reading feature allows the ED88T Plus to identify the source of electro-smog at close range by indicating the predominant RF field frequency in MHz.

- ✅ ***Example***: If the meter displays 2.4 GHz, the source is likely a Wi-Fi router or a microwave oven.
- ✅ If it reads 900 MHz, the source could be a cell tower, a mobile phone, or a smart meter.

Additionally, its fast pulse sampling rate (10,000 samples/sec.) enables it to capture short pulses from smart meters effectively.

RF Meters and Their Isotropic Sensors

RF (and microwave) meters are generally **isotropic**, meaning they are equipped with a **triaxial sensor** that provides an **accurate field reading** without needing to adjust the meter's orientation—making measurements much easier.

⚠ **Important Note:** Many RF meters have an **internal antenna (sensor)** that **should not be covered by your hand**.

- ✅ Always **hold the meter by its lower edge** if possible, or place it on a **wooden stand** for better accuracy.
- ✅ Never use **low-frequency meters** (ELF, 50 or 60 Hz) to measure **radio frequencies or microwaves**.

A Third Option: The Acoustimeter AM-10

A third RF meter worth mentioning is the Acoustimeter AM-10, a more expensive model known for its simplicity and broad frequency response, similar to the Cornet series (200 MHz – 8 GHz).

🔷 Key Features:

- LCD screen that simultaneously displays:
  - ✅ Peak electric field strength (V/m)
  - ✅ Average exposure level (µW/m²)

Many RF meters only show peak field strength, which can be confusing. However, the Acoustimeter's real strength lies in its audio function 🎧:

- ✅ As soon as a measurement is taken, you can hear the RF signal through a speaker or headphones.
- ✅ Different sources produce distinct sounds (e.g., GSM, DECT, 3G/4G, Wi-Fi).
- ✅ This feature helps identify the type of RF radiation in your environment.

📌 ***Example Use Case :*** An Acoustimeter was used to measure the RF field of a Kindle e-reader.

Additionally, the Acoustimeter AM-10 has:

✅ LED scale for instant reading (from 20 mV/m to 6 V/m)

✅ Excellent directional sensitivity—although not truly directional, it allows users to detect where an RF signal is coming from by tilting the meter at different angles.

Many RF meters only indicate radiation levels, but with the Acoustimeter, you can locate hidden sources of RF radiation—such as a concealed cell tower or a distant Wi-Fi router—which you might not have expected to detect. [17]

⚠ However, in environments with multiple RF sources, getting a precise directional reading may be difficult.

Measurement Accuracy & Differences Between RF Meters

Regardless of the tool you choose, be aware that your RF meter may give different readings compared to other brands.

📌 Why?

- ✅ In the past, analog signals were easier to measure.
- ✅ Today, in the digital and microwave era, many different types of digital signals exist, making it more challenging to establish a definitive measurement method.

Different manufacturers:

- ✅ Use slightly different calculations to measure RF fields.
- ✅ Offer varying frequency ranges and sensor types.
- ✅ May display different readings at different frequencies.

Advanced Measurement Tools

For more precise investigations, sophisticated instruments are required.

- ✅ Meters with higher frequency ranges may be needed to measure uncommon electromagnetic fields (though not necessarily in most cases—except for 5G frequencies, which are not yet covered by most low-cost commercial RF meters).
- ✅ Other advanced tools such as:
  - Spectrum analyzers
  - Active directional antennas

These instruments are particularly useful when:

✅ Pinpointing the source of an electromagnetic field

✅ Needing higher sensitivity

✅ Measuring intermittent signals (e.g., pulsed signals with low repetition frequencies)

In summary, choosing the right RF measurement tool depends on what you need to measure, the frequency range, and the level of accuracy required.

IV-3 Spectrum Analyzers and Their Use

The primary instrument used by professionals to measure both the frequency and intensity of electromagnetic fields is the spectrum analyzer. This device scans a wide range of frequencies incrementally, storing and/or displaying the results for each narrow frequency band. Spectrum analyzers are expensive, as a quick online search will confirm. Additionally, it is important to note that a low-frequency electromagnetic field meter (50 or 60 Hz, in the ELF—Extremely Low Frequency—band) cannot measure the frequency of RF electromagnetic fields.

Two Main Methods for Measuring High-Frequency Electromagnetic Fields

There are essentially two methods available for measuring high-frequency electromagnetic fields:

1. Using portable isotropic field sensors:
    - ✅ These sensors provide a simple, non-selective measurement of electric field intensity.
2. Using a spectrum analyzer with a directional antenna:
    - ✅ This more complex method allows for frequency-selective measurements, which helps identify specific sources of radiation.
    - ✅ A major disadvantage of broadband meters (which are easy to use) is their lack of selectivity, meaning they cannot isolate individual sources of radiation.

IV-3.1 Spectrum Analyzer with Selective Antenna and PC Interface

Spectrum analyzers are essentially broadband tunable receivers whose reception bandwidth can be adjusted over a wide frequency range. They measure the power at the antenna terminal, which is connected to the device via a coaxial cable, at a selected frequency.

They can be used with different types of antennas, including:

✅ Dipole antennas (gain of ~2.15 dBi)

✅ Low-directivity antennas (e.g., biconical antennas)

✅ High-directivity antennas

When used with a narrowband selective antenna, a spectrum analyzer functions similarly to a "field strength meter". However, spectrum analyzers can also be connected to relatively short non-directional antennas, providing a broad response over a given frequency range.

In this case, the analyzer displays the environmental signal spectrum, allowing users to identify the relevant frequencies and their contribution to the overall power density measured with a broadband instrument.

📌 Example : A spectral analysis obtained with a spectrum analyzer allows the identification of individual sources.

Directional Measurement Using a Spectrum Analyzer

If the direction of the incoming radiation is known, measurements can be taken by:

1. Aiming the directional antenna at the source and acquiring the spectrum.
2. Repeating the measurement at two orthogonal positions, corresponding to two different polarizations.
3. Summing the two acquired spectra to obtain the overall result.

If multiple radiation sources are present in different locations, it is necessary to conduct multiple measurements, each time orienting the directional antenna toward a different source.

📌 In some cases, an initial survey with a non-directional antenna is useful before switching to a directional antenna for detailed measurements.

Figure III.18: Compact Spectrum Analyzer (0.3 – 87 GHz): Spectrum Compact
(Illustration of a compact spectrum analyzer capable of measuring frequencies between 0.3 GHz and 87 GHz.)

V. Digital Sensors

The monitoring of movement and position in automated systems is a common challenge.

One of the most widely used position sensors is the rotary encoder, which measures angular position.

How a Rotary Encoder Works

The encoder is mechanically connected to a shaft, which rotates a disk with alternating opaque and transparent sections.

1. A light source (LEDs) shines through the disk's slits.
2. Photodiodes detect the transmitted light, generating an analog signal.
3. An electronic interface amplifies and converts this signal into a square wave, which is then sent to a processing system (typically a PLC—Programmable Logic Controller).

Types of Rotary Encoders

◈ 1. Incremental Encoder (Pulse Generator)

◈ 2. Absolute Encoder

1. Incremental Encoders

Incremental encoders are used for positioning and movement control by counting or subtracting pulses.

The encoder disk has two types of tracks:

✅ Outer tracks (Channels A & B):

- Divided into "n" equal-angle segments, alternating between opaque and transparent sections.
- "n" represents the resolution, i.e., the number of pulses per complete revolution.

✅ Two photo-sensitive diodes are placed behind these tracks, generating quadrature signals (A & B).

Determining the Direction of Rotation

The 90° phase shift between signals A & B determines the rotation direction:

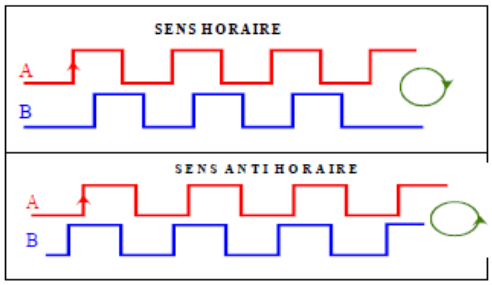
▶️ Clockwise Rotation:

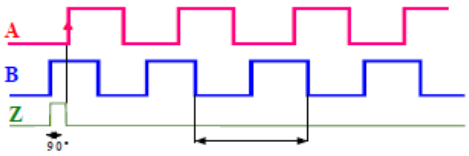
- When signal A rises, signal B = 0

🔄 Counterclockwise Rotation:

- When signal A rises, signal B = 1

This phase relationship allows a controller to interpret the direction and movement of the rotating shaft.





The Inner Track (Z Channel): The inner track (Z channel) has a single transparent window, meaning it generates only one signal per revolution. This Z signal, known as "zero pulse", determines a reference position and allows for resetting at each full rotation. [17]

III.Exercise 1

1. Calibration of a Thermistor: We have recorded the resistance RthR_{th}Rth of a thermistor as a function of temperature q:

q (°C)	0	8	15	20	31	42	51	71	78
Rth (W)	1280	960	715	605	392	246	171	105	85

Questions :

a) What measuring instrument is used to determine R_{th}?

b) Plot R_{th} as a function of q on graph paper.

2. Application

This thermistor is integrated into a probe placed in a **water bath**. The measuring device indicates a **resistance of 580 Ω**. What is the temperature of the **water bath**?

III.Exercise 2.

An **LED** is used as a **temperature sensor**. The **voltage U** across its terminals is measured as a function of temperature q:

q (°C)	2	5	1	1	2	2	3	4	5	6	7
U (V)	1,795	1,784	1,770	1,764	1,745	1,730	1,716	1,705	1,680	1,655	1,632

Questions:

1. Plot U=f(q) and model the curve. What mathematical relation links U and q?
2. To which **sensor category** does the **LED** belong?

At what temperature does the voltage **U=1.750**?

III.Exercise 3.

1. Influence of Temperature on a Silicon Diode's Characteristic Curve

To study the effect of temperature on a **silicon diode's characteristic curve**, we use a **data acquisition system** and the following setup:

Tasks:

1.1. Indicate the voltage **uD** across the diode D, **uRu** across the resistor R, and **uSu** across the transformer's secondary winding, using the appropriate conventions.
1.2. Before connecting the setup to the **data acquisition card**, we visualize the characteristic curve on an **oscilloscope**.

- Indicate on the diagram the oscilloscope connections required to visualize:
  - ☑ **Channel 1:** Voltage **uD** across the diode.
  - ☑ **Channel 2:** Voltage **uR** across the resistor (**mention "INV" if any inversion is required**).

- Assume both oscilloscope channels can be inverted.

1.3. **Which oscilloscope function** should be used to obtain the **iD)** characteristic?

2. Role of the Resistor R in the Circuit

2.1. Sensor Role

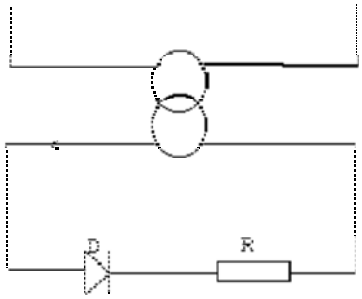
The resistor **R** acts as a **sensor**.

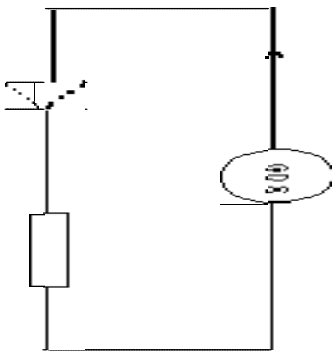
- ☑ What type of sensor is it?
- ☑ What is the **input** and **output** quantity of this sensor?

2.2. Protective Role

The resistor also **protects the diode**.

- **Calculation:** Determine the **minimum value** of R needed to **limit the maximum current to 800 mA**.
- Given:
  - ☑ **Effective voltage across the transformer's secondary:** 6V
  - ☑ **Diode voltage threshold:** 0.75V
- **3. Temperature Effect on the Diode**
  After setting up the circuit, we connect it to the **data acquisition system** and record measurements at **three temperatures (0°C, 54°C, and 100°C)**:





Diode Temperature	Voltage uDu across diode (at 2mA current)	Calculated using uD=U0−0.002q
0 °C	.	.
54 °C	.	.
100 °C	.	.

- ☑ Use the **three oscilloscope readings** to fill in the **second column** of the table.
- ☑ **Calculate** the values in the **third column** using U0=0.718V and compare them.

Graphical Representation

1.7. **Plot uD as a function of q** using the equation and the calculated values.

4. Using a Silicon Diode as a Temperature Sensor

4.1. Definition of a Sensor

- Provide the **definition** of a **sensor**.

4.2. *Practical Considerations*

- ☑ **Demonstrate** why using a **silicon diode alone (without a signal conditioning system)** is **not practical** by completing the following table:

Observation	Is the setup satisfactory? Why?	What should be changed for better usability?
Variation of uD with q	.	.
Value of uD at q=0	.	.
Change in uD when q increases from 0 to 100°C	.	.

Exercise 4

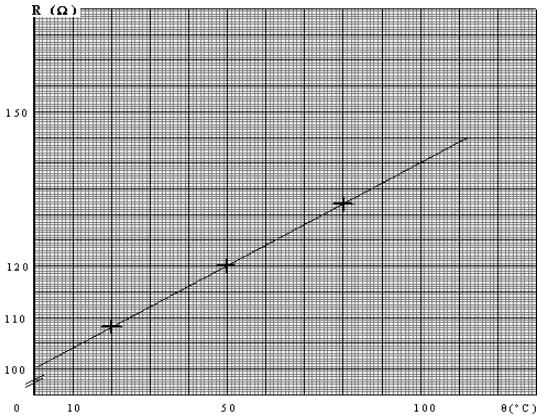
Platinum Resistance Thermometers (Pt100)

Platinum resistance thermometers are high-stability temperature sensors, suitable for a wide range of applications.

We study a Pt100 temperature sensor and determine its function RT=f(q) using an experimental setup.

Tasks:

1. Measure the resistance for various temperatures.
2. Plot the sensor's calibration curve.
3. Analyze the obtained relationship.



I. Multimeters

The multimeter is a device that allows measurements of current, voltage, and resistance. It is therefore an ammeter, a voltmeter, and an ohmmeter combined into a single instrument.

Depending on the quantity to be measured, the appropriate "zone" must be selected on the multimeter using the function selector:

- ☑ V for voltage measurement (voltmeter);
- ☑ A for current measurement (ammeter);
- ☑ Ω for resistance measurement (ohmmeter).

Measurements can be read either in an analog manner (needle) or digitally (liquid crystal display). [18]

Figure IV.1 a) Digital Multimeter

b) Analog Multimeter

I-1. The Voltmeter

A voltmeter measures voltage U, which is expressed in volts (V).

Here is what a voltmeter looks like:

Figure IV.2 Multimeter Set as a Voltmeter

I-2. The Ammeter

An ammeter measures current i, whose unit is the ampere (A).

Here is what an ammeter looks like:

Figure IV.3 Multimeter Set as an Ammeter

I-3. Types of Multimeters

A multimeter (sometimes called a universal tester) is a combination of electrical measuring devices grouped into a single unit, typically consisting of a voltmeter, an ammeter, and an ohmmeter. It measures voltage, current, resistance, etc.

I-4. Characteristics of a Multimeter

- ✅ ***Characteristics of an Analog Multimeter***
- ✅ ***Accuracy:*** approximately 2% for voltmeters, 3% for ammeters, and 5% for ohmmeters.
- ✅ ***Measurement range:***
- ✅ ***Maximum****: 300V or 1000V, 10A, 100MΩ*
- ✅ ***Minimum:*** *3µV or 10µV, 30pA, 1Ω*
- ✅ ***Response time***: The time required for the needle to reach its final deviation within 5% accuracy is about 1 second, but it can take up to ten seconds for lower ranges.

Input resistance: 100kΩ to 100MΩ.

- ✅ ***Characteristics of a Digital Multimeter***
- ✅ ***Accuracy:*** approximately 2% for voltmeters, 3% for ammeters, and 5% for ohmmeters.
- ✅ ***Measurement range:***

***Maximum**: 300V or 1000V, 10A, 100MΩ*

***Minimum:** 3µV or 10µV, 30pA, 1Ω*

- ✅ ***Response time***: Similar to analog multimeters, the time required for the needle to reach its final deviation within 5% accuracy is about 1 second, but it can take up to ten seconds for lower ranges.
- ✅ ***Input resistance*** *:* 100kΩ to 100MΩ, depending on the range, in voltmeter mode.
- ✅ ***Adjustments:***
  - ❖ Mechanical zero adjustment must be done without voltage.
  - ❖ Electrical zero adjustment must be performed under voltage once thermal equilibrium is reached (about 30 minutes).
  - ❖ Full-scale adjustment must be done under voltage after the previous two adjustments.
- ✅ ***Bandwidth***: Every measuring device has a defined bandwidth that must be respected.

Example: 10Hz - 10MHz

A 2Hz signal causes the needle to oscillate.

A 20MHz signal also produces an indication.

However, in both cases, the measurement is not reliable.

II - Spectrum Analyzer

A spectrum analyzer is a measuring instrument designed to display a signal in the frequency domain, unlike an oscilloscope, which displays the signal in the time domain. The signals can be of various types: electrical, optical, sound, or radiofrequency.

Figure IV.4: Spectrum Analyzer

II-1 Classification

❖ Classification by Type of Measurement

➢ ☑ ***Electrical Spectrum Analyzer***

An electrical spectrum analyzer measures the voltage of electrical signals in the frequency domain. The measurements can range from a few tenths of a hertz (Hz) to several hundred gigahertz (GHz).

Figure IV.5: Spectrum Analyzer Display

➢ ☑ ***Network Analyzer***

A network analyzer is an electrical spectrum analyzer equipped with a signal generator, allowing for frequency analysis of transmission lines. However, it does not allow the analysis of wireless networks.

➢ ☑ ***Electromagnetic Field Analyzer***

An electromagnetic field analyzer measures magnetic and electric fields emitted by electronic equipment, ensuring compliance with electromagnetic compatibility (EMC) standards.

An electromagnetic field analyzer consists of two sensors:

1. One for measuring the electric field in air (in V/m).
2. One for measuring the magnetic field (typically in µT/m).

Figure IV.6 Electromagnetic Field Analyzer (800 MHz – 2,500 MHz) by GigaHertz Solutions, Model HF 32D.

Uses of an Electromagnetic Field Analyzer It is generally used for:

- Qualifying electronic devices or electrical systems in accordance with electromagnetic compatibility (EMC) standards.
- Measuring the field produced by a radio antenna.
- Adjusting a radio antenna.

➢ ☑ **Spectrometer**

A spectrometer is a measuring device that decomposes an observed quantity—such as a beam of light in spectroscopy or a mixture of molecules in mass spectrometry—into its basic components, forming its spectrum.

In optics, a spectrometer identifies the specific wavelengths that make up a light beam (**electromagnetic spectrum**). In the case of a chemical mixture, it determines the specific masses of each molecule (**mass spectrum**). Spectrometers are also used in acoustics to analyze the composition of a sound signal. In general, the study of spectra is called **spectrometry**.

Various types of spectrometers are used:

- ☑ **Electromagnetic spectrometer** (infrared spectrometer, spectrofluorimeter, X-ray spectrometer);
- ☑ **Mass spectrometer**;
- ☑ **NMR spectrometer** (Nuclear Magnetic Resonance spectrometer).

Figure IV.7 Pocket Spectrometer

Figure IV.8 Spectrometer

➢ ☑**spectrogram:**

A spectrogram (also known as a **sonogram**) is an audio spectrum analyzer that displays sound variations over time. It represents **time** on the x-axis and **frequencies** on the y-axis. The color of each point depends on the power of a frequency band at a given moment. Spectrograms are commonly used for: [19]

- ☑Musical analysis.
- ☑Voice recognition and vocal signature analysis.

A spectrogram visualizes three key parameters in a two-dimensional diagram:

1. ☑Time.
2. ☑Frequency.
3. ☑Sound intensity (power).

❖ Classification by Processing Type

1. ***Swept-Tuned Spectrum Analyzer***

A swept-tuned spectrum analyzer measures the frequency distribution of a signal by analyzing each frequency separately. The principle involves either using a sliding band-pass filter (Tuned-filter spectrum analyzer) or multiplying the signal with a variable frequency oscillator (Heterodyne spectrum analyzer).

2. ***Real-Time Spectrum Analyzer***

A real-time spectrum analyzer simultaneously converts a signal within a frequency band. Parallel filter analyzers use multiple band-pass filters, each with a different frequency. FFT

analyzers convert the digitized signal into the frequency domain using a mathematical transformation called the Fast Fourier Transform (FFT), derived from the discrete Fourier transform equations.

II-2 Understanding Spectrum Analyzers

Spectrum analyzers are essential instruments in electronics and communications. They enable engineers and technicians to visualize and measure the spectral composition of a signal. In this section, we will explore the fundamentals of these valuable tools by examining their operation and main applications.

A spectrum analyzer captures electrical signals and breaks them down into their frequency components. This decomposition is crucial for understanding signal behavior in various environments and applications. For example, in telecommunications, spectrum analyzers are used to measure signal quality and detect interference.

II-3 Types of Spectrum Analyzers

There are several types of spectrum analyzers, each designed for specific needs. The most common are analog and digital spectrum analyzers.

- ☑ ***Analog Spectrum Analyzers***: These use filters and electronic circuits to analyze signals. Although they are less precise than their digital counterparts, they are often preferred for their fast response time and ease of use.
- ☑ ***Digital Spectrum Analyzers***: These rely on digital signal processing (DSP) technology for more accurate and detailed analysis. They are particularly useful for analyzing complex signals and modern communication systems.

II-4 Applications of Spectrum Analyzers

Spectrum analyzers are used in a wide range of fields:

Telecommunications*:* Monitoring signal quality, identifying sources of interference, and optimizing system performance. ***Research and Development***: Essential for characterizing new electronic devices such as oscillators and amplifiers. ***Audio Engineering***: Used to visualize and adjust sound spectra, which is crucial for mixing and music production. ***Security and Surveillance***: Helps detect and analyze unauthorized or suspicious signals.

II-5 Choosing the Right Spectrum Analyzer

Selecting an appropriate spectrum analyzer depends on several factors, including: Required frequency range, Precision and resolution, Budget. For general applications, a standard digital spectrum analyzer may be sufficient. However, for high-precision measurements, particularly at higher frequencies, a more advanced model may be required.

It is also important to consider:

User interface: An intuitive interface improves ease of use.

Connectivity options: Features such as USB, Ethernet, or Wi-Fi can greatly enhance usability and integration with existing systems.

Conclusion

In conclusion, spectrum analyzers are powerful and versatile tools in electronics and communications. Their ability to break down and analyze the frequency components of signals makes them indispensable across various applications, from communication system design to music production.

Choosing the right spectrum analyzer, combined with proper usage and maintenance, allows users to maximize the potential of this essential technology. Whether you are an experienced professional or a beginner, understanding and effectively using a spectrum analyzer can open up a world of possibilities in exploring and manipulating electronic signals.

III - Reflectometer

A time-domain reflectometer (TDR) is an electronic measuring instrument used to characterize and locate faults in metallic cables (twisted pair, coaxial cable, etc.) and, in the optical domain, optical fibers. It can also be used to detect discontinuities in a connector, a printed circuit board (PCB), or any electrical circuit. Additionally, it is used to measure the speed of an approaching train at a railway crossing to avoid unnecessarily prolonged closures if the train is relatively slow. The equivalent device for optical fibers is an optical time-domain reflectometer (OTDR).

Figure IV.9 Image of a Time-Domain Reflectometer (TDR)

III-1 Description

A time-domain reflectometer emits a very fast-rising pulse into the conductor. In the case of an impedance-matched line, the transmitted pulse will be fully absorbed at the end of the line, and no signal will be reflected back to the time-domain reflectometer. Any impedance discontinuity will result in a portion of the incident signal being reflected toward the source, similar to the principle of radar.

An increase in impedance creates a reflection that reinforces the original pulse, while a decrease creates a reflection that opposes the original pulse.

The resulting reflected pulse is measured at the input/output of the time-domain reflectometer and displayed or plotted as a function of time. Since the propagation speed of the signal is relatively constant for a given material, it can be viewed as a function of cable length.

Due to this sensitivity to impedance variations, a time-domain reflectometer can be used to verify cable impedance characteristics, splice and connector locations, associated losses, and cable length estimation.

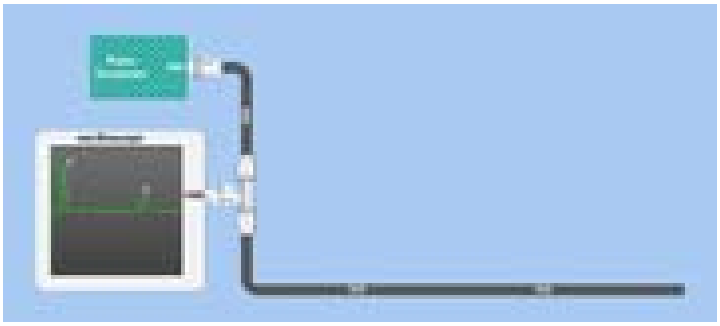


Figure IV.10 Simple TDR Made from Laboratory Equipment

Figure IV.11Simple TDR Made from Laboratory Equipment

III-2 Reflectometry: Principles, Applications, and Uses

At the heart of modern technologies, an often-overlooked technique reveals the secrets of optical and electrical infrastructures. This method, which allows for the internal probing of cables without damaging them, is a valuable tool for preventive maintenance and network diagnostics.

Thanks to this technique, hidden anomalies become visible, ensuring the reliability and performance of communication systems. By skillfully employing a reflectometer, faults can be detected with precision and speed. Mastering reflectometry thus opens new opportunities to optimize resource utilization and enhance industrial applications based on well-established scientific principles.

In practice, reflectometry operates by sending a test signal into the system under examination. This signal travels through the medium until it encounters a discontinuity or a physical variation, causing partial reflection back to the source. Analyzing this reflected signal helps determine the nature and location of existing anomalies. The obtained information can then be used to diagnose and resolve identified problems. Concrete applications of this technique include:

- ☑ Detection of breaks in electrical cables
- ☑ Identification of faults in optical fibers
- ☑ Localization of short circuits in printed circuit boards
- ☑ Detection of corrosion in pipelines
- ☑ Evaluation of the structural integrity of composite materials

III-3 Different Types of Reflectometry

Among the methods used for system and material analysis, time-domain reflectometry (TDR) and frequency-domain reflectometry (FDR) stand out for their specific approaches. TDR involves sending a pulse into a medium and measuring the time it takes for the signal to return, allowing the detection of anomalies such as faults or internal discontinuities. This technique is particularly effective for precisely locating problem areas in cables or electronic circuits. Conversely, FDR analyzes a system's frequency response by subjecting the medium to various frequencies, providing a comprehensive view of material characteristics over a given frequency range. This method is preferred for identifying subtle variations in medium properties, useful in various applications. [19]

A comparative analysis of TDR and FDR highlights the advantages of each for specific applications. TDR is ideal for quick and precise analysis of defect locations in linear supports such as electrical cables, thanks to measuring the reflection time of pulses. FDR, on the other hand, offers a detailed evaluation of the system's frequency response, necessary for characterizing materials or devices sensitive to frequency variations. Thus, the choice between these two techniques largely depends on the specific analysis requirements and the characteristics of the medium under study.

Type of Reflectometry	Principle	Application Domains
Time-Domain Reflectometry (TDR)	Measures the return time of pulses to detect anomalies.	Cable diagnostics, fault localization, electronic circuits.
Frequency-Domain Reflectometry (FDR)	Analyzes frequency response to characterize materials.	Optical fiber studies, coating evaluation, sensitive material measurements.

III-4 Applications of Reflectometry in Cables and Optical Fibers

In telecommunications, reflectometry is used for cable diagnostics. This technique enables the inspection of line integrity and the identification of potential failures that could impact service quality. Professionals specifically use OTDR (Optical Time-Domain Reflectometer) to analyze optical fibers, a valuable tool for detecting insertion losses, excessive reflections, and network breaks.

The use of reflectometry is an asset for infrastructures in terms of fault detection. By identifying anomalies before they cause failures, targeted interventions can be planned,

avoiding costly service interruptions. This proactive approach helps improve network reliability and ensures optimal service continuity for users, promoting effective preventive maintenance.

- ✅ Quick identification of breakpoints in optical fibers.
- ✅ Precise localization of faults in electrical cables.
- ✅ Efficient planning of preventive maintenance operations.
- ✅ Improved network reliability and reduced downtime.

IV - Optical Fiber Tester

The concept of optical fiber testing encompasses all procedures, tools, and standards used to test optical components, fiber optic links, and deployed optical networks. This includes optical and mechanical tests for each distinct element, as well as global transmission tests to verify the integrity of complete optical network installations.

Fiber optics has become the primary transport medium for global communications due to three distinct advantages over copper infrastructures: reduced operational costs (power and maintenance), reliability (fiber optic cables are immune to electromagnetic and radio frequency interference), and high bandwidth/transmission speeds. The growing diversity of fiber optic applications and point-to-point (PTP) and point-to-multipoint (PTMP) architectures has highlighted the need for technician training and versatile, user-friendly testing solutions.

Figure IV.12: Optical Fiber Tester

IV-1 Why Conduct Tests?

Market performance standards, service level agreements, and warranty requirements make optical network testing inevitable, but there are many other good reasons to test and monitor network performance. Currently, the objective of testing is to maximize the performance of optical network assets in terms of bandwidth, reliability, and return on investment.

The market demand for bandwidth has led to increased optical network size and complexity. Passive optical network (PON) architecture, dense wavelength division multiplexing (DWDM), and other innovations such as coherent optical modules have introduced even more cable segmentation and specific components that may increase additional attenuation risks. At the same time, performance requirements have risen while budgets have decreased. Detailed and precise fiber optic testing at all levels and throughout all phases of the network lifecycle ensures customer satisfaction and secures a competitive advantage.

IV-2 The Three Components of an Optical Fiber

The three basic elements of an optical fiber for fiber testing are as follows:

- ***Core**:* The center of the optical fiber cable, made of specially treated glass or plastic. It is used to transmit light along the entire length of the cable and must therefore be as pure and clean as possible.
- ***Cladding:*** An additional layer made of a material similar to that of the core but with a lower refractive index to facilitate the continuous reflection of the optical source back into the core.
- ***Coating*:** The outer layer of the cable that encloses, protects, and insulates the core and cladding.

IV-3 Types of Optical Fiber

Optical fiber is classified into different types (multimode or single-mode) based on how it allows light to travel. The type of fiber is closely related to the diameter of the core and cladding. Multimode fiber has a larger core diameter, which allows multiple modes of light to travel simultaneously.

Multimode fiber offers several advantages, including lower cost and simpler coupling to transmitters and receivers. However, its high attenuation (optical loss) and limited bandwidth restrict transmission to short distances.

Single-mode fiber is favored for its superior performance in terms of bandwidth and attenuation. Due to the small size of its core, single-mode fiber requires more expensive transmitters and alignment systems to achieve efficient connector coupling. Nevertheless, for high-performance systems or those spanning more than a few kilometers, single-mode fiber remains the best option.

IV-4 Methods

To evaluate the quality of an optical fiber installation, approve its commissioning, and ensure the reliable long-term operation of a fiber optic link, certain tools and testing methods must be employed.

Several important elements must be measured, evaluated, and controlled:

IV-4.1 Inspection of Optical Connectors

When two optical fibers are coupled, it is crucial to ensure that light passes from one fiber to the other without loss or excessive backscattering. In the field, however, it is difficult to keep connectors clean and free from scratches. A single particle on the center of the fiber can cause significant insertion loss, backscattering, and even damage to the equipment. Proactive inspection of optical connectors is essential to ensure the reliability of connections between two fibers.

IV-4.2 Optical Fiber Continuity Testing

When testing fiber optic cable networks, a visible laser source connected to one end of the cable can be used to verify transmission to the opposite end. This type of fiber optic test is solely intended to detect major fiber anomalies, such as breaks. Optical fiber continuity tests can also determine whether the correct fiber optic cable is connected to the correct patch panel.

A fiber identifier (FI) is a convenient portable fiber optic testing tool capable of identifying and detecting optical signals from the outside at any point along the fiber optic link. Fiber identifiers can confirm the presence of traffic on a fiber optic cable as well as the direction of transmission.

A visual fault locator (VFL) uses a visible spectrum laser light to test fiber optic continuity and detect faults. The red optical source is visible through the coating wherever a fiber break, splice defect, or macro bend occurs. [19]

IV-4.3 Optical Loss Measurement

When light travels through an optical fiber, its power decreases. This reduction in power, also called optical loss, is expressed in decibels (dB). The most accurate way to measure the total optical loss of a fiber using a tester is to inject a known level of light at one end and measure the light level at the other end using an OLTS (Optical Loss Test Set). The attenuation is the difference between the source power and the received power. Since the optical source and

the power meter are connected to opposite ends of the link, this method requires access to both ends of the fiber optic cable.

IV-4.4 Optical Power Measurement

A power measurement is a test of the signal strength from the transmitter once the system is activated. An optical power meter displays the optical power received on its photodiode and can be directly connected to the output of the optical transmitter or to the location where the optical receiver would be on a fiber cable. The unit of measurement for optical power is dBm (absolute value), where "m" stands for 1 milliwatt and "dB" (used when a reference level is defined) refers to decibels.

IV-4.5 Testing Optical Fiber to Measure Optical Loss

To measure the optical loss of a fiber, fiber optic testers must connect to a test source to provide a standard optical light level, as well as to a launch reel to provide a calibrated "0 dB loss" reference. A power meter at the opposite end of the circuit measures the optical source with and without the fiber under test to quantify the fiber's loss in dB.

Other methods for testing fiber optic cable connections use a launch reel and a receive reel connected to the power meter. This type of method is the standard for optical loss testing on a cabled installation and includes loss measurements at both ends of the tested cable. This is why it is important to ensure that all optical connectors are impeccably clean.

It is also possible to use an Optical Time Domain Reflectometer (OTDR) to test the optical loss of a fiber. Using a high-intensity laser light emitting at a predefined pulse interval connected via a patch cord or launch reel to one end of the fiber optic cable, the OTDR analyzes the backscattered light returned to the source. [19]

I-Introduction

At a time when communication and technology are the key pillars of our society, there is no doubt that the future of computer networks is to grow and develop. This future is largely linked to the techniques and communication media used in these networks. Currently, the trend is towards digital transmission and the use of wireless communication. Additionally, current technology allows for increased volumes and transfer speeds of data while reducing costs. Network interconnections are countless, and practically all networks today are intertwined with one another. In particular, the Internet is the unifying network for the world's networks. Trend analysis shows that mobile networks could become predominant in voice transmission, leaving high-speed data transfer to fixed networks. [19]

The integration of local and long-distance networks into the company's information and communication system has led to the concept of the corporate network, where users can access all computer resources through the real distribution of applications. Connecting a company's network to the Internet makes all its computers vulnerable to intrusions. It forces the company to adopt stringent security procedures for all users, especially when mobile computers, located outside the company, wish to use the network via the Internet to access certain services.

However, the explosive development of the Internet should not obscure the fact that it is an uncontrolled system. Previously subsidized by research and universities, the Internet is now accessible to everyone; the best coexists with the worst and, too often, with the mediocre. Censorship does not exist, as all possible topics are addressed and made available to all, without any restraint. The exponential growth in the number of computers connected to the Internet raises new issues: the IP address plan is reaching saturation, and available addresses are running out. A new version of IP, called IPv6 (IP version 6), which provides a much larger addressing field to cope with this explosion of connection demands, is gradually being implemented. It also seeks to introduce elements of authentication and confidentiality, topics not addressed in previous versions of IP.

It can therefore be stated that computer networks represent a very important economic focus at the beginning of this third millennium. Technological changes follow

one another, and the search for new products with ever-higher performance is ongoing.

The constant evolution of a computer network requires, on the one hand, a management and administration tool, and on the other hand, tools for measuring the quality of physical media, traffic analysis, information consistency analysis, and diagnostics. There are different systems for collecting information, which will then be processed and presented in the most user-friendly way possible.

The technical, economic, and geographical environments, along with the growth of information flows, lead to minor or major modifications to existing networks. It is therefore up to network managers to continuously monitor the proper flow of information as well as the quality of this flow. Indeed, the complexity of architectures, the heterogeneity of equipment and protocols, can cause difficulties in analyzing problems. The fact that the exact path of communication is not always known increases this complexity. The resolution times for dysfunctions can be incompatible with the ones required by users. Therefore, it is essential to prevent potential issues (compliant installations and alarm thresholds), detect them when they arise (alarms), and correct them as quickly as possible (analysis and diagnosis).

II. Cable Testers

Often used for maintenance or certification of a cabling installation, cable testers detect problems at the physical layer of the OSI model. Their primary role is to measure the quality of the signal (measuring crosstalk on twisted pairs, noise, impedance, etc.) on the physical medium. They can check cables of different types: fiber optic, twisted pairs, and coaxial cables.

Figure V.1: Example of a cable tester.

A network cable tester allows field technicians to effectively monitor network activity, troubleshoot and diagnose potential problems, and ensure reliable connections for data transmission. Understanding the needs of your network, considering factors such as accuracy, reliability, and key features, will help you choose the best cable tester to support your system infrastructure.

II-1 Solutions for Common Problems

There are many reasons why network cables fail—from defective installation or signal transmission problems to general wear and tear or cable twist. However, with regular maintenance, you can identify common and complex network issues with the push of a button, well before they become major problems.

Network testers are essential for troubleshooting copper and fiber cables used in voice, data, and video installations. Portable network testers help find and resolve many network connectivity problems and provide quick and simple solutions to reduce downtime. These intuitive and user-friendly devices conduct in-depth diagnostic tests, analyze the transmission capabilities of copper and fiber optic cables, and produce quick and accurate results. Test results are displayed on the unit's interface or even remotely transmitted to network managers, so immediate actions can be taken to resolve any issues.

II-2 Range of Network Testers and Their Functions

Network cable testers are divided into three categories. Validation testers examine the connectivity of individual wires; qualification testers assess the quality of cables and their ability to support the required bandwidth and transmission speed; certifiers ensure that your network infrastructure complies with industry standards. Network cable testers are also used to test twisted-pair data cables to support Ethernet applications.

Some network testers perform more than one function. It's important to be aware of your equipment's limits and performance parameters to ensure that you can provide comprehensive maintenance service.[19]

II-3 Validation Network Cable Testers

Validation testers examine the connectivity of individual wires. An electrical pulse is sent along the wire to identify errors such as breaks, short circuits, or wiring patterns that may affect network connectivity. More sophisticated validation testers use Time Domain Reflectometry (TDR), which involves transmitting an electrical pulse through an open or unfinished cable at the endpoint. This allows the unit to measure and interpret electrical reflections to find defects, locate their location, and determine the cable's length.

II-4 Qualification Testers

The cabling must be of sufficient quality to provide the required bandwidth and ensure that data can be transmitted without error. Qualification testers assess the ability of wired networks to carry data at a particular speed and throughput without error. To generate and measure the transmission rate, two testers are needed at each end of the network. A pre-configured rate of network traffic is generated in both directions and measured at each end. Running a test over an extended period (usually more than 24 hours) helps identify intermittent issues and noise events that may disrupt network traffic.

Other qualification testers measure electrical signal parameters such as insertion or return loss, near and far-end crosstalk, and compare them with specific wiring standards to assess effectiveness. Some also include basic cable validation functions.

II-5 Certification Testers

All wired networks must comply with industry standards. Certification testers compare specific electrical signaling and parametric measurements with requirements defined by Ofcom to determine compliance with TIA, IEC, and ISO standards. Test results show whether the network meets or fails the relevant standards.

Conclusion:

As maintenance devices often used in heterogeneous environments by time-pressed users, cable testers are highly ergonomic and simple to use. Manufacturers have maintained these advantages while incorporating more advanced features into these devices. Today, protocol analyzer functions are built into these devices, allowing for the practical placement of testers/analyzers on each network segment. However, these

testers/analyzers are limited in the number of supported protocols and are often dedicated to one type of network (e.g., Ethernet). They do not have the storage capacity or processing power of full-fledged protocol analyzers.

III. Protocol Analyzers

IT administrators must ensure the reliability and resilience of the organization's network as the complexity of modern networks continues to grow. From the adoption of hybrid infrastructures to maintaining security across multi-cloud environments, and managing the ever-increasing demand for bandwidth, managing enterprise networks is becoming more challenging. This requires a solution that gives organizations control and visibility over the entire infrastructure while offering the advantage of scaling as the organization grows.

III-1 What is a Protocol Analyzer?

In a dynamic network environment, common problems can go unnoticed for an extended period due to a lack of visibility, which can significantly impact the network's performance and security. Protocol analyzers are tools that analyze network traffic to help administrators identify persistent issues in a network and facilitate the troubleshooting process. These tools can identify the type of traffic and analyze its context to understand which traffic is business-related and which may pose a threat, helping to secure the network from malicious attacks.

Protocol analyzers capture data packets flowing across the network and provide traffic insights in the form of charts and diagrams. They visualize the entire infrastructure, pinpoint the root cause of a problem, and send alerts if abnormal traffic behavior is detected.

III-2 How Do Protocol Analyzers Work?

There are two main types of protocol analyzers widely used: ad-hoc analysis and packet capture. Ad-hoc analysis involves capturing packets and filtering traffic parameters by analyzing a specific segment. Packet capture, on the other hand, involves collecting all traffic 24/7 to identify performance or security bottlenecks. While packet capture is an effective method, it may incur additional storage costs, as it captures both packet headers and payloads.

III-3 Why Choose a Protocol Analyzer?

When an entire packet is captured, storing raw data can increase storage needs. As a result, organizations must invest more in their storage capacity and allocate more bandwidth to data analysis. While packet capture devices are connected to the network, analysis uses a centralized server that displays all necessary information, such as the origin of most data, specific devices connected to the network, the frequency of communication, and details about the port and protocol.

III-4 Different Categories

There are generally two main categories of protocol analyzers: ad-hoc protocol analysis tools and enterprise protocol analysis tools.

Ad-hoc protocol analysis tools are primarily used to troubleshoot or analyze a specific problem and can be implemented at little cost or even for free with minimal planning or technical expertise. However, they are more suitable for targeted analysis (such as a specific protocol or host) and are not ideal for monitoring an entire network over an extended period. Enterprise analysis tools, on the other hand, are better suited for monitoring the entire enterprise infrastructure 24/7 and offer options for scheduling various alerts when the network is under threat.

Ad-hoc Protocol Analysis

Security professionals sometimes need a protocol analyzer to troubleshoot network issues, such as authentication failures, or to confirm that encryption is sufficient. In the past, there was fierce competition among ad-hoc protocol analysis tools to attract security professionals (and network administrators). However, WireShark (formerly Ethereal) has dominated the space to the point that many other tools (including Microsoft Network Monitor) have been abandoned.

The two most important characteristics of an ad-hoc analysis tool are flexibility and ease of use. WireShark is capable of filtering packets during capture or analysis, at various complexity levels, making it suitable for both beginners and seasoned professionals. Since it is open source and available on all major platforms, it enjoys strong community support. Cost is not a barrier, and training resources are easily accessible. Another advantage of WireShark is its ability to ingest and analyze traffic

captured from other protocol analysis tools. Thus, it is easy to review network traffic at any point in history (provided that traffic has been captured) without additional cost.

Conclusion:

Whether for ad-hoc analysis of an issue or continuous monitoring, a protocol analyzer can be a valuable tool for security professionals. Protocol analyzers are software or computer tools used on a PC that allow administrators and IT security teams to capture network traffic and analyze the captured data to identify traffic-related issues or potential malicious activities. These traffic data can be viewed in real-time by a technician for troubleshooting, monitored by an alert tool to identify active threats, or preserved for forensic analysis in the event of a network breach. These devices allow:

- ☑ Viewing all traffic on the network segment where they are installed;
- ☑ Decoding frames based on protocols (OSI layer 1 to 4);
- ☑ Capturing frames for later interpretation or exploitation;
- ☑ Filtering frames based on various criteria such as protocol type, frame size, source and/or destination addresses;
- ☑ Generating traffic from frame models, or reissuing previously captured frames to replay scenarios;
- ☑ Setting alarm thresholds.

IV. Frame Analyzers (Sniffers)

The first tools that allowed system administrators to analyze computer networks and pinpoint problems with precision were sniffers. These tools are also within reach of hackers, who use them to spy on computer networks and steal various types of data.

IV-1 Network Analysis

A "network analyzer" (also known as a frame analyzer or, in English, a sniffer) is a device that "listens" to network traffic, meaning it captures the information flowing through it. The term "sniffer" is more popular than other terms like "protocol analyzer" or "network analyzer."

A sniffer is a program that allows capturing all packets traveling on a network and editing their contents. It can capture any information sent through a local network,

including users' identities and passwords transmitted by any unencrypted data service, such as Telnet, DNS, SMTP, POP3, FTP, and HTTP. If the data is not encrypted and passes through the network interface of the machine running the sniffer, it captures and displays them for direct reading.

IV-2 Sniffer Using

A sniffer is an excellent tool for studying network traffic. It is generally used by administrators to diagnose network problems and understand the traffic flowing through it. Intrusion detection systems (IDS) are based on sniffers for packet capture and use a rule database to detect suspicious frames.

Unfortunately, like all administrative tools, the sniffer can also be used by a malicious person with physical access to the network to collect information. This risk is even higher on wireless networks, as it is difficult to contain radio waves within a defined area, allowing malicious actors to listen to traffic simply by being nearby.

The vast majority of Internet protocols transmit information in plain text, meaning unencrypted. Thus, when a network user checks their email using POP or IMAP, or browses a website with an address that does not begin with HTTPS, all information sent or received can be intercepted. This is how hackers have developed specific sniffers to capture passwords circulating on the network.

IV-3 Countermeasures

There are several ways to protect against the issues that might arise from a sniffer being used on your network:

- ✔ Use encrypted protocols for all communications containing sensitive data.
- ✔ Segment the network to limit the spread of information. It is particularly recommended to prefer switches over hubs because switches route communication, meaning information is only delivered to the intended machines.
- ✔ Use a sniffer detector. This is a tool that scans the network for devices using promiscuous mode.

For wireless networks, it is recommended to reduce the power of equipment so

that it only covers the necessary area. This doesn't stop potential hackers from listening to the network, but it reduces the geographical range within which they can do so.

IV-4 Who Uses Sniffers and Why?

- ☑ LAN/WAN administrators use sniffers to analyze network traffic and help identify problems on the network.
- ☑ A security administrator might use sniffers strategically placed throughout the network as an intrusion detection system.
- ☑ They are also one of the most common tools used by hackers.

IV-5 How can a network be spied on using a sniffer?

The vast majority of Internet protocols transmit information in an unencrypted form. Therefore, when a network user checks their email via the POP or IMAP protocol, or opens a website with an address starting with HTTP, all the information sent or received can be intercepted.[19]

I- Example of Measurement for Mobile Telephony

I-1 Mobile Telephony

Mobile telephony, or cellular telephony, is a means of telecommunication, more specifically radiocommunication, through mobile phones. This means of communication became widely spread in the late 1990s. The associated technology benefits from improvements in electronic components, particularly their miniaturization, which allows phones to acquire functions that were previously reserved for computers. [20]

Figure VI.1 A Sagem My700xi mobile phone released in 2007.

I-2 The Network

Mobile telephony is based on radiocommunication, which means the transmission of voice and data using radio waves (frequencies in the UHF bands ranging from 700 to 2,600 MHz) between a base station that can cover an area with a radius of several tens of kilometers and the user's mobile phone.

The first mobile systems operated in analog mode. The terminals were large in size, only usable in cars where they took up part of the trunk and used the vehicle's power supply.

Modern mobile systems operate in digital mode: voice, like data, is sampled, digitized, and transmitted as bits, then synthesized upon reception. Advances in microelectronics have allowed mobile phones to shrink to pocket size. The advantages of digital systems include lower terminal prices, a greater number of services, an increase in the number of subscribers, and better voice reception quality.

Transmission bases are spread across the territory in a cellular scheme. In GSM/GPRS technology (2G), each antenna uses a frequency group different from its neighbors. The same frequencies are only reused at a sufficient distance to avoid interference. [20]

To know which relay antenna to direct an incoming call to, the mobile network periodically exchanges location information with mobile phones in the form of signaling messages.

Figure VI.2 : Relay Antenna

I-3 Radio Communication Standards

I-3.1 Network Standards

Since 1976, the various standards used for mobile telephony have been:

1G:

- ***Advanced Mobile Phone System (AMPS)***: First-generation analog standard deployed in the United States starting in 1976.
- ***Nordic Mobile Telephone (NMT):*** Analog standard primarily introduced in Europe in the early 1980s.
- ***Radiocom 2000***: First-generation (1G) analog standard deployed in France by France Télécom starting in 1986.

2G:

- ***Global System for Mobile Communications (GSM)***: Second-generation (2G) digital standard developed by ETSI and commercialized in the early 1990s in the 900 MHz frequency range. A variant called Digital Communication System (DCS) uses the 1,800

MHz range. This standard is particularly used in Europe, Africa, the Middle East, and Asia.

- ***Code Division Multiple Access (CDMA):*** Second-generation standard primarily used in North America and derived from the ANSI-41 standard, with patents owned by the American company Qualcomm.
- ***General Packet Radio Service (GPRS):*** Standard derived from GSM that allows for higher data rates. It is often referred to as 2.5G.
- ***Enhanced Data Rates for GSM Evolution (EDGE):*** Standard derived from GSM that enables higher data rates for stationary users. It is often referred to as 2.75G because it is an evolution of GPRS. [21]

3G:

- ***CDMA 2000:*** Third-generation (3G) evolution of the CDMA standard (incompatible with UMTS), primarily deployed in North America.
- ***Universal Mobile Telecommunications System (UMTS)*** or Wideband Code Division Multiple Access (WCDMA): Third-generation evolution of GSM (incompatible with CDMA-2000), supported by Europe and Japan, but also deployed elsewhere in the world, including in Africa, China, Canada, and the United States.
- ***High Speed Downlink Packet Access (HSDPA):*** Evolution of 3G, often called 3G+ or 3.5G, capable of reaching a maximum download speed of 14.4 Mbps.
- ***High-Speed Uplink Packet Access (HSUPA):*** Improvement of 3G+ (3.5G) data upload speeds (packet-mode data upload from terminal to operator) that improves the quality of services like video calls.
- ***HSPA+:*** High Speed Packet Access+: Evolution of HSUPA and HSDPA towards download speeds of 21 Mbps and 42 Mbps (in Dual Cell HSPA+ mode) and potentially 84 Mbps (in DC + MIMO 2x2 mode).

4G:

- ***LTE ("Long Term Evolution"):*** LTE, initially considered a "pre-4G" standard (3.9G), is now marketed as "4G"; since October 2010, the ITU has officially recognized LTE as a commercial "4G" standard. The download speed (in 2013) can theoretically reach 150 Mbps with compatible terminals.

- ***LTE Advanced:*** An evolution of the LTE standard towards higher speeds, while maintaining backward compatibility with LTE terminals. Initial deployments began in 2014 in some countries. Download speeds can exceed 1 Gbps thanks to carrier aggregation, provided the operator has enough frequency bands.
  - 5G: First commercial networks in 2020.

I-3.2 Ancillary Standards

- ***i-mode***: A protocol that connects mobile phones to the internet. The language used for sites is a modified version of HTML called C-HTML.
- ***Multimedia Messaging Service (MMS):*** A multimedia messaging service for mobile phones.
- ***Personal Ring Back Tone (PRBT):*** A service that allows subscribers to replace their usual waiting ringtone with music.
- ***Short Message Service (SMS):*** A messaging service for mobile phones, allowing the sending of text messages with a maximum of 160 characters. This channel can also be used to transfer data (business cards, application data for SIM cards, ringtones, logos, etc.).
- ***Wireless Application Protocol (WAP):*** An extension of the GSM protocol that connects mobile phones to the internet. However, the language used for WAP sites employed a specific markup language, Wireless Markup Language (WML), which led to its gradual abandonment in favor of the HTML language used by smartphones.

I-3.3 Standards Generations

Table VI.1: Main Mobile Telephony Standards Used in Europe

Generation	Acronym	Title
1G	Radiocom 2000 NMT	Radiocom 2000 Nordic Mobile Telephone
2G	GSM CDMA	Global System for Mobile Communication Code Division Multiple Access
2.5G	GPRS	General Packet Radio Service
2.75G	EDGE	Enhanced Data Rate for GSM Evolution
3G	CDMA 2000 1x EV UMTS, WCDMA	Code division multiple access 2000 1X Evolution Universal Mobile Telecommunications System
3.5G	HSDPA HSUPA	High Speed Downlink Packet Access High Speed Uplink Packet Access
3.75G	HSPA+	evolution du « High Speed Packet Access »
4G	LTE WiMAX	Long Term Evolution Worldwide Interoperability for Microwave Access
4G+	LTE Advanced	Perfectionnement of « Long Term Evolution »

GPRS and EDGE are used solely for data exchange and not for voice.

I-4 Usage

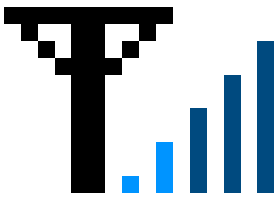
I-4.1 Smartphone

In 2007, the number of mobile phone subscribers exceeded the number of fixed phone lines in 191 countries and territories out of a total of 197 for which data was available. The exceptions were Cuba, American Samoa, Kiribati, Turkmenistan, Myanmar, and Vietnam. However, caution is required when making such comparisons: fixed phones are often shared by more people than mobile phones, and more people now own multiple active mobile phones. Data on the percentage of a given age group ("excluding babies") with access to a private fixed phone, a private mobile phone, or both is still quite rare.[21]

According to the International Telecommunication Union, 4 billion mobile phone subscriptions were registered by the end of 2008, representing 60% of the global population. More and more people are subscribing to multiple plans simultaneously. The use of mobile phones has surged in the poorest countries, where the fixed telephone network is often in its early stages. In 2008, three out of four subscriptions (three billion) were taken out in developing countries, compared to one in four in 2000.

I-4.2 Mobile Phone Signal

✅ The mobile phone signal "A" (or "reception") is the strength of the signal (measured in dBm) received by a mobile phone from the mobile network it is connected to. It varies depending on various factors, such as the proximity of the transmitting station, obstacles like buildings (walls, elevator shafts), trees, or terrain. Most mobile devices that use radio waves display signal strength using a set of bars of different heights, indicating the signal strength at the device's location. Traditionally, five bars are used.



📌 ***Figure VI.3 : Display of 5 reception bars on a mobile phone screen***

Generally, a strong signal is easier to obtain in an urban area, where there are the most antennas, although urban areas do have some "dead zones" where reception cannot be established. In contrast, in some rural or sparsely populated areas, it is sometimes difficult to obtain a stable signal, even though mobile phone providers attempt to set up relay antennas in areas most likely to be frequented by users, such as along major highways. The goal is to limit

"white zones"; even some national parks and other popular tourist destinations, far from urban areas, now have good reception. For example, in 2014, more than 99% of the French population and over 97% of the territory were covered in 2G or 3G by at least one mobile operator.[21]

I-4.3 Improving Reception

In an area where the signal is usually stable, certain factors can interfere with reception, either making it stronger or weaker, and sometimes causing interference that prevents the phone from being used. For example, a building with thick walls can prevent a mobile phone or a cordless phone from functioning.

Many underground areas, such as tunnels and subway stations, prevent signal reception (strong attenuation due to the materials that absorb UHF waves). Additionally, weather and network traffic volume can also affect the signal strength. Some companies try to sell devices that, when installed in a mobile phone, could improve reception in a given area. However, none of these devices have been scientifically proven to be effective to date.

I-4.4 Dead Zones

The signal strength, therefore, depends on the distance between the mobile terminal and the antenna, but also on obstacles that block radio waves. Areas where mobile phones cannot transmit or receive a radio signal from a nearby mobile relay antenna (a base station or Node B) are known as "dead zones." In these areas, the mobile phone is said to be in a "non-connected" state. Dead zones are typically areas where cellular phone service is unavailable because the signal between the phone and the relay antenna is too weak or blocked by an obstacle. This usually occurs in rugged terrain, on highways, due to excessive foliage, a long distance between transmitter and receiver, or in large buildings such as factories or supermarkets.

Several factors can cause these dead zones, even in places where operators offer radio coverage, due to architecture, limited mobile network density, interference from other cellular sites, or topography. Since mobile phones rely on radio waves, and radio waves travel through the atmosphere, which can easily attenuate them (depending on weather conditions, especially rain), mobile phones can quickly show their limitations. Like other radio transmissions, mobile phone calls can be interrupted by large buildings, terrain, trees, or other obstacles.

Mobile service providers seek to improve and modernize their networks by increasing the number of antennas to minimize the risk of dropped calls, network access failures, and dead or uncovered zones.

II. IP Telephony: The Voice Communication Technology

II-1 INTRODUCTION

IP telephony is an emerging voice communication technology that is part of a turning point in the communication world. The convergence of triple play (voice, data, and video) is now one of the main challenges for telecommunications players. More recently, the internet has partially extended into the intranet of each organization, with total traffic based on IP packet network transport surpassing the traditional voice network traffic (circuit-switched network). It became clear that, in the wake of this technological advancement, operators, businesses, organizations, and providers had to introduce new voice and video services to take advantage of the unique IP transport. This led to the creation of the first version of voice over IP, called H323, in 1996. Originating from the European ITU-T standardization organization based on ISDN voice signaling (Q931), this standard has now led to numerous developments, with some new standards taking other technological directions. To standardize, protocols such as IAX, SIP, and H323 emerged, allowing IP telephony.

IP telephony (VoIP) is a modern technology that enables voice communications over data networks using the IP protocol.

Thanks to this technology, businesses can achieve significant savings by avoiding the high costs of traditional long-distance calls. IP telephony also offers increased flexibility, allowing users to make calls from any device connected to the network, whether it's a computer, an IP phone, a smartphone, or a tablet. [22]

In the constantly evolving world of communication technologies, IP telephony (Internet Protocol) has become an essential solution for businesses seeking to optimize customer relationship management. The way IP telephony works—transmitting voice over an IP network like the internet—offers remarkable flexibility and efficiency compared to traditional telephone systems.

In an age where the speed and quality of communication are key pillars of professional success, IP telephony stands out for its ability to integrate and simplify interactions within a

company. It transcends geographical barriers, allowing employees to stay connected regardless of their location worldwide.

II-2 From Traditional Telephony to IP: An Evolutionary

The transition from traditional telephony to IP telephony marks a true revolution in the world of communications. This technological evolution is not just a change in method, but a fundamental transformation in how communications are established, managed, and experienced by both businesses and customers. Let's explore the key differences and the significant advancements brought about by this evolution.

II-2.1 Technical Distinction Between Traditional and IP Telephony

Traditional telephony, also known as analog telephony or PSTN (Public Switched Telephone Network), relies on physical telephone lines and circuit-switched connections to establish communication. Each call uses a dedicated line, limiting the system's flexibility and scalability.

In contrast, IP telephony uses the Internet Protocol (IP) to transmit calls in the form of data packets. This system relies on the existing internet network or private networks, allowing easier integration with other technologies and applications. IP telephony converts voice into digital data packets that can be sent over any IP network, making the system more flexible and scalable.

IP telephony ("Internet Protocol") harnesses the full potential of high-speed internet for your communications through VoIP (Voice over IP) technology to optimize your phone system. Flexible and versatile, it provides access to useful features for improving your phone communications (call routing, voicemail, conference calls, etc.).

II-2.2 How Does IP Telephony Work?

In practice, the shift to cloud telephony involves fully dematerializing your telephony system: you make phone calls from a connected device (computer, smartphone, softphone, etc.) rather than from a landline phone. Your conversations travel through the internet, and your associated tools are hosted on servers that you connect to through the application provided by your service provider.

II-2.3 Advantages of IP Telephony Versus Traditional Telephony

1. ✅***Cost*:** IP telephony is generally more economical, especially for long-distance and international calls, as it uses the internet network to transmit calls.
2. ✅***Flexibility and Mobility***: It allows users to connect from anywhere with internet access. Employees can thus use their professional phone number anywhere in the world.
3. ✅***Advanced Features***: IP telephony integrates features such as instant messaging, video conferencing, and file sharing, offering a richer communication experience.
4. ✅***Ease of Integration:*** It easily integrates with other business systems and software, enhancing customer relationship management and internal collaboration.
5. ✅***Call Quality***: With constant technological improvements, the quality of calls in IP telephony has greatly improved, rivaling or even surpassing traditional telephony.

II-2.4 How Does IP Telephony Function?

Let's dive into the technical details to explore the inner workings of IP telephony. This technology, which has revolutionized the way we communicate, relies on specific concepts and protocols for the effective transmission of voice over digital networks. Understanding these elements is key to fully grasping how IP telephony is transforming business communications.

II-2.4.1 IP Networks

IP telephony operates over IP networks, which are computer networks using the Internet Protocol (IP) to send and receive data in the form of packets. These networks can be private, like those of a company, or public, like the internet. They offer a flexible and scalable infrastructure, essential for deploying IP telephony systems.

II-2.4.2 The TCP/IP Protocol

IP telephony uses the TCP/IP protocol for data transmission. TCP (Transmission Control Protocol) ensures that data packets reach their destination reliably and in the correct order, while IP (Internet Protocol) is responsible for routing the data packets from source to destination.

II-2.5 Establishing and Terminating a VoIP Connection

1. ✅Call Initialization: When a call is initiated, the IP phone system uses protocols like SIP (Session Initiation Protocol) to establish a session between the caller and the receiver.
2. ✅Negotiating Parameters: Both parties negotiate the call parameters, such as which codec to use for voice compression.
3. ✅Establishing the Connection: Once the parameters are agreed upon, the connection is established, and voice data can be transmitted.
4. ✅Ending the Call: At the end of the call, the session is terminated using the same protocol that was used to initiate it.

II-2.5.1 Call Transmission

Call transmission in VoIP involves converting voice into digital data packets. These packets are then transmitted over the IP network and converted back into a voice signal at the other end. This method of transmission provides greater flexibility and better bandwidth usage compared to traditional telephony. [22]

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