CHAPTER 1

FUNDAMENTALS OF FIELDBUS SYSTEMS

1 – INTRODUCTION AND INDUSTRIAL CONTEXT

1.1 Motivation and Historical Background

Before the 1980s, most industrial control systems were entirely analog.
Each sensor or actuator was connected to the controller through dedicated wiring — one pair of wires per signal.

For example:
A system with 100 temperature sensors required nearly 200 wires (plus grounding and shielding). This caused several major problems:

- Very complex and expensive cabling.
- Difficult troubleshooting and maintenance.
- High risk of wiring errors.
- Limited information: only one analog value per line, no diagnostics or configuration data.

To overcome these limits, engineers introduced the concept of the fieldbus (réseau de terrain) — a shared communication network that allows several devices (sensors, actuators, PLCs, etc.) to exchange digital information through a single cable or communication medium.

1.2 Definition of a Fieldbus

A fieldbus is a digital serial communication network designed to connect field-level devices such as sensors, actuators, and controllers within an industrial automation system. Its purpose is to transfer measurement, command, and diagnostic data reliably in a deterministic and real-time manner.

➢ In other words: A fieldbus acts as the "nervous system" of an industrial process — collecting information from the field, sending it to controllers, and distributing commands back to actuators.

1.3 Functional Levels in Industrial Networks

Industrial systems are often divided into three main hierarchical levels:

Level	Typical Devices	Communication Objective
Field Level	Sensors, actuators, variable-speed drives	Data acquisition and control of physical processes
Control Level	PLCs (Programmable Logic Controllers), industrial controllers	Local process control, data coordination
Supervision Level	SCADA, HMIs, industrial PCs	Visualization, data archiving, management

Fieldbuses operate mainly between the Field and Control levels.
At higher levels, the communication is often handled through Ethernet-based protocols or industrial IoT networks.

1.4 Typical Fieldbus Topologies

Different topologies can be used depending on the system design:

1. Bus (Linear) – All devices are connected along a single cable (typical of PROFIBUS, Modbus RTU).
2. Star – Each device connects to a central hub or switch (common in Ethernet-based buses like PROFINET).
3. Ring – Offers redundancy: if one link fails, communication continues in the opposite direction (e.g., EtherCAT).
4. Tree (Hybrid) – Combination of bus and star, adapted to large systems.

1.5 Physical Media and Transmission

Fieldbuses use different physical supports depending on performance and environmental constraints:

Medium	Description	Example of Use
Twisted Pair (Cu)	Balanced signal, low noise, short distance	PROFIBUS DP, Modbus RTU
Coaxial Cable	High noise immunity	FOUNDATION Fieldbus H1
Fiber Optics	Long distance, total EMC immunity	PROFINET IO, EtherCAT
Wireless	Short-range flexible deployment	WirelessHART, ISA100

Fieldbus networks often include shielding, galvanic isolation, and termination resistors to ensure signal integrity and immunity against electromagnetic interference (EMI).

1.6 Categories of Fieldbuses

Fieldbuses can be classified according to their application domain and performance:

Category	Typical Protocols	Characteristics
Sensor/Actuator Buses	AS-Interface (AS-i), IO-Link	Simple, low speed (10 kbps), 2-wire (power + data)
Control Buses	PROFIBUS-DP, Modbus RTU, CANopen, DeviceNet	Deterministic, moderate speed (1 Mbps), real-time I/O
High-Performance / Ethernet-Based Buses	PROFINET, EtherCAT, EtherNet/IP	High speed (100 Mbps – 1 Gbps), IP-based, distributed control

- Example:
  In a packaging system (an industrial facility where products are packed, labeled, and prepared for shipment) **:**

Level	Fieldbus Used	Purpose
Sensor/Actuator Level	AS-i (Actuator Sensor Interface)	Connects sensors (e.g., item detection) and actuators (valves, small motors)
Control Level	PROFIBUS-DP	Links AS-i gateways, motor drives, and PLCs
Supervision Level	PROFINET	Connects PLCs to the SCADA system and factory network

This hierarchical organization reduces wiring, simplifies diagnostics, and improves maintainability.

1.7 Key Advantages of the Fieldbus Approach

- Reduced cabling costs: one shared line replaces many point-to-point connections.
- Digital and noise-resistant communication.
- Bidirectional exchange: devices can send both measurement data and diagnostic information.
- Easier scalability: new devices can be added with minimal wiring.
- Standardized communication layers: interoperability between manufacturers.

1.8 Limitations and Design Constraints

However, fieldbus systems are not without challenges:

- Limited bandwidth (1–12 Mbps for classic buses).
- Real-time determinism must be guaranteed by strict scheduling (e.g., token passing, master/slave cycles).
- Protocol-specific design: each fieldbus (PROFIBUS, CANopen, etc.) has its own timing rules, frames, and physical layer constraints.
- Complex network planning: topology, termination, and segment lengths must respect strict specifications.
- Compatibility and legacy: many systems still combine old 4–20 mA devices with new digital fieldbus nodes.

1.9 Determinism and Real-Time Behavior

In industrial automation, communication must be predictable. The bus must ensure that messages are transmitted within a guaranteed time window; this property is called determinism.

Examples of Deterministic Fieldbus Systems

Protocol	How It Ensures Determinism	Typical Performance
PROFIBUS-DP	Uses a **master–slave polling mechanism**. The master (PLC) queries each slave (sensor/actuator) in a fixed order, so every device gets communication access in a known cycle.	Typical cycle time < **10 ms** — suitable for precise control loops.
CANopen	Uses **priority-based arbitration** on message identifiers. If two nodes send messages simultaneously, the one with the highest priority (lowest ID number) always wins. This guarantees **bounded latency** — no message waits indefinitely.	Deterministic under heavy bus load; widely used in automotive and robotics.
EtherCAT	Implements a **real-time synchronized "logical ring"** over standard Ethernet. A single frame passes through every node, which reads/writes its data "on the fly." This results in **microsecond-level latency** and extremely precise timing.	Cycle times < **1 ms**, ideal for motion control and robotics.

1.10 Cyclic and Acyclic Communication

Fieldbus communication is divided into:

- Cyclic traffic: continuous exchange of process data (sensor values, actuator commands).
- Acyclic traffic: occasional messages for configuration, parameterization, or diagnostics.

Example:
A PLC polls sensors every 5 ms (cyclic) while sending configuration data only once at startup (acyclic).

"The fieldbus concept emerged to solve the limitations of traditional analog wiring by providing a shared, digital, deterministic communication medium for industrial systems.It forms the foundation of modern Industrial Communication Networks, serving as a bridge between the physical process and high-level Ethernet or IoT-based systems."

2 — FROM THE 4–20 mA CURRENT LOOP TO DIGITAL FIELDBUSES

2.1 Introduction: Why Study the 4–20 mA Loop?

Before modern fieldbuses emerged, almost every industrial measurement system relied on analog signal transmission using a 4–20 mA current loop.
Understanding this system is essential because:

- it explains why fieldbuses were needed,
- it remains widely used today for critical or legacy instrumentation,

- and it introduces key principles such as signal integrity, noise immunity, and standardization.

Even in advanced industrial facilities, you'll still find pressure transmitters, flowmeters, and temperature sensors communicating through 4–20 mA loops; often coexisting with digital buses.

2.2 Principle of Operation

The 4–20 mA current loop is a two-wire analog communication system used to transmit a single measurement variable (e.g., temperature, pressure, or flow rate). The principle is simple but robust:

1. A sensor (transmitter) converts the measured physical quantity into a current between 4 and 20 mA.
2. The current flows through a loop that includes a power supply, a receiver (e.g., PLC analog input), and sometimes a load resistor for voltage measurement.
3. The magnitude of the current represents the value of the measurement.

Example:
For a 0–100 °C temperature sensor:

- 4 mA corresponds to 0 °C,
- 20 mA corresponds to 100 °C,
- 12 mA corresponds to 50 °C.

2.3 Why Current Instead of Voltage?

Using current instead of voltage offers major technical benefits:

- Immunity to voltage drops due to long cable lengths.
- Less sensitive to electrical noise and EMI (electromagnetic interference).
- Simple series connection: multiple receivers can read the same current.
- Self-monitoring:
  - 0 mA indicates a broken wire or device failure,
  - <4 mA indicates fault or underrange,
  - 20 mA indicates overrange.

In practice, 4–20 mA systems can reliably transmit data over distances up to 1 km, depending on wire gauge.

2.4 Mathematical Relationship

The analog signal can be expressed linearly:

$$I = 4 + 16 \times \frac{(X - X_{min})}{(X_{max} - X_{min})}$$

where:

- I = transmitted current (mA)
- X = measured physical quantity
- X_{min} , X_{max} = measurement range limits

Example:
If a pressure sensor measures 0–10 bar and outputs 12 mA:

$$12 = 4 + 16 \times \frac{(X - 0)}{10} \implies X = 5\ bar$$

2.5 Typical Architecture of a 4–20 mA Loop

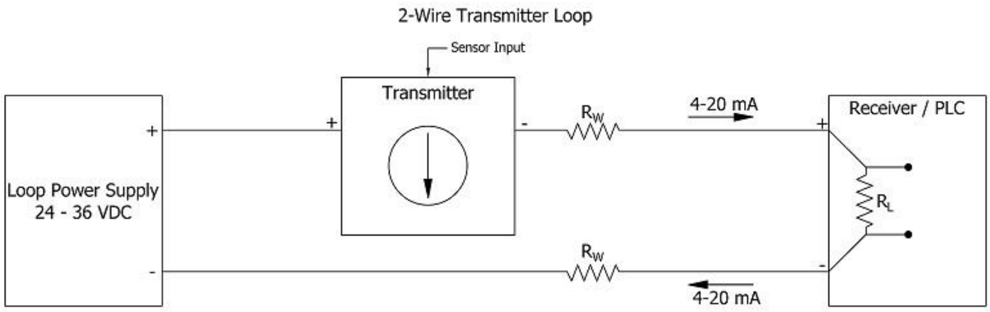

Figure 1 Typical -20mA loop

Each loop must be independent — one cable pair per measurement.
This is reliable but expensive and inefficient for large systems (hundreds of signals).

2.6 Advantages of the 4–20 mA Loop

- High reliability, even in harsh environments.
- Simple and well-understood by technicians.
- Standardized globally (IEC 60381-1).
- Linear, accurate signal transmission.
- Easy fault detection via “live zero” at 4 mA.

2.7 Limitations of Analog Loops

Major limitations appeared as automation needs increased:

- One loop per variable: high cabling cost.
- No digital information: only one measurement value, no diagnostics.
- Calibration drift: analog errors accumulate over time.
- No bidirectional communication: the controller cannot configure or interrogate the sensor.
- No synchronization or timing control.

These constraints made analog systems unsuitable for complex automated systems with hundreds of sensors and distributed controllers.

2.8 The Transition: The HART Protocol

The first step toward digital communication was the HART protocol (Highway Addressable Remote Transducer), developed in the 1980s by Rosemount Inc.

HART allows digital data to be transmitted on top of the 4–20 mA analog signal; using a technique called Frequency Shift Keying (FSK).

- Two frequencies represent binary bits:
  - 1200 Hz → logic ‘1’
  - 2200 Hz → logic ‘0’
- The FSK signal is superimposed on the DC current without affecting the average value.

Thus, the analog signal continues to carry the measurement, while the digital overlay carries:

- device status and diagnostics,
- calibration data,
- configuration parameters.

2.9 Advantages of HART

- Backward compatibility: works with existing 4–20 mA installations.
- Bidirectional communication: field devices can “talk” to controllers or handheld configurators.
- Standardized protocol: open specification maintained by the FieldComm Group.
- Diagnostic and maintenance capabilities: predictive maintenance possible.

Example:
A HART temperature transmitter continuously sends its 4–20 mA process value, but a maintenance engineer can also query it digitally for:

- sensor type,
- last calibration date,
- device serial number,
- internal temperature.

2.10 Limitations of HART

- Limited speed (1,200 bps).
- Still based on point-to-point wiring.
- Not suitable for real-time control or large-scale distributed systems.
- Each loop remains an individual channel.

This led to the development of fully digital fieldbuses (like PROFIBUS, FOUNDATION Fieldbus, CANopen) which replaced analog signals with pure digital frames capable of multiplexing many devices on one line.

2.11 Legacy and Coexistence

Even today, 4–20 mA and HART loops remain widespread in:

- process industries (oil & gas, chemical, water treatment),
- safety-critical applications,
- long-distance sensor installations.

Modern controllers often include analog + HART hybrid interfaces, allowing gradual migration toward digital fieldbuses without replacing all existing devices.

2.12 Summary

Technology	Type	Data Carried	Communication	Typical Use
4–20 mA	Analog	1 variable	Unidirectional	Simple measurements
HART	Hybrid	Analog + digital	Bidirectional	Smart transmitters
Fieldbus	Fully digital	Multiple variables + diagnostics	Bidirectional, multiplexed	Distributed automation

3 — STANDARDIZATION AND COMMUNICATION MODELS OF FIELDBUS SYSTEMS

3.1 The Need for Standardization

In the 1980s and early 1990s, every manufacturer developed their own proprietary fieldbus:

- Siemens → PROFIBUS
- Schneider → FIP / Modbus
- Rockwell → DeviceNet
- Honeywell / Yokogawa → FOUNDATION Fieldbus

This diversity caused:

- Lack of interoperability between devices,
- Vendor lock-in,
- Complex maintenance, and
- High integration costs in multi-vendor environments.

To solve this, international standards were developed to unify communication models, electrical characteristics, and data exchange mechanisms.

3.2 Main International Standards

Standard / Reference	Description	Purpose / Domain
IEC 61158	Defines the complete Fieldbus standard	Physical layer + Data link + Application layer
IEC 61784	Defines Communication Profiles	Specifies how to implement various protocols (PROFIBUS, Modbus, etc.)
IEC 62026	For sensor/actuator interfaces	Defines low-level buses like AS-i, DeviceNet
EN 50170	European standard grouping several fieldbus technologies	Harmonized European version of IEC norms
ISO/OSI Model	Conceptual 7-layer model	Theoretical foundation for all communication systems

3.3 Families of Fieldbuses (According to IEC 61158)

IEC 61158 doesn't define one single bus but a family of compatible technologies, each adapted to different industrial needs:

Type	Representative Bus	Typical Use Case
Type 1	FOUNDATION Fieldbus H1 / HSE	Process automation
Type 2	ControlNet	Manufacturing automation
Type 3	PROFIBUS	Discrete & hybrid automation
Type 4	P-Net	Distributed control
Type 5	WorldFIP	Real-time control (Europe)
Type 6	SwiftNet / INTERBUS	Motion & sensors
Type 7	HART (hybrid)	Legacy systems
Type 8	Ethernet-based buses (Profinet, EtherCAT, etc.)	Modern real-time industrial networks

Each type defines:

- its physical layer (RS-485, fiber, radio, Ethernet, etc.),
- its medium access control method (token, master/slave, CSMA/CA, etc.),
- and its application profile (how data and diagnostics are structured).

3.4 OSI Model Refresher

The OSI model (Open Systems Interconnection) defines a 7-layer framework for any communication system:

Layer	**Function**
7	Application – user data exchange
6	Presentation – encoding, compression, encryption
5	Session – managing logical connections
4	Transport – segmentation, reliability
3	Network – routing, logical addressing
2	Data Link – access control, framing, error detection
1	Physical – transmission of bits (electrical, optical, radio)

However, industrial fieldbuses don’t need all seven layers.
They prioritize speed, determinism, and simplicity over flexibility and routing.

3.5 Fieldbus Simplified Model

Fieldbuses typically use only three layers (sometimes four):

Fieldbus Function	Equivalent OSI Layer	Role
Physical Layer	Layer 1	Electrical or optical transmission of bits (RS-485, fiber, radio)
Data Link Layer	Layer 2	Media access control, synchronization, CRC, addressing
Application Layer	Layer 7	Process data, cyclic exchange, device parameters, diagnostics

The Network, Transport, and Session layers are either absent or integrated inside the Application layer to simplify processing.

3.6 Communication Organization in Fieldbuses

a) Cyclic Data Exchange

- Data is transmitted periodically between controller (PLC) and field devices.
- Deterministic — every device gets access at a predictable time.
- Used for real-time process control.

b) Acyclic Data Exchange

- For configuration, maintenance, and diagnostics.
- Does not interfere with cyclic data.
- Example: a maintenance station reads temperature sensor health data without affecting control loop timing.

c) Event-Driven Data

- Triggered only when a condition changes.
- Saves bandwidth and reduces bus load.
- Example: limit switch sending “ON” signal only when triggered.

3.7 Example — PROFIBUS

PROFIBUS (Process Field Bus) is one of the most successful standardized fieldbuses, defined in IEC 61158 Type 3 and IEC 61784-1 CPF3.

Architecture

- Physical Layer: RS-485 (copper) or fiber optic
- Speed: up to 12 Mbit/s

- Topology: linear bus or tree
- Max nodes: 126 devices

Communication Model

- Master/Slave + Token Passing hybrid
- Deterministic access: the master controls communication cycle time.
- Message types:
  - Cyclic:Fast , regular, real-time process data (sensor values, actuator states) exchanged between the transmitter and the controller (PLC).
  - Acyclic: parameters, diagnostics Non-time-critical, information exchanged only when needed (on demand or during configuration/diagnostics).

A PROFIBUS temperature transmitter might send:

Cyclic Data: [Temperature = 85.3°C]
Acyclic Data: [Device serial = 104392, Status = OK, Calibration = 2025-09-01]

3.8 Example — FOUNDATION Fieldbus

FOUNDATION Fieldbus (FF) is mainly used in the process industry (oil, gas, chemical systemss).

Key Features:

- Fully distributed control: field devices (transmitters, valves) can execute control logic without PLCs.
- H1 version (31.25 kbps): low-speed, intrinsically safe, for process control.
- HSE version (100 Mbps Ethernet): for plant-level integration.
- Function blocks: standardized control algorithms (PID, arithmetic, logic).

Example:
A FOUNDATION Fieldbus pressure transmitter may directly control a valve using an internal PID block — no external PLC needed.
This increases system redundancy and reduces control latency.

3.9 Migration Toward Ethernet-Based Fieldbuses

With the need for higher data rates and integration into enterprise networks, new Ethernet-based industrial protocols emerged:

Ethernet Fieldbus	Base Technology	Main Feature
PROFINET	Standard Ethernet	Real-time + deterministic scheduling
EtherCAT	Ethernet + on-the-fly processing	Ultra-low latency (<100 µs cycle)
EtherNet/IP	Ethernet + CIP protocol	Integration with enterprise networks
POWERLINK	Ethernet with time slots	Hard real-time automation

Ethernet-based fieldbuses combine IT and OT (Operational Technology), enabling the Industrial Internet of Things (IIoT) and Industry 4.0.

3.10 Interoperability and Profiles

To guarantee cross-manufacturer compatibility, the IEC 61784 standard defines Communication Profile Families (CPF), which describe:

- Common data structures (object dictionaries, device profiles)
- Uniform addressing and diagnostics
- Shared configuration tools

Example:
A sensor made by ABB can work on the same PROFIBUS network as a Siemens actuator, because both follow the same PROFIBUS DP profile defined in IEC 61784.

3.12 Conclusion — The Role of Fieldbus in Modern Industry

Fieldbus systems represent a crucial step between analog control and fully networked industrial automation.
They provide:

- Deterministic communication,
- Diagnostic and maintenance capabilities,
- Reduced cabling and cost,
- Interoperability through international standards,
- Scalable integration with modern Ethernet and IIoT systems.

Today’s industry moves toward converged architectures, where traditional fieldbuses coexist with industrial Ethernet and cloud-based monitoring.
Still, understanding fieldbus fundamentals remains essential for engineers designing safe, reliable, and real-time control systems.