ARINC 429 Protocol – All Aspects in Great Detail

1. Overview of ARINC 429

- **Standard name**: ARINC Specification 429 – "Mark 33 Digital Information Transfer System (DITS)".
- **Purpose**: Defines a unidirectional, point-to-multipoint digital data bus used extensively in commercial transport aircraft.
- **Typical use**: Communication between avionics LRUs (Line Replaceable Units) such as:
    - Air Data Computers (ADC)
    - Inertial Reference Systems (IRS)
    - Flight Management Computers (FMC)
    - Flight Control Computers
    - Radios, Navigation receivers, etc.
- **Communication model**:
    - Each physical link is **simplex** (one-way only).
    - One **transmitter** (talker) per pair of wires.
    - Up to **20 receivers** (listeners) can be connected to one transmitter on that pair.
    - If bidirectional exchange is required, two links are used: A→B and B→A.
- **Design goals**:
    - Deterministic behavior (no bus arbitration like CAN or Ethernet).
    - Very high reliability in a harsh EMI environment.
    - Simple, fixed word structure to ease certification and analysis.

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2. Physical Layer

2.1 Cabling and Impedance

- **Medium**: Shielded twisted pair cable.
- **Characteristic impedance**: Nominal **78 Ω**.
- **Transmitter output impedance**: Approximately **75 Ω ± 5 Ω**, balanced.
- **Receiver input impedance**: ≥ **8 kΩ**, allowing many receivers on one pair.
- **Shielding**: Cable shield is grounded appropriately to reduce electromagnetic interference (EMI).

Effects: - Matched impedance plus differential signaling → reduced reflections and noise. - High receiver impedance → one transmitter can fan out to many receivers without overloading.

2.2 Differential Signaling – BPRZ

ARINC 429 uses **Bipolar Return-to-Zero (BPRZ)** signaling on a **differential** twisted pair labeled typically as **A** and **B**:

- Three effective differential levels (measured A–B):
  - Logic **1 (HIGH)**: about **+10 V** at transmitter (receiver sees roughly +6.5 to +13 V).
  - **NULL**: about **0 V** differential (receiver roughly within –2.5 V to +2.5 V).
  - Logic **0 (LOW)**: about **–10 V** at transmitter (receiver sees roughly –6.5 to –13 V).
- **Return-to-zero behavior**:
  - Each bit time is split into two halves.
    - First half: line driven to HIGH or LOW for a '1' or '0'.
    - Second half: line returns to NULL.
  - This ensures frequent transitions → easier clock recovery and reduced DC offset.

Advantages: - Differential + twisted pair → high common-mode noise rejection. - RZ scheme → easier to maintain signal integrity and timing.

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3. Bit Rates and Timing

Two standard data rates are supported on a given bus:

- **Low speed**: Nominal **12.5 kbps** (approximately 12–14.5 kbit/s allowed).
- **High speed**: Nominal **100 kbps** (±1%).

A single physical bus operates at one of these speeds; you don't mix them on the same pair.

3.1 Timing at 100 kbps

- Bit time: ~**10 µs**.
- Bit structure at 100 kbps:
  - First half-bit (~5 µs): line is driven HIGH or LOW.
  - Second half-bit (~5 µs): line returns to NULL.
- Rise and fall times are constrained (order of 1–2 µs) to control EMI and ensure proper sampling.

3.2 Timing at 12.5 kbps

- Bit time: ~**80 µs**.
- Same BPRZ principle, just stretched in time.

- Rise/fall times are correspondingly longer (order of ~10 μs).

3.3 Inter-word Gap

- Between successive ARINC 429 **words**, the transmitter must insert a minimum of **4 bit times** of NULL (no data).
- This gap helps receivers separate words and maintain synchronization.

3.4 Throughput Intuition

- At 100 kbps:
  - 32 bits per word → 320 μs.
  - Add ≥ 4 bit times of gap → +40 μs.
  - So one word takes ≈ 360 μs → around **2,700–2,800 words/s** maximum, in theory.
- At 12.5 kbps everything is 8× slower.

System designers choose word repetition rates (e.g., 10 Hz, 20 Hz, 40 Hz, 100 Hz) so that all required data comfortably fits within capacity.

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4. Bus Architecture and Topology

4.1 Simplex, Single Talker / Multi Listener

- Each ARINC 429 channel is **simplex**:
  - Exactly one **transmitter** on that pair.
  - Multiple **receivers** (up to ~20) are listeners.
- Receivers **never drive** the bus → no collision / arbitration at this level.

4.2 Typical Topologies

- **Star**: One transmitter feeding separate short cable runs to each receiver.
- **Trunk with stubs**: Main cable with short branch stubs to LRUs.
- Systems often have many independent 429 channels connecting LRUs.

4.3 Redundancy

- Aircraft typically implement **dual or multiple redundant buses**:
  - E.g., ADC1 output on Bus A, ADC2 on Bus B.
  - Or cross-strapped buses where critical data is available on more than one channel.
- Redundancy is handled at the **system architecture** level, not by the 429 protocol itself.

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5. ARINC 429 Word Format (32 Bits)

Every ARINC 429 word is exactly **32 bits** long. The logical layout (bit numbering) is:

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Bit numbers (logical view, MSB on left):

32          31 30          29 … 11            10  9      8 … 1
+-----------+------+--------+------------------+------+-----------+
| Parity    | SSM  |  Data  | (19 bits)        | SDI  | Label     |
+-----------+------+--------+------------------+------+-----------+
```

- **Bits 1–8** : Label (8 bits)
- **Bits 9–10** : Source/Destination Identifier (SDI) (2 bits)
- **Bits 11–29** : Data field (19 bits)
- **Bits 30–31** : Sign/Status Matrix (SSM) (2 bits)
- **Bit 32** : Parity (1 bit, odd parity)

Important conventions: - The spec often draws bit 32 on the left (MSB) and bit 1 on the right (LSB) in documentation. - However, **transmission order on the wire** is special and must be understood separately.

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6. Bit Transmission Order and Label Peculiarities

6.1 Transmission Order

- The word bits are logically numbered from 1 to 32.
- On the wire, bits are transmitted in the order:
  - **Bit 1 first**, then 2, 3, ..., 32.

6.2 Label Bit Order

- **Label (bits 1–8)** is special:
  - Within the label field, **bit 8 is transmitted first**, then 7, 6, ..., down to bit 1.
  - So the label appears **MSB first**.
- For the rest of the word (SDI, DATA, SSM, Parity), many implementations treat each byte as transmitted **LSB first** within the byte, but the exact handling can be implementation-specific.

Practical consequence: - Many ARINC 429 interface chips expect you to load the label byte in a **bit-reversed order** compared to how you write it in octal on paper. - For example, the label 203_8 might need to be written as a particular hex value with reversed bits to be transmitted correctly.

This is one of the most common “gotchas” when first programming ARINC 429 hardware.

7. Detailed Field Definitions

7.1 Label (Bits 1–8)

- **Purpose**: Identifies the **type of data** contained in the word.
- 8-bit value, traditionally expressed in **octal**.
- ARINC documentation defines standardized label sets per equipment type:
    - Air Data Computer labels (altitude, airspeed, temperature, etc.).
    - Inertial Reference System labels (pitch, roll, heading, acceleration, etc.).
    - Flight Management labels (waypoints, performance data, etc.).

Example: - A specific label (e.g., 203_8) may represent barometric altitude from an ADC.

Important: - Labels are **contextual**: their meaning depends on the equipment type and sometimes on SDI. - To interpret a word, you need to know both the **label** and which **LRU / channel** it came from.

7.2 SDI – Source/Destination Identifier (Bits 9–10)

- 2-bit field used for:
    1. Identifying the **source channel** of the data (e.g., ADC #1 vs ADC #2).
    2. Or specifying the **intended destination** in older or specialized schemes.

Common usage today: - SDI represents **which instance** of a system the data belongs to (e.g., left vs right system). - Combined with bus/channel and label, SDI helps uniquely identify a data stream.

7.3 Data Field (Bits 11–29, 19 bits)

The core payload of the word. ARINC 429 supports several data coding schemes:

1. **BNR (Binary Number Representation)** – signed binary fraction.
2. **BCD (Binary Coded Decimal)** – decimal digits coded in 4-bit nibbles.
3. **Discrete** – individual bits representing boolean flags.
4. Miscellaneous or mixed formats for special applications.

For each label, the ARINC spec (and aircraft documentation) define: - Encoding type (BNR/BCD/discrete). - Bit significance and resolution. - Units, ranges, and scaling factors.

7.3.1 BNR (Binary Number Representation)

- Used for continuous numeric values: angles, velocities, temperatures, etc.
- Representation:
    - **Bit 29**: Sign bit (1 = negative, 0 = positive) for BNR.
    - **Bits 28–11**: Magnitude bits in fractional two’s-complement.

- Each bit has a defined weight:
    - Bit 28 is the most significant magnitude bit.
    - Weighting is typically defined relative to full-scale or a scaling factor (e.g., 2^{-1}, 2^{-2}, etc.).
- Resolution and range are determined by the label definition.

Example concept: - A BNR field might represent an angle from –180 to +180 degrees with some resolution. - Scaling might be such that one LSB = 0.01°, for instance (exact values are given per label in the spec).

7.3.2 BCD (Binary Coded Decimal)

- Used for numeric values where decimal representation is convenient (e.g., altitude, flight number).
- Data bits are grouped into **4-bit nibbles**, each representing a decimal digit 0–9.
- There may be up to 5 digits; sometimes the most significant group uses fewer bits.
- Often the **SSM** bits encode sign or direction (e.g., plus/minus, north/south).

Example: - A BCD altitude could encode digits of an altitude in feet. - SSM may indicate plus or minus or other directional info.

7.3.3 Discrete Data

- Each data bit is a separate boolean flag.
- Used for on/off or status indicators such as:
    - Gear down
    - Autopilot engaged
    - Flight director on
    - etc.
- The meaning of each bit position is defined for that label.

7.4 SSM – Sign/Status Matrix (Bits 30–31)

These two bits summarize **sign and/or status**, with detailed meaning depending on data type (BNR vs BCD vs discrete).

Typical encodings (simplified view):

- For **BNR values**:
    - One combination indicates **Normal Operation**.
    - Others indicate **No Computed Data (NCD)**, **Functional Test (FT)**, and **Failure Warning (FW)**.
- For **BCD values**:
    - Combinations can encode **sign/direction** (plus/minus, N/S, E/W) and/or status.
- For **discretes**:

- Used mostly for status: normal, test, NCD, failure, etc.

SSM enables downstream systems to differentiate between: - Valid numeric data. - Data under test mode. - Missing or invalid data. - Known failure conditions.

7.5 Parity Bit (Bit 32)

- ARINC 429 uses **odd parity** for each 32-bit word.
- The total number of ‘1’ bits in bits 1–32 must be **odd**.
- The transmitter sets the parity bit accordingly.
- This provides a **single-bit error detection** mechanism.
- If a receiver detects parity error, it normally discards the word or flags it as invalid.

Note: There is no built-in retransmission at the ARINC 429 level; higher-level logic must decide what to do.

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8. System-Level Behavior and Data Rates

8.1 Word Repetition and Scheduling

- Each data source (e.g., ADC, IRS) repeats its important labels at fixed rates:
  - Example: attitude data at 50 Hz or 100 Hz.
  - Slower parameters (e.g., configuration or maintenance data) may be at 1 Hz or lower.
- Designers ensure:
  - All required data can fit in the available bandwidth.
  - Critical data has sufficiently high update rate for control tasks.

8.2 Determinism

- Because each bus has only one talker and no arbitration, transmission timing is determined purely by the transmitter’s schedule.
- This simplifies worst-case latency analysis, which is important for certification.

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9. EMI Robustness and Environmental Considerations

ARINC 429 is designed to operate reliably in the avionics environment:

- **Differential signaling** and **twisted pair** reduce susceptibility to common-mode noise.
- **Shielding** and **controlled rise/fall times** reduce emitted radiation and ringing.
- **RZ coding** ensures frequent transitions and avoids long runs of constant voltage, helping with clock recovery and EMI.

- Equipment is qualified per DO-160 (environmental conditions and test procedures for airborne equipment).

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10. Addressing and Identification in ARINC 429

Unlike CAN or Ethernet, ARINC 429 does not have an explicit node address in the word itself.

Identification comes from a combination of:

1. **Bus/channel** (physical wiring / routing).
2. **Transmitting LRU and port**.
3. **Label** and **SDI**.

Additionally: - LRUs have **equipment IDs** and may use standardized label sets. - Higher-level protocols (file transfer, data loading, maintenance) may introduce additional addressing or identifiers.

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11. Special and Extended Features

11.1 25-bit Word Format

Some implementations support a shortened **25-bit** word format:

- Bits 1–8: Label
- Bits 10–24: Data (16 bits)
- Bit 25: Parity

This is a special-case format used in certain applications; the same general principles (label + data + parity) apply.

11.2 File Transfer and Data Loading Protocols

ARINC 429 provides the physical and word-level protocol. On top of it, higher-level protocols exist, such as:

- **ARINC 429 Part 3 / Williamsburg/Buckhorn protocol** for structured message exchange.
- **ARINC 615** for software/data loading over 429 (e.g., uploading navigation databases or avionics software).

These define framing, sequencing, acknowledgments, and other functions for large data transfers.

11.3 Evolution Beyond ARINC 429

- **ARINC 629**: A later standard with multi-transmitter capability and TDMA access control; used on some aircraft but not as ubiquitous as 429.
- **ARINC 664 Part 7 (AFDX)**: An Ethernet-based, deterministic network providing virtual links that emulate dedicated data paths (in many ways conceptually similar to multiple 429 links over IP/Ethernet).
- Modern aircraft often use a mix of ARINC 429 and AFDX, with gateways translating between them.

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12. Comparisons with Other Avionics Buses

12.1 ARINC 429 vs CAN (Controller Area Network)

- **ARINC 429**:
  - Simplex, single talker per bus.
  - Fixed 32-bit words, fixed structure.
  - No arbitration, no ACK; deterministic by scheduling.
  - Widely used in commercial transport avionics.
- **CAN**:
  - Multi-master bus with bitwise arbitration.
  - Messages identified by IDs; payload is separate (0–8 bytes in classical CAN).
  - Has CRC, ACKs, error confinement mechanisms.
  - Common in automotive and some avionics subsystems, especially where flexibility and multi-master behavior is needed.

12.2 ARINC 429 vs MIL-STD-1553

- **ARINC 429**:
  - One-way traffic per channel (simplex).
  - No bus controller; each transmitter just sends on its schedule.
  - Simpler, lighter-weight protocol.
- **MIL-STD-1553**:
  - Dual-redundant, multi-drop bus.
  - Uses a **Bus Controller (BC)** that centrally schedules all communication.
  - Remote Terminals (RTs) and Monitor Terminals.
  - More flexible but more complex.

Both are widely used in aerospace, often in different roles.

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13. Practical Implementation Notes

When implementing or interfacing with ARINC 429 in hardware or software, keep in mind:

1. **Label bit order**:
   - Understand how your interface hardware expects the label bytes.
   - Often, you must bit-reverse the label from the octal representation.
2. **Scaling and units**:
   - For each label, know the specific BNR/BCD encoding, resolution, and units.
   - Misinterpreting scale or sign can lead to incorrect engineering values.
3. **SSM handling**:
   - Always check SSM bits to distinguish:
     - Normal operation
     - No Computed Data (NCD)
     - Functional test
     - Failure conditions
4. **Parity checking**:
   - Implement parity checks and discard/flag words with parity errors.
5. **Repetition rates**:
   - Know the expected update rate of each label; large gaps may indicate a fault.

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14. Summary

- ARINC 429 is a **simplex, deterministic, word-oriented** avionics bus.
- It uses **differential BPRZ signaling** over **78 Ω twisted pair** at fixed bit rates (12.5 or 100 kbps).
- Each 32-bit word is structured as **Label, SDI, Data, SSM, and Parity**.
- Data fields support **BNR, BCD, and discrete** encodings, with detailed per-label definitions.
- **SSM** and **parity** provide basic integrity and status information.
- System-level design (multiple channels, redundancy, scheduling) delivers the overall robustness and safety required in transport-category aircraft.

These fundamentals form the basis for deeper topics like ARINC label mapping for specific LRUs, gateway design, and integration with more modern networks like AFDX.