

I²CIP: Inter-Integrated Circuit Intra-networking Protocols

Requirements for a Hardware Design Specification for a Bus-Switched Intra-Network of
Hot-Swap Modules of I²C Targets and a Software Library of Intra-Network Communications
Protocols for Rapid Implementation of Plug-and-Play Embedded Systems

Jayden Lefebvre - Founder & CEO, Lead Engineer

Northumberland County, ON, Canada

Primary Contact Email: contact@peapodtech.com

Revision 1.0

PeaPod Technologies Inc.

November 2025

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1 Introduction

1.1 Purpose

The purpose of this document is to two-fold:

1. Outline the categorical requirements (Section 2.2) of an intra-network design specification for hot-swap bus-switched modules of plug-and-play I²C devices.
2. Detail the scoped requirements (Section 1.3) for the design and protocols as-proposed by PeaPod Technologies Inc., namely **I²CIP**.

1.2 Design Paradigm

All Solutions provided by PeaPod Technologies are fully documented and backed by our rigorous top-down engineering-design paradigm, applied at all steps, enabling us to frame the Problem in such a way that a Solution is a provable and self-evident combination of our Services:

- **2.1 - Problem Statement:** A scoped overview of the opportunity or **Problem**. Anything not covered by this **Statement** is not considered in the execution of the project.
- **2.2 - Solution Requirements:** Categorical requirements for *any* solution to the problem, interpolated from the scope boundaries in the **Problem Statement**. If any of these are not met, the problem is not solved, providing a distinct *pass/fail threshold*, or "razor", for possible Solutions.
- **2.3 - Stakeholders and Values:** *Perspectives* in consideration (i.e. ITCGI, the client, client-of-client), along with a summarized *value proposition* for each person or group, derived from the **Problem Statement** and **Requirements**. These are the people who are and will be *directly affected* by the **Problem**, and as such their **Values** will influence the selection of factors about which we shall select the ideal **Solution**.
- **2.4 - Problem-Solving Goals:** *Conceptual* design goals (e.g. Safety, Efficiency) derived from **Requirements** and **Stakeholder Values**.
- **2.5 - Solution Objectives:** *Tactical* implementation targets derived from the **Requirements** and **Goals**.
- **2.6 - Metrics:** Granular, *quantitative* measures of design success/fit/utility/etc. derived from the **Objectives**, which are either Constrained or Graded according to the **Requirements**, **Goals**, and **Objectives**.
- **2.7 - Constraints:** *Mandatory* thresholds (i.e. true/false, pass/fail) and extrema (minima, maxima) for evaluating and disqualifying proposed solutions along Constrained Metrics.
- **2.8 - Criteria:** *Points-based* system for evaluating and ranking proposed solutions along Graded Metrics.

1.3 Scope and Justification

1.3.1 I²C Specification

From the I²C Specification Version 7 (2021, *NXP Semiconductors*): an 8-bit-oriented one-ended (“controller”-driven) bidirectional (read & write) serial communication over a 2-wire bus (data “SDA” & clock “SCL”) for integrated circuit devices (“targets”), including (but not limited to):

- **Remote Multi-Channel Ports:** GPIO banks, internal-clock PWM drivers, Analog-to-Digital and Digital-to-Analog converters, etc.
- **System Devices:** real-time clocks, LCD screens, microcontrollers, etc.
- **Data Storage Devices:** EEPROM, SRAM, FRAM, etc.
- **Digital Sensors:** temperature, humidity, light, acceleration, pressure, etc.

1.3.2 OSI Model Analogue for I²C

The I²C Specification can be imagined as an incomplete analogue to the Internet’s OSI Model, with the following layers defined:

SC1. Physical Layer

- (a) **VDD & GND:** e.g. +5 VDC
- (b) **SDA & SCL:** Pull-Up Bias Resistors (e.g. 10 kΩ)

SC2. Data Link Layer

- (a) **Controller:** Bus Speed Control, Start & Stop Conditions, Multi-Controller Arbitration
- (b) **Targets:** 7-bit Device Addressing, Acknowledgement (“ACK”)
- (c) **Packet Structure:** “Read” & “Write” Flags, 8-/16-bit Register Addressing, Byte-Stream Data

The **Network** (data routing), **Transport** (data delivery), and **Session** (transmission context) layers of the OSI model analogy are not defined by the I²C Specification. The following proposed extensions to the I²C Specification, the focus of the **I²CIP** design, are intended to fill this gap, enabling **Presentation** and **Application** layer functionality to be rapidly implemented by developers for embedded systems (e.g. control systems).

1.3.3 Switched-Bus Intra-Networking

Suppose an I²C target device D with N possible unique addresses. A standard I²C bus controller C can communicate with N uniquely-addressed instantiations of D on each I²C bus without modification to connections or encountering conflict.

Suppose a type of I²C target device X with M possible unique addresses that acts as a multiplexer and repeater ("switch") for B bitwise-enabled output busses ("subnetworks"). Using this switch device X , the I²C bus controller C can communicate with $M \cdot B \cdot N$ independently-addressable instantiations of the target device D across $M \cdot B$ subnetworks by setting ONE active output bus on each of the M switches (and disabling ALL on the remaining $M - 1$).

1.3.4 Extended OSI Model for I²CIP

For the purposes of effective intra-network communication across switched subnetworks, it is proposed that a "fully-qualified address" be implemented at the controller level, comprising routing information that encodes the I²C bus, switch address, and subnetwork number, alongside the target device address, for each target device.

Suppose a dedicated target device E consisting of EEPROM memory containing routing information for all devices on all subnetworks of one switch. If this EEPROM device E is granted a fixed address on a consistent subnetwork on each switch, the controller can reliably retrieve routing information for all devices on all subnetworks of any switch by querying each switch's dedicated EEPROM device.

Together, the EEPROM device E , the switch device X , and all devices on all subnetworks of the switch X comprise a **Module**.

SC3. **Network Layer:** Fully-Qualified Addressing ("FQA")

SC4. **Transport Layer:** Switch & Target Ping Prior to Target Control with Quality-of-Service 2 ("only-once" delivery) via ACK

SC5. **Session Layer:** Target Discovery & Module Configuration via Dedicated EEPROM Target

1.4 Definitions

A number of useful definitions have emerged from the above scoping:

1. **Switch:** An I²C target device that acts as a repeater for bitwise-multiplexed output busses.
2. **Subnetwork:** A specific output bus of a specific switch.
3. **Intra-Network:** A general term referring to all routable targets (not including switches) on all subnetworks across all of a controller's I²C busses.
4. **Fully-Qualified Address (FQA):** A unique intra-network routing location identifier, encoding: a specific I²C bus, and; a specific subnetwork (i.e. switch and bus), and; a target's I²C address.
5. **Module:** A switch, and; a physical collection of targets located on the switch's subnetworks, and; a data storage target at a predetermined location with all routing information for all targets on this switch's subnetworks.

2 Framing

2.1 Problem Statement

Formulate a hardware design specification for a bus-switched intra-network of hot-swap modules of I²C targets, and a software library of intra-network communications protocols for fully-qualified addressing and Quality-of-Service 2 packet delivery for all targets, including dedicated routing EEPROM targets for modular target lifecycle management and configuration.

2.2 Solution Requirements

The following are the overall requirements implied from scoping (Section 1.3) and definitions (Section 1.4) of the I²CIP design:

R1. **Must** include a hardware design specification of an I²C intra-network that:

- (a) **Must** implement switching of output bus subnetworks while preventing cross-talk;
- (b) **Must** implement hot-swap capability;
- (c) **Must** implement dedicated routing EEPROM targets;

R2. **Must** include a software library for operating the I²C intra-network that:

- (a) **Must** implement fully-qualified addressing encoding routing information for any target on any subnetworks across all I²C busses;
- (b) **Must** implement Quality-of-Service 2 packet delivery for all communications across the intra-network;
- (c) **Must** implement plug-and-play modular target lifecycle management via dedicated routing EEPROM targets;

R3. **Should** support multiple I²C bus controllers.

R4. **Should** implement electrical isolation for all targets on all subnetworks.

2.3 Stakeholders and Values

- S1. Embedded Systems Designers - Modularity, Scalability
- S2. System End-Users - Reliability, Maintainability
- S3. Hobbyists, Makers, Educators - Accessibility

2.4 Problem-Solving Goals

HL1. Modularity, Scalability (S1, R1a) HL2. Reliability, Stability (S2, R1a, R1b, R2b, R2c)

2.5 Solution Objectives

LL1. Hot-Swappability (HL1) LL2. Plug-and-Play (HL1, S3, R2c)

2.6 Metrics

| # | Metric | Units |
|----|-----------------------------|--------|
| M1 | Targets Hot-Swappable (LL1) | Yes/No |
| M2 | Modules Plug-and-Play (LL2) | Yes/No |

2.7 Constraints

| Metric | Constraint | Justification |
|--------|------------|---------------|
| M1 | Yes | (R1b) |
| M2 | Yes | (R2c) |

2.8 Criteria

| Metric | Criteria | Justification |
|--------|----------|---------------|
|--------|----------|---------------|

3 Reference Designs

3.1 Reference Design XYZ

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