



Human-centric algebraic machine learning

AML-IP implementation - Final M54

Deliverable D6.4

WP6 - System and Tools



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952091.

Consortium



ALGEBRAIC AI



Chantalimaud
Foundation



Project

Title: ALMA: Human Centric Algebraic Machine Learning
 Acronym: ALMA
 Coordinator: Proyectos y Sistemas de Mantenimiento SL (eProsima)
 Grant agreement: 952091
 Call: H2020-EIC-FETPROACT-2019
 Program: Horizon 2020
 Start: 01 September 2020
 Duration: 54 months
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Deliverable

Number: **D6.4**
 Title: **AML-IP implementation - Final M54**
 Month: 54
 Work Package: WP6 - System and Tools
 Work Package leader: Proyectos y Sistemas de Mantenimiento SL (eProsima)
 Deliverable leader: Proyectos y Sistemas de Mantenimiento SL (eProsima)
 Deliverable type: DEM: Demonstrator, pilot, prototype
 Dissemination level: Public (PU)
 Date of submission: 28/02/2025
 Version: v5.3
 Status: Finished

Version history

Version	Date	Responsible	Author/Reviewer	Comments
v1.0	04/05/2021	EPROS	Javier París Uhryn	D6.1 - First Draft
v2.0	18/05/2021	EPROS	Raúl Sánchez-Mateos Lizano	D6.1 - Second Draft
v2.1	28/05/2021	EPROS	Raúl Sánchez-Mateos Lizano	D6.1 - Finished document
v3.0	07/02/2022	EPROS	Javier París Uhryn	D6.2 - First Draft
v3.1	22/02/2022	EPROS	Juan López Fernández	D6.2 - First Review (RV1)
v3.2	23/02/2022	EPROS	Javier París Uhryn	D6.2 - Apply changes from RV1
v3.3	24/02/2022	EPROS	Juan López Fernández	D6.2 - Second Review (RV2)
v3.4	28/02/2022	EPROS	Javier París Uhryn	D6.2 - Finished document
v3.5	23/05/2022	EPROS	Raúl Sánchez-Mateos Lizano	Apply PO and EU Reviewers suggestions
v3.6	01/07/2022	EPROS	Juan López Fernández	D6.2 - Third Review (RV3)
v4.0	08/08/2023	EPROS	Irene Bandera Moreno	D6.3 - First Draft
v4.1	01/09/2023	EPROS	Raúl Sánchez-Mateos Lizano	D6.3 - Review
v4.2	04/09/2023	EPROS	Irene Bandera Moreno	D6.3 - MNIST demo with AML
v4.3	10/09/2023	EPROS	Raúl Sánchez-Mateos Lizano	D6.3 - Final review
v5.0	30/01/2025	EPROS	Denisa Alexandru	D6.4 - First Draft
v5.1	30/01/2025	EPROS	Raúl Sánchez-Mateos Lizano	D6.4 - Review and update architectures
v5.2	30/01/2025	EPROS	Denisa Alexandru	D6.4 - Apply some review comments
v5.3	30/01/2025	EPROS	Raúl Sánchez-Mateos Lizano	D6.4 - Final review

Executive summary

Algebraic Machine Learning (AML) is a relatively new machine learning technique based on algebraic representations of data. Unlike statistical learning, AML algorithms are robust regarding the statistical properties of the data and are parameter-free. The aim of the EU-funded ALMA project is to leverage AML properties to develop a new generation of interactive, human-centric machine learning systems. These systems are expected to reduce bias and prevent discrimination, remember what they know when they are taught something new, facilitate trust and reliability and integrate complex ethical constraints into human-artificial intelligence systems. Furthermore, they are expected to promote distributed, collaborative learning.

This report corresponds to *Deliverable D6.4 - AML-IP implementation - Final M54* of the ALMA project. This deliverable includes the first implementation of the AML Integrating Platform (AML-IP), using nodes that mock AML ones for data generation, and establishing communication via Robot Operating System 2 (ROS 2) nodes. The goal is to develop an easy-to-deploy platform for cloud and edge computing environments leveraging the parallelization benefits of AML and the integration facilities of a robotic framework as ROS 2. The platform interconnects AML components (such as engines) and hooks these with other software including data injection nodes, task managers and edge nodes. Additionally, it interacts with the Context Broker through a FIWARE node and is integrated into the AML-Dashboard. This integration facilitates the creation and destruction of nodes via a graphical interface, enhancing user control and system flexibility.

Revision update M18

Revision of deliverable *D6.1 - AML-IP implementation - Initial* for *Work Package 6: System and Tools*.

Major Changes

- **AML-IP Agent Node (AML-IP-Agent) underneath technology:** Previous deliverable stated that Integration Service (IS) would be the base platform on which to implement the AML-IP-Agent. After thorough research and elaboration of proofs of concept with IS, it has been evinced that this is not the most appropriate tool for the purpose at hand. eProsima DDS Router (DDS Router), a novel application designed to fulfill all requirements specific to the ALMA project, is to be used instead.
- **AML-IP scenarios divisions:** Deliverable *D6.1 - AML-IP implementation - Initial* focused on exploiting the **collaborative** capabilities of AML, by implementing a prototype for distributing models among users working on the same problem. In this version a new working scenario has been added, in which the main task is to **distribute** the **workload** among multiple nodes offering their computational resources.

Progress

- **AML-IP-Agent implementation (4.3.3):** The AML-IP-Agent will relay on the DDS Router for its main behaviour, this product being already released and currently in the beta-testing phase.

New modules

- **AML-IP distributed workload scenario (6.2.2):** The AML-IP has evolved in distributed workload scenarios. This is a scenario for the AML-IP to exploit the AML features that allow for the parallelization of the training process between independent computing nodes. Within this new scenario, two new kind of nodes are presented: AML-IP Algebraic Main Node (AML-IP-Main) and AML-IP Algebraic Computing Node (AML-IP-Computing).
- **AML-IP distributed workload scenario prototype (6.2.3):** There is a new prototype of the AML-IP for *workload distribution scenarios* that, along with a demonstrator, illustrates the new functionality of the above-mentioned nodes.

Revision update M36

Revision of deliverable *D6.2 - AML-IP implementation - Revised M18* for *Work Package 6: System and Tools*.

Mayor Updates

- AML-IP v0.1.0 has been published, being the first release of this software product. Although it is a “beta” release, this is considered the first version with stable, software-ready developments. Please, refer to AML-IP v0.1.0 GitHub Release¹ for more information about this release.

Progress

- **AML-IP workload distribution scenario** (6.2.2): The AML-IP now excels in asynchronous workload distribution scenarios. In this context, AML-IP harnesses the advanced capabilities of AML to facilitate collaboration among nodes working on the same problem. It achieves this without the need for active user interaction, efficiently distributing high-computational-effort tasks to remote nodes. Within this evolved scenario, two new kind of nodes are introduced: AML-IP Algebraic Asynchronous Main Node (AML-IP-AMain) and AML-IP Algebraic Asynchronous Computing Node (AML-IP-AComputing).

New modules

- **AML-IP collaborative learning scenario** (6.1.2): AML-IP has evolved in collaborative learning scenarios. In this context, AML-IP leverages AML features to facilitate collaboration among nodes working on the same problem by sharing locally obtained models. Within this new scenario, two new kind of nodes are introduced: AML-IP Algebraic Model Manager Receiver Node (AML-IP-MMReceiver) and AML-IP Algebraic Model Manager Sender Node (AML-IP-MMSender).
- **AML-IP distributed inference scenario** (6.3.2): AML-IP has been enhanced to handle distributed inference scenarios. This scenario involves the efficient distribution of a substantial volume of data to remote nodes for their inference tasks. Within this new scenario, two new types of nodes are introduced: AML-IP Algebraic Edge Node (AML-IP-Edge) and AML-IP Algebraic Inference Node (AML-IP-Inference).
- **AML-IP monitor network state scenario** (6.4.2): AML-IP has evolved to include advanced network state monitoring capabilities. This scenario performs the monitoring action. Within this scenario, a new kind of node is introduced: AML-IP Algebraic Status Node (AML-IP-Status).
- **Remote Procedure Call** (2.8): We have implemented Remote Procedure Call based on Data Distribution Service (DDS) to facilitate the distribution of requests and replies across a network.
- **Mediation Nodes** (4.3.2): AML-IP Mediation Nodes have been introduced to transform data between different formats, offloading this task from AML-IP Algebraic Node (AML-IP-Alg).

¹<https://github.com/eProxima/AML-IP/releases/tag/v0.1.0>

Revision update M48

Revision of deliverable *D6.3 - AML-IP implementation - Revised M36* for *Work Package 6: System and Tools*.

New Nodes

- **Fiware Node:** This type of node interacts with the FIWARE context broker to manage inference data. It offers mechanisms for retrieving data from a context broker entity, soliciting inference from an Inference Node, and transmitting the inference to the context broker entity.

New Tools

- **AML-Toolkit:** AML Toolkit is a set of software tools that allows users to develop, train, and deploy Algebraic Machine Learning (AML) models. These tools are designed to be used by researchers, developers, and industry professionals who want to implement AML models in their applications.
- **AML-Dashboard:** AML-Dashboard serves as a user-friendly tool for training, evaluating, and applying AML models to several scenarios. It allows the users to manage AML-IP nodes, perform workload distribution, collaborative learning and distributed inference within the AML-IP framework, as well as monitoring the state of the network.

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Acronyms

AI	Artificial Intelligence.
AML	Algebraic Machine Learning.
AML-DL	AML Description Language.
AML-IP	AML Integrating Platform.
AML-IP-AComputing	AML-IP Algebraic Asynchronous Computing Node.
AML-IP-AEdge	AML-IP Algebraic Asynchronous Edge Node.
AML-IP-Agent	AML-IP Agent Node.
AML-IP-AInference	AML-IP Algebraic Asynchronous Inference Node.
AML-IP-Alg	AML-IP Algebraic Node.
AML-IP-AMain	AML-IP Algebraic Asynchronous Main Node.
AML-IP-Computing	AML-IP Algebraic Computing Node.
AML-IP-D	AML-IP Discovery Node.
AML-IP-DL	AML-IP Algebraic Description Language Node.
AML-IP-Edge	AML-IP Algebraic Edge Node.
AML-IP-Engine	AML-IP Algebraic Engine Node.
AML-IP-Inference	AML-IP Algebraic Inference Node.
AML-IP-Main	AML-IP Algebraic Main Node.
AML-IP-Mediation	AML-IP Mediation Node.
AML-IP-MMReceiver	AML-IP Algebraic Model Manager Receiver Node.
AML-IP-MMSender	AML-IP Algebraic Model Manager Sender Node.
AML-IP-Status	AML-IP Algebraic Status Node.
API	Application Programming Interface.
DDS	Data Distribution Service.
DDS Router	eProsima DDS Router.
DL	Description Language.
GA	Grant Agreement.
IDL	Interactive Data Language.
IP	Integrating Platform.
IS	Integration Service.
LAN	Local Area Network.
ML	Machine Learning.
MSCP	MultiService Communication Protocol.
NAT	Network Address Translation.
OS	Operating System.
P2P	Peer to Peer.
PoC	Proof of Concept.
QoS	Quality of Service.
ROS 2	Robot Operating System 2.
RPC	Remote Procedure Call.
SHM	Shared Memory Transport.
TCP	Transmission Control Protocol.
UDP	User Datagram Protocol.
UPnP	Universal Plug and Play.
WAN	Wide Area Network.
WWW	World Wide Web.

1 Introduction

The ALMA research and innovation project aims to change the Artificial Intelligence (AI) paradigm by creating a new approach to Machine Learning (ML) known as AML. AML is a novel ML technique based on the algebraic representation of data. The goal of the EU-funded ALMA project is to leverage the properties of AML to develop a new generation of interactive, human-centered machine learning systems.

The AML-IP is a framework that allows for the simple deployment of an AML distributed architecture. This design has been elaborated by *eProxima* based on the guidelines described in the WP6 of the ALMA Grant Agreement (GA), as well as taking into account the specifications, requirements and limitations of the AML nodes, developed by *ALGEBRAIC AI*.

The AML-IP is the cornerstone by which the rest of the project components are underpinned. It will serve as a platform for non-expert users to create and manage different AML nodes and the communication between them, in local and remote networks. It will also allow to create complex distributed networks, with one or multiple users working collaboratively in the same problem, and provide an easy to use framework to facilitate the process of different aspects of the AML process, as parallelizing tasks, sharing models, etc.

1.1 Purpose of document

This document describes in detail many aspects of the AML-IP; its scope, purpose, design, and the current state of its implementation and deployment. This is a complex platform that must support an evolving project. Therefore, the decisions made so far, as well as the designs and diagrams may be modified depending on the necessities of the project.

Two different AML-IP prototypes are presented in this document, and each of them refer to different components of the final AML-IP. These parts are not mutually-exclusive, but the corresponding prototypes are independent to one another. Along with these prototypes, instructions on how to execute a demo are provided, as well as a demonstrator for each of them showcasing the attained results.

This document is a revision of deliverable *D6.3 - AML-IP implementation Revised*. It incorporates new aspects of the project, eliminates deprecated information, and updates those parts of the AML-IP design that have suffered modifications over the last months of development. Main changes and additions to this revision not present in *D6.3 - AML-IP implementation Revised* are listed in Revision update M48.

1.2 Document sections

- **AML Environment Overview** (2) This section summarizes the AML environment to present the motivation for the development of the AML-IP.
- **AML available resources** (3)
- **AML-IP Architecture** (4) Here, the AML-IP requirements are presented, as well as the design chosen and the decisions made in this process.
- **AML-IP architecture scenario Prototype** (5) The first prototype refers to the collaborative learning scenario of a future AML network, and adds designs, images and links to the prototype implementation, as instructions on how to execute it.
- **AML-IP Scenarios** (6) The AML-IP framework is divided in different scenarios or use cases, each designed to leverage the full capabilities of AML.

- **Debugging tools** (8) This section introduce the debugging tools developed for an AML network. It is aimed at helping users troubleshoot and maintain the AML environment, providing essential tools for network diagnostics and problem-solving.

1.3 Partners involved

Team Leader:

- Proyectos y Sistemas de Mantenimiento SL (eProsima) (EPROS), Spain

Partners:

- ALGEBRAIC AI (ALG), Spain
- FIWARE Foundation e.V. (FF)

2 AML Environment Overview

The AML Environment provides a robust infrastructure for developing and deploying machine learning models. Within this environment, the AML-IP acts as a central framework that coordinates various AML components. These components include but are not limited to AML-IP-Edge and AML-IP-Computing. The AML-IP ensures seamless communication and integration between these components across the Internet, facilitating comprehensive machine-learning workflows.

2.1 Node oriented design

The AML environment is comprised of nodes of different kinds that communicate with one another. These nodes compute different types of data which are published and shared with other nodes that request them in the AML ecosystem.

A node must be understood as a piece of software that runs in a specific machine at a specific time. An AML network is made up of one or multiple nodes communicating with each other. A node has the following characteristics:

- It is independent of the rest of the network. This means that any node could work on its own, or in any network configuration, being able to manage its own communication and status. Nonetheless, some specific nodes could alter or modify the behaviour of others if they are designed to do so.
- The communication is not limited to the virtual or physical environment of the node. Any node has the potential to communicate with any other as long as they are connected to the same network (e.g. the Internet).
- Each kind of node has its own expected behaviour, and all nodes belonging to the same kind display exactly the same behaviour (when configured with the same settings).
- There is no limit in the amount of nodes (or the amount of nodes of the same kind) in a network. Nevertheless, some groups of nodes could make no sense without others, as many tasks require some kinds of nodes to be processed.

A node-based environment for the AML-IP offers many advantages. These are the main ones:

- **Independence:** Each node runs in a process, and is independent of the rest of the nodes. The data this node uses, the communication interfaces and its status and execution is managed inside the node, making it possible for any node to work alone and independently of the environment it is running. Obviously, it would not make any sense to run some nodes alone. But still, the process would behave as expected in this or any other scenarios.
- **Adaptability:** As any node is independent from the rest, the size and form of these networks is limitless. Any amount of nodes could work at the same time, only being affected by external factors (as network failures or saturation).
- **Dynamic deployment:** As any node is independent, the deployment of a network is straightforward given that any node will run on its own and no synchronization is needed. Also, to change the behaviour of the whole network, it would be enough to dispose some nodes and raise others, without affecting the rest of the network.
- **Scalability:** Changing the behaviour of a kind of node is easy, as all of them share the same code and are independent from the rest. Also, by creating new kinds of nodes many new configurations may be conceived, making the whole system flexible and growth-friendly.
- **Maintainability:** A large part of the node implementation is generic for all of them. In addition, each kind of node shares the same implementation. Therefore, the amount of code to implement

and maintain is greatly reduced, and highly reusable.

2.2 AML-IP scenarios

One of the biggest strengths of AML is the great parallelization capabilities that its design enables, allowing different kind of nodes to share their data in order to distribute the computational effort. These parallelization possibilities can be divided in two main types, depending on the scenario. Each of the scenarios correspond to a different use case and a parallelization method, but are not exclusive. Both can coexist at the same time in the same network.

Presenting the designs and behaviour for these scenarios is the main task of this document. The difference between them relies on the distinct communication architectures proposed, and hence the node kinds that each of them presents.

2.2.1 Collaborative learning scenario

Different AML-IP-Edge nodes collaborate on solving a common problem, each with the autonomy to work independently using distinct training datasets. This approach enables the creation of a more sophisticated and precise model by leveraging diverse data sources and perspectives. The output data being shared is independent of the dataset used to train the algorithm, so the training datasets can remain private while the resulting knowledge may be openly published and shared with the rest of the network. The AML-IP provides a collaborative and Internet wide network so remote and independent nodes have the possibility to work on the same problem and share their progress.

2.2.2 Workload distribution scenario

AML-IP-Edge nodes are responsible for training an AML model by handling individual data chunks. This training process is expensive and requires high computational power. However, it is also completely parallelizable. The AML-IP introduces a network architecture capable of efficiently distributing this computationally intensive workload across the network's nodes. This distribution occurs in a balanced and automated manner, irrespective of the nodes' physical location or ownership. This eliminates the necessity for centralized load balancing mechanisms.

2.2.3 Monitor network state scenario

AML-IP-Edge nodes perform real-time monitoring, analysis, and debugging of an AML network. This scenario plays a critical role in ensuring the health and efficiency of the network by constantly knowing and analyzing the status of the AML-IP nodes within it. Each AML-IP node is responsible for publishing its current status information, and this information is continually updated throughout the lifetime of each node.

2.2.4 Distributed inference scenario

AML-IP-Edge nodes primary objective is to efficiently distribute a substantial amount of data to remote nodes for the purpose of performing inference. This distribution aims to parallelize the inference process so that it does not interfere with other essential tasks that may need to run on the same devices. By implementing this measure, the system ensures the seamless execution of multiple tasks, optimising overall performance and resource utilisation.

2.3 Communication between AML nodes

The architecture on which this project focuses is based on the communication of different **AML nodes** through the Internet, freely distributing data and knowledge among them. The main points to be taken

into account in order to properly understand AML-IP are:

- **Distributed architecture:** There is no main access point to the network, nor is there a centralised server to provide communication. This means Peer to Peer (P2P) communication is required between different AML nodes.
- **DDS:** DDS will be the main communication protocol between nodes of the network.
- **World Wide Web (WWW):** This architecture is deployed over the Internet, allowing anyone with internet access to be part of the network.

Figure 1 presents a trivial example of an AML execution. There are several nodes along the network that work under a DDS topic. Each node can publish under these DDS topics and/or subscribe to them, communicating with all other nodes along the AML network working on these same topics. Thus a P2P communication is achieved in which communication is not centralised.

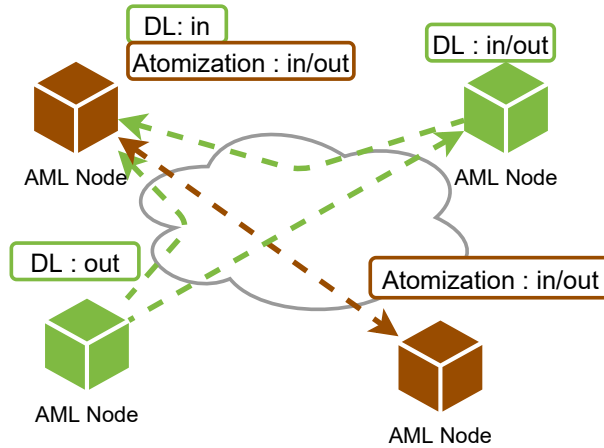


Figure 1: AML Nodes communicating with each other.

In the scenario shown in Figure 1, two types of AML nodes are presented. The green nodes communicate through the DL topic. This topic stands for the AML-IP Algebraic Description Language Node (AML-IP-DL), the language used by all AML nodes to communicate with each other. Moreover, the brown nodes represent AML computational engines. They produce a different type of data known as atomization. This atomization data can be either the input or the output of the node. Therefore these nodes can both publish this data type under the Atomization DDS topic or/and subscribe to it.

2.4 Requirements

This section describes the high-level requirements that the AML-IP must meet in order to achieve the functionality expected from such communication frameworks.

- **Decentralized Communication** Nodes must be able to communicate to each other without an intermediate communication server.
- **Publish/Subscribe Communication** Nodes must be able to communicate their data using DDS, a data-centric communication protocol used for distributed software application communications.
- **Logical Partition** Nodes must be able to communicate only with the nodes that required their information, avoiding to send data to nodes that do not require it.

- **Connection through Local Area Network (LAN)** Nodes must be able to communicate with different nodes running in the same LAN.
- **Connection through Wide Area Network (WAN)** Nodes must be able to communicate with different nodes running in various LAN, i.e. deployed in a WAN.
- **Dynamic discovery** The network must allow the creation or destruction of nodes along the execution.
- **Data Injection Nodes** AML is a growing project and hence there the platform must facilitate the addition of new types of nodes with new data formats along the project.

2.5 Enabling technologies

This section describes the different technologies that support the development of the AML-IP. All of them focus on the communication between nodes, the protocols used to support such communication and the tools used to handle the different types of data to be transmitted.

2.5.1 Data Distribution Service (DDS)

Given the distributed nature of the AML ecosystem, the use of DDS is proposed to enable real-time communication between AML nodes. As explained in the eProsima Fast DDS documentation [1]:

The Data Distribution Service (DDS) is a data-centric communication protocol used for distributed software application communications. It describes the communications Application Programming Interfaces (APIs) and Communication Semantics that enable communication between data providers and data consumers.

Since it is a Data-Centric Publish Subscribe (DCPS) model, three key application entities are defined in its implementation: publication entities, which define the information-generating objects and their properties; subscription entities, which define the information-consuming objects and their properties; and configuration entities that define the types of information that are transmitted as topics, and create the publisher and subscriber with its Quality of Service (Quality of Service (QoS)) properties, ensuring the correct performance of the above entities.

DDS uses QoS to define the behavioral characteristics of DDS Entities. QoS are comprised of individual QoS policies (objects of type deriving from QoSPolicy).

The different entities involved in the DDS protocol are also defined in [1].

In the DCPS model, four basic elements are defined for the development of a system of communicating applications.

- **Publisher.** *It is the DCPS entity in charge of the creation and configuration of the DataWriters it implements. The DataWriter is the entity in charge of the actual publication of the messages. Each one will have an assigned Topic under which the messages are published.*
- **Subscriber.** *It is the DCPS Entity in charge of receiving the data published under the topics to which it subscribes. It serves one or more DataReader objects, which are responsible for communicating the availability of new data to the application.*
- **Topic.** *It is the entity that binds publications and subscriptions. It is unique within a DDS domain. Through the TopicDescription, it allows the uniformity of data types of publications and subscriptions. See Topic for further details.*

- *Domain.* This is the concept used to link all publishers and subscribers, belonging to one or more applications, which exchange data under different topics. These individual applications that participate in a domain are called *DomainParticipant*. The DDS Domain is identified by a domain ID. The *DomainParticipant* defines the domain ID to specify the DDS domain to which it belongs. Two *DomainParticipants* with different IDs are not aware of each other's presence in the network. Hence, several communication channels can be created. This is applied in scenarios where several DDS applications are involved, with their respective *DomainParticipants* communicating with each other, but these applications must not interfere. The *DomainParticipant* acts as a container for other DCPS Entities, acts as a factory for Publisher, Subscriber and Topic Entities, and provides administrative services in the domain. See *Domain* for further details.

The dynamic addition of new entities to the network is also covered by the the DDS protocol, allowing the dynamic discovery of new instantiated DDS entities. The Discovery Protocol is the mechanism that DDS provides for the discovery of new entities.

Thus, DDS fulfills various communication requirements of the AML outlined in Section 2.4. However, the WAN communication, and specially the WAN dynamic discovery of newly instantiated DDS entities is a great challenge to DDS, as this protocol relies on multicast communication. The growing type of nodes and data formats makes a challenge in order to achieve fast DDS deployments over WAN.

2.5.2 eProxima Fast DDS

As described in the *Fast DDS* documentation [2]:

eProxima Fast DDS is a C++ implementation of the DDS (Data Distribution Service) Specification, a protocol defined by the Object Management Group (OMG). The eProxima Fast DDS library provides both an Application Programming Interface (API) and a communication protocol that deploy a Data-Centric Publisher-Subscriber (DCPS) model, with the purpose of establishing efficient and reliable information distribution among Real-Time Systems. eProxima Fast DDS is predictable, scalable, flexible, and efficient in resource handling. For meeting these requirements, it makes use of typed interfaces and hinges on a many-to-many distributed network paradigm that neatly allows separation of the publisher and subscriber sides of the communication.

Among the many features of *Fast DDS*, there are two key functionalities for the development of the AML-IP: a) the TCP transport, and b) the Discovery Server discovery mechanism.

Among the multiple transport protocols and communication mechanisms available in *Fast DDS*, the TCP transport protocol is implemented for data transmission between DDS entities in WAN networks. However, the configuration of DDS entities to use this protocol is not straightforward at this point. The purpose of the AML-IP is to implement a communications framework that uses the Transmission Control Protocol (TCP) communications protocol implemented in *Fast DDS* in a transparent manner for the user.

Moreover, according to [3]:

Fast DDS, as a Data Distribution Service (DDS) implementation, provides discovery mechanisms that allow for automatically finding and matching DataWriters and DataReaders across DomainParticipants so they can start sharing data.

The AML-IP framework will exploit the Discovery Server discovery mechanism described in [3] as follows:

This mechanism [Discovery Server] is based on a client-server discovery paradigm, i.e. the

metatraffic (message exchange among DomainParticipants to identify each other) is managed by one or several server DomainParticipants [...], as opposed to simple discovery [...], where metatraffic is exchanged using a message broadcast mechanism like an IP multicast protocol.

The *Fast DDS* Discovery Server is thought to reduce the traffic network and to assist in DDS discovery in cases where multicast is not an option in a dynamically scalable DDS networks. Moreover, it centralizes the discovery information for the *Fast DDS DomainParticipants* connected to it.

There are some key aspects that need to be covered in order to understand the Discovery Server discovery mechanism. The following can be gleaned from the *Fast DDS* online documentation [3]:

- *Discovery Server DomainParticipants may be clients or servers. The only difference between them is on how they handle discovery traffic. The user traffic [...] is role-independent.*

[...]

- *All server and client discovery information will be shared with linked clients. [...] a server may act as a client for other servers.*

- *A **SERVER** is a participant to which the clients (and maybe other servers) send their discovery information. The role of the server is to re-distribute the clients (and servers) discovery information to their known clients and servers. A server may connect to other servers to receive information about their clients. Known servers will receive all the information known by the server. Known clients will only receive the information they need to establish communication, i.e. the information about the DomainParticipants, DataWriters, and DataReaders to which they match. This means that the server runs a “matching” algorithm to sort out which information is required by which client.*

[...]

- *A **CLIENT** is a participant that connects to one or more servers from which it receives only the discovery information they require to establish communication with matching endpoints.*

2.5.3 Fast DDS Python Bindings

eProsima has recently developed a library that enables the use of Fast DDS from within a Python environment by binding the C++ library. This is a very useful feature for the ALMA project, as most of the code produced for AML is written in Python, and Python will most likely be the chosen language for the main framework with which the end users will interact.

2.6 Internal Protocols

This section briefly describes the protocols developed on top of DDS that enable AML-IP node communications as well as the deployment of the different 2.2.

2.6.1 DDS Topics

All the AML-IP Topics in the DDS AML-IP network have a previous name mangling. So an AML-IP topic named , `some_topic` would actually be named `amlip::some_topic` in the underneath DDS network.

2.7 MultiService Communication Protocol over DDS

The MultiService Communication Protocol (MSCP) is a new communication interface or protocol that exploits the advantages of DDS to create a specific protocol suitable for AML.

This new protocol has been designed by eProxima in order to fulfil the data transmission requirements for the different AML-IP-Alg, and it is not a final design but a work in progress that may be updated in the future for a more robust and efficient one.

2.7.1 Description

MSCP is a new protocol based on DDS that responds to communication necessities specific to the ALMA project. This protocol targets the communication between several clients and servers in a way that only one server processes a request from any client, thus avoiding the use of a load balancer. This allows to parallelize of certain computationally expensive tasks of a client in different servers.

Diagram 2 represents the general schema of the communication network that MultiService establishes. There are an arbitrary number of clients and an arbitrary number of servers, and each of them are independent of each other. The clients send their requirements, and one and only one server in the network will process that requirement and return a solution for it.

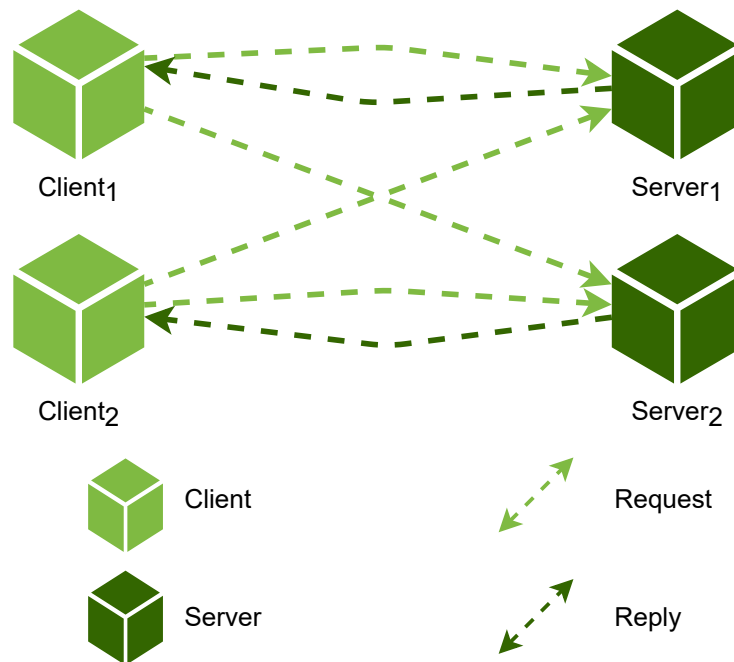


Figure 2: MSCP Schema.

2.7.2 Requirements

These are the requirements that the protocol must fulfil:

- **Remote procedure:** There must be nodes (*clients*) that create **tasks** (usually complex computational problems) and distribute them to other nodes (*servers*) that process them and return a result.

- **Node independence:** The behaviour of each node must be independent of the network where it is running. (e.g. a client must behave the same way if there are none, one or three servers in the network).
- **Dynamic network:** New nodes may enter and leave the network at any time and with any network address.
- **Efficient data distribution:** It must keep the amount of data transmitted over the network to a minimum. It must eschew duplicated or useless data transmissions. (e.g. Clients must avoid sending data to servers that will not process their requests).
- **Intelligent workload distribution:** The network must efficiently distribute the tasks between the servers available at that moment.
- **Fully distributed:** Avoid the use of central points so there are no bottle necks or single-point-of-failure nodes in the network.

2.7.3 Design

The idea behind the MSCP is to create an *intelligent* load-balanced network using only DDS communication between different nodes. For this purpose, a series of topics, QoS and data types have been created in order to accomplish such a goal.

In sequence diagram 3, it is shown the different messages that are exchanged between client and servers in order to achieve the communication of the data task and the answer with its solution.

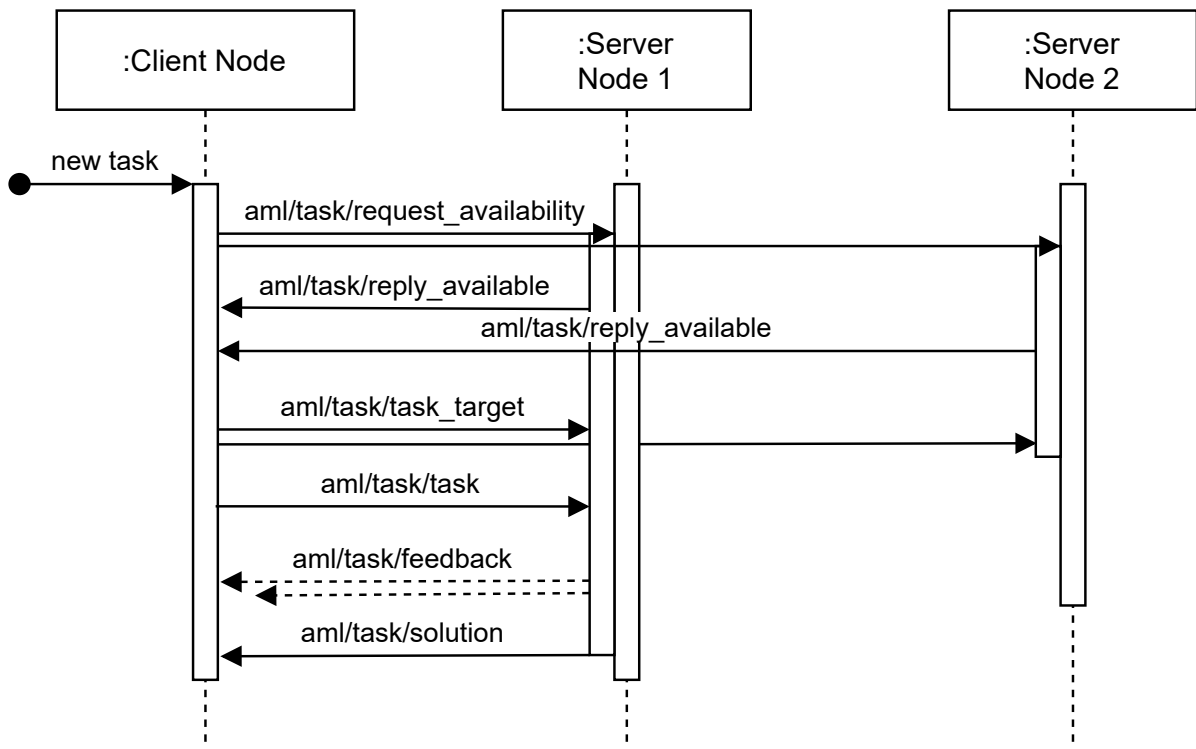


Figure 3: MSCP sequence diagram.

Figure 4 shows the different steps in the protocol communication between a client and a server. Following

are the steps of the communication process:

1. First a client publishes a request asking for any available server.
2. Whenever a server is available and receives such a request, it publishes a message reporting its availability for the task under consideration. After a server has replied, it remains blocked waiting for the confirmation from the client.
3. Once the client has received an availability reply from one of the servers, it marks it as the *target server*. That is the server that will be performing the client's task. This client publishes under a specific topic that this task is to be completed by the *target server*, communicating to this server that it is the one in charge of doing the work, and to the others that they are no longer required for the task at hand. Just after sending this message, the client sends the data relative to the task only to the *target server* (this could be achieved in DDS by using different mechanisms such as *partitions* or *ContentFilteredTopic*).
4. If a server is blocked in a specific task and it is not selected to be the *target server* when the **task_target** message is received, it unlocks and becomes available for new requests. If a server is *target server* for a client, it awaits for the task data to arrive. Once it is received, the *target server* starts the procedure.

For this reason, while the server is processing the task, there may be additional data being transmitted from the server to the client, announcing that the task is being processed (feedback).

5. In case the *target server* fails or stops, the client will start the process again. This would dissuade the client from thinking the request failed and start the process again.
6. Finally, when the server obtains the answer to the task it is sent back to the source client, which ends the communication process.

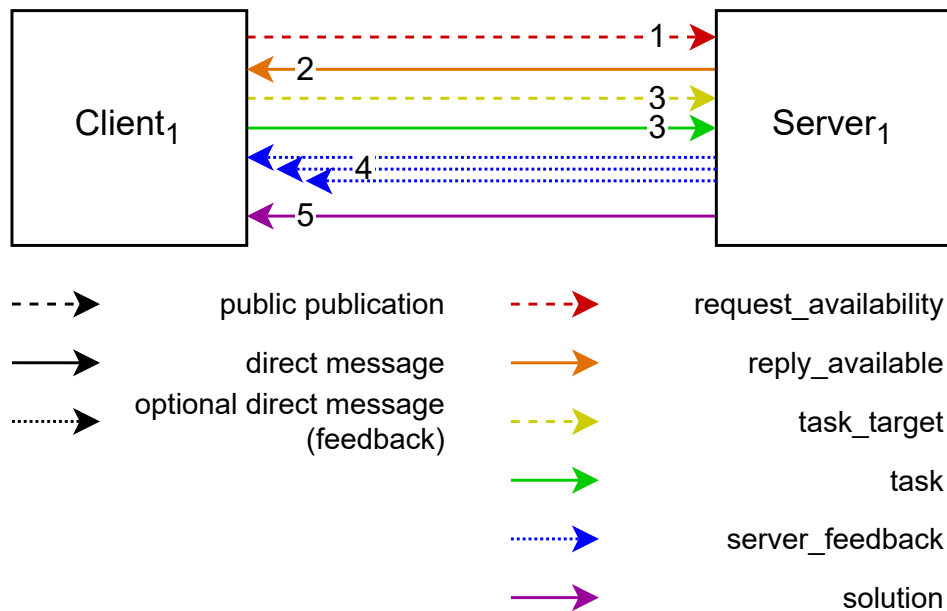


Figure 4: MSCP steps for single client-server communication.

In more complex cases involving several servers and/or several clients, the behaviour of each of them

would be the same. As it is shown in image 5, the communication process is similar when a client tries to find a server to process its task. The client will ask for availability, and for the multiple answers it could receive, it would choose only one server and communicate that decision to all servers. The target server will process the task while the other(s) will, after leaving the blocking state, start processing other availability tasks that may have arrived in the meantime. As the figure evinces, the time spent by a server in a blocking state for a task that will not process (because other servers will) is minimal, maximizing the time each server spends on execution procedures.

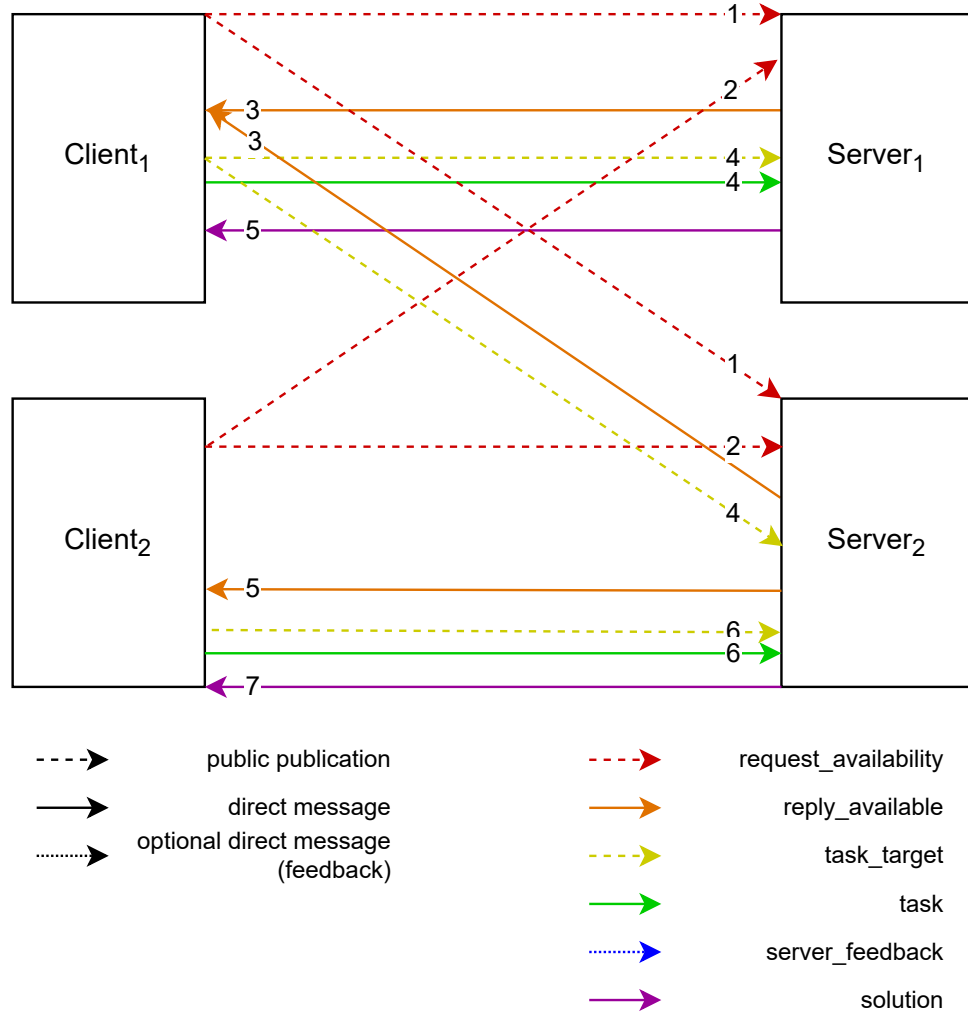


Figure 5: MSCP steps for multiple client-server communication. (In this figure, feedback messages have been removed for simplicity purposes).

2.7.4 Advantages and Limitations

The benefits that using MSCP offer are intrinsic to DDS, a fully distributed protocol, and the reliable synchronization between different nodes to decide which one processes each task. The main advantages that one could expect from this protocol (among others) are:

- **Fast response:** As can be seen in figure Figure 4, there are only three meta-traffic messages needed

in this communication protocol, avoiding extra handshaking or discovery messages of any kind.

- **Minimum blocking time:** The target server is decided upon the first reply listened by the Client. This means that, any other servers blocked for the same task will be rapidly informed that they are no longer required. Thus, the amount of time that a Server will be blocked for no useful purpose is minimum.
- **Automatic synchronization:** The synchronisation naturally arises from the protocol itself, and so does the workload balance, without the need of external nodes or agents to manage it.
- **DDS QoS:** The use of DDS protocol as the basis for MSCP allows to use certain QoS which are very convenient for its operation; the reliability QoS guarantees that every message sent is received by the corresponding destination entity, and the durability QoS that a message is kept for as long as it is required.
- **Node independence:** Each node is independent of the rest of the network, and it will behave exactly the same way in any scenario, which makes it very versatile and easy to implement. Also, the architecture does not depend on the task the server processes, what makes it very useful for many different assignments, and independent of the time in which each of them needs to be executed.

It is important to make clear that the MSCP is a communication mechanism that is in an early stage of development, and thus has not encountered any big issues so far. Still, it presents a number of limitations that may need to be addressed in later development phases. These are some of the problems that an architecture using MSCP could encounter:

- **Client drop:** When a client drops, the Server will not notice it, and will continue working on the received task even if its result no longer serves a purpose.
- **Data distribution:** Large data files (tasks and solutions) should only be sent from a client to its target server. However, this requires specific DDS features that were not available at the time of writing the present document.
- **Internal Synchronization:** This architecture is difficult to implement inside a Node, as it requires to synchronize several readers at the same time, and, in most cases, synchronize them from many threads. This leads to the challenging internal synchronization of an entity.

In future versions of this communication protocol, an effort will be made to increase the client-server feedback as well as public status information with the objective of improving the synchronization and efficiency of the architecture.

2.7.5 Topics and data types

In order to accomplish the MSCP communication, certain DDS topics and data types are required, even in the generic scenario (without knowing the specific task). It is important to notice that the MSCP is a generic protocol that does not depend on the underlying task that is being communicated. Thus, the topics and data types must be generic and reusable among tasks. One may think of a *task* as the kind of problem a server executes (e.g. in the case of AML-IP-Main and AML-IP-Computing the task is to obtain a new atomization from a batch of data).

As can be seen in figure 2, there exist 5 DDS topics (for each task). However, the number of types is lower because some topics may reuse others' types.

Data Types

- **Request Reference:** This data type uniquely identifies an availability request sent by a client to solve a particular task. Each client and task is identified by a unique id.

- **Task Reference:** This data type uniquely identifies a task that has already been assigned to a target server. It contains the client and server unique ids, as well as the id of the task.
- **Task:** This is the data type sent to the target server so it may execute the task. It references a specific task through a **TaskReference**, and contains the data to be processed. The nature of data depends on the task at hand, hence this data type must be generic enough so that, for any task under consideration, it is possible to expand this data type through class inheritance.
- **Solution:** This is the data type sent to the client after processing the task. It references a specific task through a **TaskReference**, and contains the solution for the processed task. This data also depends on the specific task, and hence must be implemented by means of inheritance.

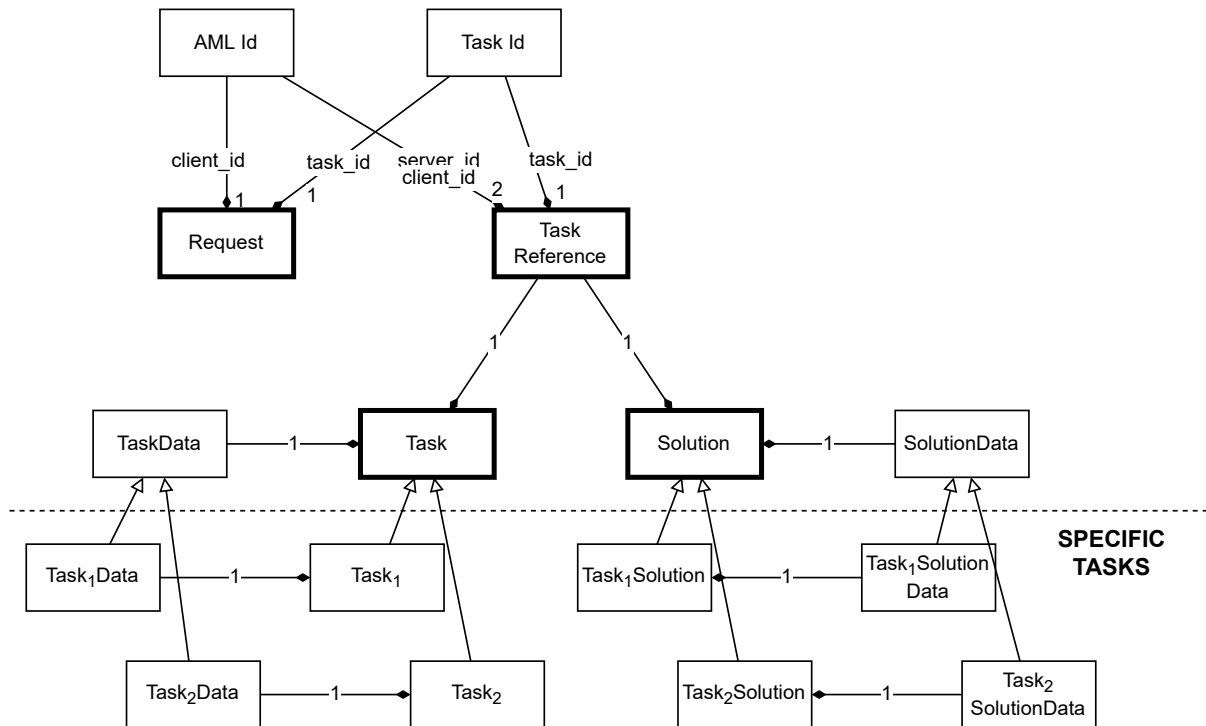


Figure 6: MSCP DDS Data Types.

Topics

- **request_availability:** client requests any server to notify their availability for a certain task.
- **reply_available:** server replies that is available for a specific client and task.
- **task_target:** client publishes which server is chosen to process that specific task.
- **task:** client publishes the task data to the target server.
- **solution:** server publishes the solution data for the given task to the source client.

Topic Name	Data Type	Node Publish	Node Subscribe
request_availability	RequestReference	Client	Server
reply_available	TaskReference	Server	Client
task_target	TaskReference	Client	Server
task	Task	Client	Server
solution	Solution	Server	Client

2.7.6 Use cases

The MSCP may be used for any scenario in which a client needs to commend a specific task to external servers that are specialized in performing such task. Obviously, this protocol perfectly fits the *AML-IP workload distribution scenario*, as it has been implemented mainly for this purpose. Nevertheless, there exist other possible scenarios within the AML-IP for which this protocol may (and will) be used:

- **Inference Request:** Certain nodes (edge) may be required to perform inference on some data for an AML model, but do not have enough computation power to do so. In this scenario, the edge node could work as a client and send the data to be processed (*task data*), so that any node with a proper atomization could perform the task and return the inference result (*solution data*).
- **Model Request:** When multiple nodes are working on the same atomization (model) collaboratively, only one of them would be the *best model* and all of them would have that knowledge. A node joining this network may request the best performing version of the model, and only one node should answer in order to avoid the exchange of redundant information.
- **Context Request:** It is very likely that a context description of the AML problems will be required in order to make the collaborative learning scenario possible, so that any node would be able to know on which problem it is working. This type of request could be sent from any node to a specific *context broker* node that would know how to handle it.

2.7.7 Alternatives

There were several already existing communication protocols that were considered for this scenario, but it was finally decided to design a new one, as none of them was able to fulfill all the requirements:

- **Server-Client over DDS:** Certain DDS environments as ROS 2 implement their own communication interfaces to recreate a Server-Client protocol using a specific architecture of DDS topics. However, this protocol is only able to connect one client with a single server, and does not allow to dynamically connect new servers to the network, neither to maintain the independence between a client and its server.
- **Master/slave model:** This communication model fulfills many of the requirements, but still fails to make possible for a server (slave) to work with different clients (masters), as every slave belongs to only one master.
- **Remote Procedure Call (RPC):** There exists an implementation of the RPC protocol over DDS developed by eProxima that could have been used for this purpose. Yet, it could not be utilized for this case because, in this architecture, every server receives requests from every client, and all of them would process the same data, thus duplicating effort.
- **Load Balancer:** A *Load Balancer* node would meet most of the requirements for this protocol. However, it is important to decentralize the application, avoiding single points of failure that would make the network highly vulnerable.

2.8 Remote Procedure Call

The RPC has been implemented based on DDS to meet the need to distribute requests and replies across an AML network.

This implementation has been crafted by eProsima in order to fulfill the distinct communication demands of the ALMA project, thereby fulfilling the essential data transmission requirements across various nodes.

2.8.1 Description

RPC based on DDS implementation responds to communication necessities specific to the ALMA project. This protocol targets the communication between several clients and servers in a way that only one server will receive and process the request of a client, thus avoiding the use of a load balancer. Unlike how it is implemented in ROS 2 (with Fast DDS as middleware), topic mangling is used for the communication between the servers and clients.

Diagram 7 represents the general schema of the communication network that RPC establishes. There are an arbitrary number of clients and an arbitrary number of servers, and each of them are independent of each other. Clients initiate requests that are channelled to a singular server in the network, which processes the request and subsequently furnishes a response.

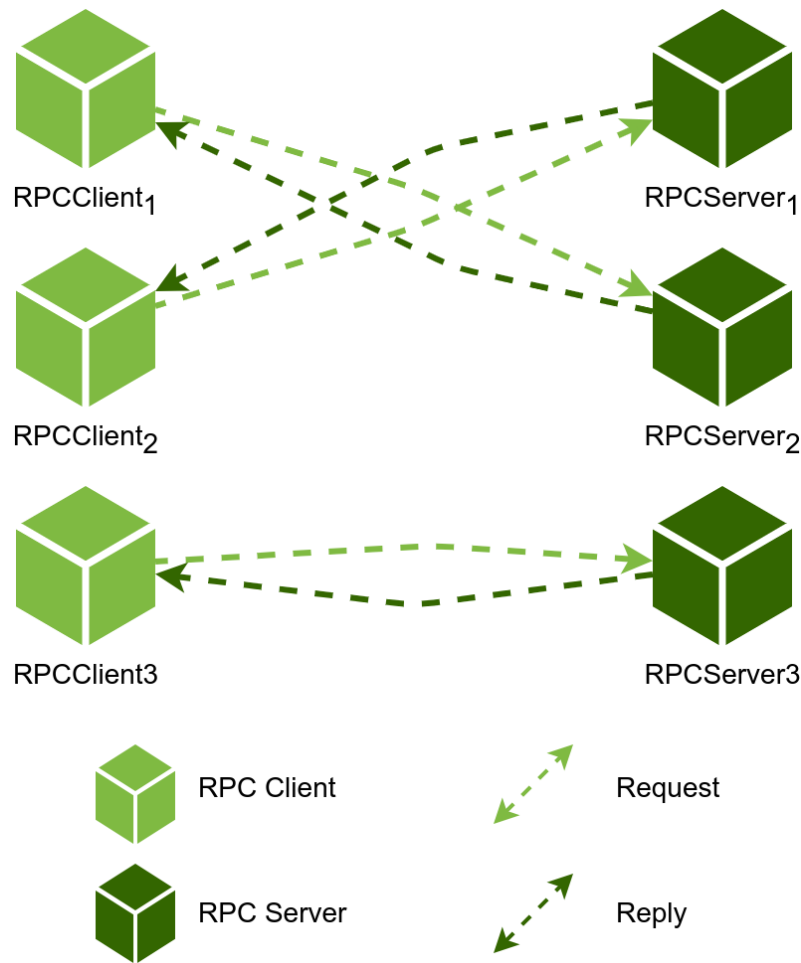


Figure 7: RPC Schema.

2.8.2 Requirements

Similar to MSCP, the RPC protocol adheres to a set of stringent requirements to ensure its seamless operation within the AML-IP ecosystem:

- **Remote procedure:** There must be nodes (*clients*) that create **requests** and distribute them to other nodes (*servers*) that process them and return a reply.
- **Node independence:** The behaviour of each node must be independent of the network where it is running. (e.g. a client must behave the same way if there are none, one or three servers in the network).
- **Dynamic network:** New nodes may enter and leave the network at any time and with any network address.
- **Efficient data distribution:** It must keep the amount of data transmitted over the network to the minimum. It must eschew useless data transmissions. (e.g. Clients only send requests to servers that match with their specific areas of interest.).

- **Fully distributed:** Avoid the use of central points so there is no bottle necks or single-point-of-failure nodes in the network.

2.8.3 Design

The idea behind the RPC is to distribute requests and replies across a network using only DDS communication between different nodes. For this purpose, a series of topics, QoS and data types have been created in order to accomplish such goal.

In sequence diagram 8, it is shown the different messages that are exchanged between client and servers in order to achieve the communication of the request and the answer with its reply.

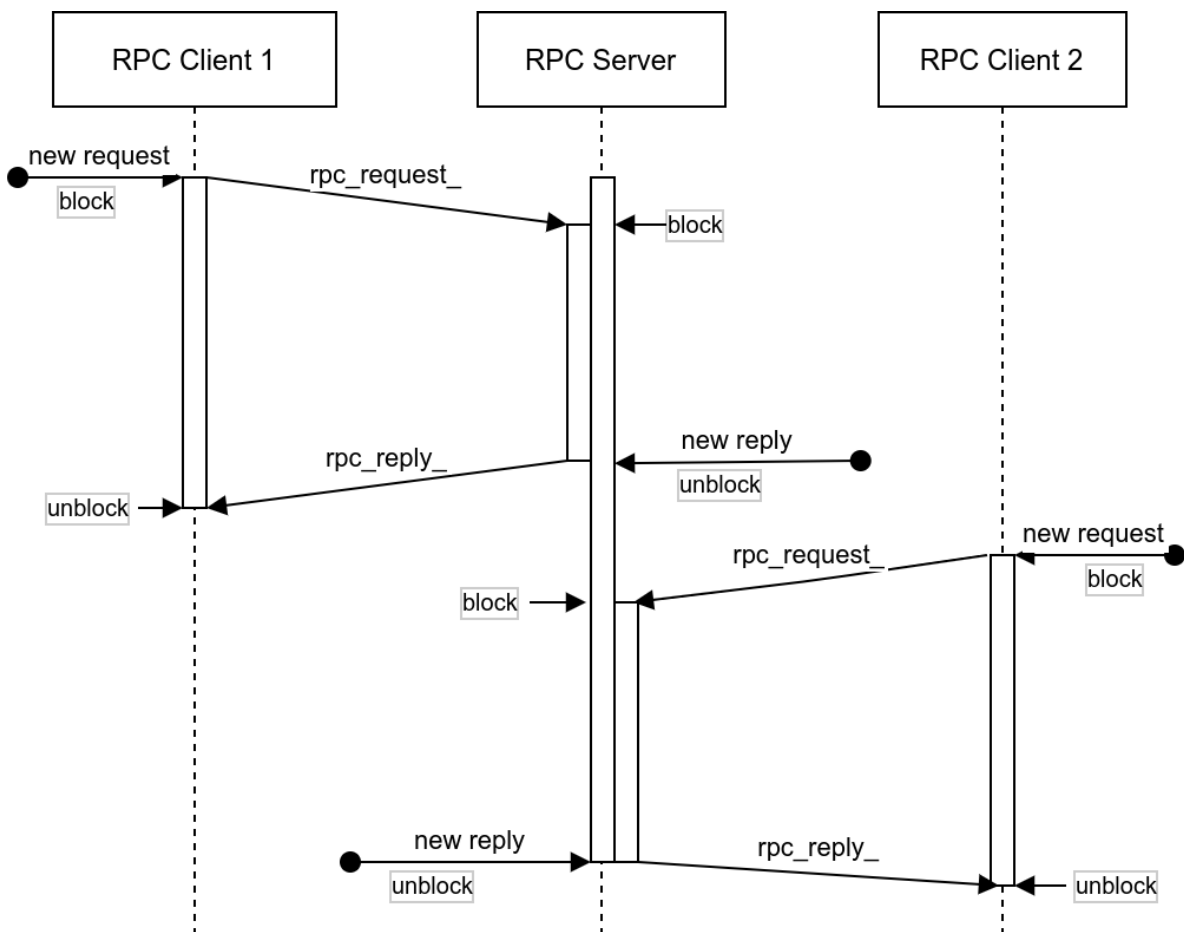


Figure 8: RPC sequence diagram.

Figure 9 shows the different steps in the protocol communication between a client and a server.

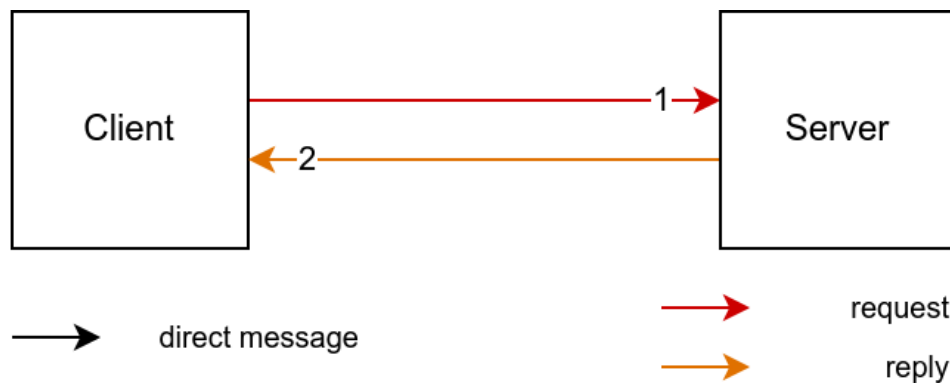


Figure 9: RPC steps for single client-server communication.

In more complex cases involving several servers and/or several clients, the behaviour of each of them would be the same.

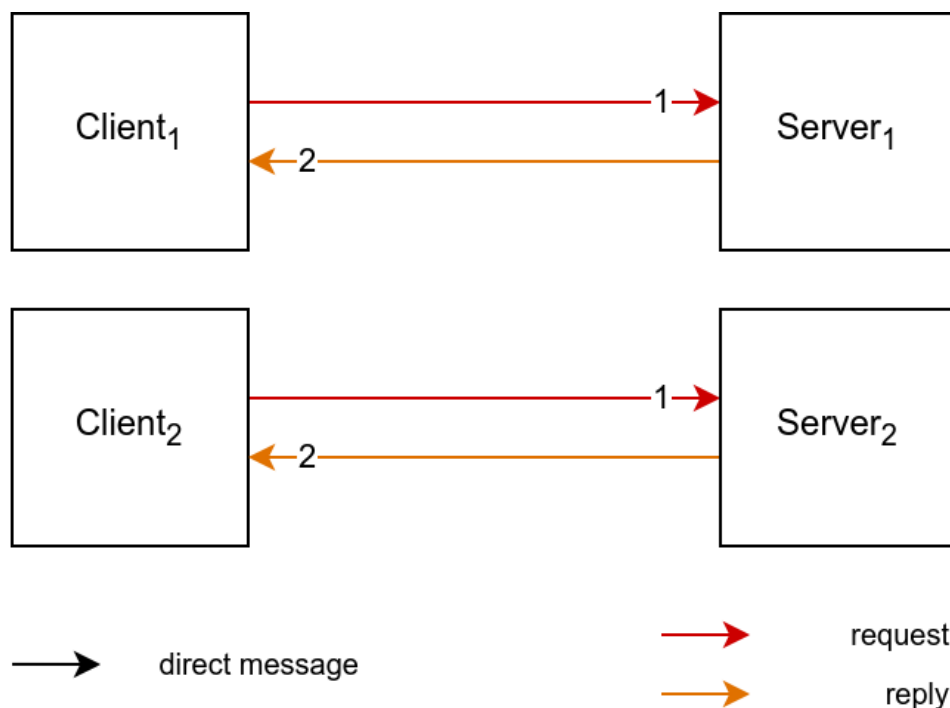


Figure 10: RPC steps for multiple client-server communication.

2.8.4 Topics and data types

In order to accomplish the RPC communication, certain DDS topics and data types are required. It is important to notice that the RPC is a generic protocol that does not depend on the underlying request that is being communicated. Thus, the topics and data types must be generic and reusable among replies. One may think of a *request* as the kind of problem a server executes (e.g. in the case of AML-IP-MMReceiver and AML-IP-MMSender the request is to obtain a new model).

Data Types

- **RpcRequestDataType**: This data type uniquely identifies an availability request sent by a client to a target server. It contains the client and server unique ids, as well as the id of the task.
- **RpcReplyDataType**: This is the data type sent to the client after processing the request. It contains the client and server unique ids, as well as the id of the task.

Topics

- **rpc_request**: client requests a server.
- **rpc_reply**: server replies.

Topic Name	Data Type	Node Publish	Node Subscribe
rpc_request	RpcRequestDataType	Client	Server
rpc_reply	RpcReplyDataType	Server	Client

2.9 AML-IP integration with external frameworks

The AML-IP is designed in order to be compatible with external frameworks, making it more usable and increasing its acceptance and range. Main frameworks that will be compatible with the AML-IP are:

- **ROS 2** is a highly widespread robotics framework. The AML-IP uses the same middleware as ROS 2, allowing to create ROS 2 nodes compatible with the AML architecture.
- **FIWARE** provides some online services (e.g. *Context Broker*). The AML-IP implements a FIWARE Node that allows communicating with some of the Context Broker services when required.

3 AML Available Resources

In this section, we will explore the various resources available for AML. These resources are essential to stay informed, to use AML-IP technology effectively, and to contribute to the ongoing success of AML.

3.1 ALMA Project Website

The ALMA Project Website ² serves as a central hub for information related to AML.

Here, you can find the latest news, updates, and important announcements regarding our efforts in the field of Algebraic Machine Learning. Additionally, the website provides access to essential publications, work package overviews, published scientific articles, and public deliverables, which can aid in understanding the complexities of AML in data science and machine learning. In addition, multiple demos and tutorials are regularly uploaded to the Latest News ³ section of the website to help users navigate and use the tools effectively.

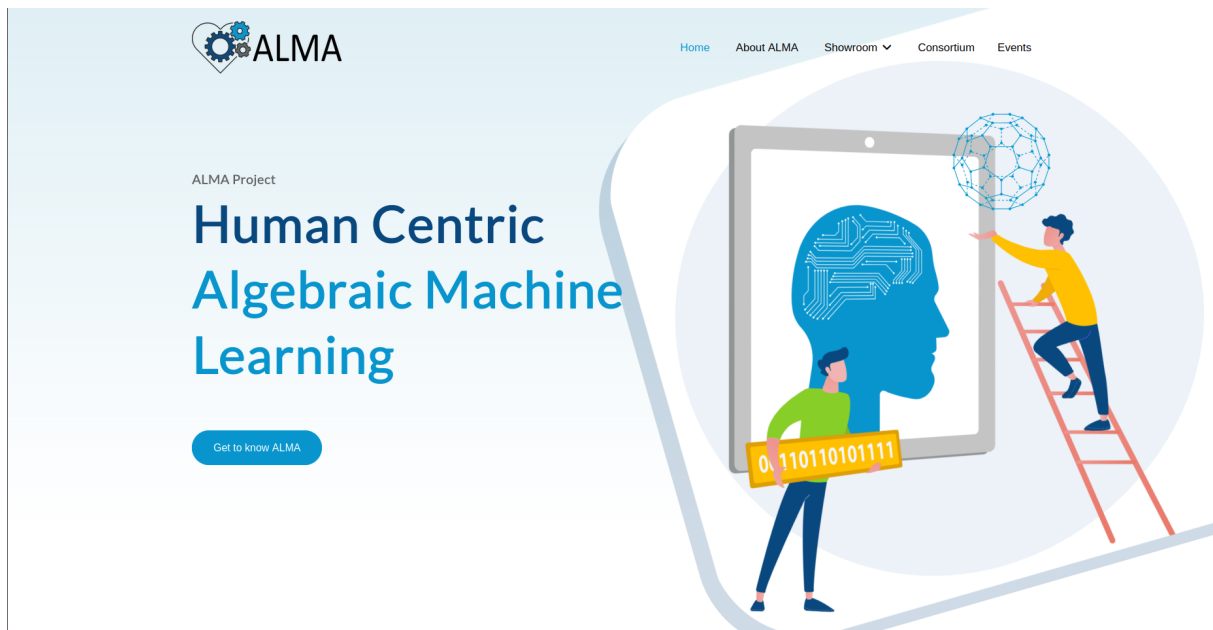


Figure 11: ALMA Website: <https://alma-ai.eu/>.

²<https://alma-ai.eu/>

³<https://alma-ai.eu/showroom/news>

3.2 AML-IP Documentation

The AML-IP Documentation⁴ offers detailed information about the AML-IP framework developed as a key component of the ALMA project.

This documentation provides a wealth of resources, including:

- An installation manual to help you set up AML-IP on Windows and Linux.
- A getting started section offering an overview of the project to facilitate a smooth initiation.
- Demonstrative examples illustrate various scenarios, making it easy for you to grasp how the framework works.
- An user manual that provides in-depth explanations of all available scenarios, nodes, and tools, ensuring that you can harness the full potential of AML-IP.
- Lastly, a developer manual with intricate details for advanced users who wish to explore the project's inner workings.

Whether you are new to AML-IP or an experienced user, this documentation is designed to meet your needs, offering guidance at various levels of expertise.

To access the Documentation, visit: <https://aml-ip.readthedocs.io>.

⁴<https://aml-ip.readthedocs.io>


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eProxima AML-IP Documentation



eProxima AML-IP is a communications framework in charge of data exchange between Algebraic Machine Learning (AML) nodes through local or remote networks. It is designed to allow non-experts users to create and manage a cluster of AML nodes to exploit the distributed and concurrent learning capabilities of AML. Thus, AML-IP is a communication framework that makes the transport protocols abstracted from the user, creating a platform that communicates each node without requiring the user to be concerned about communication issues. It also allows the creation of complex distributed networks with one or multiple users working on the same problem.

This framework is developed as part of the [ALMA project](#), which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952091. The aim of the EU-funded ALMA project is to leverage AML properties to develop a new generation of interactive, human-centric machine learning systems. These systems are expected to reduce bias and prevent discrimination, remember what they know when they are taught something new, facilitate trust and reliability and integrate complex ethical constraints into human-artificial intelligence systems. Furthermore, they are expected to promote distributed, collaborative learning.

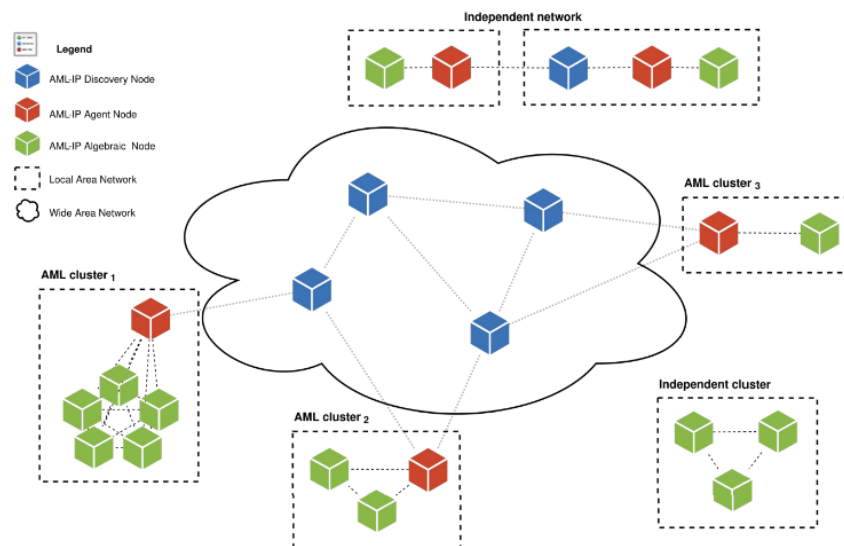


Figure 12: AML-IP Documentation.

Feel free to refer to this documentation as your go-to resource for mastering the AML-IP framework and unlocking its potential for your projects.

3.3 AML-IP GitHub Repository

For those interested in exploring the technical aspects of the AML-IP software and actively contributing to its ongoing development, the AML-IP GitHub Repository⁵ is the place to go.

This repository serves as a wealth of resources, including:

- **Source Code:** Access the heart of AML-IP technology, explore its inner workings, and leverage it for your specific needs.
- **Issue Tracker:** Collaborate effectively by reporting issues, suggesting improvements, and engaging in discussions with our development team and fellow contributors.
- **Developer Tools:** Utilize a suite of tools and resources tailored for developers and researchers to streamline your contributions.

It's a dynamic and open environment where both individuals and organizations can actively participate in shaping the future of AML-IP technology, fostering innovation, and advancing the field of AML.

To access the AML-IP GitHub Repository, please visit: <https://github.com/eProsima/AML-IP>.

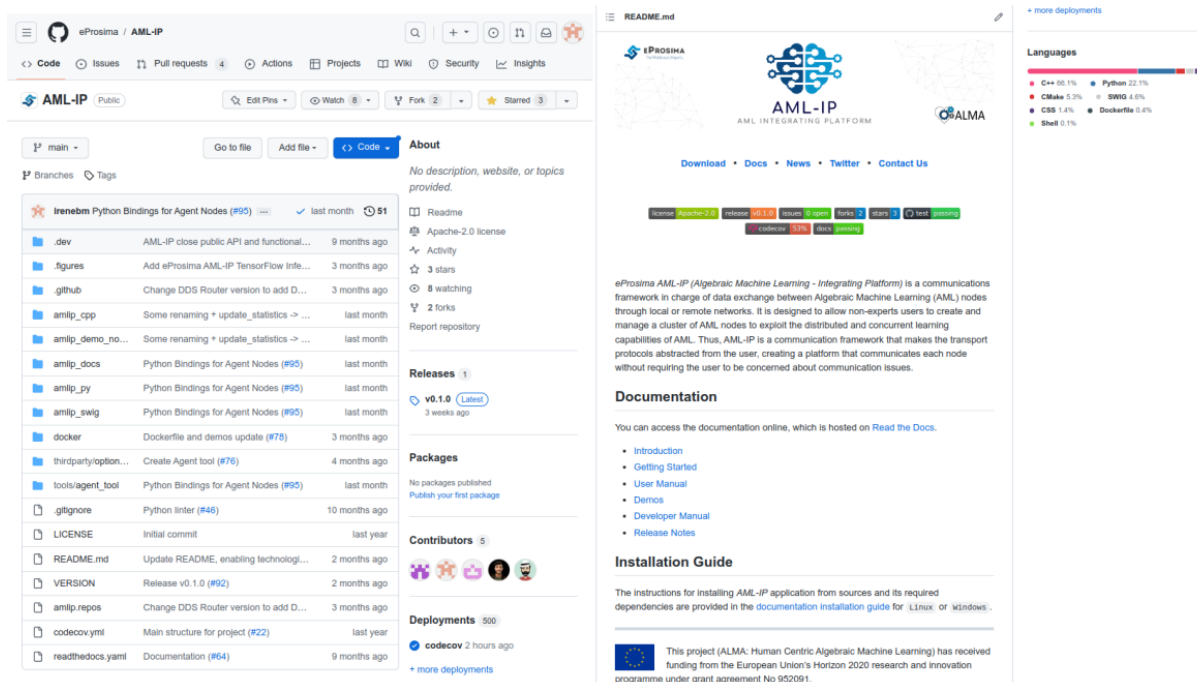


Figure 13: AML-IP GitHub Repository.

⁵<https://github.com/eProsima/AML-IP>

3.4 AML-Toolkit Documentation

AML Toolkit⁶ is a set of software tools that allow users to develop, train, and deploy AML models. These tools are designed to be used by researchers, developers, and industry professionals who want to implement AML models in their applications. AML Toolkit aims to provide users, developers, and researchers with the documentation, guides, and examples needed to start working with AML.

These tools cover the entire process of developing AML applications, from data collection and preprocessing to generating embeddings for problem description, validating those embeddings, training the model using an AML engine, performing inference using the resulting AML model, and validating the results.

To access the AML Toolkit Documentation, please visit: <https://aml-tools.readthedocs.io/en/latest/rst/formalia/titlepage.html>.

For more details on AML-Toolkit, refer to Deliverable *D6.6 - Open source experimentation tools - Final*

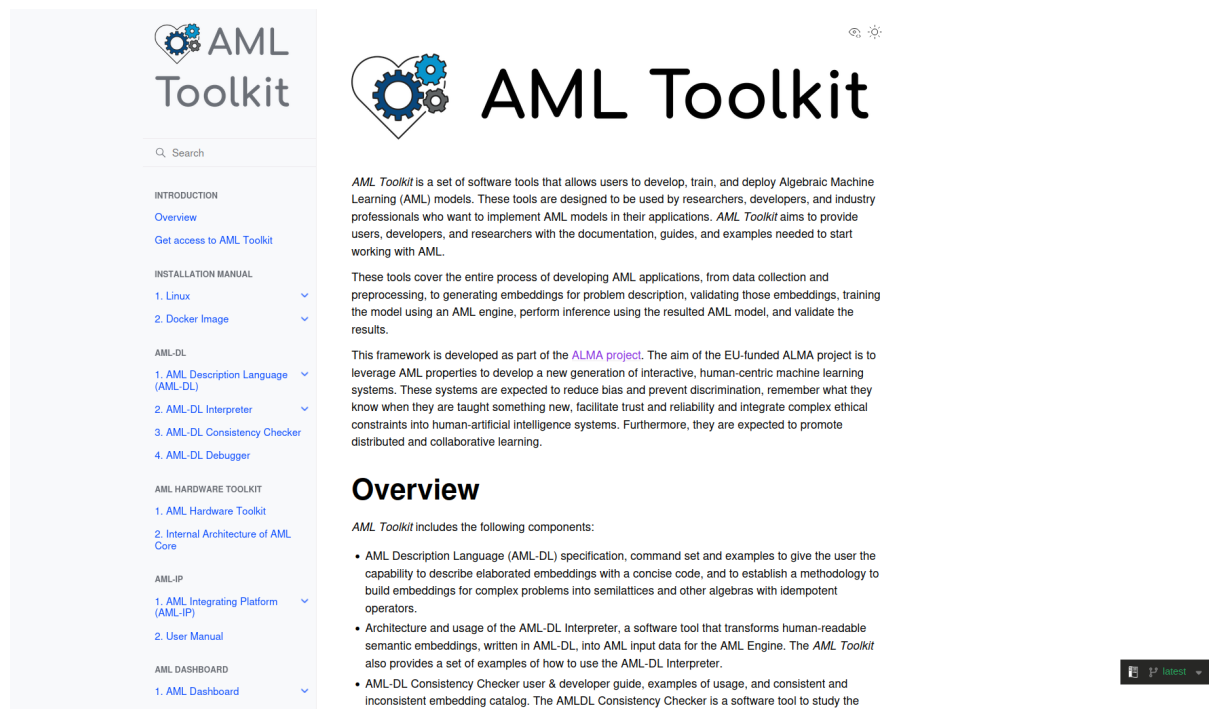


Figure 14: AML Toolkit Documentation.

⁶<https://aml-tools.readthedocs.io/en/latest/rst/formalia/titlepage.html>

3.5 AML-Dashboard

The **AML Dashboard** emerges as a user-friendly platform for training, evaluating, and applying AML models across several datasets.

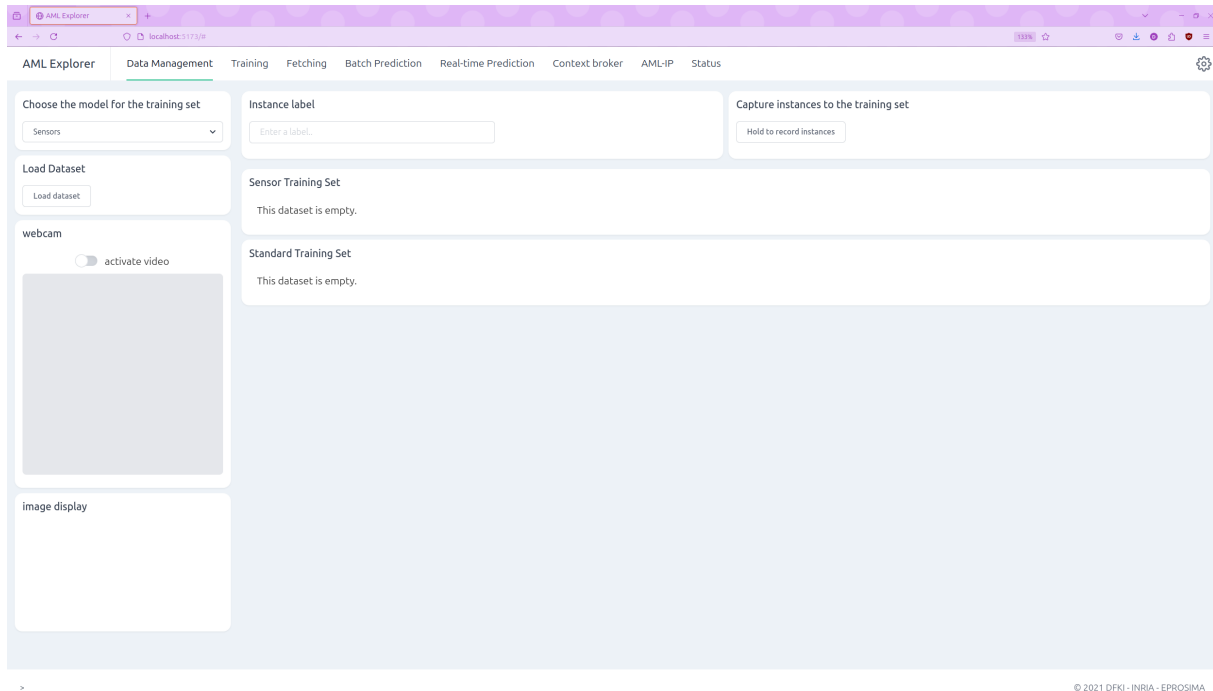


Figure 15: AML-Dashboard Data Management Tab

The primary goal of the AML Dashboard is to enable users to:

- **Collect and Manage Data:** Record personal gesture data or load existing datasets.
- **Train Models:** Train classifiers using the AML Engine.
- **Evaluate Performance:** Compare AML models with other machine learning approaches.

The Dashboard is structured into various interfaces, each tailored to specific stages of the AML workflow.

Data Collection The **Data Collection** tab allows users to efficiently create, load, and manage datasets. Users can record gesture data, load standard image classification datasets, or upload custom datasets. A dataset browser enables easy navigation, offering tools to explore, modify, or delete images and manage class labels.

Training The **Training** page is where users can configure and monitor the training process of the AML model. It provides options to set training parameters, track the training progress, and compare the performance of the AML model with other classifiers. Additionally, users can train both the AML model and a neural network model for future comparison.

Fetching This interface simplifies the retrieval of AML statistics and trained models. Users can search for specific statistics or request AML models with just a few clicks.

Explore Models A confusion matrix is provided based on the trained model. Users must actively trigger the update of the matrix, facilitating a clear before-and-after comparison.

Real Time Pattern Exploration After training the models, users can move to the **Real Time Pattern Exploration** interface. This part of the AML Dashboard allows users to explore music patterns using the self-trained models. This feature is only available when the dataset contains captured gesture data.

Context Broker Interaction This tab facilitates integration with the Context Broker, allowing users to upload images, perform inference tasks, and receive predictions from trained AML models.

AML-IP Nodes Management This interface facilitates the management of the AML-IP nodes within the network. Users can switch between tabs to create and destroy agent, computing, inference, and sender nodes.

Status The **Status** tab offers a comprehensive view of all active AML-IP nodes, displaying their ID, type, and operational status.

Use Cases

The eProsima AML Dashboard is designed for developers and computer scientists who aim to implement and evaluate multiple AML models. It offers a user-friendly interface alongside sophisticated tools that facilitate the evaluation, refinement, and validation of models across diverse scenarios. This platform enables users to systematically monitor model performance and implement necessary adjustments.

The AML Dashboard can be installed using the detailed steps provided in the AML-Tools Documentation⁷ as well as diving into more comprehensive tutorials to get started.

⁷<https://aml-tools.readthedocs.io/en/latest/rst/installation/linux/amldashboard.html#amldashboard-linux>

4 AML-IP Architecture

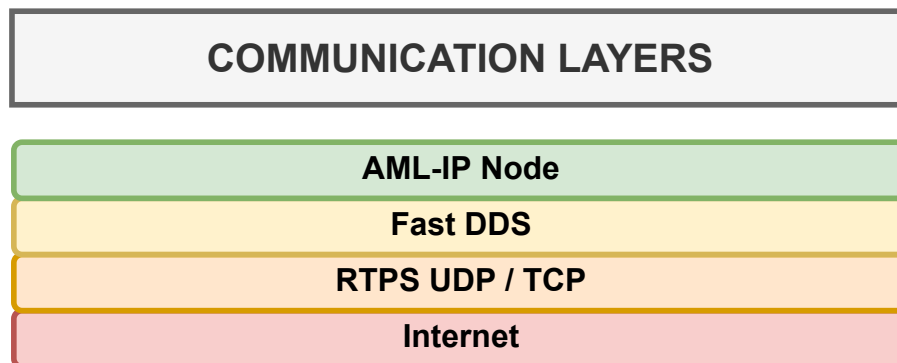
In this section the AML-IP design is presented and discussed. This does not intend to be a final product design, but a dynamic and living design that fulfills the actual project requirements and handles future scalability and emerging requirements.

4.1 AML-IP architecture description

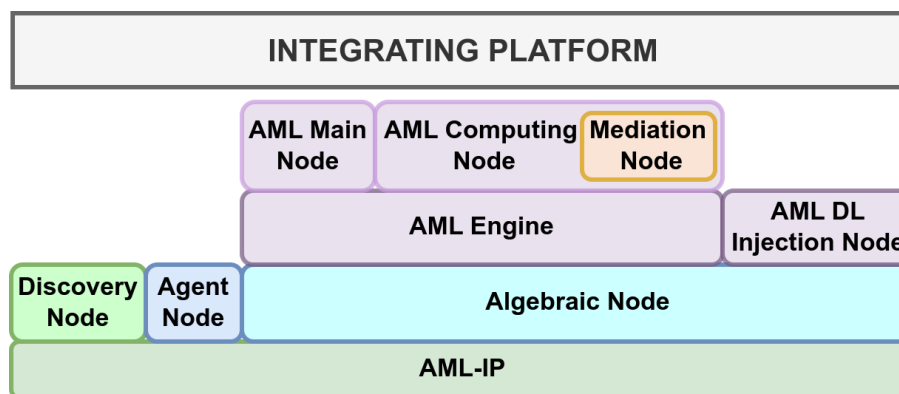
The approach this design has followed is focused on the division of the different AML-IP components that constitute the network. In order to divide the computational effort, to distribute the communication process and to create an scalable and widely usable architecture, the components of the AML-IP are divided in four categories, i.e. the AML-IP architecture consists of three types of nodes:

- **AML-IP Algebraic Node (AML-IP-Alg):** These nodes represent each of the instances of the AML.
- **AML-IP Mediation Node (AML-IP-Mediation):** These nodes have been introduced to facilitate seamless data transformation between different formats.
- **AML-IP Agent Node (AML-IP-Agent):** This is the main transport component that manages the dynamic discovery of AML-IP-Algs deployed within a LAN and the discovery of other AML clusters over WAN.
- **AML-IP Discovery Node (AML-IP-D):** These components will be disseminated along the network and made accessible through the Internet. They manage the WAN discovery process along the whole AML environment, handling the discovery of independent AML clusters and efficiently connecting the AML-IP-Alg that must connect to each other.

The general architecture of the AML-IP is displayed in Figure 16. It shows how the AML-IP would integrate all transport and network elements (16a), as well as all types of AML-IP nodes and the hierarchy among them (16b).



(a) AML-IP communication layer model.



(b) AML-IP nodes layer model.

Figure 16: AML-IP Architecture

Figure 17 shows a general example of an AML network and how the AML-IP will establish a communication method for the distributed nodes. The AML-IP Discovery Nodes (AML-IP-Ds) are network nodes that are distributed along the Internet and work as a *well known address* in order to manage the WAN discovery. Other kind of nodes are the AML-IP-Agents, network nodes deployed by each user. They manage the connection between a LAN cluster and the rest of the network. The AML cluster is just a group of nodes inside the same LAN that can communicate with each other within the LAN to which they belong.

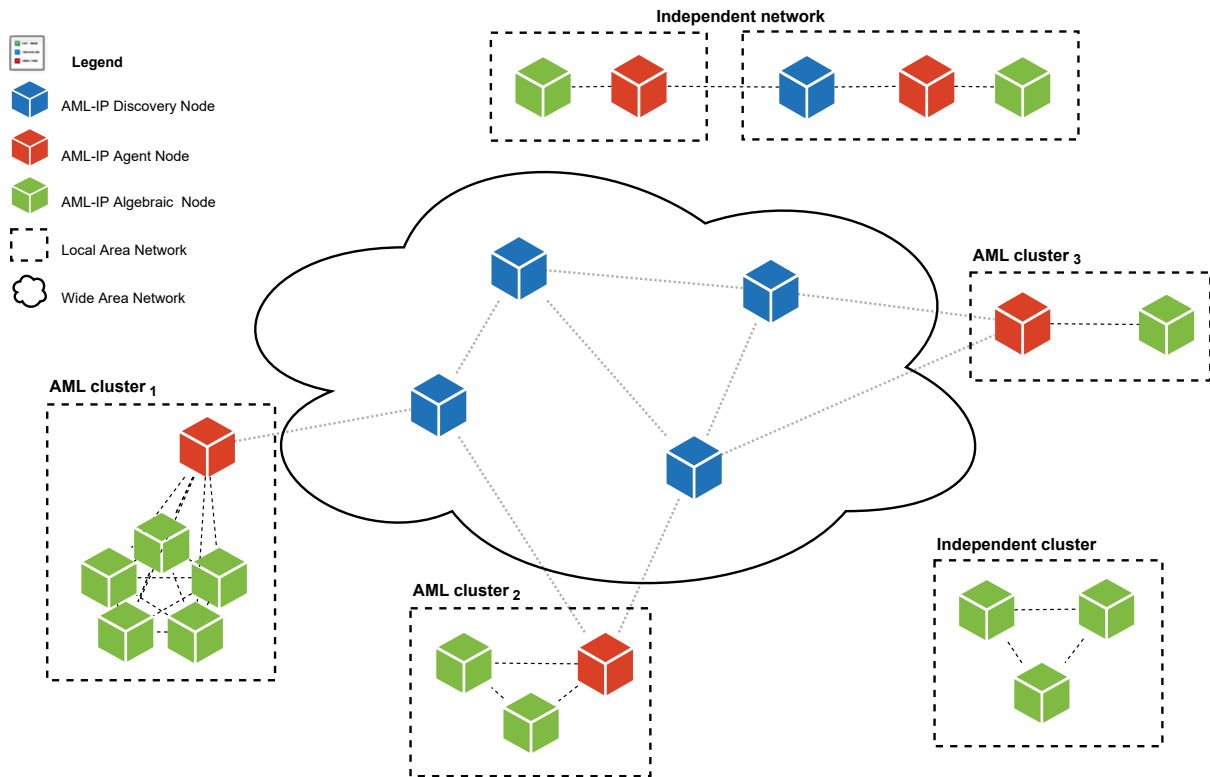


Figure 17: AML-IP example in LAN and WAN networks.

4.2 AML-IP functional operation

This section explains and exemplifies the communication process of all nodes within the the AML-IP. The differences between the various stages of inter-node communication are also explained. Finally, the type of communication is distinguished according to the location of the nodes in the network, i.e. whether the nodes belong to the same local network (LAN) or whether they are located in different networks (WAN).

4.2.1 Phases of communication

The communication process in DDS is divided in two phases: the discovery phase and the data transfer phase:

- **Discovery phase:** The discovery phase establishes the mechanism by which new DDS entities are detected by other entities already operating in the network. New entities communicate their arrival in the network via messages to a multicast group, and continue sending these messages in order to discover new entities or inform known entities of their current status. These messages are required to maintain the network state in a dynamic and distributed way.
- **AML data transfer phase:** This phase corresponds to the transfer of data required by the AML-IP-Alg to correctly execute their function.

4.2.2 AML-IP operational area networks

The networks in which the AML-IP could operate are the Local Area Network (LAN), whether all the hosts are under the same switch or router and share a private network; or the Wide Area Network (WAN), where nodes are distributed along a wide network and usually behind different Network Address Translations (NATs).

In the figure 18 it is represented an example of communication between different kinds of nodes deployed in LAN and WAN. The discovery and the data transfer phases depends on the network type. The node behaviour in each network kind are explained in the following sections.

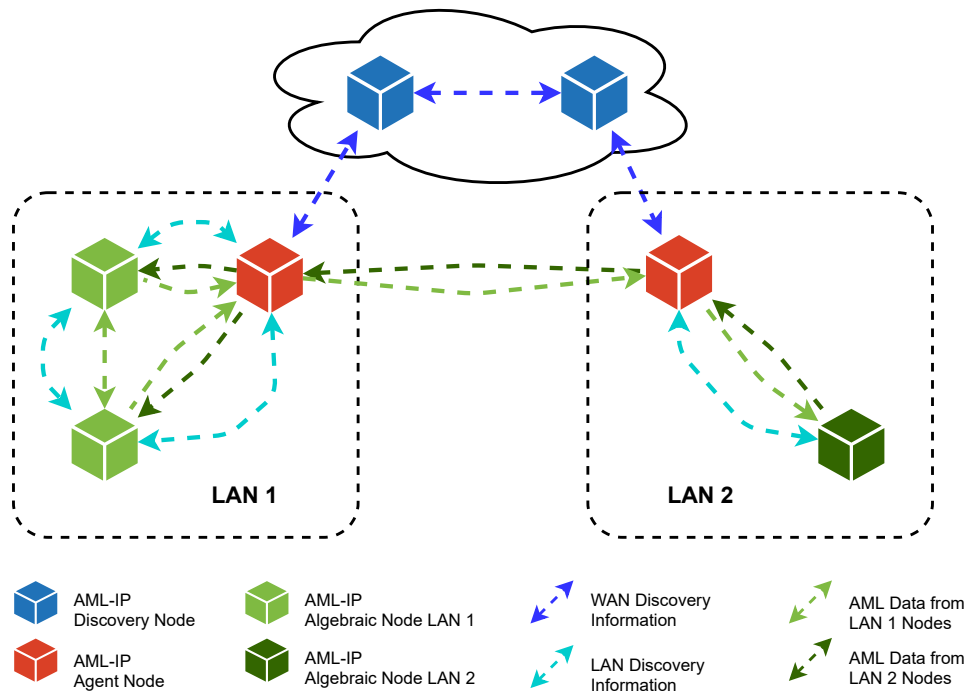


Figure 18: AML-IP minimum example to describe LAN and WAN communication.

4.2.3 AML-IP Communication in LAN

In LAN communication each node will discover each other by publishing and listening in a multicast group inside the network. In computer networking, multicast is a group communication that enables the data transmission to multiple targets [4].

The discovery mechanism used in LAN communication is called *Simple Discovery Protocol* [2], the standard protocol for dynamic discovery in DDS. This way, every AML-IP-Alg in the network will know each other, and they will discover an instance of AML-IP-Agent in case it exists. Once the discovery has been established, each node will communicate with each other directly, as long as one node is publishing and the other subscribed to the same shared topic. The AML-IP agent will subscribe to each topic existing in the network, and it will collect the data published in them and resend it through WAN.

Figure 19 represents an easy example on how the LAN communication will operate. The top and middle network architectures (steps 1 and 2) of Figure 19 show the discovery phase between all the components of the AML network, which are the AML-IP-Alg in this case. Assuming that they all belong to the same

multicast group, they will send their data to the other network nodes in that multicast group, and in turn they will all receive the information from the other nodes in that group. The network architecture at the bottom of Figure 19 (step 3) shows the data transfer phase, which is performed directly between the AML-IP-Alg that have been matched in the previous discovery phase.

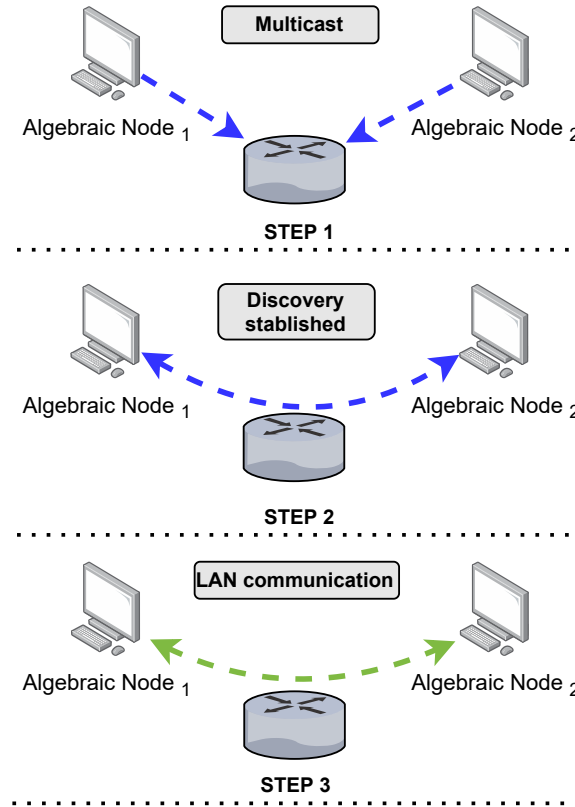


Figure 19: LAN communication schema.

4.2.4 AML-IP Communication in WAN

In WAN communication, the discovery protocol used is different than in LAN. Due to the impossibility of using multicast in WAN, the discovery mechanism must be centralized in an AML-IP node referred to as AML-IP-D. Connecting AML-IP-Agent to an AML-IP-D will make this node to know every other node in the network operating under the same topics, as well as every other AML-IP-Agents already deployed will know the new one.

A simple example of WAN communication is shown in figure 20. Once an AML-IP-Agent connects to the AML-IP-D it receives all the necessary information to communicate P2P with the rest of the nodes. The first step shows a stable network architecture in which there are two agent nodes, referred to as *AgentNode₁* and *AgentNode₂*, that have already been matched and know each other, and the appearance in the network of a new *AgentNode₃*. Moreover, during this first stage, *AgentNode₃* sends its discovery information to *DiscoveryNode₁*. In the second stage, *DiscoveryNode₁* sends to *AgentNode₁* and *AgentNode₂* the discovery information of *AgentNode₃*, and to *AgentNode₃* the discovery information of the first two agent nodes. Finally, in stage 3, all nodes have been matched and are ready to exchange AML data with each other.

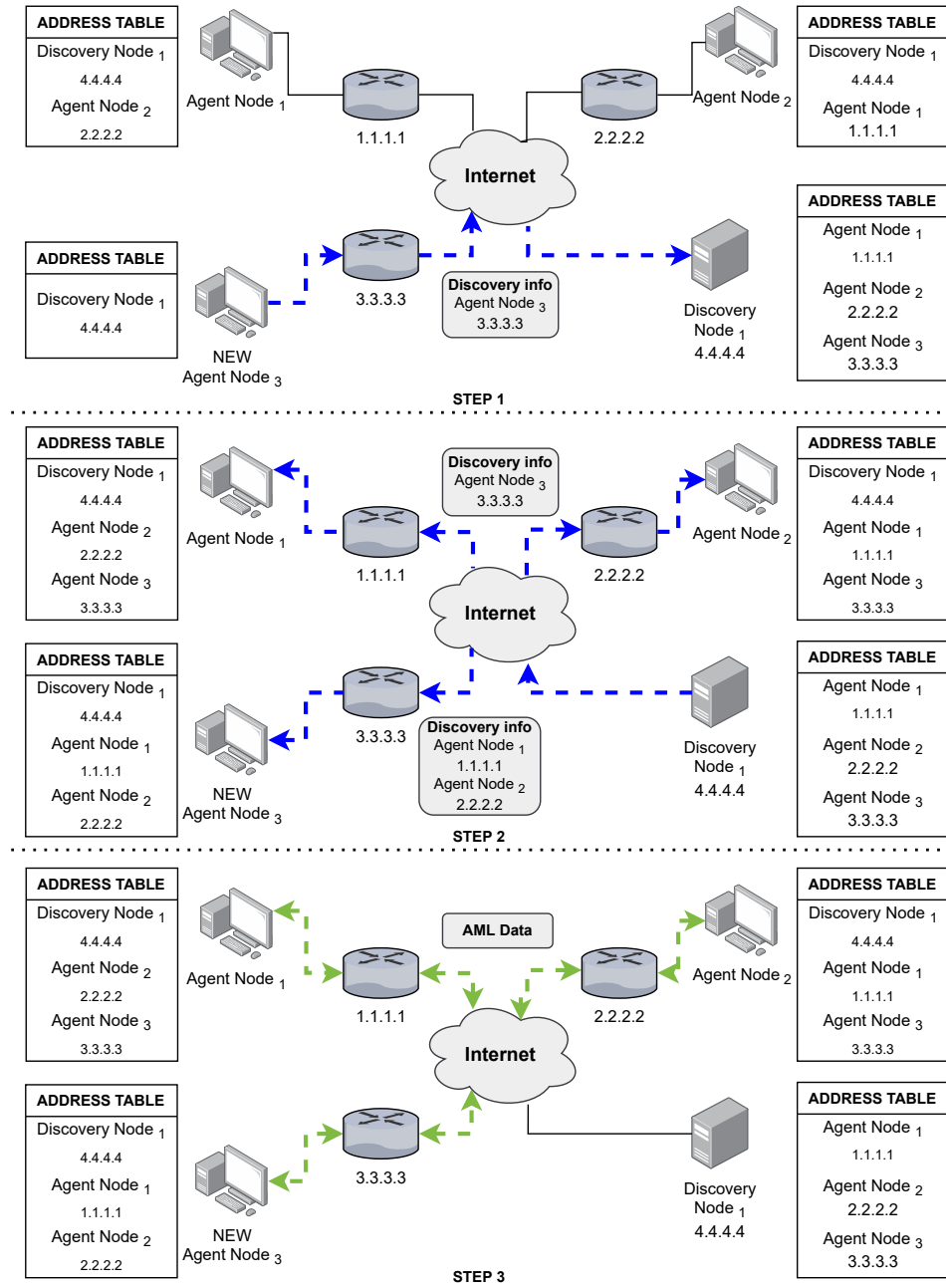


Figure 20: WAN communication schema.

These AML-IP-Ds allow to create an interconnected network that distributes the discovery information from one AML-IP-Ds to another. There is an example on how a network with two AML-IP-Ds works in Figure 21. In stage 1 shown in Figure 21, a WAN network architecture is shown in which there is one agent node ($AgentNode_1$) and two discovery nodes deployed, $DiscoveryNode_1$ and $DiscoveryNode_2$. In this same stage a new agent node ($AgentNode_2$) is added to the network which sends its discovery information to a single discovery node ($DiscoveryNode_1$) previously configured. In stage 2, $DiscoveryNode_1$

forwards the discovery information of *AgentNode₂* to *DiscoveryNode₁*, and to *AgentNode₂* the discovery information of the rest of the agent nodes it knows, which in this case is just the discovery information of *AgentNode₁*. In phase 3, which can occur in parallel in time to phase 2, *DiscoveryNode₂* sends the discovery information of *AgentNode₂* that it has just received to *AgentNode₁*. This phase ends with all agent nodes matched. Finally, since all agent nodes know each other, the P2P data transfer phase begins.

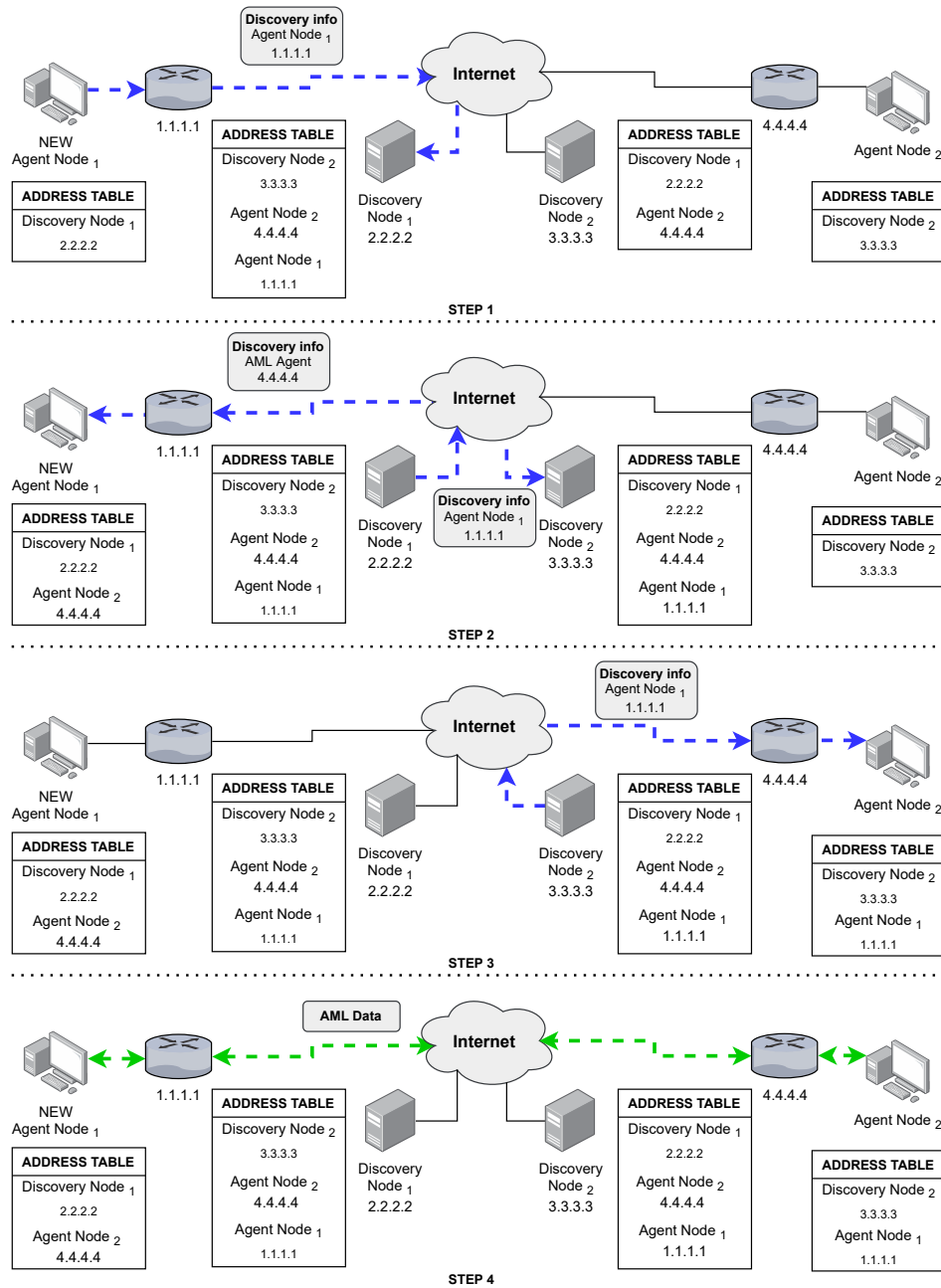


Figure 21: WAN communication schema with a network of AML-IP-D.

The use of multiple AML-IP-Ds introduces the following enhancements to the AML-IP architecture:

- Increase the number of *well known addresses* that an AML network could have.
- Enhance the robustness of the network since when one AML-IP-D has dropped, the others will still handle the discovery phase.
- Allow the redundancy of discovery information to avoid possible network issues.
- Distribute computational effort in large networks.

4.2.5 AML-IP Communication Sequence Diagram

A sequence diagram of how the communication process is managed by the AML-IP is shown in Figure 22. First, an AML-IP-Agent should be started in the network in order to allow WAN communication. This AML-IP-Agent will send its own discovery information to its *well known addresses* in order to establish the communication with the rest of the network. Besides that, and not necessarily after it, the AML-IP-Agent will know every AML-IP-Alg in its own LAN by using multicast communication. Once all the discovery has been settled, the communication from one AML-IP-Alg to the other will be performed by communicating to their respective AML-IP-Agent, and those communicating to each other.

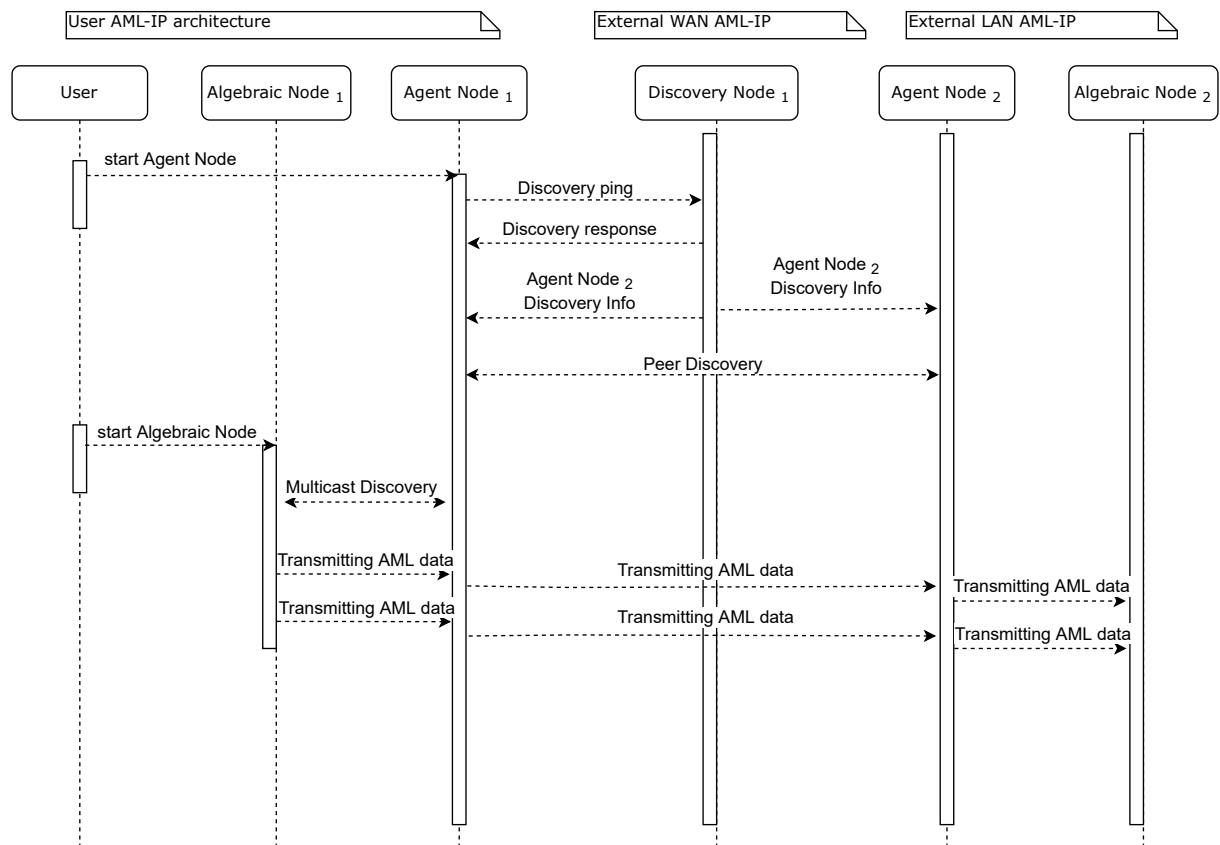


Figure 22: AML-IP sequence diagram in LAN and WAN networks.

4.3 AML-IP Components

As stated in 4.1, there are four types of AML-IP nodes: *a)* AML-IP Algebraic Node (AML-IP-Alg), *b)* AML-IP Mediation Node (AML-IP-Mediation), *c)* AML-IP Agent Node (AML-IP-Agent), and *d)* AML-IP Discovery Node (AML-IP-D). This section describes in detail each of them as well as the benefits and solutions offered by each of them to the challenges listed in Section 2.

4.3.1 AML-IP Algebraic Node

The AML-IP-Alg is the main node of an AML execution. It is where the AML algorithm and all the data it requires will be executed. An example on how these nodes will be implemented could be seen in Figure 23.

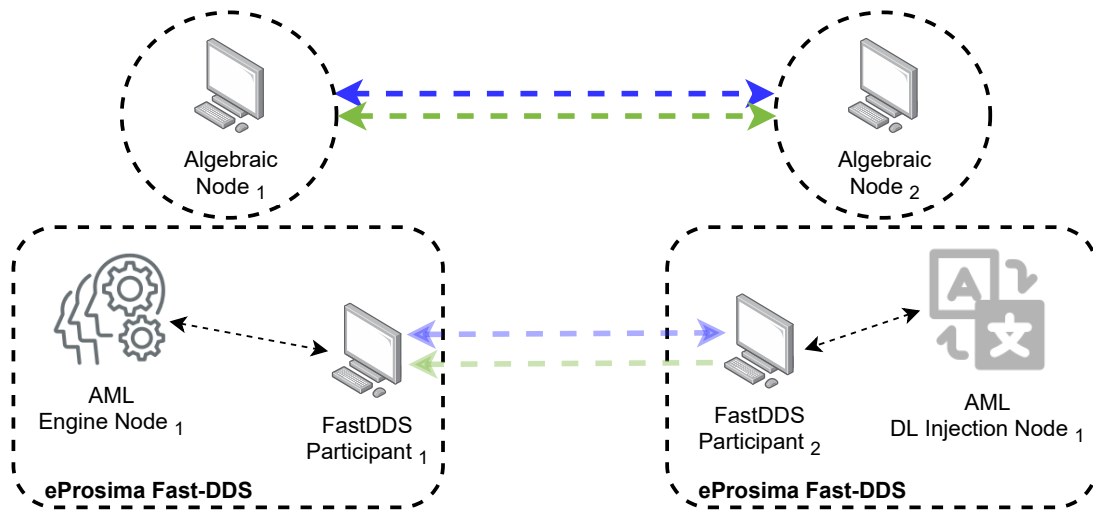


Figure 23: AML-IP Algebraic Node (AML-IP-Alg) design.

The AML-IP-Alg is an abstraction of every node required by the AML algorithm to be executed. Each kind of these nodes will send or receive under a topic that could affect to none, one or multiple remote AML-IP-Alg. This information will be distributed relying on the DDS standard to every node that requires it, using specific topics for each kind of data and each problem on which the AML node is working. *Fast DDS* will be used as the C++ library that implements the DDS communications standard. *Fast DDS* is easy to integrate in every application, and it is an Open Source project, what makes it the best candidate to be part of every AML node. Section 2.5.2 describes *Fast DDS* in detail.

The design, implementation and operation of the AML-IP-Alg is a work in progress, and will certainly be subject to change as the project advances. Two subtypes of AML-IP-Alg nodes, the AML-IP-Main and AML-IP-Computing are introduced in section 6.2.2, along with the description of the role each play in the workload distribution scenario. Some other types of algebraic nodes, as the AML-IP-Edge, the AML-IP-DL and new ones that might emerge in future versions of the AML-IP, will be defined in subsequent revisions of this document.

4.3.2 AML-IP Mediation Nodes

AML-IP Mediations Nodes transform data between different formats, allowing to offload that task from AML-IP-Alg. In particular, we focus on the preprocessing of AML Description Language (AML-DL) files and raw data. This task is performed on one or multiple AML-IP Mediation Node (AML-IP-Mediation)

Nodes where the input data is translated into AML Relations. These AML Relation are expressed in the data format that can be consumed by an AML Engine.

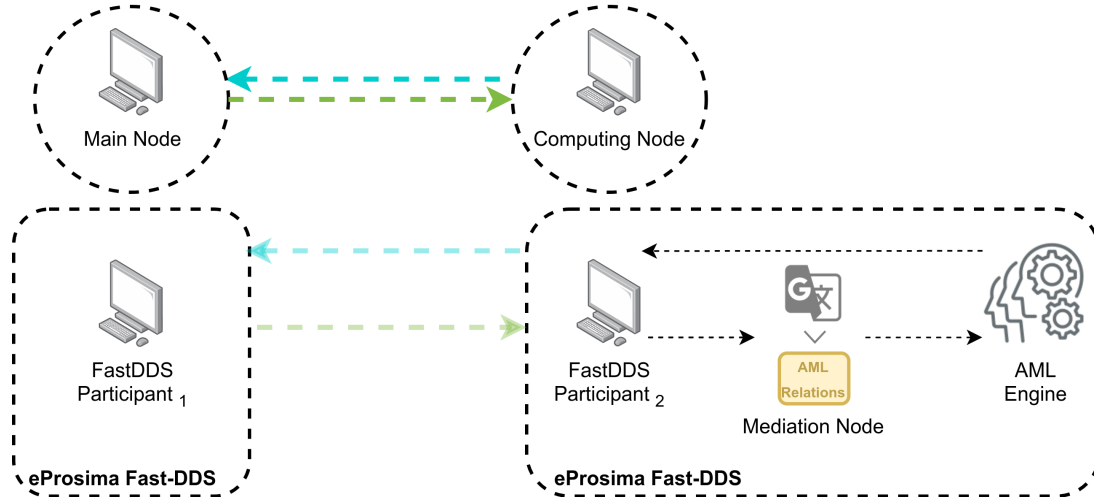


Figure 24: AML-IP Mediation Node (AML-IP-Mediation) design.

In the current version two types of processing have been implemented:

- **AML-DL:** It is designed to receive an AML-DL file (specified in *D3.3 AML-DL Specification - Revised M18*) as input and returns aml Relations.
- **Generic:** It accepts any type of data, plus a function describing the particular processing for that data. This approach is very generic, but leaves in the hands of the caller to explicitly describe the transformation function.

As this nodes are used by the public, frequently used function can be implemented. For instance, functions for handling two-dimensional images or for handling text.

It is also possible to extend these nodes with debugging tools, such as a the Consistency Checker (see deliverable D3.9). Currently that task is performed at the computing stage, so data would be transferred from AML-IP-Mediation to AML-IP-Alg before realising that a dataset cannot be used for training. By running the consistency check in the AML-IP-Mediation Nodes, we remove from the network the unnecessary transit of that data.

4.3.3 AML-IP Agent Node

The AML-IP-Agent is the node in charge of communicating a local node or AML-IP cluster with the rest of the network in WANs. It centralizes the WAN discovery and communication, i.e. it is the bridge for all the nodes in their LANs with the rest of the AML-IP components. The key functionalities of the AML-IP-Agent are *a)* the routing of data, *b)* the discovery of AML-IP components in WAN.

Internally, the AML-IP-Agent will make use of an *eProxima* product called **DDS Router**. This tool is developed and maintained by *eProxima* which facilitates certain DDS behaviours, as the WAN administration. It allows to create a bridge between two *DDS DomainParticipants*, which fill the gap between the LAN and WAN. The main benefits of using the DDS Router are the following:

- It greatly facilitates the configuration of WAN communication, making it unnoticed for an AML user.

- It leverages **eProsima *Fast DDS* Discovery Server**, which automatically creates a *Discovery Server* in client mode to share its discovery information and to get other nodes information from a AML-IP-D.

Figure 25 shows these two *DDS DomainParticipants* that comprise the AML-IP-Agent and the communication process in a WAN scenario. This figure also shows how the AML-IP-Agent acts as a central connection node in a LAN to connect AML-IP-Alg nodes in WAN. On the left side of Figure 25, it can be seen that AML-IP-Alg nodes internal to a LAN (*AlgebraicNode₁* and *AlgebraicNode₂*) discover each other and in turn automatically discover the *AgentNode₁* present in their LAN (blue dots line). Once these nodes have been discovered, the *AlgebraicNode₁* and *AlgebraicNode₂* start the AML data transfer phase within the LAN in case they are both matched, i.e. both are working under the same topic. Furthermore, all data to be published is also transmitted to *AgentNode₁*, which acts as a data broker. At this point in the communication, the *AgentNode₁* node knows the AML-IP-Alg nodes internal to its LAN, and all the data they publish outside the LAN are transmitted to it. Then, to find out if there are more AML-IP-Alg in the WAN, the *AgentNode₁* node uses its Discovery Server *client*, referred to as *FastDDSParticipant₂* in this case, to initiate the discovery process of other AML-IP-Agent and AML-IP-Alg nodes in the WAN. This process is shown in Figure 20.

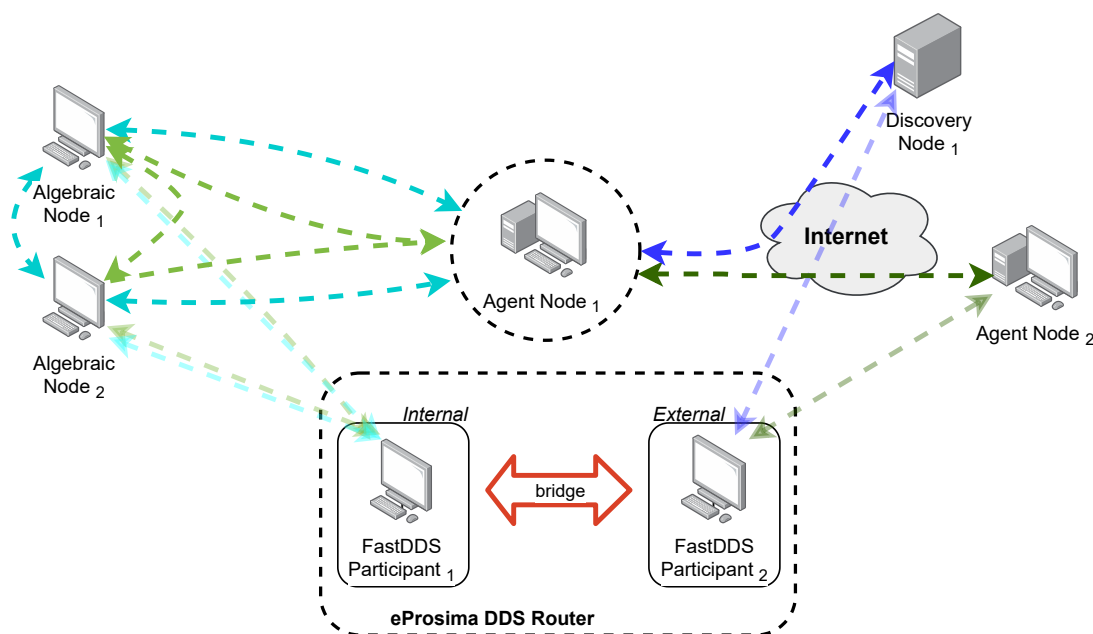


Figure 25: AML-IP Agent Node design.

a) **DDS Router**

The AML-IP-Agent centralizes communication within a LAN while ensuring messages can be transmitted and received across the WAN. This means that any message leaving the LAN or arriving from an external source must pass through it. This functionality is managed by the eProxima DDS Router.

The DDS Router is a dedicated application developed by eProxima to facilitate AML-IP communication across DDS networks in a WAN. It launches multiple DDS Participants (typically two), each connected to different DDS networks with distinct configurations. The DDS Router acts as a bridge between these Participants, forwarding all data received by one Participant to the others,

enabling communication between otherwise isolated networks.

A **Participant** serves as an abstraction over the DDS DomainParticipant, managing the dynamic discovery of DDS entities within a given network or interface. Each Participant is uniquely identified by a *Participant Name* in a DDS Router execution and assigned a *Participant Kind*, which defines its functionality.

WAN Communication: For WAN communication, a *WAN Participant* is required. This Participant, known as an *Initial Peers DomainParticipant*, facilitates communication with other WAN Participants across different networks. It acts as a bridge, linking local Participants in a LAN to remote Participants in other LANs equipped with a DDS Router with an active WAN Participant.

Discovery and NAT Considerations: The DDS Router utilizes the *Fast DDS Discovery Protocol* to send discovery information directly to configured Participants. This is particularly useful in static networks where multicast is unavailable, such as WAN environments. However, if the DDS Router is behind a NAT, a remote DDS Router in a different LAN will be unable to reach it unless NAT traversal methods are applied. The most common approach is configuring the network router to forward a specific port from the internet to a designated host.

Security and Configuration: eProxima DDS Router supports **TLS over TCP**, with configuration options available per Participant for *WAN Discovery Server* and *WAN* types. A simple diagram illustrating the role of the DDS Router within the AML-IP framework is shown in Figure 26.

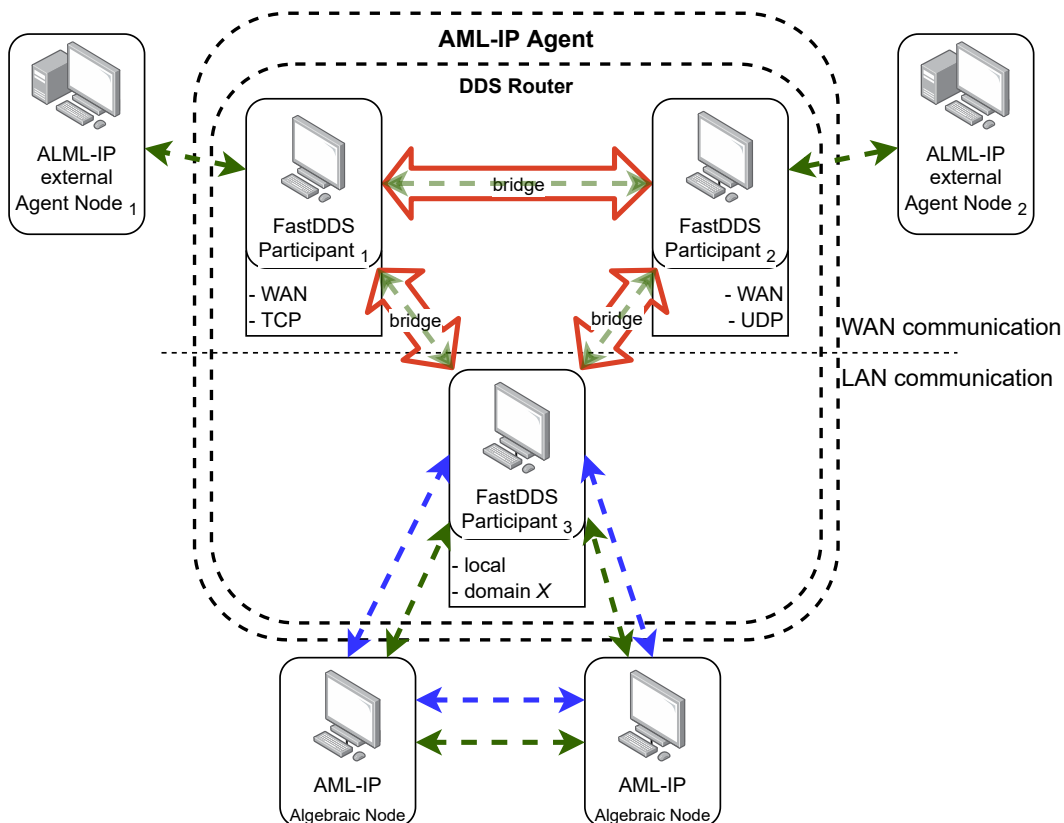


Figure 26: AML-IP Agent Node (AML-IP-Agent) powered by DDS Router.

Thus, the DDS Router enables the AML-IP-Agent to function as a communication bridge between internal (LAN) and external networks. Each independent LAN is equipped with an AML-IP-Agent, which transmits local data externally to other AML-IP-Agents, which in turn relay the external data to their internal nodes. This mechanism ensures seamless communication across all nodes, regardless of whether they belong to the same or different LANs.

The DDS Router is an **open-source** software developed by eProxima and hosted in a GitHub repository⁸ under the Open Source Apache 2.0 license.

b) WAN Discovery

The AML-IP-Agent features an internal AML-IP-D that connects as a *Client* to one or multiple AML-IP-Ds, whose addresses are preconfigured. As depicted in Figure 25, the Integration Service connects to an AML-IP-D, uploading the required internal discovery information and simultaneously downloading complete discovery data from the same AML-IP-D.

c) NAT Traversal

One of the main challenges of a P2P connection in WAN is enabling communication between two nodes behind different NATs.

NAT (Network Address Translation) is a mechanism that translates IP addresses, typically converting a single public IP into a private IP address space. This process can introduce difficulties—or even make communication impossible—in certain NAT types (e.g., symmetrical NAT [5]), as two nodes behind different NATs may be unable to reach each other without additional network configurations.

To address this, users must manually configure their network routers to forward incoming connections. This process, known as **port forwarding**, ensures that external requests are correctly routed to the intended service or application. Without port forwarding, a router's default security settings generally block unsolicited incoming connections, preventing communication between nodes behind separate NATs.

4.3.4 AML-IP Discovery Server

The AML-IP-D is the AML-IP node in charge of receive, redistribute and maintain the discovery information of the whole network. The AML-IP-D could create networks by connecting AML-IP clusters and redistributing all the discovery information between them. Thus, it could be used to build a large and redundant network, in which a single AML-IP component gives access to the rest of the whole network, without the need to know the whole network graph. Furthermore, the AML-IP-D provides the logic needed to forward the discovery information between the nodes that requires it. That is, the nodes will only receive other nodes information if they operate under the same topic. As stated in Section 2.5.2, the *eProxima Fast DDS Discovery Server* discovery mechanism implements the desired behaviour of the AML-IP-D.

An example on how the AML-IP nodes will be implemented is shown in figure 27. The AML-IP-D implements a *Fast DDS* Discovery Server, sharing the discovery information of the DDS entities that connect with it.

⁸<https://github.com/eProxima/DDS-Router>

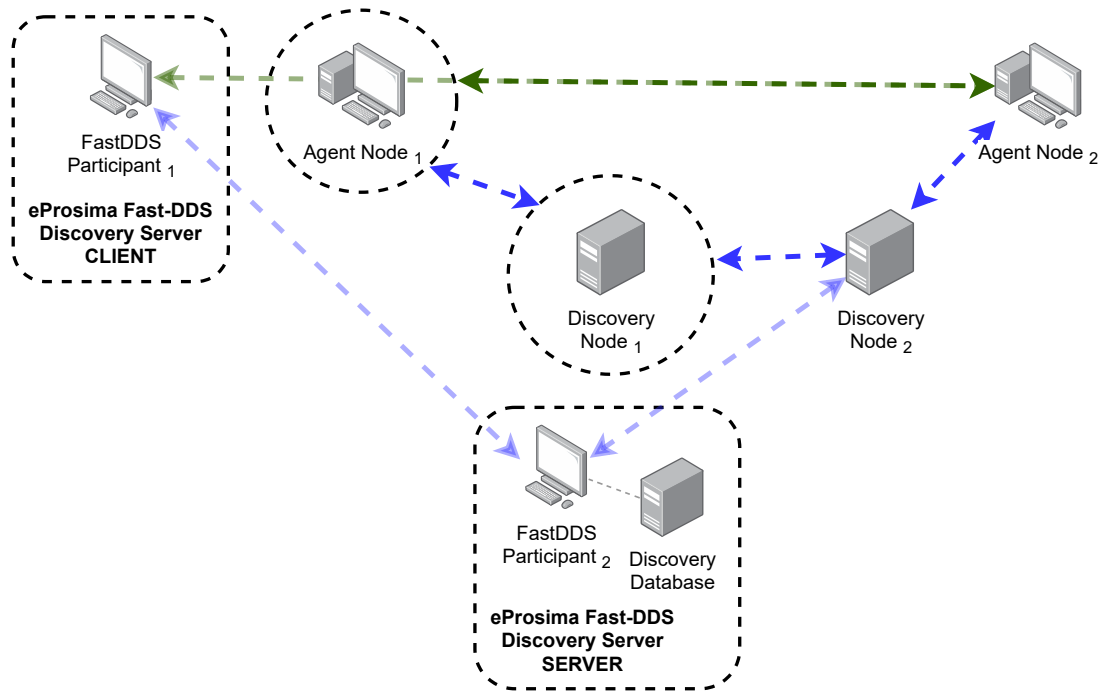


Figure 27: AML-IP Discovery Node design.

4.4 Requirements targeted

This design has been chosen as it fulfills all the requirements and being the most efficient and scalable architecture found. Being aware of the limitations and obstacles this design represents, it is considered by **EPROS** as the way to go for the AML-IP implementation. These are the main challenges encountered when designing the AML-IP, and the potential benefits offered by this architecture, making it a robust and scalable system:

4.4.1 Discovery through WAN

The first challenge is how to manage the dynamic discovery of new AML-IP nodes, which are agnostic to the state of the network to which they are connected. That is, new nodes must discover all other nodes already in the network with which they can communicate.

The default discovery process in DDS is based on signalling the presence of new DDS entities to all other entities belonging to a multicast group. Thus, the rest of the entities within this multicast group detect the presence of this new entity and start the matching process with it.

Using multicast in large networks is not achievable, and forcing new nodes to be aware of each other beforehand is unfeasible in dynamically growing networks. In such networks, new nodes can arrive and leave at any time, and the other nodes must detect this behaviour.

The architecture of the AML-IP presented here follows the state-of-the-art patterns of P2P networks. It is based on using *well known addresses* to obtain an access point to the entire network. Therefore, the nodes only need to know one point in the network, which will give access to the network status and the address of the rest of the nodes. It is only necessary to have one or more AML-IP-D at *well known addresses* where a new user can connect to gain access to the rest of the discovery information. The AML-IP-D will fulfill perfectly this feature, as it is explained in Section 4.3.4.

4.4.2 Communication through WAN

The communication through WAN in a P2P mode has important obstacles when working with nodes that are under a NAT connection, which are the most common networks [5]. The main challenges found are the access to an independent point behind a NAT. The AML-IP overcomes these problems and supports the scalability of the AML ecosystem as described in Section 4.3.3.

4.4.3 Node scalability

As the AML project is in a constant state of evolution, many of its components may change as the project progresses towards a more stable phase. To overcome this change, a generic AML-IP architecture has been designed for any type of AML node that may be added in the future.

The AML-IP-Alg represents an abstract *AML Node*, referred to as AML-IP-Alg that could be specialized in any kind of node that the future AML requires, as it is described in Section 4.3.1. Joining these nodes with the AML-IP-Agent creates a LAN and WAN AML interconnected ecosystem that could grow dynamically and be easily scalable with new types of nodes and data.

4.5 Benefits and constraints

Some of the limitations that arise in this architecture of the AML-IP are:

- An AML-IP-Agent is needed inside a LAN in order to connect with AML nodes deployed out of the LAN.
- The AML-IP-Agent will centralize the communication with the external networks, being a potential bottleneck in the communication process.

However, this design fulfills every requirement of the project:

- **Decentralized Communication.** The communication is done between AML-IP-Algs deployed in different LANs, i.e. communicating in a WANs. Thus, it is not required any centralized point or service.
- **Publish/Subscribe Communication.** The use of *Fast DDS* as the communication middleware makes it possible to create a data-centric network using the DDS standard.
- **Logical partitions.** Several networks can run simultaneously in the same WAN and be completely independent just by not sharing the network of AML-IP-D.
- **Connection through LAN.** Nodes in the same LAN discover each other by joining a multicast group, and communicate without requiring the deployment of any AML-IP-Agent.
- **Connection through WAN.** AML-IP-Agents in the same WAN discover each other by connecting to an AML-IP-D and communicate to each other P2P.
- **Dynamic discovery.** The AML-IP-D allows the network to scale up or down dynamically and minimises discovery traffic.
- **Data Injection Nodes.** The AML-IP-Alg is an abstract node that can perform any existing or future AML functionality.

Furthermore, the proposed AML-IP architecture has some advantages that exceed the requirements given:

- **Independence between process and communication.** The AML-IP-Agent is not dependent of any AML node and its only purpose is the communication between internal and external nodes. Thus, the AML process will not be affected by possible delays in the communication.

- **Easy Discovery.** It is only needed to know the public IP address and port of an AML-IP-D in order to discover and be discovered by the rest of the network.
- **Computation cluster.** Group of nodes or clusters can work in the same LAN without the need of an AML-IP-Agent, and will discover each other by joining a multicast group. However, these nodes will no longer be able to communicate with external nodes outside its LAN.

5 Prototype of AML-IP architecture scenario

In order to demonstrate the validity and usability of the design of the AML-IP proposed in this document, an AML-IP Prototype has been developed. It implements the key aspects of the AML-IP that make the prototype a minimum functional version of the final communications framework. This AML-IP prototype is available on the public Github repository **aml-ip-prototype**⁹ under the Open Source Apache 2.0 license¹⁰.

5.1 Design

The design to be explained in this section remains to the first design for the prototype of the AML-IP. This prototype is not aimed to be a robust final tool, but rather a quick-to-implement tool to serve as a Proof of Concept (PoC) for future development of the AML-IP communications framework.

The idea of the prototype is to show a minimal example of DDS communication through WAN with various AML-IP-Alg discovered by one or multiple AML-IP-D. Therefore, this prototype does not implement the AML-IP-Agent due to the complexity and effort it requires.

5.1.1 Prototype Nodes

There are three AML-IP nodes in the prototype to be differentiated:

- **AML-IP-DL:** These nodes will represent every node in the network that publish under a *Description Language* topic. The output of these nodes will be *AML-IP-DL relations* that the AML algorithm can understand. This node is the AML-IP-Alg representation of the AML-IP components described in Section 4.3.1.
- **AML-IP-Edge:** This node represents the AML node in charge of processing and executing the AML algorithm. It is the node with the highest workload. The input data-stream of this nodes will be the output data of the AML-IP-DL nodes. Its output data is the *atomization*, the knowledge built from the data given. This node is the AML-IP-Alg representation of the AML-IP components described in Section 4.3.1.
- **AML-IP-D:** These nodes will execute the discovery process that joins the different nodes to those who are related, ergo, to those that must share information that is relevant. It represents an AML-IP-D.

⁹https://github.com/eProsimia/aml-ip-prototype/tree/ALMA_AMLIP_D6.1

¹⁰https://github.com/eProsimia/aml-ip-prototype/blob/ALMA_AMLIP_D6.1/LICENSE

DomainParticipant	DataWriters	DataReaders	Topic	
			Name	Data Type
AML-IP-DL	DL		<code>_aml_ip_topic_dloutput</code>	<i>AML_IP_DLOutput</i>
AML-IP-Edge	Atom		<code>_aml_ip_topic_atomization</code>	<i>AML_IP_Atomization</i>
		Atom	<code>_aml_ip_topic_atomization</code>	<i>AML_IP_Atomization</i>
		DL	<code>_aml_op_topic_dloutput</code>	<i>AML_IP_DLOutput</i>
AML-IP-D				

Table 2: Overview table of user AML-IP node types. The first column shows the name of the node, which corresponds to the name designated for the DomainParticipant. The next two columns specify the DataWriter(s)/DataReader(s) of the DomainParticipant. Finally, the topic of each DataWriter/-DataReader is defined by its name and data type. Since the *AML_IP_DiscoveryServer* node is only involved in the entity discovery process, i.e. it does not apply to the data transfer phase, it does not contain any user DataReader/DataWriter.

5.1.2 Data types

As detailed in Section 2.3, data will be transmitted using *Fast DDS* communications middleware which implements the DDS standard. In a real scenario, the data to be transmitted will depend on the type of the problem on which the AML nodes are working, using different DDS topics to differentiate the type and content of the data. However, for the case of the prototype it is assumed that all AML nodes work on the same ML problem. Even if all nodes work on the same problem, it is required to use different DDS topics defined by the *topic name* and the *topic data type*. In the case of the prototype, the type of data ingested and generated by each type of node will be different. This results in two types of data:

- **DL** (*AML_IP_DLOutput*): Output data from AML-IP-DL nodes. This data type contains a sequence of data of type *AML_IP_Relation*. The *AML_IP_Relation* represent the relation of a Term with a number of Constants. It is formed by two sequences of integers of different sizes, and a boolean which specifies the AML relation type.
- **Atomization** (*AML_IP_Atomization*): Output data from AML-IP-Edge nodes. It represents the atomization learnt from an execution of the AML algorithm. This data type contains a sequence of data of type *AML_IP_Atom*. The *AML_IP_Atom* data type describes an Atom. It is formed by a sequence of integers of fix sized.

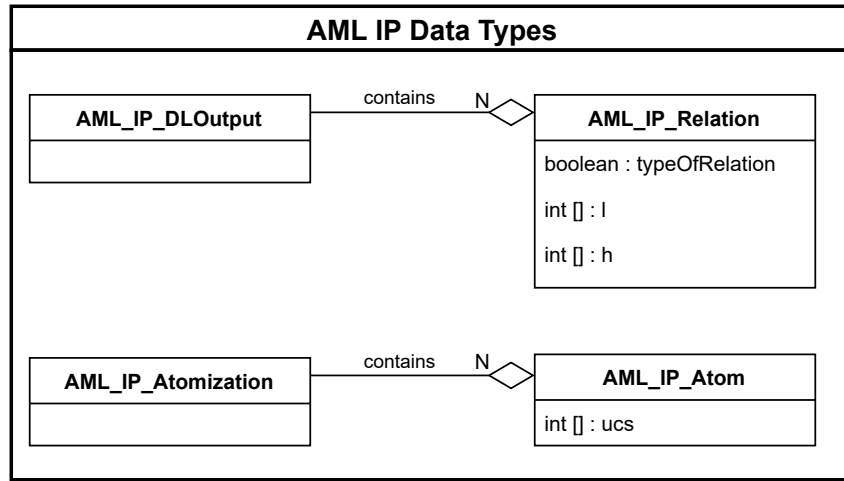


Figure 28: Data Models.

This data types are written in a description language called Interactive Data Language (IDL) [6] that can be read and converted to C++ code by an EPROS tool called *eProxima Fast DDS-Gen*¹¹. The IDL files for the data types that are used in this prototype are shown in Listing 1 and Listing 2. As it could be seen in these snippet codes, every data structure that is shown in 28 is an IDL structure, that will be converted to *std* types in C++.

```

1  // Relation Data Type
2  struct AML_IP_Relation
3  {
4      boolean typeOfRelation;
5      sequence<unsigned long> l;
6      sequence<unsigned long> h;
7  };
8
9  // DL Data Type
10 struct AML_IP_DLOutput
11 {
12     sequence<AML_IP_Relation> relations;
13 };

```

Listing 1: Description Language (DL) Data Type IDL description.

```

1  // Atom Data Type
2  struct AML_IP_Atom
3  {
4      sequence<unsigned long> ucs;
5  };
6
7  // Atomization Data Type

```

¹¹<https://github.com/eProxima/Fast-DDS-Gen>

```

8      struct AML_IP_Atomization
9      {
10         sequence<AML_IP_Atom> atoms;
11     };

```

Listing 2: Atomization Data Type IDL description.

An example of how a AML-IP-Edge node publishes random data that represents an *AML_IP_Atomization* can be found in the source code of the AML prototype publicly available on the GitHub repository *aml-ip-prototype*¹². In this same repository there is also an example of how the same AML-IP-Edge node subscribes to and receives data from a specific topic^{13 14}.

5.2 Experiments

Several experiments has been built and run in order to test the LAN and WAN communication with various network architectures, configurations, and transport methods. This section is focused to explain the experiments execution and discuss the results. These experiments has been divided in two groups: LAN communication and WAN communication.

5.2.1 LAN connectivity

These experiments test the proper behaviour of the prototype with an architecture in which all deployed nodes are on the same LAN. As described in Section 2.5.2, *Fast DDS* supports different transport mechanisms. These are:

- a) User Datagram Protocol (UDP), which is more efficient in LAN communications;
- b) TCP, for WAN communications;
- c) Shared Memory Transport (SHM), as a transport protocol for DDS applications running on the same machine
- d) intraprocess, for DDS entities running in the same system process; and
- e) data-sharing, which makes DataReaders and DataWriters running on the same machine share their database of sent and received data, which in DDS is referred to as *history* of changes.

The experiments performed are as follows:

- **Same host.** Some nodes executing and working in the same host, using UDP, TCP or intraprocess transport.
- **Docker hosts.** Nodes executed in the same physical host but in different logic hosts encapsulated in Docker¹⁵ containers.

¹²https://github.com/eProsima/aml-ip-prototype/tree/ALMA_AMLIP_D6.1

¹³AML-IP-Edge publication example:
<https://github.com/eProsima/aml-ip-prototype/blob/c6d6de24de7b3201082cb53efba49e01e733c09f/src/cpp/Engine/EngineParticipant.cpp#L240>

¹⁴AML-IP-Edge subscription example:
<https://github.com/eProsima/aml-ip-prototype/blob/c6d6de24de7b3201082cb53efba49e01e733c09f/src/cpp/Engine/EngineParticipant.cpp#L342>

¹⁵<https://www.docker.com/>

- **Different hosts.** Nodes executed in different machines connected to the same router and under the same NAT.

5.2.2 WAN connectivity

The WAN communication is not a common use case for *Fast DDS*, and therefore exhaustive testing is required in order to check TCP communication in WANs. All the experiments discussed in this section has been tested in a WAN communication.

- **PoC 1¹⁶:** Test static discovery using TCP connection between AML-IP-DL node and AML-IP-Edge node.
- **PoC 2:** Test the connection of AML-IP-DL and AML-IP-Edge nodes, each in different LANs, connected to a AML-IP-D node in an independent LAN.
- **PoC 3:** Test the same connection as PoC 2 but hosting various nodes in the same machine, i.e. one host running an AML-IP-DL and an AML-IP-Edge nodes, and another machine running an AML-IP-Edge and a AML-IP-D nodes). This experiment tests: 1. the discovery of AML-IP prototype nodes deployed on different LANs, 2. the discovery of AML-IP prototype nodes deployed on the same LANs, 3. the communication between AML-IP prototype nodes deployed on different LANs, 4. the communication between AML-IP prototype nodes deployed on the same LANs, and 5. the communication between AML-IP prototype nodes deployed on the same host and another in a different LAN.

5.3 Demonstrator

The following section presents a demonstrator of the AML-IP prototype. It details the network architecture deployed for the execution of the prototype, as well as the steps required to download, install and run it. Thus, it is possible to reproduce the results obtained and presented in this document. The main purpose of this demonstrator is to illustrate a successful connection between AML-IP prototype nodes deployed along the Internet.

5.3.1 Experiment design

As discussed in Section 5.1, this prototype does not implement the AML-IP-Agent. The nodes implemented are the AML-IP-D and two types of AML-IP-Alg, which are the *Engine* and the *DL*. The AML-IP-Algs connect to a local AML-IP-D that manage the discovery along the Internet but do not forward the data traffic through WAN.

Figure 29 shows the network architecture deployed for this demonstrator. In order to simulate a minimum real scenario, the nodes have been distributed in three different LAN. One of the networks represents a single point of discovery with an AML-IP-D, that is a well known address that will distribute the discovery information of every cluster that connects with it. The other two networks are a simulation of real clusters of AML where a single node has been deployed. Each of these networks needs an AML-IP-D that knows beforehand the address of the one already in the net. The AML-IP-Edge and the AML-IP-DL will connect to their respective AML-IP-D and will discover each other and communicate directly to each other. This demonstrator does not include the Universal Plug and Play (UPnP) feature in its *main* version, so the experiment needs a previous phase of port forwarding for every NAT.

¹⁶This configuration was built in a previous prototype version to allow the connection between specific nodes without a Discovery Server involved. The current version does not allow it, but it could be seen in a previous branch in the repository.

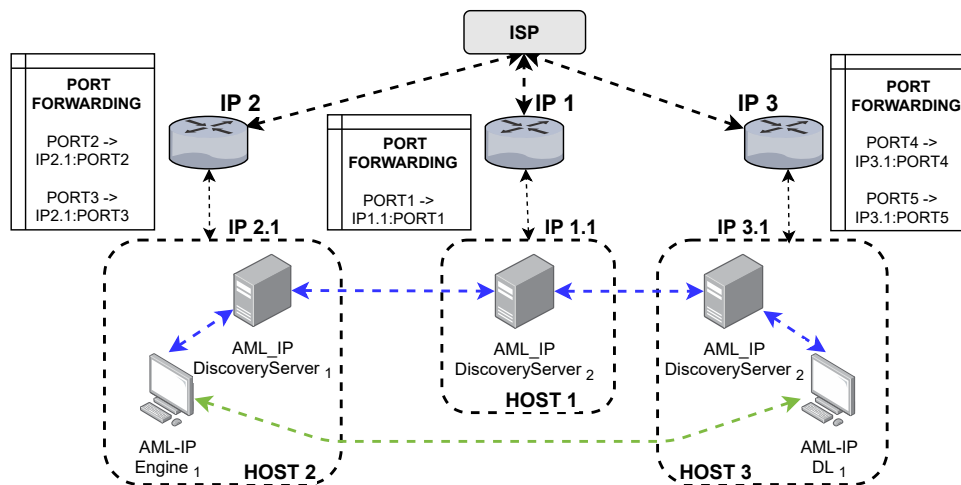


Figure 29: Experiment architecture.

5.3.2 Download and installation

The prototype has been developed as an Open Source project in GitHub. Thus, the whole code and instructions are available for every user in the `aml-ip-prototype` GitHub repository¹⁷. The project has been developed for `Ubuntu 20.04.2.0 LTS (Focal Fossa)`¹⁸ Operating System (OS) and it has not been tested in any other platforms.

In the project `README.md` file there are outlined all the instructions to install the libraries and dependencies required to correctly download and compile the project. The main dependencies are the *eProxima Fast DDS* library for DDS communication and the `colcon`¹⁹ tool to build the project. It is worth mentioning that it exists a branch in the prototype where a UPnP application is built within the project. However, this branch require to have `Boost 1.71`²⁰ installed, which is not supported by the `apt`²¹ for the Ubuntu distribution used.

To install the project together with all its dependencies, simply execute the following commands:

```
$ export WORKSPACE_PATH="/path/to/workspace"
$ mkdir -p ${WORKSPACE_PATH}/src
$ cd ${WORKSPACE_PATH}
$ wget
↳ https://raw.githubusercontent.com/eProsima/aml-ip-prototype/ALMA_AMLIP_D6.1/amlip.repos
$ vcs import src < amlip.repos
$ colcon build
```

¹⁷https://github.com/eProsima/aml-ip-prototype/tree/ALMA_AMLIP_D6.1

¹⁸<https://releases.ubuntu.com/20.04/>

¹⁹<https://colcon.readthedocs.io/en/released/>

²⁰https://www.boost.org/users/history/version_1_71_0.html

²¹<https://wiki.debian.org/Apt>

5.3.3 Experiment setup

For the description of the experiment setup, the terminology of Figure 29 has been followed to refer to the elements involved in the experiment of the prototype. All the executables must be run from the **WORKSPACE** folder and it is required to **source** the installation setup of the project for the prototype node executables to find the required dynamic libraries. For this reason, every command that will be shown from here on will previously execute the following commands in order to correctly configure the environment:

```
$ cd ${WORKSPACE_PATH}
$ source ./install/setup.bash
```

In order to achieve WAN communication between the nodes, it is necessary to perform some port forwarding on the router. This is because the NATs that the routers create do not allow external connections to internal machines if there is not a rule to forward a port to that machine. In order to open these ports manually, the user must enter in the router configuration and create a new rule to forward a specific port to the host desired, as it is shown in Figure 62.

The following describes the configuration and the steps taken to set up the machines running the prototype.

• HOST 1

This host executes a single AML-IP-D that listens in its public address and the port forwarded in the router. First, the administrator of **HOST 1** must configure its router to set a static Integrating Platform (IP) to its machine, which is **IP1.1** according to Figure 29. Then, it set a port forwarding from the router to its machine. As a result, every external request to address **IP1:PORT1** will be forwarded to **IP1.1:PORT1** and will be received by the AML-IP-D.

The following command has been used in order to run this node

```
$ ./install/amlip/bin/AML_IP_DiscoveryServer \
    --id=1 \
    --listening-addresses="${IP1},${PORT1}" \
    --time=0
```

Listing 1: Bash command to run the AML-IP-D node in **HOST 1**.

where

- **id** sets this AML-IP-D id to 1, information required to connect with it;
- **listening-addresses** sets the address or addresses where the AML-IP-D is listening; and
- **time** set to 0 implies that the AML-IP-D will be running until the **Enter** key is pressed.

• HOST 2

This host executes an AML-IP-D that communicates with the AML-IP-D deployed in **HOST 1** and listens in **localhost** in order to discover every node working on **HOST 2**. It will also execute an AML-IP-Edge that will listen to every AML-IP-DL node publishing DL data under the **AML_IP_DLOutput** topic and to every AML-IP-Edge publishing Atomization data under the **AML_IP_Atomization**. In turn, this AML-IP-Edge node will publish its own Atomization information under the latter topic at constant time intervals and under the data type format according to Figure 28.

First, as done in **HOST 1**, the administrator of **HOST 2** must configure its router to set a static IP to its machine, which is **IP2.1** according to Figure 29. Then, it set two ports forwarding from

the router to its machine. Thus, every external request to address IP2:PORT2 will be forwarded to IP2.1:PORT2 and every external request to address IP2:PORT3 forwarded to IP2.1:PORT3.

Secondly, the AML-IP-D is executed with the following command:

```
$ ./install/amlip/bin/AML_IP_DiscoveryServer \
  --id=2 \
  --listening-addresses="${IP2},${PORT2};127.0.0.1,5000" \
  --connection-addresses="${IP1},${PORT1},1" \
  --time=0
```

Listing 2: Bash command to run the AML-IP-D node in HOST 2.

where

- **id** sets this AML-IP-D id to 2, which is required to connect with it;
- **listening-addresses** is set to listen in the port forwarded in the router in order to receive the information from the HOST1, and to the localhost=127.0.0.1 address to communicate with any node internal to HOST 2;
- **connection-addresses** is the remote AML-IP-D with which this AML-IP-D is going to connect; and
- **time** set to 0 implies that the AML-IP-D will be running until the **Enter** key is pressed.

Finally, the HOST 2 administrator runs the AML-IP-Edge with the following command:

```
$ ./install/amlip/bin/AML_IP_Engine \
  --listening-addresses="${IP2},${PORT3};127.0.0.1,4000" \
  --connection-addresses="127.0.0.1,5000,2" \
  --period 4 \
  --size 100 \
  --samples 0
```

Listing 3: Bash command to run the AML-IP-Edge node in HOST 2.

where

- **listening-addresses** sets the addresses to which the AML-IP-Edge node will listen, i.e. the channel on which it intends to receive information from the topics to which its DataReaders subscribe;
- **connection-addresses** sets the addresses of the AML-IP-D deployed in the same machine;
- **period** indicates the interval in seconds to publish samples;
- **size** sets the size of the internal message; and
- **samples** sets the number of samples to publish.

For the AML-IP-Edge deployed on HOST 2, the **listening-addresses** has two values. The first one corresponds to the address through which the machine is accessed remotely, in this case this will be a WAN communication but it is also valid for LAN communications as long as the router supports loopback to the internal network, while the second one corresponds to the communications on the same machine.

• HOST 3

This host presents a similar configuration than the **HOST 2** but running an AML-IP-DL instead of an AML-IP-Edge. First, the administrator of **HOST 3** must configure its router to set a static IP to its machine, which is **IP3.1** according to Figure 29. In this case, there is no need to forward any port since the TCP communication is able to use an already opened connection in order to receive and send data. Thus, only one of the nodes in the communication requires to open an access from the router, while the other can relay in the TCP connection already opened.

Secondly, the AML-IP-D is executed with the following command, similar to the one explained for **HOST 2** but changing the ip and id configuration options.

```
$ ./install/amlip/bin/AML_IP_DiscoveryServer \
  --id=3 \
  --listening-addresses="${IP3},${PORT4};127.0.0.1,5002" \
  --connection-addresses="${IP1},${PORT1},1" \
  --time=0
```

Listing 4: Bash command to run the AML-IP-D node in **HOST 3**.

Finally, the **HOST 3** administrator run the AML-IP-DL with the following command, similar to the one used for running the AML-IP-Edge in **HOST 2**.

```
$ ./install/amlip/bin/AML_IP_DL \
  --id=3 \
  --listening-addresses="${IP3},5001;127.0.0.1,5003" \
  --connection-addresses="127.0.0.1,5002,3" \
  --period 2 \
  --size 50 \
  --samples 0
```

Listing 5: Bash command to run the AML-IP-DL node in **HOST 3**.

5.3.4 Results

This experiment has been executed using the prototype implemented and following the instructions already mentioned. The experiment has been executed remotely with each host deployed in a personal network. In Appendix A, different screenshots taken after the execution explained in Section 5.3.3 can be found.

Figure 63 represents the execution of the first AML-IP-D in **HOST 1** after executing 1. In this screenshot, the different AML-IP-Ds that connect to it and the discovery information of the nodes can be observed. This information is reported by all the AML-IP-DL and distributed to other AML-IP-DLs. Finally the two remote AML-IP-Ds leave the network, and therefore the discovery information from the working nodes is no longer distributed. This means that the nodes that already know each other could still communicate to each other, but any other new node will not discover them, nor will currently connected nodes have a periodic report on the status of remote nodes.

Figure 64 shows how the AML-IP-D in **HOST2** connects and discovers the central AML-IP-D deployed on **HOST1** after running the command 2. Once the local machine is already connected with the network of AML-IP-Ds, a new AML-IP-Edge is instantiated by running the command 3 in **HOST 2**.

Finally, in **HOST 3** the same deployment configuration is performed by executing an AML-IP-D with command 4 and a AML-IP-DL with command 5. It could be seen the execution of this AML-IP-D in

HOST 3 in Figure 66.

Once everything is deployed, the two nodes will discover each other by the network of AML-IP-Ds and will start sending and receiving data. This could be seen in Screenshot 67, which shows the data being sent by the AML-IP-DL. In the Screenshot 65 it can be seen how the AML-IP-Edge publish its own kind of data, but since there are no subscribed nodes, none receives it. Furthermore, it could be seen how this AML-IP-Edge receives data from a remote AML-IP-DL, which is in this case in HOST 3.

The following details how to understand the output of an AML-IP-Edge and AML-IP-D execution in the prototype (Figures 67 and 65). The output messages clearly show the two phases that are specified in Section 4.2.1:

- Discovery phase: the first output messages refer to the discovery of nodes in the network.
- Data transfer phase: both the AML-IP-Edge node and the AML-IP-DL node start publishing data. There are two kinds of messages.
 - Those that start with << refer to messages **published** by the node. The following output message taken from these executions shows how the AML-IP-DL send a message in topic *AML-IP-DLOutput* with 8 relations.


```
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 12
message: < Number of relations: 8 >
```
 - Those that start with >> refer to messages **received** from other nodes.

Then the remote AML-IP-Edge receive this same message with the same number of relations in topic *AML-IP-DLOutput* to which it has been subscribed beforehand. This is represented in the following output message.

```
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <
Number of relations: 8 > from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 Number of
messages received so far: 12
```

5.3.5 Experiment Conclusions

The AML-IP prototype has been used to test the feasibility and viability of the final AML-IP design. From the experiment carried out with this prototype, the following conclusions can be drawn about the proposed final design:

- To achieve dynamic discovery and communication between nodes in WAN, only one central node is required, which performs the discovery service and to which the rest of the nodes of the network will be connected.
- To achieve WAN node communication, i.e. nodes deployed in different LANs under a NAT, it is necessary to apply a network configuration, which can be either manual, performed by the user on his private network router, or automatic through a tool that implements the UPnP protocol.
- The fact of having two different phases for communication, i.e. the discovery phase and the data transfer phase, makes the discovery of new entities joining the network independent from the communication already established between stable entities in the network.

6 AML-IP scenarios

AML-IP stands as a versatile platform crafted to encompass an extensive spectrum of functionalities within the domain of AML networks. Its capabilities span diverse scenarios, including facilitating collaboration between distinct networks while safeguarding the privacy and autonomy of each node. It empowers the efficient parallelization of specific tasks across multiple nodes, whether they are local or remote, optimizing computational resources. Additionally, AML-IP enables the merging of multiple trained models, enhancing predictive accuracy and robustness. Furthermore, the platform extends its support to scenarios where multiple nodes collaboratively address shared tasks, streamlining communication and synchronization processes.

This section serves as an introductory guide to all these AML-IP scenarios.

6.1 AML-IP collaborative learning scenario

This section explains the different types of nodes that participate in the AML-IP collaborative learning scenario, and the communication between them.

6.1.1 Collaborative learning scenario

The so called *collaborative learning scenario* refers to those scenarios in AML where nodes working on the same problem share their locally obtained models with each other. This sharing occurs without the need to expose the private datasets they were trained on, thus safeguarding sensitive information. The main objective is to collaboratively create a more complex and precise model by leveraging insights from diverse sources.

A collaborative learning scenario can be implemented either locally, remotely, or simultaneously through the employment of the AML-IP-Agent. The most important nodes in this scenario are the AML-IP-MMReceiver and the AML-IP-MMSender, which are explained ahead in this section.

6.1.2 Design

This section explains in detail the design of certain nodes of AML-IP to achieve the efficient deployment of a training network exploiting the strengths of AML.

Architecture Description The main idea of this part of the AML-IP is to parallelize the computational effort in a balanced way between an arbitrary number of nodes. The work that is presented along this section refers to the process of sharing models, generated by an AML-IP Algebraic Engine Node (AML-IP-Engine). Essentially, this scenario outlines how an AML-IP-Engine disseminates its model to various computing points within the network.

Nodes In this scenario, two types of nodes are involved:

- **AML-IP-MMReceiver:** This kind of node performs the active (client) role. It receives *statistics* regarding available models and send *requests* if it is interested in a particular one. Subsequently, it waits for the requested model to be delivered.
- **AML-IP-MMSender:** This kind of node plays the passive (server) role. It shares *statistics* about the models it manages and awaits requests from other nodes. When a request is received, it responds by sending the corresponding model back as a reply to the requesting node.

Data Types To facilitate communication between nodes, we define the following data types:

- **ModelStatisticsDataType:** The Model Statistics Data Type provides statistical information about models, including details like the number of parameters or the datasets they were trained on. Messages sent from a Model Manager Sender Node to a Model Manager Receiver Node are treated as a bytes arrays of arbitrary size. Interactions with this data type can be performed using various methods, such as void*, byte arrays, or strings.
- **ModelRequestDataType:** The Model Request Data Type represents a problem request. Internally, requests sent from a Model Manager Receiver Node to a Model Manager Sender Node are treated as byte arrays of arbitrary size. So far, the interaction with this class could be done from a void*, a byte array or a string.
- **ModelReplyDataType:** The Model Reply Data Type represents a response containing the requested model. The replies sent from a Model Manager Sender Node to a Model Manager Receiver Node are treated as bytes arrays of arbitrary size. So far, the interaction with this class could be done from a void*, a byte array or a string.

Figure 30 illustrates the previously described scenario. In this example, an AML-IP-MMReceiver node and an AML-IP-MMSender work on the same problem but with different datasets. Despite having distinct datasets, the AML-IP-MMReceiver node can learn from the model generated by the AML-IP-MMSender node without requiring direct access to its dataset. As a result, the AML-IP-MMReceiver node obtain an accurate model.

This is a specific use case, but any scenario with an arbitrary number of AML-IP-MMReceiver and AML-IP-MMSender nodes is possible. The AML-IP allows the involvement of an arbitrary number of AML-IP-MMReceiver and AML-IP-MMSender nodes, making it possible to create a collaborative learning environment involving multiple participants.

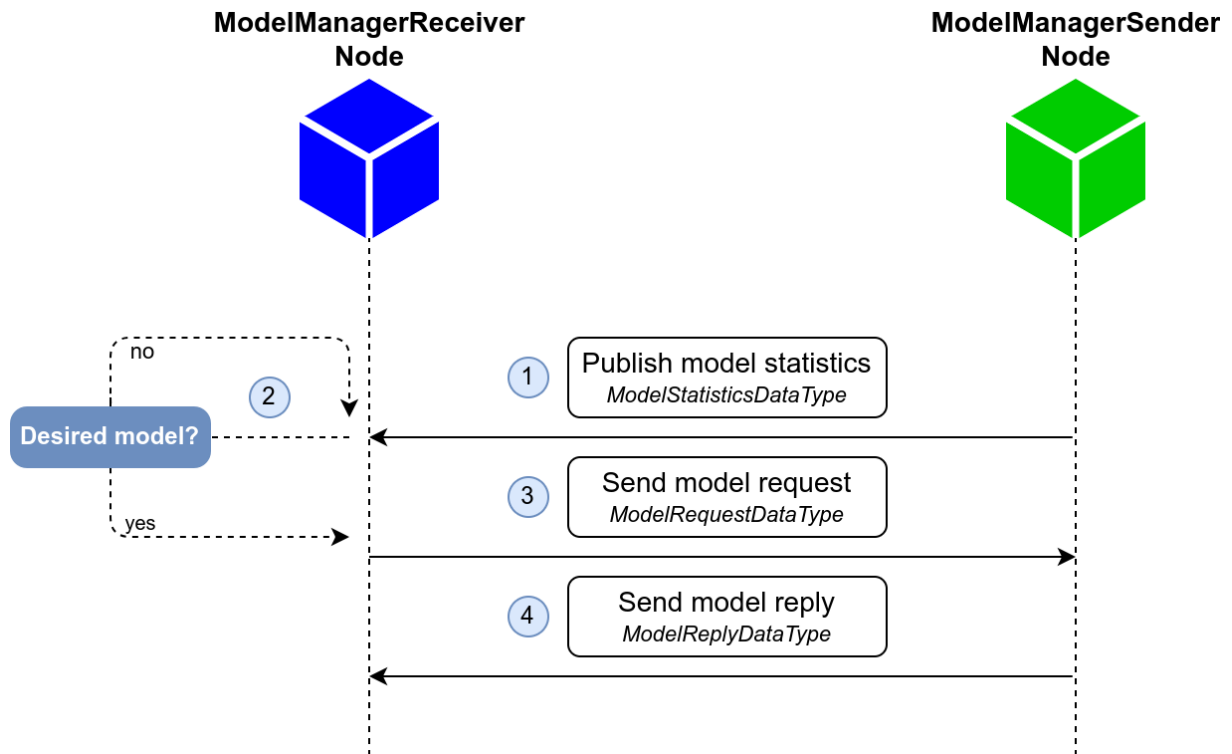


Figure 30: AML-IP collaborative learning scenario.

It is important to understand that a node is an abstract software entity designed to exhibit specific behaviors and functionalities. Unlike a physical machine, a node does not have a direct connection to a specific piece of hardware. As a result, there is no need to have access to cluster of machines in order to run this software, an AML-IP-MMReceiver and several AML-IP-MMSender could be running in the same machine (computer) at the same time.

Communication The communication takes place via **DDS**, just like the rest of the AML-IP. This choice offers significant advantages, as it enables automatic discovery between nodes and ensures completely dynamic and distributed communication. The utilization of DDS facilitates the creation of a fully decentralized network where each node operates independently of the network status. For example, an AML-IP-MMReceiver node behaves consistently, regardless of whether there are 0 or 10 AML-IP-MMSender nodes in its network.

In situations where different nodes are not in the same LAN, we would mix this scenario with the AML-IP-Agent nodes. These specialized nodes facilitate communication between nodes located in different LANs, effectively bridging the gap between distant participants. The integration of AML-IP-Agent nodes ensures that collaborative learning and model sharing can occur seamlessly even across geographically dispersed nodes.

Synchronization It is clear that a way of synchronizing the different nodes is necessary in order to achieve a correct parallel share, being the nodes independent between each other. To accomplish this, a communication protocol is implemented on top of the DDS layer, which serves as the application transport layer. This protocol enables synchronous understanding and efficient management of interactions between

nodes using publication and subscription interfaces. The communication protocol utilized is known as **Remote Procedure Call Protocol** and is explained in previous section 2.8.

Multiple scenarios The AML-IP-MMReceiver and AML-IP-MMSender nodes represent the main points in the context of a collaborative learning scenario in an AML network. This architecture is very useful to parallelize the model sharing collaborative between several nodes. This scenario is represented in Figure 31, where a single AML-IP-MMSender could distribute the model between 4 independent AML-IP-MMReceiver.

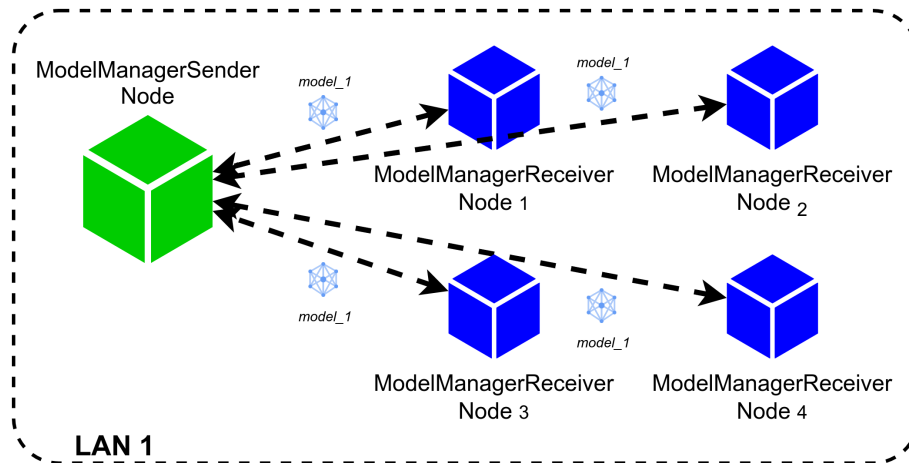


Figure 31: AML-IP local parallelization scenario.

However, this scenario is not the only possible one. It would also be possible to use these parallelization capabilities in a WAN scenario, where one or many AML-IP-MMReceiver could benefit from having a shared external cluster of AML-IP-MMSender. This could be achieved by deploying a AML-IP-Agent in each of the different LANs. This scenario is represented in Figure 32.

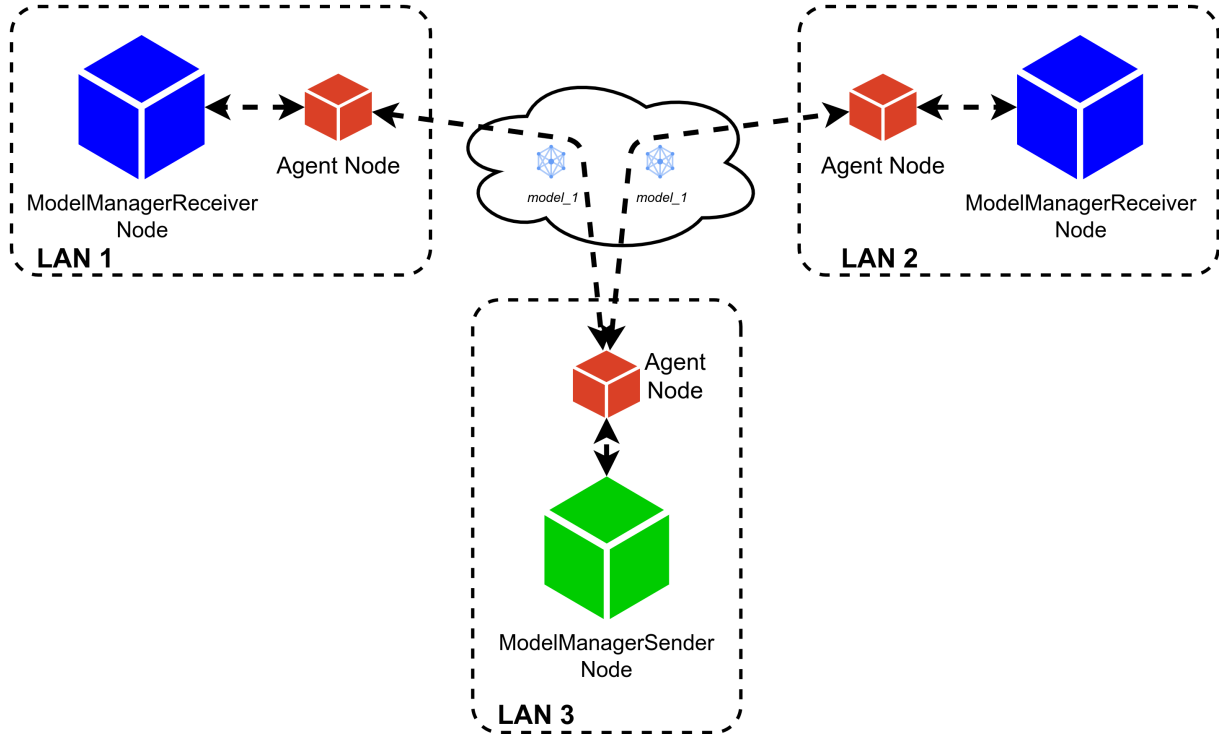


Figure 32: AML-IP WAN parallelization scenario.

And finally, to exemplify that it is possible to mix the AML-IP collaborative learning scenario with workload distribution scenario, in Figure 33 it is represented a scenario where one AML-IP-Main initiates model training using a local AML-IP-Computing. Once the model training is complete, the resulting model is shared with an external AML-IP-MMSender. The AML-IP-MMSender acts as an intermediary in this context and facilitates the distribution of the trained model to an AML-IP-MMReceiver. The AML-IP-MMReceiver node, which may be situated in a different network or location, receives the shared model from the AML-IP-MMSender node. This allows the AML-IP-MMReceiver node to benefit from the expertise and knowledge of the original AML-IP-Main, even though they are not directly connected.

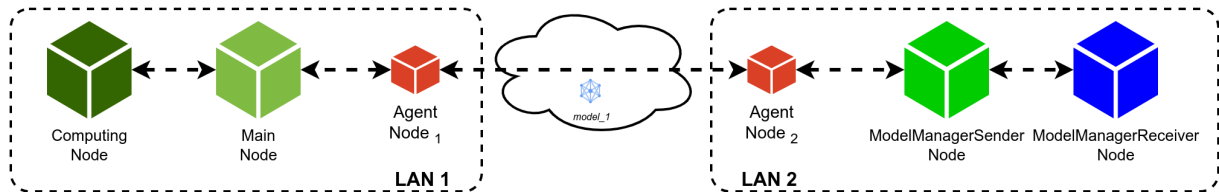


Figure 33: AML-IP workload distribution and collaborative learning scenario.

6.1.3 Implementation

In this section, we describe the implementation details of the Collaborative Learning Scenario, focusing on the Model Manager Receiver and Model Manager Sender nodes. These nodes work in unison to enhance model complexity and accuracy while preserving the privacy of their training datasets. It leverages RPC over DDS in order to exchange all required information in an efficient way.

Model Manager Sender Nodes are responsible for publishing Model Statistics Data Type, while Model Manager Receiver Nodes listen for these statistics and request models when needed.

Model Manager Receiver Node Implementation The following steps outline the implementation of a Model Manager Receiver Node:

1. **Create the Node Identifier:** Begin by creating a unique identifier for the node.
2. **Prepare Model Request Data:** Create the data that specifies the model to request.
3. **Instantiate the ModelManagerReceiver Node:** Create an instance of the ModelManagerReceiver Node class, using the previously created identifier and data.
4. **Start Execution:** Initiate the execution of the Model Manager Receiver Node.
5. **Wait for Model Reply:** Wait for a model reply to arrive from the Model Manager Sender Node.
6. **Stop Execution:** Terminate the execution of the Model Manager Receiver Node.

C++ Implementation

```
#include <cpp_utils/wait/BooleanWaitHandler.hpp>

#include <amlip_cpp/types/id/AmlipIdDataType.hpp>
#include <amlip_cpp/types/model/ModelRequestDataType.hpp>
#include <amlip_cpp/types/model/ModelReplyDataType.hpp>
#include <amlip_cpp/types/model/ModelStatisticsDataType.hpp>

#include <amlip_cpp/node/collaborative_learning/ModelManagerReceiverNode.hpp>

class CustomModelListener : public eprosima::amlip::node::ModelListener
{
public:

    CustomModelListener(
        const std::shared_ptr<eprosima::utils::event::BooleanWaitHandler>&
            ↪ waiter)
        : waiter_(waiter)
    {
        // Do nothing
    }

    virtual bool statistics_received (
        const eprosima::amlip::types::ModelStatisticsDataType statistics)
        ↪ override
    {
        // Always request model
        return true;
    }

    virtual bool model_received (
        const eprosima::amlip::types::ModelReplyDataType model) override
```

```

{
    std::cout << "Model received: " << model << " ." << std::endl;

    waiter->open();

    return true;
}

std::shared_ptr<eprosima::utils::event::BooleanWaitHandler> waiter_;
};

// Create the Id of the node
eprosima::amlip::types::AmlipIdDataType id({"ModelManagerSender"}, {10, 20, 30,
→ 40});

// Create the data
eprosima::amlip::types::ModelRequestDataType data("MobileNet V1");

// Create ModelManagerReceiver Node
eprosima::amlip::node::ModelManagerReceiverNode model_receiver_node(id, data);

// Create waiter
std::shared_ptr<eprosima::utils::event::BooleanWaitHandler> waiter =
    std::make_shared<eprosima::utils::event::BooleanWaitHandler>(false, true);

// Create listener to process statistics and replies
std::shared_ptr<CustomModelListener> listener =
    std::make_shared<CustomModelListener>(waiter);

// Start execution
model_receiver_node.start(listener);

// Wait for solution
waiter->wait();

// Stop execution
model_receiver_node.stop();

```

Python Implementation

```

from py_utils.wait.BooleanWaitHandler import BooleanWaitHandler

from amlip_py.types.AmlipIdDataType import AmlipIdDataType
from amlip_py.types.ModelRequestDataType import ModelRequestDataType
from amlip_py.types.ModelReplyDataType import ModelReplyDataType
from amlip_py.types.ModelStatisticsDataType import ModelStatisticsDataType

from amlip_py.node.ModelManagerReceiverNode import ModelManagerReceiverNode,
→ ModelListener

```

```

class CustomModelListener(ModelListener):

    def statistics_received(
        self,
        statistics: ModelStatisticsDataType) -> bool:
        return True

    def model_received(
        self,
        model: ModelReplyDataType) -> bool:
        print(f'Model reply received from server\n'
              f' solution: {model.to_string()}')

        waiter.open()

        return True

# Create the data
data = ModelRequestDataType('MobileNet V1')

# Create the Id of the node
id = AmlipIdDataType('ModelManagerReceiver')
id.set_id([10, 20, 30, 40])

# Create a new ModelManagerReceiver Node
model_receiver_node = ModelManagerReceiverNode(
    id=id,
    data=data,
    domain=100)

# Start execution
model_receiver_node.start(
    listener=CustomModelListener())

# Wait for solution
waiter.wait()

# Stop execution
model_receiver_node.stop()

```

Model Manager Sender Node Implementation The Model Manager Sender Node is responsible for publishing model statistics and responding to model requests. The following steps describe its implementation:

1. **Create the Node Identifier:** Begin by creating a unique identifier for the node.
2. **Create ModelManagerSender Node:** Instantiate the ModelManagerSender Node class with the previously created identifier.

3. **Publish Model Statistics Data:** Publish model statistics data with a unique version string.
4. **Create Model Replier:** Implement a custom Model Replier to process requests and return replies.
5. **Start Execution::** Initiate the execution of the Model Manager Sender Node.
6. **Stop Execution:** Terminate the execution of the Model Manager Sender Node.

C++ Implementation

```
#include <cpp_utils/wait/BooleanWaitHandler.hpp>

#include <amlip_cpp/types/id/AmlipIdDataType.hpp>
#include <amlip_cpp/types/model/ModelRequestDataType.hpp>
#include <amlip_cpp/types/model/ModelReplyDataType.hpp>
#include <amlip_cpp/types/model/ModelStatisticsDataType.hpp>

#include <amlip_cpp/node/collaborative_learning/ModelManagerSenderNode.hpp>

class CustomModelReplier : public eprosima::amlip::node::ModelReplier
{
public:

    CustomModelReplier(
        const std::shared_ptr<eprosima::utils::event::BooleanWaitHandler>&
            ↪ waiter)
        : waiter_(waiter)
    {
        // Do nothing
    }

    virtual eprosima::amlip::types::ModelReplyDataType fetch_model (
        const eprosima::amlip::types::ModelRequestDataType data) override
    {
        std::cout << "Processing data: " << data << " . Processing data..." <<
            ↪ std::endl;

        // Create new solution from data here
        eprosima::amlip::types::ModelReplyDataType solution("MOBILENET V1");

        std::cout << "Processed model: " << solution << " . Returning model..." <<
            ↪ std::endl;

        waiter_>open();

        return solution;
    }

    std::shared_ptr<eprosima::utils::event::BooleanWaitHandler> waiter_;
};
```

```

// Create the Id of the node
eprosima::amlip::types::AmlipIdDataType id({"ModelManagerSender"}, {66, 66, 66,
→ 66});

// Create ModelManagerSender Node
eprosima::amlip::node::ModelManagerSenderNode model_sender_node(id);

// Create statistics data
std::string data = "hello world";
model_sender_node.publish_statistics("v0", data);

// Create waiter
std::shared_ptr<eprosima::utils::event::BooleanWaitHandler> waiter =
    std::make_shared<eprosima::utils::event::BooleanWaitHandler>(false, true);

// Create listener to process requests and return replies
std::shared_ptr<CustomModelReplier> replier =
    std::make_shared<CustomModelReplier>(waiter);

// Start execution
model_sender_node.start(replier);

// Wait for the solution to be sent
waiter->wait();

// Stop execution
model_sender_node.stop();

```

Python Implementation

```

from py_utils.wait.BooleanWaitHandler import BooleanWaitHandler

from amlip_py.types.AmlipIdDataType import AmlipIdDataType
from amlip_py.types.ModelRequestDataType import ModelRequestDataType
from amlip_py.types.ModelReplyDataType import ModelReplyDataType
from amlip_py.types.ModelStatisticsDataType import ModelStatisticsDataType

from amlip_py.node.ModelManagerSenderNode import ModelManagerSenderNode,
→ ModelReplier

class CustomModelReplier(ModelReplier):

    def fetch_model(
        self,
        model: ModelRequestDataType) -> ModelReplyDataType:
        solution = ModelReplyDataType(model.to_string().upper())
        print(f'Model request received from client\n')

```



```

        f' model: {model.to_string()}\n'
        f' solution: {solution.to_string()}')

    waiter.open()

    return solution

# Create the Id of the node
id = AmlipIdDataType('ModelManagerSender')
id.set_id([66, 66, 66, 66])

# Create a new ModelManagerSender Node
model_sender_node = ModelManagerSenderNode(
    id=id,
    domain=100)

model_sender_node.publish_statistics(
    'ModelManagerSenderStatistics',
    'hello world')

# Start execution
model_sender_node.start(
    listener=CustomModelReplier())

# Wait for the solution to be sent
waiter.wait()

# Stop execution
model_sender_node.stop()

```

6.1.4 Demo

This demo shows a Collaborative Learning Scenario and the AML-IP nodes involved, an AML-IP-MMReceiver Node and an AML-IP-MMSender Node. With these two nodes implemented, users have the flexibility to deploy multiple instances of each type as desired and observe the behavior of a simulated AML-IP network running.

The purpose of the demo is to show how a AML-IP-MMSender Node and a AML-IP-MMReceiver Node can communicate.

AML-IP-MMReceiver Node awaits model statistics from the AML-IP-MMSender Node. Since the AML-IP-MMSender Node doesn't have a real AML-IP-Engine, it sends the model statistics as a string. Upon receiving the statistics, the AML-IP-MMReceiver Node return **True** and sends a model request, also as a string since it doesn't have an AML-IP-Engine. Then, the AML-IP-MMSender Node converts the received model request to uppercase and sends it back as a model reply.

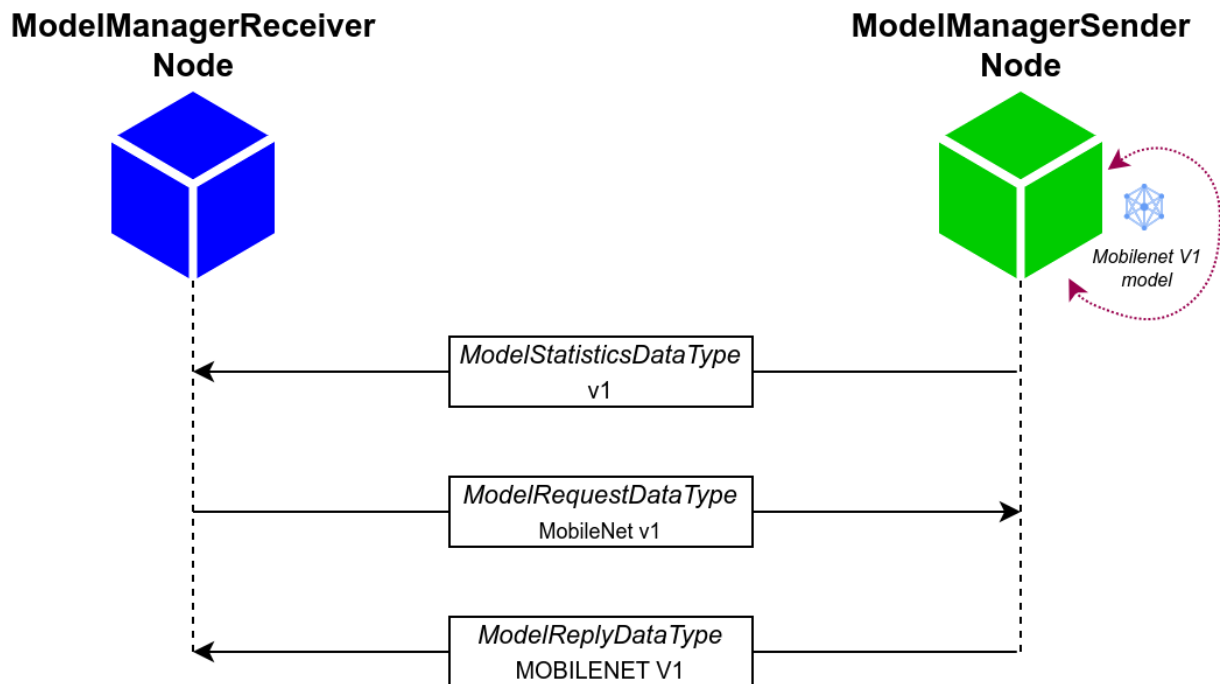


Figure 34: Collaborative Learning Demo.

Prerequisites Before proceeding with the demo, it is necessary to install AML-IP using one of the following installation methods:

- AML-IP on Linux
- AML-IP on Windows
- Docker Image

Building the demo If the demo package is not already compiled, please refer to the Build demos section in the documentation or run the command below.

```
colcon build --packages-up-to amlip_demo_nodes
```

Once the AML-IP packages are installed and built, import the necessary libraries using the following command.

```
source install/setup.bash
```

Explaining the demo This paragraph explore and explain the demo in detail.

AML-IP-MMReceiver Node This is the *python* code for the AML-IP-MMReceiver Node application. This application uses string-based data instead of real AML Models and it is implemented in *python* using **amlip_py** Application Programming Interface (API).

This code can be found [here](#).

The next block includes the *python* header files that allow the use of the AML-IP *python* API.

```
from amlip_py.node.ModelManagerReceiverNode import ModelManagerReceiverNode
from amlip_py.node.ModelManagerReceiverNode import ModelListener
from amlip_py.types.AmlipIdDataType import AmlipIdDataType
from amlip_py.types.ModelReplyDataType import ModelReplyDataType
from amlip_py.types.ModelRequestDataType import ModelRequestDataType
from amlip_py.types.ModelStatisticsDataType import ModelStatisticsDataType
```

Global variables are defined to manage the execution environment.

DOMAIN_ID allows the execution to be isolated because only DomainParticipants with the same Domain Id would be able to communicate to each other.

```
DOMAIN_ID = 166
```

waiter is a **WaitHandler** that waits on a boolean value. Whenever this value is **True**, threads awake. Whenever it is **False**, threads wait.

```
waiter = BooleanWaitHandler(True, False)
```

The **CustomModelListener** class is responsible for listening to Model Statistics Data Type and Model Reply Data Type messages received from an AML-IP-MMSender Node. This class is supposed to be implemented by the user in order to process the messages received from other nodes in the network.

```
class CustomModelListener(ModelListener):

    def statistics_received(
        self,
        statistics: ModelStatisticsDataType) -> bool:

        return True

    def model_received(
        self,
        model: ModelReplyDataType) -> bool:

        print(f'Model reply received from server\n'
              f' solution: {model.to_string()}')

        waiter.open()

        return True
```

The **main** function orchestrates the execution.

```
def main():
```

We create an instance of **ModelManagerReceiverNode**. The first thing the constructor gets is the id of the participant associated with the node. Then the data which is a **ModelRequestDataType** with the request message. And also we specified the domain equal to the **DOMAIN_ID** variable.

```
# Create request
data = ModelRequestDataType('MobileNet V1')

id = AmlipIdDataType('ModelManagerReceiver')
id.set_id([15, 25, 35, 45])

# Create node
print('Starting Manual Test Model Manager Receiver Node Py execution. Creating
↪ Node...')
model_receiver_node = ModelManagerReceiverNode(
    id=id,
    data=data,
    domain=DOMAIN_ID)
```

Then we start the node execution, passing the previously defined **CustomModelListener** class, which is responsible for managing the messages received.

```
model_receiver_node.start(
    listener=CustomModelListener())
```

Wait for the response model to arrive from the AML-IP-MMSender Node.

```
# Wait for reply
waiter.wait()
```

Finally, stop and close the node.

```
model_receiver_node.stop()
```

AML-IP-MMSender Node The *python* code for the AML-IP-MMSender Node application is provided here. Similar to the AML-IP-MMSender Node, this application uses string-based data instead of real AML Models and is implemented using the **amlip_py** API.

This code can be found [here](#).

The following *python* header files enable the use of the AML-IP *python* API.

```
from amlip_py.node.ModelManagerSenderNode import ModelManagerSenderNode
from amlip_py.node.ModelManagerSenderNode import ModelReplier
```

```
from amlip_py.types.AmlipIdDataType import AmlipIdDataType
from amlip_py.types.ModelReplyDataType import ModelReplyDataType
from amlip_py.types.ModelRequestDataType import ModelRequestDataType
```

Global variables for managing the execution:

DOMAIN_ID allows the execution to be isolated because only DomainParticipants with the same Domain Id would be able to communicate to each other.

```
DOMAIN_ID = 166
```

waiter is a **WaitHandler** that waits on a boolean value. Whenever this value is **True**, threads awake. Whenever it is **False**, threads wait.

```
waiter = BooleanWaitHandler(True, False)
```

The **CustomModelReplier** class is responsible for listening to Model Request Data Type request messages received from a AML-IP-MMReceiver Node. This class is supposed to be implemented by the user in order to process the request messages.

```
class CustomModelReplier(ModelReplier):

    def fetch_model(
        self,
        request: ModelRequestDataType) -> ModelReplyDataType:

        reply = ModelReplyDataType(request.to_string().upper())

        print(f'Model request received from client\n'
              f' request: {request.to_string()}\n'
              f' reply: {reply.to_string()}')

        waiter.open()

        return reply
```

We define the **main** function.

```
def main():
```

We create an instance of **ModelManagerSenderNode**. The first thing the constructor gets is the id of the participant associated with the node. And also we specified the domain equal to the **DOMAIN_ID** variable.

```
id = AmlipIdDataType('ModelManagerSender')
id.set_id([10, 20, 30, 40])
```

```
# Create node
print('Starting Manual Test Model Manager Sender Node Py execution. Creating
→ Node...')
model_sender_node = ModelManagerSenderNode(
    id=id,
    domain=DOMAIN_ID)
```

Call the `publish_statistics()` function, which fills a Model Statistics Data Type and publishes it.

```
model_sender_node.publish_statistics(
    'ModelManagerSenderStatistics',
    'hello world')
```

Then we start the node execution, passing the previously defined **CustomModelReplier** class, which is responsible for managing the request received.

```
model_sender_node.start(
    listener=CustomModelReplier())
```

Wait for the response model to be sent to the AML-IP-MMReceiver Node.

```
# Wait for the solution to be sent
waiter.wait()
```

Finally, stop and close the node.

```
model_sender_node.stop()
```

Running the demo

This demo runs the nodes implemented in `amlip_demo_nodes/amlip_collaborative_learning_demo`.

Run AML-IP-MMReceiver Node

Run the following command:

```
# Source colcon installation
source install/setup.bash

# To execute Model Manager Receiver Node
cd ~/AML-IP-ws/src/AML-IP/amlip_demo_nodes/amlip_collaborative_learning_demo/
→ amlip_collaborative_learning_demo
python3 model_receiver_custom.py
```

The expected output is the following:

```
Starting Manual Test Model Manager Receiver Node Py execution. Creating Node...
Node created: ModelManagerReceiver.0f.19.23.2d. Already processing models.
Model reply received from server
solution: MOBILENET V1
Finishing Manual Test Model Manager Receiver Node Py execution.
```

Run AML-IP-MMSender Node

Run the following command to answer before closing:

```
# Source colcon installation
source install/setup.bash

# To execute Model Manager Sender Node
cd ~/AML-IP-ws/src/AML-IP/amlip_demo_nodes/amlip_collaborative_learning_demo/
→ amlip_collaborative_learning_demo
python3 model_sender_custom.py
```

This execution expects an output similar to the one shown below:

```
Starting Manual Test Model Manager Sender Node Py execution. Creating Node...
Node created: ModelManagerSender.0a.14.1e.28. Already processing models.
Model request received from client
model: MobileNet V1
solution: MOBILENET V1
Finishing Manual Test Model Manager Sender Node Py execution.
```

6.2 AML-IP workload distribution scenario

This section explains the different types of nodes that participate in the AML-IP workload distribution scenarios, and the communication between them.

6.2.1 Workload distribution scenario

The so called *workload distribution scenario* refers to those scenarios in AML where one computational complex task could be divided in subtasks, and these subtasks could be processed in parallel by different computational points to finally obtain a joint result.

The scenarios are not mutually incompatible, they just differ in the kinds of nodes that participate in each of them. A workload distribution scenario could be present locally, remotely, or even both at the same time. By leveraging the versatility of the AML-IP-Agent, an AML-IP-Edge could be working distributively and at the same time collaborating with a network of AML-IP-Edges by sharing its training result. The most important nodes in this scenario are the AML-IP-Main and the AML-IP-Computing, which are explained ahead in this section.

Training parallelization The workload distribution scenario directly applies to the training process performed in the AML-IP-Edge, the one in charge of training a model by adding new atomizations resulting from the processing of batches of data. This is a very expensive process that requires a high amount of memory and computational power. But it is also a parallelizable process, where some batches of data could be trained in parallel, and then the results could be merged to obtain a better model.

6.2.2 Design

This section explains in detail the design of certain nodes of the AML-IP to achieve the efficient deployment of a training network exploiting the strengths of AML.

Architecture Description The main idea of this part of the AML-IP is to parallelize the computational effort in a balanced way between an arbitrary number of computing points. The work that is presented along this section refers to the process of creating new atomizations, generated by an AML-IP-Edge. It could be said that the scenario here exposed comprehends the detailed process of an AML-IP-Edge distributing its own workload among a number of computing points.

Nodes In this scenario, two types of nodes play pivotal roles:

- **AML-IP-Main:** This kind of node functions as a central point for a *training* process. It creates *Jobs*, that could be seen as batches of data to be processed by the training algorithm. These jobs are distributed to a number of computing nodes (as any batch could be trained in parallel thanks to the AML), and their corresponding results collected and merged back in the main node.
- **AML-IP-Computing:** This kind of node is in essence a computational point where a workload is released, so it can process a specific task on the data it has been given. This task corresponds to training over a batch of AML data and sending the pertinent result to the AML-IP-Main.

Data Types In this context, two key data types are employed:

- **JobDataType:** The Job Data Type represents a partial data-set and a model state. Internally, Jobs sent from a Main Node to a Computing Node are treated as byte arrays of arbitrary size. Users can interact with this class using various data formats, including void*, byte arrays or strings. From Python API, the only way to interact with it is by str type.

- **JobSolutionDataType:** The Solution Data Type represents the result of atomization or a new model state. When sent from a Computing Node to the Main Node, the Solution is treated as a byte array of arbitrary size. Similar to the Job Data Type, interaction with this class is possible through `void*`, byte arrays or strings. When using the Python API, interaction is exclusively through the `str` data type.

Figure 35 represents the previously described scenario. In this example, two AML-IP-Main nodes work in the same problem, but with different datasets. Each of them has two different batches of training data to process, but since an initial preprocessing phase is needed, the two batches are not required to be executed at the exact same time. With this schema it can be accomplished that, using three AML-IP-Computing nodes, the workload of the two AML-IP-Main nodes is distributed among them in an efficient way, so a task being resolved by a machine and other executions do not overlap. This is a specific use case, but any scenario with an arbitrary number of AML-IP-Main nodes and AML-IP-Computing nodes is possible, and the workload would be *intelligently* divided between available and free nodes so the parallelization of complex tasks (as, in this case, the training phase) is maximized.

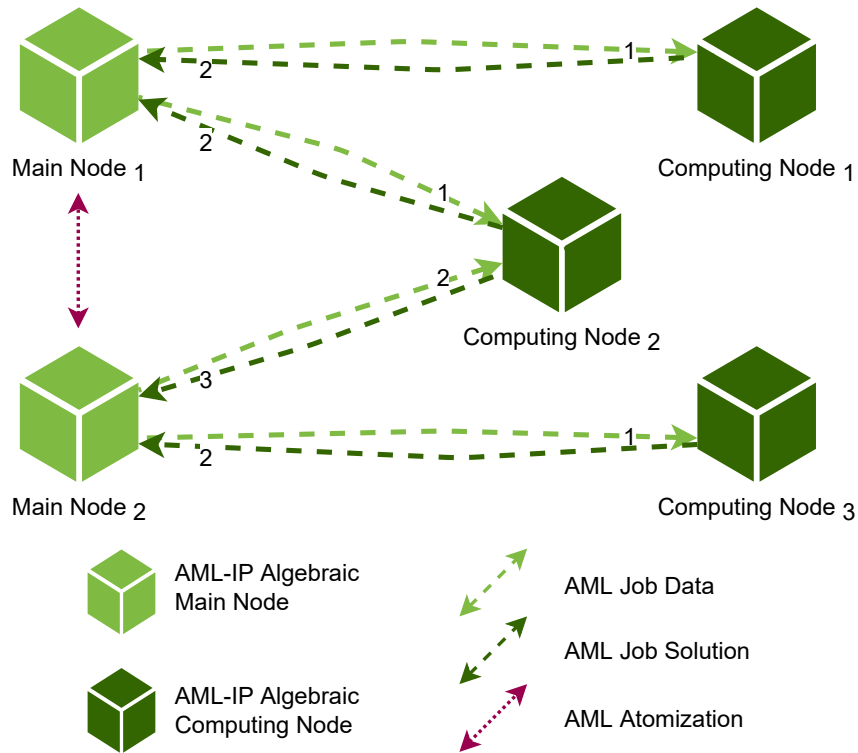


Figure 35: AML-IP workload distribution scenario.

It is important to make clear that a node is an abstract software entity that exhibits a certain behaviour, but it is not directly related with a physical machine. Thus, there is no need to have access to cluster of machines in order to run this software, an AML-IP-Main node and several AML-IP-Computing nodes could be running in the same machine (computer) at the same time. This may not be the most optimal scenario, but it still benefits from modern processors' multi-threading tasking or specific hardware advantages.

Communication Every node is communicated via **DDS**, just like the rest of the AML-IP. This is a great advantage since the discovery is made automatically between the nodes, and the communication is completely dynamic and distributed. This allows to have a completely decentralized network where every node is independent of the network status. (e.g. a AML-IP-Main node will behave the same way if there are 0 or 10 AML-IP-Computing nodes in its network. Obviously, in the first case it would not be able to train a model, and in the second it would train much faster than with just a AML-IP-Computing node).

In the case where different nodes are not in the same LAN, we would mix this scenario with the *collaborative scenario*, where a node could communicate via WAN with external nodes hosted anywhere by using the AML-IP-Agent.

Synchronization It is clear that a way of synchronizing the different nodes is necessary in order to achieve a correct parallel training, being the nodes independent between each other. This is accomplished by using a new communication protocol on top of the DDS layer (application transport layer) that allows to manage a synchronous and asynchronous understanding between nodes using publication and subscription interfaces. This new protocol is called **MultiService Communication Protocol** and is explained in previous section 2.7.

Multiple scenarios The AML-IP-Main node and AML-IP-Computing nodes represent the main points in the context of a workload distribution scenario in an AML network. This architecture is very useful to parallelize the model training workload between several nodes. This scenario is represented in Figure 36, where a single AML-IP-Main could distribute the effort between 4 independent AML-IP-Computing. This way, the time it takes to train a model is inversely proportional to the number of AML-IP-Computing in the network.

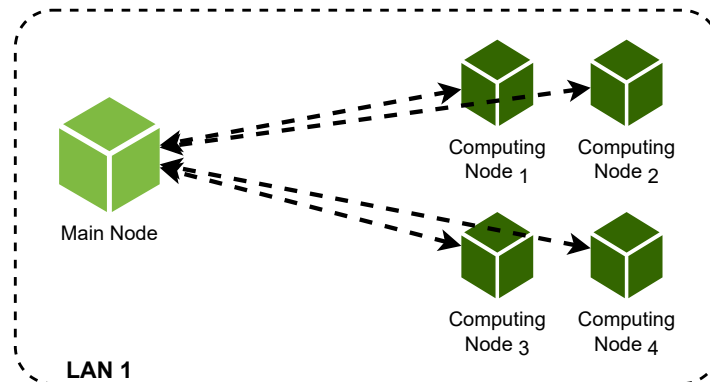


Figure 36: AML-IP local parallelization scenario.

However, this scenario is not the only possible one. It would also be possible to use these parallelization capabilities in a WAN scenario, where one or many AML-IP-Main nodes could benefit from having a shared external cluster of AML-IP-Computing nodes. This could be achieved by deploying a AML-IP-Agent node in each of the different LANs. This scenario is represented in Figure 37.

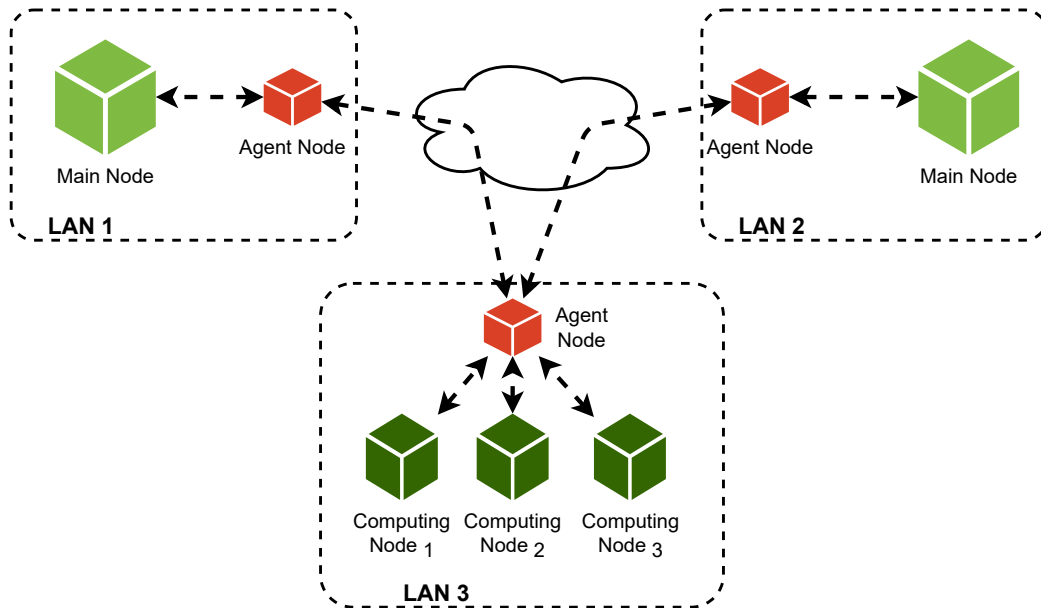


Figure 37: AML-IP WAN parallelization scenario.

Finally, to exemplify that it is possible to mix the AML-IP workload distribution scenario with any other, in Figure 38 it is represented a scenario where one AML-IP-Main node trains a model using a local AML-IP-Computing node and shares the resulting model with an external AML-IP-Main node unable to train its own model (say due to the lack of computational resources).

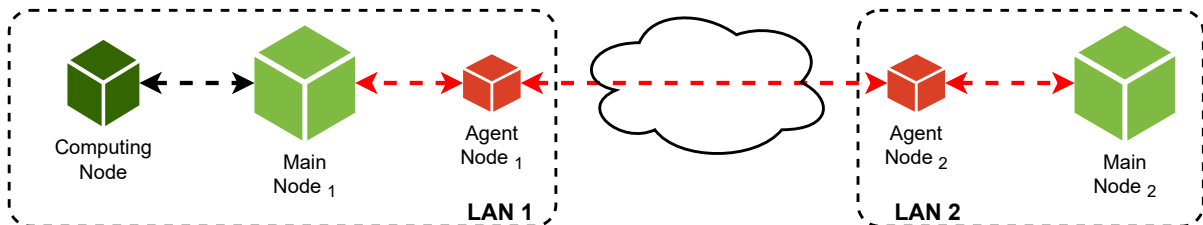


Figure 38: AML-IP workload distribution and collaborative learning scenario.

6.2.3 Prototype

In order to show the current state of the AML-IP, and to proof that the presented designs work efficiently and as expected, eProsima has implemented a prototype of the AML-IP for workload distributed scenarios. This prototype is hosted on Github and publicly available at [aml-ip-prototype](https://github.com/eProsima/aml-ip-prototype/tree/ALMA_AMLIP_D6.2)²².

Technology used This repository follows the usual architecture of ROS 2 packages or Fast DDS workspaces, and it is easy to install and execute.

²²https://github.com/eProsima/aml-ip-prototype/tree/ALMA_AMLIP_D6.2

AML-IP Algebraic Nodes The AML-IP-Alg are under development by ALGEBRAIC, and are not yet ready for deployment. For this reason, this prototype uses mocked nodes. That is, nodes that have the exact same input and output that the actual ones will have, and whose internal mechanism is simplified, or even eliminated. As the main objective of this prototype is to prove the feasibility of the communication process, and not the AML itself, these mocks are enough for this purpose.

Fast DDS Python Bindings In order to bind the ALGEBRAIC mock nodes with Fast-DDS, Fast DDS Python Bindings are used to build the DDS communication architecture. This includes the creation and management of the different DDS entities (DomainParticipants, DataWriters, DataReaders, etc.), the QoS that each of them uses, and the processes for writing and reading messages.

eProsima DDS Router This prototype is independent from the DDS Router, as restricting communication to a single LAN is enough to prove the feasibility of the given design. However, an experiment testing this prototype within a WAN scenario is also provided, in which the DDS Router is in charge of enabling the communication between external nodes.

Design This design does not intend to be robust nor represent the future implementation of these nodes, but to test the communication processes between nodes. Thus, the nodes implemented for this prototype are rather simple and restricted to the desired behaviour. Future nodes are intended to be very flexible and their behaviour will rely on higher level entities.

Prototype nodes Figure 39 schematically displays how each kind of node behaves. These nodes communicate by following the MSCP explained in subsection 2.7.

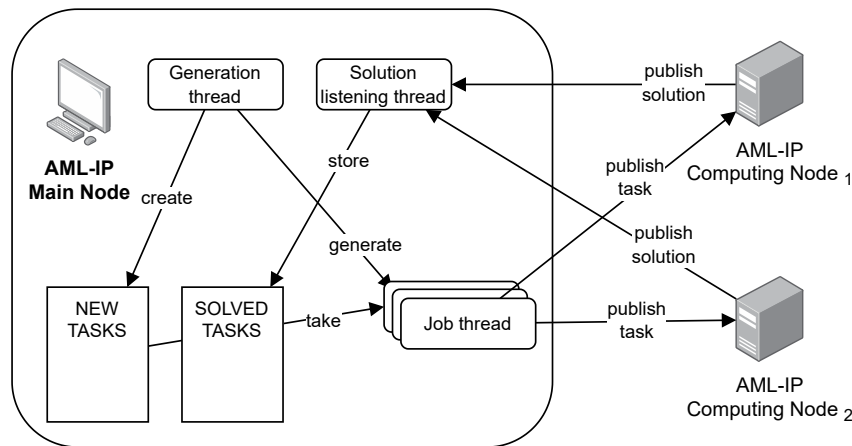


Figure 39: Prototype nodes design.

- AML-IP-Main

Each execution of this node has two main threads. The *Generation thread* creates new (random) tasks, each of them starting a new thread that is responsible for sending that corresponding data to a AML-IP-Computing and wait for the solution. Once the solution arrives, it stores it in a database. The *Solution listening thread* awakes with a fixed frequency. The mission of this thread is to join the threads that have already finished, and collect their solution to be stored in a shared database.

- AML-IP-Computing

The behaviour of the AML-IP-Computing nodes is much simpler. Each has a simple thread that awaits for a job targeted to them. Once the task arrives (after the required MSCP synchronization), the process waits for a random time, which simulates the training time, and returns the solution.

- Data

The data generated by the AML-IP-Main and the solution data retrieved by the AML-IP-Computing is transmitted as raw bytes (as will be the case for future AML data). An extra field has been added to the data being sent in order to have the possibility of verifying the correct operation of the whole system. This additional data entry consists of a string with a simple sentence randomly generated, whose end is completed (also randomly) by the AML-IP-Computing.

e.g.

<i>AML-IP-Main publish job</i>	<i>AML-IP-Computing publish solution</i>
<i>She was playing</i>	<i>She was playing alone.</i>
<i>Tim was talking</i>	<i>Tim was talking with me.</i>

- Timing

Both the time elapsed between job generations in AML-IP-Main and the time elapsed in a AML-IP-Computing since a task is received until it is resolved are random. This attempts to simulate the times that an actual node would take to process the data it is working with.

DDS Data types The data types used in this prototype are the ones described in Figure 6. The IDL files used to generate those data types that Fast DDS Python Bindings requires can be found in appendix B.

Experiments Different experiments and architectures have been tested to check the functionality of the prototype.

Simple experiment This experiment follows a very simple approach where only one AML-IP-Main communicates with only one AML-IP-Computing, both displaying their expected behaviour.

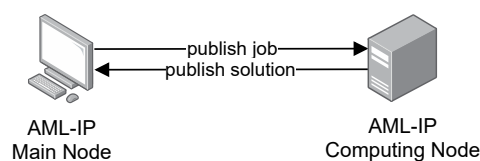


Figure 40: LAN prototype experiment architecture.

WAN experiment In this experiment, the same simple architecture is used, but the two nodes are deployed in different LANs. This requires the use of the DDS Router (in the future AML-IP-Agent) to communicate all necessary data. This scenario is meant to demonstrate the use of an AML distributed network in WAN scenarios.

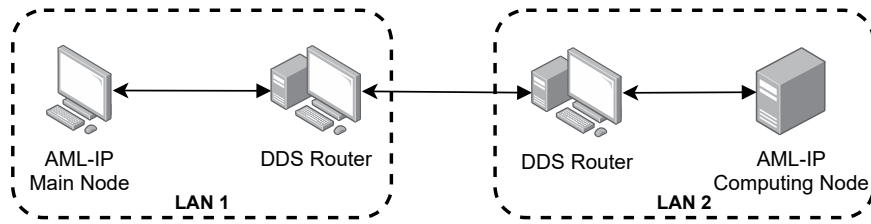


Figure 41: WAN prototype experiment architecture.

Complex experiment This is the most relevant experiment, where the potential of DDS and MSCP synchronization is tested. Two (or an arbitrary number) AML-IP-Main nodes will work concurrently by making requests to a network of three (or an arbitrary number) AML-IP-Computing nodes. The workload will be dynamically divided between the AML-IP-Computing, that will process the requests neatly. This is the scenario that is demonstrated in section 6.2.3.

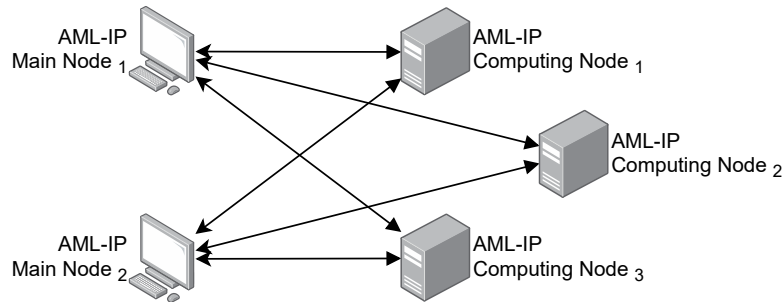


Figure 42: Complex prototype experiment architecture.

Demonstrator The following section presents a demonstrator of the AML-IP prototype for the workload distribution scenario. It details the network architecture deployed for the execution of the prototype, as well as the steps required to download, install and run it. Thus, it is possible to reproduce the results obtained and presented in this document. The main purpose of this demonstrator is to illustrate the successful connection between AML-IP prototype nodes parallelizing tasks in a local environment.

Experiment design The implemented nodes are the AML-IP-Main and the AML-IP-Computing, which are the main components of the future AML-IP-Edge. Figure 42 shows the network architecture deployed for this demonstrator. This architecture is chosen to test the complex scenario where synchronization and multiple tasks must be managed by the nodes.

The expected behaviour of the prototype is that any request sent by the AML-IP-Main will be addressed by one and only one AML-IP-Computing after a certain period of time. The prototype prints logs and stores the results in final files so the execution of the whole system can be checked. Be aware that the time periods are random, and so it may occur that the AML-IP-Computing nodes do not answer quickly enough to the tasks handed by the AML-IP-Mains, resulting in a queue of non-resolved tasks. These tasks are addressed in the same order they were emitted, so eventually the system would be able to auto-adjust.

WAN This same scenario could be replicated in WAN with any distribution of the nodes across the LANs. It is only required to deploy an instance of DDS Router in each of the LANs, using configurations 6 and 7.

Download and installation The prototype has been developed as an Open Source project in GitHub. Thus, the whole code and instructions are made available in the `aml-ip-prototype` GitHub repository²³. The project has been developed for Ubuntu 20.04.2.0 LTS (Focal Fossa)²⁴ OS and it has not been tested in any other platforms. However, every eProxima product is tested in *Windows* and *macOS* platforms, so this prototype may also be supported for these OSs.

The project `README.md` file contains all the instructions to install the libraries and dependencies required to correctly download and compile the project. The main dependencies are the *eProxima Fast DDS* library for DDS communication and the `colcon`²⁵ tool to build the project.

To install the project, together with all its dependencies, simply execute the following commands:

```
$ export WORKSPACE_PATH="/<path/to/workspace>"
$ mkdir -p ${WORKSPACE_PATH}/src
$ cd ${WORKSPACE_PATH}
$ wget
→ https://raw.githubusercontent.com/eProxima/aml-ip-prototype/ALMA_AMLIP_D6.2/amlip.repos
$ vcs import src < amlip.repos
$ colcon build
```

Experiment setup All the executables must be run from the `WORKSPACE` folder and it is required to `source` the installation setup of the project for the prototype node executables to find the required dynamic libraries. For this reason, every command that will be shown from here on must be preceded by the following instructions in order to correctly configure the environment:

```
$ cd ${WORKSPACE_PATH}
$ source ./install/setup.bash
```

The commands required to launch each kind of node are:

```
$ ./install/amlip_nodes/lib/amlip_nodes/amlip_computing
$ ./install/amlip_nodes/lib/amlip_nodes/amlip_main
```

Both AML-IP-Main and AML-IP-Computing accept configuration arguments when executing the previous commands. Using the `-h` or `--help` argument, information on its usage and possible arguments is displayed.

- **–domain** Set the Domain Id for the DDS communication. This is useful to simulate the WAN scenario in a single computer.
- **–seed** Set the initial random seed to a specific number to make the experiment deterministic.
- **–debug** Activate debug traces.

Results This experiment has been performed using the implemented prototype and following the instructions already given. In Appendix C, several screenshots taken while executing the commands from Section 6.2.3 are shown.

²³https://github.com/eProxima/aml-ip-prototype/tree/ALMA_AMLIP_D6.2

²⁴<https://releases.ubuntu.com/20.04/>

²⁵<https://colcon.readthedocs.io/en/released/>

Understanding log traces Once everything is deployed, all nodes will discover each other dynamically using DDS multicast discovery. It could be seen in screenshots 68 and 69 when these nodes has started and how the AML-IP-Main has sent `job 0` to AML-IP-Computing, that has answered (approximately in the time that it takes to generate one or two other jobs) and has answered it. From that point, the rest of the nodes start to affect the network, and then the jobs from any AML-IP-Main are automatically distributed to first AML-IP-Computing that frees from other job.

Traces from AML-IP-Computing basically log the jobs that it starts to process, and also when the job solution is retrieved.

Traces from AML-IP-Main log each new generated job, announced via a new thread that sends a request and waits for an available server. It also logs every 5 seconds those jobs that have been resolved together with their solution.

Understanding final log files

Each node generates a final log file in folder `./INTERCHANGE_FOLDER/RESULTS` with the name of the node as part of each file name. AML-IP-Computing generates a file with every job received and the solution found for it. AML-IP-Main generates a file that collects the jobs sent that have not yet been solved, as well as the resolved jobs together with their solution. Some examples of log files for AML-IP-Computing and AML-IP-Main can be seen in Listing 5 and Listing 8, respectively.

Duplicated task ids

Each task is uniquely identified by two values, the id of the client and the id of the task. There are several repeated task numbers along the final log files, as there were two AML-IP-Main generating jobs, and both started numbering from 0. Checking the logs, it is easy to determine which AML-IP-Main any task belongs to just by inspecting the message. This is the main reason why these sentences are generated and answered randomly.

Experiment Conclusions The AML-IP prototype has been used to test the feasibility and viability of the final AML-IP design. From the experiment carried out with this prototype, the following conclusions can be drawn about the proposed final design:

- The synchronization and orchestration of many nodes working in the same training process does not require a centric application, and could be achieved easily and efficiently using DDS communication with higher abstraction layers as the MSCP.
- Working across different LANs while using the DDS Router results in an architecture equivalent to having all nodes in the same LAN (disregarding the obvious increase in latency affecting communication).
- The most complex part of the design of the prototype has certainly been the synchronization of the internal threads of each node. Most of the time, simultaneous threads must notify each other and also write or read from the same data structures. More subtle designs should be considered in order to reduce this complexity.
- The MSCP requires further thought in its design in order to handle drops and desynchronizations, as the current version of the prototype does not cover the situation where the connection fails once the server has been targeted. Both Main and Computing will get stucked waiting for the other nodes to respond.

6.2.4 Implementation

This section outlines the implementation details of a Workload Distribution Scenario designed to efficiently distribute high computational tasks across remote nodes. The primary goal is to parallelize tasks,

avoiding any potential blockages for other critical processes running on the same device. To achieve this, we employ MSCP over DDS communication for task distribution.

In this scenario, the distributed task involves training an AML model using a training dataset. The model resides on a Main Node, and the training dataset is divided into various jobs. These jobs, along with the model's current state, are dispatched to Computing Nodes for parallel execution. This approach significantly reduces the computational load on the Main Node, allowing it to perform other concurrent tasks.

Main Node Synchronous Implementation The Main Node Synchronous Implementation requires active user interaction for task execution. The system waits for a job to complete before accepting another. Users can initiate this process using the *request_job_solution* method. The thread calling this method waits until the entire process, including job execution and solution retrieval, is finished. Upon node destruction, internal entities are appropriately disposed of.

C++ Implementation

```
// Create a new Main Node
auto node = eprosima::amlip::MainNode("My_Main_Node");

// Create a new job to be executed remotely
auto new_job = eprosima::amlip::JobDataType("Some Job as byte array serialized
→ from a string");

// Send a job to a remote Computing Node and wait for the solution
auto solution = node.request_job_solution(new_job);
```

Python Implementation

```
# Create a new Main Node
node = MainNode("My_Main_Node")

# Create a new job to be executed remotely
new_job = JobDataType("Some Job as byte array serialized from a string")

# Send a job to a remote Computing Node and wait for the solution
solution, server_id = node.request_job_solution(new_job)
```

Main Node Asynchronous Implementation In the Main Node Asynchronous Implementation, users can still use the *request_job_solution* method to initiate job processing. However, this implementation operates asynchronously, allowing the main thread to continue execution while the solution is processed in the background. Callbacks or listeners handle the result, which is returned in a separate thread. Node destruction ensures proper cleanup of internal entities.

Python Implementation

```
def solution_received(
    solution,
    task_id,
    server_id):
    print(f'Solution received from server: {server_id}\n'
          f'with id: {task_id}\n'
          f'solution: {solution.to_string()}')

def main():
    # Create a new Async Main Node
    node = AsyncMainNode(
        'MyAsyncMainNode',
        callback=solution_received,
        domain=100)

    # Create new data to be executed remotely
    data_str = '<Job Data In Py String Async [LAMBDA]>'
    job_data = JobDataType(data_str)

    # Send data to a remote Computing Node and waits for the solution
    task_id = main_node.request_job_solution(job_data)

    # User must wait to receive solution.
    # Out of scope, the node will be destroyed,
    # and thus the solution will not arrive.
```

Computing Node Synchronous Implementation The Computing Node Synchronous Implementation acts as a passive server, waiting for incoming jobs and processing them. It receives serialized job data and executes a user-defined calculation to produce a job solution. This implementation synchronously waits for a job to complete before accepting the next.

C++ Implementation

```
// Create a new Computing Node
auto node = eprosima::amlip::ComputingNode("My_Computing_Node");

// Create a callback to process a job and return a solution
auto process_solution = []( const eprosima::amlip::types::JobDataType& ){
    eprosima::amlip::types::JobSolutionDataType solution;
    // Do some code that calculates the solution
    return solution;
};

// Wait for 1 task from any client and answer it with process_solution callback
node.process_job(process_solution);
```

Python Implementation

```
# Create a new Computing Node
node = ComputingNode("My_Computing_Node")

def process_solution():
    JobSolutionDataType solution;
    # Do some code that calculates the solution
    return solution

# Wait for 1 task from any client and answer it with process_solution callback
node.process_job(callback=process_solution)
```

Computing Node Asynchronous Implementation The Computing Node Asynchronous Implementation supports the *request_job_solution* method for job initiation. This implementation operates asynchronously, allowing the main thread to continue execution while awaiting the solution. Users specify callbacks or listeners to process the results.

Python Implementation

```
def process_job(
    job,
    task_id,
    client_id):
    JobSolutionDataType solution;
    # Do some code that calculates the solution
    return solution

# Create a new Async Computing Node
node = AsyncComputingNode(
    'MyAsyncComputingNode',
    callback=process_job,
    domain=100)

node.run()

# Wait until Ctrl+C

node.stop()
```

6.2.5 Demo

This demonstrator shows how to implement two kind of nodes: AML-IP-Computing node and AML-IP-Main node. With these two nodes implemented, the user can deploy as many nodes of each kind as desired and check the behavior of a simulated AML-IP network running. They are implemented one in *python* and one in *c++* to demonstrate as well how to instantiate each kind of node with different API, and to prove the communication between the two implementations.

Simulation In this demonstration, the original AML-IP-Engine is not included; instead, a mock-up is employed. This mock-up replicates a complex computation by transforming a string to uppercase and introducing a random delay of 1 to 5 seconds to accomplish the task.

AML-IP-Main Node This node simulates a AML-IP-Main Node. It is implemented in *python* using **amlip_py** API. There are 2 different ways to run it, an automatic one and a manual one:

- **Automatic version:** the python executable expects input arguments. For each argument, it will convert it to a string and send it as a *Job*. Once the arguments run out, it will finish execution and destroy the Node.
- **Manual version:** the python program expects to receive keyboard input. For each keyboard input received, it will convert it to a string and send it as a *Job*. When empty string given, it will finish execution and destroy the Node.

AML-IP-Computing Node This node simulates a AML-IP-Computing Node. It does not use real AML *Job*, but strings. It is implemented in *c++* using **amlip_cpp** API.

To run it, one integer argument is required. This will be the number of *jobs* this Node will answer to before finishing its execution and being destroyed.

Installation First of all, check that *amlip_demo_nodes* sub-package is correctly installed. If it is not, please refer to Build demos.

Run demo The demo that is presented here follows the schema of the figure below.

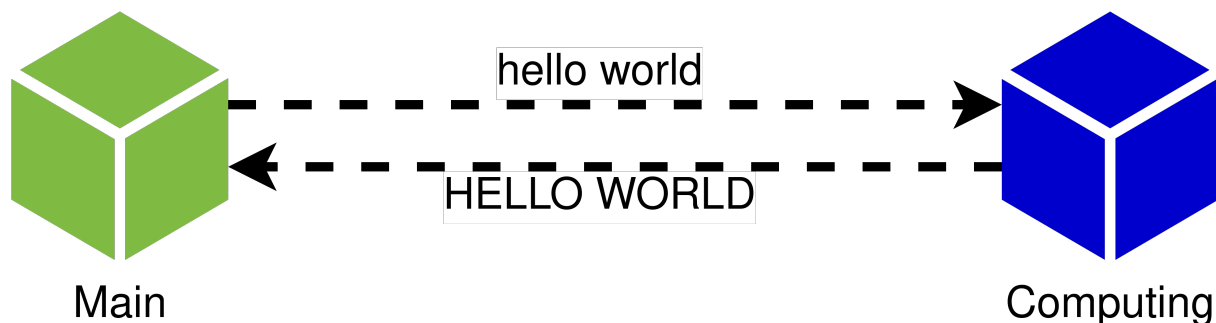


Figure 43: Workload Distribution Demo.

Run Main Node

Run the following command:

```
# Source colcon installation
source install/setup.bash

# To execute Main Node to send 2 jobs
python3 ./install/amlip_demo_nodes/bin/main_node.py first_job "second job"
```

Take into account that this node will wait until there are Computing Nodes running and available in the same LAN in order to solve the jobs.

The expected output is the following:

```
Main Node AMLMainNode.aa.a5.47.fe ready.
Main Node AMLMainNode.aa.a5.47.fe sending task <first_job>.
# ... Waits for Computing Node
Main Node received solution from AMLComputingNode.d1.c3.86.0a for job <first_job>
↪ => <FIRST_JOB>.
Main Node AMLMainNode.aa.a5.47.fe sending task <second job>.
Main Node received solution from AMLComputingNode.d1.c3.86.0a for job <second job>
↪ => <SECOND JOB>.
Main Node AMLMainNode.aa.a5.47.fe closing.
```

Run Computing Node

Run the following command to answer 2 jobs before closing:

```
# Source colcon installation
source install/setup.bash

# To execute Computing Node to answer 2 jobs
./install/amlip_demo_nodes/bin/computing_node 2
```

Take into account that this node will wait until it has solved 2 different jobs. If there are more than 1 Computing Node running, one job is only solved by one of them.

This execution expects an output similar to the one shown below:

```
Computing Node ID{AMLComputingNode.d1.c3.86.0a} computing 2 tasks.
# ... Waits for Main Node
Received Job: <first_job>. Processing...
Answering Solution: <FIRST_JOB>.
Computing Node ID{AMLComputingNode.d1.c3.86.0a} answered task. 1 remaining.
Received Job: <second job>. Processing...
Answering Solution: <SECOND JOB>.
Computing Node ID{AMLComputingNode.d1.c3.86.0a} answered task. 0 remaining.
Computing Node ID{AMLComputingNode.d1.c3.86.0a} closing.
```

Bigger scenarios There is no limit in the number of nodes of each kind that could run in the same network. However, take into account that these nodes are not meant to close nicely if they do not finish their tasks correctly, thus calculate the number of jobs sent in order for all nodes to close gently.

6.3 AML-IP distributed inference scenario

This section explains the different types of nodes that participate in the AML-IP for inference distribution scenarios, and the communication between them.

6.3.1 Distributed inference scenario

The so called *distributed inference scenario* in AML involves the parallel processing of complex data by multiple computational points to obtain their inferences. In this context, large and computationally intensive tasks are divided and executed simultaneously across various AML-IP-Inference nodes. This approach allows for faster and more efficient processing, leading to the ultimate inference or outcome.

A distributed inference scenario can be implemented either locally, remotely, or simultaneously through the employment of the AML-IP-Agent. The most important nodes in this scenario are the AML-IP-Edge and the AML-IP-Inference, which are explained ahead in this section.

6.3.2 Design

This section explains in detail the design of certain nodes of the AML-IP to achieve the efficient deployment of a training network exploiting the strengths of AML.

Architecture Description The work described in this section focuses on the process of distributing a substantial volume of data to perform inferences efficiently.

Nodes The nodes involved in this sort of scenario are the following:

- **AML-IP-Edge:** This type of node is responsible for sending data to other nodes within the network and then waiting for the inference to arrive. The AML-IP-Edge node initiates the data transmission and is involved in the data sharing phase of the distributed inference process.
- **AML-IP-Inference:** This kind of node waits for data to be received from other nodes. Once it receives the necessary data, the node proceeds to calculate the inference, which represents the output or solution to the problem being addressed. After generating the inference, it sends the result back to the requesting node.

Data Types

In this context, two data types are employed:

- **InferenceDataType:** The Inference Data Type represents a partial data-set. Internally, the data sent from an Edge Node to an Inference Node is treated as byte arrays of arbitrary size. Interaction with this class can be achieved through a `void*`, a byte array, or a string. In Python API, users can interact with it using `str` and `bytes` types.
- **InferenceSolutionDataType:** The Inference Solution Data Type embodies the inference generated from the data dispatched by the Edge Node. When an Inference Node forwards the inference solution to an Edge Node, it is represented as a bytes array of arbitrary size. So far, the interaction with this class could be done from a `void*`, a byte array or a string. From Python API, it can be manipulated using `str` and `bytes` types.

Figure 44 illustrates the previously described scenario. In this example, an AML-IP-Edge node and an AML-IP-Inference work on the same data but with different information. The AML-IP-Edge node can obtain the inference from the model of the AML-IP-Inference node without needing direct access to the underlying model.

This is a specific use case, but any scenario with an arbitrary number of AML-IP-Edge and AML-IP-Inference nodes is possible. The AML-IP allows the involvement of an arbitrary number of AML-IP-Edge and AML-IP-Inference nodes, making it possible to create a distributed inference environment involving multiple participants.

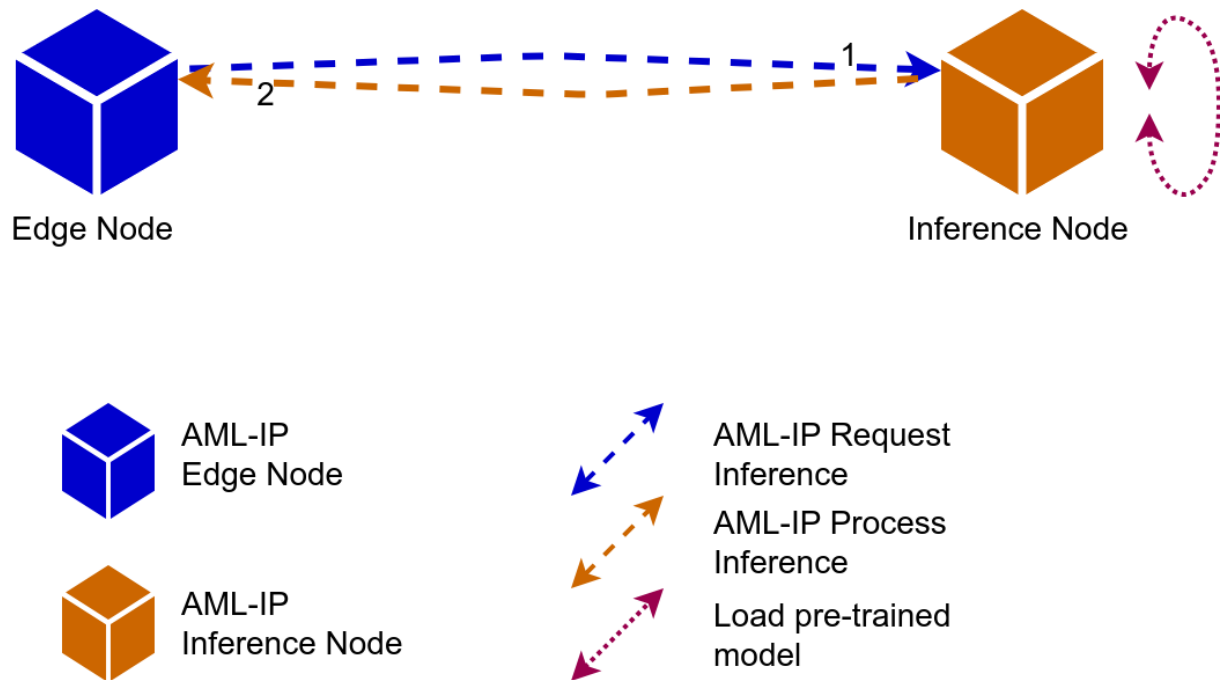


Figure 44: AML-IP distributed inference scenario.

Communication The communication occurs through **DDS**, just like the rest of the components. This choice offers notable advantages, as it enables automatic discovery between nodes and ensures a highly flexible and distributed communication process.

In situations where different nodes are not in the same LAN, we incorporate AML-IP-Agent nodes to address this scenario. These specialized nodes serve as communication facilitators between nodes situated in different LANs, effectively bridging the gap and enabling seamless interaction among participants at distant locations.

Synchronization It is evident that establishing synchronization among the various nodes is essential to ensure their proper independence. This synchronization is achieved through the communication protocol mentioned earlier, which facilitates a synchronous understanding between nodes through publication and subscription interfaces. This protocol, known as the **MultiService Communication Protocol**, is detailed in section 2.7.

Multiple scenarios The AML-IP-Edge and AML-IP-Inference nodes represent the key points in a distributed inference scenario in an AML network. This architecture offers significant advantages in terms of parallelizing data inference across multiple nodes. This scenario is represented in Figure 45, where a single AML-IP-Inference could infer the data of 4 independent AML-IP-Edge nodes.

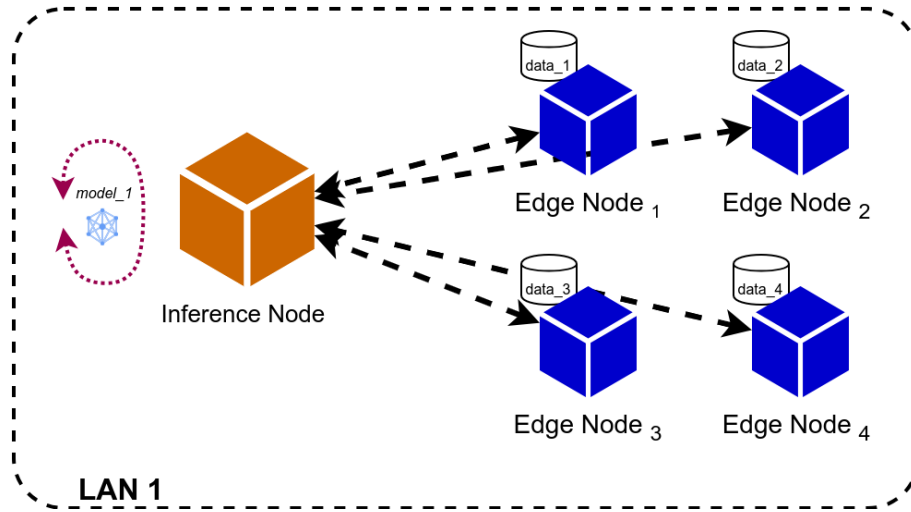


Figure 45: AML-IP local parallelization scenario.

However, it is important to note that the scenario described earlier is just one of the possibilities. The parallelization capabilities can also be leveraged in a WAN scenario, where one or multiple AML-IP-Edge nodes can take advantage of a shared external cluster of AML-IP-Inference nodes. To achieve this, an AML-IP-Agent would be deployed in each of the different LANs. This scenario is represented in Figure 46.

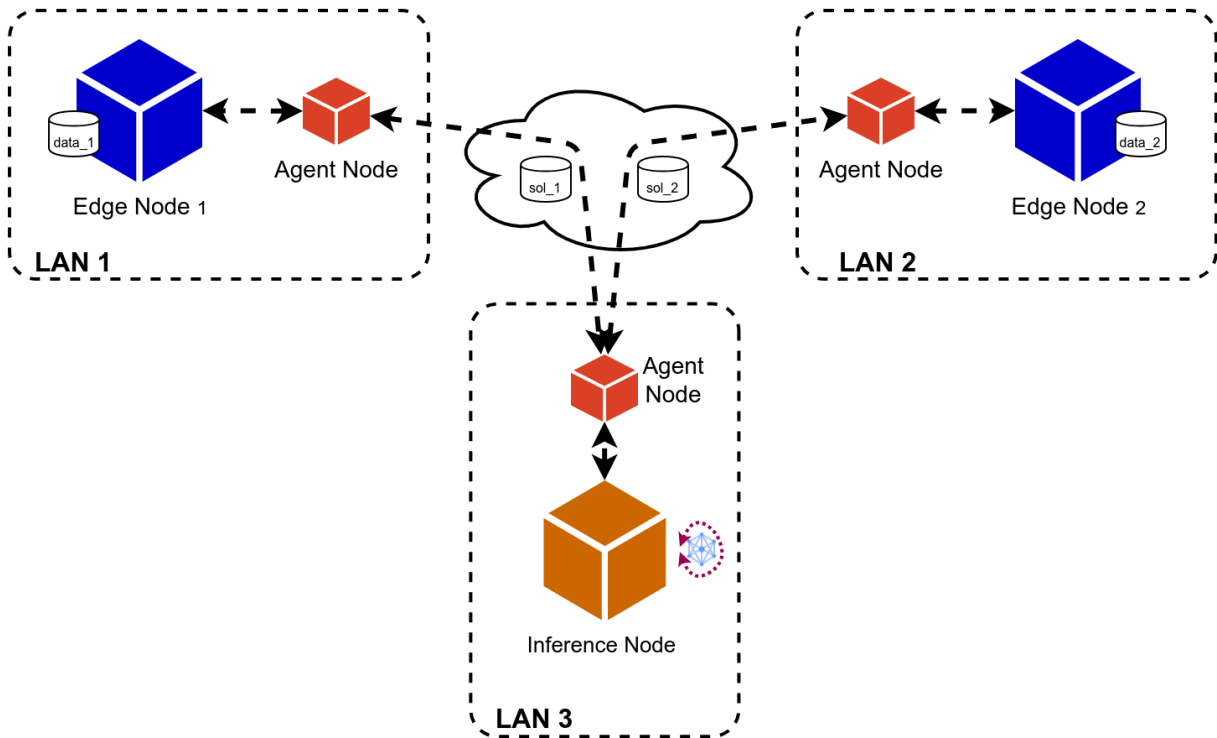


Figure 46: AML-IP WAN parallelization scenario.

Lastly, let's explore a scenario that demonstrates the integration of the AML-IP distributed inference with a workload distribution setup. In Figure 47, we have an instance where an AML-IP-Main node initiates model training using a local AML-IP-Computing node. Once the model training is completed, the resulting model is shared with an external AML-IP-Inference node. The AML-IP-Inference node uses the trained model to infer the data received from the AML-IP-Edge node. This configuration enables the AML-IP-Inference node to benefit from the expertise and knowledge of the AML-IP-Computing node's model, despite not being directly connected to it.

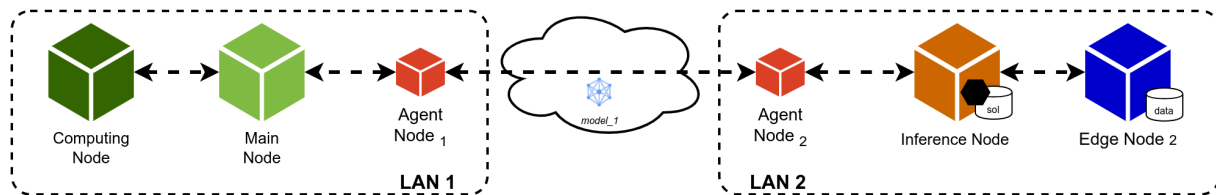


Figure 47: AML-IP workload distribution and distributed inference scenario.

6.3.3 Implementation

This section outlines the implementation details of a distributed inference scenario designed to efficiently distribute a substantial volume of data to remote nodes for inference purposes. The primary objective is to parallelize these inference tasks, ensuring that they do not obstruct any other critical actions that may need to run on the same device. This approach optimizes overall system performance and resource utilization. The implementation leverages the MSCP over DDS to publish and efficiently distribute data across remote nodes, streamlining the process for maximum efficiency.

In this scenario, the inference process occurs within an Inference Node and the resulting inferences are sent to an Edge Node.

Inference Node Synchronous Implementation The Inference Node Synchronous Implementation necessitates active interaction with the user to execute its actions. It waits for incoming data, and the process of calling `process_inference` will only conclude once the result has been sent back. Users initiate the process by using the `request_inference` method from an Edge Node. The thread invoking this method waits for the entire process to finish, including the arrival of the Inference from the Inference Node responsible for processing the data. Proper destruction of the node ensures the correct disposal of internal entities.

1. Instantiate the Inference Node creating an object of such class with a name.
2. Wait for the data by calling `process_inference`.
3. Return the inference as an `InferenceSolutionDataType`.

C++ Implementation

```
// Create a new Inference Node
auto node = eprosima::amlip::InferenceNode("My_Inference_Node");

// Create a callback to process data and return the inference
auto engine_routine = [](const eprosima::amlip::types::InferenceDataType&
    → dataset){
    eprosima::amlip::types::InferenceSolutionDataType inference;
```

```

        // Do some code that calculates the inference
        return inference;
    };

    // Wait for 1 task from any client and answer it with process_inference callback
    node.process_inference(engine_routine);

```

Python Implementation

```

# Create a new Inference Node
node = InferenceNode("My_Inference_Node")

def engine_routine(dataset):
    # Do some code that calculates the inference
    return InferenceSolutionDataType(inference_solution)

# Wait for 1 task from any client and answer it with process_inference callback
node.process_inference(callback=lambda inference: engine_routine(dataset))

```

Inference Node Asynchronous Implementation In the Inference Node Asynchronous Implementation, users can use the `request_inference` method from an Edge Node to send new data. This implementation operates asynchronously, allowing the main thread to continue execution while waiting for the Inference. Users specify callbacks or listeners to process the results, which are returned in a separate thread. Node destruction ensures proper cleanup of internal entities.

1. Instantiate the Asynchronous Inference Node creating an object of such class with a name, a listener or callback and a domain.
2. Wait for the data by calling `run`.

Python Implementation

```

def process_inference(
    dataset,
    task_id,
    client_id):
    # Do some code that calculates the inference
    return inference_solution

def main():
    # Create a new Async Inference Node
    node = AsyncInferenceNode(
        "My_Async_Inference_Node",
        listener=InferenceReplierLambda(process_inference),
        domain=100)

    inference_node.run()

```

```
# Wait until Ctrl+C

inference_node.stop()
```

Edge Node Synchronous Implementation The Edge Node Synchronous Implementation necessitates active interaction with the user to execute its actions. Once data is sent, the thread must wait for the Inference to arrive before sending more data. Users can use the `request_inference` method to send new data. The thread invoking this method waits for the entire process to finish, including the arrival of the Inference from the Inference Node responsible for processing the data. Proper destruction of the node ensures the correct disposal of internal entities.

1. Instantiate the Edge Node creating an object of such class with a name.
2. Create a new `InferenceDataType` from an array of bytes.
3. Send a data synchronously and wait for the inference by calling `request_inference`.

C++ Implementation

```
// Create a new Edge Node
auto node = eprosima::amlip::EdgeNode("My_Edge_Node");

// Create new data to be executed remotely
auto data = eprosima::amlip::InferenceDataType("Some data as byte array serialized
→ from a string or bytes");

// Send data to a remote Inference Node and waits for the inference
// This could be called with an id as well, and it will return the server id that
→ send the inference
auto solution = node.request_inference(data);
```

Python Implementation

```
# Create a new Edge Node
node = EdgeNode("My_Edge_Node")

# Create new data to be executed remotely
data = InferenceDataType("Some data as byte array serialized from a string or
→ bytes")

# Send data to a remote Inference Node and waits for the inference
inference, server_id = node.request_inference(data)
```

Edge Node Asynchronous Implementation In the Edge Node Asynchronous Implementation, users can use the `request_inference` method to send new data. The thread invoking this method waits for the entire process to finish, including the arrival of the Inference from the Inference Node responsible for

processing the data. Users specify callbacks or listeners to process the results, which are returned in a separate thread. Node destruction ensures proper cleanup of internal entities.

1. Instantiate the Asynchronous Edge Node creating an object of such class with a name, a listener or callback and a domain.
2. Create a new InferenceDataType from an array of bytes.
3. Send a data synchronously calling request_inference.
4. Wait for the inference.

Python Implementation

```
def inference_received(
    inference,
    task_id,
    server_id):
    print(f'Data received from server: {server_id}\n'
          f'with id: {task_id}\n'
          f'inference: {inference.to_string()}')

def main():
    # Create a new Async Edge Node
    node = AsyncEdgeNode(
        "My_Async_Edge_Node",
        listener=InferenceListenerLambda(inference_received),
        domain=DOMAIN_ID)

    # Create new data to be executed remotely
    data = InferenceDataType("Some data as byte array serialized from a string or
    ↪ bytes")

    # Send data to a remote Inference Node and waits for the inference
    task_id = node.request_inference(data)

    # User must wait to receive solution.
    # Out of scope, the node will be destroyed,
    # and thus the solution will not arrive.
```

6.3.4 TensorFlow Inference Demo

Inference, in the context of machine learning, is the process of utilizing a trained model to make predictions or draw conclusions based on input data. It involves applying the knowledge and statistical relationships encoded within the model to new, unseen data. The inference of an image involves passing the image through a trained AI model to obtain a classification based on the learned knowledge and patterns within the model.

This section presents a comprehensive guide to the TensorFlow Inference Demo showcases the implementation of two types of nodes, AML-IP-Inference Node and AML-IP-Edge Node, to perform TensorFlow inference on a given image. With these 2 nodes implemented, the user can deploy as many nodes of each kind as desired and check the behavior of a simulated AML-IP network running.

The demo that is presented here follows the schema of the figure below:

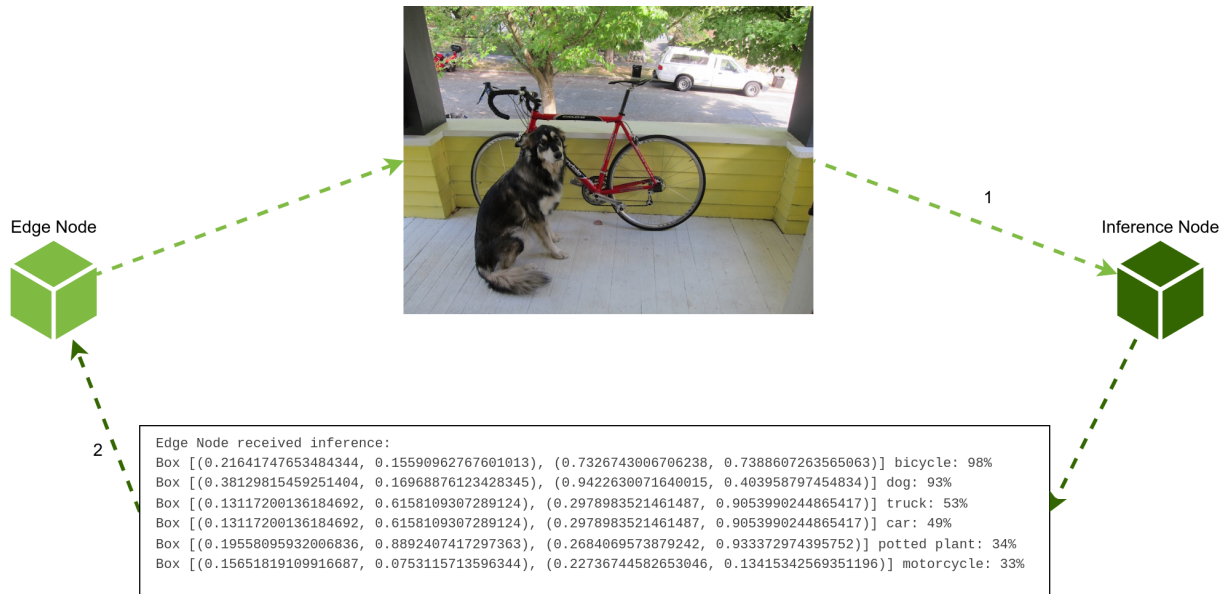


Figure 48: TensorFlow Inference Demo scheme.

- TensorFlow is an end-to-end machine learning platform with pre-trained models.
- Edge Node simulates an AML-IP Algebraic Asynchronous Edge Node (AML-IP-AEdge) Node. It is implemented in *python* using *amlip.py* API.
- Inference Node simulates an AML-IP Algebraic Asynchronous Inference Node (AML-IP-AInference) Node. It is implemented in *python* using *amlip.py* API.

Prerequisites Before running the TensorFlow Inference Demo, ensure that the following prerequisites are met:

- The *amlip.tensorflow.inference.demo* sub-package is correctly installed. For installation instructions, refer to Build demos.
- The following tools and libraries are installed on your system:
 - SWIG
 - ALSA utilities
 - OpenCV development libraries
 - Miniconda (for managing environments)
 - CUDA Toolkit (cudatoolkit) version 11.8.0
 - CUDNN library (linked to CUDA)

Please follow the installation instructions for each of the above prerequisites.

Ensure that you have TensorFlow and TensorFlow Hub installed in your *python* environment before proceeding. You can install them using pip by executing the following commands:

```
pip3 install tensorflow tensorflow-hub tensorflow-object-detection-api
→ nvidia-cudnn-cu11==8.6.0.163 protobuf==3.20.*
```

Additionally, it is required to obtain the TensorFlow model from TensorFlow Hub, follow the steps below:

```
cd
→ ~/AML-IP-ws/src/AML-IP/amlip_demo_nodes/amlip_tensorflow_inference_demo/resource/tensorflow/1
wget -O centernet_hourglass_512x512_kpts_1.tar.gz
→ https://tfhub.dev/tensorflow/centernet/hourglass_512x512_kpts/1?tf-hub-format=compressed
mkdir centernet_hourglass_512x512_kpts_1
tar -xvf centernet_hourglass_512x512_kpts_1.tar.gz -C
→ ./centernet_hourglass_512x512_kpts_1
```

Building the demo To build the demo, follow these steps:

1. Build the required packages with Colcon:

```
colcon build --packages-up-to amlip_demo_nodes
```

2. Import the necessary libraries:

```
source install/setup.bash
```

Explaining the demo

Edge Node The Edge Node serves as the entity responsible for sending data to be inferred to the Inference Node. It is typically situated at the edge of a network, closer to the data source, such as a sensor or data-generating device.

This is the *python* code for the Edge Node application. This code can be found here.

The next block includes the *python* header files that allow the use of the AML-IP *python* API.

```
from amlip_py.node.AsyncEdgeNode import AsyncEdgeNode, InferenceListenerLambda
from amlip_py.types.InferenceDataType import InferenceDataType
```

Let's continue explaining the global variables. The **waiter** allows the node to wait for the inference. **DOMAIN_ID** allows the execution to be isolated because only DomainParticipants with the same Domain Id would be able to communicate to each other.

```
# Variable to wait to the inference
waiter = BooleanWaitHandler(True, False)

# Domain ID
```

```
DOMAIN_ID = 166
```

The definition of the **inference_received** function prints the details of the received inference.

```
def inference_received(
    inference,
    task_id,
    server_id):
    print(f'Edge Node received inference from {server_id}')
    print(f'Edge Node received inference {inference.to_string()}')
    waiter.open()
```

We define the **main** function.

```
def main():
```

First, we create an instance of AML-IP-AEdge. The first thing the constructor gets is the given name. Then a listener, which is an **InferenceListenerLambda** object is created with the function **inference_received** declared above. This function is called each we receive an inference. And also we specified the domain equal to the **DOMAIN_ID** variable.

```
node = AsyncEdgeNode(
    'AMLASyncEdgeNode',
    listener=InferenceListenerLambda(inference_received),
    domain=DOMAIN_ID)
```

The next code block loads the image using **cv2.imread** based on the specified image. It converts the size information and the image into bytes and combines the two to send them to the Inference node.

```
current_path = os.path.abspath(__file__)
image_path = current_path.split('amlip_tensorflow_inference_demo', -1)[0] \
    + 'amlip_tensorflow_inference_demo/resource/tensorflow/models/research' \
    + '/object_detection/test_images/dog.jpg'
img = cv2.imread(image_path)
width = img.shape[1]
height = img.shape[0]

# Convert size to bytes
str_size = str(width) + ' ' + str(height) + ' | '
bytes_size = bytes(str_size, 'utf-8')
# Convert image to bytes
img_bytes = base64.b64encode(img)
# Size + images
img_size_bytes = bytes_size + img_bytes
```

After that, the **request_inference** method is called to request the inference of the image.

```
task_id = node.request_inference(InferenceDataType(img_size_bytes))
```

Finally, the program waits for the inference solution using **waiter.wait**.

```
waiter.wait()
```

Once the solution is received, the execution finish.

Inference Node The Inference Node is responsible for making inferences or predictions on incoming data using a TensorFlow model. The Inference Node is typically a server or a computing resource equipped with high-performance hardware optimized for executing machine learning models efficiently.

This is the *python* code for the Inference Node application. This code can be found [here](#).

The next block includes the *python* header files that allow the use of the AML-IP *python* API.

```
from amlip_py.node.AsyncInferenceNode import AsyncInferenceNode,
    ↳ InferenceReplierLambda
from amlip_py.types.InferenceSolutionDataType import InferenceSolutionDataType
```

Let's continue explaining the global variables. **DOMAIN_ID** allows the execution to be isolated because only DomainParticipants with the same Domain Id would be able to communicate to each other. **tolerance** sets a limit to ignore detections with a probability less than the tolerance.

```
# Domain ID
DOMAIN_ID = 166

# Not take into account detections with less probability than tolerance
tolerance = 25
```

It loads the model from TensorFlow based on the specified path.

```
current_path = os.path.abspath(__file__)
# Initialise model
path = current_path.split('amlip_tensorflow_inference_demo', -1)[0]\
    + 'amlip_tensorflow_inference_demo/resource/\
tensorflow/models/centernet_hourglass_512x512_kpts_1'
dataset = current_path.split('amlip_tensorflow_inference_demo', -1)[0]\
    + 'amlip_tensorflow_inference_demo/resource/\
tensorflow/models/research/object_detection/data/mscoco_label_map.pbtxt'

print('Model Handle at TensorFlow Hub: {}'.format(path))
print('loading model...')
hub_model = hub.load(path)
```


The **process_inference** function is responsible for computing the inference when data is received. Inference is performed using the input data and the loaded model. Note that detected objects are filtered based on the specified tolerance.

```
def process_inference(
    inference,
    task_id,
    client_id):
    # Size / Image
    height, width = (inference.to_string().split(' | ', 1)[0]).split()
    image_str = inference.to_string().split(' | ', 1)[1]
    # Convert string to bytes
    img_bytes = base64.b64decode(image_str)
    # Convert bytes to image
    image = np.frombuffer((img_bytes), dtype=np.uint8).reshape((int(width),
    ↪ int(height), 3))
    string_inference = ''
    image_np = np.array(image).reshape((1, int(width), int(height), 3))
    results = hub_model(image_np)
    result = {key: value.numpy() for key, value in results.items()}
    category_index = label_map_util.create_category_index_from_labelmap(dataset,
    ↪ use_display_name=True)

    classes = (result['detection_classes'][0]).astype(int)
    scores = result['detection_scores'][0]
    for i in range(result['detection_boxes'][0].shape[0]):
        if (round(100*scores[i]) > tolerance):
            boxes = result['detection_boxes'][0]
            box = tuple(boxes[i].tolist())
            ymin, xmin, ymax, xmax = box
            string_inference = string_inference + \
                'Box [({}, {}), ({} , {})] {}: {}% \n' \
                .format(xmin, ymin, xmax, ymax,
                ↪ category_index[classes[i]]['name'],
                round(100*scores[i]))
    print('Inference ready!')
    print('sending inference: ' + string_inference)
    return InferenceSolutionDataType(string_inference)
```

We define the **main** function.

```
def main():
```

We create an instance of AML-IP-AInference. The first thing the constructor gets is the name **AMLInferenceNode**. Then the listener which is an **InferenceReplierLambda(process_inference)**. This means calling the **process_inference** function to perform the inference requests. And also we specified the domain equal to the **DOMAIN_ID** variable.

```
node = AsyncInferenceNode(
    'AMLInferenceNode',
    listener=InferenceReplierLambda(process_inference),
    domain=DOMAIN_ID)
```

This starts the inference node. It will start listening for incoming inference requests and call the **process_inference** function to handle them.

```
node.run()
```

Finally, waits for a **SIGINT** signal **Ctrl+C** to stop the node and close it.

```
def handler(signum, frame):
    pass
signal.signal(signal.SIGINT, handler)
signal.pause()

node.stop()
```

Running the demo The TensorFlow Inference Demo can be executed as follows:

Run Edge Node In the first terminal, execute the Edge Node using the following commands:

```
# Source colcon installation
source install/setup.bash

# To execute Edge Node to send an image to inferred
cd
→ ~/AML-IP-ws/src/amlip/amlip_demo_nodes/amlip_tensorflow_inference_demo/amlip_tensorflow_inference_demo
python3 edge_node_async.py
```

Take into account that this node will wait until there is an Inference Node running and available in the same LAN in order to process the inference.

The expected output is the following:

```
Edge Node AMLEdgeNode.fb.d4.38.13 ready.
Edge Node AMLEdgeNode.fb.d4.38.13 sending data.

Edge Node received inference from AMLInferenceNode.b8.34.4d.a3
Edge Node received inference:
Box [(0.15590962767601013, 0.21641747653484344), (0.7388607263565063,
→ 0.7326743006706238)] bicycle: 97%
Box [(0.16968876123428345, 0.38129815459251404), (0.403958797454834,
→ 0.9422630071640015)] dog: 92%
```

```
Box [(0.6158109307289124, 0.13117200136184692), (0.9053990244865417,
→ 0.2978983521461487)] truck: 53%
Box [(0.6158109307289124, 0.13117200136184692), (0.9053990244865417,
→ 0.2978983521461487)] car: 48%
Box [(0.8892407417297363, 0.19558095932006836), (0.933372974395752,
→ 0.2684069573879242)] potted plant: 34%
Box [(0.0753115713596344, 0.15651819109916687), (0.13415342569351196,
→ 0.22736744582653046)] motorcycle: 32%
```

Edge Node AMLEdgeNode.fb.d4.38.13 closing.

Run Inference Node In the second terminal, run the following command to process the inference:

```
# Source colcon installation
source install/setup.bash

# To execute Inference Node with pre-trained model from TensorFlow
cd
→ ~/AML-IP-ws/src/AML-IP/amlip_demo_nodes/amlip_tensorflow_inference_demo/amlip_tensorflow_inf
python3 inference_node_async.py
```

The execution expects an output similar to the one shown below:

```
2023-02-14 14:50:42.711797: I tensorflow/core/platform/cpu_feature_guard.cc:193]
→ This TensorFlow binary is optimized with oneAPI Deep Neural Network Library
→ (oneDNN) to use the following CPU instructions in performance-critical
→ operations: AVX2 FMA
To enable them in other operations, rebuild TensorFlow with the appropriate
→ compiler flags.
Inference Node AMLIInferenceNode.b8.34.4d.a3 ready.
Model Handle at TensorFlow Hub:
→ /home/user/AML-IP-ws/src/AML-IP/amlip_demo_nodes/amlip_tensorflow_inference_demo/resource/te
loading model...
WARNING:absl:Importing a function
→ (__inference_batchnorm_layer_call_and_return_conditional_losses_42408) with
→ ops with unsaved custom gradients. Will likely fail if a gradient is
→ requested.
WARNING:absl:Importing a function
→ (__inference_batchnorm_layer_call_and_return_conditional_losses_209416) with
→ ops with unsaved custom gradients. Will likely fail if a gradient is
→ requested.
WARNING:absl:Importing a function
→ (__inference_batchnorm_layer_call_and_return_conditional_losses_220336) with
→ ops with unsaved custom gradients. Will likely fail if a gradient is
→ requested.
...
```

```

WARNING:absl:Importing a function
→ (__inference_batchnorm_layer_call_and_return_conditional_losses_55827) with
→ ops with unsaved custom gradients. Will likely fail if a gradient is
→ requested.
WARNING:absl:Importing a function
→ (__inference_batchnorm_layer_call_and_return_conditional_losses_56488) with
→ ops with unsaved custom gradients. Will likely fail if a gradient is
→ requested.
model loaded!
Selected model:tensorflow
2023-02-14 14:51:14.165305: W
→ tensorflow/core/grappler/optimizers/loop_optimizer.cc:907] Skipping loop
→ optimization for Merge node with control input:
→ StatefulPartitionedCall/cond/then/_918/cond/Assert_2/AssertGuard/branch_executed/_1123
inference ready!
sending inference:
Box [(0.15590962767601013, 0.21641747653484344), (0.7388607263565063,
→ 0.7326743006706238)] bicycle: 97%
Box [(0.16968876123428345, 0.38129815459251404), (0.403958797454834,
→ 0.9422630071640015)] dog: 92%
Box [(0.6158109307289124, 0.13117200136184692), (0.9053990244865417,
→ 0.2978983521461487)] truck: 53%
Box [(0.6158109307289124, 0.13117200136184692), (0.9053990244865417,
→ 0.2978983521461487)] car: 48%
Box [(0.8892407417297363, 0.19558095932006836), (0.933372974395752,
→ 0.2684069573879242)] potted plant: 34%
Box [(0.0753115713596344, 0.15651819109916687), (0.13415342569351196,
→ 0.22736744582653046)] motorcycle: 32%

Inference sent to client AMLEdgeNode.fb.d4.38.13.

```

Next steps Based on the information acquired, we have successfully generated the next image:

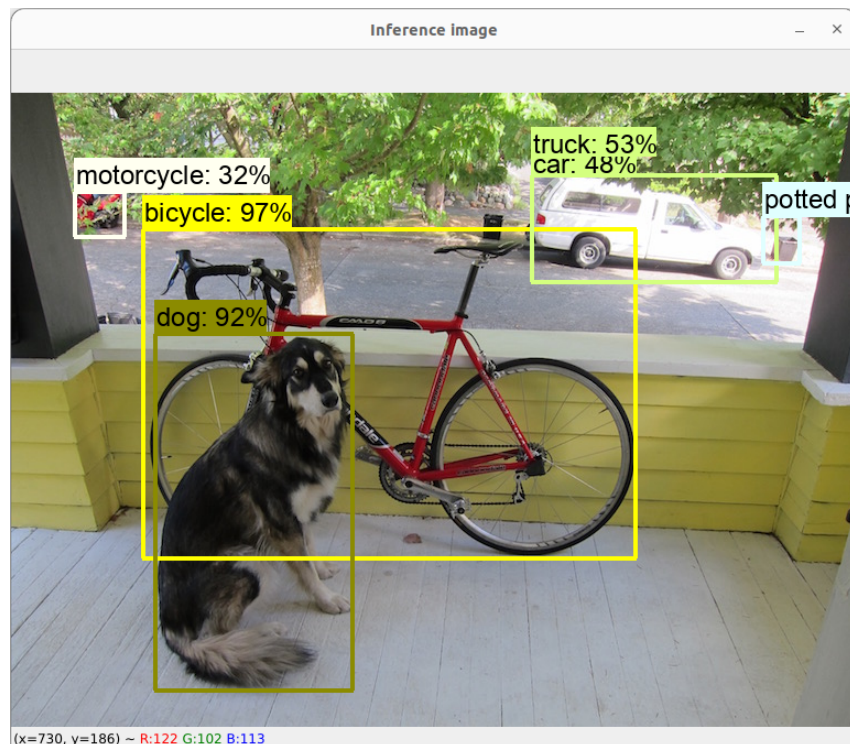


Figure 49: Generated inferred image.

Run multiple nodes of each kind One of the advantages inherent to this architecture lies in its ability to support multiple models operating concurrently across multiple Inference Node, while simultaneously requesting inferences from Edge Node in parallel. This architectural design fosters a highly efficient and scalable system, enabling the execution of diverse inference tasks in a distributed manner.

Using Your Own Model To use a custom TensorFlow model, simply download the model and load it by specifying the model's path in the code. Replace **your_model_path** with the actual path to your model:

```
hub_model = hub.load(your_model_path)
```

The TensorFlow Inference Demo demonstrates the integration of TensorFlow for performing image inference within the AML-IP framework. By following the provided guidelines, users can implement and run their own inference tasks efficiently and effectively.

6.3.5 TensorFlow Inference using ROSbot 2R

This document provides comprehensive instructions for deploying an Edge Node on a **ROSbot 2R** from **Husarion**. The Edge Node captures images using the *Orbbec Astra* camera and sends them to an Inference Node deployed on a laptop to perform TensorFlow inference on the given image. When the TensorFlow inference detects the presence of a person with a probability of 80% or higher, the **ROSbot 2R** will execute a turning action.

The **ROSbot 2R** is an autonomous mobile robot designed by **Husarion**. It serves as an excellent platform for learning **ROS 2** and conducting research and development in the field of robotics. It is an affordable platform that can serve as a base for a variety of robotic applications, including inspection robots and custom service robots. The robot features a solid aluminum frame and is equipped with a *Raspberry Pi 4* with 4GB of RAM, distance sensors, an *RPLIDAR A2* laser scanner, and an *RGB-D Orbbec Astra* camera.



Figure 50: ROSbot 2R.

The demonstration presented here follows the architecture illustrated in the diagram below:



Figure 51: TensorFlow Inference using ROSbot 2R demo scheme.

Prerequisites Before proceeding, ensure the following prerequisites are met:

- Build *amlip-demos:inference-tensorflow* Docker Image from the workspace where the *Dockerfile* is located. In order to do so, execute the following command:

```
cd
↪ ~/AML-IP-ws/src/AML-IP/amlip_demo_nodes/amlip_tensorflow_inference_rosbot2r_demo
docker build -t amlip-demos:inference-tensorflow -f Dockerfile .
```

ROSbot 2R Deployment The Docker Compose used for the demo can be found in *compose.yaml*.

It launches the following containers:

- **astra**: This container enables the use of Orbbec 3D cameras with ROS Humble. It publishes images captured by the camera to the */camera/color/image_raw* topic. Edge Node subscribes to this topic to receive and process the camera images.

```
astra:
  image: husarion/astra:humble
  network_mode: host
  ipc: host
  devices:
    - /dev/bus/usb/
  volumes:
    - ./astra_params.yaml:/ros2_ws/install/astra_camera/share/astra_camera/
      ↪ params/astra_mini_params.yaml
  privileged: true
  command: ros2 launch astra_camera astra_mini.launch.py
```

- **rostop**: This container initializes the basic functionalities for **ROSbot 2R**. It subscribes to the */cmd_vel* topic. This topic is used to control the robot's movement by publishing velocity commands.

```
rostop:
  image: husarion/rostop:humble
  network_mode: host
  ipc: host
  privileged: true
  command: ros2 launch rostop_bringup bringup.launch.py mecanum:=False
```

- **microros**: This container communicates with the robot's firmware functionalities.

```
microros:
  image: husarion/micro-ros-agent:humble
  network_mode: host
  ipc: host
  devices:
    - ${SERIAL_PORT:?err}
  environment:
```

```
- SERIAL_PORT
privileged: true
command: ros2 run micro_ros_agent micro_ros_agent serial -D $SERIAL_PORT
→ serial -b 576000 # -v6
```

- **edge:** This container is responsible for initiating the execution of the AML-IP Edge Node as explained below.

```
edge:
  image: amlip-demos:inference-tensorflow
  network_mode: host
  ipc: host
  privileged: true
  command: bash -c "sleep 5 && source ./install/setup.bash && python3
→ ./src/amlip/amlip_demo_nodes/amlip_tensorflow_inference_rosbot2r_demo/
→ amlip_tensorflow_inference_rosbot2r_demo/edge_node_async.py"
```

The following diagram illustrates the data flow within the described architecture:

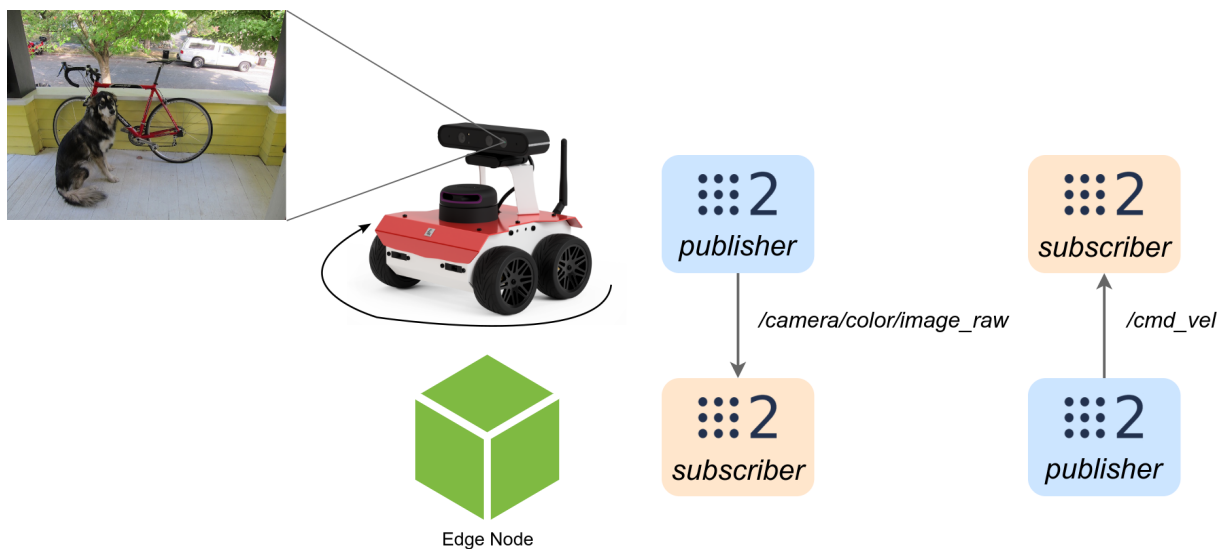


Figure 52: Deployment scheme.

Working with AML-IP Through this section, we delve into the details of the demo, examining the underlying concepts and processes involved.

Edge Node Edge Node serves as the entity responsible for sending the data to be inferred to the Inference Node. It is typically located at the edge of a network or closer to the data source, such as a sensor or a device generating the data. In this scenario, the data source is the camera of the **ROSBOT 2R**.

The *python* code for the Edge Node is explained in the previous section 6.3.4. Here, we focus on additional features added to it.

You can find the complete code here.

The following code snippet includes the *python* header files that enable the use of the AML-IP *python* API and **ROS 2**.

```
from amlip_py.node.AsyncEdgeNode import AsyncEdgeNode, InferenceListenerLambda
from amlip_py.types.InferenceDataType import InferenceDataType

from cv_bridge import CvBridge      # Package to convert between ROS and OpenCV
    ↪ Images

from geometry_msgs.msg import Twist

from py_utils.wait.BooleanWaitHandler import BooleanWaitHandler

import rclpy
from rclpy.node import Node
from rclpy.qos import QoSDurabilityPolicy
from rclpy.qos import QoSHistoryPolicy
from rclpy.qos import QoSProfile
from rclpy.qos import QoSReliabilityPolicy

from sensor_msgs.msg import Image
```

Continuing, the **SubscriberImage ROS 2 Node** subscribes to the */camera/color/image_raw* topic to receive images from a camera sensor of the **ROSbot 2R**. It converts the received **ROS Image** message to an **OpenCV image** using the **CvBridge** package, storing the image data in the image attribute of the node.

```
class SubscriberImage(Node):

    def __init__(self):
        super().__init__('subscriber_image')
        custom_qos_profile = QoSProfile(
            depth=4,
            reliability=QoSReliabilityPolicy.BEST_EFFORT)

        self.subscription = self.create_subscription(
            Image,
            '/camera/color/image_raw',
            self.listener_callback,
            custom_qos_profile)
        # Used to convert between ROS and OpenCV images
        self.br = CvBridge()
        self.image = None
        self.image_arrive = False

    def listener_callback(self, msg):
        self.get_logger().info('I received an image!!')
        # Convert ROS Image message to OpenCV image
```

```
self.image = self.br.imgmsg_to_cv2(msg)
self.image_arrive = True
```

The **PublisherVel ROS 2 Node** publishes **Twist** messages to the `/cmd_vel` topic, which controls the velocity of the **ROSbot 2R**. In the provided code, the `turn` method is implemented to set linear and angular velocities, causing the robot to turn.

```
class PublisherVel(Node):

    def __init__(self):
        super().__init__('publisher_velocity')
        custom_qos_profile = QoSProfile(
            history=QoSHistoryPolicy.KEEP_ALL,
            durability=QoSDurabilityPolicy.TRANSIENT_LOCAL,
            reliability=QoSReliabilityPolicy.BEST_EFFORT)

        self.pub = self.create_publisher(
            Twist,
            '/cmd_vel',
            custom_qos_profile)

    def turn(self):
        msg = Twist()

        msg.linear.x = 0.1
        msg.linear.y = 0.0
        msg.linear.z = 0.0

        msg.angular.x = 0.0
        msg.angular.y = 0.0
        msg.angular.z = -1.0

        self.pub.publish(msg)
```

The `turn_rosbot` function initializes the **PublisherVel** Node and repeatedly calls the `turn` method to make the **ROSbot 2R** turn.

```
def turn_rosbot():
    node = PublisherVel()

    print('Turn ROSbot')
    loop = 0
    while rclpy.ok() and loop < 13:
        node.turn()
        time.sleep(0.5)
        loop += 1

    node.destroy_node()
```

The **check_data** function extracts labels and percentages from the inference string received from the Edge Node. It searches for the label **person** with a confidence percentage greater than or equal to **80%**. If a person is detected, it calls the **turn_rosbot** function to make the robot turn.

```
def check_data(str_inference):
    labels = re.findall(r'\b(\w+):', str_inference)
    percentages = re.findall(r'(\d+)%', str_inference)
    print('Labels: ')
    print(labels)
    print('Percentages: ')
    print(percentages)
    for i in range(len(labels)):
        if (labels[i] == 'person' and int(percentages[i]) >= 80):
            print('Found a person!')
            turn_rosbot()
            return
    print('No person found.')
```

The **main** function initializes the **SubscriberImage** Node to receive images from the **ROSbot 2R** camera and waits until an image arrives before proceeding. The received image is then used to create the AML-IP-AEdge. The image is encoded as bytes and sent to the Edge Node for inference using the **request_inference** method, as in the previous demo.

```
def main():
    rclpy.init(args=None)

    minimal_subscriber = SubscriberImage()

    # Create Node
    node = AsyncEdgeNode(
        'AMLAsyncEdgeNode',
        listener=InferenceListenerLambda(inference_received),
        domain=DOMAIN_ID)

    while True:

        while rclpy.ok() and not minimal_subscriber.image_arrive:
            rclpy.spin_once(minimal_subscriber, timeout_sec=1)

        img = minimal_subscriber.image

        print(f'Async Edge Node {node.id()} ready.')

        width = img.shape[1]
        height = img.shape[0]

        # Convert size to bytes
        str_size = str(width) + ' ' + str(height) + ' | '
        bytes_size = bytes(str_size, 'utf-8')
```

```

# Convert image to bytes
img_bytes = base64.b64encode(img)
# Size + images
img_size_bytes = bytes_size + img_bytes

print(f'Edge Node {node.id()} sending data.')

task_id = node.request_inference(InferenceDataType(img_size_bytes))

print(f'Request sent with task id: {task_id}. Waiting inference...')

# Wait to received solution
waiter.wait()

minimal_subscriber.image_arrive = False

# Closing
minimal_subscriber.destroy_node()
rclpy.shutdown()

print(f'Edge Node {node.id()} closing.')

```

Inference Node The Inference Node is responsible for making the inferences or predictions on the data it receives using a TensorFlow model. The Inference Node is typically a server or a computing resource equipped with high-performance hardware optimized for executing machine learning models efficiently.

The Python code for the Inference Node is explained in the previous section 6.3.4 and can be found [here](#).

Running the Demo

Bring up ROSbot 2R and run Edge Node To begin, launch the Docker Compose `compose.yaml` to activate the containers `astra`, `rosbot`, `microros` and `edge`.

Start the containers in a new **ROSbot** terminal, run the following command:

```

cd
↪ ~/AML-IP-ws/src/AML-IP/amlip_demo_nodes/amlip_tensorflow_inference_rosbot2r_demo
docker compose up

```

Run Inference Node In a terminal on your laptop, run the following command in order to process the inference:

```

# Source colcon installation
source install/setup.bash

# To execute Inference Node with pre-trained model from TensorFlow

```

```
cd
→ ~/AML-IP-ws/src/AML-IP/amlip_demo_nodes/amlip_tensorflow_inference_rosbot2r_demo/amlip_tensorflow_inference_node_async.py
python3 inference_node_async.py
```

Teleoperate ROSbot 2R Note that **ROSbot 2R** subscribes to the `/cmd_vel` topic for movement control. To teleoperate it, use the **teleop_twist_keyboard** node, which allows you to control the robot using keyboard inputs. Follow these steps:

```
# Source ROS 2 installation
source install/setup.bash

ros2 run teleop_twist_keyboard teleop_twist_keyboard
```

6.4 AML-IP monitor network state

This section provides an overview of the different types of nodes that participate in the AML-IP monitor network state scenarios, and the communication between them.

6.4.1 Monitor network state scenario

The so called *monitor network state scenario* pertains to specific instances within the domain of AML where the monitoring process involves activities encompassing comprehension, analysis, and troubleshooting of an AML network.

A monitor network state scenario could be present locally, remotely, or concurrently through the utilization of the versatile AML-IP-Agent node. Within this context, the pivotal component is the AML-IP-Status, which is explained ahead in this section.

6.4.2 Design

This section explains in detail the design of a node of the AML-IP to monitoring action of an AML network.

Architecture Description The work that is presented along this section refers to the process of knowing, analyzing and debugging an AML network.

Nodes This scenario involves every node, as all of them publish the Status information. However, the only Node Kind properly belonging to this scenario is the following:

- **AML-IP-Status:** This kind of node requires few interaction with the user once it is running. User must start and stop this node as desired using methods *process_status_async* and *stop_processing*. Also, user must yield a callback function that will be executed with every Status message received.

Data Types

Within this context, two essential data types are employed:

- **StatusDataType:** The Status messages published by the nodes contain the following critical information:
 - **Node Id:** A unique identifier for each node.
 - **Current State:** Reflects the current operational state of the node, which can be one of the following: **stopped**, **running** or **dropped**.
 - **Node Kind:** Specifies the type of node, indicating to which scenario it belongs.

Figure 53 illustrates the previously described scenario. In this example, an AML-IP-Status node receives the status of an AML-IP-Edge node, an AML-IP-Inference node, that is communicating with the previous one, a AML-IP-MMSender node, and a AML-IP-MMReceiver node, whics is communicating with the AML-IP-MMSender. As a result, the AML-IP-Status node obtain an accurate description of the AML network endpoints.

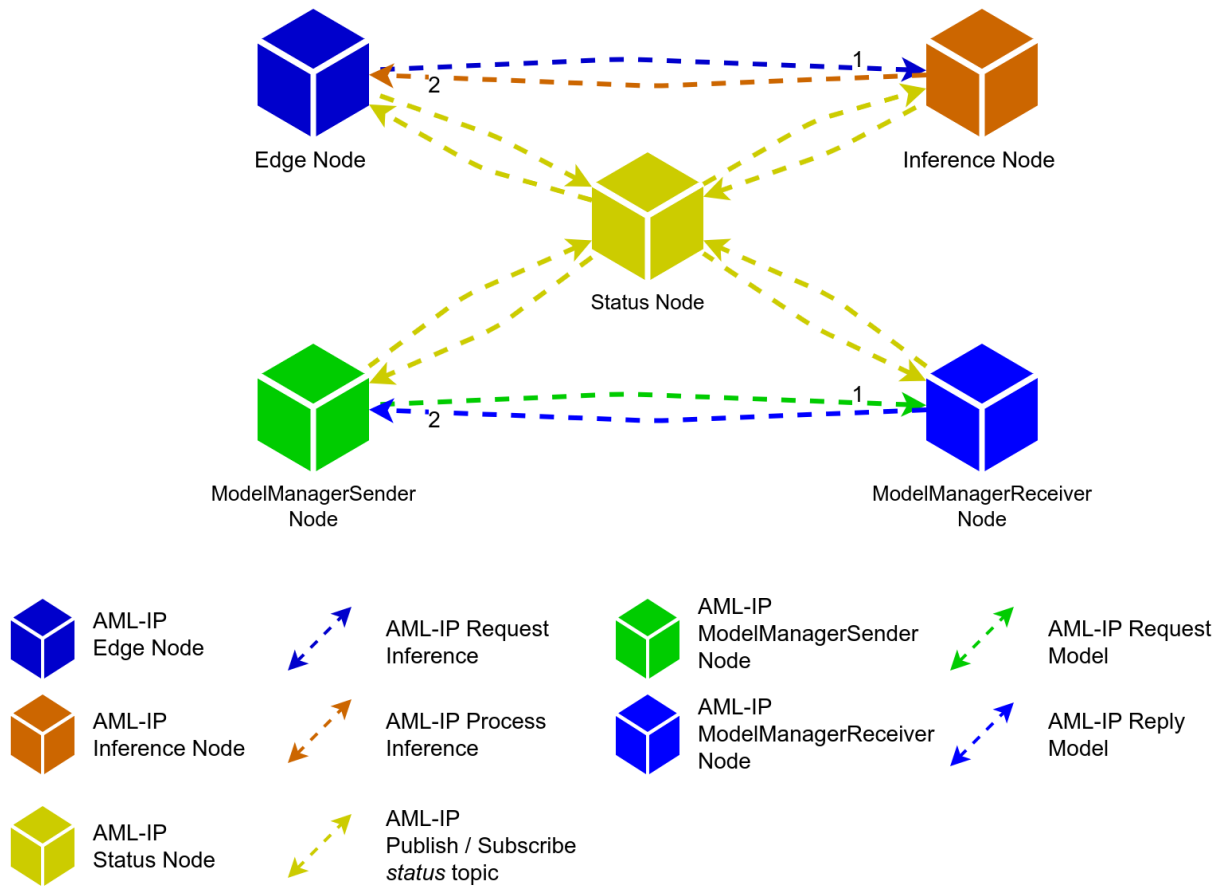


Figure 53: AML-IP monitor network state scenario.

Communication The communication takes place via **DDS**, just like the rest of the AML-IP. This choice offers significant advantages, as it enables automatic discovery between nodes and ensures completely dynamic and distributed communication. The utilization of DDS facilitates the creation of a fully decentralized network where each node operates independently of the network status. For example, an AML-IP-Status node behaves consistently, regardless of whether there are 0 or 10 AML-IP nodes in its network.

In scenarios where the participating nodes span diverse LANs, we would mix this scenario with the AML-IP-Agent nodes. These specialized nodes facilitate communication between nodes located in different LANs, effectively bridging the gap between distant participants. The integration of AML-IP-Agent nodes ensures the monitoring of a bigger AML network. This could be achieved by deploying a AML-IP-Agent in each of the different LANs. This scenario is represented in Figure 54.

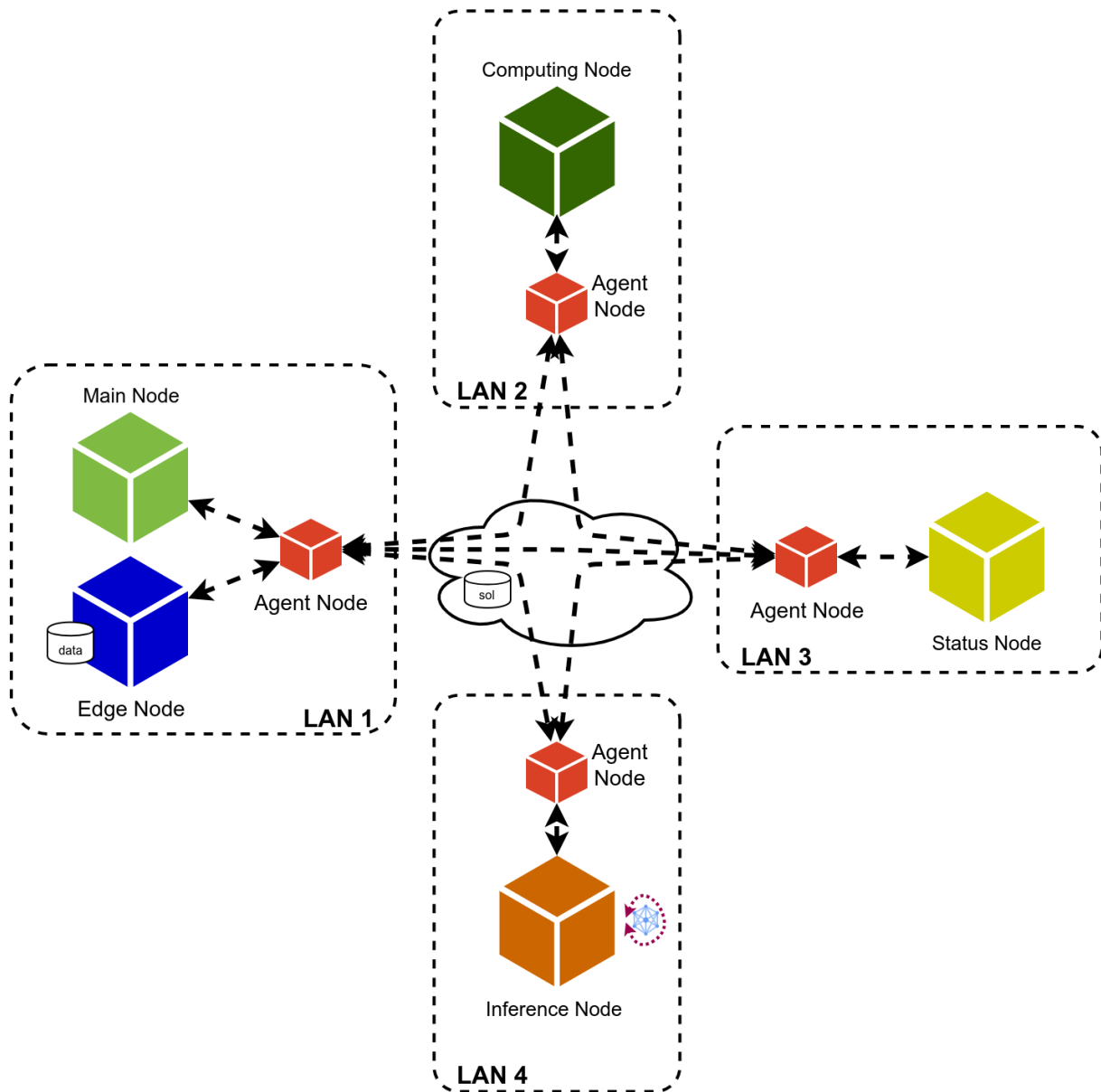


Figure 54: AML-IP WAN scenario.

6.4.3 Implementation

This section provides a detailed description of the implementation for a monitoring scenario in the context of an AML network. The primary objective is to monitor, analyze, and debug the AML network effectively. In this scenario, each AML-IP Node publishes its current Status information and continuously updates it throughout its lifecycle. Subscribers can access this Status information, allowing for various operations such as processing, storage, analysis, and more.

Status Node Implementation To achieve effective monitoring and debugging of the AML network, follow these steps:

1. **Instantiate the Status Node:** Create an instance of the Status Node class, providing it with a unique name.
2. **Start Processing Status Data:** Begin processing the network's status data by invoking the *process_status_async* method. This method takes a callback function as an argument, which defines how the received status data is handled. In the provided code samples, we print the status data to the standard output, but this callback function can be customized to perform various actions.
3. **Stop Processing Data:** When monitoring tasks are complete, stop processing data by calling the *stop_processing* method.

C++ Implementation

```
// Create a new Status Node
auto node = eprosima::amlip::StatusNode("My_Status_Node");

// Process incoming data by printing it in stdout (defined by std::function)
node.process_status_async(
    []( const eprosima::amlip::types::StatusDataType& status ){
        std::cout << status << std::endl;
    }
);

// Perform other operations or analysis here

// Stop processing data
node.stop_processing()
```

Python Implementation

```
# Create a new Status Node
node = StatusNode("My Status Node");

# Process incoming data by printing it in stdout (defined by lambda)
node.process_status_async(
    callback=lambda status: print(f'{status}'))

# Perform other operations or analysis here

# Stop processing data
node.stop_processing()
```

This implementation enables comprehensive monitoring, analysis, and debugging of the AML network, facilitating the efficient management of status information across nodes.

6.5 Context Broker Integration

This section provides a comprehensive overview of the Fiware Node and its interaction with the FIWARE Context Broker to manage inference data efficiently.

The FIWARE Context Broker is a fundamental component of any smart solution, responsible for managing, querying, and updating contextual information. It enables context producers, such as sensors, to publish data, making it accessible to context consumers—applications or systems that process this information. Both producers and consumers can be any application or even other components within the FIWARE ecosystem.

Integrating the Context Broker within AML-IP is crucial, as a contextual representation of AML problems will likely be necessary to enable collaborative learning. This ensures that any node can identify the specific problem it is working on. In such a setup, any node could send a request to a designated context broker node, which would be responsible for processing and responding to these queries appropriately.

6.5.1 Fiware Node

This kind of node interacts with the FIWARE context broker in order to handle inference data. It provides mechanisms to read data from a context broker entity, request inference from an Inference Node, and send the inference to the context broker entity. To facilitate the inference requests, the Fiware Node includes an Edge Node.

6.6 Design

This section explains in detail the design of the Fiware Node in an AML-IP Network.

Architecture Description The work described in this section focuses on the process of sending data to a context broker and performing inference over the sent data.

Nodes The nodes involved in this sort of scenario are the following:

- **AML-IP-Fiware:** This type of node is in charge of reading data from a context broker entity data, creating an Edge Node, requesting inference from an Inference Node and sending the inferred solution to the context broker entity.
- **AML-IP-Edge:** This type of node is responsible for sending data to the inference nodes within the network and then waiting for the inference to arrive.
- **AML-IP-Inference:** This kind of node waits for data to be received from edge nodes. Once it receives the necessary data, the node proceeds to calculate the inference, which represents the output or solution to the problem being addressed. After generating the inference, it sends the result back to the edge node

Data Types

In this context, two data types are employed:

- **InferenceDataType:** The Inference Data Type represents a partial data-set. Internally, the data sent from an Edge Node to an Inference Node is treated as byte arrays of arbitrary size. Interaction with this class can be achieved through a void*, a byte array, or a string. In Python API, users can interact with it using str and bytes types.

- **InferenceSolutionDataType:** The Inference Solution Data Type embodies the inference generated from the data dispatched by the Edge Node. When an Inference Node forwards the inference solution to an Edge Node, it is represented as a bytes array of arbitrary size. So far, the interaction with this class could be done from a void*, a byte array or a string. From Python API, it can be manipulated using str and bytes types.

Figure 55 illustrates the previously described scenario.

In this example, the Fiware Node publishes data to the Context Broker while simultaneously forwarding it to an Inference Node via the integrated Edge Node. Once the inference is completed, the results are sent back to the Fiware Node, which then transmits them to the Context Broker for storage.

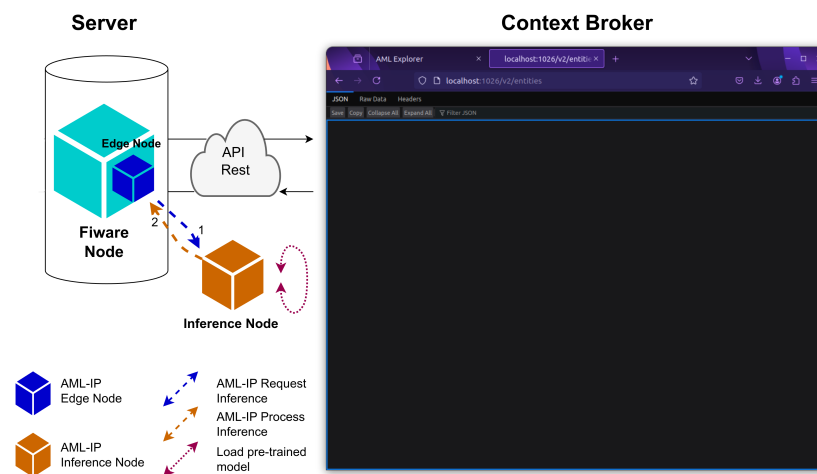


Figure 55: AML-IP Interaction with the Context Broker

Communication The communication occurs through **DDS**, just like the rest of the components. This choice offers notable advantages, as it enables automatic discovery between nodes and ensures a highly flexible and distributed communication process.

In situations where different nodes are not in the same LAN, we incorporate AML-IP-Agent nodes to address this scenario. These specialized nodes serve as communication facilitators between nodes situated in different LANs, effectively bridging the gap and enabling seamless interaction among participants at distant locations.

Meanwhile, communication with the FIWARE Context Broker relies on a REST API, allowing efficient data exchange, storage, and retrieval while maintaining interoperability with web-based services and applications.

Synchronization It is evident that establishing synchronization among the various nodes is essential to ensure their proper independence. This synchronization is achieved through the communication protocol mentioned earlier, which facilitates a synchronous understanding between nodes through publication and subscription interfaces. This protocol, known as the **MultiService Communication Protocol**, is detailed in section 2.7.

6.6.1 Implementation

This section presents the implementation details of a FIWARE node designed to efficiently transmit data to the FIWARE Context Broker and subsequently perform inference on the sent data.

Fiware Node Implementation The Fiware Node requires active user interaction to execute its actions. Data is sent to the context broker via Flask using the `post_data` method, followed by an inference request using the `request_inference` method.

1. Create a new `FiwareNode` object with at least a name, a `server_ip` and a `server_port`.
2. Start the Flask server.

Python Implementation

```
server_ip = '192.168.1.1'
server_port = 1028

# Create a new Fiware Node
node = FiwareNode(name='My_Fiware_Node',
                  server_ip=server_ip,
                  server_port=server_port,
                  context_broker_ip='localhost',
                  context_broker_port=1026,
                  entity_id='ID_entity',
                  entity_data='data',
                  entity_solution='inference',
                  domain=0,
                  logger=CustomLogger(logger_name='FiwareNode',
                                     ↪ log_level=logging.WARNING))

# Start the Flask server
fiware_node.run()
```

Inference Node Asynchronous Implementation In the Inference Node Asynchronous Implementation, users can use the `request_inference` method from an Edge Node to send new data. This implementation operates asynchronously, allowing the main thread to continue execution while waiting for the Inference. Users specify callbacks or listeners to process the results, which are returned in a separate thread. Node destruction ensures proper cleanup of internal entities.

1. Instantiate the Asynchronous Inference Node creating an object of such class with a name, a listener or callback and a domain.
2. Wait for the data by calling `run`.

Python Implementation

```
def process_inference(
    dataset,
    task_id,
    client_id):
    # Do some code that calculates the inference
    return inference_solution

def main():
```

```
# Create a new Async Inference Node
node = AsyncInferenceNode(
    "My_Async_Inference_Node",
    listener=InferenceReplierLambda(process_inference),
    domain=100)

inference_node.run()

# Wait until Ctrl+C

inference_node.stop()
```

Edge Node Asynchronous Implementation In the Edge Node Asynchronous Implementation, users can use the `request_inference` method to send new data. The thread invoking this method waits for the entire process to finish, including the arrival of the Inference from the Inference Node responsible for processing the data. Users specify callbacks or listeners to process the results, which are returned in a separate thread. Node destruction ensures proper cleanup of internal entities.

1. Instantiate the Asynchronous Edge Node creating an object of such class with a name, a listener or callback and a domain.
2. Create a new `InferenceDataType` from an array of bytes.
3. Send a data synchronously calling `request_inference`.
4. Wait for the inference.

Python Implementation

```
def inference_received(
    inference,
    task_id,
    server_id):
    print(f'Data received from server: {server_id}\n'
          f'with id: {task_id}\n'
          f'inference: {inference.to_string()}')

def main():
    # Create a new Async Edge Node
    node = AsyncEdgeNode(
        "My_Async_Edge_Node",
        listener=InferenceListenerLambda(inference_received),
        domain=DOMAIN_ID)

    # Create new data to be executed remotely
    data = InferenceDataType("Some data as byte array serialized from a string or
        ↪ bytes")

    # Send data to a remote Inference Node and waits for the inference
    task_id = node.request_inference(data)
```

*# User must wait to receive solution.
Out of scope, the node will be destroyed,
and thus the solution will not arrive.*

7 AML-IP Use Cases

The AML-IP is a communication framework focused on the easy deployment of AML nodes and the communication between them. Thus, AML-IP is not just a user-friendly application, but an intermediate library that makes the transport protocols transparent to the user. Therefore, it is thought to create a platform that communicates each node with those that are in the same AML network without requiring the user to know or understand the transport protocols behind each communication.

The AML-IP users are divided in two categories represented in the figure 56. This diagram represents only the actions of each user with the AML-IP, i.e. it does not represent the actions that a user could do with each of the AML-IP-Algs.

The first actor shown, referred to as the AML User, represents the standard AML user. This user in charge of the LAN where it deploys its AML nodes.

This user would be able to create any kind of AML-IP-Alg within its own LAN, and to start a new AML-IP-Agent in order to connect with an external AML network deployed in another LAN, creating a wider AML environment over WAN. Starting an AML-IP-Agent may require to set one or more *well known addresses* in order to connect with a bigger network.

The second actor is the AML-IP Administrator. This kind of actor represents a platform administrator with every level of permissions over the networks. In addition to the actions that a *User* can do, the *Administrator* is able to deploy AML-IP-D in order to increase the range and redundancy of a network.

All types of nodes as well as the different architectures that may exist in an AML environment are described in Section 4.1.

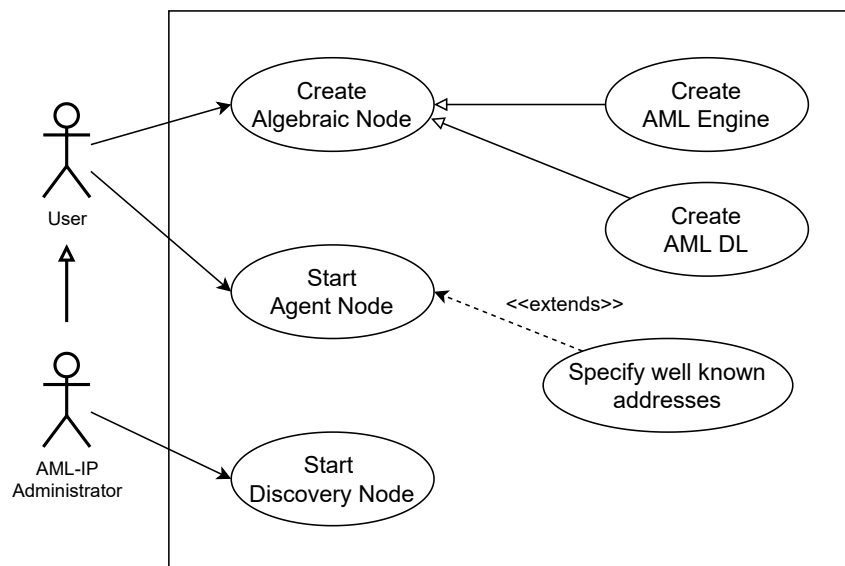


Figure 56: Use case diagram.

7.1 General overview AML-IP Nodes

The following use case describes a general environment composed of the main elements of the AMLIP architecture.

In each of the LANs (Local Area Networks), there is an Agent Node that facilitates connectivity through the WAN (Wide Area Network).

LAN 1 consists of a Status Node that receives status updates from all other nodes that are publishing information.

On the other hand, LAN 2 includes a ModelManagerSender Node with a Mediation Node and the AML Engine. This node provides its models to anyone who sends it a request. The Mediation Node is responsible for managing and arbitrating all incoming requests.

LAN 3 contains a Computing Node with an AML Engine and a Mediation Node, similar to the previous LAN 2 setup. In this case, it handles executing the jobs it receives from the Main Node and returns solutions.

LAN 4 is composed of an Edge Node that sends data to an Inference Node, which then provides inferred data in response.

LAN 5 houses a ModelManagerReceiver Node, responsible for making requests for models it needs to the ModelManagerSender Node in LAN 2, as previously explained.

LAN 6 has an Inference Node with an AML Engine and a Mediation Node that manages incoming requests. The Inference Node is responsible for performing data inference based on the data it receives.

Finally, LAN 7 features a Main Node that sends jobs to the Computing Node in LAN 3 and awaits the receipt of solutions.

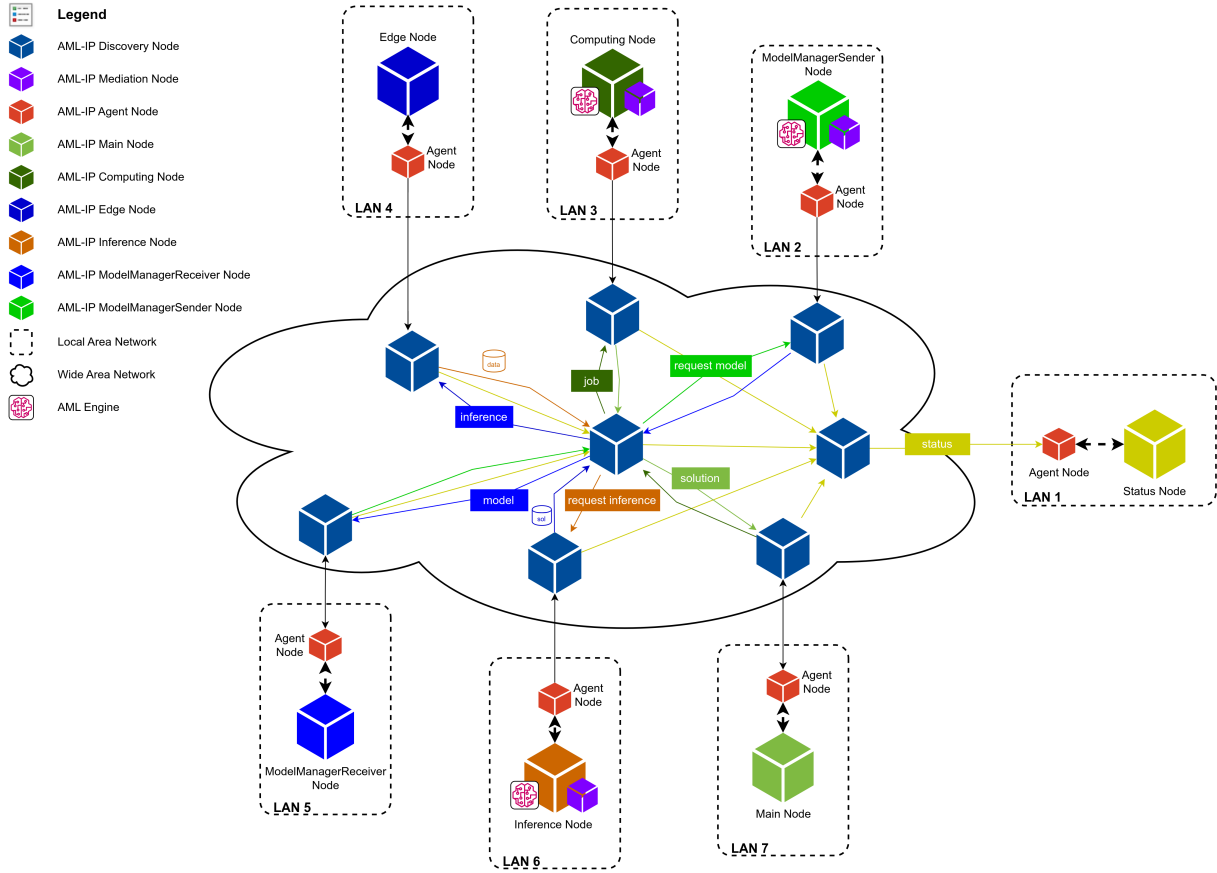


Figure 57: General overview use case

7.2 Training MNIST

The MNIST database is well known for providing images of handwritten digits, consisting of a training set of 60,000 examples, of which 10,000 are designated for testing, and the remainder for training. Derived from the NIST database, the MNIST digits have been size normalised and centred in a fixed size image.

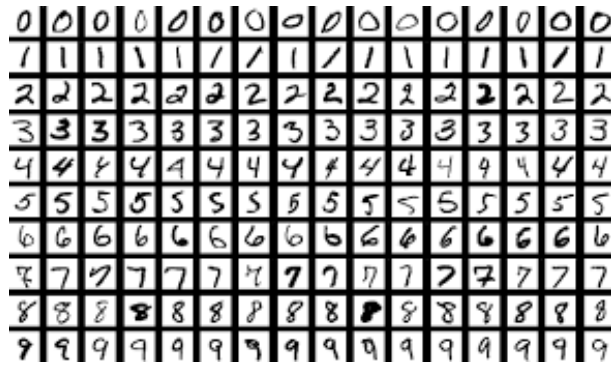


Figure 58: MNIST Database

7.2.1 Collaborative Learning Scenario

This demonstration integrates the Collaborative Learning scenario with the MNIST database. It provides users with the flexibility to choose between two primary training modes: training on the complete MNIST dataset, which encompasses all ten digits (0-9), or focusing exclusively on training the model to recognize a specific digit of their choice. In this example, we have chosen to train on a single digit.

The Collaborative Learning scenario is composed by the AML-IP-MMSender Node and the AML-IP-MMReceiver Node. These nodes enable an iterative training process, after each training iteration, the knowledge gained from that iteration is merged or combined with the knowledge acquired from previous iterations. This process continues for the specified number of iterations.

AML-IP-MMSender Node plays a crucial role in the collaborative learning process. It serves as a sender or distributor of model information and knowledge. During each training iteration, this node is responsible for packaging and transmitting the knowledge gained from that specific iteration.

AML-IP-MMReceiver Node is the counterpart to the sender node, it is designed to receive and collect knowledge and model updates. It acts as a repository for the insights acquired during each training iteration.

The Collaborative Learning scenario encourages cumulative learning. This means that the model doesn't start from scratch in each iteration. Instead, it builds upon the knowledge it has acquired from previous iterations. This approach often leads to a more robust and knowledgeable model over time.

The traces generated by the nodes explained above in this demonstration can be observed in Figure 59. On the left terminal, you will discover the AML-IP-MMSender Node, which displays the traces generated during model training and the transmission of the resulting model. Meanwhile, on the right side, the traces provided from the AML-IP-MMReceiver Node offer insight into the content of each received updated model.

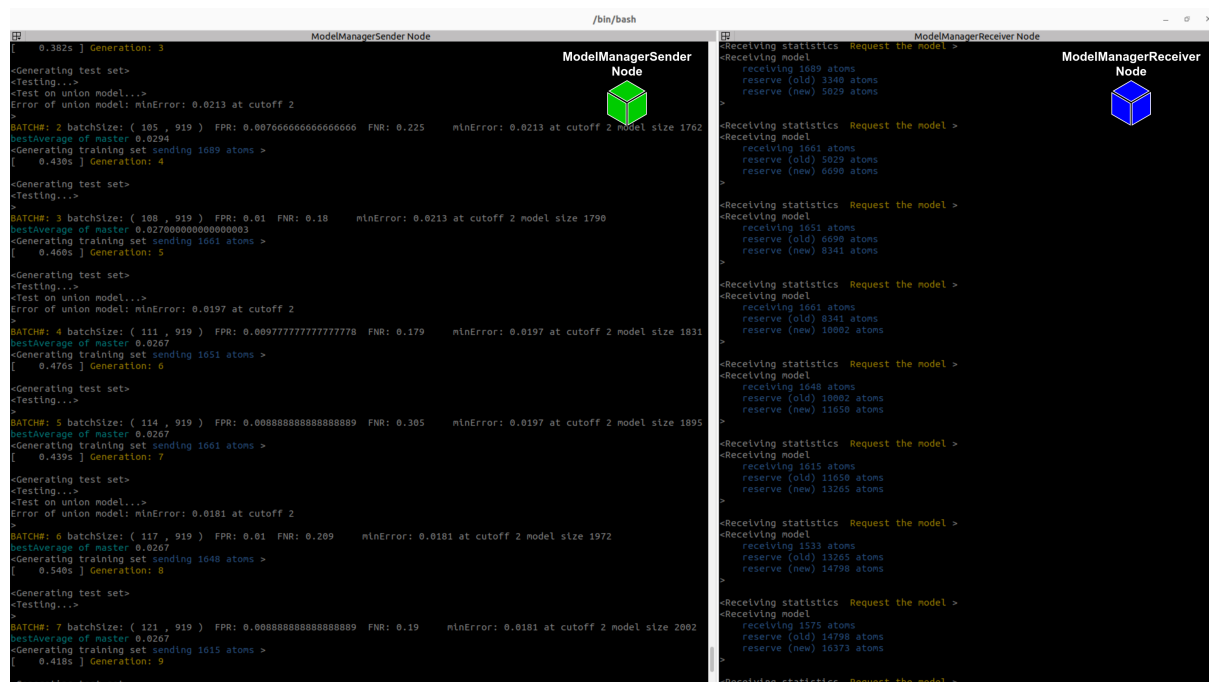


Figure 59: Training MNIST in a Collaborative Learning Scenario

7.2.2 AML Network

This presentation builds upon the demonstration previously elucidated, by introducing a Workload Distributed scenario and an AML-IP-Status Node..

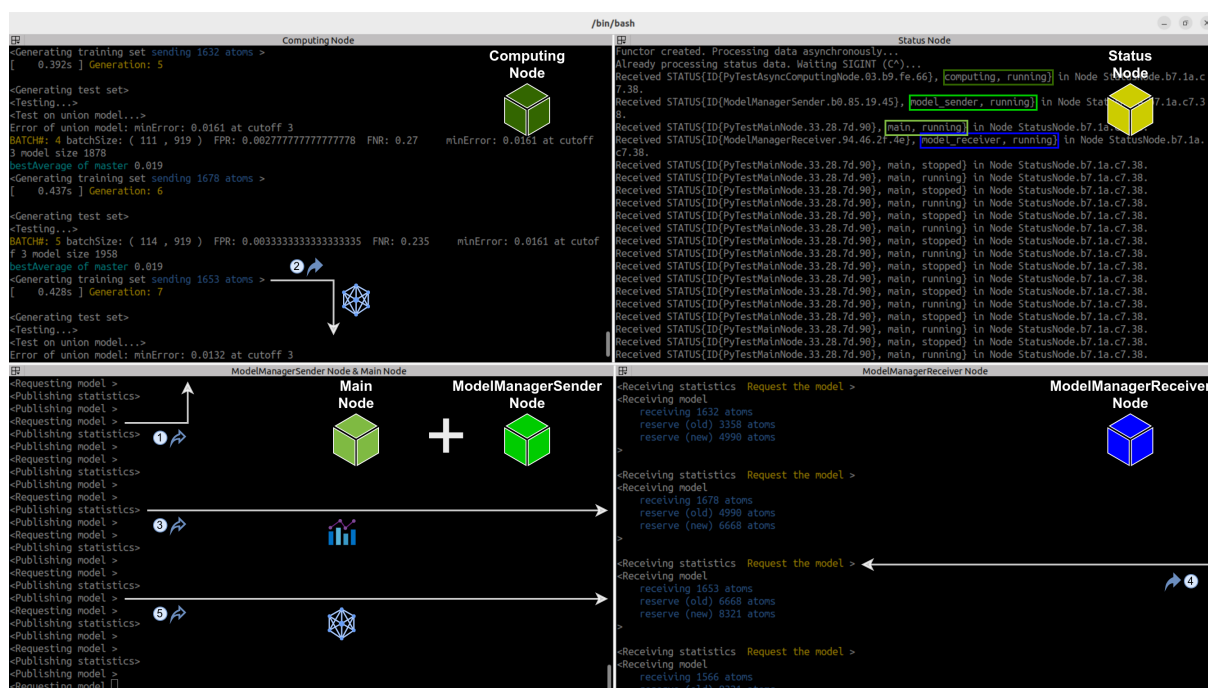
Within the Workload Distributed scenario, we maintain the same fundamental components discussed earlier: an AML-IP-Main Node responsible for distributing the training dataset of an AML model and an AML-IP-Computing Node dedicated to executing the model training process. The AML-IP-Computing Node returns the trained model to the AML-IP-Main Node.

In this expanded context, the AML-IP-MMSender Node takes the model received by the AML-IP-Main Node from the AML-IP-Computing Node and publishes its associated statistics. The AML-IP-MMReceiver Node works as the previous demonstration, requesting the model based on the statistics received from the AML-IP-MMSender Node.

These nodes adhere to the steps outlined below, and their traces can be seen in Figure 60.

1. The AML-IP-Main Node initiates a request to the AML-IP-Computing Node to obtain the model.
2. The AML-IP-Computing conducts the model training process and, upon generating a new version, sends it in response to the AML-IP-Main.
3. Given that the AML-IP-MMSender operates within the same process as the AML-IP-Main node, it can access the model received from the AML-IP-Computing node and share its statistics with any potentially interested parties.
4. The AML-IP-MMReceiver Node receives the published statistics and, based on this information, requests the model.
5. The AML-IP-MMSender Node, upon receiving the request, responds by providing the model.

Additionally, it's worth noting that the AML-IP-Status node oversees and controls all nodes currently status.



8 Debugging Tools

This section is dedicated to presenting a collection of specialized tools that have been created to assist users in troubleshooting and maintaining an AML network. These tools are designed to serve as invaluable aids for diagnosing issues, resolving problems, and ensuring the smooth operation of the AML environment.

8.1 Fast DDS Monitor

The eProsima Fast DDS Monitor is a powerful graphical desktop application designed for monitoring AML networks deployed using the eProsima Fast DDS library. This tool empowers users to perform real-time monitoring of communication status among AML-IP entities. It offers a wide array of customizable communication parameters to measure, including latency, throughput, packet loss, and more. Additionally, users can record and compute real-time statistical measurements for these parameters, such as mean, variance, and standard deviation.

Moreover, the Fast DDS Monitor enables users to inspect the status of the deployed AML network at any given moment. This includes detailed information on each DDS Domain, including instantiated DomainParticipants, their associated publishers and subscribers, and the respective topics they publish to or subscribe to. Users can also visualize the physical architecture of the network on which the AML-IP applications are running.

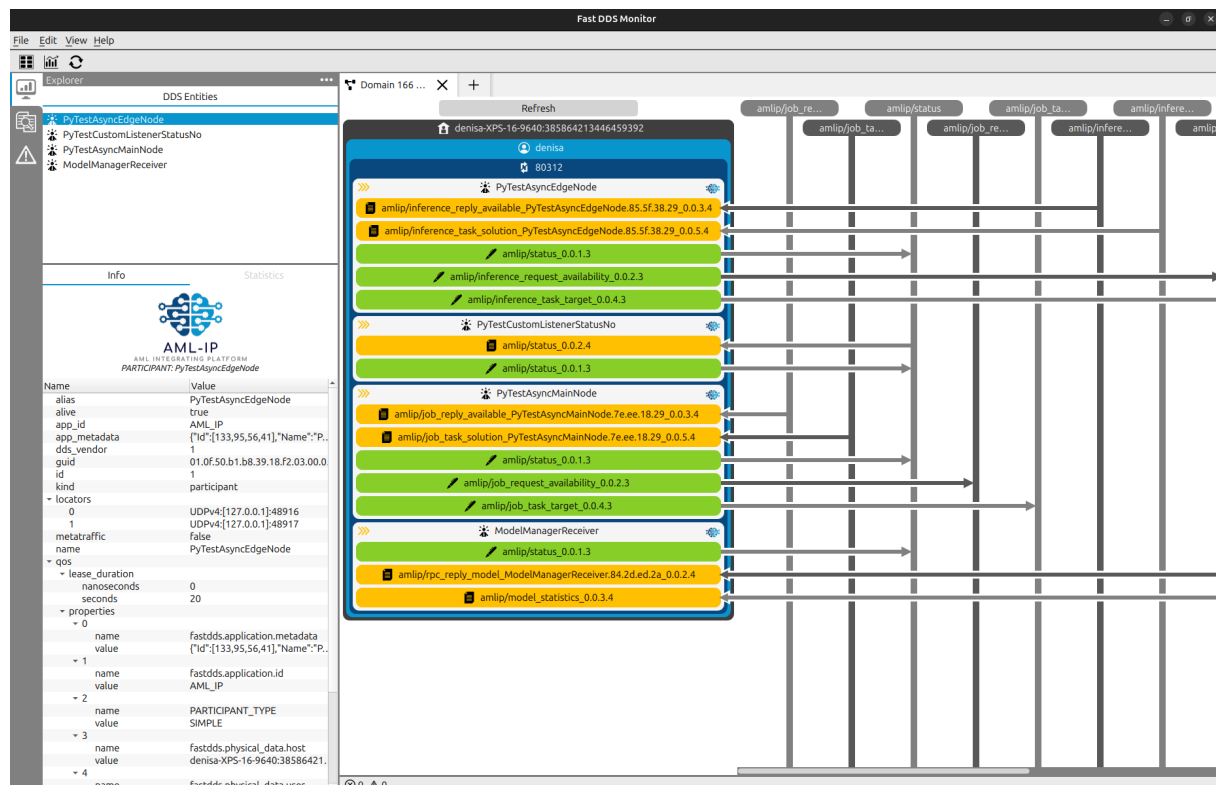


Figure 61: Fast DDS Monitor Interface.

eProsima Fast DDS Monitor is designed to meet the following criteria:

1. **Monitoring:** It offers real-time tracking of network status and communication parameters.
2. **Intuitive:** The graphical user interface follows a user experience design approach, ensuring ease of use.
3. **Introspection:** Users can effortlessly navigate through the deployed and active AML-IP entities, inspect their configurations, and understand their physical deployment.
4. **Troubleshooting:** Users can quickly identify potential issues or anomalous events within the communication network.

8.2 Integration with ROS 2

The integration of Fast DDS Monitor with ROS 2 provides seamless monitoring and analysis capabilities for ROS 2 networks. Leveraging its automatic discovery capabilities within a local network, Fast DDS Monitor provides a comprehensive view of the Participants, their associated Endpoints, the Topics they engage with, and even the specific network interfaces they employ for communication. Furthermore, this integration facilitates the reception of statistical data from each network endpoint, offering a rich dataset essential for assessing network performance and swiftly identifying potential communication issues. To fully unlock these monitoring capabilities, it is essential to ensure that Fast DDS serves as the chosen middleware within the ROS 2 ecosystem. This collaborative synergy between Fast DDS Monitor and ROS 2 not only enhances network visibility but also empowers users to proactively optimize and troubleshoot their ROS 2-based systems.

9 Conclusions

This document presented the design of the AML-IP. It is not intended to be the final design but a sketch on how it is going to be built, and it could change as the project advances depending on the necessities that may appear or the limitations encountered during the development process. However, it is intended to be a complete, robust and functional design fulfilling all the ALMA project requirements. The main advantages of this design are described below.

9.1 Advantages

The AML-IP communication platform described in this document addresses all requirements needed for the correct and efficient execution of an AML environment.

Reliable software tools This architecture is based on several already available tested products, which facilitates the implementation and reduces the number of errors that could appear. Moreover, all these products are released under the Apache 2.0 Open Source license, and are receiving technical support by *EPROS*.

The development of the communication platform will have the AML environment as main focus, and so it will count with specific improvements in usability and efficiency as stated in the ALMA Project GA.

Easy deployment The AML users could leverage the AML-IP communication benefits without the need of knowing, configuring or having to understand the communication protocols.

The independence between the AML-IP and the AML nodes is very useful for the AML final user. The only requirement for a user in order to use the AML-IP will be to execute an internal AML-IP-Agent in its LAN (in case it wants to communicate over WAN) and to know the network address (i.e. IP-port pair) of a remote AML-IP-D. This will be addressed in future versions by maintaining fixed points of discovery over the Internet.

Network Scalability The architecture proposed for the AML-IP is highly scalable. Every AML-IP-Alg is independent of the network state and the number of remote nodes connected. Moreover, the AML-IP framework is also aware of the nodes participating in the same LAN. This allows to build robust local clusters independent of other components deployed outside the user's private network.

Finally, the discovery mechanisms used for a dynamic AML-IP node discovery over WAN are highly reliable due to the distribution of the discovery information along redundant networks. Furthermore, the information sent along WAN connections between AML-IP-Agents is only forwarded to the nodes that require this information, i.e. the data is only transmitted to the nodes subscribed to the same topics under which the data has been published. This highly reduces the network traffic when compared to other P2P possible solutions as Block Chain.

Security The security of communications when working in the Internet is crucial, so it is a matter to be taken into account in every communications framework. The AML-IP separates the data required to train an AML algorithm, and the data of the algorithm itself, avoiding to share personal or private information.

The user authentication, access permissions and data encryption over the Internet is given by *Fast DDS* communications middleware, avoiding the need for extra security features. There exists the possibility of increasing point to point communication security by using TLS over TCP, but it may not be a desired feature as the AML-IP is designed to be an open environment where any new node could enter the network

at any point and receive the whole information. The possibility of adding a logging or authentication mechanism to join a network of AML-IP-D nodes will be considered for future versions of the AML-IP.

9.2 Limitations

There exist several limitations in the design here presented. These have been taken into account, and will be addressed in future versions of the AML-IP. The constraints identified, together with the potential approaches proposed to overcome them, are discussed below.

Centralized communication from LAN to WAN The AML-IP-Agent centralizes the connection between the user private network and the Internet, while creating a secure, independent WAN communication that does not affect the correct operation of the AML nodes. Therefore, it is a single point of failure in the AML environment. However, the communication over WAN of nodes behind a NAT is a well-known problem with very limited options to address it.

The approach studied to overcome this issue would be to allow multiple AML-IP-Agent nodes inside a LAN, what would avoid the single point of failure by deploying redundant nodes.

Large amount of data AML-IP-Alg nodes are expected to generate and transmit a large amount of data. This is a problem for communication purposes, as the whole data needs to be sent from one AML-IP-Alg to the rest of the network in a reliable way and with a frequency higher than that with which new data is generated.

The first approach considered to address this problem would be to fragment the data to be then sent reliably. Another option considered would be that of reducing the amount of data required by an AML node. Thus, not all the data generated by an AML node would be sent, but only an update with respect to previously sent data. The possible features of this functionality will be discussed and agreed with ALG and the AML development team.

Data privacy mixing scenarios There are two principal scenarios where, by using the AML-IP, two of the main strengths of the AML algorithm are exploited: the *collaborative learning* and *workload distribution* scenarios. These scenarios are not mutually exclusive. Nodes are designed to work in one specific scenario, but any machine or process could have different nodes from different scenarios working together. There is however a problem encountered when combining the two scenarios.

Data privacy when training a model is a main concern for AML, and the data used is kept private within the collaborative learning scenario. However, if a node requests the use of remote nodes for computational purposes (workload distribution), the privacy of data exchanged in this process can no longer be assured, and may be difficult to do so.

Several solutions are being considered to solve this issue, the main ones relying on the encryption of data in the communication phase, or even in the training one, and to decrypt the solution in a later step.

A Screenshots of Demonstrator results

network

DHCP	NAT/PAT	DNS	UPnP	DynDNS	DMZ	NTP	ONT
------	---------	-----	------	--------	-----	-----	-----

These rules are needed to authorise a remote communication from Internet to reach a specific device of your LAN. You can also define the port(s) that this communication will use.



warning : make sure you have not filtered these ports in the firewall.

customize rules

status	application / service	internal port	external port	protocol	device	activate	
	Web Server (HTTP) ▼	80	80	TCP ▼	HUAWEI ▼		save
✓	AML-IP Discovery Server 1	6000	6000	TCP	Laptop eProxima	✓	delete
✓	AML-IP Engine	7000	7000	TCP	Laptop eProxima	✓	delete

Figure 62: Example of port forwarding configuration on a private user router.

```
eProxima@eProxima-XPS-15-7590:~/AML$ ./install/amlip/bin/AML_IP_DiscoveryServer --id=1 --listening-addresses="37.11.18.30,5000" --time 0
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43
with id 1 and GUID 01.0f.01.41.4c.47.45.42.52.41.49.43
listening in addresses:
IP: 37.11.18.30 port: 5000
connecting with servers in addresses:
Please press enter to stop it at any time.
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.02.41.4c.47.45.42.52.41.49.43
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 discovered publisher 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 discovered subscriber 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 discovered subscriber 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.03.41.4c.47.45.42.52.41.49.43
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 discovered publisher 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 removed participant 01.0f.02.41.4c.47.45.42.52.41.49.43
DiscoveryServer Participant 01.0f.01.41.4c.47.45.42.52.41.49.43 removed participant 01.0f.03.41.4c.47.45.42.52.41.49.43
eProxima@eProxima-XPS-15-7590:~/AML$
```

Figure 63: AML-IP-D in HOST 1

```
[~/aml-ip-prototype_ws]$
> ./install/amlip/bin/AML_IP_DiscoveryServer --id=2 --listening-addresses="127.0.0.1,5000;87.219.112.233,6000" --connection-addresses="37.11.18.30,5000,1" --time=0
DiscoveryServer Participant 01.0f.02.41.4c.47.45.42.52.41.49.43
with id 2 and GUID 01.0f.02.41.4c.47.45.42.52.41.49.43
listening in addresses:
IP: 127.0.0.1 port: 5000
IP: 87.219.112.233 port: 6000
connecting with servers in addresses:
IP: 37.11.18.30 port: 5000 id: 1
Please press enter to stop it at any time.
DiscoveryServer Participant 01.0f.02.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.01.41.4c.47.45.42.52.41.49.43
DiscoveryServer Participant 01.0f.02.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.02.41.4c.47.45.42.52.41.49.43 discovered publisher 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.02.41.4c.47.45.42.52.41.49.43 discovered subscriber 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.02.41.4c.47.45.42.52.41.49.43 discovered subscriber 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.02.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
DiscoveryServer Participant 01.0f.02.41.4c.47.45.42.52.41.49.43 discovered publisher 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00

[~/aml-ip-prototype_ws]$
```

Figure 64: AML-IP-D in HOST 2.

```
[~/aml-ip-prototype_ws]$
> ./install/amlip/bin/AML_IP_Engine --listening-addresses="87.219.112.233,7000;127.0.0.1,4000" --connection-addresses="127.0.0.1,5000,2" --period 4 --size 100 --samples 0
Engine Participant created with guid: 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
listening in addresses:
IP: 87.219.112.233 port: 7000
IP: 127.0.0.1 port: 4000
connecting with servers in addresses:
IP: 127.0.0.1 port: 5000 id: 2
Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 publishing. Please press enter to stop it at any time.

<< Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 sent atomization number: 1 message: <Number of atoms: 41>

<< Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 sent atomization number: 2 message: <Number of atoms: 10>
Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 matched DL reader with a new DL: 1.f.3a.1f.d7.d5.c7.1d.1.0.0.0.0.1.3
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 3> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 1

<< Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 sent atomization number: 3 message: <Number of atoms: 74>
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 15> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 2
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 34> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 3

<< Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 sent atomization number: 4 message: <Number of atoms: 54>
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 11> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 4
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 43> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 5

<< Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 sent atomization number: 5 message: <Number of atoms: 84>
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 32> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 6
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 32> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 7

<< Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 sent atomization number: 6 message: <Number of atoms: 19>
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 48> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 8
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 13> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 9

<< Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 sent atomization number: 7 message: <Number of atoms: 41>
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 35> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 10
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 25> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 11

<< Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 sent atomization number: 8 message: <Number of atoms: 89>
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 8> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 12
>> Engine Participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00 receive DL message <Number of relations: 10> from: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
. Number of messages received so far: 13
[~/aml-ip-prototype_ws]$
```

Figure 65: AML-IP-Edge in HOST 2.

```

AML_IP_DiscoveryServer
paris@paris-XPS-15-9570:~/projects/AML-IPS ./install/amlip/bin/AML_IP_DiscoveryServer --listening-addresses="127.0.0.1,5002;37.35.177.91,5000" --connection-addresses="37.11.18.30,5000,1" --time 0 --id 3
DiscoveryServer Participant 01.0f.03.41.4c.47.45.42.52.41.49.43
with id 3 and GUID 01.0f.03.41.4c.47.45.42.52.41.49.43
listening in addresses:
IP: 127.0.0.1 port: 5002
IP: 37.35.177.91 port: 5000
connecting with servers in addresses:
IP: 37.11.18.30 ports: 5000 id: 1
Please press enter to stop it at any time.
DiscoveryServer Participant 01.0f.03.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.01.41.4c.47.45.42.52.41.49.43
DiscoveryServer Participant 01.0f.03.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.03.41.4c.47.45.42.52.41.49.43 discovered publisher 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.03.41.4c.47.45.42.52.41.49.43 discovered subscriber 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.03.41.4c.47.45.42.52.41.49.43 discovered subscriber 01.0f.47.a1.f3.16.0f.8d.01.00.00.00
DiscoveryServer Participant 01.0f.03.41.4c.47.45.42.52.41.49.43 discovered participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
DiscoveryServer Participant 01.0f.03.41.4c.47.45.42.52.41.49.43 discovered publisher 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
paris@paris-XPS-15-9570:~/projects/AML-IPS

```

Figure 66: AML-IP-D in HOST 3.

```

amlip DL
paris@paris-XPS-15-9570:~/projects/AML-IPS ./install/amlip/bin/AML_IP_DL --connection-addresses="127.0.0.1,5002,3" --listening-addresses="37.35.177.91,5001;127.0.0.1,5003" --period 2 --size 50 --samples
0
DL Participant created with guid: 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00
listening in addresses:
IP: 37.35.177.91 port: 5001
IP: 127.0.0.1 port: 5003
connecting with servers in addresses:
IP: 127.0.0.1 port: 5002 id: 3
DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 publishing. Please press enter to stop it at any time.
DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 matched with 1.f.47.a1.f3.16.f.8d.1.0.0.0.0.2.4
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 1 message: <Number of relations: 3>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 2 message: <Number of relations: 15>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 3 message: <Number of relations: 34>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 4 message: <Number of relations: 11>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 5 message: <Number of relations: 43>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 6 message: <Number of relations: 32>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 7 message: <Number of relations: 32>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 8 message: <Number of relations: 48>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 9 message: <Number of relations: 13>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 10 message: <Number of relations: 35>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 11 message: <Number of relations: 25>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 12 message: <Number of relations: 8>
<< DL Participant 01.0f.3a.1f.d7.d5.c7.1d.01.00.00.00 sent DLOutput number: 13 message: <Number of relations: 10>
paris@paris-XPS-15-9570:~/projects/AML-IPS

```

Figure 67: AML-IP-DL in HOST 3.

B IDLs for workload distribution scenario prototype

```

1
2 // Uniquely identifies a request from a client
3 struct Multiservice_RequestAvailability
4 {
5     string requester_id;
6     unsigned long task_id;
7 };
8
9 // Uniquely identifies a processing task by the client , the task and the
   target server
10 struct Multiservice_TaskReference
11 {
12     string requester_id;
13     unsigned long task_id;
14     string server_id;
15 };
16
17 // Request Data Type for the specific task
18 struct Multiservice_Task_Data
19 {
20     // To inherit in specific task data type
21 };
22
23 // Identifies the task processing and adds the data (that depends on the
   specific task)
24 struct Multiservice_Task
25 {
26     Multiservice_TaskReference task_reference;
27     // This must be implemented in the subclass
28     // Multiservice_Task_Data data;
29 };
30
31 // Solution Data Type for the specific task
32 struct Multiservice_Solution_Data
33 {
34     // To inherit in specific task data type
35 };
36
37 // Identifies the task processing and adds the solution data (that depends
   on the specific task)
38 struct Multiservice_Solution
39 {
40     Multiservice_TaskReference task_reference;
41     // This must be implemented in the subclass
42     // Multiservice_Solution_Data data;
43 };

```

Listing 3: MultiService Communication Protocol generic Data Types.

```

1
2 // Specific Data Type for a Job-task request
3 struct Job_Task_Data : Multiservice_Task_Data
4 {
5     // Raw data in bytes
6     sequence<octet> job;
7 };
8
9 // Specific Data Type for a Job-task solution
10 struct Job_Solution_Data : Multiservice_Solution_Data
11 {
12     // Raw data in bytes
13     sequence<octet> solution;
14 };
15
16 // Inherit Data Type for a Job-task
17 struct Job_Task : Multiservice_Task
18 {
19     Job_Task_Data data;
20 };
21
22 // Inherit Data Type for a Job-task solution
23 struct Job_Solution : Multiservice_Solution
24 {
25     Job_Solution_Data data;
26 };

```

Listing 4: MultiService Communication Protocol specific Data Types for Job.

C Screenshots of Demonstrator for workload distribution results

```
allowlist:
  # each of the AML-IP MSCP topics required
  - name: aml/status
    type: aml::status
  - name: aml/ms/request_availability/job
    type: aml::ms::request
  - name: aml/ms/reply_available/job
    type: aml::ms::task_reference
  - name: aml/ms/task_target/job,
    type: aml::ms::task_reference
  - name: aml/ms/task/job
    type: aml::ms::task::job
  - name: aml/ms/solution/job
    type: aml::ms::solution::job

simple_0:      # Simple Participant to communicate locally in Domain Id 0
  type: local
  domain: 0

wan:          # External Participant
  type: wan
  id: 0
  listening-addresses:
    - ip: "x.x.x.x"      # This machines IP
      port: 11666        # This machine open port to Internet
```

Listing 6: eProsimas DDS Router YAML configuration for WAN communication as a Server.

```
paris@paris-XPS-15-9570:~/projects/amlip$ ./install/amlip_nodes/lib/amlip_nodes/amlip_computing
2022-02-24 15:41:02,966 - USER - Starting AML-IP Computing Node 049 execution.
2022-02-24 15:41:06,568 - USER - AML-IP Computing Node 049 calculating result for job 0 (approximately 3.305 ms).
2022-02-24 15:41:09,877 - USER - AML-IP Computing Node 049 finish calculating job 0.
2022-02-24 15:41:15,280 - USER - AML-IP Computing Node 049 calculating result for job 1 (approximately 2.8 ms).
2022-02-24 15:41:18,084 - USER - AML-IP Computing Node 049 finish calculating job 1.
2022-02-24 15:41:18,580 - USER - AML-IP Computing Node 049 calculating result for job 2 (approximately 4.378 ms).
2022-02-24 15:41:22,961 - USER - AML-IP Computing Node 049 finish calculating job 2.
2022-02-24 15:41:22,965 - USER - AML-IP Computing Node 049 calculating result for job 4 (approximately 6.692 ms).
2022-02-24 15:41:29,661 - USER - AML-IP Computing Node 049 finish calculating job 4.
2022-02-24 15:41:29,664 - USER - AML-IP Computing Node 049 calculating result for job 5 (approximately 3.328 ms).
2022-02-24 15:41:32,996 - USER - AML-IP Computing Node 049 finish calculating job 5.
2022-02-24 15:41:34,482 - USER - AML-IP Computing Node 049 calculating result for job 7 (approximately 4.136 ms).
2022-02-24 15:41:38,623 - USER - AML-IP Computing Node 049 finish calculating job 7.
^C2022-02-24 15:41:45,291 - USER - Signal handler called with signal 2.
2022-02-24 15:41:45,291 - USER - Signal received, stopping node AML-IP Computing Node 049. This could take few seconds.
2022-02-24 15:41:45,292 - USER - Finishing AML-IP Computing Node 049 execution.
paris@paris-XPS-15-9570:~/projects/amlip$
```

Figure 68: Prototype AML-IP Algebraic Computing Node execution traces.

```

allowlist:
  # each of the AML-IP MSCP topics required
  - name: aml/status
    type: aml::status
  - name: aml/ms/request_availability/job
    type: aml::ms::request
  - name: aml/ms/reply_available/job
    type: aml::ms::task_reference
  - name: aml/ms/task_target/job,
    type: aml::ms::task_reference
  - name: aml/ms/task/job
    type: aml::ms::task::job
  - name: aml/ms/solution/job
    type: aml::ms::solution::job

simple_1:      # Simple Participant to communicate locally in Domain Id 1
  type: local
  domain: 1    # Another non default domain is used in case is proven in same LAN

wan:          # External Participant
  type: wan
  id: 1        # This Router id
  connection-addresses:
    - id: 0      # Remote Router id
      addresses:
        - ip: "x.x.x.x"      # Remote machines IP
          port: 11666        # Remote machine open port

```

Listing 7: eProxima DDS Router YAML configuration for WAN communication as a Client.

```

2022-02-24 15:41:04,345 - USER - Starting AML-IP Main Node 382 execution.
2022-02-24 15:41:06,566 - USER - Main Node AML-IP Main Node 382 has created a new job:
  JOB: {0: <She is bubbling >}

2022-02-24 15:41:11,383 - USER - Main Node AML-IP Main Node 382 has created a new job:
  JOB: {1: <He was bubbling >}

2022-02-24 15:41:11,571 - USER - Main Node AML-IP Main Node 382 has received the solution to job:
  JOB: {0: <She is bubbling >}
  with result:
  SOLUTION: {0: <She is bubbling badly.>}

2022-02-24 15:41:15,646 - USER - Main Node AML-IP Main Node 382 has created a new job:
  JOB: {2: <He is reading >}

2022-02-24 15:41:18,778 - USER - Main Node AML-IP Main Node 382 has created a new job:
  JOB: {3: <Jack was bubbling >}

2022-02-24 15:41:21,578 - USER - Main Node AML-IP Main Node 382 has received the solution to job:
  JOB: {1: <He was bubbling >}
  with result:
  SOLUTION: {1: <He was bubbling like a boss.>}

```

Figure 69: Prototype AML-IP Algebraic Main Node execution traces.

```

1 JOBS ANSWERED
2 {0: <She is bubbling >} : {0: <She is bubbling badly.>}
3 {1: <She was speaking >} : {1: <She was speaking with me.>}
4 {2: <Tim is reading >} : {2: <Tim is reading like a boss.>}
5 {4: <Tim was reading >} : {4: <Tim was reading like a boss.>}
6 {5: <Lorenzo was reading >} : {5: <Lorenzo was reading alone.>}
7 {7: <He likes speaking >} : {7: <He likes speaking very well.>}

```

Listing 5: AML-IP Algebraic Computing Node final log file from node **AML-IPComputingNode049**.

```

1 JOBS ANSWERED
2 {0: <Jack is bubbling >} : {0: <Jack is bubbling with me.>}
3 {3: <Jack was bubbling >} : {3: <Jack was bubbling very well.>}
4 {3: <He is reading >} : {3: <He is reading like a boss.>}
5 {4: <Tim was bubbling >} : {4: <Tim was bubbling like a boss.>}
6 {6: <Tim is bubbling >} : {6: <Tim is bubbling like a boss.>}
7 {7: <She was speaking >} : {7: <She was speaking like a boss.>}
8 {8: <She likes reading >} : {8: <She likes reading like a boss.>}

```

Listing 6: AML-IP Algebraic Computing Node final log file from node **AML-IPComputingNode263**.

```

1 JOBS ANSWERED
2 {1: <He was bubbling >} : {1: <He was bubbling like a boss.>}
3 {2: <He is reading >} : {2: <He is reading like a boss.>}
4 {5: <He likes talking >} : {5: <He likes talking alone.>}
5 {6: <Tim is talking >} : {6: <Tim is talking badly.>}

```

Listing 7: AML-IP Algebraic Computing Node final log file from node **AML-IPComputingNode977**.

```

1 PENDING
2 {8: <She was playing >}
3 SOLUTION
4 {0: <She is bubbling >} : {0: <She is bubbling badly.>}
5 {1: <He was bubbling >} : {1: <He was bubbling like a boss.>}
6 {3: <Jack was bubbling >} : {3: <Jack was bubbling very well.>}
7 {2: <He is reading >} : {2: <He is reading like a boss.>}
8 {4: <Tim was reading >} : {4: <Tim was reading like a boss.>}
9 {7: <She was speaking >} : {7: <She was speaking like a boss.>}
10 {6: <Tim is bubbling >} : {6: <Tim is bubbling like a boss.>}
11 {5: <He likes talking >} : {5: <He likes talking alone.>}

```

Listing 8: AML-IP Algebraic Main Node final log file from node **AML-IPMainNode382**.

```

1 SOLUTION
2 {0: <Jack is bubbling >} : {0: <Jack is bubbling with me.>}
3 {2: <Tim is reading >} : {2: <Tim is reading like a boss.>}
4 {1: <She was speaking >} : {1: <She was speaking with me.>}
5 {3: <He is reading >} : {3: <He is reading like a boss.>}
6 {5: <Lorenzo was reading >} : {5: <Lorenzo was reading alone.>}
7 {4: <Tim was bubbling >} : {4: <Tim was bubbling like a boss.>}
8 {8: <She likes reading >} : {8: <She likes reading like a boss.>}
9 {7: <He likes speaking >} : {7: <He likes speaking very well.>}
10 {6: <Tim is talking >} : {6: <Tim is talking badly.>}

```

Listing 9: AML-IP Algebraic Computing Node final log file from node **AML-IPMainNode413**.

References

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