

# Open Source OPC UA over TSN Ecosystem

Project phase #3: “Scalability & Tool chain”



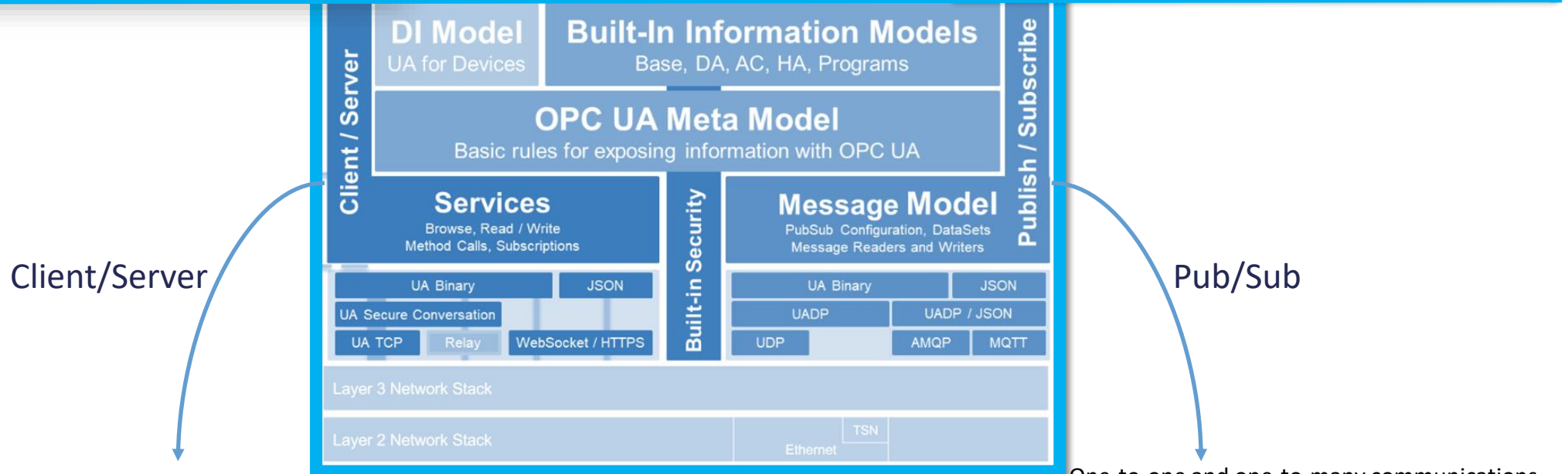
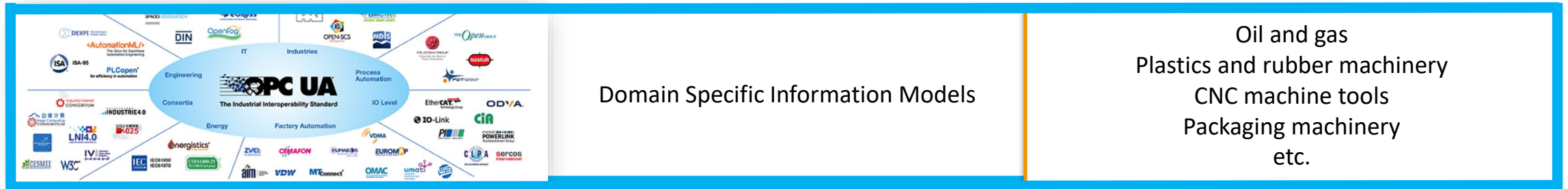
# Why OPC UA?

OPC UA has travelled some distance in the endeavor of

- being the “English” language of the equipment world
- through its industry widespread adoption, cooperation and collaboration and
- enabling digitization and Industry 4.0 use-cases by offering an **O**pen **P**latform for **C**ommunications & an **U**nified **A**rchitecture



# Unlike MQTT, OPC UA is a complete package



Client/Server

- Browse information model for device capabilities
- Read and write current and historical data
- Execute actions through method calls
- Data change and event notifications

Pub/Sub

- One-to-one and one-to-many communications
- High frequency data and event notifications
- Power and latency constrained devices
- One-to-many communications

# How does OPC UA fit into Industry 4.0?

OPC UA has been recommended as an important technology in the implementation strategy of the Industry 4.0 platform.

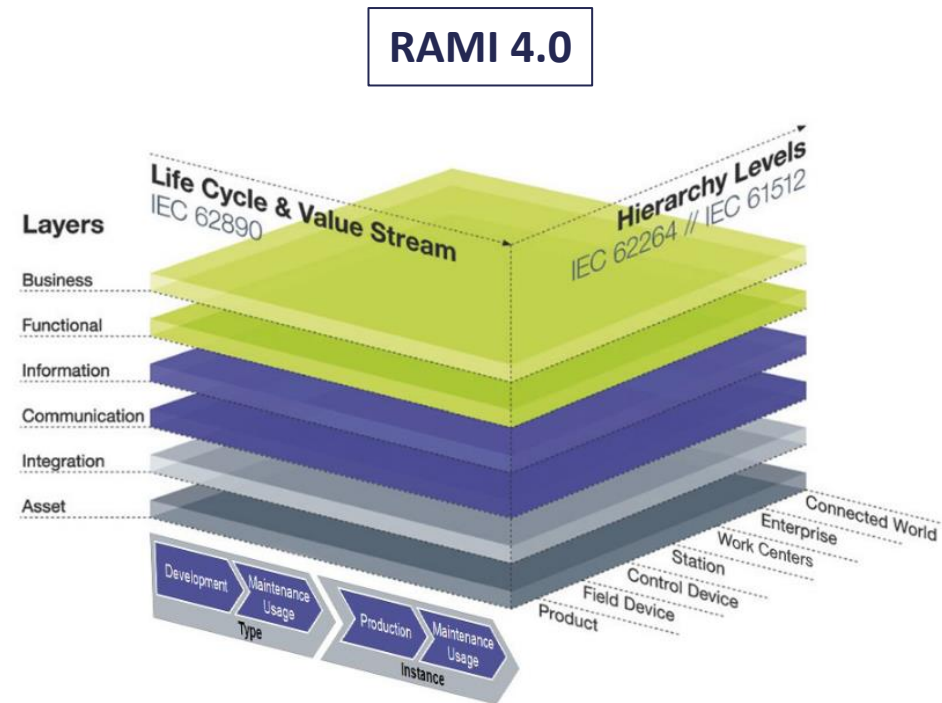
-Platform Industrie 4.0

<https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/secure-implementation-of-opc.pdf?blob=publicationFile&v=5>

OPC-UA IS THE COMMUNICATION TECHNOLOGY IN RAMI4.0

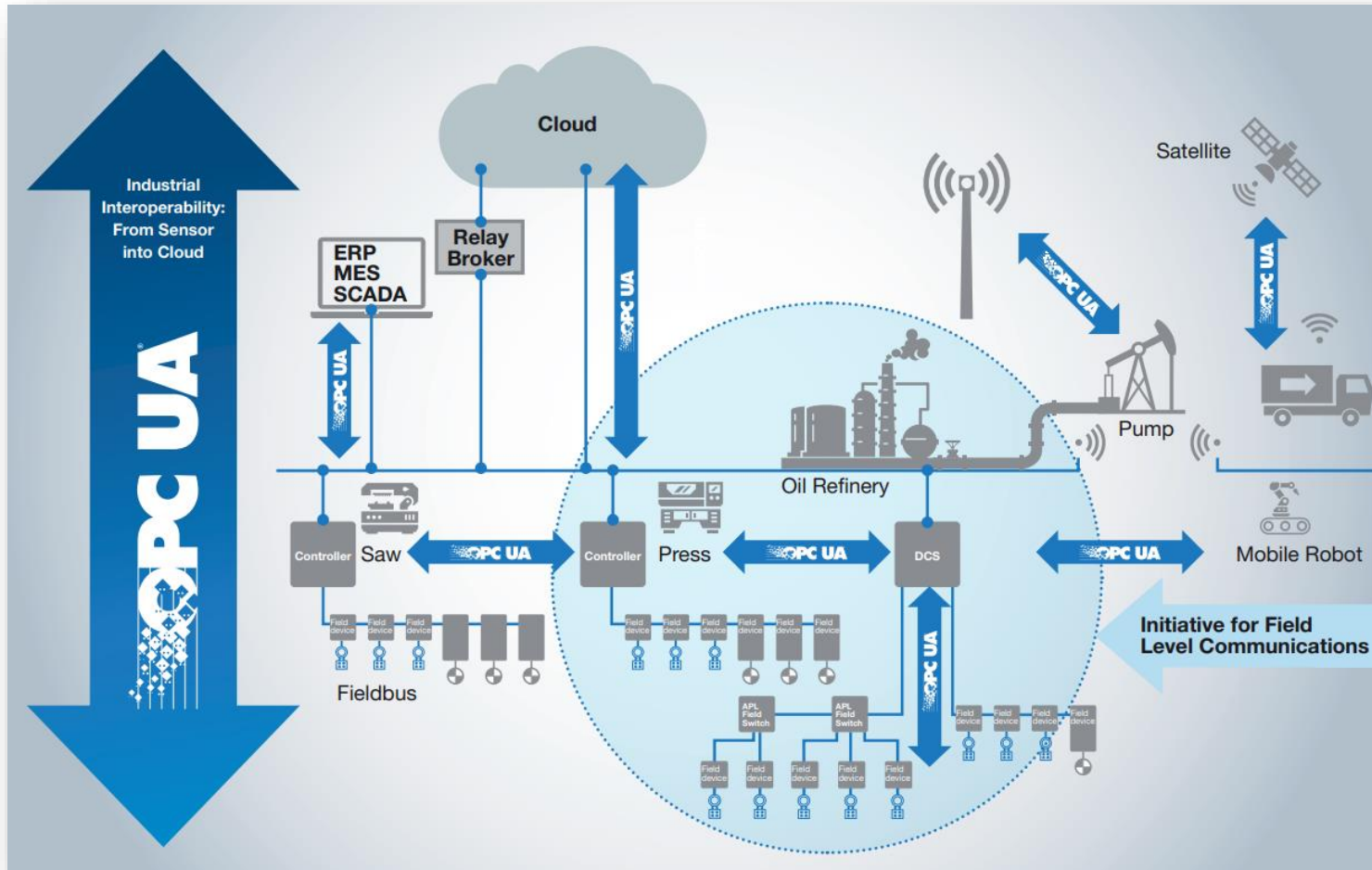
-OPC Foundation

<https://opcfoundation.org/wp-content/uploads/2016/05/OPC-UA-Interoperability-For-Industrie4-and-IoT-EN-v5.pdf>



# OPC UA Field Level Communications

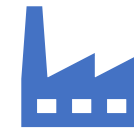
# Why OPC UA Field Level Communications?



Security  
by design



Interoperability  
by design



Enable all Industrial  
use-cases (IEEE 60802)

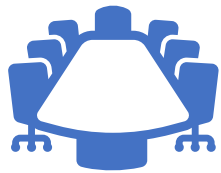


Realtime pub/sub and  
scaling down to  
embedded devices



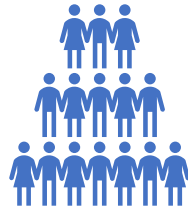
# FLC steering committee

## OPC Foundation Organization & Members Companies



### Board of Directors

Mitsubishi Electric, Ascolab, ABB, Siemens AG, BECKHOFF, Schneider Electric, Honeywell Process Solutions, Microsoft, Yokogawa, SAP AG, Rockwell Automation, Emerson



### Members companies

Over 750 typically from small system integrators to the world's largest automation and industrial suppliers.

FLC steering committee

ABB BECKHOFF rexroth  
A Bosch Company  
CISCO EMERSON FESTO hirschner  
HIRSCHMANN HUAWEI intel kalycito  
A BELDEN BRAND creating a difference  
KUKA Lenze MITSUBISHI ELECTRIC molex  
MOXA MURR ELEKTRONIK OMRON PILZ  
stay connected THE BRAND OF SAFETY  
PHOENIX CONTACT Rockwell Automation Schneider Electric  
SIEMENS TTTech WAGO YOKOGAWA  
Ingenuity for life industrial

Nearly all major automation suppliers are part of this group  
Recently Google Cloud and Amazon AWS became members of OPC Foundation

# Open Source Ecosystem for OPC UA



# Why Open Source

## Going forward

You will see open source becoming a critical part of your commercial solutions

### Standard Hardware

- Intel x86, ARM, FPGA
- IEEE 802.1 AS
- IEEE 802.1 Qbv, etc

### Standard Software

- Linux Kernel 5.4+
- Realtime Linux (PREEMPT\_RT is now a mainline)
- Linuxptp 3.0+
- Iproute 2+
- Open62541 1.0+

## Standard interfaces for Industry 4.0

will result in common software components to be delivered via collaborative effort

## Landscape is complex

Open-source projects enable sharing of costs and lets you invest more on your core differentiators

# Why this community project?

- Lean, Scalable, Standards-based, Secure, Open-Source path for customers to achieve:
  - real-time machine to machine applications, as well as
  - simplified cloud integration
- Top Goals of Phase 3
  - Upgrade certification for Embedded profile (Current: Micro Embedded + Security)
  - Load configuration during runtime for use in production environments
  - First implementation of Pub/Sub security

# OPC UA and TSN

## Frequently Asked Questions

# Why should I spend money on an open-source project?

- OPC UA is a standard - it is not your core differentiator
- You can
  - Share cost of development
  - Avoid duplication of work
  - Reduce standard compliance and certification effort
  - Reduce after sales support cost – interoperability surprises from the field
- By investing money in open source, you can have a say in prioritizing features that you need and also influence the long-term roadmap of the project

## If its already a successful project, then why should I fund now?

- Phase 1 added PubSub
- Phase 2 certified the stack for micro-embedded & optimized for CPU cycles
- Phase 3 will focus on
  - Pub/Sub security (Work has commenced with joining of a diamond contributor)
  - Upgrade certification for Embedded profile (Current: Micro Embedded + Security)
  - Load configuration during runtime for use in production environments

## Standard Ethernet Vs TSN

- With TSN, extensions for standard Ethernet in accordance with IEEE 802.1 that break free of past limitations have successfully been developed.
- Thus, there's now a standardized layer 2 in the ISO 7-layer model with upward compatibility to the previous Ethernet and hard real-time capability.
- With 802.1AS-rev, TSN also defines an interoperable, uniform method for synchronizing distributed clocks in the network.

# Other Industrial Ethernet Protocols Vs TSN?

- TSN is not an extension to Ethernet – it is the new Ethernet
  - Economy of scale
  - Elimination of custom hardware
  - Possibility for open-source software eco-systems



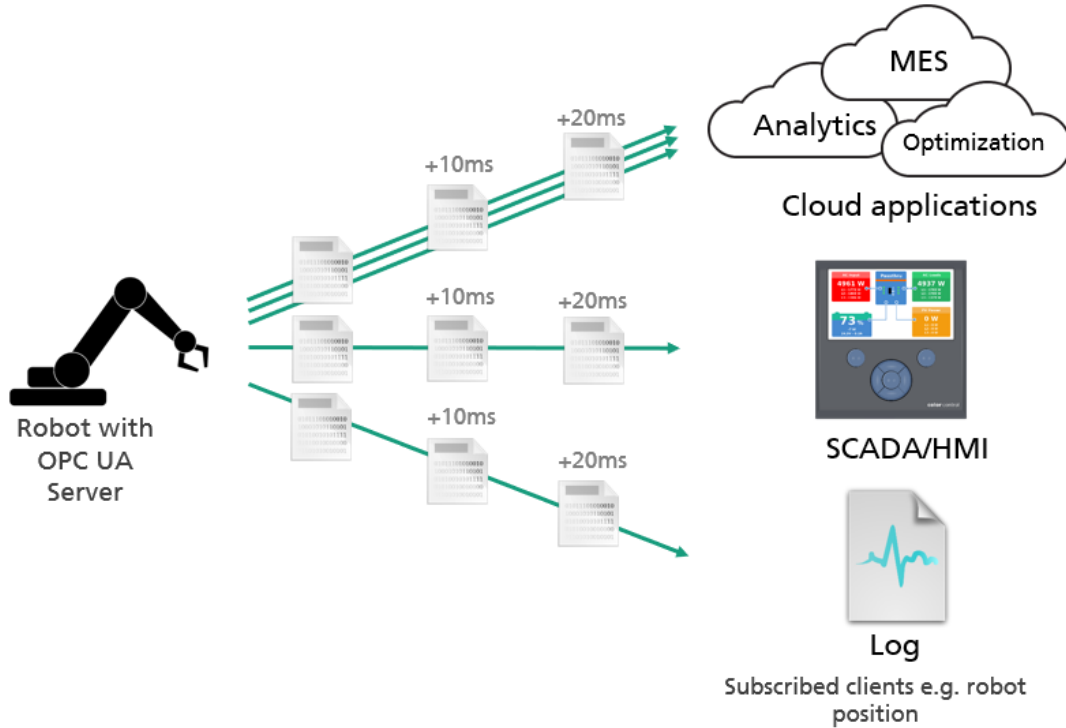
## Why open62541?

# open62541

- Open Source OPC UA SDK (Stack / Server / Client)
- Licensed under the MPLv2 (weak copyleft)
- Professional Development Processes and Continuous Integration
  - 80%+ test coverage
  - Static Code Analyzers
  - Runtime Sanitizers
  - Build on several Platforms and Setups
- Used in commercial products
- Extended Plugin concept for ease integration and customization
- +70k Downloads



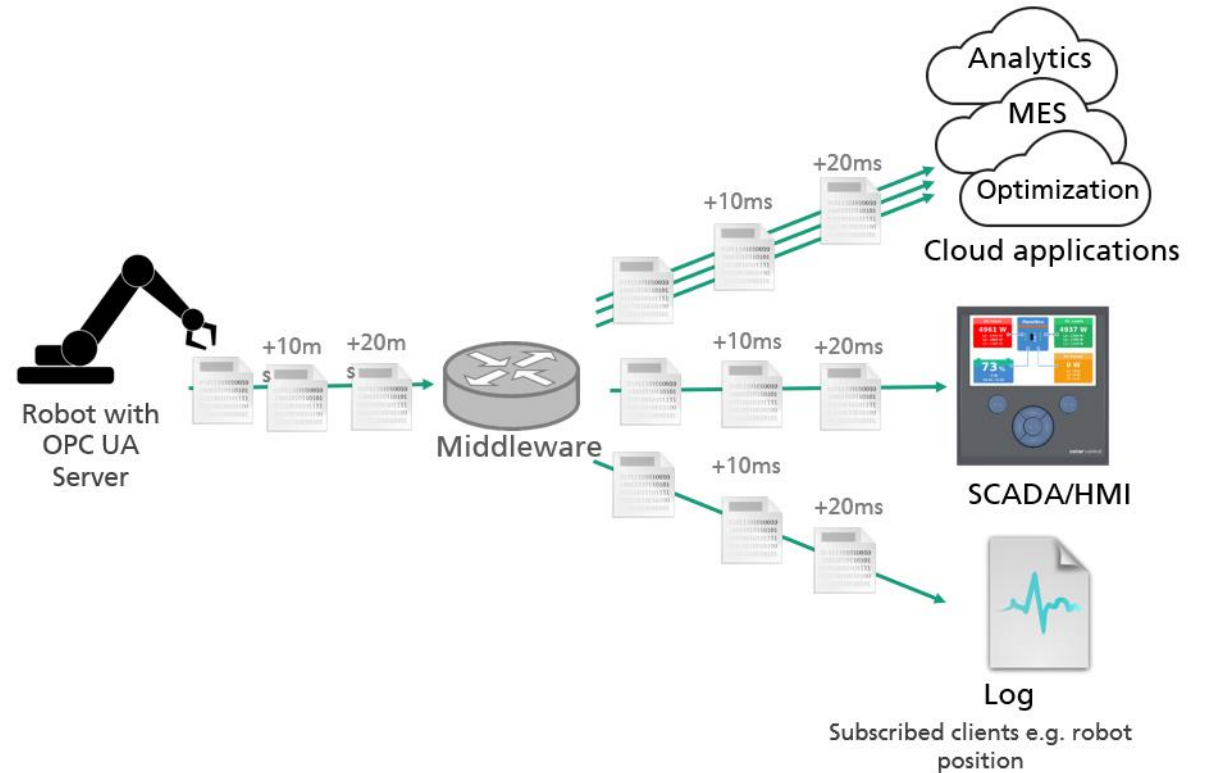
# Why PubSub?



## OPC UA **without** PubSub

OPC UA Server Load : e.g. 5 Clients @ 10ms

msg per sec \* devices = 100 \* 5 = 500 msg/sec



## OPC UA **with** PubSub

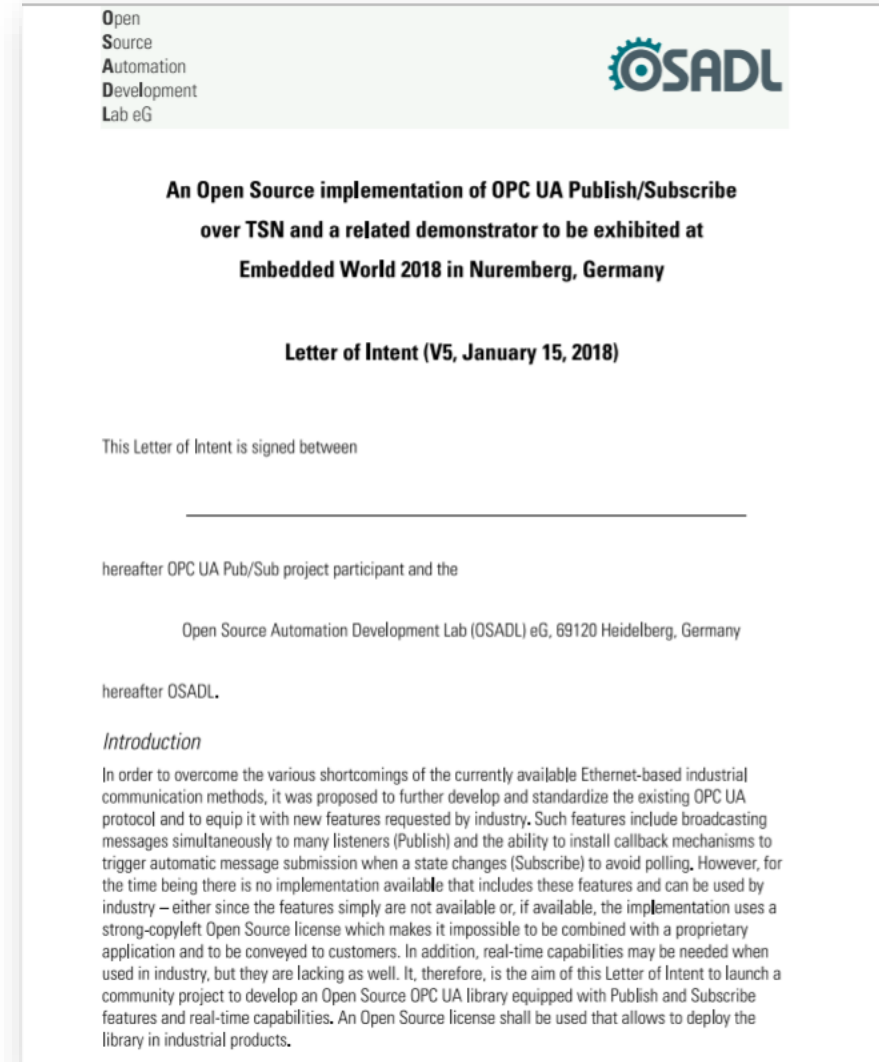
OPC UA Server Load : e.g. 5 Clients @ 10ms

msg per sec = 100 msg/sec (const)

# Deliverables

## LoI Phase #1

- Deliverables
  - Brokerless OPC UA PubSub with binary message encoding via IP multicast
  - Integration of the publisher in a regular OPC UA server with additional real time interrupting
  - Standalone subscriber
  - Integration of TBS in OPC UA Publisher to publish the packets at hard real time (nano second jitter)
  - First step of secure Client/Server communication
- The above deliverables were gradually merged in existing open62541 repository in April 2018




# Deliverables

## LoI Phase #2

- Deliverables
  - Integration of TSN functionalities with user defined time triggered send (ETF) in OPC UA Brokerless PubSub Ethernet communication
  - Improvement in the real-time (RT) capabilities of PubSub
    - Faster encoding and decoding – Encode and decode only the modifiable values (datasets, timestamps, sequence number, ...)
    - Introduction of external Datasource variable for the faster access of value nodes in the Information model
  - Certified SDK - The open62541 v1.0 (server\_ctt sample) is certified by the OPC Foundation regarding the 'Micro Embedded Device Server' profile
  - Alpha release of OPC UA PubSub Security Layer (SKS) & MQTT

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**Building an Open Source OPC UA/TSN Ecosystem**  
**Project phase #2: "Security & Certification"**  
**Letter of Intent, 2<sup>nd</sup> edition**  
**(V6, January 31, 2019)**

This Letter of Intent is signed between

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and the

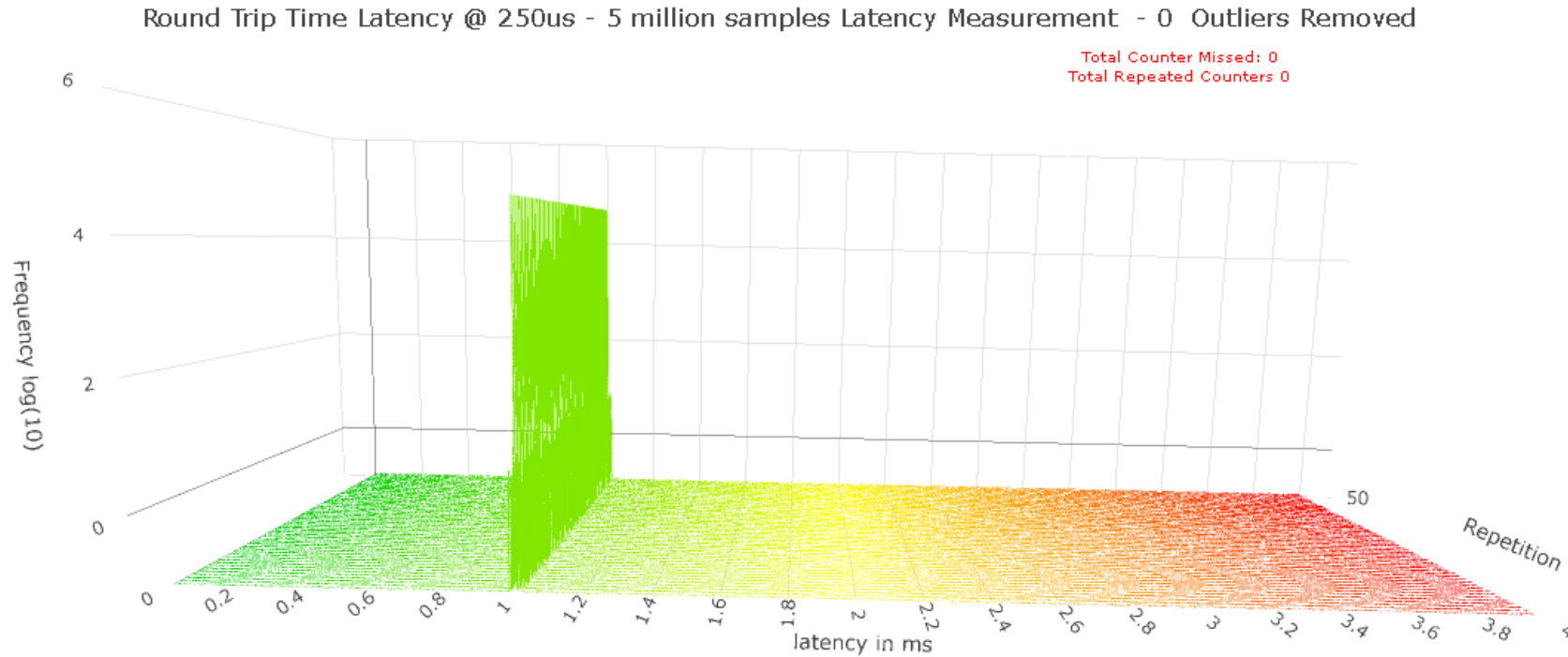
Open Source Automation Development Lab (OSADL) eG, 69120 Heidelberg,  
Germany

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*Introduction*  
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The next important evolution of OPC UA after having implemented the base technology were the Publish/Subscribe (PubSub) components to allow for a connection-less and, thus, resource saving communication suitable for the low-power devices that are expected to be used throughout the future Internet of Things. For this purpose, Fraunhofer IOSB in Karlsruhe, Germany, the India based system integrator Kalycito In-

# OPC UA PubSub Application

## Round Trip Time @ 250us cycle time – 5 million samples



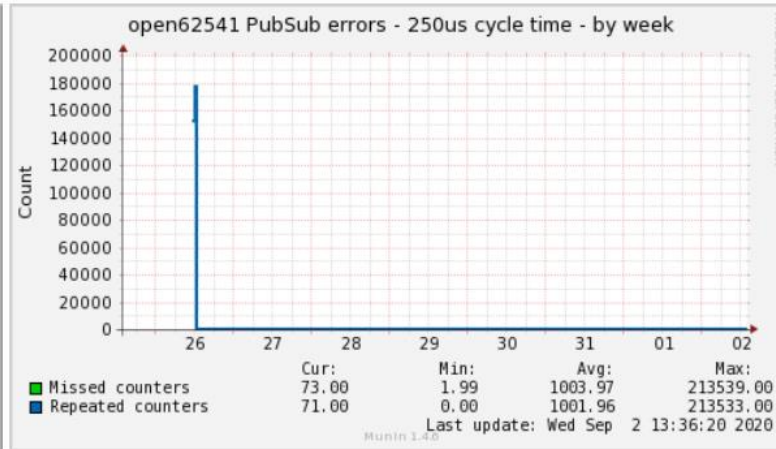
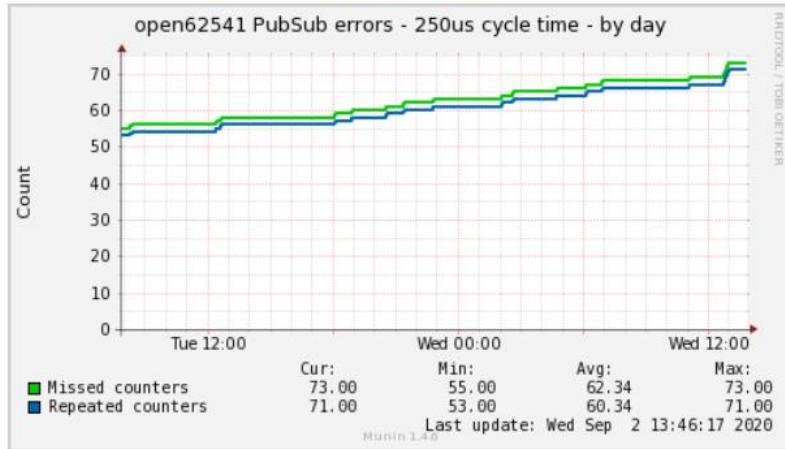
This shows the performance graph with Round Trip Time (RTT) of PubSub TSN Application running in peer to peer connected nodes with 250 microseconds cycle time for 5 million samples. It shows RTT is always 4\*cycle time as expected i.e. 1ms when configured at 250us



# OPC UA PubSub Application

Round Trip Time @ 250us cycle time – 24x7 results @ <http://munin.osadl.org>

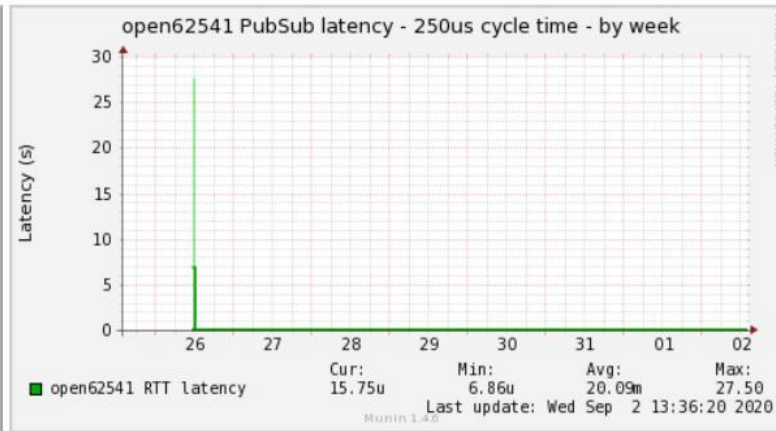
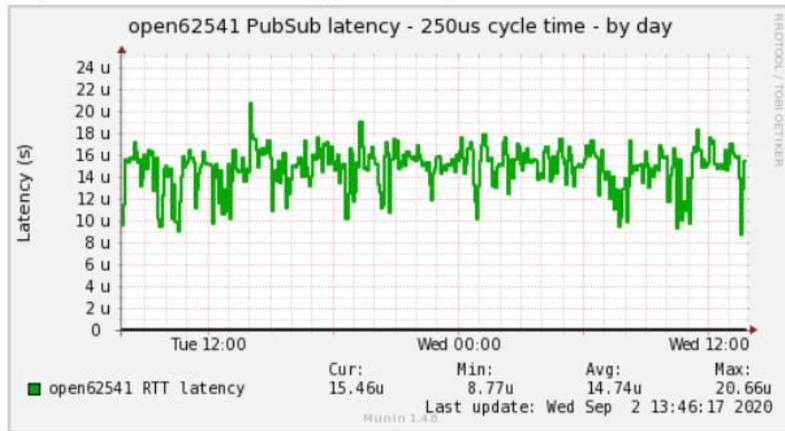
:: open62541 PubSub errors - 250us cycle time



Shows the two remaining bugs that we are working on as on 02-Sep-2020:

- Crash seen on 26<sup>th</sup> Aug
- Missed/repeated counters

:: open62541 PubSub latency - 250us cycle time



Next steps:

- Latest hardware and kernel
- Lower cycle times – 125, 62.5, 31.25
- More nodes in the network
- Simultaneous m2m and m2c
- Mixed traffic scenarios

# Results of the Lol#2 Project

## open62541 certification

- The open62541 v1.0 (server\_ctt sample) is certified by the OPC Foundation regarding the 'Micro Embedded Device Server' profile
- Support for the security policies 'Basic128Rsa15', 'Basic256' and 'Basic256Sha256' was added
- Based on our certified code base, the certification process for your products should be simplified
- The PubSub implementation can't be certified due to lack of official test cases

open62541

Github

Documentation

Community

Certified SDK

<https://open62541.org/certified-sdk>

### Certified SDK



The sample server (server\_ctt) built using open62541 v1.0 is in conformance with the 'Micro Embedded Device Server' Profile of OPC Foundation supporting OPC UA client/server communication, subscriptions, method calls and security (encryption) with the security policies 'Basic128Rsa15', 'Basic256' and 'Basic256Sha256' and the facets 'method server' and 'node management'.

PubSub (UADP) is implemented in open62541. But the feature cannot be certified at this point in time (Sep-2019) due to the lack of official test cases and testing tools.

open62541 is maintained by a community of developers and users. The certified release v1.0 was prepared by Fraunhofer IOSB and Kalycito Infotech with funding from an industry consortium via the Open Source Automation Development Lab (OSADL)

eG.

open62541 is developed and maintained by a community of contributors from a wide range of backgrounds. The certification is the result of the joint work of all contributors to open62541. The following organizations are mentioned explicitly for leading the certification effort on behalf of the overall community.





# Results of the Lol#2 Project

## Alpha Releases

- Initial release of early version implementations
  1. Publish/Subscribe Security (SKS)
  2. Publish/Subscribe over MQTT
  3. MQTT Security
  4. Multiple traffic classes/types
  5. Memory optimization using binary encoded node store

# Customer feedback after phases 1 and 2

Many major companies are now using open62541 for their products and many more are using it in their proof-of-concept activities. This can be inferred from the increased downloads, increased activity in the forums and use for joint prototyping activities in different standardization bodies. The following are the feedback from these companies, and this serves as the input for the next phase.

- Use case 1: When there is a new information model, today we have to recompile the binary. Most customers do want to recompile and want to reload the new information model along with the same binary.
- Use case 2: Customers would like to have multiple client/server event loops in the same application.
- Use case 3: Customer would like to have support for multithreading without breaking deterministic use cases.
- Use case 4: We are already certified for micro embedded device server profile and security. Customers want us to implement the full embedded profile and undergo certification for the same.
- Use case 5: More optimal solutions for bare metal and FreeRTOS targets.
- Use case 6: Tool concept and ecosystem of an OPC UA modeler.
- Use case 7: Tool concept and ecosystem of a Pub/Sub TSN configurator.

# Phase 3: Overview

# Why LOI3?

- After the successful completion of the project phases #1 and #2, there is now an Open Source licensed OPC UA SDK available to be used by industry to create a state-of-the-art OPC UA server that can be certified by OPC Foundation to adhere to the “micro embedded device server” profile.
- In addition, a PubSub implementation is available that allows using Virtual Local Area Network (IEEE 802.1Q) along with components of Time-Sensitive Networking (TSN) such as high-precision time synchronization (802.1AS) and time-aware traffic shaping (IEEE 802.1Qbv) to establish real-time communication via Ethernet.
- To further enhance the existing Open Source ecosystem software pool with the goal to make open62541 the single fully fledged state-of-the-art hard real-time successor of the wide variety of former real-time Ethernet communications systems, more features of the software itself and additional software components around the SDK are needed.
- It, therefore, was decided to launch phase #3 of the community project. Since it continues to primarily take care of base technologies, it addresses the various target groups (e.g. controller vendors, field device vendors, machine builders, end users) in the same way.

# The Letter of Intent Phase 3

## Subproject and priorities

- The project activities are divided into two different subprojects
  - Project #1: OPC UA specific developments
  - Project #2: Realtime Linux + TSN + OPC UA + PubSub + Support for new hardware + Technology demonstrator + Tools ecosystem

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### Building an Open Source OPC UA over TSN Ecosystem Project phase #3: "Scalability & Tool chain" Letter of Intent (V11, January 25, 2021)

This Letter of Intent is signed between

hereafter Open Source OPC UA over TSN Ecosystem participant or simply participant

and the

Open Source Automation Development Lab (OSADL) eG, Heidelberg,  
Germany

hereafter OSADL.

#### *Introduction and overview about previous project phases*

A rapidly growing number of companies and organizations is fostering the development of a standardized method for real-time network communication based on OPC UA as platform protocol and Time Sensitive Networking (TSN) as link layer. This broad interest has led to the open62541 project (<https://open62541.org/>). It was founded to provide an OPC UA implementation that can be freely copied and distributed under the Mozilla 2.0 Open Source license.

The next important evolution of OPC UA after having implemented the base technology were the Publish/Subscribe (PubSub) components to allow for a connection-less and, thus, resource saving communication suitable for the low-power devices that are expected to be used throughout the future Internet of Things. For this purpose, Fraunhofer IOSB in Karlsruhe, Germany, the India based system integrator Kalycito Infotech and the Open Source Automation Development Lab (OSADL) founded a joint interest working group. This group launched a community project and distributed a call for contributions in form of a Letter of Intent of project phase #1. This Letter of Intent was signed by the working group participants

- Heidelberger Druckmaschinen AG
- Kontron AG
- Linutronix GmbH
- Pilz GmbH & Co. KG
- SICK AG
- TQ-Systems GmbH

which resulted in sufficient funding to execute the project in addition to the contributions made by Fraunhofer IOSB, Kalycito Infotech and OSADL.

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Auditing association: Baden-Württembergischer Genossenschaftsverband e.V. · Location: Karlsruhe, Germany

# The Letter of Intent Phase 3

## Project #1: OPC UA specification development

- Parse server/client configuration from a text file
- Common event loop for multiple clients/servers
- Client multi-threading
- Implement the entire feature set of the “Full Embedded Profile” certification category as defined by OPC Foundation
- Undergo the regular OPC Foundation procedure to obtain certification for the “Full Embedded Profile”
- RAM/ROM optimizations for constrained devices (e.g., binary file node store) and tooling
- Custom memory manager (static memory allocation)

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# The Letter of Intent Phase 3

## Project #2: OPC UA Pub Sub + TSN ecosystem

- Security support for the PubSub UADP protocol
- Creating a new technology demonstrator using 11th Gen Intel Core processors with TSN capability based on the most recent Linux 5.x-rt
- Creating a new Quick Start Guide for OPC UA PubSub over TSN-capable realtime Linux that works out of the box
- Incorporating all software components that are needed to successfully follow the new Quick Start Guide boards using 11th Gen Intel Core processors with TSN capability in an image for virtualization and automatically executing a script with the Quick Start Guide commands when the image is booted

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# The Letter of Intent Phase 3

## Project #2: OPC UA Pub Sub + TSN ecosystem

- Testing and optimizing multicast real-time PubSub in a larger network with up to 16 nodes
- Architecture concepts/application design for PubSub time offsets and RT interrupting based on publishing offset, thread synchronization and wakeup latency of threads
- Generic interface to TSN
- Open Source tool concept and ecosystem of an OPC UA modeler
- Open Source tool concept and ecosystem of a Pub/Sub TSN configurator
- Represent PubSub over TSN configuration in the OPC UA information model as per the latest FLC specification

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Auditing association: Baden-Württembergischer Genossenschaftsverband e.V. · Location: Karlsruhe, Germany

# The Letter of Intent Phase 3

## Project funding and management

- The project will be managed in form of a so-called OSADL mixed-funded project, i.e. a subgroup of OSADL members and non-members is formed who contribute to the project.
- Project management, software development and testing provided by OSADL is partly funded by the project and partly provided from the regular annual OSADL budget while employing existing office and laboratory infrastructure.

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### Building an Open Source OPC UA over TSN Ecosystem Project phase #3: "Scalability & Tool chain" Letter of Intent (V11, January 25, 2021)

This Letter of Intent is signed between

hereafter Open Source OPC UA over TSN Ecosystem participant or simply participant

and the

Open Source Automation Development Lab (OSADL) eG, Heidelberg,  
Germany

hereafter OSADL.

#### *Introduction and overview about previous project phases*

A rapidly growing number of companies and organizations is fostering the development of a standardized method for real-time network communication based on OPC UA as platform protocol and Time Sensitive Networking (TSN) as link layer. This broad interest has led to the open62541 project (<https://open62541.org/>). It was founded to provide an OPC UA implementation that can be freely copied and distributed under the Mozilla 2.0 Open Source license.

The next important evolution of OPC UA after having implemented the base technology were the Publish/Subscribe (PubSub) components to allow for a connection-less and, thus, resource saving communication suitable for the low-power devices that are expected to be used throughout the future Internet of Things. For this purpose, Fraunhofer IOSB in Karlsruhe, Germany, the India based system integrator Kalycito Infotech and the Open Source Automation Development Lab (OSADL) founded a joint interest working group. This group launched a community project and distributed a call for contributions in form of a Letter of Intent of project phase #1. This Letter of Intent was signed by the working group participants

- Heidelberger Druckmaschinen AG
- Kontron AG
- Linutronix GmbH
- Pilz GmbH & Co. KG
- SICK AG
- TQ-Systems GmbH

which resulted in sufficient funding to execute the project in addition to the contributions made by Fraunhofer IOSB, Kalycito Infotech and OSADL.

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# The Letter of Intent Phase 3

## Contribution levels

Contribution Level	OSADL Member (EUR)	Non-Members (EUR)
Silver	5,000	7,500
Gold	10,000	15,000
Platinum	20,000	30,000
Diamond	30,000	45,000

### Project assignment and participative project management

Selection (please tick)	Project #1: OPC UA specific developments	Project #2: Realtime Linux + TSN + OPC UA + PubSub + Support for new hardware + Technology demonstrator + Tools ecosystem
<input type="checkbox"/>	100 %	0 %
<input type="checkbox"/>	75 %	25 %
<input type="checkbox"/>	50 %	50 %
<input type="checkbox"/>	25 %	75 %
<input type="checkbox"/>	0 %	100 %

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# The Letter of Intent Phase 3

## Benefit of various contribution levels

Contribution level	Logo display and listed as contributor	Certification assistance	Number of votes when deciding on the development priority of components
Silver	yes	no	1
Gold	yes	no	2
Platinum	yes	yes	4
Diamond	yes	yes	6

The Diamond contribution provides the privilege on adding the company's hardware or software components as part of the technology demonstrator that is built.

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# The Letter of Intent Phase 3

## Overall budget and schedule

- The overall budget to provide the below given software components is estimated to amount to about 120,000 euros.
- However, the project will already be launched when and if a minimum funding threshold of 30,000 euros will have been reached.
- If this also is the final budget, the low-priority and some of the other below given software components will only have a partial or even rudimentary or no implementation at all.
- The more budget will be available, the more software components will be developed and reach production quality. It, therefore, is expected that project participants will also join in after the start of the project which will be possible during its entire duration.

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**Building an Open Source OPC UA over TSN Ecosystem  
Project phase #3: "Scalability & Tool chain"  
Letter of Intent (V11, January 25, 2021)**

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Phase 3: For more Information

Visit: <https://www.osadl.org/OPCUA-Project>

# Open Source Resources



# Quick Start Guide

Running OPC UA stack open62541

https://www.kalycito.com/how-to-run-opc-ua-open62541-with-realtime-p

**TEST SETUP**

Image below shows the test setup followed to run the PubSub application

**PEER TO PEER NETWORK**

**SWITCH NETWORK**

You can follow either of the above listed network to run the application

**STEPS TO RUN OPC UA PUBSUB APPLICATION**

Clone the open62541 stack with the following command

```
git clone https://github.com/open62541/open62541.git
```

Image attached below shows the overview of the target applications

## How to run OPC UA stack open62541 with Realtime PubSub on Realtime Linux and TSN using Intel i210 ethernet card

This quick start guide serves as a starting point for a user in learning/evaluating OPC UA including TSN technology for their products/projects.

This quick start guide uses “Open Source OPC UA stack open62541 with Pub/Sub feature” and leverages the TSN features available on “standard Linux kernel + PREEMPT\_RT patches” on an X86 PC hardware with intel i210 Ethernet Card.

The initial release of the quick start guide may not have worked on all platforms, but the most recent version repeatedly and successfully underwent test runs of more than 24 hours duration.

<https://www.kalycito.com/how-to-run-opc-ua-open62541-with-realtime-pubsub-on-realtime-linux-and-tsn-from-source/>

# Whitepaper

## Real-time Open Source Solution for Industrial Communication Using OPC UA PubSub over TSN

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**Abstract**—The world is moving in a direction where any future Industry 4.0 device shall support Open Source Industrial Communication (OPC UA) as a platform independent, service-oriented modeling framework to achieve interoperability through a vendor neutral standard. There is general alignment among different industry players to leverage OPC UA along with emerging time aware Ethernet standard Time Sensitive Networking (TSN) for seamless connectivity between different Industry 4.0 devices (spanning from sensor to cloud). The OPC UA Publisher/Subscriber (Pub/Sub) standard together with TSN standards will enable deterministic real-time networking capabilities that is far ahead proprietary systems. TSN is expected to be established as a standard with wide availability of network interfaces chips in two years from now.

In this whitepaper, the requirements for such Industry 4.0 devices are extracted from the scenarios described in the IEC/IEEE 60802 TSN Profile for Industrial Automation, implemented and tested using Open Source Software components. The performance measurements in this whitepaper focus on industrial communication traffic as specified in the IEC/IEEE 60802 documents while other traffic types according to IEC/IEEE 60802 are still present in the network for the purpose of recreating load conditions similar to actual application use cases.

This whitepaper improves the results from the previous whitepaper of the same name and will help OEMs looking at technology readiness aspects for adoption into their products and services.

**Keywords**—Industry 4.0, IEC, IEC, OPC UA, TSN

### I. INTRODUCTION

Prior to Industry 4.0, manufacturers and users of automation components such as sensors, drives and PLCs were predominantly using a variety of different fieldbus industrial communication standards that are not interoperable (analog signaling before moving to digital fieldbus protocols such as Modbus, Profibus, DeviceNet over physical medium such as RS485, CAN, etc for the last 40 years).

Since the last 10 years, there are multiple Ethernet based communication protocols promoted by different PLC vendors in the market. This has created a fragmented ecosystem where device manufacturers constantly face additional costs to support as many protocols as possible in their automation products. This also prevents

### TSN STANDARDS

Standard	Description
IEEE 802.1AS	Timing and Synchronization for Time Sensitive Applications
IEEE 802.1AS-01	IEEE 802.1AS which is more relevant for industrial applications in real-time environment
IEEE 802.1Q	Forwarding and Queuing Mechanisms for Time-Sensitive Streams
IEEE 802.1Qbb and IEEE 802.1Qbr	Frame Preemption
IEEE 802.1Qbu	Enhancements for Scheduled Traffic
IEEE 802.1Qca	Path Control and Reservation

The performance measurements in this whitepaper focus on industrial communication traffic while other traffic types according to IEC/IEEE 60802 are still present in the network for the purpose of recreating load conditions similar to application use cases that are relevant in actual end-user use cases. This is also the first version of the whitepaper prepared after the integration of fully featured implementation of the subscriber part. This is also the first time that the Fast Path Message (FPM) optimization is included in the publisher part of OPC UA PubSub.

### III. TEST SETUP

#### A. Hardware setup



Figure 1: Hardware setup for performance measurements

The hardware setup consists of two quad-core Atom processor systems with 1210 network interface cards connected via PCs. Both the systems are connected port to port with an Ethernet cable at a link speed of 1 Gbps.

#### B. Software setup

All the software packages used in the system are open source and available to download from the respective developer forums. Linux OS is used for the publisher part. The publisher part is implemented using the IEC/IEEE 60802 TSN Profile for Industrial Automation, implemented and tested using Open Source Software components. The performance measurements in this whitepaper focus on industrial communication traffic as specified in the IEC/IEEE 60802 documents while other traffic types according to IEC/IEEE 60802 are still present in the network for the purpose of recreating load conditions similar to actual application use cases.

While OPC UA can address this at higher layers, it cannot by itself guarantee deterministic real-time data transfer  $\Rightarrow$  a typical requirement for field level devices. In such a scenario, TSN is an IEEE 802.1 standard that is fast emerging as the upgrade to the IEEE 802.3 Ethernet standard capable of delivering deterministic, real-time performance at the layer 2 - data link. Going up to the higher layers, IEC 62541 OPC UA is fast emerging as the application data modeling standard to enable interoperable data exchange between devices, systems and applications.

Table 1 lists the related TSN standards both released and under development for industrial, industrial and automotive use cases. This paper is focusing on the time synchronization standard IEEE 802.1AS and scheduled traffic IEEE 802.1Qbu that are important for industrial use cases. The configuration standard IEEE 802.1Qc is an important topic for interoperability but is beyond the scope of this paper.

### SOFTWARE PACKAGE INFORMATION

Software package	Version
Linux OS	Ubuntu 18.04.3, Kernel 4.19.37-rt19
Linux RT	OPC 2.0
OPC UA stack	opcua4j, opcua4j-rt, opcua4j-rt-rt
OpenSSL	1.1.1

### IV. REAL-TIME PERFORMANCE

The deterministic real-time performance (max latency or worst-case latency) of the system is measured using the *eggsalot* application. *Eggsalot* consists of a main task that initially starts a number of child tasks. The latter start cyclic alarms using a real-time capable timer at a given interval and eventually stop for the expiration of the timer. When a timer expires the current time is obtained and compared to the theoretically expected wake-up time. The difference that represents the inability of the system to exactly wake up in time, but a little later represents the so-called system latency. If the measurement is repeated frequently enough and under as many conditions as possible, the longest latency ever obtained may be used to describe a system's worst-case latency.

Figure 4b shows the results of the PTP accuracy measurement between the two nodes over a period of 12 hours; the observed clock offset is in the range of  $\pm 1.2$  ns to  $\pm 1.2$   $\mu$ s end, thus, close to the performance that is theoretically achievable.

#### C. PTP hardware clock to system clock synchronization

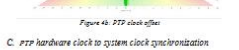


Figure 4b: PTP clock offset

The system clock is used by most user-space applications hence the system clock needs to be synchronized between nodes on the network. This can be achieved by synchronizing the system clock with the PTC by using the *ph2psync* utility.

#### D. ph2psync accuracy on Master System (Node 1)



Figure 5: ph2psync accuracy on Master System (Node 1)

#### E. ph2psync accuracy on Slave System (Node 2)

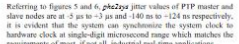


Figure 6: ph2psync accuracy on Slave System (Node 2)

Referring to figures 5 and 6, *ph2psync* jitter values of PTP master and slave nodes are at  $\pm 5$  ns to  $\pm 5$   $\mu$ s and  $\pm 10$  ns to  $\pm 12$  ns respectively. It is evident that the system can synchronize the system clock to hardware clock at single-digit microsecond range which matches the requirements of most, if not all, industrial real-time applications.

### V. PUBLISH-NETWORK PERFORMANCE

Once the PTP synchronization was established and was verified to work accurately, the next step was to test the OPC UA PubSub application. In this case, OPC UA PubSub application was configured to publish Ethernet packets at 100  $\mu$ s cycle time. One of the main factors that affect the performance is the jitter we experience to place the packet in the network. Figures 7 and 8 show the jitter performance of the OPC UA PubSub application for 1 million samples without PTP and with PTP respectively. It must be noted that the cycle time needs to be a multiple of 31.25 ns i.e. 125  $\mu$ s. We

Note: T3 denotes packets captured at Node 2 (for packets transmitted from Node 1). T7 denotes packets captured at Node 1 (for packets transmitted from Node 2).

Figure 9b is similar to 9a except that it shows only best effort ping traffic (leaving out the six other types of traffic) along with time critical OPC UA PubSub traffic that is always placed at the intended time in the beginning of the second window.

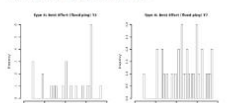


Figure 9a: Histogram showing the distribution of time critical OPC UA PubSub traffic

Figure 9b illustrates only the time critical OPC UA PubSub traffic for a clearer view when compared with 9a and 9c.

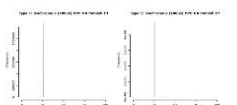


Figure 9b: Histogram showing the distribution of time critical OPC UA PubSub traffic

Figure 10 illustrates only the time critical OPC UA PubSub traffic for a clearer view when compared with 9a and 9c.

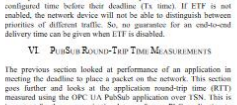


Figure 10: Histogram showing the distribution of time critical OPC UA PubSub traffic

Figure 11 illustrates only the time critical OPC UA PubSub traffic for a clearer view when compared with 9a and 9c.



Figure 11: Histogram showing the distribution of time critical OPC UA PubSub traffic

Figure 12 shows a scenario where there is sensor value change just after the application control loop sends the sensor inputs. In this case, the change will be available to the application control loop only after one cycle delay i.e. until the application control loop executes in the next cycle.



Figure 12: Sensor value change just after the application control loop sends the sensor inputs

Note: On both nodes, Core 0 is made entirely available for OS and kernel. Core 1 is entirely reserved to run PTP to maintain time synchronization. Core 2 is used for running OPC UA PubSub application. Core 3 is used for any specific real-time applications. Network loads (i.e. multiple load on Apache, sftp, OPC UA Client/Server) are run on Core 0 in this test setup which is a four-core system in which Cores 1, 2 and 3 are reserved as described above.

Figure 13 shows a scenario (in addition to the one cycle delay introduced in figure 12) where the application loop takes longer to complete execution (than the configured application safety margin) and introduces one more cycle of delay. This means the data finally

# Based on IEEE 60802 use-cases...

If we know the max latency of our system (from *eggsalot* results) and also the time spent in the locks inside each thread involved in publish, subscribe and application control loop as well as the priorities of each thread, it is possible to compute the application safety margin and the transfer safety margin. Then it will be possible to configure the maximum values for application safety margin and transfer safety margin and guarantee the deadline in the ideal scenario as shown in figure 11.



Figure 11: Ideal Scenario - Deterministic Publish Latency

However, it should be noted that this may mean the network cycle time is not the smallest possible value. Also, the final goal is to provide the lowest possible deterministic deadline for end-to-end transfer of data and not merely providing a very low number for the lowest possible network cycle time. In this paper, we are trying to achieve the lowest possible network cycle time and also commit on the worst-case deterministic deadline for end-to-end transfer of data in the lowest possible network cycle time as we see that in the most common cases are expected to take. For example, figures 12 and 13 additionally show the practical and worst-case scenarios that can occur for an implementation that is based on the design in figure 11.

Figure 12 shows a scenario where there is sensor value change just after the application control loop sends the sensor inputs. In this case, the change will be available to the application control loop only after one cycle delay i.e. until the application control loop executes in the next cycle.



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Figure 13 shows a scenario (in addition to the one cycle delay introduced in figure 12) where the application loop takes longer to complete execution (than the configured application safety margin) and introduces one more cycle of delay. This means the data finally

value to be available at the application control loop of node 1. Therefore, it will take  $1+1+1+1+1+1+1+1$  cycles for the worst-case round-trip of the counter value to complete.

With the above design and the worst-case latency possible from it, we tried to configure the minimum possible application safety margin and transfer safety margin and a very low cycle time (say where the measured max latency was 34  $\mu$ s, we were configuring the network cycle time to be 100  $\mu$ s = a value that looks impractical to work). However, we measured the maximum RTT in 1 million samples for a payload size of 100 bytes when XDP was disabled in the receiver side, to be 340  $\mu$ s as shown in figure 15. We found a packet miss of about 30% in a total of 1 million samples.

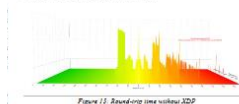


Figure 15: Round-trip time measurement in 25 us

When XDP was enabled in the OPC UA Subscriber, the maximum RTT in 1 million samples for a payload size of 100 bytes was measured to be 701  $\mu$ s as shown in figure 16. The packet miss was 7% in a total of 1 million samples.

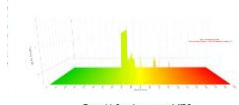


Figure 16: Round-trip time with XDP

This shows that when XDP is used with the OPC UA Subscriber, the performance was increased to about 25%. The above measurements were taken under normal load conditions in which realistic CPU and network loads were applied to both the nodes. The CPU load was about 30% utilization on each of the four cores. Realistic network loads were created using Apache, sftp and OPC UA Client/Server traffic.

Note: On both nodes, Core 0 is made entirely available for OS and kernel. Core 1 is entirely reserved to run PTP to maintain time synchronization. Core 2 is used for running OPC UA PubSub application. Core 3 is used for any specific real-time applications. Network loads (i.e. multiple load on Apache, sftp, OPC UA Client/Server) are run on Core 0 in this test setup which is a four-core system in which Cores 1, 2 and 3 are reserved as described above.

Figure 17 shows a scenario (in addition to the one cycle delay introduced in figure 12) where the application loop takes longer to complete execution (than the configured application safety margin) and introduces one more cycle of delay. This means the data finally



Figure 17: Sensor value change just after the application control loop sends the sensor inputs

Note: On both nodes, Core 0 is made entirely available for OS and kernel. Core 1 is entirely reserved to run PTP to maintain time synchronization. Core 2 is used for running OPC UA PubSub application. Core 3 is used for any specific real-time applications. Network loads (i.e. multiple load on Apache, sftp, OPC UA Client/Server) are run on Core 0 in this test setup which is a four-core system in which Cores 1, 2 and 3 are reserved as described above.

Figure 18 shows a scenario (in addition to the one cycle delay introduced in figure 12) where the application loop takes longer to complete execution (than the configured application safety margin) and introduces one more cycle of delay. This means the data finally



Figure 18: Sensor value change just after the application control loop sends the sensor inputs

Note: On both nodes, Core 0 is made entirely available for OS and kernel. Core 1 is entirely reserved to run PTP to maintain time synchronization. Core 2 is used for running OPC UA PubSub application. Core 3 is used for any specific real-time applications. Network loads (i.e. multiple load on Apache, sftp, OPC UA Client/Server) are run on Core 0 in this test setup which is a four-core system in which Cores 1, 2 and 3 are reserved as described above.

Figure 19 shows a scenario (in addition to the one cycle delay introduced in figure 12) where the application loop takes longer to complete execution (than the configured application safety margin) and introduces one more cycle of delay. This means the data finally

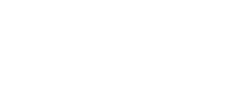


Figure 19: Sensor value change just after the application control loop sends the sensor inputs

run next steps involve improving the stability and reducing the network cycle time to achieve better performance at cycle time lower than 250  $\mu$ s.

### VII. KNOWN CHALLENGES & NEXT STEPS

The above measurements were made in a test setup that used OPC UA PubSub packets with 100-byte payload size of 100  $\mu$ s application of network cycle time. When we shortened the cycle time, the several occurrences of data application or data loss (i.e. counter does not reporting or missed respectively) was minimum in XDP registered Subscriber than that of the Subscriber without XDP.

Figure 20 shows the Round-trip time measured with 100-byte payload size at 31.25  $\mu$ s application cycle time and network cycle time measured in 1.6GHz Intel Atom processor PCs shows a total missed number occurrence of 2.5 million in a total of 5 million samples. By registering just in Time compilation (RT) and XDP transmit in the publisher side along with the XDP ZC in the subscriber we can reduce this existing performance further than achieving the duty standard 31.25  $\mu$ s at network cycle time in 1.6 GHz Intel Atom successor PCs thus enabling the solution to run in current loop applications.

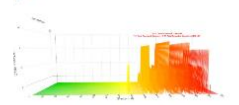


Figure 20: Round-trip time measurement in 31.25 us

As market requirements expects the number of Industry 4.0 devices (the test network shall be increased and each of the devices shall be configured to publish more packets as well as subscribe to a larger number of publishers). The impact of OPC UA Client/Server changes in the volume (i.e. number) applied to the same nodes in the formation model for both PubSub and Client/Server needs to be understood. The performance impact introduced due to using security (both Client/Server and PubSub shall also be explored). There is so the possibility to achieve more real-time performance in 1 ms to meet the network cycle time further. The design calculation need to give at the number '9' can be promised as the deterministic

### ACKNOWLEDGMENT

We would like to thank the industry consortium supporting a joint project for developing the PubSub extension for the open2541 OPC UA SDK. Special thanks go to Carsten Fiedler of the pro Service Automation Development Lab (PSADL) for assistance setting up the real-time systems and to Julius Pfriemmer of Transponder RM for providing continuous support on the open2541 stack development and maintenance.

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<https://www.kalycito.com/how-to-run-opc-ua-open62541-with-realtime-pubsub-on-realtime-linux-and-tsn-from-source/>

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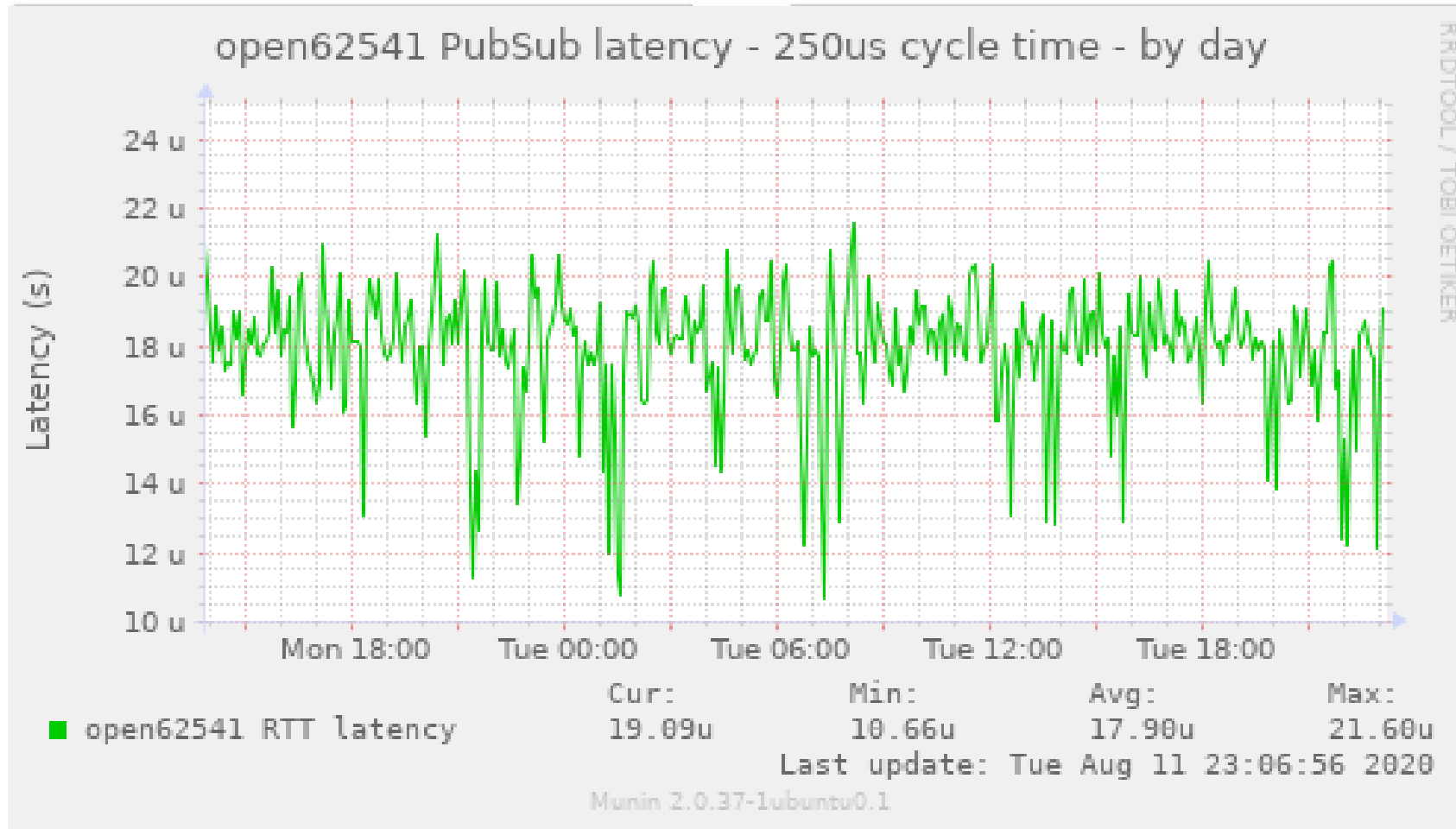
## 24x7 Demonstrator @ OSADL

- OSADL primarily defines the criteria for real-time Linux and focuses on benchmarking the identified kernel in different processors using a Quality Assurance (QA) farm.
- The tests are performed in the systems hosted in the QA farm on OSADL Test Racks in several OSADL testing labs to monitor the systems under stress test.
- One pair of real-time verified nodes (latency value < 70us in cyclicttest results) is used to run OPC UA Publisher/Subscriber over TSN application at 250us cycle time and the round trip time latency of the application is monitored for 24\*7. (<https://www.osadl.org/?id=3394>)



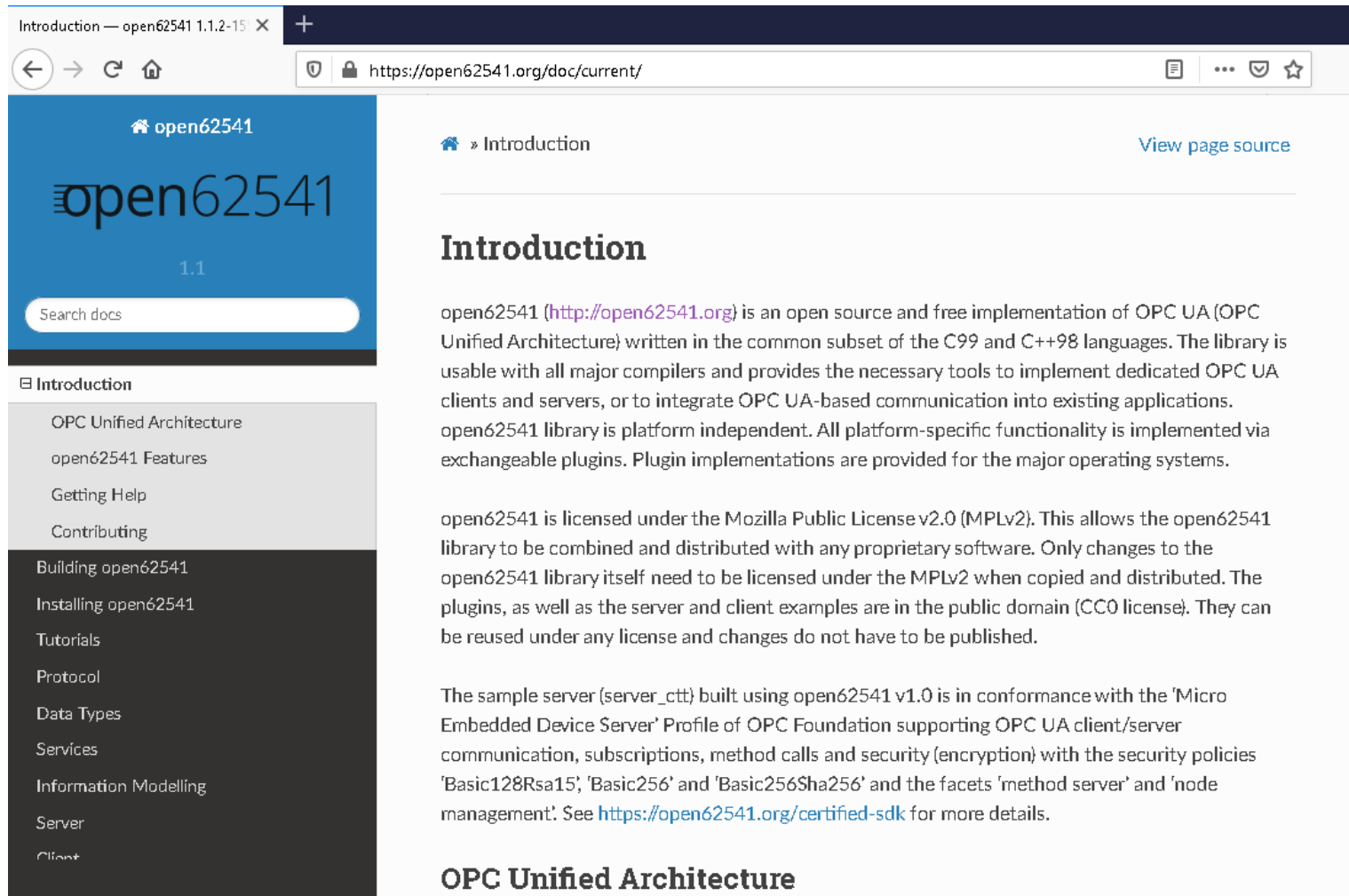
# OPC UA PubSub TSN Application

## Round Trip Time Results – 24 \* 7



This shows the performance graph with Round Trip Time (RTT) of PubSub TSN Application running in peer to peer connected nodes with 250 microseconds cycle time.

# open62541 documentation



The screenshot shows a web browser displaying the open62541 documentation page. The browser's address bar shows the URL <https://open62541.org/doc/current/>. The page features a blue header with the open62541 logo and version 1.1. A search bar is located below the header. On the left side, there is a navigation menu with the following items: Introduction (selected), OPC Unified Architecture, open62541 Features, Getting Help, Contributing, Building open62541, Installing open62541, Tutorials, Protocol, Data Types, Services, Information Modelling, Server, and Client. The main content area is titled 'Introduction' and contains the following text:

open62541 (<http://open62541.org>) is an open source and free implementation of OPC UA (OPC Unified Architecture) written in the common subset of the C99 and C++98 languages. The library is usable with all major compilers and provides the necessary tools to implement dedicated OPC UA clients and servers, or to integrate OPC UA-based communication into existing applications. open62541 library is platform independent. All platform-specific functionality is implemented via exchangeable plugins. Plugin implementations are provided for the major operating systems.

open62541 is licensed under the Mozilla Public License v2.0 (MPLv2). This allows the open62541 library to be combined and distributed with any proprietary software. Only changes to the open62541 library itself need to be licensed under the MPLv2 when copied and distributed. The plugins, as well as the server and client examples are in the public domain (CC0 license). They can be reused under any license and changes do not have to be published.

The sample server (server\_ctt) built using open62541 v1.0 is in conformance with the 'Micro Embedded Device Server' Profile of OPC Foundation supporting OPC UA client/server communication, subscriptions, method calls and security (encryption) with the security policies 'Basic128Rsa15', 'Basic256' and 'Basic256Sha256' and the facets 'method server' and 'node management'. See <https://open62541.org/certified-sdk> for more details.

**OPC Unified Architecture**

This open62541 documentation page serves as a starting point for a user in learning OPC UA technology using open62541 for their products/projects.

<https://open62541.org/doc/current/>

# open62541 forum support

open62541 / open62541

<> Code **Issues** 373 Pull requests 73 Actions Wiki Security Insights

Filters

373 Open ✓ 1,483 Closed

**Memory not properly handled in UA\_Server\_newWithConfig**

#3853 opened 6 hours ago by cochicde 0 of 7

**OPCUA PubSub over AMQP**

#3849 opened 2 days ago by waheedejaz 0 of 7

**PubSub Unit Tests' Usage of UA\_Server\_run\_iterate doesn't reliably process all needed callbacks**

#3835 opened 13 days ago by jmachauer-codewerk 0 of 7

**Maximum client connection**

#3833 opened 13 days ago by kusumy 0 of 7

**ValueRank of -2 (Any) not compatible with a ValueRank of -1 (Scalar) on base type**

#3826 opened 15 days ago by mgroenhoff 3 of 7

This forum exhibits active collaboration and support in improving open62541 stack.

<https://github.com/open62541/open62541/issues/new>



# Help us help you

## Its easy, just a few steps

- 1) Print the LOI document - OSADL-OPC-UA-TSN-Open-Source-Ecosystem-LoI-Phase-3-V11.pdf
- 2) Choose the contribution level in page 8
- 3) Choose the split between Project #1 and Project #2 in page 8
- 4) Sign the document (page 8)
- 5) Send it to [office@osadl.org](mailto:office@osadl.org)