Rail to Digital automated up to autonomous train operation

D23.3 – List of Solution Candidates

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EXECUTIVE SUMMARY

The present document constitutes the Deliverable D23.3 "List of Solution Candidates" in the framework of ERJU's Innovation Pillar Flagship Project R2DATO WP23 T23.3.

The deliverable is the third of a series of deliverables leading to a proposal for the next TSI 202x (after the release of that deliverable) for the future common onboard communication network specified in SUBSET-147 [1].

In the task T23.3 related to this deliverable D23.3 various candidates of existing communication etechnologies on the OSI Layers 3 to 6 and partly on the safety layer were investigated.

The elaboration is made for the main fields of requirements in determinism, safety, bandwidth (gross data rate), openness and maturity. The list of solution candidates were: TRDP, PROFINET, CIP, OPC UA, DDS/RTPS, MQTT, AMQP, ROS/ROS2 and SOME/IP.

The pre-selected solution candidates were jointly elaborated and carefully aligned among all members of the work package. As a conclusion three solution candidates were defined. They all fulfil the core requirements and are most promising to fulfil the residual system requirements as well. The solution candidates are:

- TRDP according to IEC/EN 61375-2-3 [4]
- OPC UA PubSub according to IEC 62541
- DDS/RTPS according to DDSI-RTPS [5]

The pre-selected solution candidates will be assessed in detail requirement by requirement of D23.2 [3] in the following step.

ABBREVIATIONS AND ACRONYMS

AMQP	Advanced Message Queuing Protocol
ATC	Automatic Train Control
ATO	Automatic Train Operation
CCS	Control, Command and Signalling
CIP	Common Industrial Protocol
COTS	Commercial off-the-shelf
DDS	Data Distribution Service
ECN	Ethernet Consist Network
ERA	European Railway Agency
ERJU	Europe’s Rail Joint Undertaking
ETB	Ethernet Train Backbone
FRMCS	Future Rail Mobile Communication System
HW	Hardware
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
MAC	Media Access Control
MQTT	Message Queuing Telemetry Transport
OCORA	Open CCS On-board Reference Architecture
ODVA	Open DeviceNet Vendors Association
OPC UA	Open Platform Communications Unified Architecture
OSI	Open Systems Interconnection
PROFINET	Process Field Network
PoC	Proof of Concept
QoS	Quality of Service
R2DATO	Rail to Digital automated up to autonomous train operation
ROS	Robot Operating System
RPC	Remote Procedure Call
RTPS	Real-Time Publish Subscribe
SDT	Safe Data Transmission
SIL	Safety Integrity Level

SOME/IP	Scalable Service-Oriented Middleware over IP
SW	Software
TCMS	Train Control and Management System
TCN	Train Communication Network
TCP	Transmission Control Protocol
TRDP	Train Real-Time Protocol
TRL	Technical Readiness Level
TSI	Technical Specification of Interoperability
TWG	Topical Working Group
UDP	User Datagram Protocol
WP	Work Package

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1 INTRODUCTION

The present document constitutes the Deliverable D23.3 “List of Solution Candidates” in the framework of ERJU’s Innovation Pillar Flagship Project R2DATO WP23 T23.3.

A modular and upgradeable next-generation automatic train control (ATC) asks for a seamless communication among on-train domains. The new on-board communication network (aka One Common Bus), as started in the ERA TWG Modular Architecture, will be a big step forward in that direction. Starting from the CCS and FRMCS systems, it will offer further separated logical domains for TCMS and the operator to use the same (physical) network.

The work of the ERA TWG Modular Architecture resulted in the SUBSET-147 v1.0.0 [1] being part of the current TSI 2023 release. It specifies the future harmonised communication backbone for the on-board CCS subsystems (like ETCS on-board, ATO on-board, FRMCS, etc.). The first stage of the specification of the communication backbone contains the definition of OSI-layers 1 and 2 in the SUBSET-147 v1.0.0 [1]. A common Ethernet CCS consist network has to be established in newly developed vehicles. For the higher OSI-layers 3 to 6 the three possible communication technology protocols TRDP, OPC-UA and PROFINET are currently specified.

In the first phase of EU-RAIL, the focus is on foundations for the onboard communication network building upon and substantially extending the prior work from CONNECTA and OCORA beyond TCMS and CCS and also toward higher protocol layers. Overall the project strives for a TRL of 4/5 (technology validated in a lab setup that represents practical train deployments). For higher TRLs the later phases of the projects will be used.

The aim of the work package WP23 is to specify a dedicated set of protocols on the OSI-layers 3 to 6 for the next TSI revision. With this specification the future onboard communication backbone is harmonized which paves the way for future modularization and upgradability of the CCS and other domains.

This deliverable is the third of a series of deliverables leading to a proposal for the next TSI 202x (after the release of that deliverable) for the future common onboard communication network.

To shape and guide the technical specification of WP23 and later WP24, WP23 takes a top-down approach first. This means:

- The WP’s work starts from the application and stakeholder perspective to first define scope and cornerstones of the future work (top level view). Main deliverable here is as a comprehensive set of user stories (see deliverable WP23-D23.1).
- Based on the user stories as guiding input, a set of system requirements for the communication functionality has been derived (see deliverable WP23-D23.2 [3]).
- In the task T23.3 related to this deliverable D23.3 various candidates of existing communication technologies on the OSI Layers 3 to 6 and corresponding safety layer were investigated and roughly checked against the core requirements (see chapter 2). As a conclusion of the first investigation three solution candidates were defined. They all fulfill the core requirements and are the most promising to fulfill the residual system requirements as well (see chapter 2.10).
- The solution candidates will then be assessed in detail requirement by requirement in a following step. Based on that a harmonized communication backbone will be specified in the next deliverable D23.4.

- Later WP24 will start from the user stories in the first WP23 deliverable and concentrate on the technical management functionality and associated processes. By using the common user stories both WP23 and WP24 share the same scope, thus leading to matching specifications.

2 ELABORATION OF SOLUTION CANDIDATES

This chapter 2 shortly describes various possibilities of existing communication technologies on session/presentation layer (OSI-layer 5 or 6). For simplicity the term session layer is used for a combination of session and presentation layer. With the session layer the OSI-Layers 3 to 4 are implicitly defined. All communication technologies have to be based on standard Ethernet data link layer as defined in SUBSET-147 v1.0.0 [1]. The possible communication technologies were investigated and roughly checked against nine core requirements. The core requirements were derived from the requirements list of D23.2 [3] due to the first main goal of the specification enhancement in the next version of the SUBSET-147 v2. This is the specification of an open standard Ethernet based communication protocol stack supporting safe process data communication. This allows to have a common communication infrastructure for all the application data specified in different SUBSETs of today's ETCS specification. The core requirements are listed up in the following table.

ID(s)	Title	Requirement
ComStackReq-Func-07	Determinism	The communication infrastructure technology stack shall enable train-local real-time data exchange for process data. (Latency ≤ 10ms, Jitter ≤ 10 ms)
ComStackReq-NonFunc-15	Safety	The communication infrastructure technology stack shall support the implementation of safety layers for functions with safety requirements up to SIL 4.
ComStackReq-NonFunc-34	Bandwidth	The communication infrastructure technology stack shall support a minimum link speed of 1 Gbit/s on all shared links.
ComStackReq-NonFunc-24	Openness	The communication infrastructure technology stack shall be based on publicly available and open standards, developed by a transparent and standardized process.
ComStackReq-NonFunc-42 to ComStackReq-NonFunc-46	Maturity	The communication infrastructure technology stack shall… … make use of functionality that is available on the market. … make use of solutions that are available from multiple vendors. … make use of proven technology. … use components that are available in significant quantities. … be supported by a community approach.

Table 1: Core Requirements on higher Layer Protocols

As possible technologies on higher layers different Ethernet based technologies from different sectors were considered. First all Ethernet based protocols that are already used in the railway sector were considered. These are:

- TRDP according to IEC/EN 61375-2-3 [4]
- PROFINET according to IEC 61158 and IEC 61784
- CIP (Common Industrial Protocol) according to ODVA specifications

But also, other protocols from other sectors (e.g. automotive) were considered. Among others, all the protocols are intended to be used for process data communication. The considered protocols from non-railway sectors are:

- OPC UA PubSub according to IEC 62541
- DDS/RTPS according to DDSI-RTPS [5]
- MQTT according to ISO/IEC 20922
- AMQP according to ISO/IEC 19464
- ROS/ROS2
- SOME/IP

For all the investigated session layer protocols a short description is given in the following subchapters. For a detailed insight into the protocol and its working mechanisms the references or other literature have to be consulted. The focus of the investigation of the session layer protocols lies on the core requirements. If a core requirement cannot be fulfilled, the corresponding protocol will not be in the list of solution candidates. Only protocols that fulfill all core requirements will be on the list of solution candidates. The solution candidates will then be assessed in detail on all requirements of D23.2 [3] in a following step.

2.1 TRDP WITH SDTv2/v4

TRDP was primarily defined and designed for the use by rolling stock. It basically offers process and message data communication. Besides, it features special provisions to react to leading direction and train topology changes, which no other protocol provides. TRDP was defined by the working group 43 of the technical committee 9 of the IEC (TC 9/WG 43) and it is currently standardized in IEC 61375-2-3 [4]. It is based on a standard TCP/UDP transport layer. The standard IEC/EN 61375-2-3 also defines a safety layer SDTv2 on top of TRDP for functions with SIL 2 requirements. But this safety layer is generally applicable also on other session layer protocols. During the Shift2Rail (S2R) projects CONNECTA and SAFE4Rail a new safety layer SDTv4 was elaborated. It is defined in [2]. It is intended to be used as an extension of the standardized SDTv2. The use of TRDP is mandatory for TCMS communication on the ETB (train level) and optional within the ECN (consist level).

<table>
<tr><th>Layer</th><th colspan="2">Protocol</th></tr>
<tr><td>Safety Layer</td><td colspan="2">SDTv2/v4</td></tr>
<tr><td>Session Layer</td><td colspan="2">TRDP</td></tr>
<tr><td>Transport Layer</td><td>UDP
(for process and message data)</td><td>TCP
(for message data)</td></tr>
<tr><td>Network Layer</td><td colspan="2">IPv4</td></tr>
<tr><td>Data Link Layer</td><td colspan="2">Ethernet IEEE 802.3</td></tr>
<tr><td>Physical Layer</td><td colspan="2">100BASE-TX or 1000BASE-T</td></tr>
</table>

Table 2: Protocol Stack TRDP with SDTv2/v4

According to the specification of TRDP in IEC/EN 61375 and market investigations the characteristics of TRDP including SDTv2/v4 for the core requirements can be summarized as follows:

Property	Characteristics
Determinism	TRDP is soft real-time capable. With QoS mechanisms according to IEEE 802.1Q maximum latencies can be guaranteed for high priority data. Thus, sufficient determinism for high priority data can be achieved.
Safety	SDTv2/v4 enables safe communication for functions of SIL 2 or SIL 4 respectively.
Bandwidth (Gross Data Rate)	100 Mbit/s or 1 Gbit/s or more
Openness	TRDP and SDTv2 are standardized in IEC/EN 61375-2-3 [4]. SDTv4 is intended to be standardized in the same standard until 2026. UDP, TCP and Ethernet on the lower layers are also open standards of RFC and IEEE. TRDP is available as open-source software implementation (TCNopen).
Maturity	COTS hardware for railway applications from different suppliers is already available.

Table 3: Properties TRDP with SDTv2 / SDTv4

TRDP is a solution candidate as it fulfils every core requirement. It is already proven in use for railway applications, and it is easy to implement and easy to use. With SDTv2/v4 already a standardized safety layer is available and intended to be used on TRDP.

2.2 PROFINET WITH PROFISAFE

PROFINET and PROFIsafe are defined in IEC 61158 and IEC 61784. There are three different communication channels in PROFINET with its own protocol stack: Real-Time (RT), Non-Real-Time (NRT), and Isochronous Real-Time (IRT).

Layer	Protocols NRT	Protocols RT	Protocols IRT
Safety Layer	PROFIsafe	PROFIsafe	PROFIsafe
Presentation	PROFINET (Fieldbus Application Layer)	PROFINET (Fieldbus Application Layer)	PROFINET (Fieldbus Application Layer)
Session Layer			
Transport	UDP	PNIO	PNIO
Network	IPv4		
Data Link Layer	Ethernet IEEE 802.3		
Physical Layer	100BASE-TX or 100BASE-FX (optical)		

Table 4: Protocol Stack PROFINET with PROFIsafe

According to the specification of PROFINET and PROFIsafe in IEC 61158 and IEC 61784 and market investigations the PROFINET with PROFIsafe properties for the core requirements can be summarized as follows:

Property	Characteristics
Determinism	With its RT and IRT communication channels, PROFINET adds services on Ethernet layer (layer 2) for deterministic networking with low latency and low jitter. Cyclic RT and IRT frames are transmitted directly through Ethernet without an UDP/IP header. For RT and IRT frames a time division multiple access scheme ensures a quite strong determinism for real-time applications.
Safety	PROFIsafe enables safe communication for functions up to SIL 3
Bandwidth (Gross Data Rate)	100 Mbit/s
Openness	PROFINET and PROFIsafe are standardized in IEC 61158 and IEC 61784.
Maturity	Special hardware (switch and ethernet ports) needed. Hardware and software for PROFINET from several suppliers available but dominated by one company. Widely used in automation industry.

Table 5: Properties PROFINET with PROFIsafe

As PROFINET only supports physical layers with 100 Mbit/s data rate, a core requirement is violated. Additionally, the technology has strong hardware restrictions on data link layer. That means standard Ethernet switches cannot be used for PROFINET. Therefore, PROFINET is not acceptable as a solution candidate.

2.3 CIP

The Common Industrial Protocol (CIP), formerly named as Control and Information Protocol is an industrial protocol for industrial automation applications. It encompasses a comprehensive suite of messages and services like control, safety, synchronization, motion, configuration and information. These manufacturing applications can be integrated into enterprise-level Ethernet networks and the Internet. It is supported by Open DeviceNet Vendors Association (ODVA). The ODVA also offers network technologies based upon CIP such as EtherNet/IP, CIP Safety and CIP Sync.

To get the CIP specifications from ODVA every company has to become a licensed vendor or an ODVA member. The standards are therefore not openly available. Also, the support is managed only by ODVA. Therefore, the core requirement on openness is violated and CIP is not acceptable as a solution candidate.

2.4 OPC UA WITH OPC UA SAFETY

OPC UA is a platform-independent and service-oriented communication standard specified in IEC 62541. It is typically used for machine-to-machine communication. Traditionally, it provides client/server communication patterns over HTTP or TCP which is normally used for message data. For deterministic process data, a publish-subscribe mechanism over different transport layers (e.g. UDP or RAW Ethernet) was introduced subsequently in IEC 62541-14. For safety applications there is a dedicated safety layer for OPC UA called OPC UA Safety available. It is specified in IEC 62541-15.

Besides its encoding on the wire, OPC UA also specifies an information model as well as concepts of service discovery, security key distribution and other services. For OPC UA PubSub there are discovery messages defined for subscribers and publishers to discover each other at runtime.

According to the specification of OPC UA in IEC 62541 and market investigations the characteristics of OPC UA including OPC UA Safety for the core requirements can be summarized as follows:

Property	Characteristics
Determinism	OPC UA PubSub is soft real-time capable. With QoS mechanisms according to IEEE 802.1Q maximum latencies can be guaranteed for high priority data. Thus, sufficient determinism for high priority data can be achieved.
Safety	OPC UA Safety enables safe communication for functions up to SIL 4.
Bandwidth (Gross Data Rate)	100 Mbit/s, 1 Gbit/s or more
Openness	OPC UA is standardized in IEC 62541. UDP, TCP and IP on the middle layers are also open standards of RFC. There are open-source software implementations of OPC UA incl. PubSub available (e.g. open62541).
Maturity	As OPC UA is based on standard Ethernet, COTS hardware for railway application from different suppliers is already available.

Table 6: Properties OPC UA with OPC UA Safety

Even though it is not used in railway sector, OPC UA is a solution candidate as it fulfils every core requirement. With OPC UA Safety already a standardized safety layer is available and intended to be used on OPC UA.

2.5 DDS / RTPS

Data Distribution Service on Real-time Publish-Subscribe (DDS/RTPS) is a data centric middleware that works with a global data space. The DDS specification DDSI-RTPS [5] mainly specifies abstractions of an application. The contained specified transport protocol supports soft real-time with built-in QoS features. The standard was released by the Object Management Group (OMG).

DDS/RTPS implements a data-centric publish/subscribe pattern for sending and receiving data, events, and commands among the network nodes. The DDS publish/subscribe mechanism is done with direct unicast or multicast connections between publisher and subscriber which eliminates the need of a broker component. The transport of DDS/RTPS is normally done over UDP. Besides the publish/subscribe mechanism DDS also offers built-in security. Unfortunately, there is no dedicated safety layer available for DDS. Generally, it is possible to use another safety protocol on top of DDS that is not intended to be used on DDS.

DDS/RTPS is one of many protocols used in different industry sectors but not in railway. DDS/RTPS is also used as communication protocol within the AUTOSAR Adaptive platform and in the ROS2 middleware.

According to the specification of DDS/RTPS in [5] and market investigations the characteristics of DDS/RTPS for the core requirements can be summarized as follows:

Property	Characteristics
Determinism	DDS/RTPS is soft real-time capable. With built-in QoS mechanisms sufficient determinism for high priority data can be achieved.
Safety	There is no dedicated safety layer available for DDS. Generally, it is possible to use another safety protocol on top of DDS.
Bandwidth (Gross Data Rate)	100 Mbit/s, 1 Gbit/s or more
Openness	DDS is standardized in DDSI-RTPS [5] and openly available from OMG. DDS/RTPS is based on standard UDP, TCP and IP middle layer protocols that are also open standards of RFC. Originally it was developed by Real-Time Innovations (RTI) and Thales Group. Today, RTI delivers a commercial implementation of DDS/RTPS. But there are also open implementations like openDDS available.
Maturity	As DDS/RTPS is based on standard Ethernet, COTS hardware for railway applications from different suppliers is already available.

Table 7: Properties DDS/RTPS

Even though it is not used in railway sector, DDS/RTPS is a solution candidate as it generally fulfils the core requirements. Unfortunately, there is no dedicated safety layer for DDS/RTPS available. Therefore, another safety layer has to be implemented.

2.6 MQTT

Message Queuing Telemetry Transport (MQTT) is an open and lightweight machine to machine publish/subscribe network protocol. It is specified in ISO/IEC 20922. Usually, the protocol runs on TCP but can be implemented on top of every lossless bidirectional connection (e.g. raw Ethernet, UDP, Bluetooth, RS 232) with the additional variant MQTT for Sensor Networks (MQTT-SN). It is especially designed to connect remote devices with low bandwidth. The message architecture of the publish/subscribe mechanism of MQTT needs a broker which handles the publications and subscriptions as well as the data. The broker adds high latency with high jitter which leads to a highly non-deterministic communication behavior. Thus, it violates the core requirement on determinism (real-time communication). Therefore, MQTT is not acceptable as a solution candidate.

2.7 AMQP

The Advanced Message Queuing Protocol (AMQP) is a very versatile, standardized binary network protocol for message-oriented middleware. It is specified in ISO/IEC 19464. It is working on top of a standard TCP/IP protocol stack. There are two transport options defined. One option is a Publish Subscribe mechanism with a broker as a central component. The other option is a direct peer-to-peer connection. It can be used for a broad variety of different kinds of messaging capabilities. AMQP is set up on a reliable TCP transport protocol with a broker between publisher and subscriber. The retransmissions of TCP and the AMQP broker may both add latency and increase jitter which leads to a highly non-deterministic communication behavior. Thus, it violates the core requirement on determinism (real-time communication). Therefore, AMQP is not acceptable as a solution candidate.

2.8 ROS / ROS2

ROS (Robot Operating System) is an open-source software framework (middleware) originally developed for robotics. Today it is supported by the Open-Source Robotics Foundation (OSRF). Its main targets are research institutes in various areas with a focus on robotics software.

The successor of ROS, ROS2 is built on top of DDS/RTPS. Due to this fact, only the original protocol DDS/RTPS is taken as solution candidate. See chapter 2.5.

2.9 SOME/IP

Scalable Service-Oriented Middleware over IP (SOME/IP) is a service-oriented communication protocol. It is designed as part of the AUTOSAR Adaptive software platform used in cars. While signal-oriented data transmission is used on classic fieldbus (e.g. CAN) systems, SOME/IP allows the introduction of service-oriented transmission of information. It should be noted, however, that

SOME/IP does not only describe communication. Rather, it is a middleware that has an impact on the software components of the communication entities.

Basically SOME/IP implements a broker-less Publish/Subscribe mechanism. The subscription of a content takes place with the help of the SOME/IP Service Discovery (SOME/IP-SD). UDP/IP or TCP/IP can be used as transport protocol. In case of UDP, the publisher can send the data to all subscribers via unicast, multicast or broadcast. If the content is made available via TCP, a connection to the server must be established by each client, which enables the respective sending of the data.

Since 2018 the AUTOSAR Adaptive platform supports DDS/RTPS as main communication standard. Due to this fact, only the original protocol DDS/RTPS is taken as solution candidate. See chapter 2.5.

2.10 Summary of the Elaboration

As a summary, three solution candidates were identified. They all fulfil the core requirements and are most promising to fulfil the residual system requirements as well. In the following table the assessment of the protocols is summarized.

Protocol	Assessment on Core Requirements	Solution Candidate
TRDP	Fulfills every core requirement	✓
PROFINET	Does not support 1000BASE-T and is not based on standard Ethernet according to IEEE 802.3	×
CIP	Standards and implementation are not openly available.	×
OPC UA	Fulfills every core requirement	✓
DDS/RTPS	Fulfills every core requirement	✓
MQTT	Is not real-time capable	×
AMQP	Is not real-time capable	×
ROS/ROS2	Transport protocol of ROS is replaced by DDS/RTPS in ROS2	×
SOME/IP	Replaced by DDS/RTPS	×

Table 8 Summary on assesment of core requirements

The main difference between the three candidates is principal approach in specification:

- TRDP itself focusses on process data communication itself. No other functionality is addressed, following a principle called "one tool, one purpose". Instead, TRDP-based solutions add other protocols/technologies for any other functionality in a "mix-and-match" way. This kind of technology specification is how the Internet is defined. Therefore, this approach is called the "Internet Approach".

- In contrast, OPC UA and DDS are so called “Integrated Technologies”. They focus not only on a single purpose, but offer a broad variety of functionality and services, all aligned on each other and fully integrated.

2.10.1 Basic Services

Basic services are those which are needed for a fully functional middleware, e.g. address assignment, address and name resolution, service discovery etc.

Due to the different nature of the differing approaches “Internet Approach” (TRDP) and “Integrated Technology” (OPC UA and DDS), a direct comparison of the technologies in regards basic technologies is not possible in this deliverable. In the next deliverable D23.4, TRDP will be completed by other services, following the “Internet Approach”.

2.10.2 Security

In regards of security, the difference between the two approaches is also crucial. While OPC UA and DDS comprise both a security layer, in case of TRDP a supplemental security layer has to be chosen. Therefore, like in the case of the basic services, also the discussion on security has to be postponed to D23.4.

3 CONCLUSIONS

As a conclusion of the first investigation of all possible technologies a pre-selection was made. The pre-selection was jointly elaborated and carefully aligned among all members of the workpackage. As a conclusion three solution candidates were defined. They all fulfil the core requirements and are most promising to fulfil the residual system requirements as well. In the following table the assessment of the protocols is summarized.

Protocol	Assessment on Core Requirements	Solution Candidate
TRDP	Fulfills every core requirement	✓
PROFINET	Does not support 1000BASE-T and is not based on standard Ethernet according to IEEE 802.3	×
CIP	Standards and implementation are not openly available.	×
OPC UA	Fulfills every core requirement	✓
DDS/RTPS	Fulfills every core requirement	✓
MQTT	Is not real-time capable	×
AMQP	Is not real-time capable	×
ROS/ROS2	Transport protocol of ROS is replaced by DDS/RTPS in ROS2	×
SOME/IP	Replaced by DDS/RTPS	×

Table 9: Summary on assesment of core requirements

Therefore, the following protocols were retained as solution candidates:

- TRDP according to IEC/EN 61375-2-3 [4]
- OPC UA PubSub according to IEC 62541
- DDS/RTPS according to DDSI-RTPS [5]

The pre-selected solution candidates will be assessed in detail requirement by requirement of D23.2 [3] in a following step.

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