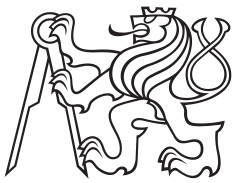
Master's Thesis



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F3

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Implementation of actual version of DDSI-RTPS protocol for distributed control in Ethernet network

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Open Informatics

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Acknowledgement / Declaration

Podekovani..

Prohlasuji..

.....

Abstrakt / Abstract

Czech abstract..

Klíčová slova: RTPS, ORTE, Ethernet, Real-Time

Překlad titulu: Implementace aktuální verze protokolu DDSI-RTPS pro distribuované řízení v síti Ethernet

English abstract..

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[intro]

Chapter 1
Introduction

The Real-Time Publish-Subscribe (RTPS)[1] is the protocol of Data Distribution Service (DDS)[2] family. It supports Data-Centric Publish-Subscribe communication for real-time applications in a decentralized network. Specification of protocol is maintained by Object Management Group[3] - international, open membership, not-for-profit technology standards consortium, since version 1.0 on February 2002 till version 2.2 on September 2014. ORTE was finished before version 1.0 of DDS specification of RTPS protocol and was used as proof of concept. ORTE was also implemented in some interesting projects as aerodynamic wind tunel, networked vehicle systems and Eurobot2008 [4].

This thesis aims on upgrading ORTE implementation of RTPS protocol in order to achieve compatibility with the latest standard version 2.2. Good understanding of RTPS standard nad actual ORTE implementation is required. In Chapter 1, there is an introduction to RTPS and ORTE. Chapter 3 provides overview of the latest RTPS protocol version 2.2 with the section dedicated for comparison with version 1.0 of the protocol. Changes made for achieving the compatibility with version 2.2 of the RTPS protocol and possible future development are covered in chapter 4 and chapter 5 documents results of updated ORTE implementation testing. In chapter 6, demo application of ORTE called *Shape* for Android is introduced. Original ORTE version based demonstration application has been developed as part of preparation for main work to gain experience with RTPS protocol and its implementation. Security considerations and proposal for security protocol extension is discussed in chapter 7.

[over]

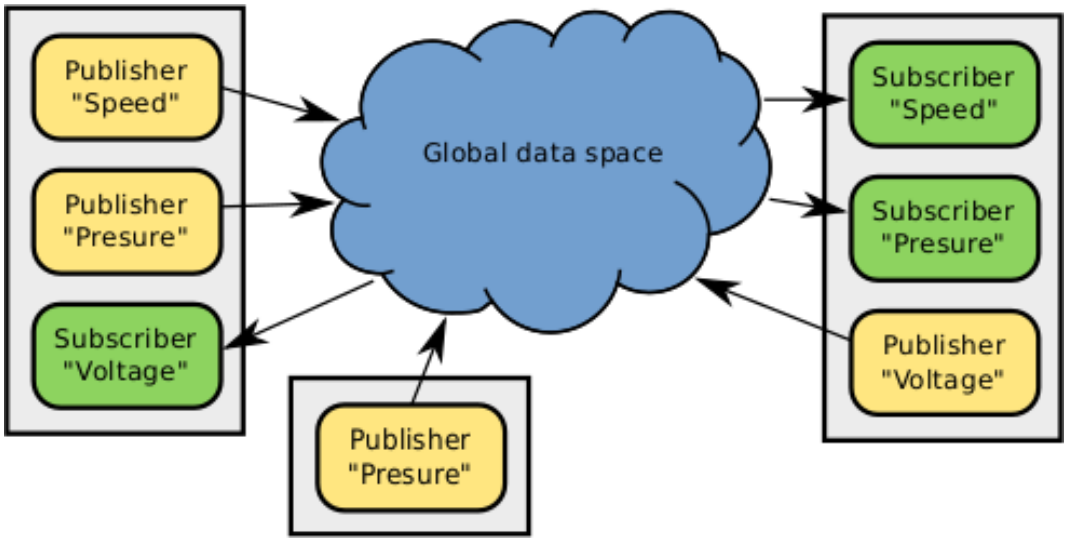
Chapter 2
Technology overview

2.1 DDS

There are two main models used in Data Distribution Services. *Centralized* model with the single point of failure throw which all the communication goes is vulnerable. When the central server is unreachable, the whole network is non-functional. By contrast, *decentralized* approach has no central server, no single point of failure. When one node of the network is non-functional, the rest of the network can continue in data transfers.

2.2 DCPS

In the Data-Centric Publish-Subscribe network, data are sent by *Publishers* and received by *Subscribers*. It depends on application what kind of data is *Published*, *Subscribed*, how are data sent and ifat all. Data-Centric Publish-Subscribe network is responsible for delivery of right data between right nodes with right parameters.



[pic:dcps] **Figure 2.1.** Example of DCPS application model ([5]).

2.3 RTPS

Real-Time Publish-Subscribe is wire protocol developed to ensure interoperability between DDS implementations. It's fault tolerant (decentralized), scalable, tunable, with plug-and-play connectivity and ability of best-effort and reliable communication in real time applications.

2.4 ORTE

Open Real-Time Ethernet (ORTE)[6] is the implementation of RTPS 1.0. It's implemented in Application layer of UDP/IP stack, written in C, under open source license, with own API and it should be easy to port ORTE to many platforms, where UDP/IP stack is implemented.

[compare]

Chapter 3
Actual RTPS protocol

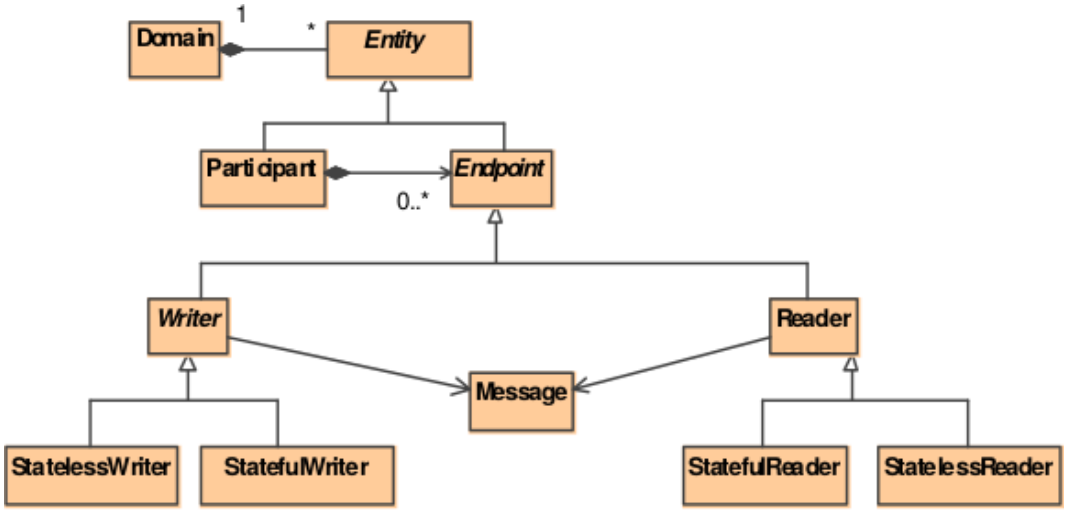
When the *User Application* needs to exchange *Data Object* beetween multiple nodes in the network (*Entities* in the *Domain* in terms of RTPS), the RTPS protocol suits perfectly.

This chapter follows Platform Independent Model (PIM) of the RTPS protocol introduced in [1]. PIM is divided in four modules: basic objects are discussed in section 3.1, messages used for communication is described in 3.2 and behavior - messages exchange between objects - is discussed in 3.3. The last module of discovering *Domain* is convered in section 3.4. In the last section 3.5, versions 2.2 and 1.0 of RTPS protocol are compared.

[struct]

3.1 Structure Module

The communication take place in the RTPS *Domain*, consisting of multiple *Entities*. Each *Entity* can be either *Participant* or *Endpoint*, where *Endpoints* can be specialized as *Writer* or *Reader*. Each *Endpoint* has it's own database of *Cache Changes* called *History Cache*. The whole structure is shown in figure 3.1.



[pic:struct] **Figure 3.1.** Structure Module diagram (chapter 7.1 in [1]).

It should be mentioned that there is also proxy *Participant* - *Participant Proxy* and another two proxy *Endpoints* - *Reader Proxy* and *Writer Proxy*. These objects represents remote *Participants* and their *Writers* and *Readers* and are introduced in chapter 8.4 in [1]. The local *Participant* maintains the topology of the *Domain* and needs to store information about remote *Participants*. For this purpose, *Participant Proxy* is used. Sometimes, local *Writer* needs to store information about remote *Reader* and therefore, *Reader Proxy* is used. Also local *Readers* are sometimes in need of storing information about remote *Writers* and then *Writer Proxy* is used.

3.1.1 Participant

Domain Participant is container for *Endpoints* within the same application. It has the following attributes:

- GUID
- Protocol Version
- Vendor Id
- Default Unicast Locator List
- Default Multicast Locator List

Where the *GUID* is globally-unique RTPS-entity identifier consisting of *GUID Prefix* and *EntityId*, *Protocol Version* is version of actual implementation and vendor of implementation is represented by *Vendor Id*.

Default Unicast Locator List and *Default Multicast Locator List* are lists of IP address and port combinations used to send User-data traffic to, when there is no such an information contained in *Writers* of the *Participant*.

Each *Endpoint* within the same *Participant* has to have the same *GUID Prefix*.

3.1.2 Writer Endpoint

Writer is the source of *Cache Changes* which are sent to *Readers*. It has the following attributes:

- GUID
- Topic Kind
- Reliability Level
- Unicast Locator List
- Multicast Locator List
- Push Mode
- Heartbeat Period
- Nack Response Delay
- Nack Suppression Duration
- Last Change Sequence Number
- Writer Cache

Where *Topic Kind* can be either NO_KEY or WITH_KEY. WITH_KEY is used, when the topic consists of more than one data instances identified by *key*. *Reliability Level* can be either BEST_EFFORT or RELIABLE, saying if it should be verified that *Cache Change* reached the *Reader*.

Unicast Locator List and *Multicast Locator List* are lists of IP address and port combinations on which is the *Writer* listening. If lists are empty, it's presumed that *Writer* is listening on *Default Unicast Locator List* respective *Default Multicast Locator List* of the *Participant*.

Push Mode defines if data are sent (*Push Mode* is set to TRUE) or just Heartbeats with Sequence Numbers of available *Cache Changes* and *Reader* has to ask for *Cache Change* delivery.

Heartbeat Period, *Nack Response Delay* and *Nack Suppression Duration* are protocol tunning parameters, which defines announce interval of available data, how long the response to data request should be delayed respective how long can be data request for rightly sent data ignored.

Last Change Sequence Number is the highest Sequence Number in *History Cache* and the *Writer Cache* is the *History Cache* of the *Writer* containing *Cache Changes* associated with the *Writer* itself.

3.1.3 Reader Endpoint

Reader is the destination of *Cache Changes* which are sent by *Writers*. It has the following attributes:

- GUID
- Topic Kind
- Reliability Level
- Unicast Locator List
- Multicast Locator List
- Expects Inline Qos
- Heartbeat Response Delay
- Heartbeat Suppression Duration
- Reader Cache

Where *Unicast Locator List* and *Multicast Locator List* are lists of IP address and port combinations on which is the *Reader* listening. If there is no IP address and port combination in list, it's presumed that *Reader* is listening on *Default Unicast Locator List* respective *Default Multicast Locator List* of the *Participant*.

The value of *Expects Inline Qos* is set to TRUE if the *Reader* expects in-line Qos to be sent along with data.

Heartbeat Response Delay and *Heartbeat Suppression Duration* are time parameters used for protocol tunning, which defines how long the acknowledgement of data should be delayed respective how long can be Heartbeat announces ignored after just received Heartbeat.

Reader Cache is the *History Cache* of the *Reader* containing *Cache Changes* associted with the *Reader* itself.

3.1.4 History Cache

History Cache is the database of *Cache Changes* serving as the API for *Writer* and *Reader Endpoints*. It has the following attributes:

- Changes

Where *Changes* are *Cache Changes* stored in the *History Cache*.

3.1.5 Cache Change

Is the change of the data object that should be propagated from the *Writer* to the matching *Readers*. It has the following attributes:

- Change Kind
- Writer GUID
- Instance Handle
- Sequence Number
- Data value

Where *Change Kind*[1]) is used to distinguish the change that was made to a data object. *Writer GUID* is the identifier of the source of the *Cache Change*, *Instance Handle* identifies the instance of the data object (in DDS the value of the *key* is used) and the *Sequence Number* is unique identifier of the *Cache Change* in the *History Cache* of the *Endpoint*. The last attribute, *Data value*, represents data associated to the *Cache Change*.

[1]) Possible values are: ALIVE, NOT_ALIVE_DISPOSED and NOT_ALIVE_UNREGISTERED

3.1.6 Participant Proxy

Represents the information about remote *Participant* in the *Domain*. It has the following attributes:

- Protocol Version
- Guid Prefix
- Vendor Id
- Expects Inline Qos
- Available Builtin Endpoints
- Metatraffic Unicast Locator List
- Metatraffic Multicast Locator List
- Default Multicast Locator List
- Default Unicast Locator List
- Manual Liveliness Count
- Lease Duration

Where *Protocol Version* specify the version of the RTPS protocol implementation used by remote *Participant* and the vendor of this implementation is represented by the *Vendor Id*. *Guid Prefix* is the common part of the GUID for the *Participant* and all of it's *Endpoints*, *Expects Inline Qos* describes whether the *Readers* of the remote *Participant* expects in-line Qos sent along with data and *Available Builtin Endpoints* parameter specify which builtin *Endpoints* used for plug-and-play interoperability are available by remote *Participant*.

Metatraffic Unicast Locator List and *Metatraffic Multicast Locator List* are IP address and port combinations that can be used to reach the remote builtin *Endpoints* and *Default Unicast Locator List* and *Default Multicast Locator List* are IP address and port combinations that can be used to reach the remote *Endpoints* defined by user that serve for user data exchange.

Manual Liveliness Count is used to implement MANUAL_BY_PARTICIPANT liveliness Qos and *Lease Duration* specify the time period for which the remote *Participant* should be considered alive.

3.1.7 Reader Proxy

Represents the information about remote *Reader*. It has the following attributes:

- Remote Reader GUID
- Unicast Locator List
- Muticast Locator List
- Changes for Reader
- Expects Inline Qos
- Is Active

Where *Remote Reader GUID* is unique identifier of remote *Reader*, *Unicast Locator List* and *Multicast Locator List* are lists of IP address and port combinations on which is the remote *Reader* listening, *Changes for Reader* is the list of *Cache Changes* that should be sent to the remote *Reader*, *Expects Inline Qos* attribute specify if the remote *Reader* expects in-line Qos to be sent along with data and attribute *Is Active* is set to TRUE if the remote *Reader* is responsive to the local *Writer*.

3.1.8 Writer Proxy

Represents the information about remote *Writer*. It has the following attributes:

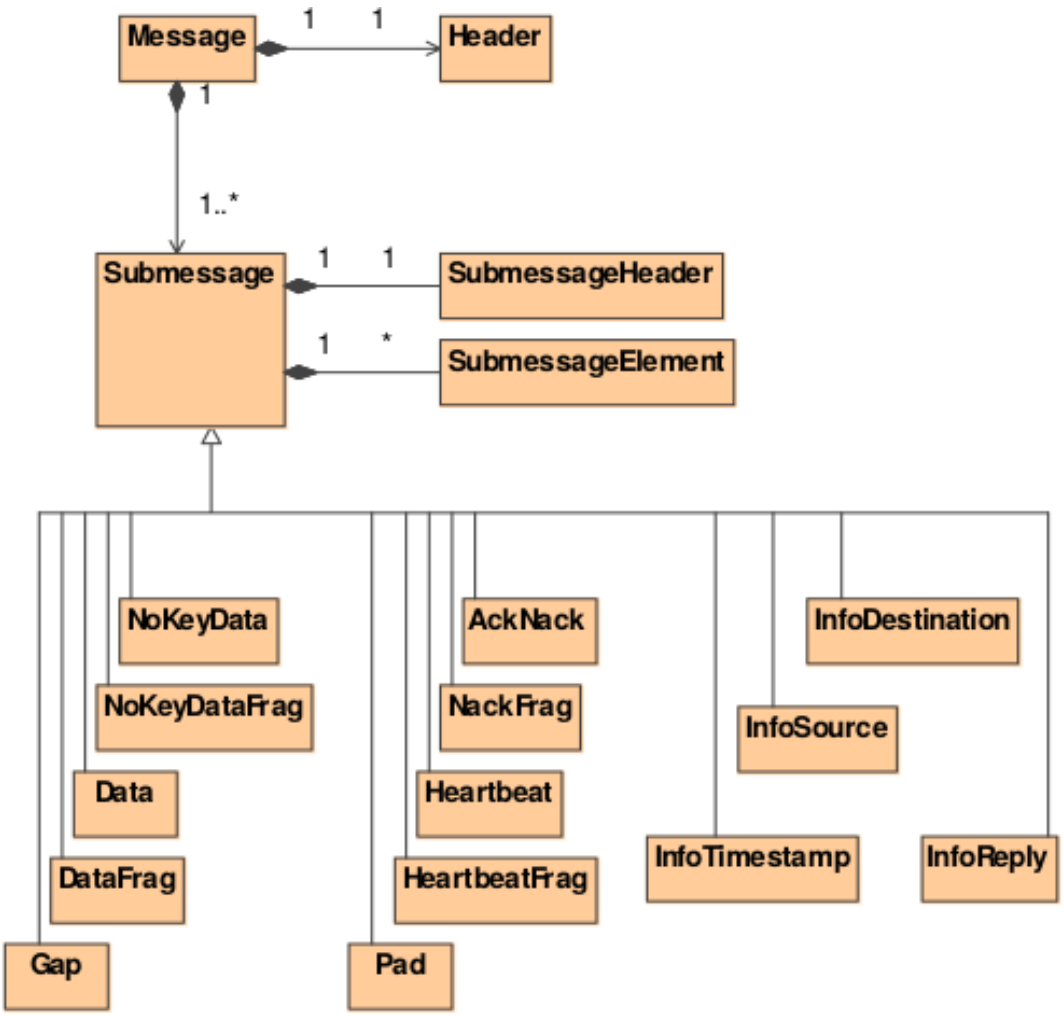
- Remote Writer GUID
- Unicast Locator List
- Multicast Locator List
- Changes from Writer

Where *Remote Writer GUID* is unique identifier of remote *Writer*, *Unicat Locator List* and *Multicast Locator List* are lists of IP address and port combinations on which is the remote *Writer* listening and *Changes from Writer* is the list of *Cache Changes* that are received or expected from the remote *Writer*.

[message]

3.2 Messages Module

For communication between *Writers* and *Readers*, RTPS messages are used. Each message consists of *Header* and one or more *Submessages*, where each *Submessage* has it's own *Submessage Header* and *Submessage Elements* based on the kind of the *Submessage*. The structure of RTPS message is shown in figure 3.2.



[pic:msg]

Figure 3.2. Structure of RTPS message (chapter 8.3.3 in [1]).

The interpretation of *Submessage* may depend on previously received *Submessages* within the same *Message*, therefore it's needed to store the state for each *Message*.

Message Receiver ensures this function by storing information about *Source Protocol Version*, *Source Vendor Id*, *Source GUID Prefix*, *Destination GUID Prefix*, *Unicast Reply Locator List*, *Multicast Reply Locator List*, *Have Timestamp* and *Timestamp*. State of the *Message Receiver* is reset to default values each time the *Message* is received.

Submesssages can be divided to *Entity Submessages* which target an RTPS *Entity* affecting it's behavior and *Interpreter Submessages* changing the state of the *Message Receiver*.

3.2.1 Header

The first change in the state of *Message Receiver* is made by *Header* of the received *Message*. The *Header* identify RTPS *Message*, *Protocol Version* used, *Vendor* of the implementation and common part of GUID - *GUID Prefix* - used to interpret source *EntityId* in the *Submessage*.

3.2.2 Submessage Header

Submessage Header is included in each *Submessage*, it has the following attributes:

- Submessage Kind
- Flags
- Submessage Lenght

Where *Submessage Kind* specify the meaning of *Submessage*, *Flags* is an array of 8 bits, which identifies endianness used in the *Submessage* (LSB), the presence of optional elements and possibly changes the interpretation of the *Submessage*. The *Submessage Length* specify the length of the *Submessage*.

3.2.3 Interpreter Submessages

List of *Submessages* and their changes to the *Message Receiver* follows.

InfoDestination is sent from *Writer* to *Reader* to modify the *Destination GUID Prefix* value of *Message Receiver* used to interpret *Reader EntityId* in the *Submessage*.

InfoReply is sent from *Reader* to *Writer* to explicitly define where to send a reply to the *Submessage* that follow.

InfoSource modifies the source *Protocol Version*, *Vendor Id* and *GUID Prefix* of the *Submessages* that follow.

InfoTimestamp is used to send the *Timestamp* that apply to the *Submessages* that follow.

3.2.4 Entity Submessages

List of *Submessages* and their interpretation follows.

AckNack is sent by *Reader* to inform the *Writer* about which sequence numbers are received and which are missing.

Data is sent from *Writer* to *Reader* and is used to inform about changes to a data object. Changes may be in value or in lifecycle of the object.

DataFrag is used when the **Data** *Submessage* exceeds the MTU of lower communication layers, otherwise it has the same function as **Data** *Submessage*.

Gap sent by *Writer* indicates to the *Reader* which sequence numbers are no longer relevant.

Heartbeat announces to *Readers* sequence numbers of *Cache Changes* that are available in *Writer*.

HeartbeatFrag is used when fragmentation occures and until all fragments are available. Once all fragments are available, **Heartbeat** *Submessage* is used.

NackFrag is sent by *Reader* to inform the *Writer* about which fragments are missing.

Pad is padding message used for desired alignment. It has no other meaning.

[behavior]
3.3 Behavior Module

The purpose of the RTPS protocol can be simplified to propagating *Cache Change* from *Writer* to *Reader*. The manner of propagation in relation to properties of communication is discussed in this section. There are two main properties of communication:

- Topic Kind
- Reliability Level

Where *Topic Kind* can be either NO_KEY or WITH_KEY and *Reliability Level* can be either BEST_EFFORT or RELIABLE. Pairing of *Writers* with *Readers* must acknowledge the following restrictions.

Writer and *Reader* can be paired up and the communication may begin when the *Topic Kind* matches, because both *Endpoints* relate to the same DDS Topic which is either NO_KEY or WITH_KEY.

The reliability depends on the *Reader*. If the *Reader* has the *Reliability Level* set to RELIABLE, the corresponding *Writer* has to also have the *Reliability Level* set to RELIABLE, while the *Reader* has the *Reliability Level* set to BEST_EFFORT, the *Reliability Level* of the corresponding *Writer* doesn't matter.

The behavior required for interoperability between implementations is summarized in section 3.3.1. In chapter 8.4 in [1], there are two reference implementations of *Endpoints* that are summarized in section 3.3.2. In the remaining sections, these implementations are discussed in detail.

[inte]
3.3.1 Interoperability

In order to be compliant with protocol specification and interoperable with other implementations, the implementation of the RTPS protocol must satisfy the following requirements.

- General Requirements:
  - Only RTPS messages are used for communication.
  - Message Receiver must be implemented.
  - Timing characteristics must be tunable.
  - Simple Participant Discovery Protocol must be implemented.
  - Simple Endpoint Discovery Protocol must be implemented.
  - Writer Liveliness Protocol must be implemented.
- Required Writer Behavior:
  - Data must be sent in-order.
  - If requested, in-line Qos must be included.
- Additional requirements for Reliable Writer:
  - Periodic HEARTBEAT messages must be sent.
  - Response to ACKNACK message must be eventually sent.
- Required Reader Behavior:

- No specific behavior needed as best-effort reader is completely passive.

- Additional requirements for Reliable Reader:
  - Response to HEARTBEAT with final flag not set must be eventually sent.
  - Response to HEARTBEAT indicating missing sample must be eventually sent.
  - Once acknowledged, always acknowledged.
  - ACKNACK can be only sent in response to HEARTBEAT.

Writer Liveliness Protocol is required by DDS to exchange information about the Liveliness of *Writers* by *Participants*. Builtin *Endpoints* are used for sending samples at rate faster than the smallest lease duration among *Writers* sharing the same liveliness Qos.

[impl]

3.3.2 State Maintenance

In [1], two reference implementations of RTPS protocol are introduced.

Stateless implementation maintains no state about remote *Endpoints*, which suits for best-effort communication over multicast. While this implementation scales well in large systems and memory usage is reduced, additional bandwidth may be required.

Stateful implementation, on the other hand maintains full state on remote *Endpoints*. More memory is needed and scalability is limited, but bandwidth usage decreases. Also, strict reliable communication and Qos based filtering on the *Writer's* side may be applied.

It's important to mention that these are *reference implementations*. It means that there is no need for two kinds of *Endpoints* - *Stateless* and *Stateful*, because the only behavior needed for interoperability is introduced in 3.3.1. *Reference implementations* just helps to understand and implement this behavior. Both *reference implementations*, *Stateless* as well as *Stateful* may be BEST_EFFORT, RELIABLE, NO_KEY or WITH_KEY. Excaptions are discussed and explained below.

3.3.3 Stateless Writer

To be compliant with 3.3.2, *Stateless Writer* must send data in order and include in-line Qos if needed. BEST_EFFORT *Stateless Writer* has no other requirements and data are sent each *Resend Data Period* or on demand by user application.

If *Stateless Writer* is RELIABLE, periodic HEARTBEATs with available data are sent. Sending of data then depend on *Push Mode*. If *Push Mode* is TRUE, data are sent each *Resend Data Period* or on demand by user application, if it's FALSE, data are stored in *History Cache* of *Writer* and sent only in response to ACKNACK.

Readers uses ACKNACK messages to request interesting data from *Reliable Writer*. DATA submessage is sent if data are still available in *Writer's History Cache* or GAP submessage indicating that data are no longer relevant.

Even the bandwidth can be reduced if the information of acknowledged Sequence Numbers would be stored for remote *Readers*, it's not needed for interoperability.

3.3.4 Stateless Reader

Receive and process data is the meaning of BEST_EFFORT *Stateless Reader*. However, to ensure RELIABLE communication, the problem arise, because at least Sequence Numbers of announced, requested but not received *Cache Changes* are needed, so some information about remote *Writer* has to be stored and therefore *Reader* can't be *Stateless*.

As mentioned above, this is the only exception. *Stateless Reader* can't be RELIABLE.

3.3.5 Stateful Writer

For each remote *Reader*, *Stateful Writer* stores information in *Reader Proxy* structure. When *Cache Change* is added to the *History Cache* of *Writer*, filtering can occures to determine if *Cache Change* is relevant for *Reader* and consequently stored in *Changes for Reader* of *Reader Proxy*.

BEST_EFFORT traffic is sent on demand by user application to each *Reader Proxy* whenever there are any unsent changes in *Changes for Reader*.

For RELIABLE *Stateful Writer*, periodic HEARTBEATs must be sent to each *Reader Proxy*. Sending of data then depends on *Push Mode* - when the value is TRUE, *Cache Change* pass the filter and is added to *Changes for Reader*, the *Cache Change* is marked as unsent and will be sent as soon as the needed resources would be available. When tha value of *Push Mode* is FALSE, only HEARTBEATs are sent and *Reader* has to ask for data by sending ACKNACK for interested data. In response to ACKNACK, *Reliable Writer* then sends DATA submessage if the data are still available or GAP submessage when the data are no longer relevant.

It should be mentioned that in general, *Reader's Entity Id* of submessages is set to ENTITYID_UNKNOWN, stating that each *Reader* of remote *Participant* should receive the data. The only situation when *Writer* knows exactly the destination and therefore may set *Reader's Entity Id* properly is sending DATA submessage in response to ACKNACK by *Stateful Writer*.

3.3.6 Stateful Reader

For BEST_EFFORT traffic, *Stateful Reader* stores information about expected Sequence Number for each remote *Writer*. This information is stored in *Writer Proxy* structure. Storing Sequence Number ensures that there are no duplicated nor out-of-order data changes.

If the communication is RELIABLE and DATA submessage or GAP is received, expected Sequence Number is set correspondingly. When HEARTBEAT is received, databases of missing and lost changes are updated for *Writer Proxy* and the rest of behavior depends on *Final* and *Liveliness Flags*. When both, *Final* and *Liveliness Flags* are set, nothing happens. When *Liveliness Flag* is not set, then ACKNACK with missing changes may be sent and when *Final Flag* is not set, ACKNACK must be sent.

[discovery]

3.4 Discovery Module

The communication as described in 3.3 between *Endpoints* described in 3.1 by the *Messages* described in 3.2 assumes that both ends of communication are known. *Discovery Module* introduces two processes of probing *Domain* due to discovering *Participants* called *Simple Participant Discovery Protocol* and theirs *Endpoints* known as *Simple Endpoint Discovery Protocol*.

SPDP and SEDP are only discovery protocols described in RTPS specification and have to be implemented in order to enable interoperability between implementations. However vendor specific discovery protocols can be implemented in addition to overcome some drawbacks of *Simple Discovery Protocols*.

The difference between *Builtin* and *User-defined Endpoints* needs to be clear. *Builtin Endpoints* are predefined by RTPS specification and once a *Participant* is discovered,

it can be assumed that *Builtin Endpoints* are present, while *User-defined Endpoints* are defined by user application and it's purpose and can't be known in advance. Therefore the purpose of *Discovery Module* can be roughly simplified to discovering *User-defined Endpoints* of remote *Participants* with help of *Builtin Endpoints*. *Builtin Endpoints* are used by *Simple Discovery Protocols*.

3.4.1 SPDP

Best-effort Writer with predefined Entity Id[1]) and *Best-effort Reader* with predefined Entity Id[2]) are used to exchange *SPDPdiscoveredParticipantData* containing *Participant Proxy* information about remote *Participant*. This traffic is sent to predefined IP address and port discussed in PSM in [1]. Remote *Participants* and their attributes are discovered by SPDP.

3.4.2 SEDP

Reliable Writer with predefined Entity Id[3]) and *Reliable Reader* with predefined Entity Id[4]) are used to exchange *DiscoveredWriterData* containing information about *Writers* of remote *Participant*.

Reliable Writer with predefined Entity Id[5]) and *Reliable Reader* with predefined Entity Id[6]) are used to exchange *DiscoveredReaderData* containing information about *Readers* of remote *Participant*.

The last pair of *Reliable Endpoints*[7]) can be used to exchange *DiscoveredTopicData*, but these *Endpoints* aren't mandatory and the interoperability is not affected by them.

Endpoints of remote *Participants* are discovered by SEDP.

[rtps10]
3.5 RTPS 1.0

ORTE is one of the implementations of the RTPS protocol used as proof of concept to standardize RTPS 1.0. This section discuss the difference between version 1.0 and 2.2 of the RTPS protocol, viewed from the perspective of the version 2.2.

3.5.1 Structure Module

Important change in version 2.2 is that the *GUID* consists of *Guid Prefix* (12B) and *Entity Id* (4B), while in version 1.0, *GUID* consists of *Host Id* (4B), *Application Id* (4B) and *Object Id* (4B). *Entity Id* may be compared with *Object Id* and *Guid Prefix* corresponds to *Host Id* and *Application Id*. The size of *GUID* in version 2.2 was increased by 4B.

New *Locator* type is introduced in version 2.2, containing IP address, port and kind. *Locator* type is introduced because of IPv6, it's kind can be either LOCATOR_KIND_UDPv4 or LOCATOR_KIND_UDPv6.

[1]) ENTITYID_SPDP_BUILTIN_PARTICIPANT_WRITER
[2]) ENTITYID_SPDP_BUILTIN_PARTICIPANT_READER
[3]) ENTITYID_SEDP_BUILTIN_PUBLICATIONS_WRITER
[4]) ENTITYID_SEDP_BUILTIN_PUBLICATIONS_READER
[5]) ENTITYID_SEDP_BUILTIN_SUBSCRIPTIONS_WRITER
[6]) ENTITYID_SEDP_BUILTIN_SUBSCRIPTIONS_READER
[7]) ENTITYID_SEDP_BUILTIN_TOPIC_WRITER and ENTITYID_SEDP_BUILTIN_TOPIC_READER

3.5.2 Messages Module

The structure of the *RTPS Header* remains same, but because of change in size of GUID in version 2.2, size of the *Header* also increased. *Host Id* and *Application Id* are replaced by *Guid Prefix* indeed.

The structure of the *Submessage* remains completely same.

Following are changes in *Submessages*:

- VAR is deprecated
- ISSUE is deprecated
- ACK is renamed to ACKNACK
- INFO_REPLY is renamed to INFO_REPLY_IP4
- INFO_REPLY is introduced
- NACK_FRAG is introduced
- HEARTBEAT_FRAG is introduced
- DATA is introduced
- DATA_FRAG is introduced

3.5.3 Behavior Module

Writers are divided to *CSTWriters* and *Publications*, *Readers* to *CSTWriters* and *Subscriptions* in version 1.0.

CSTWriters and *CSTReaders* are builtin "endpoints" used for Composite State Transfer protocol and the communication between them is reliable. Messages used are VAR, GAP, HEARTBEAT and ACK. *CSChanges* are exchanges between *CSTWriters* and *CSTReadres*.

Publications and *Subscriptions* are used for user data exchange and the communication can be either reliable or best-effort. Messages used are ISSUE, HEARTBEAT and ACK. User data in ISSUE messages are represented in CDR format.

In version 2.2, only difference between builtin and user defined *Endpoints* are predefined Entity Ids. Both, builtin and user defined *Endpoints* can be reliable or best-effort and DATA, HEARTBEAT, GAP and ACKNACK submessages are used independently on the purpose of the communication.

3.5.4 Discovery Module

In version 1.0, two kinds of "entities" are discussed in specification - *Managers* and *Managed Applications*. The purpose of *Managers* is *Managed Application* discovery and the purpose of *Managed Applications* is to exchange user data. Each *Managed Application* needs to be registered to one of the *Managers*.

Discovery in version 1.0 is ensured by following protocols:

- *Inter-Manager Protocol* allows *Managers* to discover each other.
- *Manager-Discovery Protocol* allows every *Managed Application* to discover other *Managers*.
- *Registration Protocol* allows *Managers* to find theirs *Managed Applications*.
- *Application-Discovery Protocol* is used by *Managed Application* to discover other *Managed Applications*.
- *Services-Discovery Protocol* allows to find *Publications* and *Subscriptions* in other *Managed Appliations*.

In version 2.2, SPDP and SEDP are only required protocols used for discovery.

[upgrade]

Chapter 4
Required changes in ORTE

In this chapter, changes required for ORTE to be compatible with the version 2.2 of the RTPS protocol are discussed. Following is the state of work, where what is done is blue, working is green, not finished is red and needless for interoperability is black.

- Structure Module
  - Participant (tested)
  - History Cache (tested)
  - Cache Change (tested)
  - Participant Proxy (tested)
  - Writer Endpoint (working)
  - Reader Endpoint (working)
  - Reader Proxy (working)
  - Writer Proxy (working)
- Messages Module
  - Header (tested)
  - Message Receiver (tested)
  - Data (tested)
  - InfoDestination (done)
  - InfoReply (done)
  - InfoSource (done)
  - InfoTimestamp (done)
  - Pad (done)
  - AckNack (working)
  - Gap (working)
  - Heartbeat (working)
  - DataFrag
  - HeartbeatFrag
  - NackFrag
- Behavior Module
  - Best-Effort Stateless Writer (tested)
  - Best-Effort Stateless Reader (tested)
  - Reliable Stateless Writer (not finished)
  - Reliable Stateful Reader, Writer Proxy (not finished)
  - Best-Effort Stateful Writer
  - Reliable Stateful Writer, Reader Proxy
  - Best-Effort Stateful Reader
- Discovery Module
  - SPDP (tested)
  - SEDP (not finished)

In section 4.1, specific types used in ORTE are introduced, their purpose and legacy of previous implementation. In 4.2, 4.3, 4.4 and 4.5, implementation of each module from chapter 3 is discussed. Proposal of consequential development is introduced in section ??.

[orte:spec]

4.1 ORTE specific

4.1.1 Version 1.0

In RTPS 1.0 implementation, the core structure is `ORTEDomain`. Following are specific types contained in `ORTEDomain` structure:

- `TaskProp`
- `TypeEntry`
- `ObjectEntry`
- `PSEntry`
- `CSTPublications`
- `CSTSubscriptions`

`TaskProp` maintains properties of *Tasks*, including own socket, thread and `MessageBuffer` (used for sending and receiving data) for each *Task*. There are five *Tasks*: `taskRecvUnicastMetatraffic`, `taskRecvMulticastMetatraffic`, `taskRecvUnicastUserdata`, `taskRecvMulticastUserdata` and `taskSend`.

`TypeEntry` is database of *Types* used for data encapsulation, containing name of *Type* and functions to serialize and deserialize it.

The database of all "endpoints" is stored in `ObjectEntry`. In `ORTEDomain`, variable `objectEntry` of type `ObjectEntry` is the root of 3-layered AVL tree ([7]), where each layer correspond to *Host Id*, *Application Id* and *Object Id*. Also, *Application Id* layer serves as the root for *Hierarchical Timer* ([7]) used for timing in ORTE.

`PSEntry`, `CSTPublications` and `CSTSubscriptions` are databases of *Publications* and *Subscriptions*. In context of version 1.0 of the RTPS protocol, "endpoints" used for user data communication are stored here.

Builtin "endpoints" are defined directly in `ORTEDomain` structure, there are nine of *CSTWriters* and *CSTReaders* used for CST protocol:

- `writerApplicationSelf`
- `readerManagers`
- `readerApplications`
- `writerManagers`
- `writerApplications`
- `writerPublications`
- `readerPublications`
- `writerSubscriptions`
- `readerSubscriptions`.

4.1.2 Version 2.2

Domain is abstract term involving communication of nodes that have something in common. The core structure in implementation of version 2.2 of RTPS protocol was therefore renamed to `ORTEDomainParticipant`. Following types persisted:

- `TaskProp`

- `TypeEntry`
- `ObjectEntry`

`TaskProp` has the same purpose as in previous implementation, just some of names changed to be more appropriate (see below).

`TypeEntry` remains completely same.

Because of substitution of *Host Id* and *Application Id* for *Guid Prefix*, `ObjectEntry` changed from 3-layered to 2-layered AVL tree ([7]), where the first layer corresponds to *Guid Prefix* and the second one to *Entity Id*. The root for *Hierarchical Timer* ([7]) is at the *Guid Prefix* layer.

`ORTEEndpoint` structure was added to `ObjectEntry` at the *Entity Id* layer. `ORTEEndpoint` can be *Stateless Writer* or *Stateless Reader* at present (see 4) and *Stateful Writer*, *Stateful Reader*, *Participant Proxy*, *Reader Proxy* and *Writer Proxy* will be added in the future. So one database containing all *Endpoints* in *Domain* is used for each *Participant* and there is no need for directly defined *Endpoints* or separate database of publishers and subscribers.

[orte:struct]

4.2 Structure Module

Examples of implementation of basic types used in RTPS protocol follow.

```
typedef uint8_t *GuidPrefix;
typedef uint32_t EntityId;
typedef struct {
  GuidPrefix guidPrefix;
  EntityId entityId;
} GUID_RTPS;
```

`*GuidPrefix` is pointer because of AVL tree [7] implementation.

```
typedef struct {
  int32_t               kind;
  uint32_t              port;
  uint8_t               address[16];
} Locator;
```

```
typedef struct {
  int32_t               seconds;         // time in seconds
  uint32_t              fraction;        // time in seconds / 2^32
} NtpTime;
```

Implementation follow Platform Specific Model (PSM) of the RTPS protocol introduced in [1].

4.2.1 Participant

In the correspondence to PIM (3.1) and as mentioned above, `ORTEDomain` structure changed to `ORTEDomainParticipant`:

```
struct ORTEDomainParticipant {
  uint32_t                    domainId;
  ObjectEntryEID              *myself;
  uint32_t                    participantId;

  GUID_RTPS                   guid;
```

```
  ProtocolVersion             protocolVersion;
  VendorId                    vendorId;

  Locator                     *defaultUnicastLocatorList;
  uint32_t                    defaultUnicastNumLocators;
  Locator                     *defaultMulticastLocatorList;
  uint32_t                    defaultMulticastNumLocators;
  Locator                     *sendingLocator;
  uint32_t                    sendingNumLocators;

  TaskProp                    taskRecvUnicastDiscoveryTraffic;
  TaskProp                    taskRecvMulticastDiscoveryTraffic;
  TaskProp                    taskRecvUnicastUserTraffic;
  TaskProp                    taskRecvMulticastUserTraffic;
  TaskProp                    taskSend;

  // db of types (ORTETypeRegister)
  TypeEntry                   typeEntry;
  // db of objects (ObjectEntryGP, ObjectEntryEID)
  ObjectEntry                 objectEntry;
};
```

Identifiers of `ORTEDomainParticipant` are `domainId`, `participantId` and `guid`, where `guid` is generated as discussed in [8]. The version of implementation is stored in `protocolVersion` and the vendor of implementation in `vendorId` attributes. *Domains* are distinguished by `domainId`, only *Participants* in the same *Domain* can communicate. *Participants* within the *Domain* are distinguished by `participantId`, so it's needed to be unique.

Locator Lists are implemented as pointers[1]) and corresponding number of elements. It's assumed that *Locator Lists* don't change frequently, so there is no need for AVL.

Task for sending data doesn't make a difference between *Discoverry*, *User*, *Unicast* nor *Multicast* traffic, there is only one socket, thread and `MessageBuffer` for data sending. However each kind of receiving traffic like *Unicast Discovery*, *Multicast Discovery*, *Unicast User* or *Multicast User* has it's own *Task* and so it's own socket, thread and `MessageBuffer`. This approach allows to process multiple kinds of traffic received on different ports at once.

Because `ORTEDomainParticipant` containing database of all *Entities* in *Domain* is shared between *Tasks* (and so between all threads), rwlock and mutex are used for this shared database of *Endpoints* and theirs related *Timers* stored in `objectEntry` in order to prevent multiple access. Attribute `*myself` is used to store pointer to the *Participant* in the database of all *Entities*.

The root for database of *Types* discussed above is `typeEntry`.

Basic functions for `ORTEDomainParticipant` are:

```
extern ORTEDomainParticipant *
  ORTEDomainParticipant_new(
      uint32_t domainId,
      uint32_t participantId
      );

extern void
```

[1]) In C, pointer can be understood as array with need for memory allocation.

```
  ORTEDomainParticipant_start(
      ORTEDomainParticipant *dp
      );

extern Boolean
  ORTEDomainParticipant_destroy(
      ORTEDomainParticipant *dp
      );
```

Where `ORTEDomainParticipant_new` and `ORTEDomainCreate` functions can be compared - both return core structure (`ORTEDomainParticipant` in version 2.2 and `ORTEDomain` in version 1.0) and initialize core attributes, structures and tasks.

The `ORTEDomainParticipant_start` function can be compared to `ORTEDomainStart` - both are used to start threads for corresponding *Tasks*.

The `ORTEDomainParticipant_destroy` and `ORTEDomainDestroy` functions can be compared - both are used to release sources related to the core structure.

4.2.2 Endpoints

Because *CSTWriter* evolves to *Stateful Writer* and *CSTReader* to *Stateful Reader*, new structures `StatelessWriter` and `StatelessReader` are introduced in correspondence to reference implementation.

```
struct StatelessWriter {
  // it's Entity
  GUID_RTPS              guid;

  // it's Endpoint
  TopicKind               topicKind;
  ReliabilityKind         reliabilityLevel;
  Locator                 *unicastLocatorList;
    uint32_t                unicastNumLocators;
  Locator                 *multicastLocatorList;
    uint32_t                multicastNumLocators;

  // it's Writer
  Boolean                 pushMode;
  Duration                heartbeatPeriod;
    HTimFncUserNode         heartbeatTimer;
  Duration                nackResponseDelay;
    HTimFncUserNode         nackResponseTimer;
  Duration                nackSuppressionDuration;
    HTimFncUserNode         nackSuppressionTimer;
  SequenceNumber          lastChangeSequenceNumber;

  // it's StatelessWriter
  Duration                resendDataPeriod;
    HTimFncUserNode         resendDataTimer;

  // Associations
  ul_list_head_t          writerCache;  // HistoryCache
  ul_list_head_t          readerLocators;

  // others
```

```
    gavl_node_t             node;  // StatelessPublications
    ObjectEntryEID          *objectEntryEID;
    ORTETypeRegister         *typeRegister;

    // HistoryCache
    SequenceNumber           firstSN;
    SequenceNumber           lastSN;
  };
```

Identifier of `StatelessWriter` is `guid`. *Writer* is *Endpoint* contained in *Participant*, therefore it has the same *Guid Prefix* and differs by *Entity Id*. Predefined *Entity Ids* are used for *Builtin Endpoints*. *Builtin Endpoints* differs from *User Endpoints* by the last octet (called entityKind) of *Entity Id*, see table 4.1. This description apply for each *Entity*.

Kind of Entity	User-defined Entity	Built-in Entity
unknown	0x00	0xc0
Participant	N/A	0xc1
Writer (with Key)	0x02	0xc2
Writer (no Key)	0x03	0xc3
Reader (no Key)	0x04	0xc4
Reader (with Key)	0x07	0xc7

[tab:entityId] **Table 4.1.** entityKind octet of an EntityId [1].

Attributes `topicKind`, `reliabilityLevel` and `pushMode` are discussed in 3.3.

Locator Lists and `NtpTime` or `Duration` attributes of *Writer* and their purpose is discussed in 3.1. For each `NtpTime` or `Duration` attribute, function can be inserted into *Hierarchical Timer* structure and automatically launched.

The *History Cache* is implemented as doubly linked list [7] with the head of `writerCache`.

Reader Locator wasn't introduced yet. It is auxiliary structure used by *Stateless Writer* to store information about where to send data. However it mustn't be confused with *Reader Proxy* of *Stateful Writer*, because *Reader Locator* doesn't store any information about *Endpoint*, just *Locator* (IP address, port, kind), if Qos should be included and requested and unsent *Cache Changes* needed for RELIABLE *Reliability Level*. List of *Reader Locators* is implemented as doubly linked list [7] with the head of `readerLocators`.

The remaining attributes are mostly auxiliary - `node` is needed because of AVL tree impementation, `*objectEntryEID` is pointer to *Writer* in database of all *Entities*, `firstSN` and `lastSN` are *Sequence Numbers* related to *History Cache*. Attribute `*typeRegister` is pointer to *Type* associated with *Writer*, which is used to serialize and deserialize *Data Object* related to *Writer*.

```
  struct StatelessReader {
    // it's Entity
    GUID_RTPS                guid;

    // it's Endpoint
    TopicKind                topicKind;
    ReliabilityKind          reliabilityLevel;
    Locator                  *unicastLocatorList;
```

```
    uint32_t                unicastNumLocators;
  Locator                  *multicastLocatorList;
    uint32_t                multicastNumLocators;

  // it's Reader
  Boolean                  expectsInlineQos;
  Duration                 heartbeatResponseDelay;
    HTimFncUserNode         heartbeatResponseTimer;
  Duration                 heartbeatSuppressionDuration;
    HTimFncUserNode         heartbeatSuppressionTimer;

  // it's StatelessReader

  // Associations
  ul_list_head_t           readerCache;  // HistoryCache

  // others
  gavl_node_t              node;
  ObjectEntryEID           *objectEntryEID;
  ORTETypeRegister         *typeRegister;
};
```

Attributes of *Stateless Reader* have the same meaning as attributes of *Stateless Writer* but `expectsInlineQos` is added, claiming demand of *DDS Reader* for including Qos along with data.

4.2.3 History Cache

The content of *History Cache* is made by *Cache Changes* - the replacement of *CSChange*, which is used as "transfer unit" for all data exchanges in RTPS 2.2. Because *History Cache* is implemented as doubly linked list [7], there is no special structure for *History Cache*. The next is the structure of *Cache Change*.

```
struct CacheChange {
  // it's CacheChange
  ChangeKind               kind;
  GUID_RTPS                writerGuid;
  InstanceHandle           instanceHandle;
  SequenceNumber           sequenceNumber;

  // Associations
  uint8_t                  *data_value;
  ul_list_head_t           inlineQos;

  // Backward Associations
  ul_list_node_t           nodeListHistoryCache; // for StatelessWriter
  ul_list_node_t           nodeListRequestedChanges; // for ReaderLocator
  ul_list_node_t           nodeListUnsentChanges;    // for ReaderLocator
};
```

Attributes of *Cache Chage* are discussed in 3.1. The pointer to *Data Object* of user *Application* is stored in `*data_value` attribute.

Inline Qos is sent as *Parameter List*, the sequence of *Parameters*. Each *Parameter* has it's own *Id*, *Length* and *Data*, following structure is used for implementation.

```
typedef struct {
  ul_list_node_t  node;   // for inline Qos
  int16_t         id;
  int16_t         length;
  union{
    CORBA_unsigned_long   ulong;
    CORBA_long            slong;
    CORBA_boolean         boolean;
    NtpTime               time;
    ProtocolVersion       pv;
    VendorId              vid;
    Locator               locator;
    uint32_t              ipv4;
    uint32_t              port;
    struct {
      uint8_t guidPrefix[12];
      EntityId entityId;
    } guid;
    uint32_t              eid;
    uint8_t               keyHash[16];
    uint8_t               statusInfo[4];
    uint8_t               str[MAX_PARAMETER_LOCAL_LENGTH];
  } value;
  uint8_t         *p_value;
} Parameter;
```

Inline Qos is implemented as doubly linked list [7] of *Parameters*. This approach is same as in version 1.0, only `ParameterSequence` name changed to `Parameter` and attributes of *Parameter* changed to correspond to version 2.2 types.

Backward associations are needed for doubly linked list [7] implementation.

The implementation of *History Cache* remains the same - it's implemented as doubly linked list [7]. This manner allows to save memory by maintaining only one *Cache Change*, pointed from more structures as multiple matched *Reader Proxy* or *Writer Proxy*.

4.2.4 Proxy Entities

While the name changed for *CSTRemote Reader* and *CSTRemoteWriter* to *Reader Proxy* respective *Writer Proxy*, the function of this *Endpoints* remains the same. *Participant Proxy*, *Reader Proxy* and *Writer Proxy* stores important attributes of *Participant*, *Reader* respective *Writer*.

[orte:message]

4.3 Messages Module

Generally for *Submessages*, name of the function responsible for processing of *Submessage* was changed by adding `Process` to the name (e.g. `RTPSInfoDST` function name changed to `RTPSInfoDSTProcess`).

4.3.1 Header

Because of substitution of *Host Id* and *Application Id* for *Guid Prefix* (3.5), the *Header* of RTPS messages is changed appropriately - instead of 4B for *Host Id* and 4B for *Application Id*, 12B for *Guid Prefix* are sent. The *Header* length is therefore resized to 20B.

4.3.2 Submessage Header

For *Submessages*, new structure `SubmessageHeader` is defined.

```
typedef struct {
  SubmessageKind kind;
  uint8_t flags;
  uint16_t length;
} SubmessageHeader;

#define PUT_SHEADER(submessageHeader)                  \
  do {                                                 \
    CDR_put_octet(cdrCodec, (submessageHeader).kind);      \
    CDR_put_octet(cdrCodec, (submessageHeader).flags);  \
    CDR_put_ushort(cdrCodec, (submessageHeader).length); \
  } while(0)
```

When *Submessages* are sent, predefined macro `PUT_SHEADER(submessageHeader)` ensures putting the *Submessage Header* "on the wire" in contrast to version 1.0 implementation, where local variables `flags`, `len`, `length` and global structure `SubmessageId` were used.

When receiving, *Submessage Header* is got "from the wire" only once in the thread of the receiving task. The pointer to `SubmessageHeader` and other pointers to `MessageInterpret` and `CDR_Codec` structures are then forwarded to the *Process* function of particular *Submessage*, preventing rewinding of `CDR_Codec`'s buffer and reading *Submessage Header*'s information again.

4.3.3 Message Interpret

According to *Guid Prefix* and *Locator* changes (3.5), `MessageInterpret` structure is changed - *Host Id* and *Application Id* are substituted by *Guid Prefix* and *Reply IP Addresses* are substituted by *Reply Locators Lists*. Also processing and updating of *Message Interpret* was changed accordingly.

```
typedef struct {
  ProtocolVersion         sourceVersion;
  VendorId                sourceVendorId;
  GuidPrefix              sourceGuidPrefix;
  GuidPrefix              destGuidPrefix;
  Locator                 *unicastReplyLocatorList;
    uint32_t                unicastReplyNumLocators;
  Locator                 *multicastReplyLocatorList;
    uint32_t                multicastReplyNumLocators;
  Boolean                 haveTimestamp;
  NtpTime                 timestamp;
} MessageInterpret; // is Message Receiver in RTPS2.2
```

4.3.4 Data Submessage

New **Data** *Submessage* is introduced in version 2.2 of the RTPS protocol. Two functions for **Data** *Submessage* are defined.

```
extern int
  RTPSDataCreate(
      CDR_Codec *cdrCodec,
      CacheChange *cc,
```

```
        EntityId readerId
        );

  extern int
    RTPSDataProcess(
        CDR_Codec *cdrCodec,
        MessageInterpret *mi,
        SubmessageHeader *sh,
        TaskProp *tp
        );
```

Where `RTPSDataCreate` function is used to create **Data** *Submessage* based on *Cache Change* and put the *Submessage* "on the wire". `RTPSDataCreate` function is used by sending thread represented by `taskSend` of `ORTEDomainParticipant`.

Processing of **Data** *Submessage* is ensured by `RTPSDataProcess` function. The *Submessage* is got "from the wire" and delivered to target *Reader*. All receiving threads will use this function whenever **Data** *Submessage* is received.

[orte:behavior]

4.4 Behavior Module

In order to enable communication, *Writer* and *Reader Endpoints* needs to be added to database of all *Endpoints* of the *Participant* and initialized. The function `objectEntryAdd` is used for the first task, functions used for the second one are `StatelessWriter_init` and `StatelessReader_init`.

4.4.1 Stateless Writer

When the *Writer* is in database of all *Endpoints* and it's attributes are initialized, following are steps necessary for proper functionality of the *Writer*.

- *Reader Locators* needs to be added
- *Cache Change* needs to be added
- *Resend Data Timer* needs to be launched

`StatelessWriter_readerLocatorAdd` function is used to associate *Reader Locator* with the *Stateless Writer*. *Reader Locator* is needed for information about where to send *Cache Changes* in the sense of IP address and port[1]).

`StatelessWriter_initChange` is used to initialize new *Cache Change*. Memory allocation have to precede this initialization and pointer to `CacheChange` is then forwarded to init function. The purpose of this approach is to prevent problems of storing *Cache Changes* on different memory stacks. Finally, `StatelessWriter_addChange` is used to associate new *Cache Change* with the *Writer*.

`StatelessWriter_resendDataTimer` function is used to schedule periodic sending of *Cache Changes* by calling `ORTESendData` function and adding itself with period of `resendDataPeriod` to event system of ORTE implemented as *Hierarchical Timer* [7].

4.4.2 Stateless Reader

Because the *Stateless Reader* is completely passive *Endpoint*, there are no special steps necessary for proper functionality. When the *Reader* is added to database of all *Endpoints* and initialized, it can be reached by each *Task*.

[1]) It shouldn't be confused with information about where to send data in the sence of destination GUID used in *Stateful Reference Implementation*.

[orte:discovery]

4.5 Discovery Module

In order to be interoperable with other implementations, ORTE must support SPDP and SEDP. Because **Data** *Submessages* are used for user traffic as well as for discovery traffic, only difference between *User Application* and SPDP respective SEDP would be predefined *Entity Ids* denoting builtin *Endpoints*.

4.5.1 SPDP

The approach to implement SPDP is almost same as implementing *User Application* - new *Type* is registered with name *SPDPdiscoveredParticipantData*, serialize and deserialize functions are defined and new *Writer* and *Reader* are added. As an *Data Object*, `ORTEDomainParticipant` is used.

Proper data encapsulation is needed because of interoperability between implementations. Encapsulation for SPDP traffic is discussed in [1], approach similar to transfer of *Inline Qos* is used - *SPDPdiscoveredParticipantData* is encapsulated as *Parameter List*, each attribute correspond to one *Parameter*.

`SPDPdiscoveredParticipantData_serialize` function is used to serialize information about `ORTEDomainParticipant` into *Parameter List* and put it "on the wire".

`SPDPdiscoveredParticipantData_deserialize` function is used to deserialize information about remote *Participant* "from the wire" and store this *Participant* and it's available *Endpoints* in `objectEntry`[1]) of `ORTEDomainParticipant`.

For SPDP, best-effort communication is required and therefore *Stateless Reference Implementation* is used. *Stateless Writer* and *Stateless Reader* with *SPDPdiscoveredParticipantData Type* are initialized in `RTPSSPDP_start` function used to enable SPDP.

4.5.2 SEDP

For SEDP, the approach is similar to SPDP implementation, except different *Types* as *DiscoveredWriterData* and *DiscoveredReaderData* are registered. Encapsulation as *Parameter List* remains the same.

Also reliable communication is required for SEDP, so *Statefull Reference Implementation* may be used. SEDP is not implemented yet (see 4).

[1]) The root of database of all *Endpoints*.

[test]

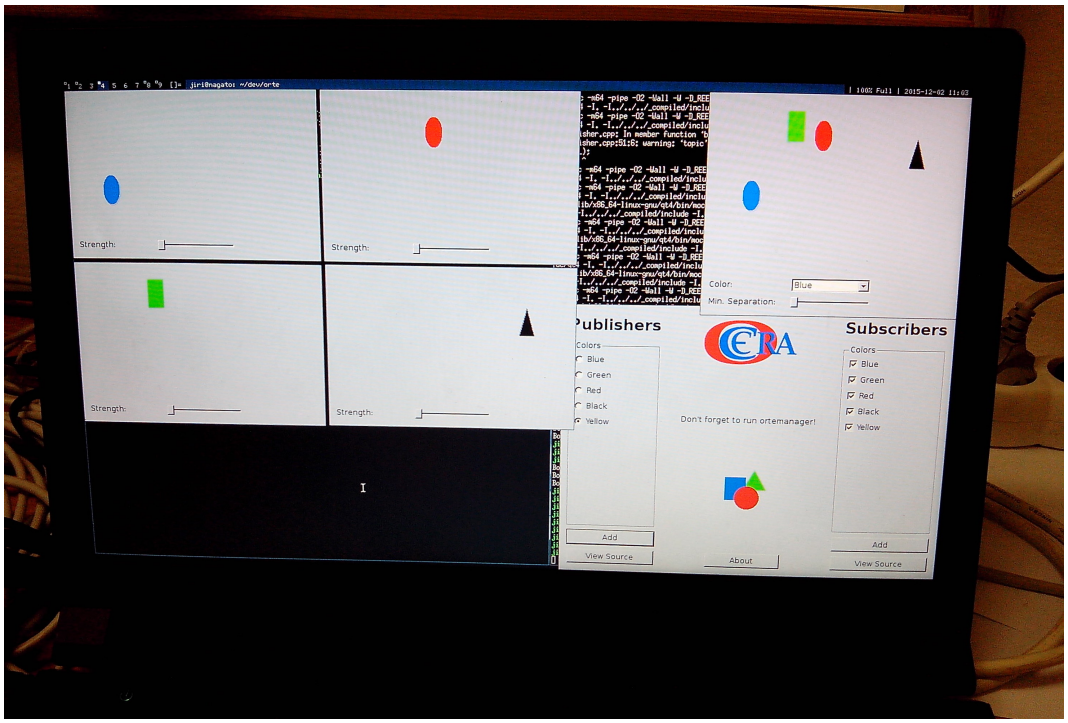
Chapter 5
Testing of implementation

[shape]

Chapter 6
Shape for Android

6.1 Shape demo

With ORTE implementation of RTPS 1.0 protocol, demo application called Shape is delivered. Shape demo demonstrates the functionality of ORTE - when the color (Blue, Green, Red, Black, Yellow) is choosen, the *Publisher* is created as random shape (Circle, Square, Triangle) moving on the screen. Then, under the topic of color name, object's shape, color and coordinates are published to the network. It's possible to receive and interpret object's data (to see colored shapes moving on the screen) by adding the *Subscribers* of specific topics (colors).



[pic:shape1] **Figure 6.1.** Shape demo - *Publishers* and *Subscribers*

6.2 Familiarization with ORTE

The familiarization with ORTE was done by creating demo application for Android compatible with Shape. Because the port of ORTE to Android has been already done in [5] and is available as library, the main task was compatibility ensurance. The application was designed to be as simple as possible. *Publishers* view allows to create new *Publisher* of specific color and random shape, *Subscribers* view allows to set up *Subscribers* of specified colors. Finally, Settings and Help views are present.

6.3 Classes

As in Shape demo, in Shape for Android the `BoxType` class is presented, allowing to create, send and receive objects. `BoxType` consists of `color` (integer), `shape` (integer) and `rectangle` (`BoxRect`), where `BoxRect` is class for storing coordinates - `top_left_x` (short), `top_left_y` (short), `bottom_right_x` (short), `bottom_right_y` (short). The `BoxType` is extension of *MessageData* class delivered with ORTE library for Android. It allows to send and receive objects.

`PublisherShape` class stores `BoxType` information about *Publisher*, it's properties needed for ORTE, methods for communication with object and prepares data to send. In *Publisher* view, *Publisher* objects are created, stored in *Array List* and drawed on screen. Data objects are sent in *Publisher* activity each time objects are redrawn.

`SubscriberElement` class receives `BoxType` object from ORTE and stores it's data and methods needed for presentation. In *Subscriber* view, all received objects are stored in *Array List* and periodically redrawn.

It's good practice [9] to include *Settings* and *Help* in Options Menu. In *Settings*, scaling needed because of various screens dimensions and the list of managers[1]) can be set and *Help* contains information about ORTE, Shape and application usage.

6.4 Compatibility

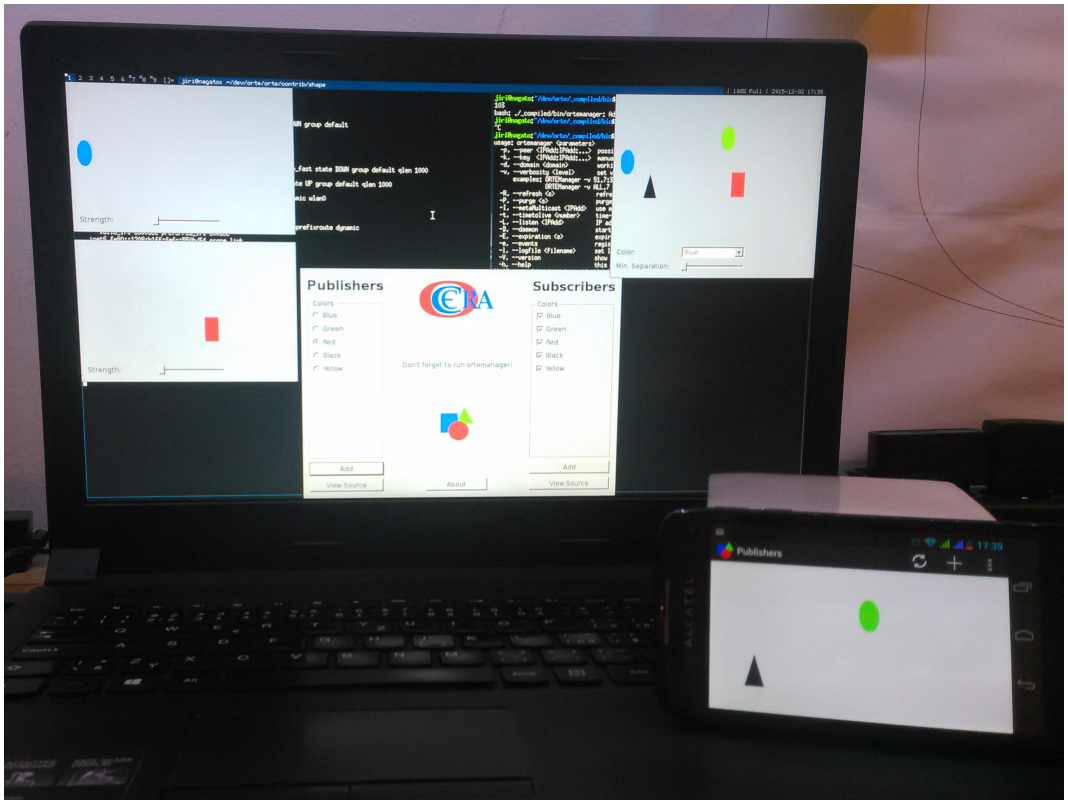
`BoxType` in Shape and Shape for Android is a little bit different. The reason is just familiarization with ORTE implementation and RTPS protocol, where misunderstooding was not fully avoided. Suggestions for improvements follows.

The first property of `BoxType` is `color`. In Shape demo, `color` is typed as CORBA_octet (macro for uint8_t, 1 byte) and in Shape for Android, `color` is of integer type (4 bytes). The reason why this approach does not break the compatibility is following: each data-type serialized by CORBA is aligned to 4 byte boundary. In this case, object color is first byte and the rest until the boundary is filled by zero bytes. This data representation corresponds to Little Endian in which the message is encoded by default (endianness is operating system dependent), so when Shape for Android deserialize data, Little Endian encoded integer is obtained. It also works in opposite direction - value of the `color` is serialized as integer, encoded as Little Endian and on the side of Shape demo, CORBA_octet is deserialized and 3 zero bytes skipped because of boundary alignment. The problem could arise when `color` would be sent as integer with Big Endian encoding and received as CORBA_octet, because the value of the first byte would be then zero. Also, the problem wouldn't persist in the opposite direction, because endianness is always part of the RTPS message so even node with Big Endian default encoding would receive Little Endian encoded message correctly.

The second property of `BoxType` is `shape`. The type in Shape demo is CORBA_long (macro for int32_t, 4 bytes) and integer (4 bytes) in Shape for Android. Therefore there is no problem with `shape` property.

The last property of `BoxType` is `BoxRect` consisting of coordinates of object. Each value of `BoxRect` is CORBA_short type (2 bytes) in Shape demo and short type (2 bytes) in Shape for Android. Because `BoxRect` is presented as CORBA autonomous data-type, the whole data-type (8 bytes) is aligned to 4 bytes boundary.

[1]) In RTPS 1.0 special application called manager is used for communication of available *Publishers/Subscribers* between nodes. In RTPS 2.2 Simple Participant Discovery Protocol (SPDP) and Simple Endpoint Discovery Protocol (SEDP) are used.



[pic:shape2] **Figure 6.2.** Shape for Android - Publishers view

The suggestion for the future improvement of Shape demo and Shape for Android is the revision of `BoxType` data-type.

[sec]

Chapter 7
Security for DDS

Nowadays, security is often considered. Technologies for securing communication differs by TCP/IP layers [10] - security at Media access layer consists of preventing deterioration of physical media, environmental noise and access to media. At Network layer, IPsec (IP Security Architecture) protocol is used while Transport layer uses TLS (Transport Layer Security) protocol. In this chapter, Application layer security for DDS standard [11] and possibilities of implementation in RTPS protocol are considered.

7.1 Threats

From point of view of DDS standard, communication takes place in the domain consisting of participants with various number of publishers and subscribers. In this context, Application layer security threats are following:

- Unauthorized[1]) subscription
- Unauthorized publication
- Tampering and replay
- Unauthorized access to data

Unauthorized subscription is a situation when malicious participant receives data for which it is not allowed to. In network infrastructure where access to media is shared, communication runs over multicast or participants sits on one node, it's practically unavoidable to restrict access to data. The solution is making data unreadable for malicious participant - in other words, applying encryption on publisher's side and sharing keys with authenticated subscribers only.

When malicious participant attempts to send data which it is not allowed to, it's called *Unauthorized publication*. For subscriber it's important to receive data only from valid publishers to avoid influence of malicious participant on data. The solution is to include authentication information to data sent by valid publishers so subscribers would be able to recognize data by authenticated publishers from data sent by malicious participant. Authentication of publishers in data can be accomplished by Hash-based message authentication code (HMAC) or by digital signature. HMAC creates authentication code using secret key shared between publisher and subscriber. Digital signature is based on private/public key pair - authentication code is created as message digest encrypted by private key of publisher. Each subscriber has access to public key of publisher and can use it to decrypt the authentication code to message digest and compare it with message digest calculated by itself. The point is that these two message digests equals if and only if the authentication code is encrypted by publisher's private key and decrypted by publisher's public key. Digital signature is called *asymmetric cryptography* (private/public key pair) and is much slower then *symmetric cryptography* (shared key), therefore the use of HMAC is preferred because of performance reasons.

[1]) Difference between authentication and authorization has to be clear. Authentication is verification of (in this context) participant - that the participant is really the one it claims to be. On the other hand, authorization is process of allowing access to data for already authenticated participant.

Valid publisher would send data to subcsriber and malicious participant (in this case, malicious participant will be allowed to subscribe but not to publish). However if the same key is shared between publisher, subscriber and malicious paritcipant, there is no way how to prevent malicious participant to use this shared key for mimicking publisher and sending data to subscriber. This threat is called *Tampering and Replay* and can be solved by sharing different keys between publishers and subscribers. When the communication is taken over multicast, multiple HMACs are needed to be included in data, but this solution is still more powerful than using digital signatures.

In the DDS network, some participants acts as relay participants forwarding data. These participants need to be trusted as valid publishers and subscribers, but it's not always desirable to let them understand data they work with. The solution for *Unauthorized Access to Data* is having different keys for HMAC and data encryption and to share keys for decrypting of data only with desired endpoints.

7.2 Securing of messages

Securing of messages is application dependent - sometimes it's sufficient to encrypt only user-data, in other applications, submessage's metadata as sequence numbers or writer/reader identifiers are needed to be secured too and in the most secure applications, the whole metatraffic submessages are considered confidential. In order to support of different application scenarios, mechanism called *Message Transformation* is introduced. It transforms one RTPS message into another RTPS message so that the original RTPS message or it's submessages may be encrypted into the new one and protected by HMAC.

Because of *Message Transformation*, new submessages and submessage elements are introduced and the questions about interoperability between secured and non-secured implementations of RTPS protocol arises. In implementations of RTPS protocol, unknown submessages should be skipped so the regular user-traffic should not be affected, but there is Discovery also. SPDP is used by DomainParticipants to discover each other, informations as IP address, port, vendor and version are exchanged to bootstrap the communication. Therefore it makes no sense to protect SPDP communication, better to use it for exchange of informations needed to bootstrap the secured system. For both - secured and non-secured implementations of RTPS protocol, *DCPSParticipants* Topic is used in SPDP and there is no new secured Topic for SPDP.

SEDP protocol is used for discovering *publishers* and *subscribers* of each DomainParitcipant. The *DCPSPublications* and *DCPSSubscriptions* Topics are used for communication with non-secured endpoints. However for DomainParticipants supporting DDS Security, *DCPSPublicationsSecure* and *DCPSSubscriptionsSecure* Topics and associated DataWriters (*SEDPbuiltinPublicationsSecureWriter*, *SEDPbuiltinSubscriptionsSecureWriter*) and DataReaders (*SEDPbuiltinPublicationsSecureReader*, *SEDPbuiltinSubscriptionsSecureReader*) are introduced. These Topics should be used for communication that is considered sensitive.

In RTPS protocol, Writer Liveliness Protocol is specified and because data exchange by this protocol could be considered sensitive, DDS Security specifies alternate protected way to exchange liveliness information. *BuiltinParticipantMessageWriter* and *BuiltinParticipantMessageReader* are used to communicate liveliness information with non-secured endpoints. *ParticipantMessageSecure* Topic is introduced with associated *BuiltinParticipantMessageSecureWriter* and *BuiltinParticipantMessageSecureReader*, used to communication liveliness information with endpoints considered sensitive.

Also, there are two completely new builtin Topics:

- ParticipantStatelessMessage
- ParticipantVolatileMessageSecure

ParticipantStatelessMessage Topic is used to perform mutual authentication between DomainParticipants. While the mechanism for participant-to-participant communication already exists, it suffers from weakness of reliable protocol - sequence number prediction. HeartBeat messages containing *first available sequence number* can be abused by malicious participant to prevent other participants to communicate. Therefore new Topic *ParticipantStatelessMessage* with associated *BuiltinParticipantStatelessMessageWriter* (Best-Effort StatelessWriter) and *BuiltinParticipantStatelessMessageReader* (Best-Effort StatelessReader) is introduced.

For key exchange between DomainParticipants, reliable and secure communication is needed. On top of that, DURABILITY Qos needs to be VOLATILE to address only DomainParticipants that are currently in the system. *ParticipantStatelessMessage* is not suitable because it's not reliable nor secured. *ParticipantMessageSecure* Topic is not suitable because it's QoS has DURABILITY kind TRANSIENT_LOCAL rather than VOLATILE (which is required). So new Topic *ParticipantVolatileMessageSecure* with associated *BuiltinParticipantVolatileMessageSecureWriter* and *BuitinParticipantVolatileMessageSecureReader* is introduced.

7.3 Plugin architecture

There are five SPIs:

- Authentication
- Access-Control
- Cryptographic
- Logging
- Data Tagging

Interactions of plugins are shown in figure 7.1.

7.3.1 Authentication plugin

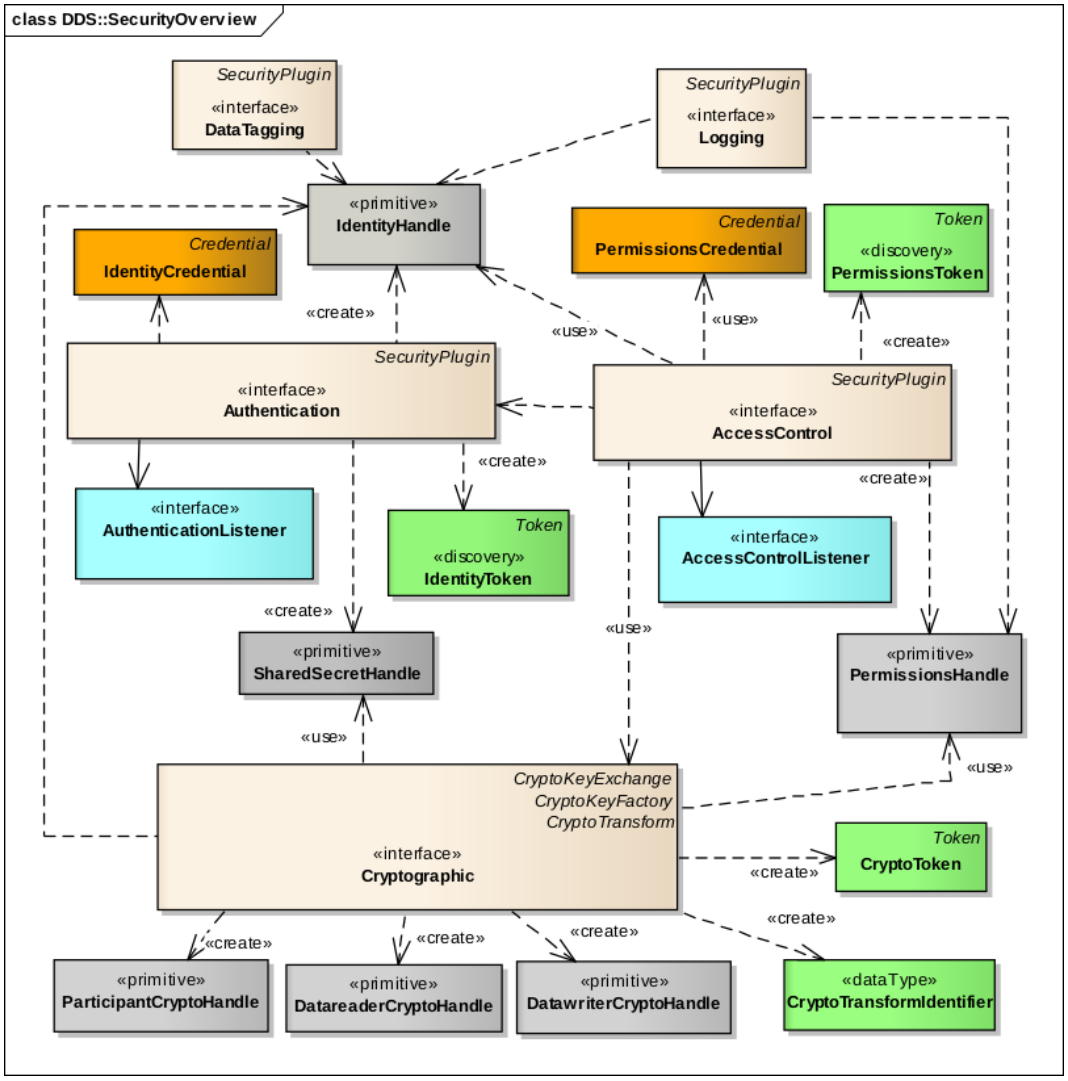
Authentication is process of verifying that (in this case) DomainParticipant is really the one it claims to be. DomainParticipant is authenticated when joining a DDS Domain, mutual authentication is supported and shared secret is established between DomainPariticpants.

7.3.2 Access Control plugin

Ensures authorization - allows or deny protectected operations of DomainPariticipant as join domain, create Topic, publish to Topic or subscribe Topic.

7.3.3 Cryptographic plugin

Encryption, decryption, digests, MAC, HMAC, key generating and exchange, signing and verifying of signatures is ensured by *Cryptographic plugin*. The plugin API has to be general enough to allow specific requirements for cryptographic libraries, encryption and digest algorithms, message authentication and signing users of DDS may need to deploy.



[pic:sec-pa] **Figure 7.1.** Plugin Architecture Model

7.3.4 Logging plugin

This plugin logs security events of DomainParticipant. Two options of collecting log data are logging all events to a local file and distributing log events securely over DDS.

7.3.5 Data Tagging plugin

Classification of data is performed by *Data Tagging plugin*. It can be used for access control based on tag, message prioritization or even don't have to be used by middleware (RTPS implementation), but by application or service. There are four kinds of tagging:

- Data Writer - used in specification, data received from DataWriter has it's tag.
- Data Instance - each instance of the data has a tag.
- Individual sample - each sample of data instance is tagged individually.
- Per field - the most complex method of tagging.

7.4 Interoperability

Out-of-the-box interoperability of DDS Security implementations is ensured analogously to RTPS implementations - while mandatory *builtin endpoints* ensures that each DomainParticipant is able to discover other DomainParticipants, in DDS Security implementations, each DomainParticipant is able to secure data by at least mandatory *builtin plugins*.

7.4.1 Requirements

This is resume of requirements for builtin plugins by out-of-the-box interoperability as presented in chapter 9.2 of [11]. Following are essential functional requirements for builtin plugins:

- Authentication of DomainParticipants joining a domain
- Access control of applications subscribing to data
- Message integrity and authentication
- Encryption of a data by different keys

Following are functions that should be required by builtin plugins:

- Sending digitally signed data
- Sending data securely over multicast
- Data tagging
- Integrating with open standard security plugins

Following are functions considered useful:

- Access control to certain samples
- Access control to certain attributes within sample
- Permissions for QoS usage by DDS Entities

Non-functional requirements are:

- Performance and Scalability
- Robustness and Availability
- Fit to DDS Data-Centric Information Model
- Reuse of existing security infrastructure and technologies
- Ease of use

7.4.2 Considerations

Usually DDS is deployed in systems where high performance for large number of DomainParticipants is needed, therefore actions performed by plugins shouldn't notably degrade system performance. In practice it means that asymmetric cryptography should be used only for discovery, authentication, session and shared-secret establishment, symmetric cryptography shoud be used for data, use of ciphers, HMACs or digital signatures should be selectable per Topic, there should be possibility of providing integrity via HMAC without data encryption and there should be support for encrypted data over multicast.

DDS used to be deployad in system where *robustness and availability* is considered critical. It's required from system to continue operating even if partial fail occures, so centralized services reprezenting single point of failure have to be avoided, DomainParticipant components have to be self-contained to be able to operate securely, multi-party

key agreement protocols should be avoided because of simplicity of discruption and tokens and keys should be compartmentalized as much as possible to avoid situations where multiple applications using same key are compromised if just one of them is compromised.

7.5 Implementation

The implementation of DDS Security into ORTE consists of changes in Modules (presented in chapter 8 of [1]). Introduction of *SecureSubMsg* Submessage and *SecuredPayload* Submessage Element assumes modification of Message Module, Discovery Module is affected by *Builtin Secure Endpoints* - if configured to, discovery of *publishers* and *subscribers* is secured and Behavior Module needs to be modified to include *Builtin Plugins* which ensures security.

7.5.1 Builtin Endpoints

This is the list of *Builtin Endpoints* presented in chapter 7.4.5 of [11]. In order to ensure out-of-the-box compatibility, following *Builtin Secure Endpoints* needs to be implemented:

- SEDPbuiltinPublicationsSecureWriter
- SEDPbuiltinPublicationsSecureReader
- SEDPbuiltinSubscriptionsSecureWriter
- SEDPbuiltinSubscriptionsSecureReader
- BuiltinParticipantMessageSecureWriter
- BuiltinParticipantMessageSecureReader
- BuiltinParticipantVolatileMessageSecureWriter
- BuiltinParticipantVolatileMessageSecureReader

7.5.2 Builtin Plugins

This is resume of *Builtin Plugins* presented in chapter 9.1 of [11]. In order to ensure out-of-the-box compatibility, following *Builtin Plugins* needs to be implemented:

- DDS:Auth:PKI-RSA/DSA-DH (Authentication plugin)
  - Uses PKI with pre-configured shared Certificate Authority
  - RSA or DSA and Diffie-Hellman for authentication and key exchange
- DDS:Access:PKI-Signed-XML-Permissions (Access control plugin)
  - Permissions document signed by shared Certificate Authority
- DDS:Crypto:AES-CTR-HMAC-RSA/DSA-DH (Cryptographic plugin)
  - AES128 for encryption (counter mode)
  - SHA1 and SHA256 for digest
  - HMAC-SHA1 and HMAC-256 for HMAC
- DDS:Tagging:DDS_Discovery (Data Tagging plugin)
  - Send Tags via Endpoint Discovery
- DDS:Logging:DDS_LogTopic (Logging plugin)
  - Logs security events to a dedicated DDS Log Topic

[concl]

Chapter 8
Conclusion

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Appendix A
Symbols

AES	Advanced Encryption Standard
API	Application Programming Interface
CDR	Common Data Representation
CORBA	Common Object Request Broker Architecture
CST	Composite State Transfer
CTR	Counter
DCPS	Data-Centric Publish-Subscribe
DDS	Data Distribution Service
DH	Diffie-Hellman
DSA	Digital Signature Algorithm
GUID	Globally Unique Identifier
HMAC	Hash-based Message Authentication Code
IP	Internet Protocol
IPsec	IP Security
LSB	Least Significant Bit
MAC	Message Authentication Code
MSB	Most Significant Bit
MTU	Maximum Transmission Unit
OMG	Object Management Group
ORTE	Open Real-Time Ethernet
PIM	Platform Independent Model
PKI	Public Key Infrastructure
PSM	Platform Specific Model
RSA	Rivest Shamir Adleman
RTPS	Real-Time Publish-Subscribe
SEDP	Simple Endpoint Discovery Protocol
SHA	Secure Hash Algorithm
SPDP	Simple Participant Discovery Protocol
SPI	Service Plugin Interface
TCP	Transmission Control Protocol
TLS	Transport Layer Security
UDP	User Datagram Protocol
XML	EXtensible Markup Language

[app:cd]

Appendix B
Attached CD

- hubacek_orte.pdf
- documentation_diagram.svg

[app:dia]

Appendix C
Documentation Diagram

Requests for correction