

An Application Framework for the IEEE 1588 Standard

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Abstract: This paper introduces an application framework for the Institute of Electrical and Electronics Engineers (IEEE) 1588 standard. This application framework, developed at the National Institute of Standards and Technology (NIST), consists of five layers: hardware layer, operating system layer, middleware and tools layer, IEEE 1588 layer, and application layer. A prototype application system has been developed based on the established IEEE 1588 application framework using the Unified Modeling Language (UML) tool. A case study of the IEEE 1588 Delay Request-Response mechanism based on the application framework is presented. The object-oriented application framework can ease integration and simplify the development of new IEEE 1588 applications by reducing the amount of time and errors to design and develop the IEEE 1588 standard infrastructure. Another benefit of this application framework is to enable developers to achieve standards compliance more readily.

Keywords: Application framework, IEEE 1588, Object-oriented framework, UML

I. INTRODUCTION

The Institute of Electrical and Electronics Engineers (IEEE) 1588 standard defines a precision time protocol (PTP) enabling precise synchronization of clocks in measurement and control systems implemented using distributed architectures comprised of evolving technologies in network communication, localized computing and distributed objects [1-2]. The IEEE 1588 protocol is applicable to distributed measurement and control systems consisting of two or more nodes communicating over a network. Figure 1 shows an example of clock synchronization based on a packet network. The slave clocks can synchronize with the master clock through packet network communications. Most measurement systems share similarities in the fundamental components. However, these systems are often developed from scratch, without reusing the available designs and implementations [3]. Since these designs are also costly to implement, object-oriented development (OOD) promises to increase code reuse while reducing development time and cost. A framework is a reusable application foundation that can be customized for a particular customer application [4, 5]. An object-oriented framework provides an important enabling technology for reusing software components [6]. Object-oriented frameworks allow reusing analysis, design, implementation,

and testing for applications within a certain domain or a certain family of problems [7]. The object-oriented framework focuses on code and design reuse. Hence the object-oriented development methodology plays a key role in the design of the framework. The object-oriented methodology, when applied to application frameworks, enables higher productivity and shorter time-to-market of application development.

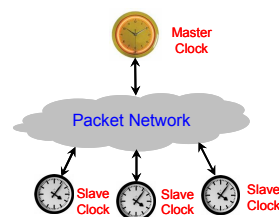


Fig. 1. Example of clock synchronization.

The Unified Modeling Language (UML) was designed to be compatible with the leading object-oriented software development methods [8]. UML is a powerful tool for object-oriented modeling and design, and development of complex software systems. Developing an application framework for the IEEE 1588 standard using UML significantly reduces the development time of IEEE 1588 applications. The current implementation focuses on the IEEE 1588 layer and application layer. Section II discusses related works. In section III, an application framework for the IEEE 1588 standard is described. Section IV shows a prototype system of an IEEE 1588 application. The conclusion is provided in Section V.

II. RELATED WORKS

The use of application frameworks is a promising approach for reusing and integrating proven software designs and implementations in order to reduce the cost and improve the quality of software. The framework concept can be found in Smalltalk** systems, which has been attributed as the first widely used framework [9]. MacApp was Apple Computer's primary object-oriented application framework for the Mac operating system during the 1990s [10]. An object-oriented framework is also used for developing distributed applications [11]. Object-oriented real-time frameworks have been used for building distributed real-time control systems in robotics and automation [12]. A framework-based approach to real-time development is used for code

generation in the Rhapsody UML tool [13]. An object-oriented framework is used for developing distributed manufacturing architectures [14]. Roberts & Johnson describe the evolution of a framework as starting from a white-box framework that is reused by sub-classing, and developing into a black-box framework that is mostly reused through parameterization [15]. Hayase introduced a three-view model for developing object-oriented frameworks. The three-view model consists of a domain analysis view, a layer view, and a mechanism view. The layer view is used to divide a framework into three layers: an infrastructure layer, a generic layer, and a domain layer [16]. Bosch describes a framework consisting of a core framework design, and its associated internal increments with accompanying implementation, such as framework internal increments and application specific increment [17]. The verifiable embedded real-time application framework (VERTAF) is an object-oriented application framework for embedded real-time systems [18]. An object-oriented application framework for the IEEE 1451.1 standard has been established [19]. Specifier, extractor, scheduler, allocator, and generator (SESAG) is an object-oriented application framework for real-time systems [20]. Becker introduces an object-oriented framework for the development of real-time industrial automation systems [21]. In summary, object-oriented application frameworks have been widely used in many different domain and cross-domain applications, especially in distributed real-time measurement and control systems.

III. APPLICATION FRAMEWORK FOR IEEE 1588 STANDARD

A. Architecture of Application Framework for IEEE 1588 Standard

A software framework is a code library that is designed to help software development and a reusable design for a software system or subsystem [22]. A software framework may consist of support programs, code libraries, a scripting language, or other software to help develop and integrate heterogeneous components of a software project. The various parts of the framework may be exposed through an Application Programming Interface (API). An application framework is a software framework that is used to implement the standard structure of an application for a specific application [23]. Figure 2 shows the layer architecture of an application framework for the IEEE 1588 standard. This framework consists of five layers: hardware layer, operating system layer, middleware and tools layer, the IEEE 1588 layer and the application layer.

- The hardware or firmware layer focuses on which hardware can be used to deploy IEEE 1588 standard applications. The hardware may include those from Freescale**, Hirschmann, Imsys, National Semiconductor,

Symmetricon, or other manufacturers of IEEE 1588 compliant hardware.

- The operating system layer focuses on the platform or operating system to which applications can be ported, such as, but not limited to, Windows (NT/2000/XP/Vista), Linux, Unix, Windows CE, and VxWorks.
- The middleware and tools layer focuses on middleware and modeling tools for implementing the framework and domain applications. Examples of such middleware includes, Common Object Request Broker Architecture (CORBA), Component Object Model (COM)/Distributed Component Object Model(DCOM), Microsoft .Net, Java 2 Platform Enterprise Edition (J2EE) middleware, and UML modeling tools.
- The IEEE 1588 layer focuses on object model of the IEEE 1588 standard, which includes data types, datasets, entities, messages, services, devices and profiles of the IEEE 1588 standard.
- The application layer focuses on the design and development of IEEE 1588-based application systems that are the composition or aggregation among objects in systems, such as a remote monitoring system and distributed measurement and control system.

This application framework has been developed at the National Institute of Standards and Technology (NIST) using UML. The IEEE 1588 layer has been built, which currently consists of Java and C++ class libraries of the IEEE 1588 standard.

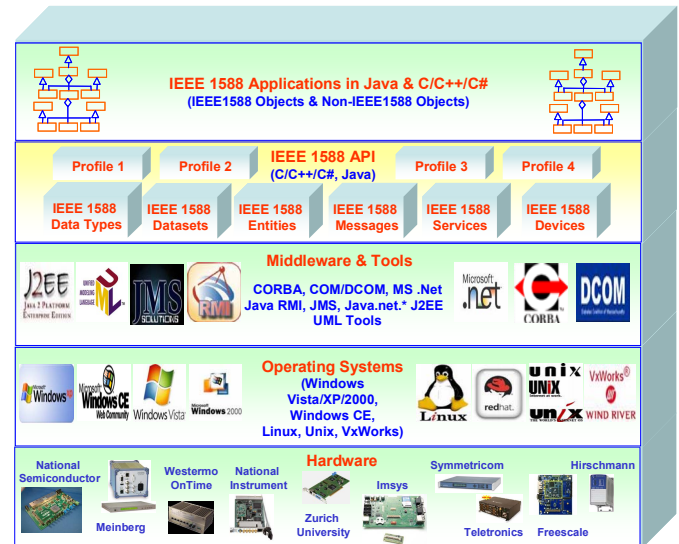


Fig. 2. Application framework architecture for IEEE 1588.

B. The IEEE 1588 Layer

As shown in Figure 2, the IEEE 1588 layer is one kind of white-box framework that relies heavily on static inheritance relationships. The framework user is supposed to customize the framework behavior through sub-classing of framework

classes. This layer mainly focuses on the object model of IEEE 1588, which consists of data types, datasets, entities, messages, services, devices and profiles of the IEEE 1588 standard [24-25].

B.1 Data Types of IEEE 1588

The IEEE 1588 data types consist of primitive data types and derived data types. The primitive data types include boolean, integers (signed and unsigned 8 bits, 16 bits, and 32 bits), and octet (one byte). The primitive data types can be mapped into the primitive data types of the C/C++/Java/C# programming language, or defined as an individual class. The derived data types of the IEEE 1588 standard are derived from these primitive data types. The derived data types of IEEE 1588, including arrays of primitive data types, enumerations, and structs, can be also defined as an individual class.

B.2 Datasets of IEEE 1588

A Precision Time Protocol (PTP) clock has two types of data sets: clock data sets and port data sets. The clock data set describes the attributes of clocks, such as default dataset, current dataset, time property dataset, and parent dataset. The port data sets describe the attributes of clock ports. There are three kinds of port datasets defined in IEEE 1588, including port data set of ordinary clock, port data set of boundary clock, and port data set of transparent clock.

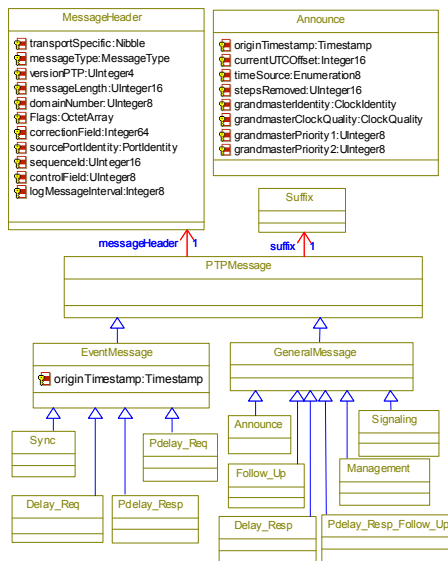


Fig. 3. PTP message.

B.3 Messages of IEEE 1588

All PTP-related communications occur via PTP messages. The PTP messages have a header, body and suffix. Figure 3 shows the class definition of PTP messages. The

PTPMessage can be subdivided into two types: EventMessage and GeneralMessage, which can inherit all the attributes of PTPMessage. The EventMessage with a timestamp attribute can be subdivided into Sync, Delay_Req, Pdelay_Req, and Pdelay_Resp messages, which inherit the timestamp attribute from EventMessage. The GeneralMessage can be subdivided into Announce, Follow_Up, Delay_Resp, Management, Signaling, and Pdelay_Resp_Follow_Up messages. Each specific PTP message inherits the common attributes (message header and suffix) from the general PTP message, and also has its own attributes.

B.4 PTP Services for IEEE 1588

Fig. 4 shows the definition of PTPService that we propose. The PTPService can be divided into EventService and GeneralService. The EventService includes Sync, DelayRequest, PDelayRequest and PDelayResponse services. The GeneralService includes Announce, FollowUp, DelayResponse, PDelayResponseFollowUp, Management, and Signaling services. Each PTP individual service is an operation with corresponding arguments (messages).

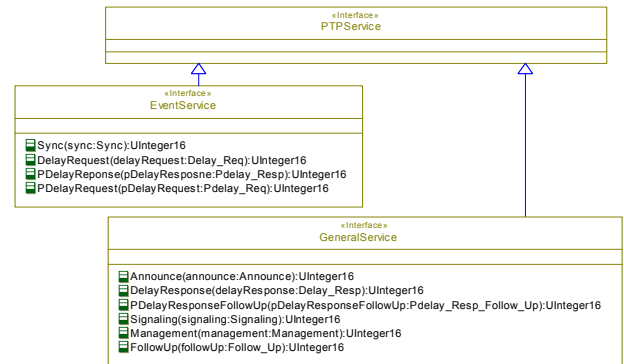


Fig. 4. PTP services.

B.5 PTP Port of IEEE 1588

Each port of the PTP ordinary, boundary, or transparent clock supports the event interface and general interface. The event interface is used to send and receive event messages, which are time-stamped based on the value of the local clock. The general interface is used to send and receive general messages, such as Announce and Management. A port may implement both the Delay Request-Response mechanism and Peer Delay mechanism, but only one mechanism is active at any time. Figure 5 shows the definition of the PTPPort class. The PTPPort can be subdivided into OClockPort, BClockPort, and TClockPort, which can inherit all the attributes of PTPPort. The OClockPort is an ordinary clock port, which has one OClockPortDS and one ForeignMasterDS. The BClockPort is a boundary clock

port, which has one BClockPortDS and one ForeignMasterDS. The TClockPort is a transparent clock port, which has one TClockPortDS. The PTPort has also one EventInterface, and one GeneralInterface. The GeneralInterface implements GeneralService, and EventInterface implements EventService. Figure 5 also shows the definition of EventInterface class. For our application framework, we implemented EventInterface and GeneralInterface using Java multicast sockets.

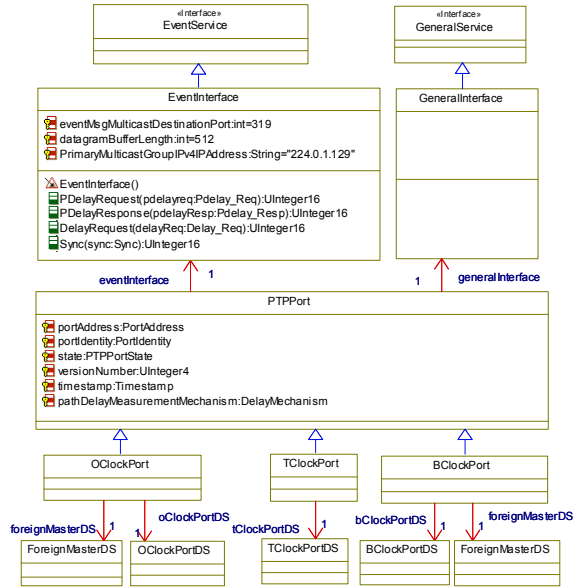


Fig. 5. PTP port.

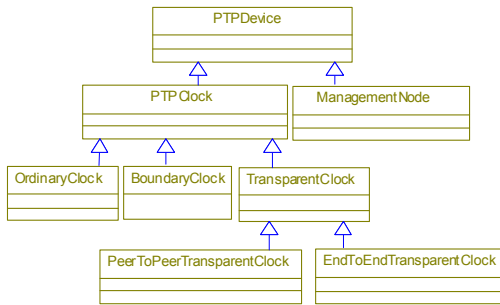


Fig. 6. PTP Device.

B.6 PTP Devices of IEEE 1588

A PTP device can send or receive PTP messages on a network. As shown in Figure 6, a PTPDevice can be sub-classified into ManagementNode and PTPClock. A clock is capable of providing a measurement of the passage of time since a defined epoch. A PTP clock is a clock that participates in the PTP protocol. The PTPClock can be sub-classified into OrdinaryClock, BoundaryClock, and TransparentClock. Furthermore, transparent clocks can

be subclassified into PeerToPeerTransparentClock and EndToEndTransparentClock. The different clocks have different datasets.

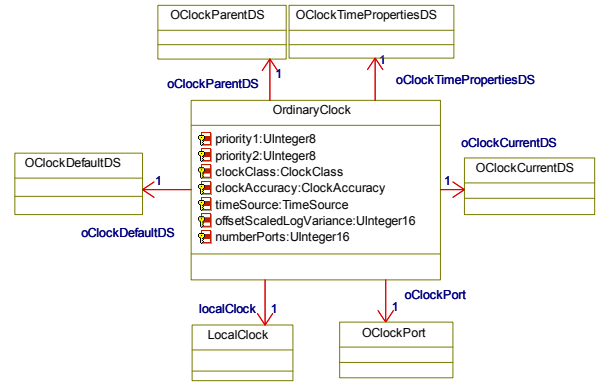


Fig. 7. Object model of ordinary clock.

An ordinary clock communicates with the network via two logical interfaces based on a single physical port. The ordinary clock can be the grandmaster clock in a system or a slave clock in the master-slave hierarchy. Figure 7 shows the object model of the ordinary clock. Each OrdinaryClock has one LocalClock, one OClockDefaultDS, one OClockCurrentDS, one OClockParentDS, one TimePropertiesDS, and one OClockPort. Each ordinary clock may have only one OClockPort. The ordinary clock can implement the Delay Request-Response mechanism or the Peer Delay mechanism.

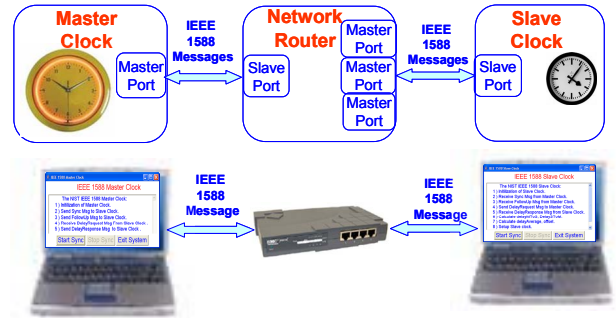


Fig. 8. Prototype system of IEEE 1588 application.

IV. PROTOTYPE SYSTEM

The application layer mainly focuses on IEEE 1588 application design and development. To design specific applications, IEEE 1588 application developers can use composition and aggregation relations among the application objects or classes that inherit from the classes of the IEEE 1588 layer to design their specific applications. Figure 8 shows a prototype system of an IEEE 1588 application based on the established application framework. This prototype system consists of a master clock (laptop), a network router,

and a slave clock (laptop). The timestamp is implemented at the application level using Java `System.currentTimeMillis()`, which can read system clock time in milliseconds.

A. Master Clock

Figure 9(a) shows the object model of a master clock system, which consists of a `MasterClockSystem`, a `DisplayMasterClock` (displays the time of the master clock), and a `MasterClock`. The master clock is a subclass of an ordinary clock. It inherits all ordinary clock attributes, which are shown in Figure 5 and Figure 7. The `MasterClock` has a few of the functions shown in the Figure 9 (a). The function `initialization()` sets all datasets and the port of a master clock. The function `masterTimeSynchronization()` sends `Sync`, `Follow_Up`, and `Delay_Resp` messages to the slave clock, and receives `Delay_Req` message in return.

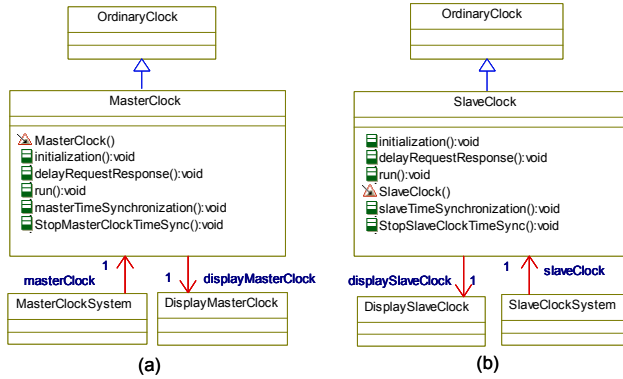


Fig.9. Object models of master and slave clock systems.

B. Slave Clock

Figure 9(b) shows the object model of a slave clock system, which consist of a `slaveClockSystem`, a `DisplaySlaveClock` for displaying the times of the slave clock, and a `SlaveClock`. The slave clock is a subclass of an ordinary clock. It inherits all attributes from the ordinary clock. The slave clock functions are shown in the Figure 9(b). The function `initialization()` sets all datasets and the port of a slave clock. The function `slaveTimeSynchronization()` sends the `Delay_Req` message to the master clock, and receives `Sync`, `Follow_Up`, and `Delay_Resp` messages in return.

As shown in Figure 9, by implementing the foundation classes of the IEEE 1588 standard in an application framework, IEEE 1588 application developers can easily create IEEE 1588 application objects, which inherit from the IEEE 1588 classes of the application framework. The development time of IEEE 1588 applications can be dramatically reduced by reusing design and code provided by the application framework.

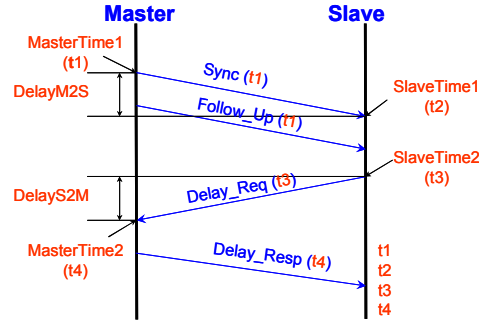


Fig. 10. Delay Request-Response mechanism.

C. Case Study of Delay Request-Response

The IEEE 1588 standard defines two types of synchronization mechanisms: Delay Request-Response and Peer Delay. The case study mainly focuses on the Delay Request-Response mechanism. Figure 10 shows the clock synchronization process between the master clock and slave clock using the Delay Request-Response mechanism. The master clock periodically sends `Sync` messages to the slave clock every 2 seconds. The `Sync` message contains a timestamp (t_1) when the packet left the master clock. The master clock may also optionally send a `Follow_Up` message containing the exact timestamp (precision t_1) for the `Sync` packet. The slave clock measures the exact reception time (t_2) of the `Sync` message. Then, the slave clock sends a `Delay_Req` message to the master. `Delay_Req` message contains a timestamp (t_3) when the `Delay_Req` packet left the slave clock. The master clock measures the reception time (t_4) of the `Delay_Req` message. The `Delay_Resp` message from the master clock includes the time t_4 to the slave clock. Slave clocks can accurately calculate the mean delay and offset between their local clock and the master clock based on the following equations defined in the IEEE 1588 standard.

$$\text{delay} = ((t_2 - t_1) + (t_4 - t_3)) / 2$$

$$\text{offset} = ((t_2 - t_1) - (t_4 - t_3)) / 2$$

The slave clocks can then adjust their local clocks based on the calculated offset to synchronize their time with the master clock. Then the slave clock can communicate with the master clock by sending and receiving these synchronization packets through the general interface and event interface.

Figure 11 shows the result of a clock synchronization. In Figure 11(a), the timing parameters of the master clock system are shown. In Figure 11(b), in addition to the timing parameters of the slave clock system, the user interface also displays the delay (14781 ms) of the master clock to slave clock, the delay (-14766 ms) of the slave clock to master clock, the calculated delay (7 ms), and offset (14774 ms) between the slave clock and master clock. Thus the slave clock can adjust its local clock based on the offset and synchronize it with the master clock. Consequently the

adjusted slave clock time (current slave clock time + offset) is shown in the slave clock user interface in Figure 11(b). Due to the unavailability of IEEE 1588-2008 compliant devices in the market at the time of this application framework implementation, the prototype shown in Figure 8 was used to verify the validity of the application framework.

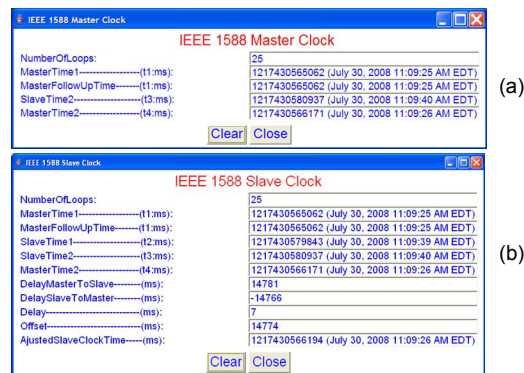


Fig. 11. Result of a clock synchronization.

V. CONCLUSION

This paper describes an application framework for the IEEE 1588 standard. A prototype application system of the IEEE 1588 is developed based on the established application framework. The case study of the Delay Request-Response mechanism was successfully tested with the established application framework. With the help of this application framework, the time-to-market for IEEE 1588 applications can be significantly reduced. Our future work is to further explore this application framework on platforms with different clock accuracies.

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