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Interoperability Test of IEEE 1451.5 Standard-Based Wireless Sensors

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***Abstract**: The Institute of Electrical and Electronics Engineers (IEEE) 1451 standard provides plug-and-play capability of smart transducers (sensors and actuators). Plug-and-play is an important aspect of interoperability, which is the ability of two or more systems to easily communicate each other. Interoperability testing verifies if these systems will communicate together based on a standard or specification in an operational environment. This paper introduces the interoperability testing of the IEEE 1451.5 standard-based wireless sensors, including interoperability test architecture, IEEE 1451.0 messages, interoperability test system, and a case study of interoperability test between the IEEE 1451.5 standard-based Network Capable Application Processor (NCAP) and Wireless Transducer Interface Module (WTIM).*

***Keywords**: IEEE 1451.0; IEEE 1451.5; IEEE 802.11; Interoperability Test; Standard NCAP; Standard WTIM.*

I. INTRODUCTION

A smart transducer is the integration of an analog or digital sensor or actuator element, a processing unit, and a communication interface [1]. An Institute of Electrical and Electronics Engineers (IEEE) 1451 smart transducer provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity. Its functionality simplifies the integration of the transducer into applications in a networked environment [2]. Figure 1 shows the basic components of an IEEE 1451 smart transducer with a wireless interface: a Network Capable Application Processor (NCAP), a Wireless Transducer Interface Module (WTIM), and a transducer physical interface between the NCAP and WTIM. The NCAP is an application processor capable of network communications. The WTIM consists of a number of sensors and actuators, signal conditioning and data conversion elements, a set of Transducer Electronic Data Sheets (TEDS), and a radio. As shown in Figure 1, three network interfaces are available for accessing IEEE 1451 smart transducers: the IEEE 1451.0 Hypertext Transfer Protocol (HTTP) [2], the IEEE 1451.1 communication protocols [3], and the proposed Smart Transducer Web Services (STWS) [4, 5]. The physical interface between a NCAP and WTIM is an IEEE 1451.5 wireless interface adopting the IEEE 802.11, Bluetooth, ZigBee, or 6LowPAN wireless communication protocols [6].

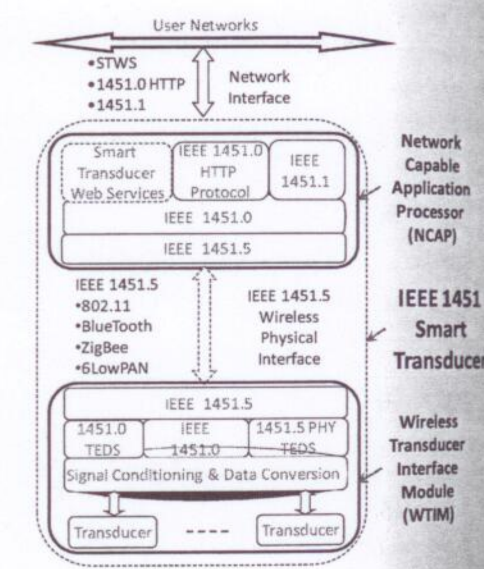

Figure 1. IEEE 1451 smart transducer with a wireless interface

The IEEE 1451.0 standard defines a set of common commands, TEDS formats, and communication protocols for the IEEE 1451 family of standards [2]. IEEE 1451.0 was designed to facilitate interoperability of devices conforming to the IEEE 1451 family of standards. The IEEE 1451 standard provides plug-and-play capability, which means that a WTIM and a NCAP built to the standard can be connected through a standardized physical interface, and operate without any change to the system configuration. There is no need for different drivers, profiles, or other software changes. Figure 2 shows the plug-and-play capability of IEEE 1451 wireless sensor modules. It can be described as follows [7]:

- WTIMs from a sensor manufacturer can "plug-and-play" with NCAPs supplied by different vendors, through the same IEEE 1451.5 communication module.
- WTIMs from different sensor manufacturers (vendor A, B, and C) can "plug-and-play" with NCAPs from a particular sensor network supplier through the same IEEE 1451.5 communication module.
- WTIMs from different sensor manufacturers can be interoperable with NCAPs from different suppliers

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through the same IEEE 1451.5 communication module.

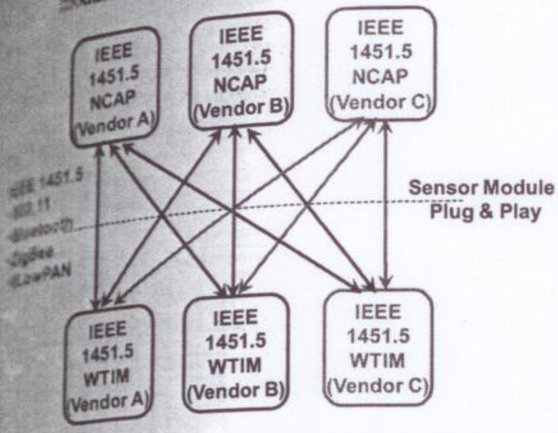

Figure 2. IEEE 1451.5 standard facilitates plug-and-play.

The plug-and-play capability is one of the best ways to achieve interoperability. Therefore, interoperability tests are important to verify the interoperability among IEEE 1451.5 NCAPs and WTIMs from different vendors or manufacturers.

II. RELATED WORK

Interoperability is the ability of systems or software applications to operate and interact smoothly with each other [8]. Interoperability involves the communications between two or more systems. It requires participating systems to communicate with each other based on a standard or specification. Interoperability tests are therefore used to verify interoperability of these systems. A generic approach to interoperability tests and its architectures is proposed [9]. The interoperability tests for web service are discussed [10]. The business-to-business interoperability test is described [11]. Interoperability testing based on simulation tools for wireless sensor networks is discussed [12]. The interoperability test between Bluetooth devices is discussed [13]. IEEE 1451.1-based sensor networking testbed is described [14-15]. This paper mainly focuses on an interoperability test of IEEE 1451.5 standard-based wireless sensors. Section II describes related work. An architecture of interoperability tests is proposed in Section III. Section IV describes an interoperability test system and case study. Conclusions and a summary are presented in Section V.

III. ARCHITECTURE OF INTEROPERABILITY TEST OF IEEE 1451.5 STANDARD-BASED WIRELESS SENSORS

A. Architecture of Interoperability Test of IEEE 1451.5 Standard-based Wireless Sensors

Interoperability is the ability of two or more systems or components to exchange information and to use the information that has been exchanged [16]. Interoperability testing verifies that these systems will communicate with each other according to a standard or specification in an operational environment. Figure 3 shows the architecture of interoperability test of IEEE 1451.5 standard-based wireless sensors, which consists of the Test Method (TM) and System Under Test (SUT). The TM consists of a Tester1 and Tester2, who collaborate to make the interoperability test cases, test logging, test procedures and test reports based on the test results. The SUT comprises an IEEE 1451.5 Qualified Device (QD) with a Test Interface1 (TI1), an IEEE 1451.5 Device Under Test (DUT) with a Test Interface2 (TI2), and IEEE 1451.5 Communication Method between the QD and DUT through the IEEE 1451.5 Communication Interface1 (CI1) and Communication Interface2 (CI2). A QD may be a simple device, and a software application based on the IEEE 1451.5 standard, such as IEEE 1451 NCAP and WTIM. A given QD will have initially been tested as a DUT, but once the full range of interoperability tests have been successfully performed, it can be considered to be a QD. The DUT may be a simple device, and a software application based on the IEEE 1451.5 standard, such as an IEEE 1451 NCAP or WTIM. Tester1 can conduct an interoperability test of the IEEE 1451.5 QD through the TI1 and the IEEE 1451.5 CI1. Tester2 can conduct an interoperability test of the IEEE 1451.5 DUT through the TI2 and CI2. Therefore, the Tester1 and Test2 can run interoperability tests between QD and DUT through Test Interfaces (TI1 and TI2), they also can monitor the interoperability test result through the IEEE 1451.5 Communication Interfaces (CI1 and CI2).

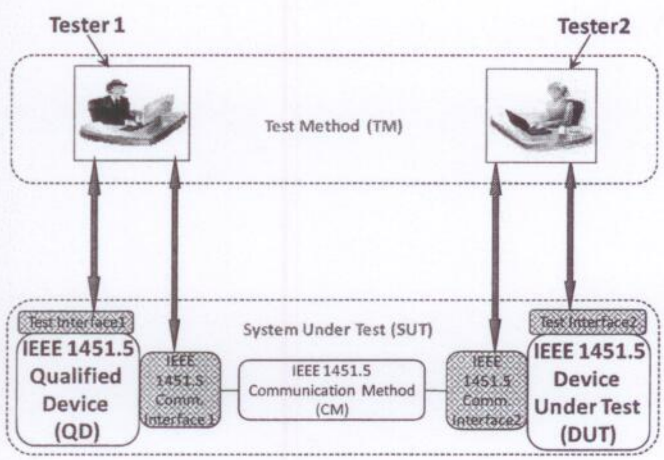

Figure 3. Architecture of interoperability test of IEEE 1451.5 standard-based wireless sensors.

B. Interoperability test of IEEE 1451.5 NCAP and WTIM

Figure 4 shows the interoperability between the IEEE 1451.5 standard-based NCAP and WTIM, which are the Qualified Devices of the IEEE 1451.5 standard and referred to as the Standard NCAP and Standard WTIM, respectively. The

Standard NCAP sends a request to the Standard WTIM and the WTIM returns a response. The request and response are based on IEEE 1451.0 messages. The interoperability of the IEEE 1451.5 Standard NCAP and Standard WTIM can be verified through tests between them. The IEEE 1451.5 Standard NCAP and Standard WTIM can also be used to test the interoperability of NCAPs and WTIMs from different vendors.

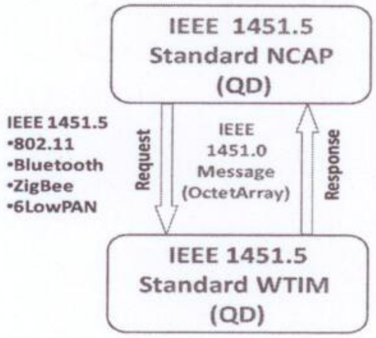

Figure 4. Interoperability of IEEE 1451.5 Standard NCAP and Standard WTIM.

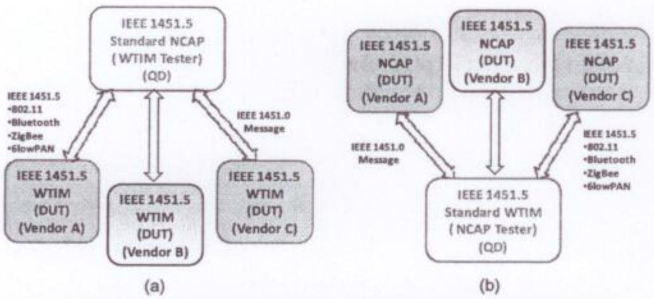

Figure 5. Interoperability tests of IEEE 1451.5 WTIMs and NCAPs against the Standard NCAP and Standard WTIM.

Figure 5 shows interoperability tests of IEEE 1451.5 NCAPs and WTIMs from different vendors. Figure 5(a) shows the tests of IEEE 1451.5 WTIMs against the IEEE 1451.5 Standard NCAP, which is a qualified device or WTIM tester. Figure 5(b) shows the Standard WTIM used as a NCAP tester to test against IEEE 1451.5 NCAPs from different manufacturers. All these interoperability tests are conducted using IEEE 1451.0 messages according to the IEEE 1451.0 standard.

C. Object-oriented IEEE 1451.0 Message

The IEEE 1451.0 messages are defined based on object-oriented methodology. Figure 6 shows an object model of IEEE 1451.0 messages, which can be divided into CommandMessage, ReplyMessage, and TIMInitiatedMessage. CommandMessage has attributes, such as destination transducer channel number, command class, command function, and length of message. It can also be subdivided into StandardCmd and ManufacturerDefinedCmd. ReplyMessage has attributes, such as flag and length of message. It can be also subdivided into StandardCmdReply and ManufacturerCmdReply. TIMInitiatedMessage is a message sent to an NCAP from a WTIM. For instance, TIMAnnouncement could be a subclass of TIMInitiatedMessage.

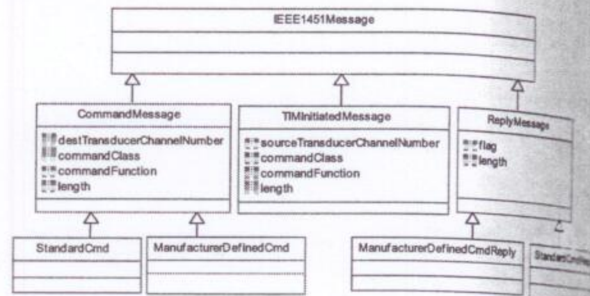

Figure 6. Classification of IEEE 1451.0 messages.

Figure 7 shows a classification of StandardCmd, which can be subdivided into TIMSleepStateCmd, TransducerIdleStateCmd, AnyStateCmd, TIMActiveStateCmd, TransducerEitherIdleAndOperatingStateCmd, CommonCmd and TransducerOperatingStateCmd,. WakeUpCmd is a subclass of TIMSleepStateCmd, whereas ResetCmd is a subclass of AnyStateCmd. TransducerOperatingStateCmd can be subdivided into ReadTransducerChannelDatasetSegmentCmd, TriggerCmd, WriteTransducerChanneldatasetSegmentCmd, and AbortTriggerCmd. TIMActiveStateCmd can be subdivided into TIMSleepCmd, StoreStateCmd, ReadStateCmd, ReadIEEE1451Dot0VersionCmd, and ReadTIMVersionCmd.

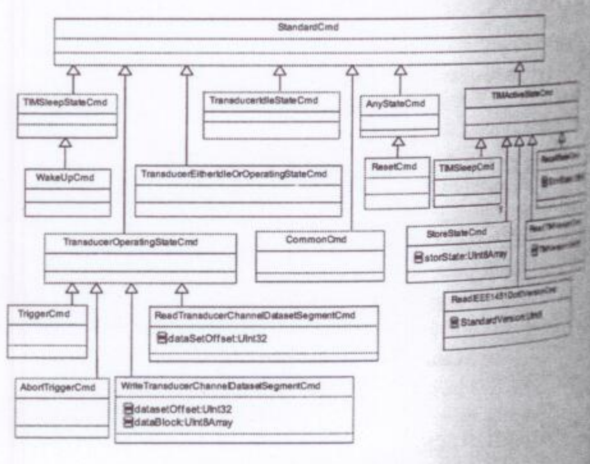

Figure 7. Classification of StandardCmd.

Figure 8 shows the classification of CommonCmd, which can be sub-classified into ReadTEDSSegmentCmd, WriteTEDSSegmentCmd, RunSelftestCmd, ReadStatusEventRegisterCmd, WriteStatusEventProtocolCmd, ReadStatusConditionRegisterCmd, ReadStatusEventProtocolStateCmd, WriteServiceRequestMaskCmd, ClearStatusEventRegisterCmd, ReadServiceRequestMaskCmd, UpdateTEDSCmd, and QueryTEDSCmd. For example, ReadTEDSSegmentCmd has attributes, such as TEDS access code, TEDS offset, and also inherits the attributes from CommonCmd and CommandMessage.

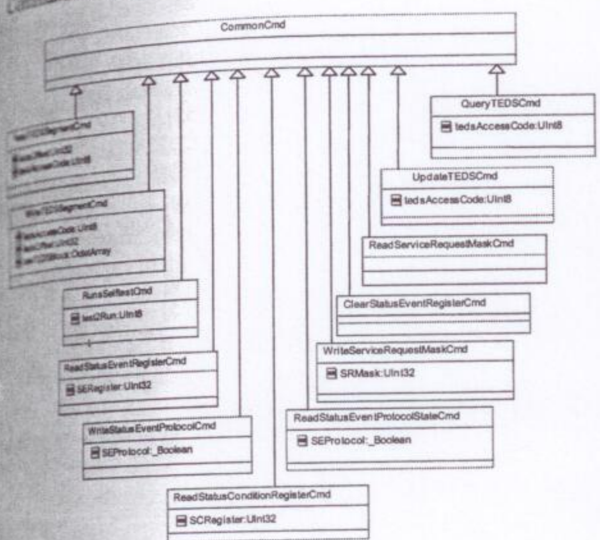

Figure 8. Classification of CommonCmd.

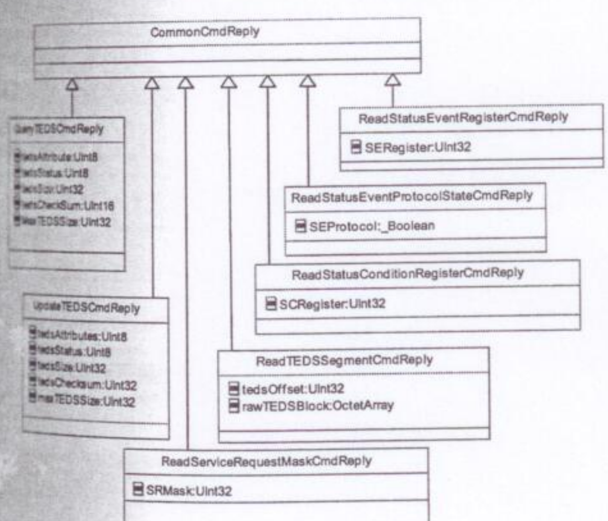

Figure 9. Classification of CommonCmdReply.

Figure 9 shows the classification of CommonCmdReply, which can be sub-classified into QueryTEDSCmdReply, UpdateTEDSCmdReply, ReadServiceRequestMaskCmdReply, ReadTEDSSegmentCmdReply, ReadStatusConditionRegisterCmdReply, ReadStatusEventProtocolStateCmdReply, and ReadStatusEventRegisterCmdReply.
ReadTEDSSegmentCmdReply has the attributes: tedsOffset and rawTEDSBlock, and also inherits the attributes from StandardCmdReply and ReplyMessage.

D. Encoding and Decoding of IEEE 1451.0 Messages

All IEEE 1451.0-based information transmitted to an IEEE 1451.5-based device (referred to as the "device") will be bundled together into a payload. The payload will be encoded as an octet array. The device should consider the payload as "opaque", which means that the device does not know what the content of the payload is. From IEEE 1451.0's perspective, the octet array and destination addressing represents the logical "on-the-wire" format. The device is expected to package the octet array into appropriate network packets for the given IEEE 1451.5 technology. Also, the device is responsible for segmenting the octet array into appropriately sized network packets and reassembling them back into the octet array on the remote node. All issues with respect to encryption, authentication, compression, and flow control are the responsibilities of the device. Figure 10 shows the processes of encoding and decoding of IEEE 1451.0 messages. Encoding is the process of transforming IEEE 1451.0 messages into an octet array format, while decoding is the process of transforming the octet array into IEEE 1451.0 messages. Each byte can be represented as $[h_0h_1]$, where left most is the higher order bit. The bytes are transmitted with high order bit first.

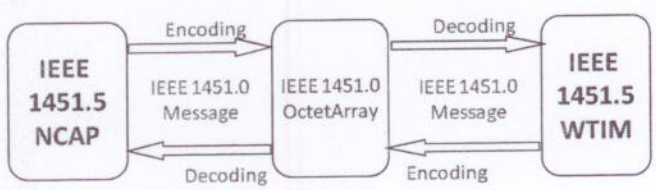

Figure 10. Encoding and decoding of IEEE 1451.0 messages.

For example, ReadTEDSSegmentCmd and ReadTEDSSegmentCmdReply messages can be encoded as follows:

ReadTEDSSegmentCmd message encoding:

- destChannelId:UInt16: $[h_0h_1]$ $[h_2h_3]$
- cmdClassId:UInt8: $[h_4h_5]$
- cmdFunctionId:UInt8: $[h_6h_7]$
- length:UInt16: $[h_8h_9]$ $[h_{10}h_{11}]$
- tedsAccessCode: UInt8: $[h_{12}h_{13}]$
- tedsOffset: $[h_{14}h_{15}]$ $[h_{16}h_{17}]$ $[h_{18}h_{19}]$ $[h_{20}h_{21}]$

ReadTEDSSegmentCmdReply message encoding:

- Flag:_Boolean: $[h_0h_1]$
- Length:UInt16: $[h_2h_3]$ $[h_4h_5]$
- tedsOffset:UInt32: $[h_6h_7]$ $[h_8h_9]$ $[h_{10}h_{11}]$ $[h_{12}h_{13}]$
- teds:OctetArray: $[h_{13+1}],\ldots,[h_{13+N}]$. N is length of Array

IV. AN INTEROPERABILITY TEST SYSTEM OF IEEE 1451.5-802.11 NCAP AND WTIM

A. Interoperability Test System

We developed an interoperability system shown in Figure 11, which consists of an IEEE 1451.5-802.11 wireless NCAP and an IEEE 1451.5-802.11 wireless TIM [17]. The wireless NCAP is implemented on a laptop. The IEEE 1451.5 NCAP implementation conforms to IEEE 1451.0 and supports the required functional specifications, the message structures, the required commands of the IEEE 1451.0 standard, and the IEEE 1451.5-802.11 communications protocols and physical media. The WTIM is also implemented on a laptop. The WTIM is a virtual wireless sensor module, which consists of a number of virtual sensors and the required TEDS. The WTIM implementation is in conformance with the IEEE 1451.0 standard and supports the required functional specifications, the message structures, the required commands of the IEEE 1451.0 standard, the required TEDS that meet the format and content of the IEEE 1451.0 standard, and the IEEE 1451.5-802.11 communication protocols and physical media. The communication between the NCAP and WTIM is through an IEEE 802.11 access point. The NCAP and WTIM are developed in Java with the help of the IBM Rhapsody tool[1].

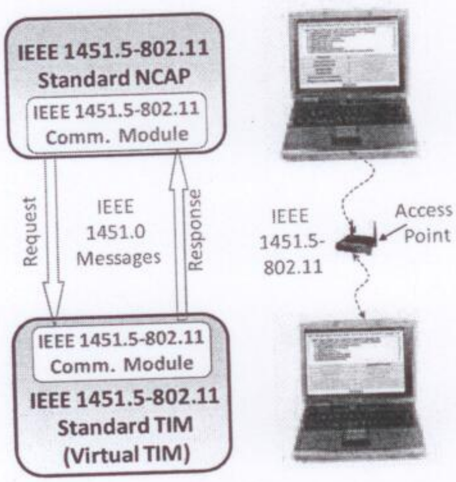

Figure 11. An interoperability test system of IEEE 1451.5-802.11 NCAP and WTIM.

B. Case Study

The NCAP communicates with the WTIM using IEEE 1451.0 messages and formats. Test cases include WTIMAnnouncement, ReadTransducerChannelData, ReadWTIMMetaTEDS, ReadTransducerChannelTEDS, ReadWTIMPhyTEDS, ReadUserTransducerNameTEDS. This paper focuses on a test case on reading IEEE 1451.5-802.11 PhyTEDS. The IEEE 1451.5-802.11 PhyTEDS includes detailed information of the IEEE 1451.X physical layer, such as radio type and max bits per second. The NCAP sends a ReadPhyTEDS command to a WTIM and gets a reply from the WTIM. The command and reply are described in the following.

Command Message:

- timId:UInt16:[0, …, 65535]:[1]
- destChannelId:UInt16:[0, …, 65535]:[0]
- cmdClassId:UInt8:[0,…,255]:[1]
- cmdFunctionId:UInt8:[0, …, 255]:[2]
- length:UInt16:[0, …, 65535]:[5]
- tedsAccessCode:UInt8:[0, …, 255]:[13]
- DatasetOffset:UInt32[0, …, 4294967295]:[0]

Reply message:

- Flag:_Boolean:[0,1,2, … , 20]
- Length:UInt16: [0, …, 65535]
- phyTedsOffset:UInt32: [0, …, 4294967295]
- PhyTeds:OctetArray: [0, …, 255] , …,[0, …, 255]

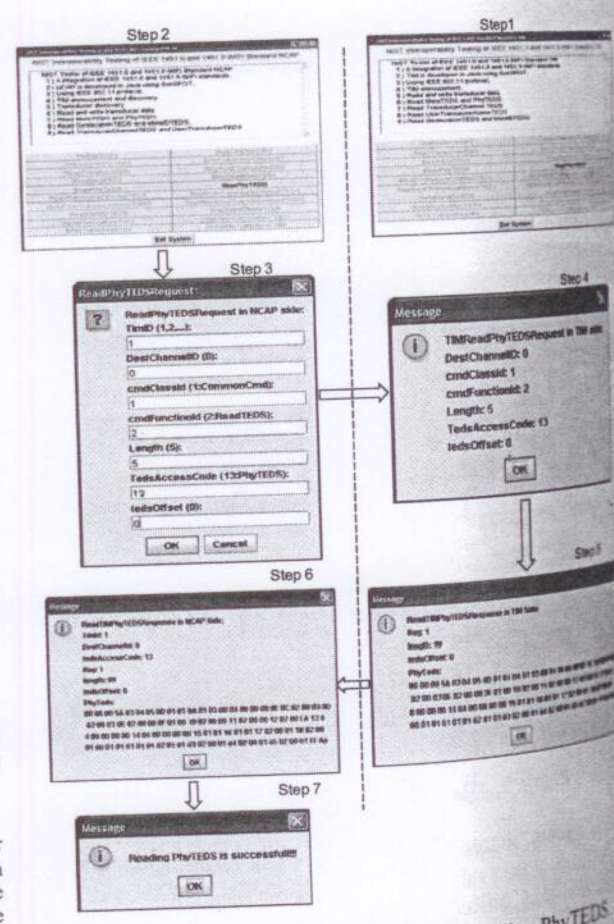

Figure 12. Interoperability test steps of reading PhyTEDS

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1 Commercial equipment and software, many of which are either registered or trademarked, are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Figure 12 shows the results of stepping through the interoperability test of ReadPhyTEDS between the IEEE 1451.5-802.11 NCAP and WTIM. The detailed steps are described in the following:

- Step1: Start ReadPhyTEDS in the WTIM side.
- Step2: Start to read ReadPhyTEDS in the NCAP side.
- Step3: Input parameters of the ReadPhyTEDS request in the NCAP side. When a user inputs the paramenters: timid (1), destChannelId (0), cmdClassId (1), cmdFunctionId (2), length (5), tedsAccessCode (13), datasetOffset (0), and click the OK button, the NCAP sends the ReadPhyTEDS request message to the WTIM.
- Step4: the WTIM receives the ReadPhyTEDS request message from the NCAP.
- Step5: the WTIM understands the ReadPhyTEDS command message, reads the PhyTEDS, then sends the reply to the NCAP.
- Step6: the NCAP gets the reply message from the WTIM.
- Step7: the NCAP shows that reading the PhyTEDS is successful.

V. CONCLUSIONS

This paper introduces an interoperability test of the IEEE 1451.5 standard-based wireless sensors, and an interoperability test architecture is proposed. An interoperability test system consisting of an IEEE 1451.5-802.11 Standard NCAP and Standard WTIM is illustrated. A test case is explained in detail for testing the interoperability between the Standard NCAP and Standard WTIM. This work establishes a basis for an interoperability test method for IEEE 1451.5-802.11 NCAPs and WTIMs from different vendors and manufacturers. Development of interoperability tests of the IEEE 1451.5-Bluetooth, ZigBee, and 6LowPAN standards is planned for the future.

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