IEEE 1451 Smart Transducer Interface Standards for IoT, IIoT, and CPS

IEEE P1451.9 WG Kick-off Meeting
January 10, 2020

Kang B. Lee

IEEE Life Fellow

Chair, IEEE IMS Technical Committee on Sensor Technology TC-9
Internet of Things (IoT) apps and verticals are popping up everyday.

**Global Connectivity**

**Standardized Protocols & Interfaces**

- IEC 61850
- IEC 60870
- IEEE 1815 (DNP3)
- IEEE 1451
- OGC-SWE
- Modbus
- ANSI C12
- IEC 61968 CIM
- IEC 61850
- IEC 60870
- IEEE 802.15.4
- IEEE 802.15.4e
- IEEE 802.15.4 MAC
- IEEE 802.15.4 PHY
- IEEE 802.15.4a (FSK, DSSS, OFDM)
- IEEE P1901.2 MAC
- IEEE P1901.2 PHY
- IEEE 802.11 Wi-Fi
- IEEE 802.3 Ethernet
- 2G/3G/LTE Cellular
- IEEE 802.16 WiMax

In all these applications and use cases, smart sensors can play key roles to enable IoT functions. Adjust IEEE 1451 Standards to meet challenges.
Industrial Internet Revolution is here

- Industry consists of many Physical Systems
- The Internet revolution brings Cyber Systems into the picture
- The Industrial Internet Revolution combines Cyber with Physical systems leading to:
  - Cyber Physical Systems (CPS)
  - Industrial Internet of Things (IIoT)
  - Internet of Things (IoT)
  - Internet of Every Things (IoET)
  - What is your name?…

- CPS & IoT are hybrid networks of cyber and physical components integrated to create systems that have adaptive and predictive capabilities. These systems can respond in real-time to enhance system performance automatically or through human interactions.
Industrial Internet Consortium (IIC) also defines IIoT Architecture Framework.

Functional Domains:
- Business
- Operations
- Information
- Application
- Control
- Sense
- Actuation
- Physical Systems
Internet of Things (IoT) is a network that connects uniquely identifiable “Things” to the Internet. (IEEE P2413)
Cyber-Physical Systems (CPS)

*Cyber-physical systems (CPS) are smart systems that include engineered interacting networks of physical and computational components.* (NIST)
IoT and CPS

IoT vs CPS

- **IoT** is mainly concerned with unique identification, connecting with the Internet and accessibility of “things.”
- **CPS** is mainly concerned about the collaborative activities between cyber and physical system through sensing and actuation.
- **CPS** uses **IoT** systems to achieve the collaborative activities of the distributed systems.

IEEE IoT Architecture

- Applications
- Networking and Data Communications
- Sensing

NIST CPS Conceptual Model
Sensors & Actuators are used Everywhere

Networked sensors connected using wired or wireless means can be used in many applications in IoT, IIoT, & CPS:

- Aerospace
- Automobile
- Global warming / environmental monitoring
- Global asset tracking (supply chain, secure container)
- Green / smart home and building
- Health condition monitoring
- Industrial automation
- Manufacturing
- Smart Grid & more …. Smart Grid must have Smart transducers to support it.
Main Features of Smart Transducers

- Transducer = Sensor or Actuator
- Network Connection ready
- Self-identification
- Self-description
- Calibration data
- Time-aware
- Location-aware
- Intelligence (signal processing)
- Output in standardized, international physical measurement units, e.g., temperature in degree C, pressure in Pascal.
Smart Transducers - IEEE 1451 Definition:

- “A smart transducer is a transducer that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity. This functionality typically simplifies the integration of the transducer into applications in a networked environment.”

- In other words, an IEEE smart transducer is either a smart sensor or smart actuator that
  - can **identify and describe** itself,
  - has **processing capability** to present **sensor data** or **actuation values**, respectively, in **measurement units**, and
  - has **network access** capability, and
  - is **easy to use** (enabling plug-and-play).
A Representation of a Smart Transducer

Wired or Wireless Network Communication

Signal conversion, Signal processing, data fusion, etc.

Sensor(s) & Actuator(s) with ID info

Network

Clients

Smart Transducer
IEEE 1451 with Transducer and Network Interfaces

IEEE 1451 Networkable Sensors and Actuators (Smart Transducers)

In the discussion to make IEEE P1451 Physical Transport Media Agnostic – that means it can support any wired, wireless, and cellular technologies

Advantages: no need to deal with and upkeep of
1. Transducer Interface with numerous wireless and cellular interfaces
2. PHY TEDS, and complex Cyber Security and Time Sync at Transducer level

User Network or Internet (Wired or Wireless)
Deployment of IEEE 1451 Smart Transducers and Sensor Networks for IoT - to help achieve sensor data interoperability

(a) IEEE 1451 Smart Transducer (Sensor and Actuator)
(b) IEEE 1451.2-Serial Wired Sensor Network
(c) IEEE 1451.5-802.11 Wireless Sensor Network (WSN)
(d) IEEE 1451.5-BlueTooth WSN
(e) IEEE 1451.5-ZigBee WSN
(f) IEEE 1451.5-6LowPAN WSN

IoT Sensor Application -

Smart Transducer node

Sensor Node (TIM)

Wireless Node (WTIM)

Wireless Sensor Node (WTIM)

Network Node

Network Node

Network Node

Network Node

Network Node

Network Node
Deployment of IEEE 1451 Smart Transducers and Sensor Networks for IoT - to help achieve sensor data interoperability

(a) IEEE 1451 Smart Transducer (Sensor and Actuator)
(b) IEEE 1451.2-Serial Wired Sensor Network
(c) IEEE 1451.5-802.11 Wireless Sensor Network (WSN)
(d) IEEE 1451.5-BlueTooth WSN
(e) IEEE 1451.5-ZigBee WSN
(f) IEEE 1451.5-6LowPAN WSN

New to be added: NB-IoT
Basically we use standardized messaging to access standardized sensor data and to command actuation

**Commands**
- e.g., Read Sensor 1, Sensor 8, Sensor 10
- e.g., Write Actuator 1, Actuator 7

**Response**
- e.g., Sensor 1 value, Sensor 8 value, Sensor 10 value
- e.g., status: Actuator 1 done, Actuator 7 done
Example of Sensors in Smart Grids
Sensor Requirements for Smart Grids

- **Smart grids** require sensors to provide real-time information and status of power grids.

- Sensors enable the grids to be “smarter”.

- Sensors play a key role in real-time monitoring, protection, and control of grid operations.
Sensor Requirements for Smart Grids

- High accuracy timing and time synchronization to UTC
- High measurement accuracy, e.g., AC current and voltage magnitudes, phase angles, and frequency.

Time-accuracy requirements for Smart Grids*:
- 1s SCADA
- 100ms distribution automation
- 1ms substation automation
- 10μs process bus
- 1μs synchrophasors

IEEE C37.118 Phasor Measurement Unit (PMU) Measurement Accuracy*

<table>
<thead>
<tr>
<th>Class</th>
<th>M</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVE</td>
<td>&lt; 1 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>FE</td>
<td>&lt; 0.005 Hz</td>
<td>&lt; 0.05 Hz</td>
</tr>
<tr>
<td>RFE</td>
<td>&lt; 0.1 Hz/s</td>
<td>&lt; 0.4 Hz/s</td>
</tr>
</tbody>
</table>

Sensor Requirements for Smart Grids

- High sampling rate to capture signal characteristics
- High-speed data processing and intelligent algorithms to reduce data processing latency
- Multiple sensing capabilities of electrical and physical parameters including voltage, current, power flow, and temperature, …..
- More intelligent capabilities:
  - Self-description
  - Self-identification
  - Self-calibration
  - ……

IEC 61850-9-2 Merging Unit (MU):
- Frequency: 60Hz
- Sampling rate: 80(s/c) (P), 256 (s/c) (M)
  For example, $256 \text{ (s/c)} \Rightarrow 256 \times 60 = 15360 \text{ (s/s)}$
Sensor Requirements for Smart Grids

- High speed, secure, and reliable network communications
- Standards-based network communication protocols and interfaces
- Interoperability and plug-and-play

<table>
<thead>
<tr>
<th>Performance metrics</th>
<th>Teleprotection</th>
<th>Inter-Trip Protection</th>
<th>Current Differential Protection</th>
<th>Distance Protection</th>
<th>Inter-Substation Protection</th>
<th>Intra-Substation Process Bus Communication</th>
<th>Wide Area Monitoring and Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>One way delay</td>
<td>4-10 ms</td>
<td>5 ms</td>
<td>5 ms</td>
<td>5 ms</td>
<td>5 ms</td>
<td>5 ms</td>
<td>5 ms</td>
</tr>
<tr>
<td>Max jitter</td>
<td>&lt;250 us</td>
<td>Not critical</td>
<td>&lt;250 us</td>
<td>Not critical</td>
<td>Not critical</td>
<td>Not critical</td>
<td>Not critical</td>
</tr>
<tr>
<td>Recovery time</td>
<td>&lt;50 ms</td>
<td>&lt;50 ms</td>
<td>&lt;50 ms</td>
<td>&lt;50 ms</td>
<td>&lt;50 ms</td>
<td>&lt;50 ms</td>
<td>&lt;50 ms</td>
</tr>
<tr>
<td>Packet loss</td>
<td>0.1% ~ 1%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>1%</td>
<td>0.1%</td>
<td>1%</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>64Kbps</td>
<td>64 kbps</td>
<td>64Kbps</td>
<td>64 Kbps</td>
<td>64 Kbps</td>
<td>64 Kbps</td>
<td>100 Kbps</td>
</tr>
</tbody>
</table>

A Generic Smart Sensor Model for Smart Grids

Five Basic Capabilities:
• Sensing
• Data processing (intelligence)
• Metadata and/or data storage
• Network communication
• Timing & synchronization

This generic model applies for smart sensors:
• IEEE C37.118 PMU-based Smart Sensors
• IEC 61850-9-2 MU-based Smart Sensors
• IEEE 1815 (DNP3)-based Smart Sensors
• IEEE 1451-based Smart Transducers
• ……
IEEE 1451
Enables “Plug and Play” of Transducers

Example: IEEE 1451.4 transducer demonstration (acceleration, load cell, position, and temperature sensors, etc)
IEEE 1451 NCAP and TIM combo demonstrated real-time control of an Inverted Pendulum
- to demonstrate high-speed control applications
Examples of IEEE 1451 Applications

- NI integrated IEEE 1451.4 interface into LabView.
- EDC applied IEEE 1451.2 in health monitoring of casing for oil drilling.
- 3eti applied IEEE 1451 in naval vessels for Condition Based Maintenance.

ISO/IEC/IEEE 21450 = IEEE 1451.0
Reminder - Main Features of Smart Transducers

- Transducer = Sensor or Actuator
- Network connection ready
- Self-identification via TEDS
- Self-description via TEDS
- Enable self-calibration via Calibration TEDS
- Output in standard international physical units
- Intelligence (signal processing, event notification, data fusion...)
- Time-aware
- Location-aware based on work with Open Geospatial Consortium (OGC)
- Cyber Security
- Time-synchronized measurements to improve overall measurement accuracy
The IEEE 1451 family of smart transducer interface standards for sensors and actuators consist of:

1. P1451.0 – Common commands, functions, messaging, and transducer electronic data sheet formats (TEDS) - Std published and being revised
2. P1451.1 – Common network services for smart sensors and actuators - Std being revised
3. P1451.2 – Serial interface for smart sensors and actuators - Std being revised
4. P1451.4 – Mixed-mode Transducer Interface and TEDS for smart transducers - Std being revised
5. P1451.5 – Wireless interface for sensors and actuators - Std published and being revised
6. P1451.7 – RFID to sensor interface - Std published and is planned to be revised
7. P1451.8 – Wind Turbine Health Monitoring System Wireless Communication Protocols and Transducer Electronic Data Sheet (TEDS) Format - Std being developed
8. P1451.9 – Tidal Turbine Health Monitoring System Wireless Communication Protocols and Transducer Electronic Data Sheet (TEDS) Format - Std being developed
10. P1451.002 – Low-power operation for IEEE 1451 smart transducers - Std being developed
11. P21451-1-4 – XMPP interface for secure sensor data access - Std being developed
12. P21451-1-5 – SNMP interface for secure sensor data access - Std being developed
13. P21451-1-6 – MQTT interface for secure sensor data access - Std being developed
14. P1451.99 – Harmonization of IoT devices and systems - Std being developed

Some family standards have been adopted as:
IEEE 1451 has changed the Sensor Measurement Paradigm

- **A Disruptive Technology**
  - Concept of distributed, networked measurement and control system at the time centralized control dominated in industry that needed to be modernized in 1990s.

- **Creation of a Measurement Data Model**
  - Recognizes that a measurement is more than a number — it is important to associate units (Celsius for temperature, Pascal for pressure, etc.) with sensor readings, not just voltage or current.
  - Improves the accuracy of measurements (via its calibration TEDS).

- **Additional Features**
  - Cyber Security enabled for secure communication of transducer data and information at difference levels of security as needed or desired.
  - Time synchronization and time stamp of data enable various levels of accuracy as needed or desired.
Sensor Identification via Transducer Electronic Data Sheets (TEDS)

- TEDS, a memory device attached to a smart transducer node that stores metadata, transducer identification, measurement range, calibration, correction data, user and manufacture-related information, which can be used for transducer self-identification and description. Virtual TEDS, not standardized, is also practiced.

- Many different TEDS are defined:
  - Meta-ID TEDS
  - Transducer Channel TEDS
  - Physical TEDS
  - Calibration TEDS
  - Frequency Response TEDS
  - Manufacturer-defined TEDS
  - Application Specific TEDS
  - Geo-location TEDS
  - User-defined TEDS, e.g., Health, etc.
IEEE P1451.1 Categories of Common Network Services

- Identification
- Transducer Access
- TEDS Access
- Event Notification
- Transducer Management
IEEE P1451.1 Common Services: Identification

- Discovery (Top-down process)
  - NCAP Clients and NCAP Servers discover one another (and other high-level network management nodes)
  - NCAP Servers discover TIMs and Transducers

- Registration (Bottom-up process)
  - TIMs and Transducers register with NCAP Servers
  - NCAP Servers register with NCAP Clients
IEEE P1451.1 Common Services: Transducer Access

- Transducer Access
  - Read Services
    - Single or Block data from single or multiple channels of a TIM or TIMs
  - Write Services
    - Single or Block data to single or multiple channels of a TIM or TIMs
  - Synchronous and Asynchronous
IEEE P1451.1 Common Services: TEDS Access

- Support Required TEDS
  - Read or Write
    - TIM
  - Metadata or Transducer Channel or User Transducer Name TEDS

- Physical TEDS
  - P1451.5: 802.11/Bluetooth/Zigbee/6LowPAN
  - P1451.2
IEEE P1451.1 Common Services: Event Notification

- TIM Announcement
  - Subscribe or Notify

- Alerts from Single or Multiple Channels of TIM or TIMs
  - Subscribe or Notify

- Alert Thresholds
  - Setup Single or Multiple Channels of TIM
IEEE P1451.1 Common Services: Configuration Management

- NCAP or TIM Configuration
  - Read or Write
- NCAP or TIM Health
  - Read or Write Health metrics (Health TEDS)
  - Read or Write Maintenance
    - Calibrate
  - Read or Write Self-test
- Other
  - Geo location
  - Time synchronization (IEEE 1588 or known globally as Precision Time Protocol (PTP))
Smart Transducer System Concept of Operations (Con-Ops)

- Resources are discovered
  - Resources are discovered on power up (or other trigger)
    - NCAPs, TIMs, Transducers

- Resources are registered
  - NCAP Clients, Servers; TIMs or Transducers

- NCAPs are joined into groups
  - NCAP Clients create communities of associated NCAP Servers with their collections of TIMs + Transducers to satisfy application requirements

- Sustaining operations: The system performs actions required to accomplish reliable operations
In Summary

- IEEE 1451 Standards work well to support sensing and actuation functions for IoT, IIoT, and CPS.
- IEEE 1451 supports both wired and wireless sensor networks for IoT to achieve sensor data interoperability and plug-and-play capability.
- A strong business case for using IEEE 1451 standards
  - Reduce human errors by using TEDS (metadata)
  - Improve and maintain sensor measurement accuracy by using calibration TEDS data
  - Ease field installation, upgrade, and maintenance (by plug & play)
  - Reduce the total life-cycle costs of sensor systems
Often I encounter questions like standards. Manufacturers or users choose to use them in the product as they see fit. Example, WiFi took more than 15 years to become popular as today. Once I met Vint Cerf at NIST Director’s conference room, Vint is often referred to as Father of Internet. We talk about the future of his Internet and my Smart Sensors standards. He said it took 15 to 20 years before Internet became popular. If you think you have a great idea, keep it going and wait until the right time, it will pick up by industry. IoT could be a great opportunity. One time, I was invited by Oak Ridge National Lab to speak about smart sensors in it sensor workshop. After the speech, a young man came up to talk to me and today it bring back memory. That was an encouragement to continue to push IEEE 1451.

2. Do users have to pay for the use of IEEE 1451 standards?
IEEE standards are free for anybody to use. You only need to purchase the standards document.
An example of a very successful standard under my Committee, TC9
IEEE 1588 Standard (Precision Time Protocol)

2000: Specification taken from IEEE P1451, I sponsored and started the standards project development.

2002: IEEE 1588-2002 was approved as a full-use standard with 1 microsecond time synchronization accuracy, 1000X more accurate than NTP (network time protocol) Users - industrial automations and instrumentation measurement systems.

2008: IEEE 1588-2008 was approved as a revised standard. Added users – smart grids, telecom, military, financial, worldwide, Timing accuracy to 1 nanoseconds

2019: IEEE 1588-2019 was approved as a revised standard. Added users – CERN Timing accuracy to 256 picoseconds

Today: My friends, John Eidson, has worked with me over the years chairing the P1588 WG has the honor of being referred to as the Father of IEEE 1588 or PTP.
For More Information About IEEE I&MS TC-9 Sponsored IEEE Standards

- Published IEEE standards can be purchased at [http://www.techstreet.com/cgi-bin/results](http://www.techstreet.com/cgi-bin/results)

- Contacts: Kang Lee, [kang.lee@ieee.org](mailto:kang.lee@ieee.org)
THANK YOU!

Questions?