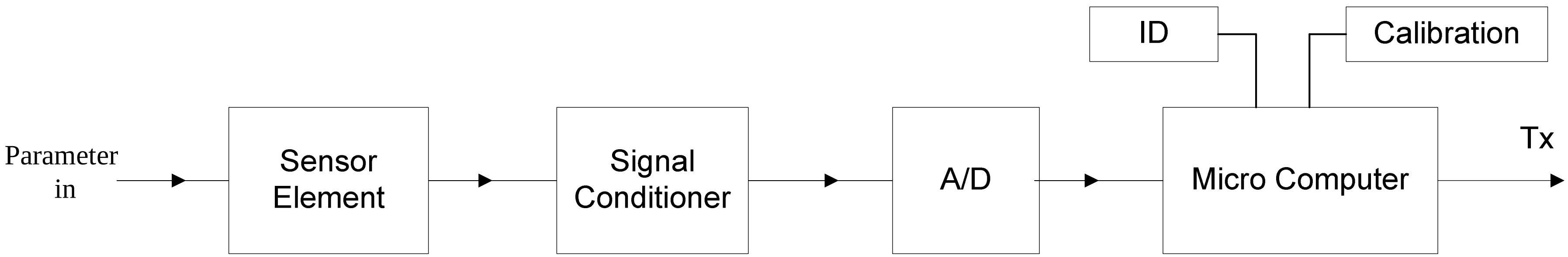
Precision RTD Signal Conditioner with IEEE 1451 TEDS and Protocol

Darold Wobschall, Wai Sing Poh and Ken Yian Chow
Esensors Inc.

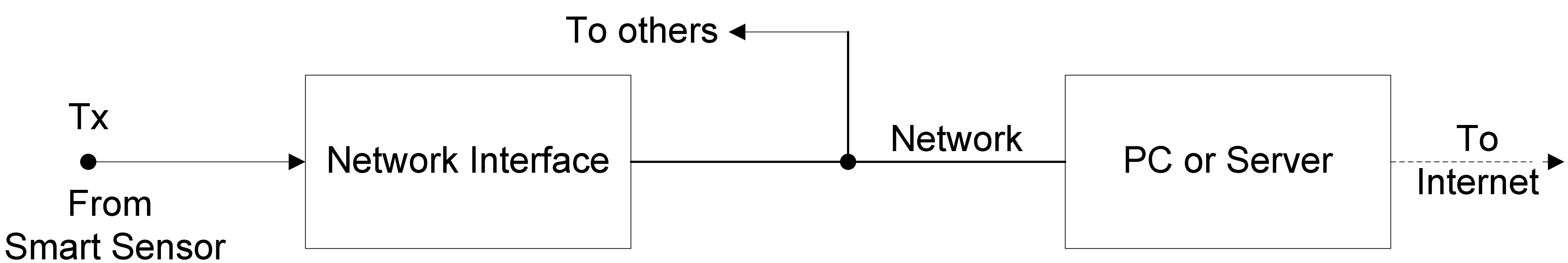
Goals

- Describe a precision digital (smart) RTD temperature sensor
- Configure and test the sensor as a IEEE 1451 TIM with a serial interface
- Test the IEEE 1451.0 TIM & NCAP with a PC and with direct Internet access via Ethernet

Smart Sensor Block Diagram

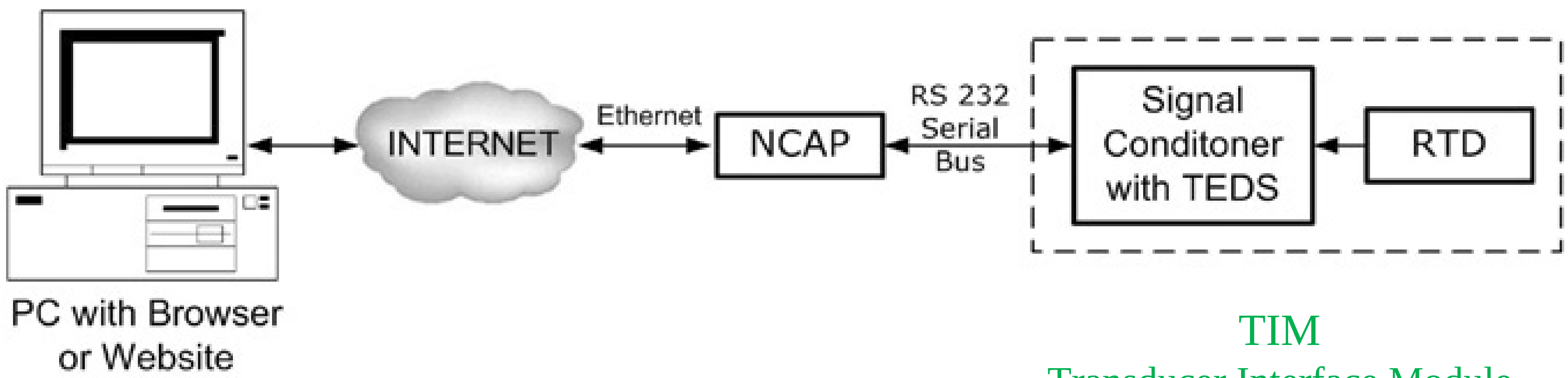


SMART SENSOR



With network connection

RTD System Block Diagram

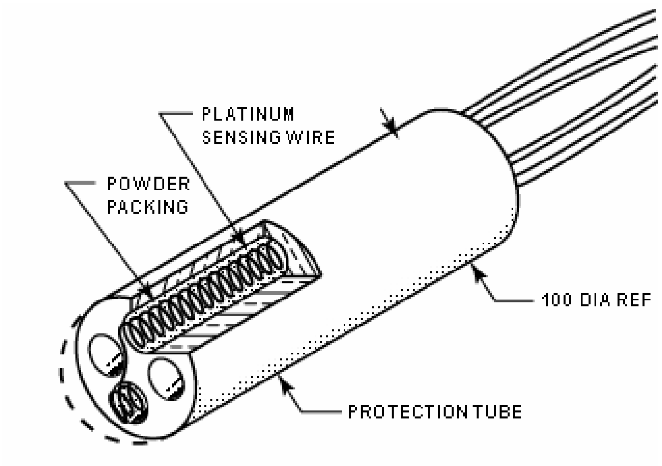


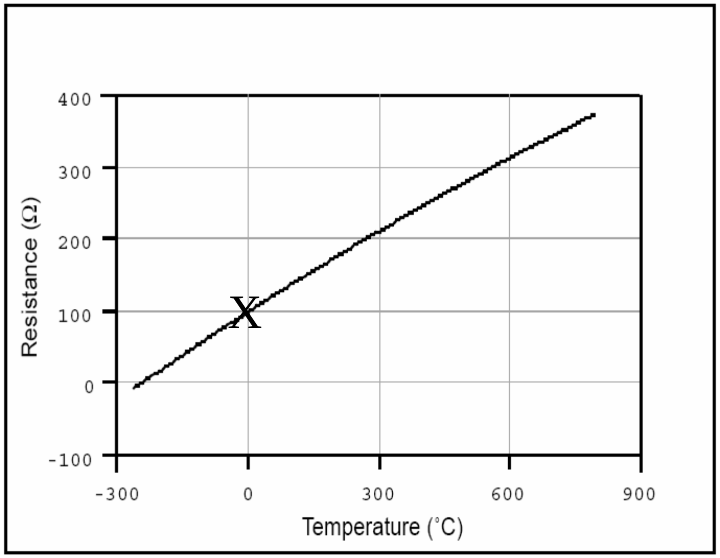
TIM
Transducer Interface Module

RTD Information and Specifications

- Temperature Coefficient
  $\alpha = (R'_t - R_o)/(R_o*100)$
  where R_o is R_t at 0^oC
  and R'_t is R_t at $100\ ^oC$

  [typically α is 0.00385 /^oC]



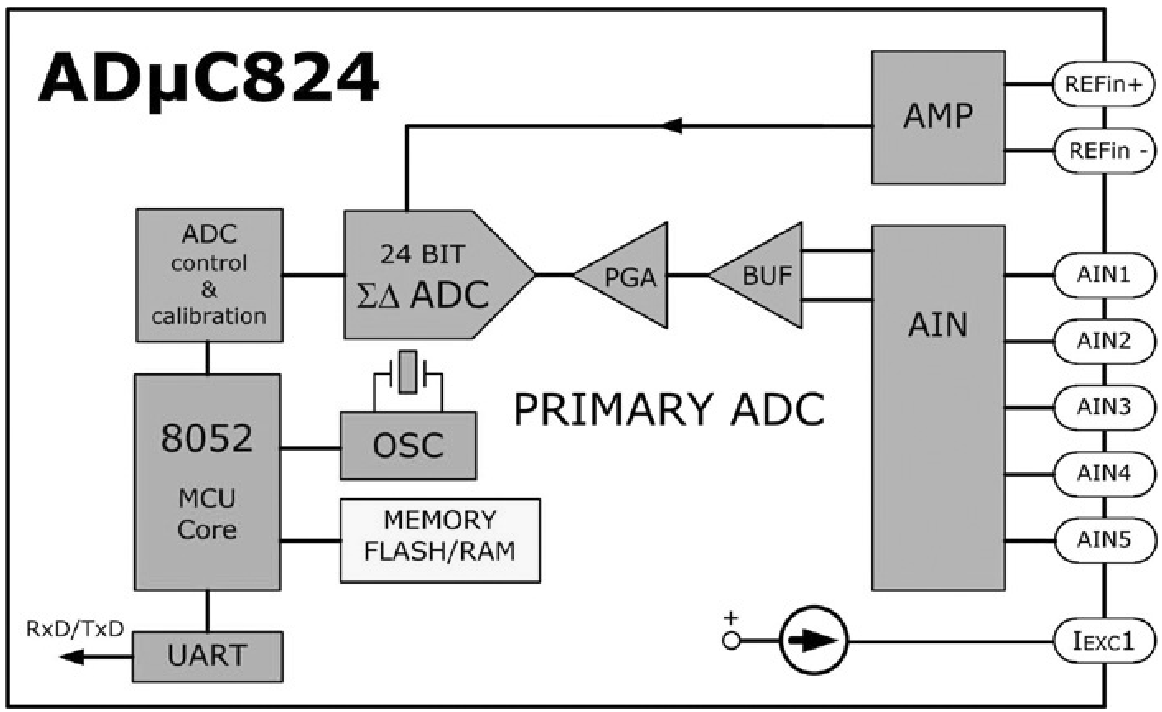


RTD as a Temperature Standard

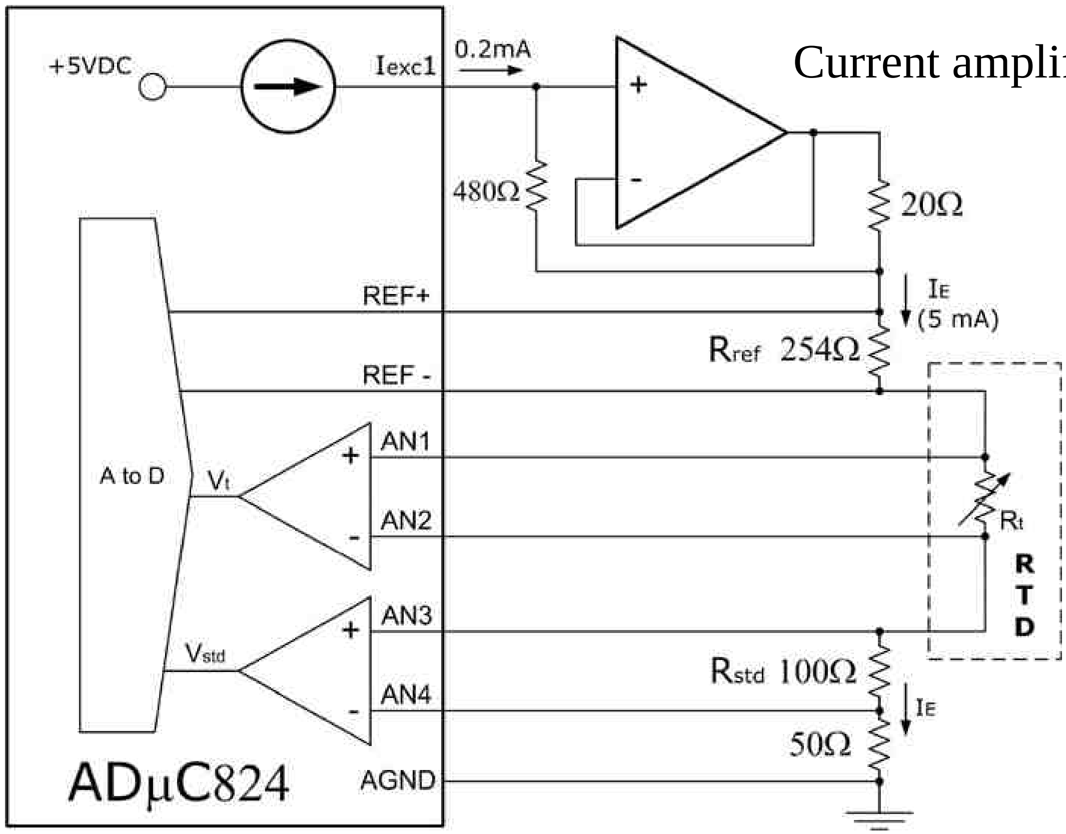
- Platinum RTD is basis of Scientific Temperature scale [International Temperature Scale of 1990 (ITS-90)]
- Standard maintained by **National Institute of Standards and Technology** (NIST)
- Pt RTD interpolates between defined fixed points

Specifications	5681	5683
Temperature Range	–200°C to 670°C	–200°C to 480°C
Nominal RTPW	25.5Ω	
Current	1 mA	
Resistance Ratio	W(302.9146 K) ³ 1.11807 and W(234.3156 K) £ 0.844235	

Microcomputer Block Diagram
with high resolution a/d



Signal conditioner for RTD



Current amplifier (x25)

4-wire configuration

Measurement of RTD Resistance

- Standard resistor $R_{std} = R_o$ approx (100.0 ohms)
- More precisely: $R_o = f_{cor} * R_{std}$

  where f_{cor} is a known correction factor (near 1.0)
- V_t and V_{std} are measured by the a/d
- $W' = V_t/V_{std} = f_{cor} * R_t/R_{std}$
- Thus R_t is calculated

Callendar-Van Dusen equation

Relationship between RTD resistance and temperature

$$R_t = R_0 [1 + AT + BT^2 + C (T-100)^3]$$

R_t: RTD Resistance (Ω) at Temperature T (°C)
R_0: RTD Resistance (Ω) at 0 °C
T: Temperature in °C
A, B, C: Constants derived from the ITS-90 standard (C=0 for T> ^{0}O C)

Temperature calculation
from RTD resistance

$$T_R = \frac{-A + \sqrt{A^2 - 4B(1 - \mathrm{w})}}{2B}$$

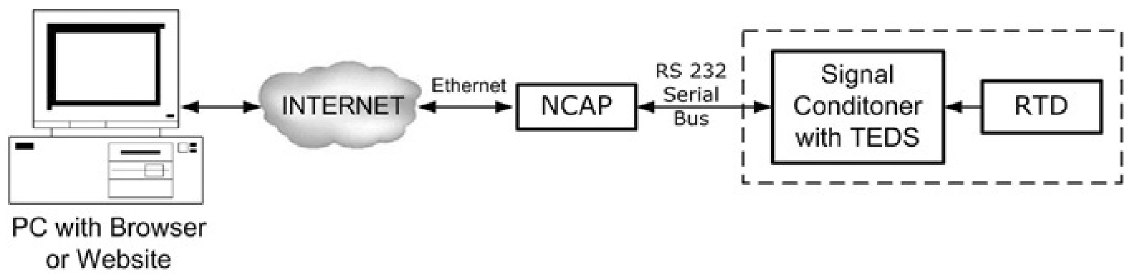
where T_R is calculated temperature from RTD resistance
and
w = R_t/R_o is the RTD resistance ratio

Inverse Callendar-Van Dusen equation
– done by microcomputer using floating point (23 bit precision)
[Alternative is ITS-90 polynomial equation (9^{th} order)]

Why Not Analog Readout?

- Required RTD temperature data resolution is high, 0.005% to 0.0002% of reading (e.g. 123.456)
- 4-20 mA current loop precision is typically only 0.2% to 0.02% of reading (but little error due to noise or lead resistance).
- Voltage readout precision is typically only 0.05% to 0.005% of reading (and subject to noise and ground offset errors)

Digital Data Transmission
with IEEE 1451.2 protocol



Transducer Interface Module
TIM

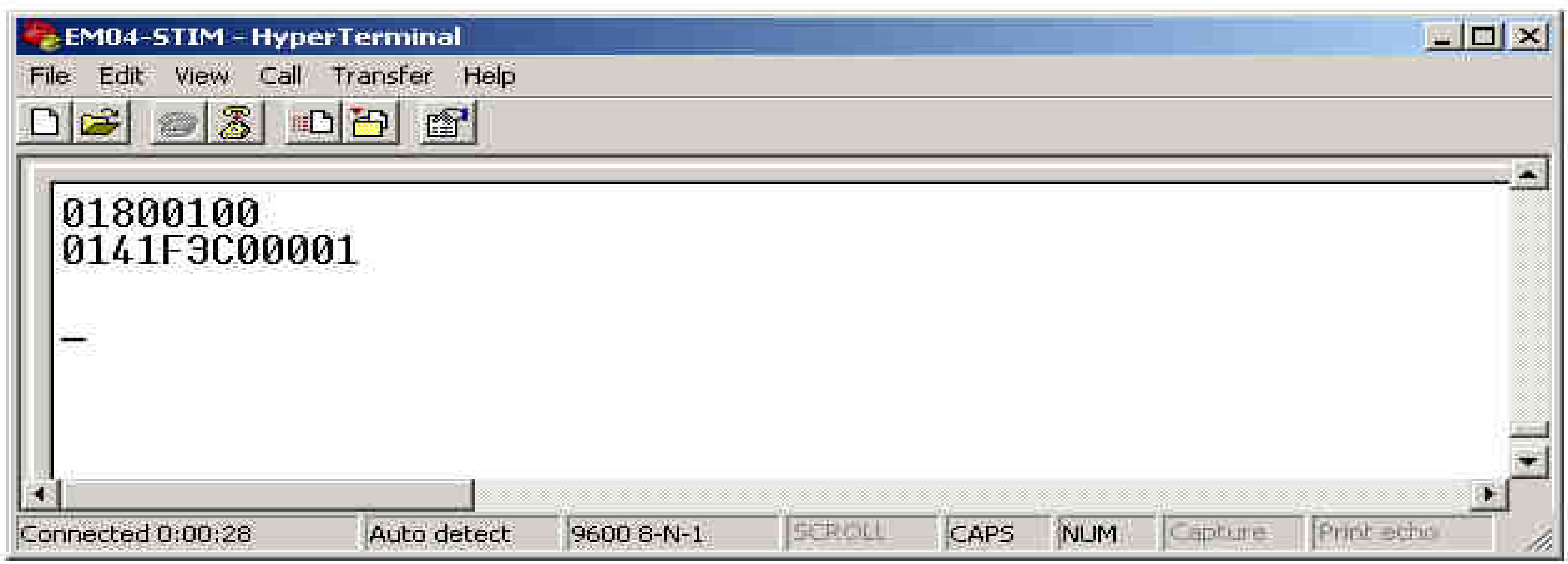
Problem:

High resolution digital data (e.g.123.456 ^{o}C) needs to be transmitted

We have selected the RS232 serial (point-to-point) bus (later USB)

We wish to use a standard format and have chosen the IEEE 1451.2 (proposed update compatible with the new Dot 0 format)

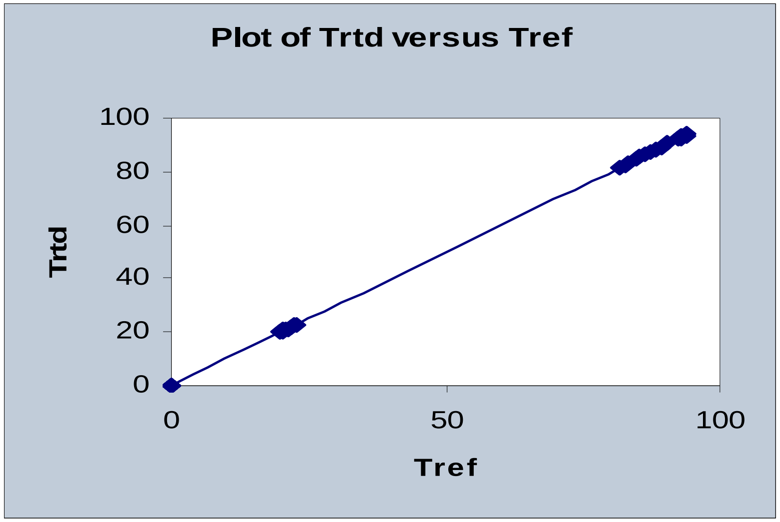
RTD TIM data readout via PC (RS232)

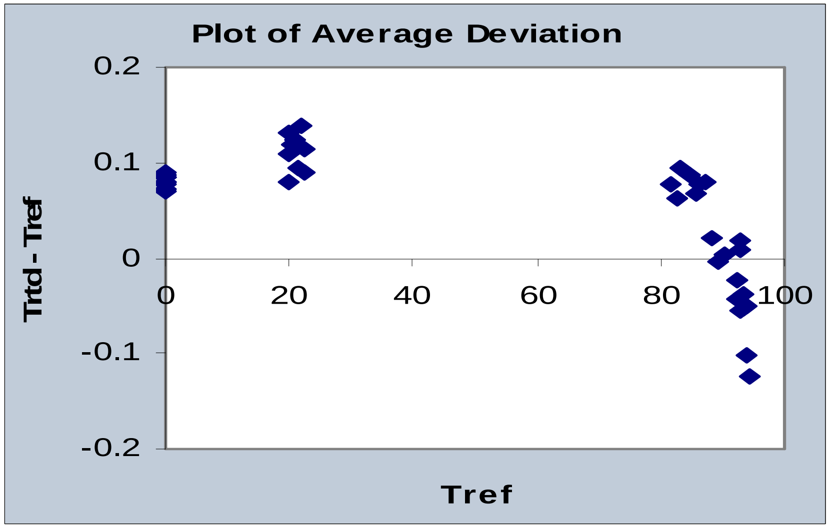


Hyper Terminal Displaying Access Command Sent and TIM Data Returned

Note: Data may be read via Internet also

RTD Temperature Tests





Note: Data resolution is +/- 0.001 °C but avr deviation about 0.1°C (showing measurement/calibration technique needs improvement)

Conversion of RTD Smart Sensor to a Networked Sensor (IEEE 1451 compatible)

- Our Viewpoint:

  Smart Sensors should be networked sensors

- Next group of slides describe smart networked sensors with the 1451 format

Sensor/Transducer Networks

- A network connects more than one addressed sensor (or actuator) to a digital wired or wireless network
- Both network and sensor digital data protocols are needed
- Standard data networks can be used but are far from optimum
- Numerous (>100) incompatible sensor networks are currently in use – each speaking a different language

The Tower of Babel

Networked Sensor Applications and Advantages

- Automatic testing
- Plug and play
- Multiple sensors on one network or bus
- Machine to Machine (M2M) sensor data communications
- Wide area (Nationwide) data collection ability

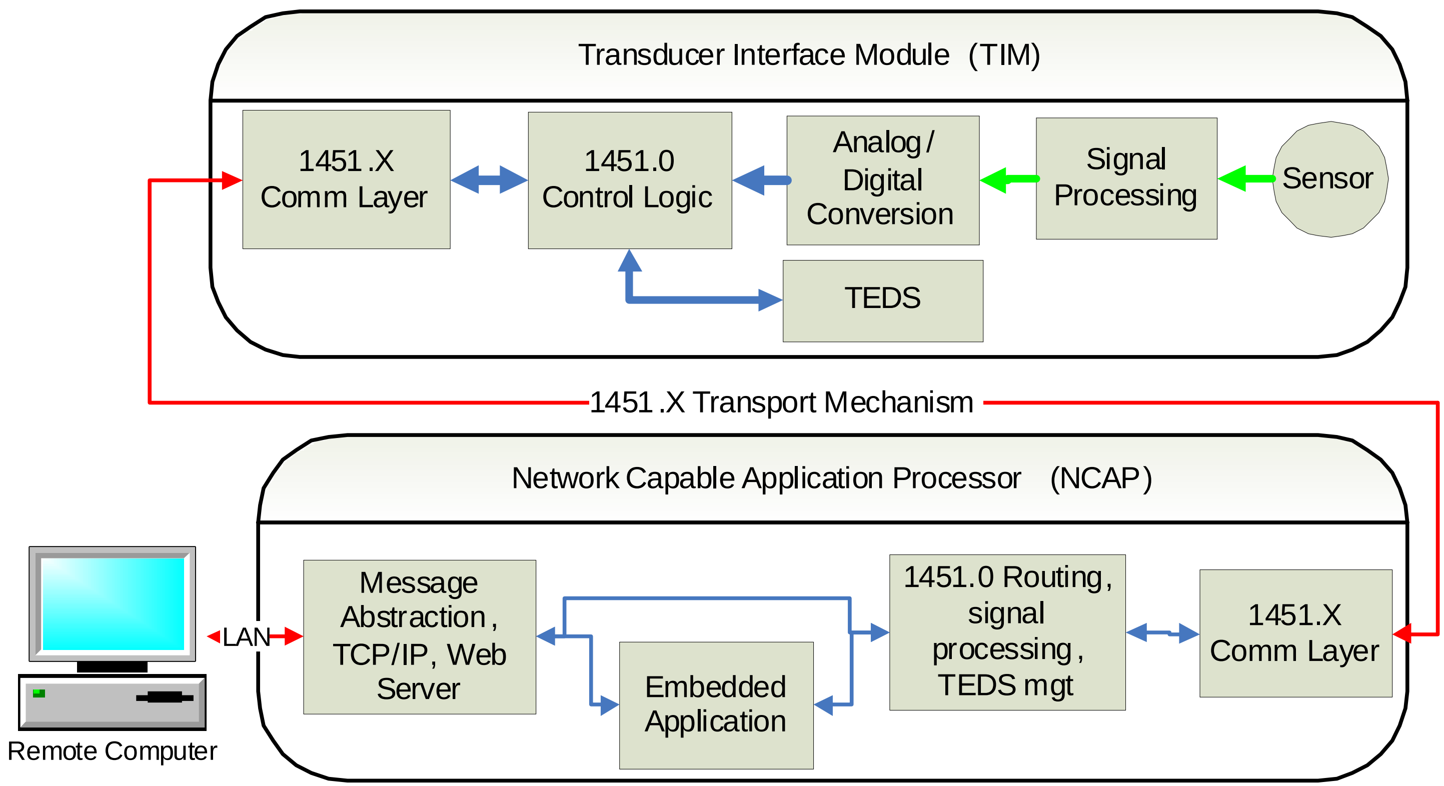
IEEE 1451 – the Universal Transducer Language

- *Problem:*
- Too many network protocols in common use
- Narrow solutions and borrowed protocols have not worked
- Sensor engineers in the fragmented sensor industry need a simple method of implementation

- *How can it be done*?
- We need something like USB, except for sensors
- Solution: the IEEE 1451 Smart Transducer Protocol open standard is the best universal solution
- Supported by NIST, IEEE and many Federal agencies

A review of the

IEEE 1451 Smart Transducer Concept

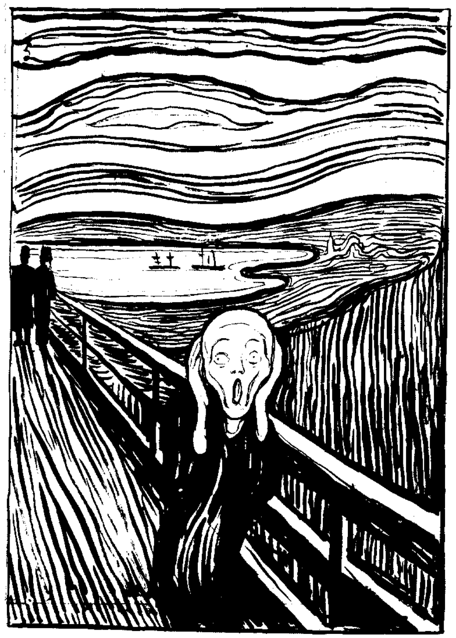


IEEE 1451 Advantages

- Comprehensive enough to cover nearly all sensors and actuators in use today (not 20/80% approach)
- Many operating modes
  (buffered, no-buffer, grouped sensors, timestamps, timed data, streaming …)
- Extensive units, linearization and calibration options
- Multiple timing and data block size constraints handled.
- Compatible with most wired and wireless sensor buses and networks (point-to-point, mesh, TIM-to-TIM, mixed networks).
- Efficient binary protocol (especially suitable for wireless)
- Standard is 400+ pages for basic part, over 1500 page total

But the Complexity!

- A comprehensive standard is necessarily complex
- There was little adoption of the original IEEE 1451.2 (TII) standard because of its perceived complexity
- Manual preparation of the TEDS is not practical -- A TEDS compiler is needed
- A compliance test procedure is also desirable to prove that a design is correct



Munch –The scream

Status of Various Parts of IEEE 1451

1451.0 – Basic data/TEDS format	**Done (2007)**
1451.1 – NCAP/Computer Interface	Done (1999)*
1451.2 – RS-232	Done (1997)*
1451.3 – Wired Multi-drop	Done (2002)*
1451.4 – TEDS Only	Done (2005) Most used
1451.5 – Wireless (WiFi, Zigbee, etc)	Done (2007)
1451.6 – CAN Bus	In process
1451.7 – RFID	In process

* Needs revision

IEEE 1451.0 (Dot 0) TEDS Format

- Required TEDS [Memory block with defined format]
  - MetaTEDS
  - Channel TEDS
  - Calibration TEDS (unless SI units)
  - Xdr-name TEDS
  - Phy TEDS
  - Also optional TEDS

- Data Transmission [specific octet format]
  - TEDS/Status requests
  - Triggering and configuration
  - Sensor read commands and data return
  - Actuator write commands and data sending

TEDS Binary Format

- General format for each TEDS section:

Field	Description	Data Type	Number of Bytes
-------	TEDS Length	UInt32	4 bytes
1 to N	Data Block	Variable	Variable
-------	Checksum	Uint16	2 bytes

- Binary TEDS Tuple format for each data block:

  Type-Length-value (TLV)

  Example: 01 02 A3 04

  Field type is 1, Length is 2 bytes, field value is "A304" hex

- Field example: Meta-TEDS (TEDS # 1)

  13: Number of Implemented Transducer Channels (default=1)

Standard Transducer Units
(binary format)

SI Based Units

Base Quantity	Name	Unit Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	Kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

Field	Description	Data Type	Number of octets
1	Physical units interpretation	UInt8	1
2	(2 * <exponent of radians>) + 128	UInt8	1
3	(2 * <exponent of steradians>) + 128	UInt8	1
4	(2 * <exponent of meters>) + 128	UInt8	1
5	(2 * <exponent of kilograms>) + 128	UInt8	1
6	(2 * <exponent of seconds>) + 128	UInt8	1
7	(2 * <exponent of amperes>) + 128	UInt8	1
8	(2 * <exponent of kelvins>) + 128	UInt8	1
9	(2 * <exponent of moles>) + 128	UInt8	1
10	(2 * <exponent of candelas>) + 128	UInt8	1

Dot 0 Command/Response Headers

Byte Number	Description
1	Destination Transducer Channel Number (Most significant byte)
2	Destination Transducer Channel Number (Least significant byte)
3	Command Class
4	Command Function
5	Length (Most significant byte)
6	Length (Least significant byte)
7-N	Command dependent bytes

NCAP Command Message Structure

Byte Number	Description
1	Success/Fail Flag
2	Length (Most significant byte)
3	Length (Least significant byte)
4-N	Reply dependent bytes

TIM Reply Message Structure

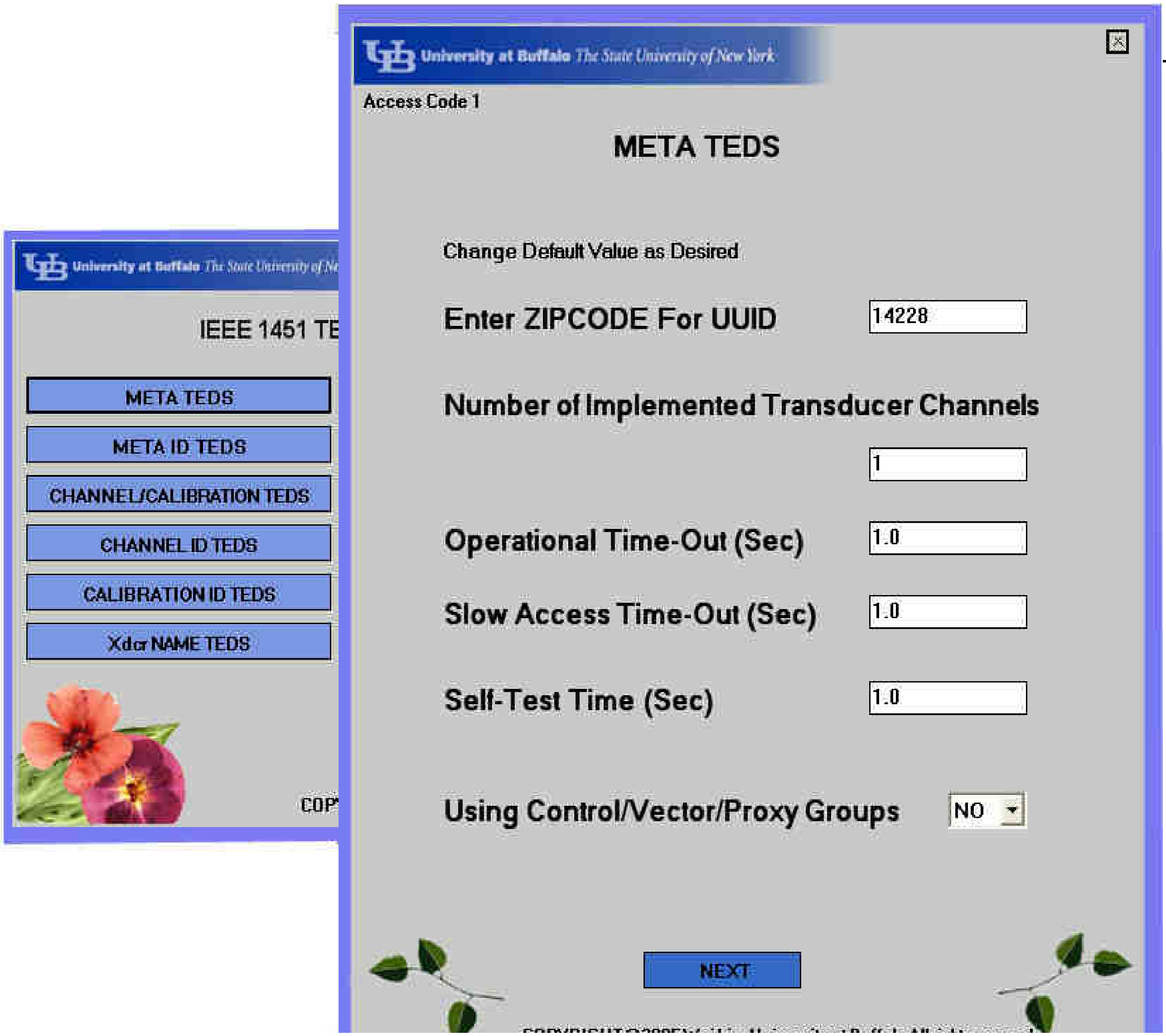
Compiler TEDS Sections Implemented

- Meta TEDS
- Meta ID TEDS
- Transducer Channel TEDS
- Transducer Channel ID TEDS
- Calibration TEDS
- Calibration ID TEDS
- XdrcName TEDS

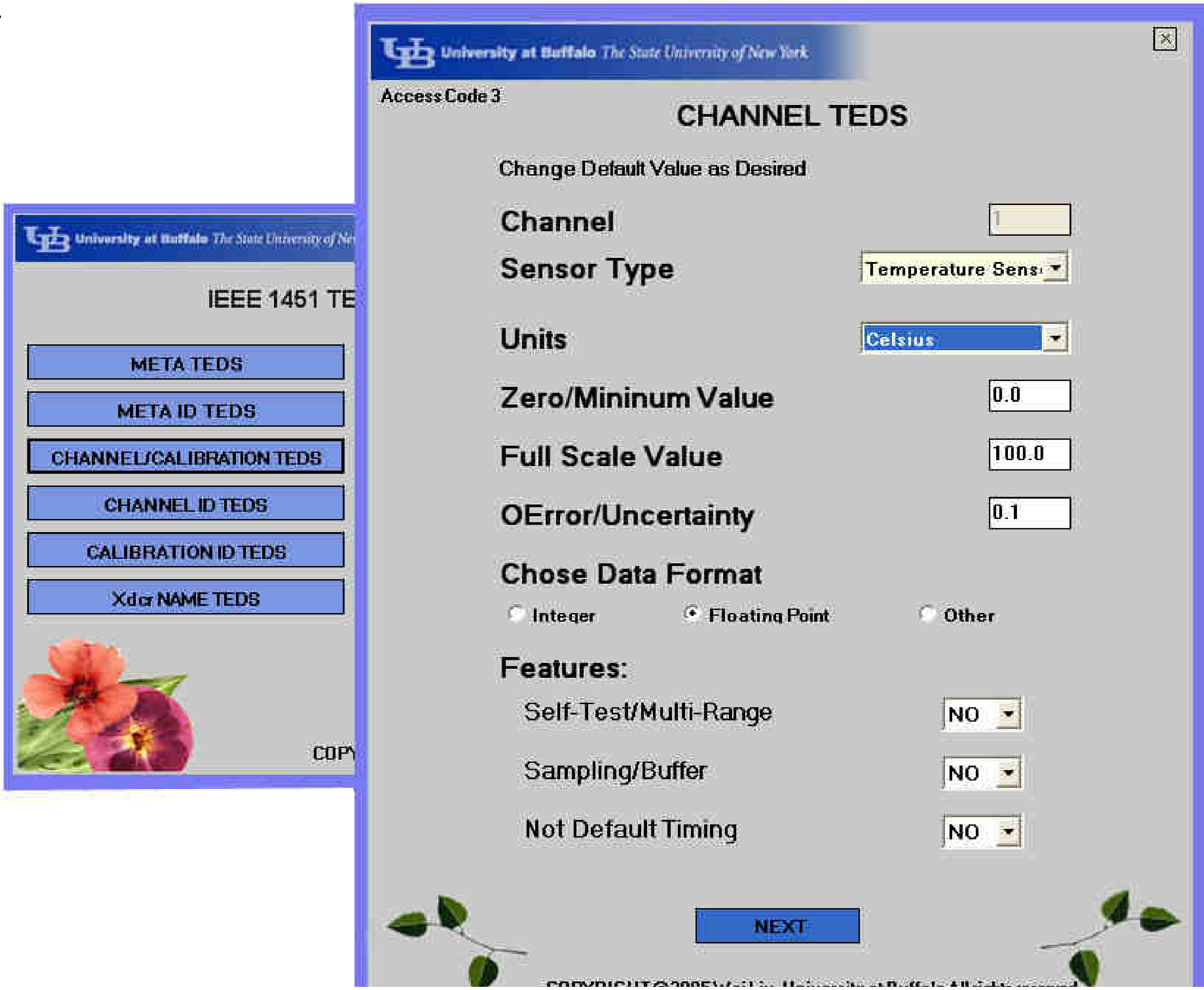
Referenced by TEDS section/access code (e.g. #1 for Meta-TEDS)

Compiler developed by Wei Liu, University at Buffalo

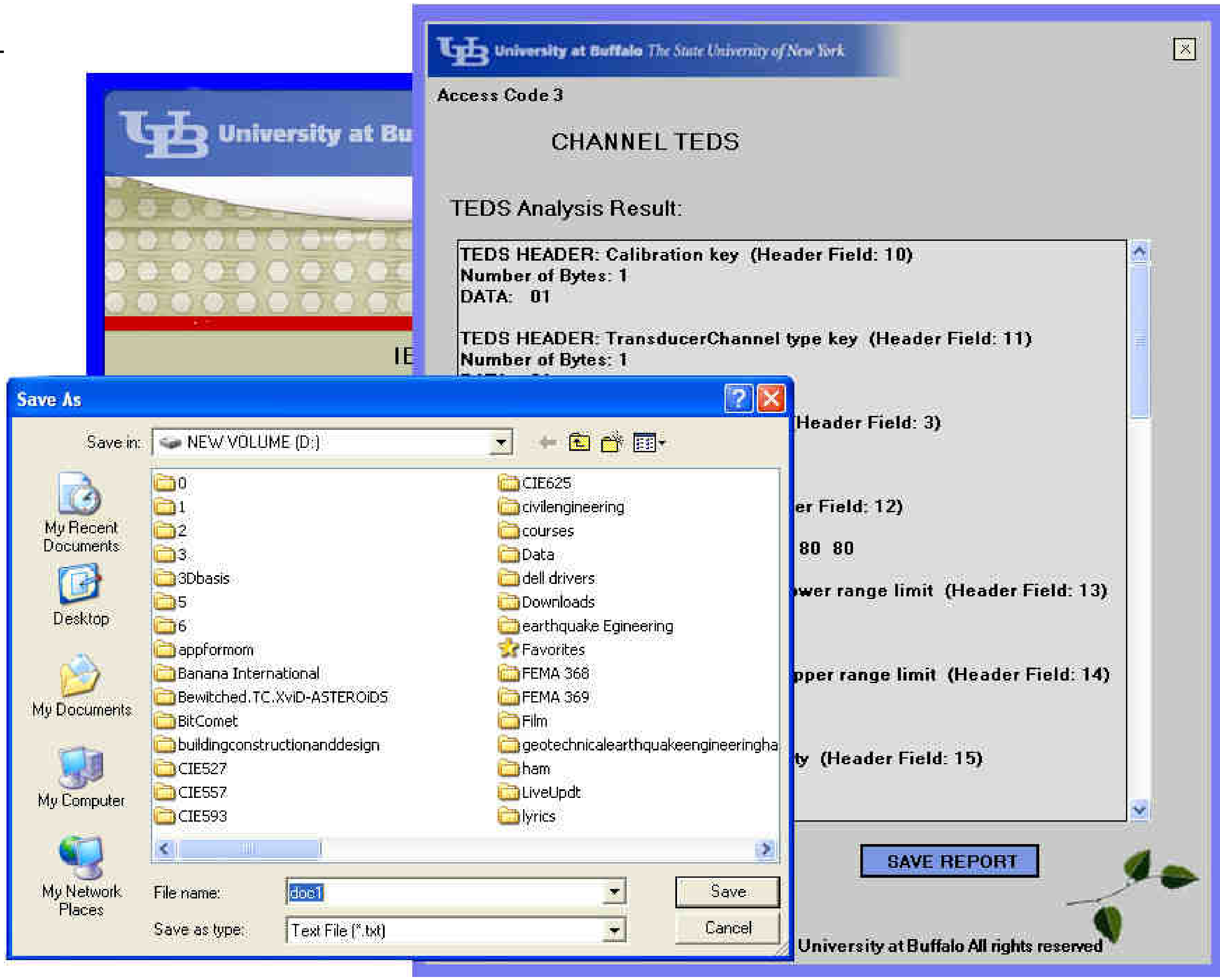
Compiler Meta-TEDS Writer Screen



Channel/Calibration TEDS (for linear sensors)



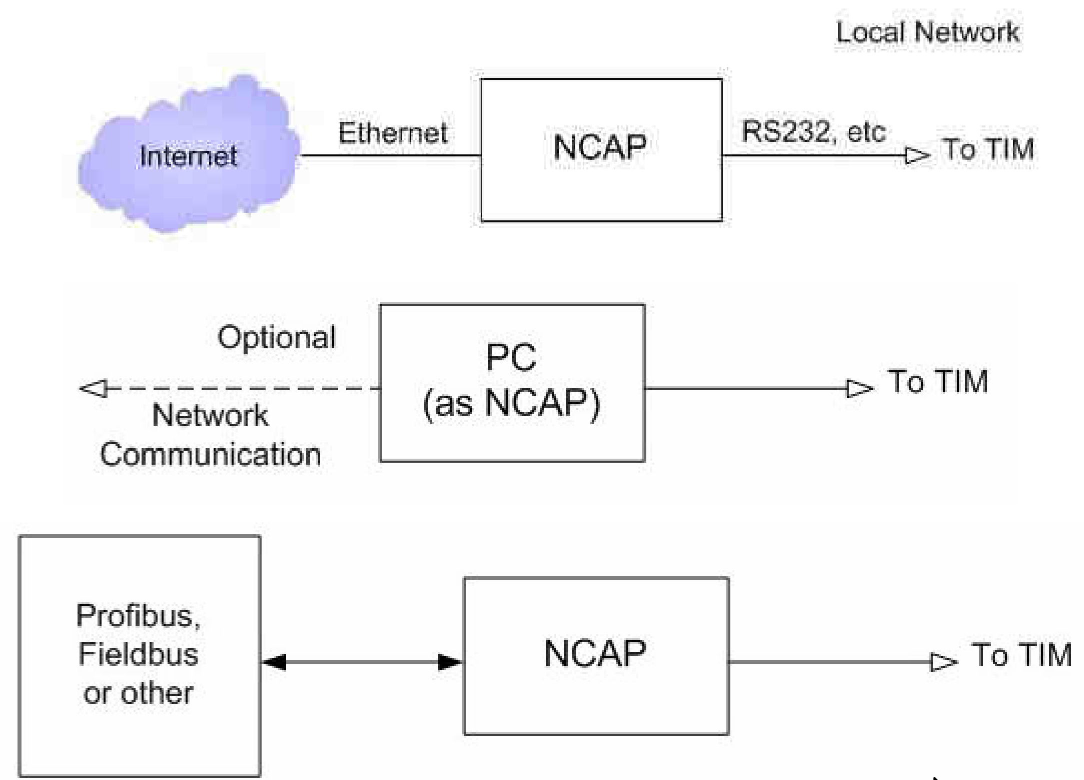
TEDS Reader



University at Buffalo The State University of New York
Access Code 3
CHANNEL TEDS
TEDS Analysis Result:
TEDS HEADER: Calibration key (Header Field: 10)
Number of Bytes: 1
DATA: 01
TEDS HEADER: TransducerChannel type key (Header Field: 11)
Number of Bytes: 1
SAVE REPORT
University at Buffalo All rights reserved
Save As
Save in: NEW VOLUME (D:)
My Recent Documents
Desktop
My Documents
My Computer
My Network Places
File name: doc1
Save as type: Text File (*.txt)
Save
Cancel

Network side (NCAP) options (wired)

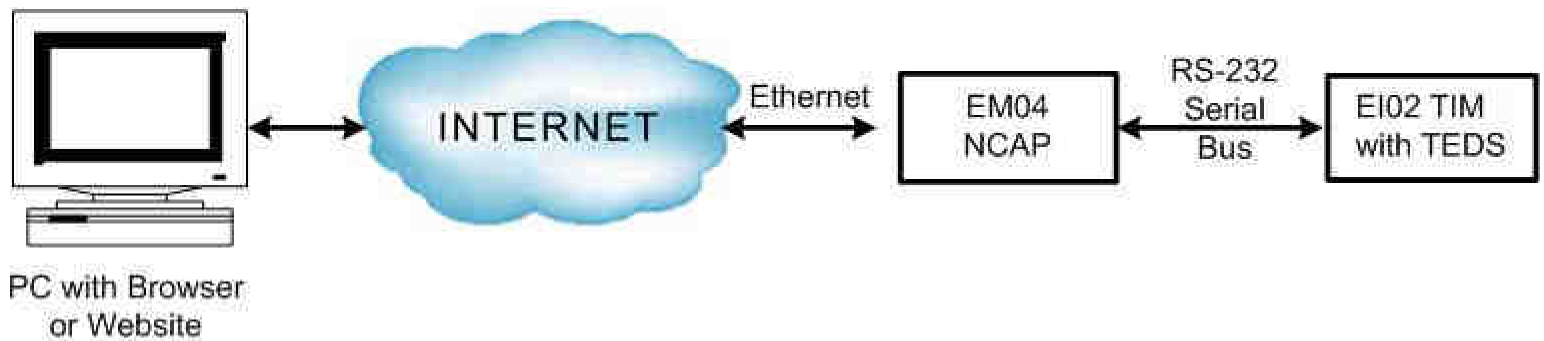
- Internet/Ethernet
- PC Readout
- Industrial network



All use Dot 0 protocol

Prototype TIM and NCAP

- NCAP interfaces to Internet via Ethernet



Serial Bus Format
and Relation to other Networks

- Tester uses RS232 serial bus only but…
- Interfaces to other physical devices (USB, RS485, Bluetooth, Zigbee, ….) available.
- TEDS retrieval is one feature
- Sensor data read (protocol check) for each channel:

    Idle mode – full scale value of sensor reading

    (Checked against TEDS, error flag is not correct)

    Operating mode – actual sensor reading

    (Must be within sensor range)

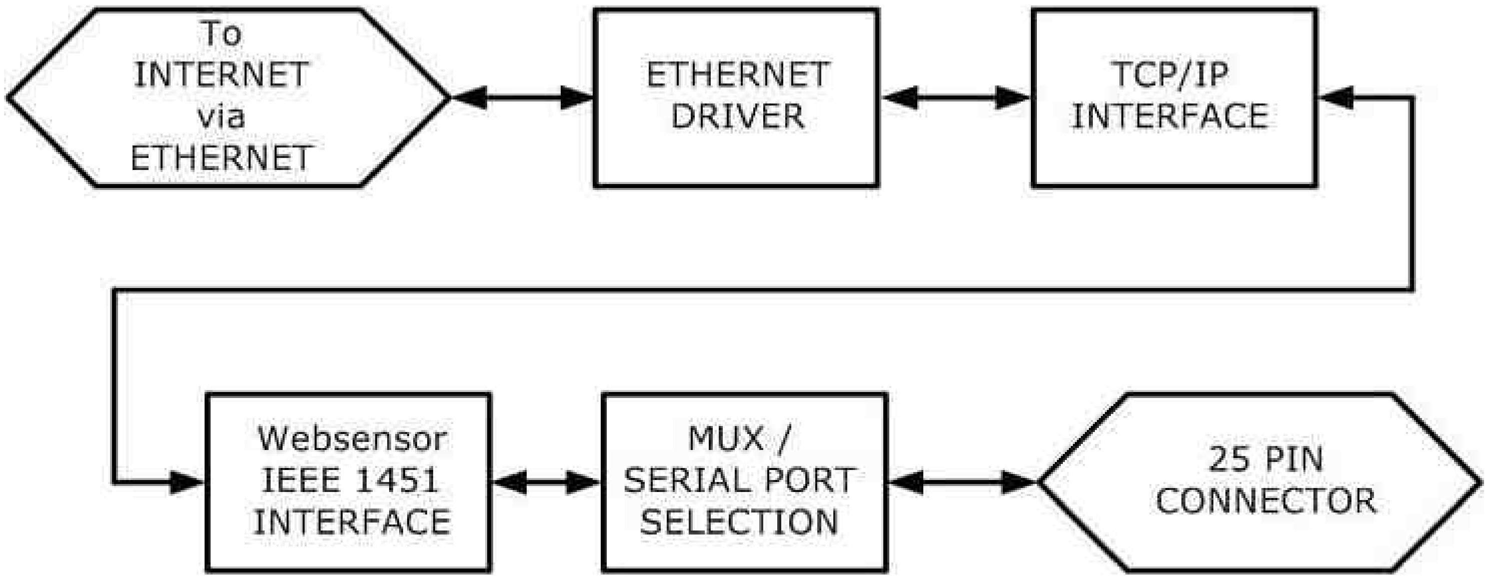
IEEE 1451 as a Universal Digital Sensor Base Format

- Specialized networks can handle only a limited number of sensor types or uses non-compact format
  - – 1451 is much superior at the sensor end
- Most applications require individualized displays or graphical user interfaces – 1451 is a fixed format and poorly suited at the user end
- Network oriented applications prefer XML or similar formats which are convenient, but are too verbose at the sensor end
- 1451 at the sensor end (Sensor Fusion level 0) combined with translators is the best solution.

Return to RTD TIM and NCAP

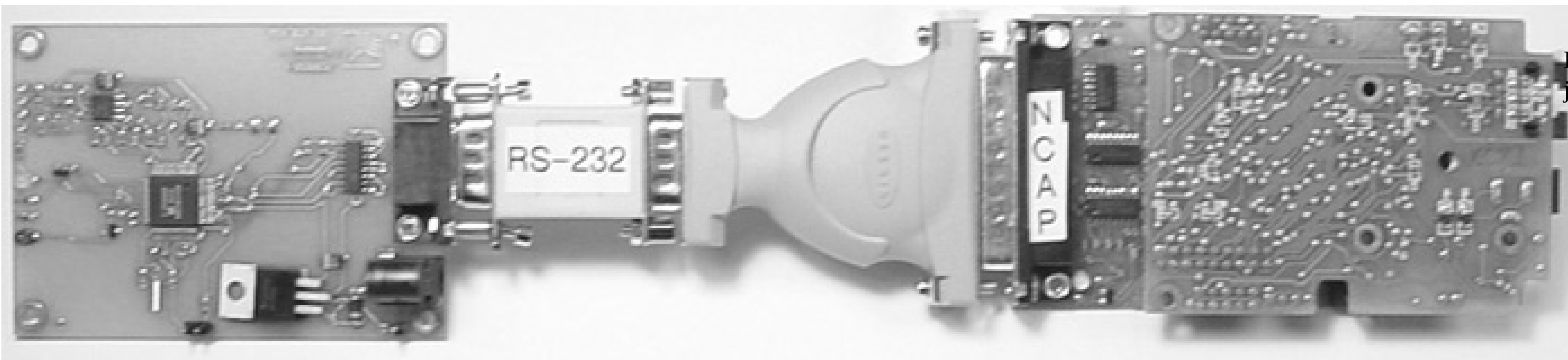
- RTD TIM is based on Serial Point-to-point bus
- Currently uses RS232
  (but easily converted to USB)
- We want IEEE 1451.0 (Dot 0) format

NCAP Block Diagram



Note: details of this NCAP were described in previous talks

Photograph of RTD (TIM) and NCAP Boards

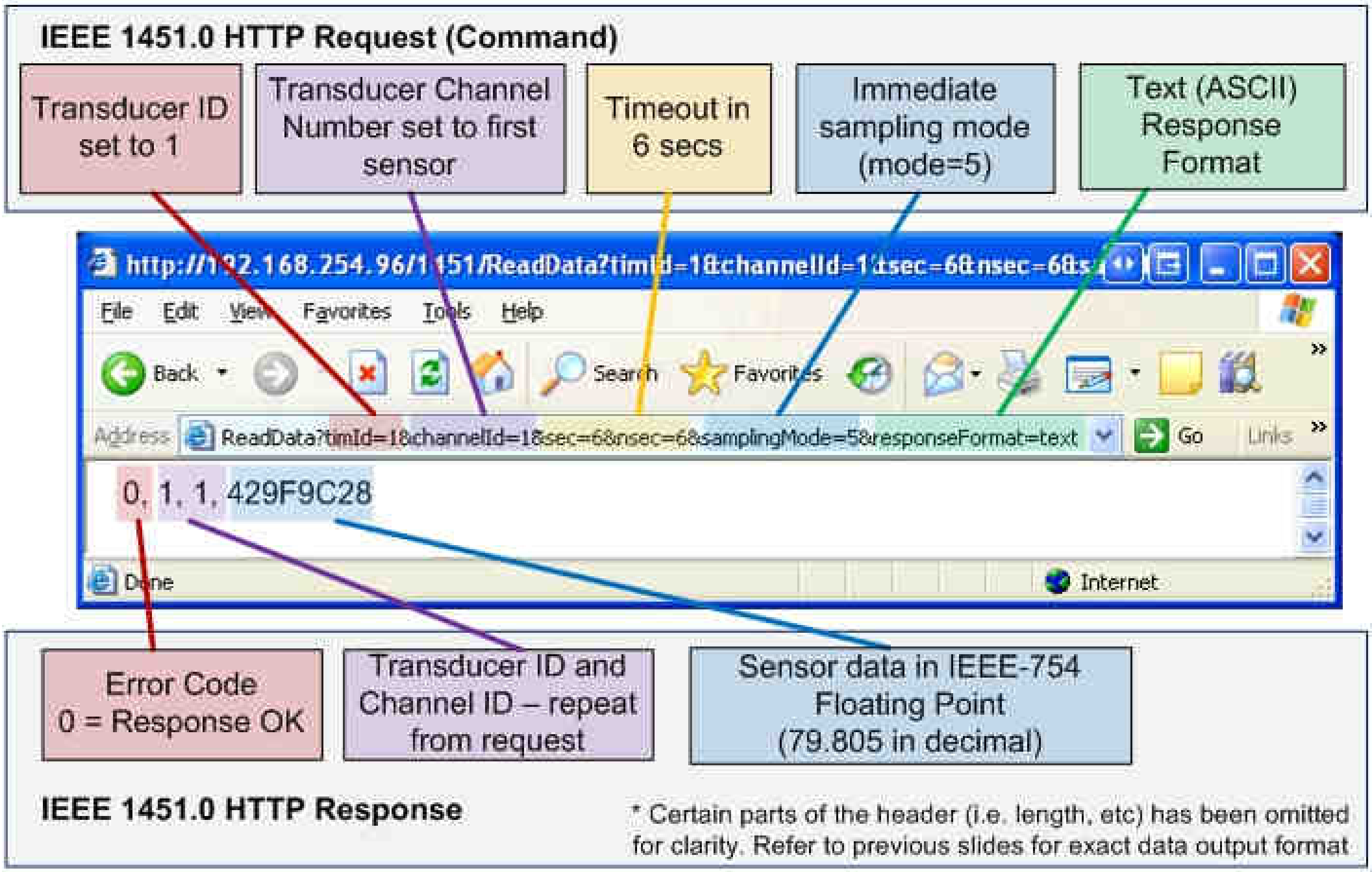


Ethernet jack

TIM
RTD Signal Conditioner

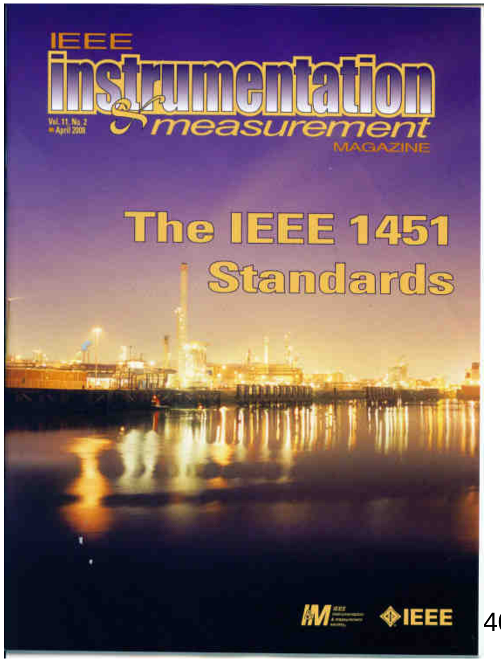
NCAP
To Internet via Ethernet

RTD Data in IEEE 1451.0 format



References

- [**NIST IEEE**-P1451 Draft Standard Home Page](#) **ieee1451**.**nist**.gov/
- "The IEEE 14451 Standards", April 2008 issue (Vol .11, No. 2) of IEEE Instrumentation and Measurements magazine
- www.eesensors.com/ieee1451.html



Summary

- A high resolution digital (smart) signal conditioner for an RTD temperature sensor has been designed and tested.
- The signal conditioner was formatted to use a prototype IEEE 1451 serial interface (TIM with TEDS).
- The RTD signal conditioner or TIM was tested using a PC.
- The TIM was then tested using an NCAP with the Internet (via Ethernet) capability.
- Features, advantages and complexity of the IEEE 1451 smart transducer universal standard were discussed

Further information:designer@eesensors.com

End

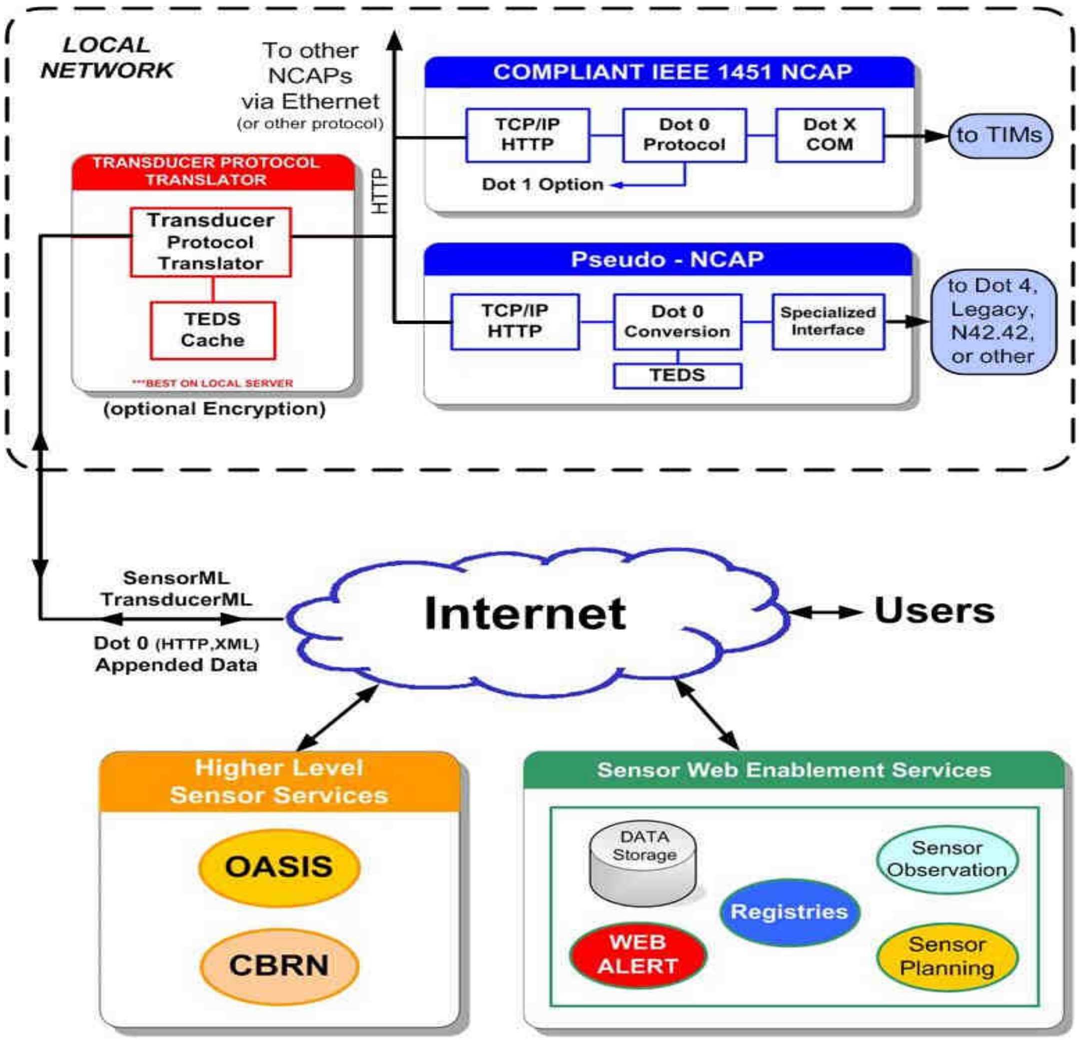
- Backup Slides Follow

www.eesensors.com

More References

- R. Frank "Understanding Smart Sensors", 2nd ed, Artech House (2000)
- R. Johnson, et al "A Standard Smart Transducer Interface" http://ieee1451.nist.gov/Workshop_04Oct01/1451_overview.pdf
- IEEE Std. 1451.2-1997 "IEEE Standard for a Smart Transducer Interface for Sensors and Actuators – http://ihome.ust.hk/~yangrd/pdf/ieee14512.pdf
- D. Wobschall, "Websensor Design – Smart sensors with an Internet Address" Proceeding Sensors Expo (Philadelphia, Oct. 2001)
- D. Wobschall "IEEE 1451 Prototype Dot 2 and Dot 4 NCAPs with Internet Access", Proc. Sensors Expo (Sept 2003)
- www.eesensors.com/IEEE1451

Harmonization of IEEE 1451 with Internet sensor standards



Harmonization Meeting Summary

- 25 attendees, mostly government
- DOD, DHS, DJ, DS represented (also NASA subcontractor)
- All working under directives to implement standards
- DHS new directive requires new sensors to use existing open standards if available (not proprietary or invent new)
- DOD joint task group working on standards and expects to support test bed. Possible FY’10 requirement.
- Several test beds involving IEEE 1451 started (Esensors has some part in all).

Wireless Sensor Networks

- Currently fashionable in academic and VC circles
- Recently available low-cost, high performance RF transceiver chips greatly simplify design
- Improvements in embedded microcomputers and smart sensor design also make wireless sensors much more practical now
- Can be lower cost and easier to use than wired sensors
- Point-to-point and mesh protocols available.
- Specialized sensor networks (e.g. Zigbee) much more efficient for wireless sensors, especially battery operated.
- Lack of standards inhibiting growth of industry.

IEEE 451 TIM Compliance Tester

- TIM (Transducer Interface Module) is most complex and done by sensor design engineers
  - (TIM tester can be used by the few NCAP designers)
- Tester verifies compliance of a TIM to IEEE 1451.0 (Dot 0) protocol
- Focus is on TEDS checking and data transfer format
- Physical device compliance not checked (part of other standards, e.g. RS485, Bluetooth)
- Tester uses serial bus (RS232)
- Testing may be done by Internet

Need for Network Standards

- Smart sensors more effective with a digital network
- Over 50 sensor networks and busses in common use
- Users and manufactures would like one standard to reduce manufacturing/installation costs and for plug&play capability
- No single local network is likely to dominate in near future due to divergent needs
- The Internet via Ethernet will likely be one of the dominate networks (but cost and complexity are problems)
- The IEEE 1451 standard for sensor interfacing overcomes many of the complications of multiple networks

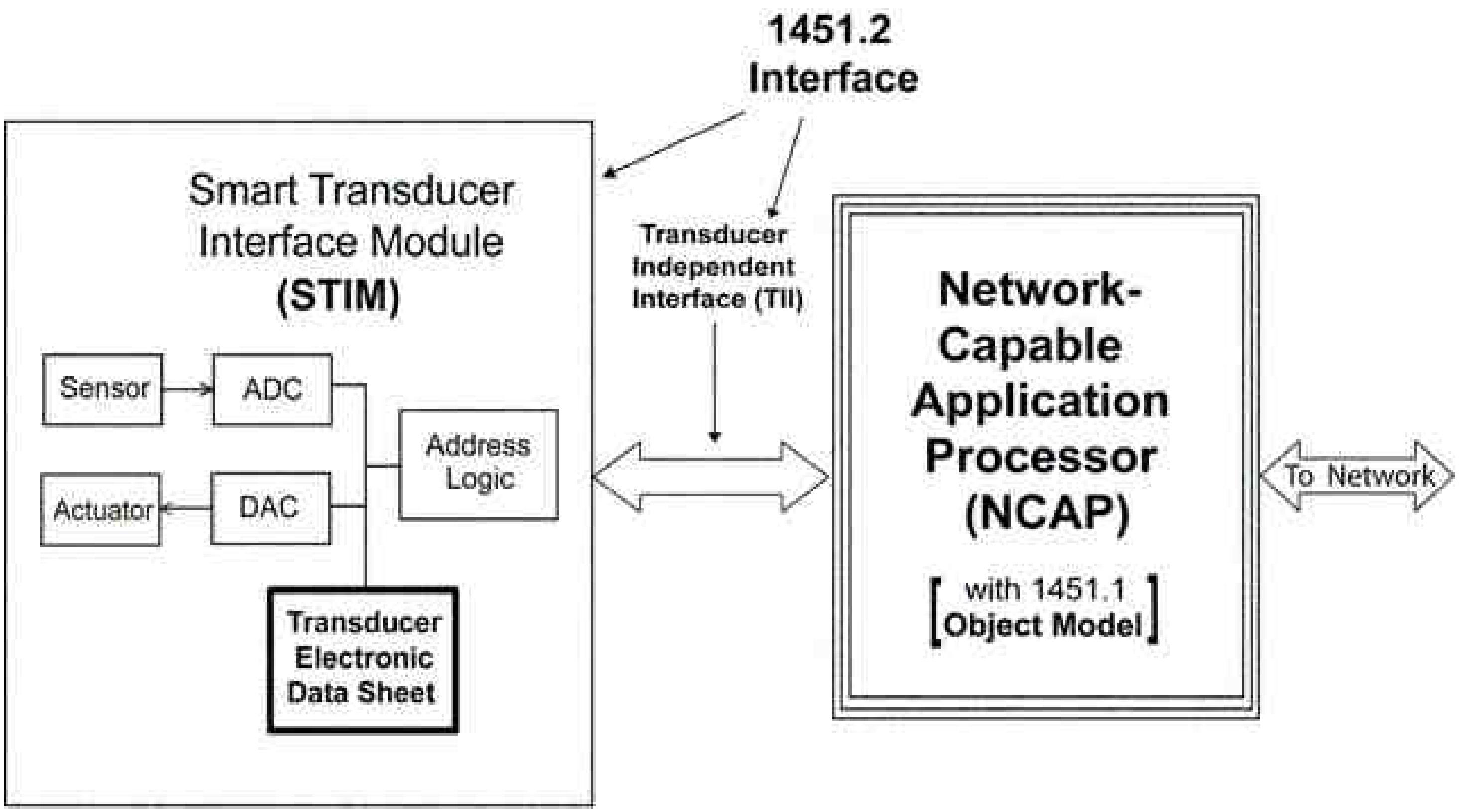
Advantages of IEEE 1451 Standard

- Continuing network interface and microcontroller cost reductions have made interface more attractive.
- The sensor industry is closer to recognizing the necessity for a sensor network standard.
- The general concept of the IEEE 1451 approach, especially TEDS, is supported by many.
- Working groups are defining details for different types of local busses and networks (e.g wired and wireless)

Future Prospects for IEEE 1451

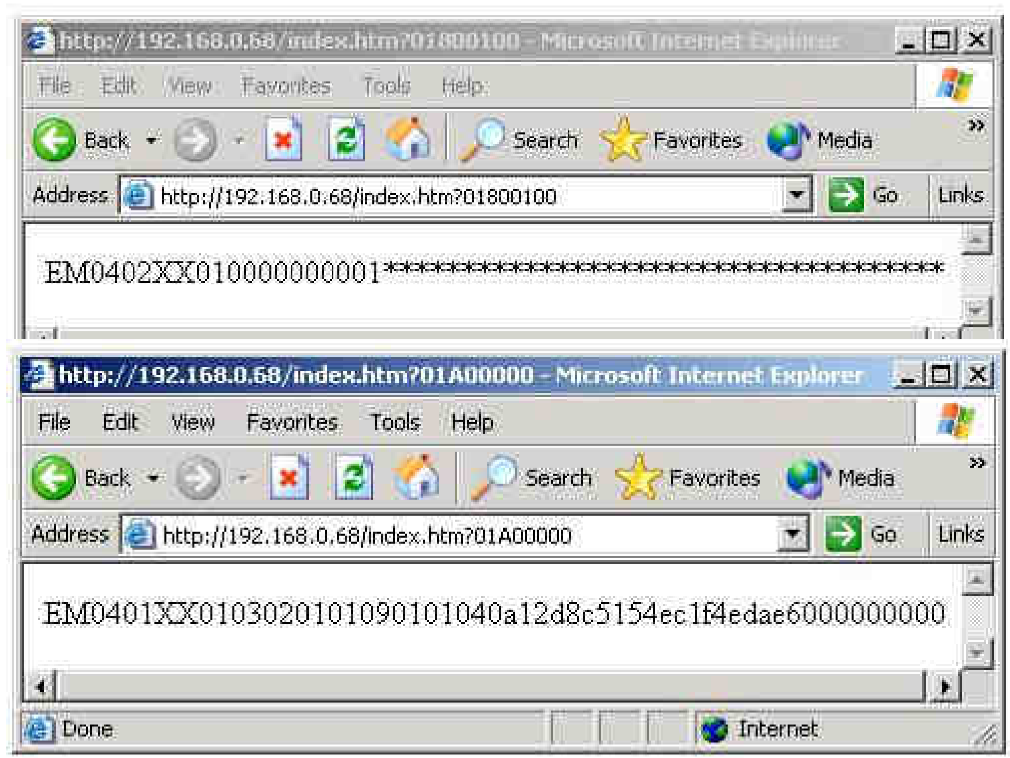
- There has been little interest in previous parts of IEEE 1451 (Dots 2, 1 & 3), except for Dot 4 in certain areas.
- The basic Dot 0 (and Dot 5) are more carefully composed and thus likely to be accepted.
- The compiler may answer the complexity issue but still implementation of any full-featured standard will be difficult.
- The US government may mandate a sensor data standard and the NIST-supported IEEE 1451 is the most recognized candidate.
- The sensor industry, especially the wireless network sector, must recognize the business advantages of a single sensor data standard.

Old (1997) IEEE 1451.2 System Block Diagram



Data Readout Examples
(via Internet but not IEEE 1451 format)

- Sensor data converted to ASCII for display



- TEDS data is displayed in hexadecimal form

Future of Networked Sensors

- Computer-based monitoring and control applications are increasing in commercial, industrial and military sectors.
- Networked, and often wireless, sensors offer performance and cost advantages over traditional methods.
- Wider use of networked sensors is inhibited by lack of standards (especially National scale networks, wireless and multi-vendor, long-term installations).
- I expect sensor standard and harmonization efforts to succeed within 2 to 5 years and Federal Agencies (DHS, DOD; NASA) to favor IEEE 1451.

RFID with Sensors (Dot 7)

- Combines Radio Frequency IDentification with sensors
- Uses standard (ISO/IEC) RFID communication/format with additional sensor memory section
- Sensor format is based in IEEE 1451 protocol
- Typical application is tracking and monitoring perishable shipments (temperature, shock/vibration)

Dot 4 TEDS Writer and Reader
(PC Screens)

Writer

Reader

TIM Tester – Data retrieval