SAS 2009 – IEEE Sensors Applications Symposium
New Orleans, LA, USA - February 17-19, 2009

A ZigBee wireless sensor network compliant with the IEEE1451 standard

Jorge Higuera, Jose Polo, Manel Gasulla
Instrumentation, Sensors and Interfaces Group
Universitat Politécnica de Catalunya
Castelldefels (Barcelona), Spain
higuera@eel.upc.edu, jose.polo@upc.edu, manel.gasulla@upc.edu.

***Abstract*—Wireless sensor networks are becoming very attractive for monitoring and control applications with smart sensor nodes. We present an implementation of a ZigBee wireless sensor network compliant with the IEEE1451 standard to improve the interoperability. This paper describes the message structure, commands and transactions. Furthermore, a proposal is presented to enhance the IEEE1451.5 ZigBee physical transducer electronic datasheet (PHY TEDS).**

Keywords: IEEE1451 , interoperability, NCAP, WTIM, TEDS, ZigBee, WSN.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are becoming very attractive in many pervasive computing environments and constitute a key technology for monitoring and control. They are composed of low cost, small size and low power nodes. One of the nodes actuates as the coordinator of the network.

The implementation of commercial WSNs involves, in many cases, proprietary application programming interfaces (APIs) and protocols. The use of different proprietary data formats and protocols constitutes a bottleneck for the expansion of these networks. The recent introduction of the IEEE802.15.4 -2006 standard [1] and ZigBee specification can help in adopting a common manufacturer-independent communication protocol for WSNs. At a higher level, the IEEE1451 standard family [2] was introduced in the last decade as a set of open standards, organized around a set of common architectures and protocols to permit the interoperability of multiple smart sensors. In this way, smart sensors can be connected in a plug and play way in a distributed wireless or wired network. The main advantages of this envision is a new design of smart sensors with digital communication standard interface and many options including self diagnosis, autocalibration, multi sensing, data storage in a electronic data sheet, and signal output in engineering units.

The IEEE1451.5 is compatible with radio-specific protocols for WSNs such as 802.11 (WiFi), 802.15.1 (Bluetooth), ZigBee, and 6LowPAN [3]. Still, few implementations have been reported. Sweetser et al. [4] implemented a smart sensor based on IEEE1451 and Bluetooth communication interface. Song and Lee [5] used the IEEE802.11 interface. The same authors [6] provide a set of guidelines for implementing applications based on the IEEE1451 using the unified modeling language (UML). Wobschall [7] shows a wireless smart sensor with point-to-point connectivity by using the IEEE 1451.4 physical layer. However, to the best of our knowledge, no solution has been proposed for an IEEE1451.5 Zigbee network. This paper proposes a Zigbee network compliant with the IEEE1451 standard.

II. PROPOSED ARCHITECTURE

Figure 1 shows the basic architecture of a smart IEEE1451 transducer particularized for a wireless sensor based on IEEE1451.5. It includes the following parts:

- Wireless Transducer Interface Module (WTIM). In our architecture, it includes the physical sensors, signal conditioning, a MSP430 microcontroller unit with internal analog to digital converter, and the Transducer Electronic Data Sheet (TEDS) embedded in external serial Flash memory. The TEDS contains information about calibration, functionality parameters, vendor, data units, etc. A WSN is composed of multiple WTIMs
- Network Capability Application Processor (NCAP). The NCAP consists of a processor with an embedded operating system and timing capability. It actuates as the coordinator of the WSN. The NCAP is a device between the wireless transducer modules and the wired network and performs the connections to multiple WTIMs with the same physical layer. In our application the physical layer is IEEE802.15.4. The NCAP may initiate the discovery and association of wireless node at any time.
- Transducer Independent Interface (TII). The IEEE 1451 defines a set of standard interfaces that support different networks: wired and wireless networks. Our approach uses a ZigBee IEEE1451.5 interface.

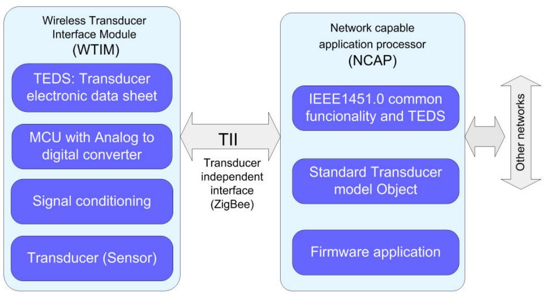

Fig 1. IEEE1451 Smart sensor model.

9781-4244-2787-1/09/$25.00 ©2009 IEEE

A. Network architecture

Figure 2 shows the proposed WSN architecture with WTIMs and the NCAP. Database support and monitorization via Internet has been added. NCAP and STIMs nodes are implemented with Sky Tmote modules (MoteIV, now Sentilla) [8] working under a real time operative system (RTOS) TinyOS [9]. All firmware for WTIMs and NCAP was developed in NesC language [10].

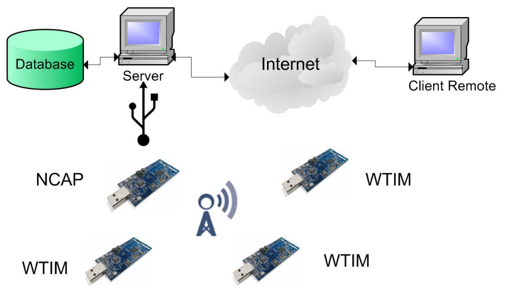

Fig 2. Proposed WSN architecture.

B. Nodes

Each Sky Tmote module includes several sensors, a 16 bit MSP430 microcontroller, 6 analog input channels, and a Zigbee compliant CC2420 transceiver [11] working at the 2.4 GHz ISM band. Additionally, a USB interface is present. Figure 3 shows the block diagram of the module.

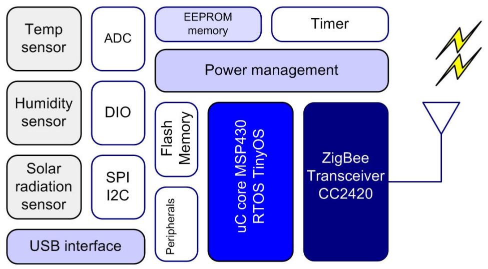

Fig 3. Block diagram of a Sky Tmote module.

C. NCAP

The NCAP is composed of a Sky Tmote module connected via USB to a PC. The NCAP coordinates the activity of all WTIMs by sending IEEE1451.0 standard commands through the Zigbee transceiver. Received data from WTIMs are stored in a MySQL database and accessed via Internet.

D. WTIM

Each WTIM includes four sensor channels (temperature, humidity, solar radiation and battery voltage), and all mandatory TEDSs stored in an EEPROM memory. Mandatory TEDS include: Meta-TEDS (IEEE1451.0), Transducer Channel TEDS (IEEE1451.0), User's Transducer Name TEDS (IEEE1451.0) and PHY TEDS (IEEE1451.5) for the ZigBee interface. Power is provided by two AA primary batteries of 2700 mAh connected in series.

Firmware has been developed for the WTIMs to read the transducer channels and mandatory TEDS.

E. Power management

The WTIMs use different operation power modes including active, idle and sleep, in order to preserve power and to extend the battery life. Our application includes a synchronized protocol (SP) for low power operation [12], which establishes and maintains a schedule whereby the entire network wakes up together and then returns to sleep. The activation period is 400 s and the duty cycle is 1%, so each WTIM only operates for 4 s in active mode and then returns to sleep mode for 396 s.

F. User interface

A graphical user interface (GUI) has been developed in LabVIEW that includes the commands compliant with the IEEE1451 ZigBee radio sub-specification to send and receive the information in the WSN and shows all active messages in the frontal panel. Figure 4 shows the command menu of the frontal panel. This application operates in a PC server and users can control and monitor all parameters of the WTIMs channels using the IEEE1451 standard commands.

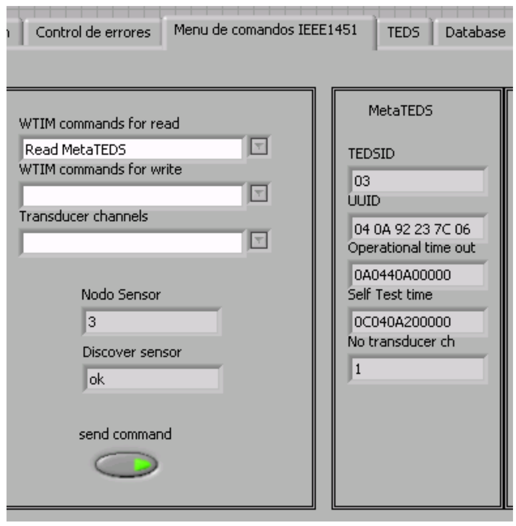

Fig 4 Frontal panel (command menu) of graphical user interface (GUI) implemented.

III. IEEE1451 TRANSACTIONS, COMMANDS AND TEDS

IEEE1451.0 Transactions can be initiated either by the NCAP or the WTIM [13]. In our case only transactions initiated by the NCAP have been implemented. Figure 5 shows this type of transactions, where the NCAP sends a request command and the WTIM returns, if required, a reply.

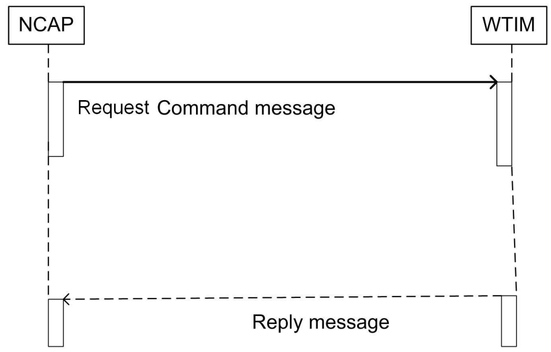

Fig 5. Transaction initiated by the NCAP.

Figure 6 shows the compliant IEEE1451.0 message structure of both the request command and the reply.

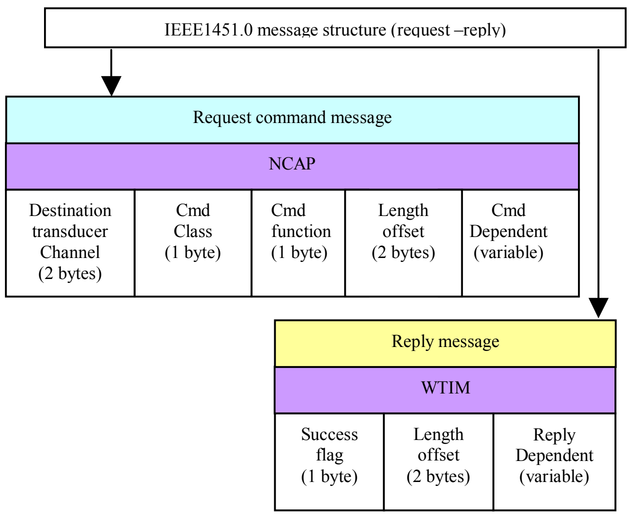

Fig. 6. IEEE1451.0 compliant message structure

The request command message from the NCAP includes:

- Destination transducer channel (2 bytes): is the maximum number of transducer channels per WTIM (65535).
- CmdClass (1 byte): defines the class of command (see Table 1).
- Cmdfunction (1 byte): defines the function of the IEEE1451 command (see table 2).
- Length offset (2 bytes): defines the number of bytes present in the next field.
- Cmd dependent (variable): contains additional information or data that depends on the specific command.

The reply message (WTIM response) includes:

- Success flag (1 byte): states if the command succeded or failed.
- Length offset (2 bytes): number of bytes present in the next field
- Reply dependent: contains additional data that depends on the specific command.

A. IEEE1451.0 commands

The IEEE1451.0 defines eight standard command classes (0-7), some reserved classes (8-127), and open classes to manufactures (128-255). Table 1 shows the three IEEE1451.0 standard commands classes implemented in our application. The CommonCmd class is used to configure all mandatory TEDS whereas the XdcrOperate class allows reading or writing the transducer channels in each WTIM.

CmdClassID	**Atribute name**	**Category**
1	CommonCmd	Common commands
3	XdcrOperate	Transducer operating state
6	TIMActive	TIM active state commands

Table 1. IEEE1451.0 standard command classes implemented.

Table 2 shows the specific functions implemented within each class. Some functions need a reply (yes) of the WTIM.

CmdFunctionId	**CommonCmd command**		**Reply**
0	Reserved		
1	Query TEDS		yes
2	Read TEDS		yes
3	Write TEDS		no
4	Update TEDS		yes
5	Run self-test		no
CmdFunctionId	**XdcrOperate command**	**Transducer channel**	**Reply**
1	Read TransducerChannel	yes	yes
2	Write TransducerChannel	yes	no
CmdFunctionId	**TIM Active command**	**TIM**	**Reply**
1	Read TIM version	yes	yes
3	Store operational setup	yes	no
5	Read IEEE 1451.0 Version	yes	yes

Table 2. CommonCmd, XdcrOperate, and TIM Active commands.

B. IEEE1451.5 compliant ZigBee PHY TEDS

The concept of transducer electronic data sheet (TEDS) defines the information that requires each WTIM to operate in a WSN with IEEE1451.5 interoperability. TEDS information is stored in a non-volatile flash memory. Four mandatory TEDSs are required for each WTIM:

- Meta-TEDS: store the common information of all WTIMs.
- TransducerChannel TEDS: store the information of each Transducer Channel of the WTIM.
- User's Transducer Name TEDS: store the name by which the end user will know this WTIM.
- Physical TEDS: IEEE1451.5 TEDS.

Others TEDS are optional for example Frequency Response TEDS or Transfer Function TEDS. Table 3 shows the PHY TEDS implemented for the WTIMs.

Field type	Field	Description	type	# octets	Actual value
-		TEDS length	Uint32	4	00 00 00 3E
3	TEDSID	TEDS Identification Header	UInt8	4	05 13 0 1
4-9		Reserved			
10	Radio	Radio Type	UInt8	1	2=ZigBee
11	MaxBPS	Max data throughput	UInt32	4	250Kbps
12	MaxCDev	Max Connected WTIMs	UInt16	2	00 FF
13	MaxRDev	Max Registered WTIMs	UInt16	2	00 FF
14	Encrypt	Encryption	UInt16	2	00 00
15	Authent	Authentication	Boolean	1	False
18	MaxSDU	Max SDU Size	UInt16	2	12 02 00 FF
19	MinALat	Min Access Latency	UInt32	4	us
20	MinTLat	Min Transmit Latency	UInt32	4	us
21	MxXact	Max Simultaneous Transactions	UInt8	1	1
22	Battery	Device is battery powered	UInt8	1	battery
23	RadioVer	Radio Version #	UInt16	2	01
24	MaxRetry	Maximun Retries Before discon	Uint16	2	00
64	Phy_Ch	ZigBee Channels supported	Uint16	2	16
65	Phy_ch_w	ZigBee channel used	Uint16	2	26
66	Phy_pwr	ZigBee Transmit power	Uint16	2	0db
67	phyFrec	ZigBee Frecuency band	Uint16	2	2.480 GHz
68	MacChanAcc	Type Channel access	Uint16	2	CSMA/CA
69	BattLife	Battery life specifications	Uint16	2	recharg
70	Modulation	Used modulation	UInt8	1	OQPSK
71	RangeMax	Maxim range	Uint16	1	200m
72	AntennaType	Antenna type	UInt8	1	integrate
73	PhySensitivity	Receiver sensitivity	UInt8	1	-92db
74	PhyDutyCycle	Duty cycle operation	UInt8	1	1%
75		Cheksum	UInt16	2	F7 41

Table 3. IEEE1451.5 compliant ZigBee PHY TEDS.

Registers (field types) 3 to 24 are common in an IEEE1451.5 WSN deployment. We have added 11 new registers for ZigBee support (registers 64-74) not included in the IEEE1451.5 standard. These registers provide useful information about the WTIM and could be included in a future revision of the IEEE1451.5 standard.

IV. RESULTS

Tests were carried out with one NCAP and three WTIMs. We used the message structure for the NCAP request commands shown in Figure 7, where the IEEE1451.0 message (Figure 6) is encapsulated within a ZigBee IEEE1451.5 compliant frame:

- Header: includes a local group identifier (1 byte), address node (2 bytes), and data counter (2 bytes).
- ZigBee command header: includes a command type header (1 byte), packet identifier header (1 byte), sequence number (2 bytes) and data octects that have the correspondence with the IEEE1451.0 messages (Figure 6).
- Cycle Redundancy Check (CRC): detects possible errors in the transmission of the message.

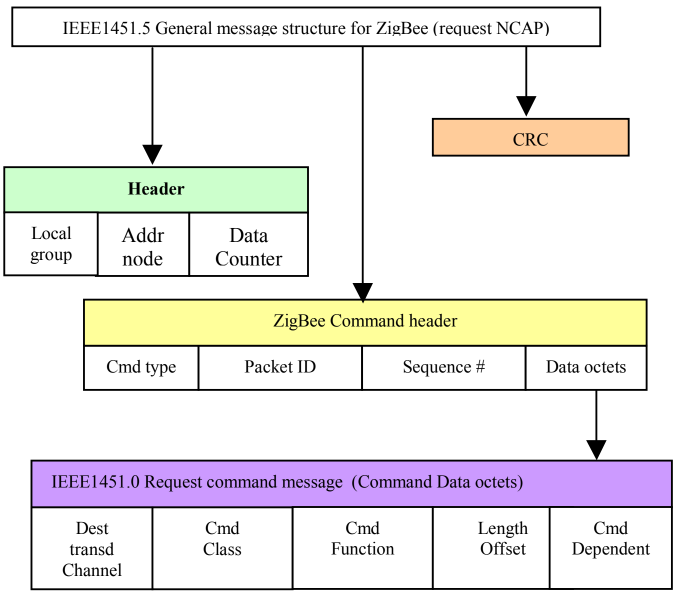

Fig. 7. General message structure for IEEE1451.5 with ZigBee interface containing a IEEE 1451.0 message (see Fig. 6)

The used steps to connect the NCAP with WTIMs were:

- Discover phase: NCAP discovers all WTIMs using the ZigBee specifications.
- Registration phase: NCAP register all WTIMs transducer channels (temperature, humidity, solar radiation, battery voltage).
- TEDS query: NCAP request information about the mandatory TEDS in each WTIM.

- Configuration: NCAP configures the WTIMs and mandatory TEDS.
- Data exchange: Data transfer between NCAP and WTIMs to read temperature, humidity, solar radiation and battery voltage.

The NCAP node sends IEEE1451 commands and receives data information from WTIM nodes depending on the identification number (ID) in the network. Each transaction is done using an structure based in Figure 7. Each WTIM automatically performs all environmental measurements and returns the result by polled operation.

Figure 8 shows the current consumption in active mode (22 mA) and sleep mode (8 µA) for each WTIM. Expected lifetime of the batteries is more than 1 year. In the active mode the NCAP can send IEEE1451 request commands and read each WTIM transducer channel and mandatory TEDS. Each WTIM sends a data payload of 20 bytes.

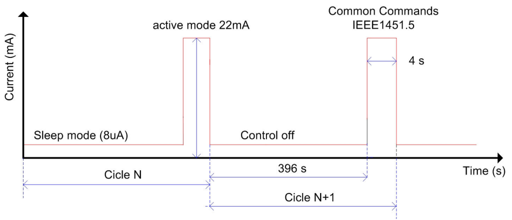

Fig 8. Operation duty cycle of a WTIM.

V. CONCLUSION

A ZigBee network compliant with IEEE1451 has been implemented and tested in a real deployment. The IEEE1451.0 commands have been encapsulated with IEEE1451.5 transactions for monitoring all WTIMs in active mode operation. An PHY TEDS ZigBee has been also proposed for future inclusion in the standard IEEE1451.5.

All prototype nodes WTIM include a mandatory IEEE1451.0 and IEEE1451.5 TEDS allowing interoperability and support plug and play capabilities to self-diagnosis, node calibration in environmental monitoring applications.

This deployment with IEEE1451.5 support, explores the new capabilities of smart sensor nodes in WSN with ZigBee interface using only IEEE1451.5 request - response transactions compatible with IEEE1451.0 standard.

ACKNOWLEDGMENT

This work is partially supported by the Spanish Ministry of Education and Science under contract TEC2007-66331 and by the European Regional Development Fund. Jorge Higuera is supported by the Programme Alban, the European Union Programme of High Level Scholarships for Latin America, scholarship No. E07D400433CO.

REFERENCES

[1] IEEE 802.15.4-2006 Standard for Information technology- Telecommunications and information exchange between systems- Local and metropolitan area networks- Specific requirements Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs). IEEE Computer Society. Revision of IEEE Std 802.15.4-2003). ISBN 0-7381-4996-9. 8 September 2006

[2] National Institute of standards and technology. Standard IEEE1451. http://ieee1451.nist.gov.

[3] IEEE 1451.5 Standard for a Smart Transducer Interface for Sensors and Actuators Wireless Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats. IEEE Instrumentation and Measurement Society. ISBN: 978-0-7381-5599-9. Publication Date: Oct. 5 2007

[4] D. Sweetser, V. Sweetser, J Nemeth. Modular Approach to IEEE-1451.5 Wireless Sensor Development. SAS 2006 – IEEE Sensors Applications Symposium. Houston, Texas USA. February 2006.

[5] E. Song, K. Lee. An Implementation of the Proposed IEEE 1451.0 and 1451.5 Standards. IEEE Sensors and Applications Symposium SAS 2006. Houston Texas, USA, 7-9 February 2006.

[6] K. Lee, E. Song. "A Wireless Environmental Monitoring System Based on the IEEE 1451.1 Standards". Instrumentation and Measurement Technology Conference, 2006. IMTC 2006. Proceedings of the IEEE. pp.1931 – 1936. April 2006.

[7] D. Wobschall. "Networked sensor monitoring using the universal IEEE 1451 standard". IEEE Instrumentation and measurement magazine, pp.18 – 22. April 2008.

[8] Sentilla. "Low power wireless sensor module Sky Tmote" http://www.sentilla.com/

[9] Real time operative system (RTOS) TinyOS. http://www.tinyos.net.

[10] D. Gay, P. Levis, D. Culler, R. Behren. "The NesC Language: A Holistic Approach to Networked Embedded Systems". In Proceedings of Programming Language Design and Implementation (PLDI) 2003, June 2003.

[11] Texas Instruments. Single-Chip 2.4 GHz IEEE 802.15.4 Compliant and ZigBee(TM). http://focus.ti.com/docs/prod/folders/print/cc2420.html.

[12] J. Polastre, J. Hui, P. Levis, J. Zhao. "A unifying link abstraction for wireless sensor networks". Conference On Embedded Networked Sensor Systems. Proceedings of the 3rd international conference on Embedded networked sensor systems. pp: 76 – 89. 2005

[13] IEEE 1451.0 Standard for a Smart Transducer Interface for Sensors and Actuators. Common Functions, Communication Protocols, and Transducer Electronic Data Sheet (TEDS) Formats. IEEE Instrumentation and Measurement Society. ISBN: 0-7381-5597-7. Publication Date: Sept 21 2007.