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ZigBee™ Technique for Distributed Sensing

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Defence R&D Canada – Atlantic

Technical Memorandum

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Abstract

This document describes a high-level communication protocol, the ZigBee™ technique, and its potential use for distributed sensing and monitoring. The framework for a ZigBee™ based wireless sensor network is proposed and a feasibility study is carried out employing a Microchip development kit (PICDEM Z) with built-in temperature sensor. Temperature measurements in the range of 25°C and 65°C with 1°C accuracy were demonstrated. It is expected that other types of sensors, which can be applied to aircraft structural health monitoring, can be integrated with the ZigBee™ technique. Furthermore, it is recommended that this document is used as a reference for programming the Microchip PICDEM Z board.

Résumé

On décrit dans ce document un protocole de communication évolué, la technique ZigBee™, et la possibilité de l’exploiter pour la détection et la surveillance distribuées. On y propose le cadre d’un réseau de capteurs sans fil basés sur ZigBee™, et on mène une étude de faisabilité au moyen de la trousse de développement Microchip (PICDEM Z) doté d’un thermocapteur intégré. On a mesurés des températures dans la fourchette de 25°C à 65°C avec une exactitude de 1 °C. On espère parvenir à intégrer à la technique ZigBee™ d’autres capteurs de surveillance de la bonne tenue structurale des aéronefs. Enfin, on recommande d’utiliser ce document à titre de référence pour la programmation d’une plaquette de circuit Microchip PICDEM Z.

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Executive summary

ZigBee™ Technique for Distributed Sensing

Mrad, N. and Liu, Z.; DRDC Atlantic TM 2006-220; Defence R&D Canada – Atlantic; November 2006.

Introduction or background

The increasing interest in in-situ and online health monitoring of civilian and military platforms and the drive to deliver such capabilities at reduced weight and increased efficiency has significantly impacted the use of wired systems and wireless networks. Wireless sensors technology is expected to significantly impact any future development in data acquisition, analysis and transmission along with decision making on the state of platforms. We currently enjoy a diverse range of services employing several wireless protocols including Bluetooth and Wi-Fi. The emerging ZigBee™ protocol is a specification for a suite of high level communication protocols using small, low-power digital radio based on the IEEE 802.15.4 standard for wireless personal area networks (WPANs). ZigBee™ is poised to become the global control/sensor network standard. It can be simply implemented and contains features like low power consumption and low data rate. The focus of ZigBee™ technique is to define a general-purpose, inexpensive, self-organizing low power mesh network that can be used for various applications like industrial control, embedded sensing, medical data collection, etc. where low data transfer rate is sufficient for these applications.

Results

The feasibility study of this emerging wireless protocol employing a microchip development kit (PICDEM Z) provided an introduction to ZigBee™ protocol and the IEEE 1451 standard. In addition, it provided a mean for increased level of understanding of the requirement and potential applications of wireless sensors and sensors networks, through the case study of temperature monitoring.

Significance

The knowledge developed through this feasibility study is expected to contribute to efforts underway in the development of advanced sensor technology for enhanced structural health monitoring and prognostics health management.

Future plans

Future efforts will focus on evaluating such ZigBee™ protocol employing other sensors such as, resistive strain gauges and piezoelectric materials and expand such evaluation to multi-nodes using specific network topology.

Sommaire

Technique ZigBee™ en vue de la détection distribuée

Mrad, N. et Liu, Z.; RDDC Atlantique TM 2006-220; R&D pour la Défense Canada – Atlantique; novembre 2006.

Introduction ou contexte

L'intérêt accru pour la surveillance sur place et en ligne de la bonne tenue des plateformes civiles et militaires et la volonté d'en arriver à livrer des capacités de cette nature de façon moins encombrante et avec plus d'efficacité ont eu une incidence importante sur la façon d'utiliser les réseaux câblés et les réseaux sans fil. La technologie des capteurs sans fil devrait, selon les prévisions, avoir un impact majeur sur le développement futur de l'acquisition, de l'analyse et de la transmission des données, ainsi que sur le choix de l'état des plateformes. Actuellement, nous avons la chance de disposer d'une gamme diversifiée de services fonctionnant avec des protocoles sans fil comme Bluetooth et Wi-Fi. Le protocole émergeant ZigBee™ est la spécification d'une suite de protocoles de communication évolués qui emploie de petites radios numériques de faible puissance basées sur la norme IEEE 802.15.4 pour les réseaux personnels sans fil (WPAN). ZigBee™ est destiné à devenir la norme pour le réseau global de contrôle et de capteurs. Il peut être mis en oeuvre sans problèmes et possède des caractéristiques comme une faible consommation et un petit débit de données. La technique ZigBee™ est axée sur la définition d'un réseau maillé de faible puissant, à organisation automatique, peu coûteux et polyvalent. Un tel réseau peut servir dans diverses applications comme le contrôle industriel, la détection embarquée, la collecte de données médicales, qui sont des applications où un faible taux de transfert des données est acceptable.

Résultats

L'étude de faisabilité de ce protocole sans fil émergeant qui se fonde sur une trousse de développement de microchip (PICDEM X) se veut une introduction au protocole ZigBee™ et à la norme IEEE 1451. En outre, cette étude vise à rehausser votre niveau de connaissance des besoins et des possibilités des applications de capteurs sans fil et de réseau de capteurs, par le truchement de l'étude de cas d'une surveillance de la température.

Importance

Les connaissances acquises durant cette étude de faisabilité devraient contribuer à faire progresser le développement d'une technologie de détection avancée nécessaire à la surveillance de la bonne tenue structurale et à sa gestion prévisionnelle.

Plans futurs

Les travaux annoncés graviteront autour de l'évaluation d'un tel protocole ZigBee™ mettant en oeuvre d'autres capteurs comme des extensomètres résistifs et des matériaux piézoélectriques. Ces travaux d'évaluation aborderont les noeuds multiples au sein d'une certaine topologie de réseau.

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Acknowledgements

The Authors would like to acknowledge the financial support of the Director General Air Equipment Program Management (DGAEPM) of the Department of National Defence (DND).

1. Introduction

ZigBee™ is the name of a specification for a suite of high level communication protocols using small, low-power digital radio based on the IEEE 802.15.4 standard for wireless personal area networks (WPANs) [1]. ZigBee™ has three radio bands, i.e. 868 MHz (Europe), 915MHz (USA), and 2.4GHz (worldwide) [2]. As shown in Figure 1 [3], each frequency band offers a fixed number of channels. The IEEE 802.15.4 standard defines both the physical layer (PHY) and medium access layer (MAC) of the low-rate WPANs. The PHY defines a low-power spread spectrum radio operating at 2.4 GHz with a basic bit rate of 250 Kbps. The MAC defines how multiple 802.15.4 radios operating in the same area will share the airwave. The ZigBee™ protocol starts with IEEE 802.15.4 standard and defines the application profiles that allow devices provided by different vendors to talk to each other [4]. The MAC and PHY of ZigBee™ use the specifications of the IEEE 802.15.4 standard.

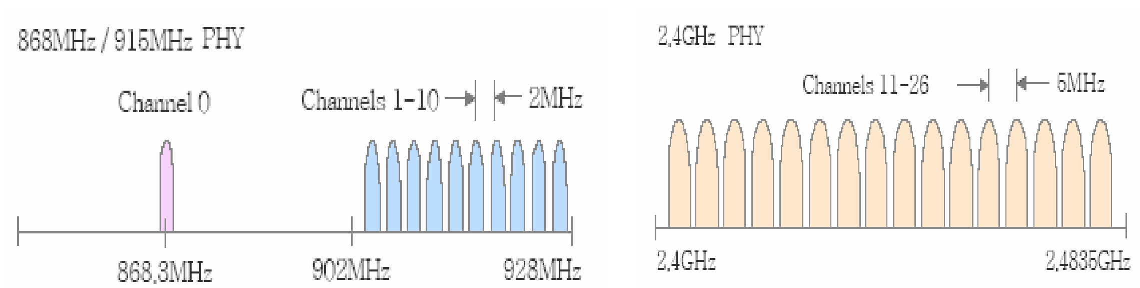

Figure 1: Communication channels defined by IEEE 802.15.4

ZigBee™ is poised to become the global control/sensor network standard [5]. It can be simply implemented with features like low power consumption and low data rate. The focus of ZigBee™ technique is to define a general-purpose, inexpensive, self-organizing low power mesh network that can be used for various applications like industrial control, embedded sensing, medical data collection, etc. where low data transfer rate is sufficient for these applications.

Table 1: Comparison of wireless communication standards (I)

	Wireless PAN		***Wireless LAN***		
	IEEE 802.15.4 (ZigBee)	**802.15.1 (Bluetooth)**	**802.11b (Wi-Fi)**	**802.11g**	**802.11a**
Frequency (Hz)	868M, 915M, 2.4G	2.4G	2.4G	2.4G	5G
Modulation	DSSS	FHSS	DSSS/CCK	OFDM/PBCC	OFDM
MAC	CSMA/CA	TDMA	CSMA/CA	CSMA/CA	CSMA/CA
Data Speed (bps)	250k, 40k, 20k	1M, 723k	11M	20M	54M
Node number	254	8	256	256	256
Channel Band (Hz)	600k, 2M, 5M	1M	22M	22M	16.6M

Table 2: Comparison of wireless communication standards (II)

Feature(s)	*IEEE 802.11b*	*Bluetooth*	*ZigBee*
Power Profile	Hours	Days	Years
Complexity	Very Complex	Complex	Simple
Nodes per Master	32	7	64000
Latency	Enumeration up to 3sec	Enumeration up to 10sec	Enumeration 30ms
Range	100 m	10 m	70m-300m
Extendability	Roaming possible	No	Yes
Data Rate	11Mbps	3Mbps/1Mbps	250Kbps
Security	Authentication Service Set ID (SSID)	64bit,128bit	128bit AES and application Layer user defined
Audio Connection	X	O	X

Table 3: Comparison of ZigBee^{TM} and Bluetooth – Competitive or Complementary

Feature(s)	*Bluetooth*	*ZigBee^{TM}*
Best	• For ad-Hoc networks between capable devices • For hands free audio • For on screen graphics display • For file transfer	• If the network is static • If many infrequently used devices are needed • if small data sets are needed
Air Interface	• 1 M Symbol / second • Peak Information Rate ~720 Kbit / second	• 11 chips/ symbol • 62.5 K symbols/s • 4 Bits/ symbol • Peak Information Rate ~128 Kbit/second
Timing Consideration	• New slave enumeration ≥3s • Sleeping slave changing to active in 3s typically • Active slave channel access time is 2ms typically	• New slave enumeration = 30ms typically • Sleeping slave changing to active in 15ms typically • Active slave channel access time is 15ms typically
Power Consideration	• Power model as a mobile phone (regular charging) • Designed to maximize ad-hoc functionality	• 2+ years from 'normal' batteries • Designed to optimize slave power requirements
Cost Standpoint	• Low added cost connectivity • Take advantage of host processor power • 802.11 functionality but with simplified r.f. specifications	• Minimum slave cost • Minimum software and processing (80C51), no host platform • System design for eventual single-chip antenna-to-application realization
Prices Solution	• Price Now - $10 - $15 • Price 2005 - $5	• The ZigBee alliance will meet the cost sensitivity of its target applications

ZigBee™ is actually a complementary to the Bluetooth technique. ZigBee™ can accommodate maximum 255 devices per node with a capacity of 65000 nodes [6]. Moreover, ZigBee™-based chip requires only about 20mA power consumption and use direct sequence spread spectrum (DSSS) method for low power consumption with a protocol stack size less than 32KB. A comparison of ZigBee™ with other techniques is summarized in Tables 1-2. It can also be seen from Table 3 [7] that ZigBee™ and Bluetooth are neither competitive nor complimentary but are two different solutions optimized for different application areas. For instance, ZigBee™ protocol is optimized for timing critical applications.

2. Smart Sensor and Wireless Sensor Networks

2.1 Smart and intelligent sensors

The word smart is defined as "intelligent or able to think and understand quickly in difficult situations" [8]. For example, smart devices are defined as ones that operate using computers (e.g. smart bombs and smart cards). The same source defines the word intelligence as "the ability to understand and learn well, and to form judgments and opinions based on reason." Furthermore, the definition of advanced is said to be "highly developed or difficult."

According to the IEEE 1451 standard [9] a smart or intelligent sensor is defined as "one chip, without external components, including the sensing, interfacing, signal processing and intelligence (self-testing, self-identification or self-adaptation) functions". Figures 2 [10] and 3 [9], illustrate the smart sensor concept as defined by IEEE 1451, whereas Figure 4 [11] illustrates a multi-parameter smart sensor. In this case, the Analatom Inc.'s 'smart tape' system contains a main controller unit MCU that is interfaced with a linear polarization resistor LPR, two MEMS strain gauges, a wireless unit and BUS connection.

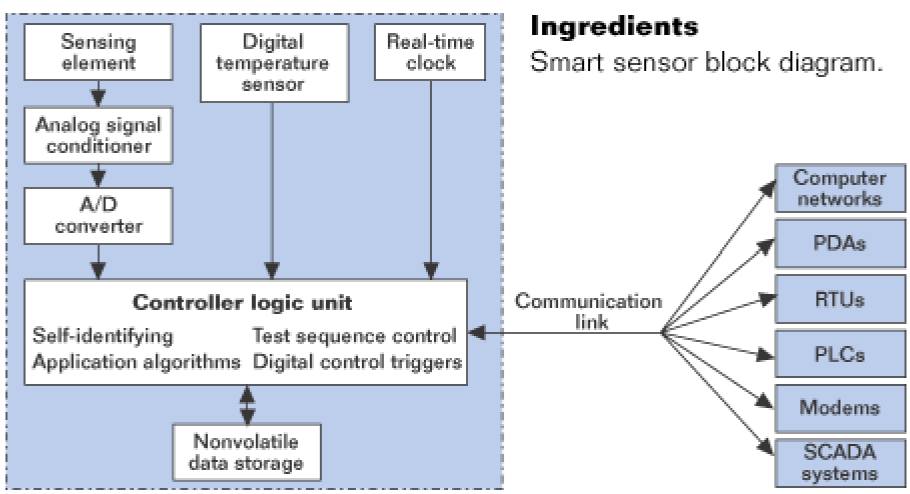

Figure 2: Smart sensor architecture

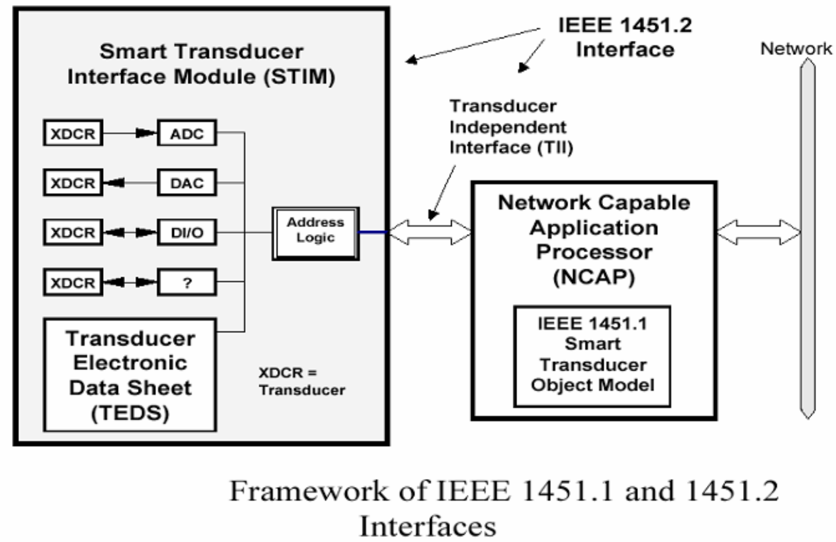

Figure 3: Smart sensor concept defined by IEEE 1451

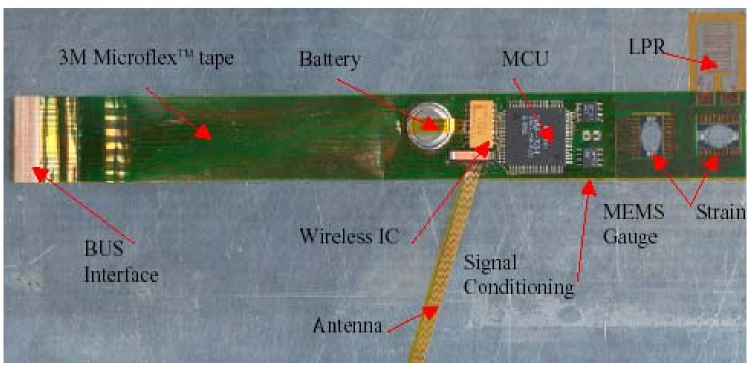

Figure 4: A prototype of a multi-parameter smart sensor concept

Depending on the field and application of interest, many smart sensors definitions can be found that closely relate to the IEEE 1451 standard. A good working "smart sensor" definition is "sensors and instrument packages that are microprocessor driven and include features, such as communication capability and on-board diagnostics that provide information to a monitoring system and/or operator to increase operational efficiency and reduce maintenance costs." [12] These smart sensors must monitor themselves and their surroundings and then be able to make decisions to compensate for the changes automatically or alert someone for needed attention. Some of the benefits of a smart sensor are: the wealth of information that can be gathered from the process leading to reduced downtime and improved quality; increased distributed intelligence leading to complete knowledge of a system, subsystem, or component's state of awareness and health for 'optimal' decision making [12].

2.2 Wireless Sensor Network Topologies

Wireless sensor networks can be arranged in different network topologies. These topologies dictate how network components communicate and interact with each other. Hypothetical models of wireless sensor network topology are illustrated in Figure 5; whereas some of their features, advantages and limitations are provided in Table 3 [13].

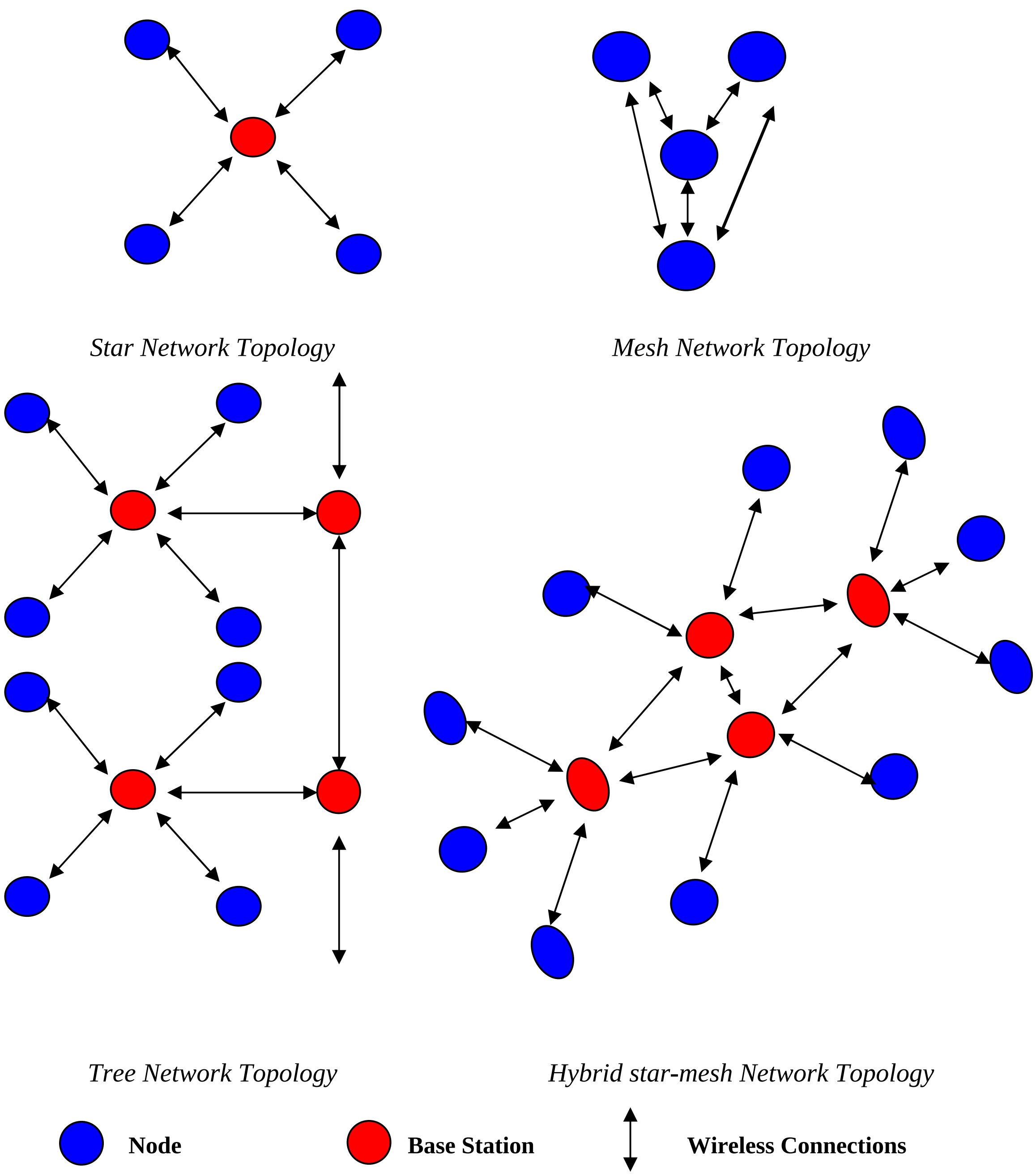

Figure 5: Example of Sensor Networks Topology

Table 4: Comparison of Networks Topology

	Benefits	**Limitations**
Star Network Topology	• Minimum power consumption • Simple to implement • Allows for low latency communication between the remote node and base station	• Base station must be within the radio transmission range of all wireless nodes • Not as robust as other topologies due to dependability on a single base station
Mesh Network Topology	• Not dependent on a centralized base station • Nodes do not have to be within the radio transmission range because multi-hop communication	• High power consumption • As the network becomes larger, time delays increase
Hybrid Network Topology	• Minimal power consumption • Flexibility of adding nodes without complicating the network	• Failure of one base station allows for failure of all the nodes connected to the failed base station

Smart sensors within a selected network topology should be connected to a ZigBee™ end device. The device-embedded micro-controller needs to carry out the sensors excitation, data acquisition, local data processing, and data transmission to corresponding coordinators. The design and implementation of a smart sensor unit within a network is critical for distributed sensing. The types of sensors raise different requirements for the sensor node including the need for high frequency signals for sensor excitation. Moreover, the wireless end device is limited by its power supply, which is usually a battery, thus the added requirement for power efficient devices.

In the implementation of a distributed sensing network, the concept for IEEE 1451 standard for smart sensor described in [9] is adopted. The smart transducer interface module (STIM), shown in Figure 3, is the ZigBee™ end device. The connection between STIM and the network capable application processor (NCAP) could be either wired or wireless solution. That is, a wireless protocol will be the transducer independent interface (TII). The IEEE 1451.5 has not yet been officially released and is open for proposals. ZigBee™ could be a potential candidate for the TII solution.

3. The ZigBee™ Protocol and Microchip Stack

Figure 6 illustrates the architecture of ZigBee™ protocol profile [14]. The ZigBee™ protocol profile is simply a description of devices and their interfaces. Different devices communicate with their endpoints, which are blocks of function codes. Each endpoint supports one or more clusters. The attributes, which is the data passed between devices, are grouped in clusters. The attribute could be the status of the sensor or its readings. A unique identifier is assigned to the profile, device, endpoint, and cluster and attribute, respectively. For example, device A can be a switch and device B can be a light. Device A (switch) has one input cluster (cluster B) and one output cluster (cluster A) on the endpoint A. The cluster A may contain one attribute, On/Off. Similarly, cluster C of the device B (light) may have an attribute D, i.e. On/Off. Data flow is at the cluster level. Binding decisions are taken by matching the output cluster identifier (e.g. cluster A) to an input cluster identifier (e.g. cluster C), i.e. the switch is bound to the light. Once the binding is setup, the switch can sends its message to the ZigBee™ coordinator, which then relays the message to the destination device (e.g. light).

Two types of messages are sent between devices: the direct and indirect type. If the device knows the network address, the sent messages are called direct. If the messages are sent through a coordinator, those are named "indirect message". The ZigBee™ protocol coordinator creates a binding table that matches the cluster/endpoint between the services and the needs of the devices in the network, as shown in the example above.

IEEE 802.15.4 defines two types of devices, i.e. a full function device (FFD) and a reduced function device (RFD). Based on this, the ZigBee™ protocol defines three device types, which include coordinator node (FFD), router (FFD) and end device (FFD or RFD). The ZigBee™ coordinator forms the root of the network tree and might bridge to other networks. There is exactly one ZigBee™ coordinator in each network. It is able to store information about the network, including acting as the repository for security keys. ZigBee™ routers can act as an intermediate router, passing data from other devices. The end device contains just enough functionality to talk to its parent node (either the coordinator or a router); it cannot relay data from other devices; it requires the least amount of memory; and therefore can be less expensive to manufacture than a router or coordinator.

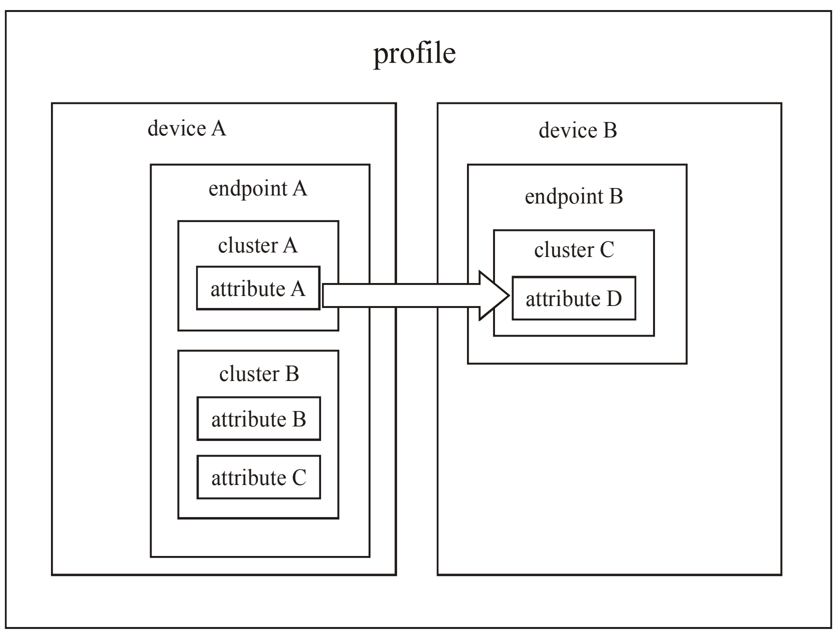

Figure 6: Description of ZigBee™ protocol profile architecture

The outline of ZigBee™ stack architecture is given in Figure 7 [2]. The ZigBee™ stack consists of several layers, which perform a specific set of services for the layer above. Each service entity exposes an interface to the upper layer through a service access point (SAP), and each SAP supports a number of service primitives to achieve the required functionality [2]. The bottom two layers, e.g. PHY and MAC, are defined by the IEEE 802.15.4 standard. The ZigBee™ alliance builds the network (NWK) layer and the framework for the application layer (layers 3 and 4). The ZigBee™ NWK supports star, tree, and mesh topologies (Figure 5). The application layer includes the application support sub-layer (APS), and ZigBee™ device objects (ZDO) and the manufacturer-defined application objects (application framework). The NWK layer manages the joining and leaving a network, applying security to frames and routing frames to their intended destinations. The NWK layer takes care of the discovery and maintenance of routes between devices, the discovery of one-hop neighbors, and the storing of pertinent neighbor information. The NWK layer of a ZigBee™ coordinator is responsible for starting a new network and assigning addresses to newly associated devices. The functionalities of the NWK sub-layers are summarized in Table 5 [2] below.

Table 5: The responsibilities of NWK sub-layers

	NWK sub-layers Responsibilities
APS sub-layer	• maintain binding table; • forward messages between bound devices.
ZDO	• define the role of the device within the network; • initiate and/or respond to binding requests; • establish a secure relationship between network devices; • discover devices on the network and determine which application services they provide.

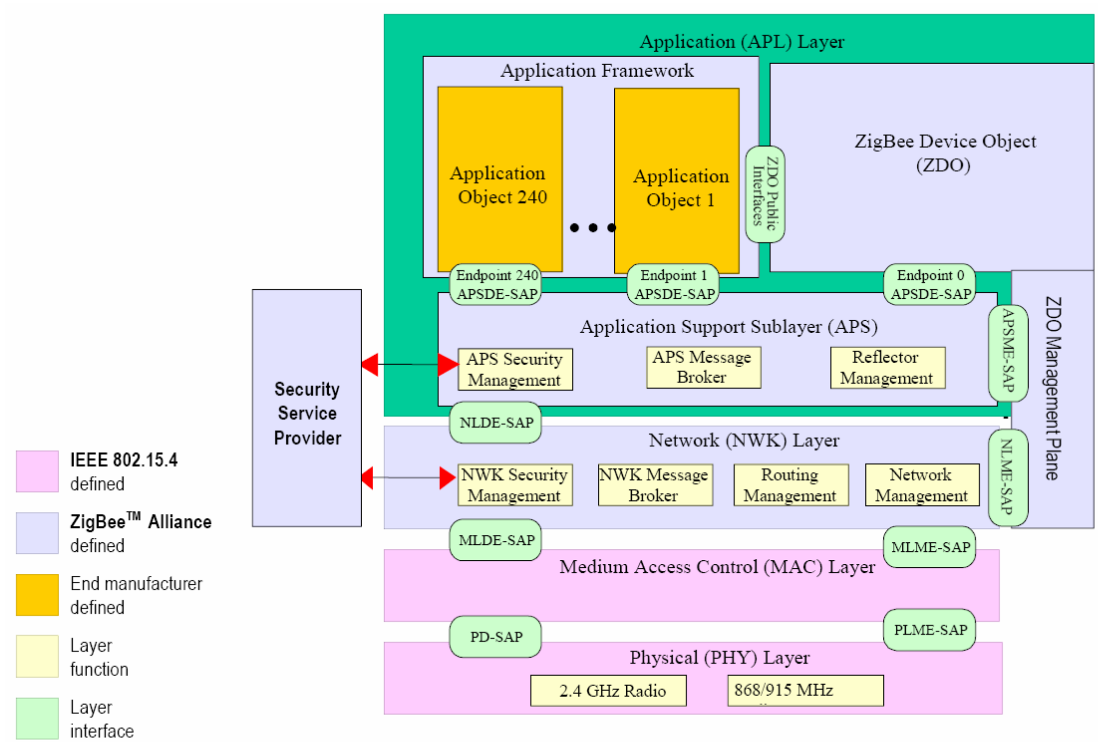

Figure 7: The architecture of ZigBee™ stack

The microchip stack selected for the feasibility study was designed to follow the ZigBee™ protocol and IEEE 802.15.4 specifications, employing a PICDEM Z board and a temperature transducer.

4. ZigBee™ based Microchip PICDEM Z Board for Temperature Measurement

A picture of the Microchip PICDEM Z ZigBee™ demo kit is shown in Figure 8. This kit includes two ZigBee™ nodes, each programmed with Coordinator and Reduced Function Device (RFD) applications. Each node consists of two boards: one motherboard and one RF card. Microchip's stack for the ZigBee™ protocol is used to implement the wireless communication. The motherboard is equipped with a PIC18LF4620 high-performance microcontroller, clocked at 4 MHz. Detailed descriptions of the demo board can be found in reference [15].

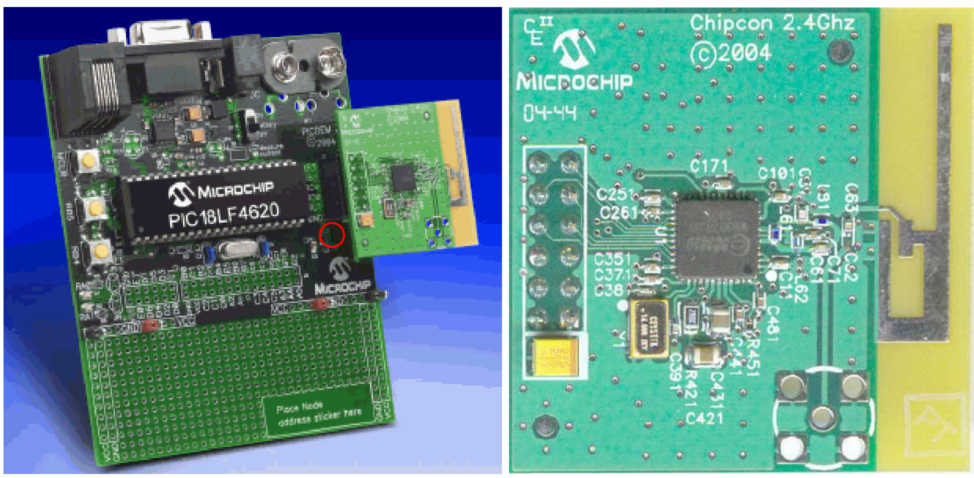

Figure 8: Microchip ZigBee™ demo board (left) and 2.4 GHz RF card (right). The location of the TC77 sensor is highlighted with a red circle

On the motherboard, a 5-pin thermal sensor TC77 (shown in figure 9) with a serial peripheral interface (SPI) is available for testing [15-16]. In the experiment, the temperature reading from a TC77 is sent via a PCB trace antenna connected to a CC2420 RF transceiver on the 2.4 GHz RF card. The TC77 is a serially accessible digital temperature sensor. Temperature data is converted from the internal thermal sensing element and made available at anytime as a 13-bit two's compliment digital word. Communication with the TC77 is accomplished via the SPI interface. The TC77 offers a temperature accuracy of ±1.0°C (max.) over the temperature range of +25°C to +65°C. The block diagram of the 5-pin thermal sensor TC77 is shown in Figure 9. Temperature results were obtained with the Microchip PICDEM Z kit. The temperature read from the end device was sent to the coordinator, which was connected to a host PC via RS-232. With windows HyperTerminal application, the changes in temperature can be observed.

Two-node communication was tested. One node was used for temperature sensing with TC77. The other node was connected to a PC via the RS-232 port. The Windows HyperTerminal was used to display the temperature obtained from a remote node. A snap shot of the application is given in Figure 10. This screen shot can be divided into three sections: (1) confirmation of the successful connection of the TC77 temperature sensor node to the PC, (2) confirmation of the sensor node binding to the TC77 reading (S2 button) and (3) acquisition of the temperature reading and transmission of the reading to the node connected to the PC, once the button S2 is pressed. Through this Hyper Terminal display, the temperature change can be monitored. Multiple-node testing was not carried out. Once the binding table is established properly, the implementation is quite straightforward. The success of integrating other types of sensors, such strain gauge, depends on the implementation of the interface between the sensor and the microcontroller.

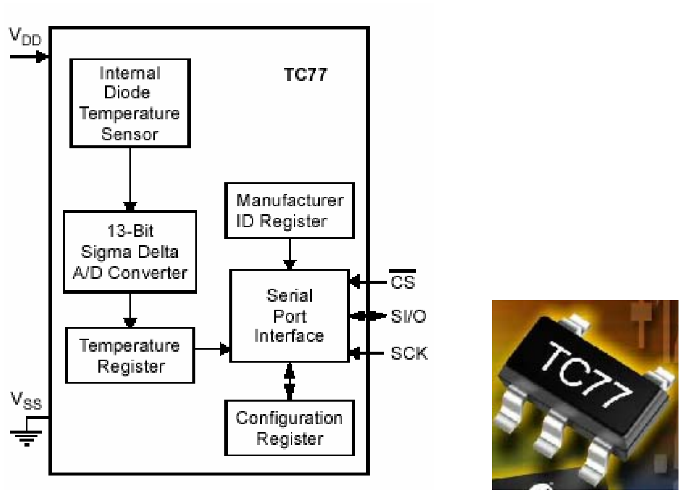

Figure 9: The block diagram of a 5-pin thermal sensor TC77

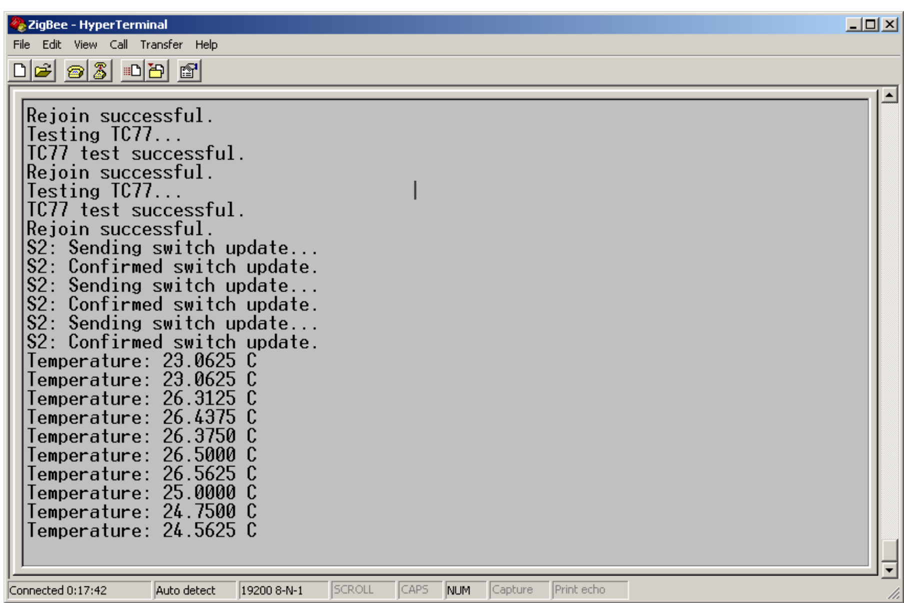

Figure 10: The HyperTerminal display of the temperature from a remote node

5. Summary

The ZigBee™ protocol provides a tool to integrate sensors within a wireless sensor network for potential wireless applications and distributed sensing. To be integrated in a distributed sensing system, the sensors must be driven by the micro-controller. For a specific application, it should be investigated whether the ZigBee™ transmission rate can meet the desired requirements, any pre-processing needs and the cost of computing in terms of power consumption. In this document, temperature measurement in the range of 25^{o}C and 65^{o}C with 1^{o}C accuracy was demonstrated using the ZigBee™ protocol. It is expected that other types of sensors, which can be applied for aircraft structural health monitoring, can be integrated with the ZigBee™ technique.

The prototype design of the system can be implemented with the Microchip DEMO Z board. The unit can be further miniaturized. The board comes with the Microchip stack for the ZigBee™ protocol. For the currently available version, it contains security feature limitations. However, new features will be added as time progresses. Although Microchip is among the first to release the development kit for ZigBee™ technology, there are many other off-the-shelf tools available on the market. The design and implementation of the system depends on the specific requirements of the application and the types of sensors involved.

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This document describes a high-level communication protocol, the ZigBee™ technique, and its potential use for distributed sensing and monitoring. The framework of ZigBee™ based wireless sensor network is proposed and a feasibility study is carried out employing a Microchip development kit (PICDEM Z) with built-in temperature sensor. Temperature measurements in the range of 25°C and 65°C with 1°C accuracy were demonstrated. It is expected that other types of sensors, which can be applied for aircraft structural health monitoring, can be integrated with the ZigBee™ technique. Furthermore, it is recommended that this document is used as a reference for programming the Microchip PICDEM Z board.

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smart sensors, wireless sensors, sensor networks, Blue tooth protocol, ZigBee Protocol, sensor networks topology

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