

ZIGBEE BASED HOME AUTOMATION WIRELESS SENSOR NETWORK

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SUMMARY

Increased demands on implementation of wireless sensor networks in automation praxis result in relatively new wireless standard – ZigBee. The new workplace was established on the Department of Electronics and Multimedia Communications (DEMC) in order to keep up with ZigBee modern trend. This paper presents the first results and experiences associated with ZigBee based wireless sensor networking. The accent was put on suitable chipset platform selection for Home Automation wireless network purposes. Four popular microcontrollers was selected to investigate memory requirements and power consumption such as ARM, x51, HCS08, and Coldfire. Next objective was to test interoperability between various manufacturers' platforms, what is important feature of ZigBee standard. A simple network based on ZigBee physical layer as well as ZigBee compliant network were made to confirm the basic ZigBee interoperability.

Keywords: ZigBee, wireless, sensor network, IEEE 802.15.4, microcontroller, Home Automation.

1. INTRODUCTION

Various progressive wireless communication standards were developed and implemented into praxis during last decade. GSM, WiFi and Bluetooth are well known by most people in the modern society. These standards have penetrated into their daily routine with outstanding popularity. "An Internet of people" has become ordinary for everyone who wants to have everybody and everything within reach. Even though it seems that all peoples' wireless requirements have fulfilled, it turns on, that they lack of something like "an internet of things" especially in mainstream Home Automation (HA). The HA systems provide mutual interoperability between various electronic, electrical, and power devices as well as interactive interface for people to control their operation. These features are very helpful to optimize and to economize energy consumption whereby saved energy during some few years could make more money than HA systems implementation cost. These technologies make peoples' life also easier, especially for elderly persons and persons with disabilities. These systems exist of course, but there are many non-interoperable, expensive, and often wired systems. Wiring complicates implementation of the HA in buildings which are already built, especially in historical ones. Therefore, an invention of an open and standardized wireless network of battery powered cheap sensors, actuators, and control devices which could effectively communicate with each other for some years, eventuate in new wireless standard. This standard was named "ZigBee". Naming this standard, the ZigBee alliance engineers were probably inspired by philosophical similarity of packet routing strategies in networks with large nodes amount and zig – zag dance which bees use for food path showing.

Although the ZigBee devices are not widely used in present, the expectations are that most of the home electronic devices will have a ZigBee chip for

simple connectivity to each other. It will be nothing unusual if ordinary home contains about 50 ZigBee chips and in the morning an alarm-clock sends message wirelessly into coffeemaker: "two cappuccinos, please". Paul Saffo from Institute for the Future says: [1] "Just as the personal computer was a symbol of the '80s, and the symbol of the '90s is the World Wide Web, the next nonlinear shift, is going to be the advent of cheap sensors."

ZigBee is a local-area network designed specifically for applications of automation or control systems to replace the proliferation of incompatible proprietary solutions. ZigBee was created to satisfy the market's need for a cost-effective, standards-based wireless networks that support low data rates, low power consumption, security, robustness and reliability. To address this need, the ZigBee Alliance [2], an industry working group, develops standardized application software on top of the IEEE 802.15.4 wireless standard [3]. The alliance works closely with the IEEE to ensure an integrated, complete, and interoperable network for the market. A result of active standard development in Alliance is new standard ratification in 2004 [4] and new versions in 2006 (ZigBee 2006) [4] and in 2007 (ZigBee PRO) [5].

The article is organized as follows: Section 2 provides more details about application of ZigBee, ZigBee alliance, and ZigBee standard version. The architecture of ZigBee standard as well as IEEE 802.15.4 standard is described in Section 3. Most of able ZigBee platforms are summarized in Section 4. Results and experiences of created wireless sensor networks are in Section 5.

2. ZIGBEE OVERVIEW

2.1. ZigBee applications, markets and forecasts

Although ZigBee standard development is still under progress, the ZigBee market is opened for many various applications. The most promising are:

- *Home Control:* Security, Heating, Ventilation, and Air-Conditioning (HVAC), Lighting control, Access control, Irrigation,
- *Personal health care:* Patient monitoring, Fitness monitoring,
- *Industrial control:* Asset management, Process control, Energy management, Environmental,
- *Building automation:* Automatic Meter Reading (AMR), Security, HVAC, Lighting control, Access control,
- *Consumer electronics:* Remote control,
- *PC & peripherals:* Mouse, keyboard, joystick,
- *Environment:* Environment monitoring.

Strong growth in wireless sensors area will help fuel the growth of ZigBee. Harbor Research reports [6] that by 2008, 100 million wireless sensors will be in use and on World reports that by 2010, more than 500 million nodes will ship for wireless sensor applications.

2.2. Advantages of ZigBee

Some of important advantages are:

1) thanks to industry standardization:

- interoperability between manufacturers,
- chip vendor independence,
- rapid innovation,
- extremely low cost,
- open standards enable markets,
- easy to deploy,

2) thanks to IEEE 802.15.4 physical layer:

- excellent performance in environments with low SNR,
- appropriate range operation (30 – 100 m),
- appropriate bit-rate: 250 kbps (at 2.4 GHz),
- very low power consumption,
- can be used globally,

3) thanks to ZigBee protocol stack:

- ease of implementation,
- reliable data transfer,
- very low power consumption,
- reliable,
- supports large number of nodes,
- mesh Networking,
- easy to deploy,
- secure: AES 128, key management,

- ZigBee protocol needs less than 64 kB of ROM and 2 – 32 kB of RAM,
- ZigBee can be implemented into low performance 8-bit MCUs such as x51, HCS08, AVR, PIC, etc.

2.3. ZigBee Alliance

The ZigBee Alliance [2] is a global consortium of companies (up to 220) creating wireless solutions for use in residential, commercial and industrial applications. The ZigBee Alliance companies work together to enable reliable, cost-effective, low-power, wirelessly networked, monitoring and control products based on an open global standard. ZigBee Alliance was founded as an independent, neutral, non-profit corporation in 2002. Membership is global and anyone can join and participate. Activities in this organization include specification creation, certification and compliance programs, market development, and users' education. ZigBee Alliance offers three alternatives of membership such as: Promoter (40.000 USD/year), Participant (9.500 USD/year), and Adopter (3.500 USD/year) with different member's benefits. Each company planning to release products incorporating ZigBee technology must become at least adopting member, an entry-level membership that provides such benefits as access to specifications and developer conferences / workshops.

2.4. ZigBee versions

The first version of ZigBee was ratified in 2004 [4]. Although this specification supports up to 65536 nodes on a network, the first practical developers' experiences show that the larger networks become unstable over time. That is because initially ZigBee used a tree structure for addressing which restricted the number of addresses to well below what was theoretically available. In the 2006 specification, a random addressing scheme with built-in address conflict resolution is used [4]. That will be a key to large deployments of ZigBee in industrial markets because it allows much more network nodes. ZigBee 2006 is incompatible with previous version. Developers in the industrial market may still be waiting for the ZigBee PRO stack which will include features aimed at industrial and commercial building automation, such as higher levels of security and improved frequency hopping [5]. The ZigBee Alliance announced a series of "ZigBee PRO" additions to the original set of features published in 2006, which is now known as the ZigBee Feature Set. An expanded set of features known as ZigBee PRO maximizes all the capabilities of ZigBee and facilitates ease-of-use as well as advanced support for larger networks. Free public availability of the new features is scheduled for early 2008.

3. ZIGBEE STANDARD ARCHITECTURE

3.1. Network reference model

Network devices, whether wired or wireless, are commonly described by the Open Systems Interconnection (OSI) reference model. This abstraction model was developed by the International Standards Organization (ISO), starting in the 1980 description of communication-related protocols and services. The generic seven-layer model is applied to all network and media types. The adaptation ISO-OSI network reference model for ZigBee purposes is illustrated in the Fig. 1. ZigBee network model does not use presentation, session or transport layer and user application is directly tied into Application layer (APL). This figure shows also IEEE, ZigBee Alliance, and ZigBee product end manufacturer particular responsibility for ZigBee certified product as well as hardware and software proportion in ZigBee.

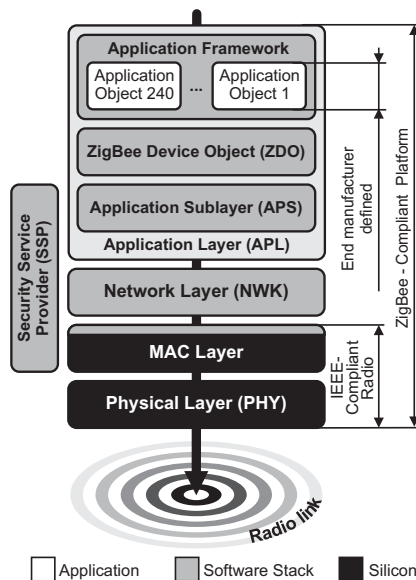


Fig. 1 Adaptation ISO/OSI to ZigBee standard

3.2. IEEE 802.15.4 Standard

The IEEE standard [3] brings the ability to identify uniquely every radio in a network as well as the method and format of communications between these radios, but does not specify beyond a peer-to-peer communications link, a network topology, routing schemes or network growth and repair mechanisms. The ZigBee Alliance selected the IEEE 802.15.4 standard, released in May 2003, as the wheels and chassis upon which ZigBee networking and applications have to be constructed. IEEE 802.15.4 defines three frequency bands to employ a standard over the world. Overview of available bands, modulation method and other properties of each is resumed in Tab. 1.

	868 MHz	915 MHz	2.45 GHz
frequency band	ISM	ISM	ISM
area	Europe	USA Australia	World
bit-rate	20 kbps	40 kbps	250 kbps
number of channels	1	10	16
modulation	BPSK	BPSK	O-QPSK

Tab. 1 Available frequency bands within IEEE 802.15.4 spec with appropriate bit-rate and modulation method

The 2.45 GHz platform is used the most frequently thanks to worldwide availability and 250 kbps bit-rate. Physical layer (PHY) of an IEEE 802.15.4 uses Direct-Sequence Spread Spectrum (DSSS) mechanism for data transmitting and Offset Quadrature Phase-Shift Keying (OQPSK) method of modulation what ensures high level of robustness for the ZigBee. Except frequency bands, modulation and spreading methods IEEE 802.15.4 also define relatively simple protocol, based on CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) access method to the medium. ZigBee does not use all abilities of this protocol.

3.3. ZigBee Standard

The ZigBee specification identifies three kinds of devices that incorporate ZigBee radios, with all three found in a typical ZigBee network (Fig. 2):

- *Coordinator (ZC)*: organizes the network and maintains routing tables,
- *Routers (ZR)*: can talk to the coordinator, to other routers and to reduced-function end devices,
- *End devices (ZED)*: can talk to routers and the coordinator, but not to each other.

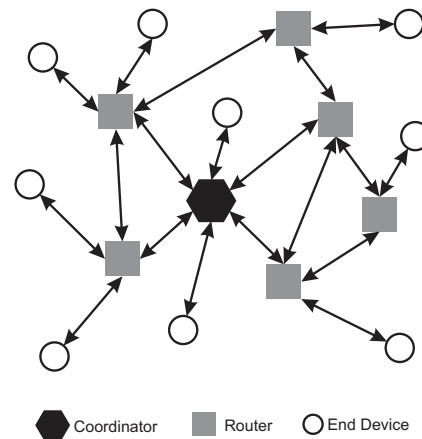


Fig. 2 ZigBee network incorporating coordinators, routers, and reduced-function end devices in a variety of topologies (mesh topology shown)

ZC and ZR are defined as Full-Function Devices (FFD), which are powered on all the time where mains power is recommended. ZED is defined as Reduced Function Device (RFD) where the protocol stack is shorter without ability of routing but this device could be battery powered. Sensors and actuators could be connected to each of these three ZigBee devices. Except common used mesh topology, shown in Fig. 2, it is possible to use tree or star topology, which take less HW and SW resources of the microcontroller (MCU). According to Fig. 1, ZigBee spec contains Network layer (NWK), Application layer (APL), Application Sub-layer (APS), ZigBee Device Object (ZDO), and Security Service Provider (SSP). Manufacturers may define various application objects. ZDO defines the role of device in network (ZC, ZR, or ZED), creates or answers the connection requests and forms security connection between ZigBee devices. ZDO ensures finding the devices in the network and investigates provided services of them as well. The main task of NWK is securing of frames and routing to the end nodes. NWK finds direct neighbor nodes and saves information about them. The coordinator NWK ensures communication and distributes addresses to newly connected devices. MAC layer synchronizes the network, ensures access to the radio channel, checks validity of frame, acknowledges reception of frame, controls connection, generates and recognizes the addresses. APS takes care about binding tables,

which allow matching (binding) of devices according their provided services. Communication between devices depends on ZigBee profile what is device properties summary and definition of message formatting so that the devices create practical application. ZigBee profiles have to have 16-bit identifier that ZigBee Alliance distributes on the demand. The manufacturer can define various descriptors of devices, message identifiers, and provided services within a profile. A ZigBee protocol profile is simply a description of logical components (devices) and their interfaces [7].

4. HARDWARE PLATFORMS OVERVIEW

Each ZigBee product consists of ZigBee compatible RF chip, microcontroller, sensors or actuators, and power source. MCU has to contain ZigBee stack software of course. The manufacturer is advised for using ZigBee stack created by chip vendor or third party if manufacturer would like to reduce time-to-market and simplify developing of product. In most cases the ZigBee stack is distributed in object form, with one exception – Microchip distributes its stack in open C form [8] but 2004 version only till now (October 2007). Some producers of ZigBee stack created more user-friendly IDE for configuring ZigBee devices (e.g. BeeKit by Freescale [9], described in the next

	Vendor	Atmel	Ember		Freescale				Jennic		Microchip	Texas Instruments		
	ZigBee Chip	AT86 RF230	EM 250	EM 260	MC 13193	MC 13203	MC 13213	MC 13225	JN 5121	JN 5139	MRF 24J40	CC 2420	CC 2430	CC 2431
IEEE 802.15.4 Features	Sleep Current [uA]	0.1	1	1	1	1	1	NA	5	1.3	2	2	1	1
	RX Current [mA]	16	36	36	42	42	42	20	50	34	18	20	27	27
	TX Current [mA]	17	36	36	35	35	35	20	45	34	22	18	27	27
	RX Sensitivity [dBm]	-101	-98	-98	-92	-92	-92	NA	-90	-97	-91	-95	-92	-92
	TX Power [dBm]	+3	+5	+5	+4	+3	+3	NA	0	+3	+5	0	0	0
MCU Features	In Package		X	The ZigBee Coprocessor			X	X	X	X			X	X
	External	X			X	X					X	X		
	Core	AVR	XAP2b		HCS08	Coldfire	HCS08	ARM7	RISC	RISC	PIC	MSP430	x51	x51
	Bus Width [bits]	8	16		8	32	8	32	32	32	8	16	8	8
	RAM [kB]	8	5		4	~32	4	NA	to 96	to 96			8	8
	ROM [kB]	256	128		60	~256	60	NA	64	192			128	128
Core Freq. [MHz]	16	12	20	50	40	26	16	16			32	32		
ZB Stack	Availability	yes	yes	in ROM	yes	soon	yes	soon	yes	yes	yes	yes	yes	yes
	License Price				995 \$		995 \$				free	free	free	free
	Latest Version	PRO	2006	2006	2006	2006	2006	2006	2006	2006	2004	2006	2006	2006

Tab. 2 IEEE 802.15.4, MCU, and ZigBee Stack features overview of available ZigBee platforms (features taken from: www.atmel.com, www.ember.com, www.freescale.com, www.microchip.com, www.ti.com, and www.jennic.com)

paragraph). The ZigBee stack is distributed either for free (Texas Instruments) or it is necessary to pay license fee (Freescale). RF chips have various RF parameters. Some chips are either in one package with MCU (what is very important to save board area) or stay alone. Ember even produces EM260 chip [10], the ZigBee coprocessor, where onchip microcontroller contains ZigBee stack with SPI connection to another manufacturer favorite MCU for application extension. There are vendors who make RF chips and MCUs (e.g. Atmel) by stack support of third party companies, e.g. MeshNetics [11] or AirBee [12]. AirBee even offers the ZigBee PRO version. It is essentially simpler to certify ZigBee product with certified ZigBee stack. On the other hand, the open C stack is very interesting for academic or “amateur” purposes. The overview of available ZigBee platforms is shown in Tab. 2. MC13193 and MC13203 by Freescale are supported by both Coldfire or HCS08 MCU platforms.

4.1. BeeKit overview

Development Environment BeeKit is a stand alone software application targeting Windows operating systems. BeeKit provides a Graphical User Interface (GUI) in which the users can create, modify, save and update wireless networking solutions. A snapshot of GUI is shown in Fig.4. With the solution explorer property list dialogs, users are able to set configuration parameters that will control the setup and execution behavior of the wireless link within their application. The configuration parameters can be validated inside the BeeKit to ensure all values provided are within

acceptable ranges prior to the generation of a workspace. All this functionality provides a mechanism for developers to configure and validate their network parameters without need to navigate through multiple source files to configure these parameters. In addition to the graphical user interface, the BeeKit includes a comprehensive code base of wireless networking libraries, application templates, and sample applications. This code base provides the networking software infrastructure in which developers tap into when creating their own applications. The code base includes Freescale’s ZigBee Protocol Stack (BeeStack), pre-configured ZigBee application samples and templates. BeeKit also provides a path for inclusion of 802.15.4 MAC, 802.15.4 based applications, Simple MAC (SMAC) and SMAC based applications to the code base. Once a developer has completed the configuration of their wireless solution, BeeKit allows the developer to export the solution for use in the building and debugging of their application on an integrated development environment.

5. EXPERIMENTAL RESULTS

5.1. Experimental hardware platforms

An evaluating hardware was developed with intention to build a HA network workplace and to test interoperability of various stacks. A Freescale MC13203 chip was chosen for data retransmitting due to its availability in time of consideration and the original RF board with compatible chip was also available. A board (Fig. 5) was designed with onboard F-antenna with the MC13203 chip.

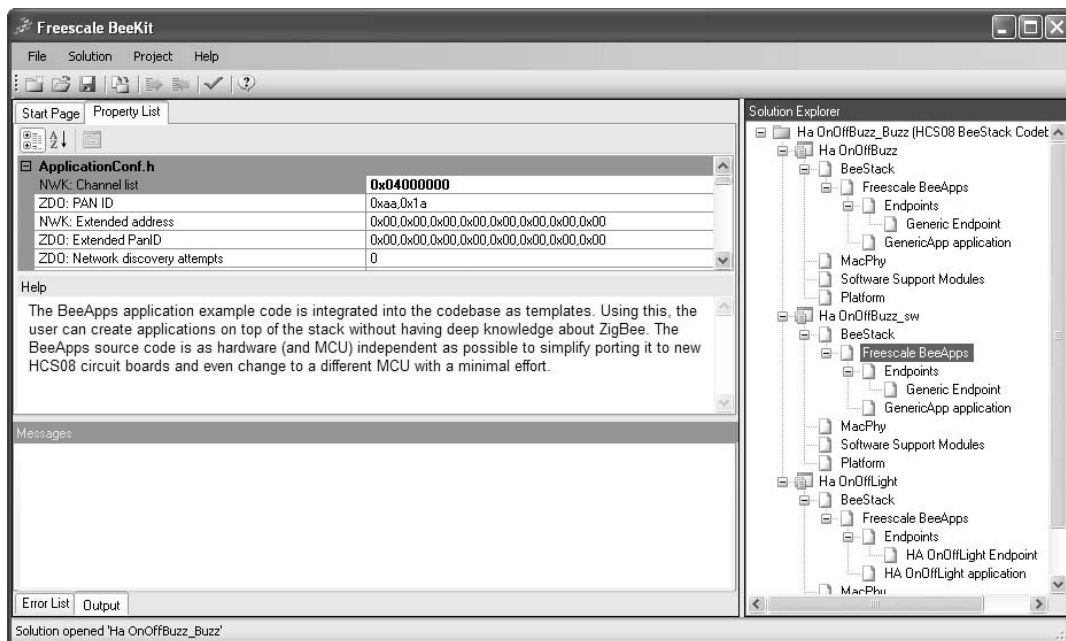


Fig. 4 The GUI of the Freescale BeeKit Development Environment, in which the users can create, modify, save and update wireless networking solution

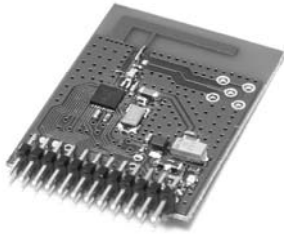


Fig. 5 The experimental RF board with Freescale MC13203 chip developed at DEMC

A Phillips LPC2138 and an Analog Devices ADuC836 were chosen as the MCU platform regarding maximal functionality and peripheral connectivity for HA purposes. Evaluation boards were designed for these MCUs. Both ones have adequate options of peripheral connectivity for HA sensors and actuators. These boards are for evaluation purposes only, therefore to test a functionality of the design. The LPC2138 is built on ARM 7TDMI-s based architecture [13] what ensures a very good performance for time-critical tasks.



Fig. 6 The DEMC ARM BOARD with LPC2138 microcontroller with inserted Freescale RF board

Large 512kB flash and 32kB RAM memory is available on this chip what designate ARM based board for network coordinator purpose. The board with this chip could be used also as 1-wire [14] bridge also. The Keil uVision 3 IDE with free GNU Code Sourcery C compiler was chosen for software development. The DEMC ARM BOARD based on LPC2138 (Fig. 6) also contains 10bit ADC and DAC, USB and RS232 UARTs, SD/MMC card slot, 4 general purpose LEDs and buttons, external interrupt button, reset button, JTAG interface, RF card slot and connector for various peripherals connections. The second DEMC ADuC BOARD based on micro-converter Analog Devices ADuC836 is shown in Fig. 7 (micro-converter is a special name for MCU device with high-end sigma-delta analog to digital converter (ADC)). This MCU is based on modern single cycle x51 clone with 64kB FLASH and 2.3kB RAM. The most powerful peripheral in this MCU is a 24-bit sigma-delta ADC with programmable input gain amplifier in 1-128 gain range. This converter is very useful for precise low-voltage measurements (e.g. various sensors based on

wheatstone bridge, or thermocouple as well). DEMC ADuC BOARD contains similar peripherals as DEMC ARM BOARD, such as SD/MMC card connector, analog input, analog output, LEDs, buttons, RS232, and buzzer. ADuC836 has on-chip thermometer. This board is designed for sensors nodes especially, thanks to rich connectivity of an ADuC836.



Fig. 7 The DEMC ADuC BOARD with x51 core micro-converter with inserted Freescale RF board

5.2. SMAC based wireless network

The main intention was to try interoperability between open Microchip's and Freescale's (BeeStack) ZigBee protocol stacks and compare energy consumption and memory requirements. Only the interoperability of SMAC based protocol was tried up to now. The SMAC is Simple Medium Access protocol distributed in open (ASCII-C functions) form by Freescale for their HCS08 and Coldfire MCUs. This protocol was ported on ARM and x51 compatible microcontroller. SMAC is set of functions for basic interfacing the IEEE 802.15.4 compliant radio. The SMAC is subset of the IEEE 802.15.4 compatible protocol and offers basic peer-to-peer connectivity only. A simple routing algorithm was written as extension for the SMAC. This routing algorithm allows star network building with 10000 end devices.

MCU	HCS08	Coldfire
SMAC ROM	4491B	9512B
Routing ROM	462B	1608B
SMAC RAM	12B	197B
Routing RAM	413B	152B

Tab. 3 SMAC protocol and routing algorithm memory requirements of various microcontrollers

A simple HA network was crated for interoperability demonstration with structure shown in Fig. 8. This network allows remote light switching, temperature regulation or detects door and window movements by accelerometers. There are Passive InfraRed (PIR) motion detector and Smoke Detector as well. Two options to visualize the network in computer are either USB connection of coordinator or Ethernet connection provided by

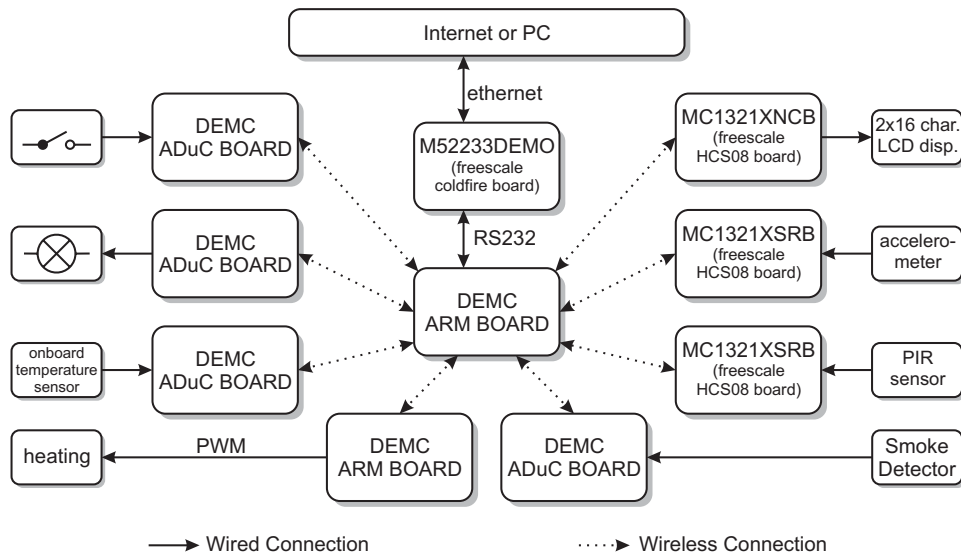


Fig. 8 Realized SMAC based Home Automation (HA) experimental network for testing hardware functionality of designed boards, HA sensors and actuators with proprietary routing algorithm and with Internet connection

Freescale M52233DEMO board with web-server software. There is 128kB space to store simple webpage in Coldfire MCP52233 microcontroller. Coverage radius of this network was about 40m, what is enough for flat or small house. A SMAC memory requirement for various used microcontrollers is shown in Tab. 3.

5.3. ZigBee network

One of main aims was to create ZigBee compatible network. For quick building of it, Freescale offers very smart solution which consists of some evaluation boards, ZigBee stack code generator BeeKit, and Code Warrior IDE to compile, debug, and download codes into boards. Evaluated network has three nodes: Coordinator (MC1321XNCB board), End Device1, and End Device2 (both based on MC1321XSRB board). End devices were configured as remote dimmer switch and remote dimmer light in HA profile as is shown in Fig. 9. ZigBee stack code was generated in BeeKit. BeeKit is high – level code generator which features were described above. Freescale's ZigBee stack (BeeStack) code fills FLASH memory almost completely. It is quite impossible to put compiled codes with all options of BeeStack into memory resources of MC13213 chip. This chip is composite of HCS08 core and ZigBee compliant radio. It suits for purpose of the end device or of the small network coordinator quite well. There is option to run ZigBee stack in Coldfire with enough RAM memory for larger networks, but BeeStack for Coldfire is not available yet. Next impressive option is to use announced MC13225 what is composite of IEEE 802.15.4 radio and ARM7 TDMI-s processor. This chip has only 20 mA current consumption in RX or TX mode, what ensures very long battery life for ZigBee end-device with appropriate active mode duty cycle. 32-bit computing power is great for

coordinator purposes. Created network was visualized in PC via USB using the Environment Demonstration (ZeD) software.

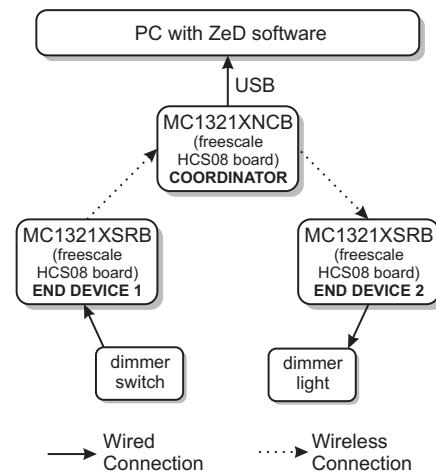


Fig. 9 Realized ZigBee experimental network with USB connection to PC and network visualization in ZeD software

6. CONCLUSION

This article describes features of the ZigBee standard that is great solution for wireless sensor network. The workplace for wireless sensors networking was prepared and tried out within works at DEMC. This workplace consists of development boards based on perspective ARM and x51 microcontrollers as well as the Freescale's ZigBee development tool chain. Their tool chain includes evaluation hardware, the smart code generator BeeKit and Code Warrior IDE. The HA multiplatform wireless network was based on evaluation hardware, SMAC protocol and

proprietary routing algorithm. The interoperability and functionality of used hardware and software were confirmed to achieve sufficient coverage for flat or smaller house. Memory requirement of each MCU platform was also compared. Next step was realization of small ZigBee compliant network using Freescale's tool chain. This tool chain ensures relatively easy network creation and modification. Even though only three nodes was used in the ZigBee network, works at department continue with ambition to realize larger interoperable HA network based on different manufacturer ZigBee chips.

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BIOGRAPHIES

Michal Varchola was born in 1984 in Košice. He received his MSc degree in electronics and telecommunications in 2007 after defending his Master's Thesis - Measurement modules for sensor network with telemetric data transfer in the 2.4 GHz range. Currently he is a PhD student at the Department of Electronics and Multimedia Communications, Technical University of Košice and his main research areas are cryptography algorithms and protocol for sensor networks.

Miloš Drutarovský was born in 1965 in Prešov, Slovak Republic. He received the MSc degree in radioelectronics and PhD degree in electronics from Technical University of Košice, Slovak Republic, in 1988 and 1995, respectively. He defended his habilitation work - Digital Signal Processors in Digital Signal Processing in 2000. He is currently working as an Associated Professor at the Department of Electronics and Multimedia Communications, Technical University of Košice. His current research interests include applied cryptography, sensor networks, digital signal processing, and algorithms for embedded cryptographic architectures.