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Contents

Volume 90
Special Issue
April 2008

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ISSN 1726-5479

Special Issue on Modern Sensing Technologies

Editorial

Modern Sensing Technologies

Subhas Chandra Mukhopadhyay and Gourab Sen Gupta 1

Sensors for Medical/Biological Applications

Characteristics and Application of CMC Sensors in Robotic Medical and Autonomous Systems

X. Chen, S. Yang, H. Natuhara K. Kawabe, T. Takemitsu and S. Motojima 1

SGFET as Charge Sensor: Application to Chemical and Biological Species Detection

T. Mohammed-Brahim, A.-C. Salaün, F. Le Bihan 11

Estimation of Low Concentration Magnetic Fluid Weight Density and Detection inside an Artificial Medium Using a Novel GMR Sensor

Chinthaka Gooneratne, Agnieszka Łekawa, Masayoshi Iwahara, Makiko Kakikawa and Sotoshi Yamada 27

Design of an Enhanced Electric Field Sensor Circuit in 0.18 μm CMOS for a Lab-on-a-Chip Bio-cell Detection Micro-Array

S. M. Rezaul Hasan and Siti Noorjannah Ibrahim 39

Wireless Sensors

Coexistence of Wireless Sensor Networks in Factory Automation Scenarios

Paolo Ferrari, Alessandra Flammini, Daniele Marioli, Emiliano Sisinni, Andrea Taroni 48

Wireless Passive Strain Sensor Based on Surface Acoustic Wave Devices

T. Nomura, K. Kawasaki and A. Saitoh 61

Environmental Measurement OS for a Tiny CRF-STACK Used in Wireless Network

Vasanth Iyer, G. Rammurthy, M. B. Srinivas 72

Ubiquitous Healthcare Data Analysis And Monitoring Using Multiple Wireless Sensors for Elderly Person

Sachin Bhardwaj, Dae-Seok Lee, S.C. Mukhopadhyay and Wan-Young Chung 87

Capacitive Sensors

Resistive and Capacitive Based Sensing Technologies

Winncy Y. Du and Scott W. Yelich 100

A Versatile Prototyping System for Capacitive Sensing <i>Daniel Hrach, Hubert Zangl, Anton Fuchs and Thomas Bretterklieber</i>	117
The Physical Basis of Dielectric Moisture Sensing <i>J. H. Christie and I. M. Woodhead</i>	128
Sensors Signal Processing	
Kalman Filter for Indirect Measurement of Electrolytic Bath State Variables: Tuning Design and Practical Aspects <i>Carlos A. Braga, João V. da Fonseca Neto, Nilton F. Nagem, Jorge A. Farid and Fábio Nogueira da Silva</i>	139
Signal Processing for the Impedance Measurement on an Electrochemical Generator <i>El-Hassane Aglzim, Amar Rouane, Mustapha Nadi and Djilali Kourtiche</i>	150
Gas Sensors	
Gas Sensing Performance of Pure and Modified BST Thick Film Resistor <i>G. H. Jain, V. B. Gaikwad, D. D. Kajale, R. M. Chaudhari, R. L. Patil, N. K. Pawar, M. K. Deore, S. D. Shinde and L. A. Patil</i>	160
Zirconia Oxygen Sensor for the Process Application: State-of-the-Art <i>Pavel Shuk, Ed Bailey, Ulrich Guth</i>	174
Image Sensors	
Measurement of Digital Camera Image Noise for Imaging Applications <i>Kenji Irie, Alan E. McKinnon, Keith Unsworth, Ian M. Woodhead</i>	185
Calibration-free Image Sensor Modelling Using Mechanistic Deconvolution <i>Shen Hin Lim, Tomonari Furukawa</i>	195
Miscellaneous	
Functional Link Neural Network-based Intelligent Sensors for Harsh Environments <i>Jagdish C. Patra, Goutam Chakraborty and Subhas Mukhopadhyay</i>	209
MEMS Based Pressure Sensors – Linearity and Sensitivity Issues <i>Jaspreet Singh, K. Nagachenchaiah, M. M. Nayak</i>	221
Slip Validation and Prediction for Mars Exploration Rovers <i>Jeng Yen</i>	233
Actual Excitation-Based Rotor Position Sensing in Switched Reluctance Drives <i>Ibrahim Al-Bahadly</i>	243
A Portable Nuclear Magnetic Resonance Sensor System <i>R. Dykstra, M. Adams, P. T. Callaghan, A. Coy, C. D. Eccles, M. W. Hunter, T. Southern, R. L. Ward</i>	255
A Special Vibration Gyroscope <i>Wang Hong-wei, Chee Chen-jie, Teng Gong-qing, Jiang Shi-yu</i>	267
An Improved CMOS Sensor Circuit Using Parasitic Bipolar Junction Transistors for Monitoring the Freshness of Perishables <i>S. M. Rezaul Hasan and Siti Noorjannah Ibrahim</i>	276

Sensing Technique Using Laser-induced Breakdown Spectroscopy Integrated with Micro-droplet Ejection System <i>Satoshi Ikezawa, Muneaki Wakamatsu, Joanna Pawlat and Toshitsugu Ueda</i>	284
A Forward Solution for RF Impedance Tomography in Wood <i>Ian Woodhead, Nobuo Sobue, Ian Platt, John Christie.....</i>	294
A Micromachined Infrared Sensor for an Infrared Focal Plane Array <i>Seong M. Cho, Woo Seok Yang, Ho Jun Ryu, Sang Hoon Cheon, Byoung-Gon Yu, Chang Auck Choi.....</i>	302
Slip Prediction through Tactile Sensing <i>Somrak Petchartee and Gareth Monkman.....</i>	310
Broadband and Improved Radiation Characteristics of Aperture-Coupled Stacked Microstrip Antenna for Mobile Communications <i>Sajal Kumar Palit.....</i>	325
The Use of Bragg Gratings in the Core and Cladding of Optical Fibres for Accurate Strain Sensing <i>Ian G. Platt and Ian M. Woodhead.....</i>	333

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Coexistence of Wireless Sensor Networks in Factory Automation Scenarios

¹Paolo FERRARI, ¹Alessandra FLAMMINI, ¹Daniele MARIOLI,
¹Emiliano SISINNI, ²Andrea TARONI

¹Department of Electronics for Automations, University of Brescia, Brescia, Italy

Tel.: +39 030 3715445

E-mail: paolo.ferrari@ing.unibs.it

²Carlo Cattaneo University, Castellanza, Italy

Tel. +390331572214

E-mail: ataroni@liuc.it

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Abstract: The factory automation world can take advantage from innovative wireless sensors network applications, but installation of several wireless systems in the same industrial plant will raise coexistence problems. However, in general, industrial Wireless Sensor Networks (WSNs) operate cyclically and coexistence can be obtained exploiting this characteristic. The paper proposes a methodology based on a central arbiter that assigns medium resources according to requests coming from WSN coordinators. An infrastructure (e.g. a wired Real-Time Ethernet (RTE) network) assures synchronization and distribute resource allocation results. A simulation framework has been designed to evaluate allocation scheme and WSNs coexistence before physical implementation. The real feasibility of the proposed approach has been demonstrated by means of prototype WSNs (based on IEEE802.15.4) synchronized by means of PROFINET IO RT_Class 3 network. Experimental results show a synchronization accuracy below 4 μ s that allows reading of two WSNs (32 nodes) in 128 ms without collisions. *Copyright © 2008 IFSA.*

Keywords: Wireless sensor, Wireless network, Synchronization, Factory automation

1. Introduction

Wireless sensor networks (WSNs) are not diffused in industry, yet. Nowadays, their most diffused application for factory automation is the so called “cable replacement”, where wireless links are used

for bridging two wired fieldbus segments. For instance, wireless communication is employed to replace brush-contacts in rotating machine. Up to now, a relatively small number of products are available for industrial of applications.

Generally, WSNs are employed for monitoring and not for control, since they still have reliability problems. In fact, radio transmission is subjected to a higher Bit Error Rate (BER) than cable transmission, especially if transmission power is low (in order to preserve battery charge) and interference is heavy (as on industrial sites). Moreover, most of the wireless technologies in use today have been developed without any kind of cooperation between their promoters. This means that, in general, wireless standards are not only incompatible, but also “competing”. They share the same media and, in many cases, also the same frequency bandwidth (ISM, Industrial Scientific and Medical). A new standard must adopt some “surviving” strategies in order to share the medium with an older standard [1]. As an example, spread spectrum modulation techniques like Frequency Hopping (FHSS) and Direct Sequence (DSSS) have been adopted to minimize interferences. This approach, that considers interfering communications as mere noise sources, is effective, since these systems can operate without caring about other “things” emitting in the same area. However, there are some drawbacks. First of all, “surviving” does not mean “working at best”; actions like retransmissions, frequency change, etc. etc. require a lot of overhead reducing efficiency (energy waste!). Secondly, the available medium is misused, reducing the number of nodes (i.e. sensing elements) that can be effectively utilized in the same area.

In our opinion, the key feature that must be stressed to ensure the highest efficiency is coexistence. It stands for the ability of wireless systems to slightly modify their behaviour in order to eliminate any mutual interference. In other words, two WSNs in the same area can change, accordingly, their media access strategies to avoid collisions (in the time and frequency domains). Clearly, the behavioral change is possible because the involved systems have knowledge about other co-located wireless devices.

In [2] system architecture to synchronize WSNs by means of synchronization services offered by Real-Time Ethernet protocols has been proposed. Factory automation is the application area for the proposed solution, and in this field the use of Ethernet as fieldbus is well accepted. Recently, new RTE protocols (like PROFINET, Ethernet/IP, EtherCAT, TCnet, Vnet/IP, etc.) have been standardized by IEC FDIS 61784-2. Some of them offer synchronization accuracy among nodes well below 1 μ s, a good value for the proposed use.

In this paper we suggest that coexistence of wireless-equipped machines must be reached with a minimum exchange of information among systems and with no alteration of the machine characteristics. Particularly, the synchronization among WSNs is a good basis on which the coexistence among different types of network can be build. The idea is to have a central arbiter that knows the requirements of all the WSNs; it allocates medium access rights to WSN coordinators that can apply these rules safely because they are synchronized by means of an RTE network.

The paper introduces wireless sensing in automation in Section 2 and presents some conclusions on coexistence of the most diffused wireless protocol in Section 3. The proposed architecture and the associated simulation framework are illustrated in Section 4. The experimental tests are in Section 5.

2. Factory Automation and Wireless Sensors

A current scenario of industrial automation is composed of several tool machines from different manufacturers working close together in the same area (the industrial plant). A typical example is shown in Fig. 1, where a machine prepares the work pallets which are fed to several adjacent

production lines (e.g. extruders in plastic machining, mechanical tool machines, etc.). Products are then packed and placed in a storage area by conveyors belt or “pick and place” robots. All these tools are plenty of wired sensor networks realized using conventional fieldbuses technologies (e.g. thermocouples along the extruder hot barrel). In the next future, it is hoped for integration of wireless communication technologies in new machineries; in many applications the goal is not to completely remove cables in the plant, but just to replace links at the cell level.

As a result, being the air a shared medium, a troublesome fight for media access can be foreseen. Several machineries can be collocated in the same radio coverage area interfering one with each other. In addition, it must be considered that the industry is a close world and the competition among manufacturers is high. No company will agree on sharing “computational” resources of their system to solve the communication problems of adjacent machines produced by competitors. For all these reasons, it is more and more important to ensure coexistence among different communication systems without affecting data transmissions or relying on peculiar hardware implementation.

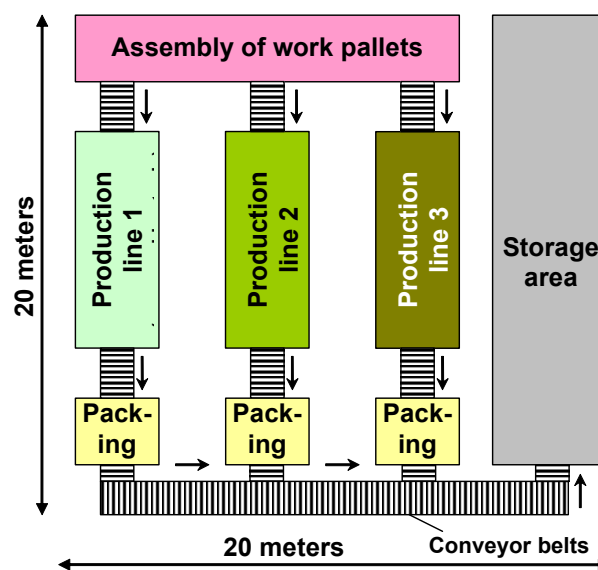


Fig. 1. Factory automation plant with three production lines in parallel.

3. Wireless Technologies to Create WSNs

The last few years have been characterized by the appearance of several standards in the wireless communication field. However, most of them are designed to obtain high transfer rate and ensure nodes mobility. Both these aspects are not relevant from the factory automation point of view; in this work, the attention has been focused on the IEEE802.15 and IEEE802.11 families. In particular, the former deals with the so called Wireless Personal Area Network (WPAN), while the latter deals with the Wireless Local Area Network (WLAN). WPAN requirements are simpler and there is a much greater concern about power consumption, size, and final product cost. Some details are provided in the following.

3.1. Overview of Standards

All IEEE802 subgroups cover just the first two layers of the ISO/OSI model, i.e. the PHYSical (PHY) and the Data Link, which includes the Medium Access Control (MAC). Particularly attractive are solutions that operate in the unlicensed ISM band around 2.4 GHz, the only free spectrum region all

around the world. Lower frequencies could have a lower attenuation, but the better behaviour in terms of electromagnetic interference and frequency reuse makes ISM the best choice. The previously mentioned WPAN is defined around the concept of Personal Operating Space (POS), i.e. “the space about a person that typically extends up to 10 meters in all directions and envelops the person whether stationary or in motion”; a concept that can be easily applied also to machineries. IEEE802.15 is composed of four working groups. Only two of them will be discussed.

IEEE802.15.1 is the standard version of the Bluetooth solution. It employs a narrowband radio and implements spreading by means of FHSS over 79 (1-MHz wide) channels. A scheduled MAC is adopted, since time is divided into 625 μ s-slots alternatively assigned to network master and slaves. The same physical channel is shared within the so called piconet that can include up to 8 active members; if a node exists in more than one piconet it belongs to a scatternet. The gross transfer rate is 1Mbps.

IEEE802.15.4 emphasizes low power consumption; it allows for a gross transfer rate of up to 250 Kbps. The spreading technique is the DSSS and the available band is divided into 16 channels 5-MHz wide. Both star and peer-to-peer topologies are supported and the MAC technique is based on carrier sensing, even if it is possible to allocate particular time slots to nodes with restrictive time requirements. Two kinds of nodes are defined: Full Functionalities Device (FFD), that implements the whole stack and require more resources, and Reduced Functionalities Device (RFD), that implements a subset and can be easily implemented on low cost hardware.

On the contrary, IEEE802.11 has been designed to replace Ethernet connection and offers transmission rate comparable with the 10/100BaseT wired link. Power consumption is not of main concern and usually the implemented network is infrastructured, i.e. it relies on several “Access Points” interconnected by a wired backbone that manages wireless nodes. However, “ad hoc” implementations are also described. The 802.11b version employs DSSS with a gross transfer rate of up to 11 Mbps, while 802.11g employs OFDM with a gross transfer rate of 54 Mbps. Both of them define 14 channels in the 2.4 GHz band, each having a distance of 5 MHz. Since the WLAN radio signal has a bandwidth of 22 MHz, not all channels can be used concurrently, but there is room only for three non-overlapping channels: 1, 6 and 11 (in Europe). The MAC strategy is based on carrier sensing, but some form of time scheduling and priority services is provided.

3.2 Interoperability and Coexistence

Different systems that work using the same set of rules are said to be interoperable; on the contrary, coexistence is the capability to work in an environment where other devices can operate following dissimilar rules. As previously stated, each manufacturer generally considers other communication systems as noise sources. Some efforts have been done to overcome this approach and to give indications on how ensure coexistence. Task Group IEEE 802.15.2 (TG2) was formed in 2000 to address issue of coexistence of WLAN and WPAN, primarily 802.11b and 802.15.1 (i.e. Bluetooth). However, it must be remembered that now IEEE802.15.2 is in hibernation; its suggestions have only partially been included in IEEE802.11 and IEEE802.15 standards.

TG2 defines two different approaches: collaborative and non-collaborative. In the former, systems exchange information and thus are linked together, while in the latter each one guesses the existence of other systems analyzing the medium itself. Best results may be obtained with collaborative mechanisms, i.e. exploiting all information available on fighting communication systems [3]. The simplest collaborative method is the so called “Alternating Wireless Medium Access” (AWMA). The basic idea is to coordinate the medium access so that no collision occurs at all. This implies that both the WLAN and the WPAN coordinators are linked together and synchronized; the WLAN node

schedules network accesses defining a “Medium free signal” that is used to notify the WPAN interval. The WLAN Beacon packet is modified in order to add a MSE (Medium Sharing Element) field that specifies intervals time duration. Particularly interesting is the “Packet Traffic Arbitration” (PTA), where an additional arbiter uses knowledge of networks status, packet priorities and PHY characteristics to deny transmission of packets that may result in collisions. The last collaborative method is the “Deterministic Interference Suppression” (DIS); this approach can be used when one of the communication systems can be considered as a narrow band interfering signal, as occur in WLAN transmissions with respect to IEEE802.15.1. This kind of interfering signal can be filtered out knowing its time and frequency behaviour in the receiving demodulator, thus improving robustness. Non-collaborative methods must be employed when a-priori knowledge is not available and they are useful when dealing with changing data streaming.

There is also the IEEE802.19 Wireless Coexistence Technical Advisory Group, formed in 2001 to address wireless coexistence across all of IEEE 802. The aim is to develop a document called Coexistence Assurance (CA) document, which is a study showing how well a proposed wireless standard, planned for unlicensed operation, coexists with current standards. Anyway, it is still in a draft state.

3.3. The Industrial Scenario

In the literature, several proposals have been done in order to improve coexistence of wireless systems for the consumer market (especially for IEEE802.15.1 and IEEE802.11b [4, 5]). In this case problems may arise when both radios are co-located within the same device, e.g. a laptop. The considered scenario involves bursty and asynchronous transmissions of a relatively high amount of data. Usually, latency is not of main concern and suggested solutions implement data queuing and postponed data transmission.

The industrial scenario is just the opposite; the data delivery model involves cyclic data transmission (to ensure determinism) of a relatively small data amount at a low transfer rate. In fact, first available wireless sensing solutions for the factory automation [6] adopt star topology with Time Division Multiple Access (TDMA) strategy. Non-collaborative approaches are preferred in the home/office environment, since scalability and self healing are key features in consumer applications. Again, the industrial scenario has completely different requirements; wired links are always present and best results can be reached recurring to collaborative schemes.

4. The Proposed Architecture

As previously stated, in industrial applications it is very difficult to ensure coexistence relying on collaboration between systems of different manufacturers. On the other hand, all vendors propose wireless solutions that do not constantly occupy the entire free spectrum. This means that sometimes a system has to leave the bandwidth free of traffic. Synchronization of network coordinators can help in exploiting such “fairness” characteristics in order to allow for coexistence among networks even from different vendors. The proposed solution (Fig. 2) is a sort of arbiter that harmonizes medium accesses by means of time reference sharing and global knowledge of the whole plant. The arbiter does not care about application data transmitted on the networks, it just exchanges some configuration information to quantify requirements of each network. In particular, the arbiter creates a map of {time, frequency, geographical area} requests of every network. Successively, it “orthogonalizes” these specifications in order to avoid or decrease mutual interference.

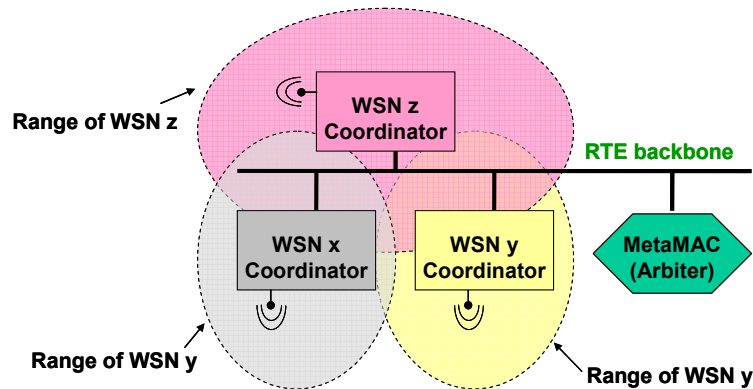


Fig. 2. The proposed system.

The proposed arbiter works at the MAC level, since strategies at the PHY level implies hardware modifications which are not tolerated. For this reason the proposed arbiter has been called “MetaMAC”.

Rather than organize all the nodes collocated in the same area of interest, the MetaMAC only talks with WSN coordinators that continue to manage their subnets on their own. This allows for a simpler solution with a lower impact on existing solutions. WSN coordinators are usually connected by means of fieldbuses or RTE networks and MetaMAC could also use this infrastructure. Since in new installations RTE is preferred, the exchange of configuration and synchronization data can rely on RTE performance.

The previously introduced map should also be flanked by ancillary information, such as channel/link quality (RSSI, PER, BER...), retry strategies (Automatic Repeat Request - ARQ, number of retries...), etc. Using this knowledge the MetaMAC can more effectively apply safety strategies. In this scenario frequency hopping or ARQ should be performed under the MetaMAC supervision. For instance, it could be preferable to disable retransmission to ensure several TDMA networks coexistence.

4.1 Simulation Framework

A simulation framework has been created, in order to test the architecture behavior with arbitrary networks and protocols. OMNeT++ has been used as simulation environment: models of wireless nodes as well as models of resource allocators can be implemented as C++ objects that exchange messages. Each node has its own properties like position, transmission power, sensitivity, protocol, and internal state machine. The compound module representing a WSN is shown in Fig. 3: several nodes are collected together representing a wireless network.

At least one coordinator is present in every WSN and each coordinator has a double data path (wired and wireless), so it can send (or receive) information along a wired connection in a sort of double tier network. The model of the MetaMAC has been created and it can be interfaced with other coordinators by means of the wired network. A snapshot of the simulator appearance at the highest level of abstraction is shown in Fig. 4.

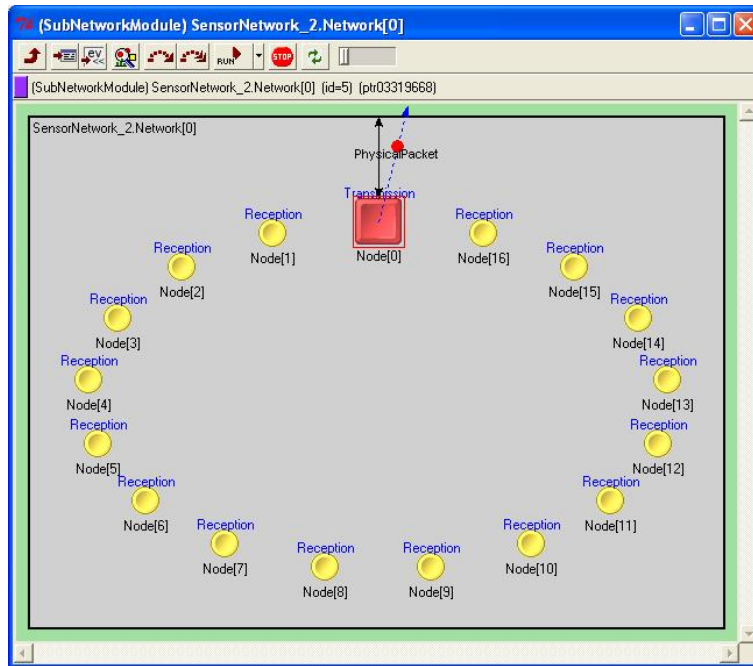


Fig. 3. Simulation module representing a WSN.

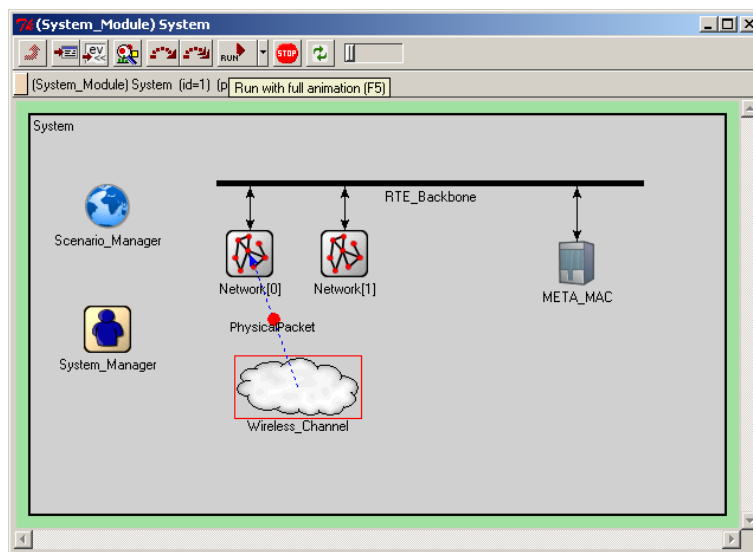


Fig. 4. Simple coexistence simulation: two WSNs are coordinated by a MetaMAC. Both networks receive medium access rights via the RTE_backbone and try to access the wireless channel accordingly.

It should be noted the presence of another compound module (the “cloud”) that models the wireless channel behavior; in fact wireless nodes exchange message passing through the wireless channel model in order to simulate the shared nature of the medium. The wireless channel model takes into account the presence of a finite number of radio channels, the attenuation and the fading due to physical node position (i.e. the x and y coordinates), the noise, the collisions when two nodes attempt transmitting at the same time/on the same frequency.

The framework is versatile, since no assumptions has been done on the nature of the wireless network or the wired network; the scenario can be customized by the user before starting the simulation.

5. Example of a Real Application

The simulation scenario described in the previous section has been tested on a real application. A plastic machining plant, where two extruders are flanked one each other, has been considered. The fluid temperature is continuously measured by means of wireless thermocouples [7]; each extruder has its own star network with up to 16 nodes operating with an hybrid CSMA/TDMA strategy and exploiting a PHY level compliant with IEEE802.15.4. A wireless thermocouple prototype is shown in Fig. 5.

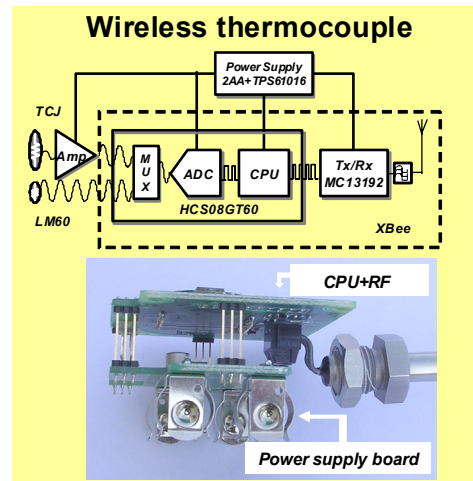


Fig. 5. Photo and block diagram of a wireless thermocouple prototype.

Usually, in order to assure coexistence of multiple WSNs and to increase the number of sensors, different frequency channels are chosen. With the aim of implementing a prototype of two interfering WSNs, authors considered two systems operating on the same channel.

The wireless protocol of both WSNs is very simple; each network coordinator divides time into segments by means of particular packets called Beacons. The portion that immediately follows a Beacon (JP, Join Period) is used for acyclic communications and uses CSMA/CA. Once a node has joined its coordinator, it receives a communication time slot and performs cyclic data exchange on TDMA basis in the remaining portion of the frame (RTP, Real-Time Period). Obviously, if more than one network operates on the same channel and covers the same area collisions may arise as in Fig. 6. For instance, Beacon overlap condition can last for several seconds, while the offset between time segments of the two WSNs shifts (randomly) for thermal drift.

The considered protocol has two kinds of packet: Beacon and Data. No ACK packets are provided since data exchange is continuous and cyclic (i.e. retries are useless). The Beacon packet is 13 bytes long ($416 \mu\text{s}$ @ 250 Kbps) including IEEE 802.15.4 header and footer. The Data packet is 18 bytes long ($576 \mu\text{s}$ @ 250kbps). In the current implementation, the segment is 128 ms wide: JP lasts 32 ms and RTP lasts 96 ms (16 time slots of 6 ms). However, each time slot is occupied for just the duration of a Data packet in air.

The proposed MetaMAC has been used to opportunely shift frames of both networks in order to avoid collisions (see Fig. 7). The offset accuracy between Beacons of the two WSNs depends on RTE synchronization accuracy. On the other hand, the relative position of time slots depends on the WSN synchronization accuracy.

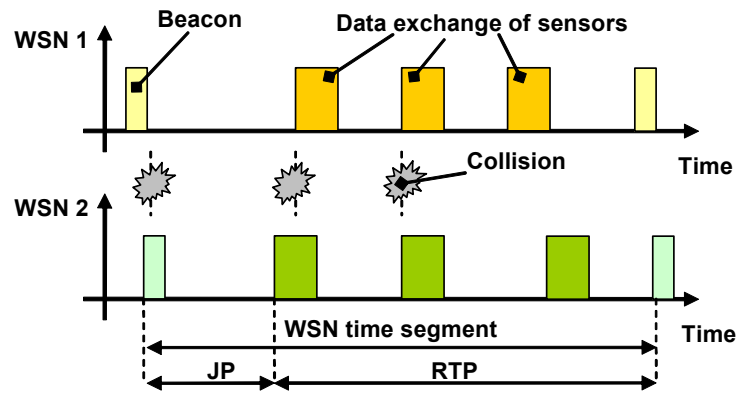


Fig. 6. Two unsynchronized WSNs with collisions.

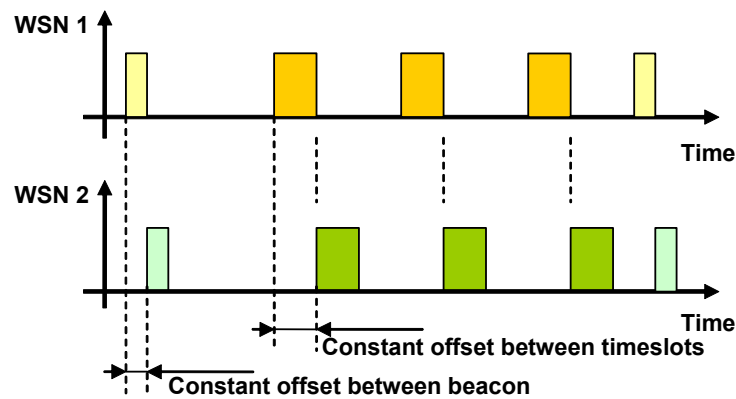


Fig. 7. The MetaMAC decides the offset between WSN time segments, avoiding collisions.

The realized prototype system is shown in Fig. 8. RTE Node 1 includes also the MetaMAC functionalities, since it has a high performance microprocessor. A total of 32 wireless sensors (16 sensors for each coordinator) are present in the system.

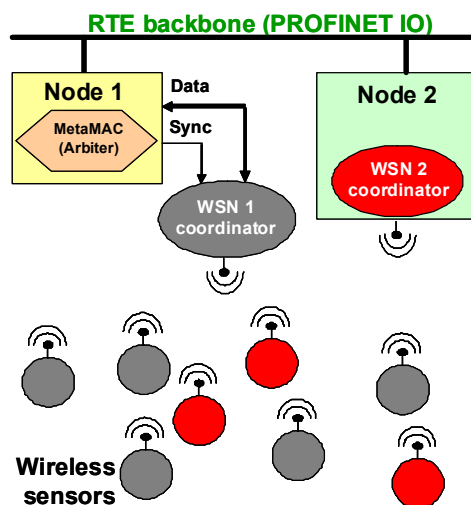


Fig. 8. Block diagram of the prototype system.

5.1. RTE Network

In the prototype system, PROFINET IO RT_Class_3 has been used as RTE protocol. PROFINET IO RT_Class 2 and 3 cover the CP 3/6 of the new international standard IEC FDIS 61784-2. A good introduction to PROFINET IO is presented in [8]. Briefly, PROFINET IO defines IO-Controllers (i.e. intelligent devices which carry out automation tasks) and IO-Devices (i.e. field devices like sensors, actuators, IO module etc.). IO-Controllers and IO-Devices exchange process data using real-time communication channels; for configuration, statistics, and management data non real-time channels (i.e. UDP/IP) are used. PROFINET IO grade of determinism is described with the class number: RT_Class 2 and RT_Class 3 (often called IRT, Isochronous Real-Time) are used with applications requiring isochrony and cycle time in the order of 1 ms. In particular, RT_Class 3 (also called IRTtop) is the top performance class. No delays can happen within this RT_Class since the frame scheduling sequence in each cycle is “a priori” known and always identical. The network configuration tool calculates the trip for every frame of a cycle and downloads the schedule in the RTE network infrastructure (i.e. RT_Class 3 compliant switches).

In [9], performance of a PROFINET RT_Class 3 system has been experimentally evaluated. At the network level the synchronization accuracy is below 150 ns. At the application layer interface, results indicate that maximum offset errors between real nodes of an RT_Class 3 system is less than 3 μ s with a standard deviation of 500 ns. Moreover, the performance could be improved in the future with simple firmware modifications.

In this paper the PROFINET IO network is composed of an IO-Controller (Node 1) and an IO-Device (Node 2). Both of them are based on ERTEC400 ASIC (Siemens) which includes an ARM9 core, running WxVorks operating system, and Ethernet interfaces.

5.2. WSN

Two kinds of wireless coordinator have been realized, as illustrated in Fig. 8. The first one is obtained joining the IOC 1 node, described in previous section, with a traditional dual chip (a microcontroller, HCS08GT60 and a transceiver, MC13192, both from Freescale) coordinator. The Node 1 furnishes a synchronization signal that is used by the network coordinator to mark Beacon transmission instants.

In the other coordinator the same processor of the Node 2 handles both wireless and PROFINET protocols. The only other component is the radio frequency transceiver (MC13192).

Wireless nodes are based on the same hardware (μ C: HCS08GT60, transceiver: MC13192; see Fig. 5) and are battery powered; a DC/DC converter (TPS60016 from TI) has been adopted to obtain power supply from two AA batteries; life has been estimated in about 4 months of continuous working. The sensing element is a common J-type thermocouple whose conditioning chain has been designed around a low-power low-noise amplifier (OPA330 from TI). The overall accuracy is in the order of 1°C and resolution is 0.1°C.

6. Experimental Results

WSN coordinators are always on and remain in the transmitting state only to send Beacons, otherwise they listen to what happens on air. On the contrary, wireless sensors use low power modality in order to extend their life. They spent most of their time turned off (Doze mode of the MC13192); wakeup instants are determined using the high accuracy crystal based timer (resolution 1 μ s).

In order to precisely determine time position of packet in air, a purposely designed sniffer has been realized. It uses a different transceiver compliant with the IEEE802.15.4 (CC2420 from TI), which offers a digital line that signals the arrival time of each packet and its duration. The signal goes high after the packet Start Frame Delimiter has been detected and goes low at the packet end. Therefore, the signal pulse durations are $256\ \mu\text{s}$ for the Beacon and $416\ \mu\text{s}$ for the Data, since the 4-bytes preamble and the 1-byte SFD fields are not included.

Referring to Fig. 9, a mixed signal scope (MSO6054A from Agilent) has been used to simultaneously show: the packet duration signal given by the sniffer (AIRPKT trace); the transmission and reception signals from the MAC layers of WSN coordinators (traces CRD1 and CRD2) and nodes (the traces NODES1 and NODES2 are the OR combination of all the node signals). The synchronization pulse sent by IOC 1 (trace SYNC) is also displayed.

The proposed MetaMAC decides to separate the begin of WSN 1 and WSN 2 cycle of 2 ms, achieving coexistence of the two networks. The synchronization through the PROFINET IO network allows the exact positioning of Beacons. As a result, the system correctly manages 32 co-located wireless sensors in a time segment of 128 ms, harmonizing their operations on the same frequency channel.

Fig. 10 is a detail of the end of time segment n and the begin of time segment $n+1$. Data packets coming from the 16th sensor of WSN 1 and WSN 2 are visible, together with the Beacons of the new time segment. In the two boxes are shown, by means of oscilloscope persistence, the magnification of the transmission instant of: the 16th sensor; the Beacon of WSN 2. The offset accuracy, measured over 15 minutes, is very good; the jitter (the maximum offset minus the minimum offset) is $3.5\ \mu\text{s}$ for Beacons and $5.5\ \mu\text{s}$ for sensors. It should be remarked that the last wireless node has the largest time inaccuracy because it remains in the doze mode for the longest time after receiving a Beacon.

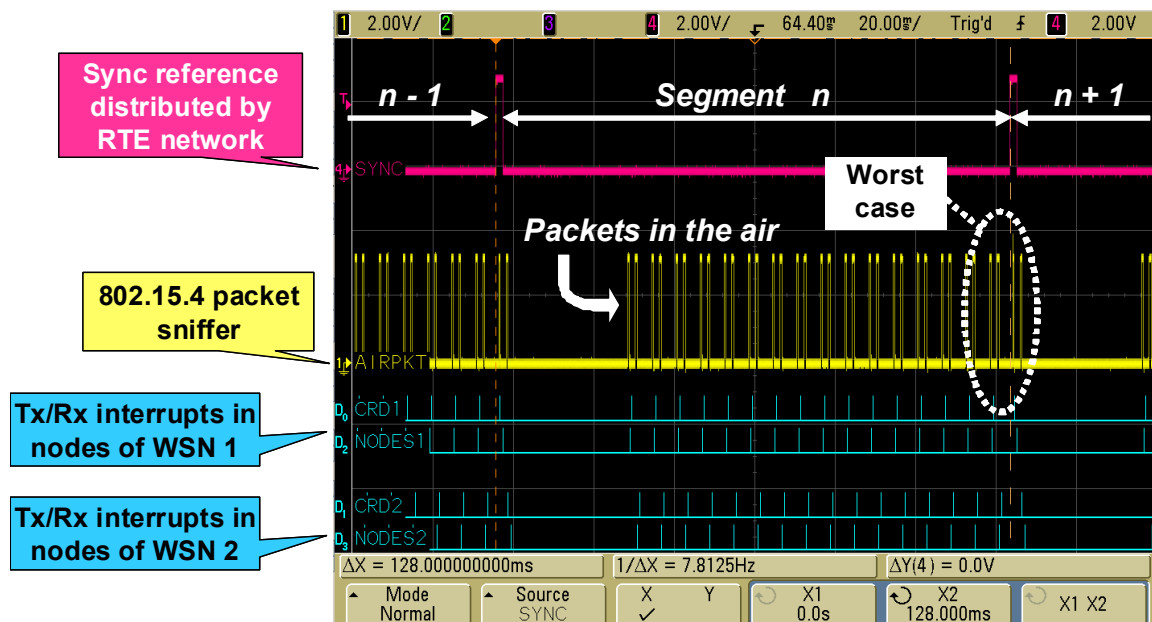


Fig. 9. A complete time segment (128 ms) of the real system. AIRPKT: signal given by the network sniffer indicating the position of packets in the air.

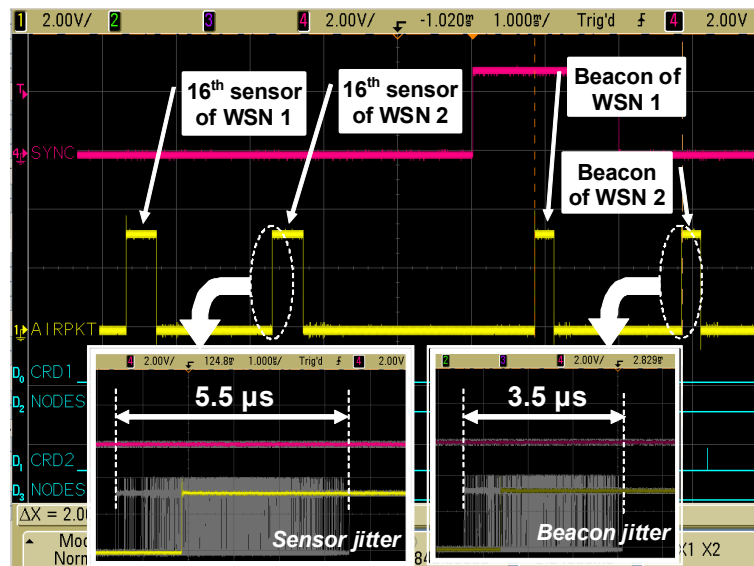


Fig. 10. Last part of a time segment and Beacons of the next segment. In the boxes: jitter of the 16th sensor of WSN 2 and jitter of WSN 2 Beacon.

7. Conclusion

In this paper, a methodology based on an arbiter for coexistence of different WSNs has been proposed. Resources harmonization is obtained by means of a common sense of time among WSN coordinators; synchronization is done using a wired Real-time Ethernet network. A simulation framework has been also provided in order to test resource allocation strategies with different WSN protocols.

Last, the applicability of the architecture has been demonstrated by means of a prototype system that can interleaved time scheduling of two WSNs (operating on the same frequency channel) with an error less than 10 μ s. In conclusion, the proposed architecture and the related simulation tool give the possibility to test coexistence among generic WSNs (e.g. Bluetooth and IEEE802.15.4 Zigbee) before the physical placement of the networks.

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