Cognitive Internet-of-Things Solutions Enabled by Wireless Sensor and Actuator Networks

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***Abstract*—In this paper, the design and development of wireless sensor and actuator networks that enable Internet-of-Things (IoT) solutions are investigated from the perspective of cognitive infocommunications. The reasons, requirements, and issues related to adaptive systems and architectures are presented, and the corresponding intra-cognitive and inter-cognitive communications are examined. The current and future roles of infocommunications in the design of IoT solutions are indicated via several case experiments in different application domains.**

***Keywords*—wireless sensor and actuator networks, internet of things, intra-cognitive communication, inter-cognitive communication, adaptive structures and architectures.**

I. INTRODUCTION

Cognitive infocommunication (CogInfoCom) aspects [1], [2] are essential when developing Internet-of-Things (IoT) solutions. According to [3] the IoT paradigm's basic idea is the pervasive presence around us of variety of things or objects (e.g., sensors, actuators, radio-frequency identification (RFID) tags, mobile phones), which are connected to the Internet. These objects are able to interact both between themselves and with the external systems. The objects cooperate with their neighbors to reach common goals. In intra-cognitive communication, two cognitive beings have the same cognitive capabilities. In inter-cognitive communication, natural and artificial cognitive systems have different cognitive capabilities but should work together efficiently (e.g., a human and a digital menu based restaurant system). Considering the heterogeneous nature of IoT and different capabilities of various IoT devices, both inter-cognitive and intra-cognitive communications are essential for IoT.

In Section II, we first present related work about IoT focusing on solutions and applications that are enabled by the utilization of wireless sensor and actuator networks (WSANs). Section III discusses the architectural choices of WSAN-based IoT and the requirements and issues related to adaptive systems and architectures. In Section IV, we present some case study experiences from different IoT application domains. Finally, these experiences are discussed and conclusions are drawn.

II. RELATED WORK

Multiple research studies have been conducted about IoT e.g., [3]-[6]. We have adopted the classification of IoT application domains of industry, environment, an,d society according to [4]. The future vision and architectures have been discussed in [5]. Engineering and industrial aspects of IoT applications have been covered in [6], where some of the current research challenges are reviewed. The authors have proposed a service-oriented IoT architecture emphasizing the need for adaptive architecture.

As our examination perspective is CogInfoCom, the inclusion of human and social aspects is important. The social IoT concept has been introduced and discussed in [7]. Some results of using CogInfoCom approach for studying situation-aware robotic and transporter solutions were reported in [8]-[10].

The WSAN technology is developing fast. The recent trends in industrial applications and industrial WSANs (IWSANs) can be found in e.g., [11]-[14]. As reported in these studies, there are a number of challenges for contemporary IWSANs. The first and, probably, the most well studied topic is the energy efficiency and energy management [11], [12]. Among the most perspective energy-related trends are the energy harvesting (EH) [15], [16] technologies, which enable powering the WSAN node using the energy collected from the environment. The second issue is the integration of the IWSAN with the other systems and networks [13]. The collected by the IWSAN data often needs to be accessible from the Internet, which emphasizes the importance for Internet Protocol support in IWSANs. Finally, the IWSANs are often installed in the already existing industrial environment. This requires the nodes to support the specific interfaces that are already used by the deployed industrial machinery.

III. ADAPTIVE SENSOR AND ACTUATOR NETWORK SYSTEM STRUCTURES AND SOFTWARE ARCHITECTURES

A. General IoT Architechures

One of the key ideas behind the IoT concept is to provide cloud services and Internet connectivity to *various* device-related or machine-related applications. Machine-related solutions have traditionally been developed in different application-specific domains utilizing the limited set of domain-specific machine-to-machine (M2M) communication protocols and technologies. The paradigm shift from stand-alone and application domain-specific "silo-solutions" to general Internet-based solutions has posed new challenges for interoperability and architectural design. One way to overcome

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the current challenges relies on the adaptive system structures, hardware and software architectures.

One of the most important challenges is how to enable seamless integration of the devices with different capabilities and targets within single system. This problem inevitably contains both inter-cognitive and intra-cognitive aspects. E.g., the intra-cognitive M2M communication is the base for improving the efficiency of the system (e.g., boosting the energy efficiency, reliability and security). The inter-cognitive M2M and machine-to-human communication are important for controlling the system as whole, for obtaining the results, and presenting those to the end-users. In order to address those challenges, we have gradually developed our own IoT system architecture and platform. The major design issue was the integration of the heterogeneous networks allowing location and context-aware applications; thus, the platform was named Locawe. Simultaneous with the architectural and platform development, the platform has been adapted and utilized in several, mainly industrial, real-life business cases meaning that the original platform design was for the industrial domain. Later, the platform was upgraded to enable its use in the environmental domain by adding the geosensor support [17]. As an example of our vision, the system structure/software architecture is presented in Fig. 1. The further details discussing the enablement of the intelligent networking and Web services for sensor nodes are reported in [18].

B. *Adaptivity to Limited Energy Resources*

It is well known that WSAN nodes are resource constraints e.g., [14], meaning that the nodes often have strict restrictions for their size, weight, and costs. Besides, IWSAN nodes are often limited in energy and computational power. Our previous research focused on several important aspects of the EH-powered WSANs. In an experiment, we studied and evaluated how the operation of a WSAN node and its processing unit should be optimized to increase the lifetime of the nodes powered by EH and batteries [19], [20]. We discussed the possibilities for restoring the data on the EH-powered WSAN nodes after the power-downs that might happen during low energy-income periods once the stored energy is depleted [21]. We suggested a simple mechanism to identify the type of power source of a WSAN node (i.e., an EH system, batteries, or mains), and used it to propose the routing protocols for the heterogeneous networks consisting of nodes powered by different sources [22]. This enabled us to significantly improve the lifetime of such networks. An interesting approach for the EH WSAN application architecture was suggested in [23], where Mascarenas and colleagues proposed using a remotely controlled, mobile host node to retrieve the data and to charge the WSAN nodes by wireless power delivery.

C. *Radio Access Adaptivity*

In their analysis, Singh and colleagues [24] pointed out the bandwidth as one of the most important design issues of the future IoT, since the number of sensor nodes increases and the system should be able to handle the resource constraints. Similarly, Xu and colleagues' [6] analysis identified radio access among the major standardization issues for the further development and spread of industrial IoT.

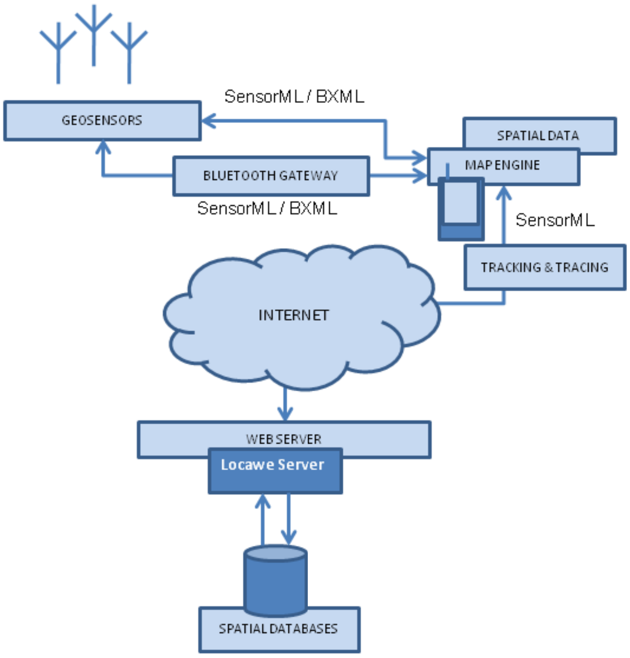


Fig. 1. The Locawe system structure.

The WSANs generally utilize license-free industrial, scientific and medical (ISM) radio bands. A common frequency band is 2.4 GHz, which is used for various wireless applications, including e.g., Wi-Fi. The ISM frequency bands are already overcrowded and the forecasts expect even more users to come, resulting that the mobile traffic is predicted to grow rapidly over the next years [25].The overcrowded ISM bands negatively affect the performance of WSANs due to unsuccessful channel access attempts. One possible solution of this problem is to utilize a cognitive radio technology. A cognitive radio device is aware of the radio spectrum conditions and can monitor its own resources (e.g., energy) [26]. We expect that the number of the cognitive wireless sensor networks will significantly increase in future. The major research challenge for those is the development of the mechanisms for spectrum sensing, data processing, and decision making to enable their use by the sensor nodes having limited energy and processing capacity. One possible solution is to integrate in the networks the specialized nodes, which are capable of spectrum sensing and spectrum data processing, and will share those data with the neighboring nodes. Then, the spectrum decisions can be centralized or distributed. The distributed solutions demand higher processing capabilities from nodes and results in non-optimal spectrum usage. In the centralized method, one sink is responsible for making spectrum decisions [27].

IV. EXPERIENCES IN WSAN-BASED IOT SOLUTIONS

A. *Examples in Industrial Domain*

An interesting example for using the IoT for food supply chain management is the Intelligent Container [28] project, which targets developing a sensor network to be used in logistics. Namely, the proposed WSAN manages and controls the transportation of perishable goods, such as vegetables and fruits. The Intelligent Container can measure the current status of the contained cargo and can locally make decisions to adjusts the environment conditions inside the container.

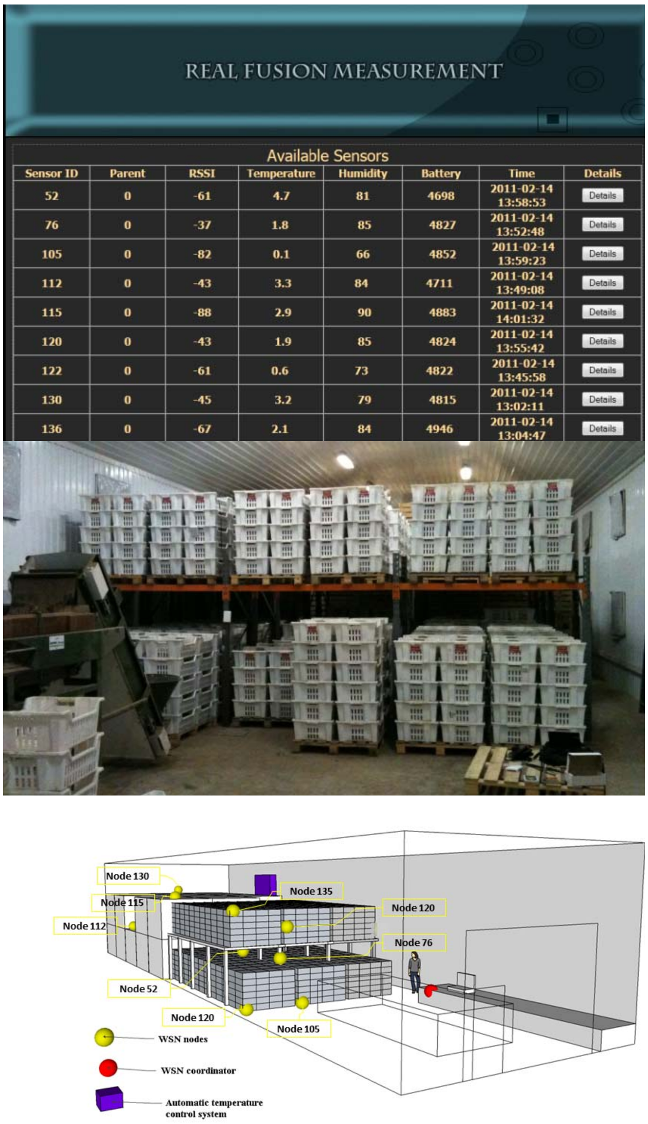
The management of the food supply chain includes the storage phase, which was one of the industrial case examples [29] considered by us in Real Fusion research project. We monitored the conditions (i.e., temperature and humidity) of a warehouse where the seed potatoes for the next growing season were stored. The warehouse was equipped with an Internet connection and an automatic temperature control system that was configured to maintain the temperature at around 3° Celsius. Our goal was to demonstrate the IoT concept system, in which the actual measurement database was running on a remote server located in the company's main office and was accessible through the Internet. Our WSAN nodes provided information on the conditions at different locations in the warehouse, as shown in Fig. 2.

The CogInfoCom approach has been widely used in robotics [8]-[10], [30]-[33]. The integration of the robots in the IoT infrastructure greatly improves the performance and opens new opportunities for both systems.

Blazovics and colleagues [30] discussed the aspects of a group of robots. The most important benefits of using a group of individual robots are low cost and robustness. If one of the robots is damaged, it can be replaced with minimal financial loss. A group of individual robots performing cooperatively to solve a collective task is called a swarm. This kind of swarm can solve much harder tasks than a single robot can. However, robots' capabilities are still limited; therefore, the rules and algorithms used should be very simple and easily adoptable. Because these entities lack communication skills, they need to make decisions individually relying on the individually gathered information. These decisions can be improved by giving the robots better sensor equipment and enabling information sharing among the members of the swarm. The benefits of distributed algorithms are obvious, even better results can be achieved by providing the swarm with additional communication networks. When using CogInfoCom, the quality of shared information will be significantly better, more accurate, and much easier to understand. This property makes this concept ideal for intelligent swarms. It is possible to generate a higher-level cognitive entity by using this method and to increase the effectiveness of individual swarm members.

Levi and colleagues [31] presented an architecture for a swarm of modular and self-configurable robots. This survival cycle-based cognitive framework, i.e., swarm-organism-swarm, enables switching between the swarm and the organism modes in an alternating manner. The 100-robot set is able to react to changing environmental conditions using a catalogue of self-organization and is completely aware of the reasons to change the swarm's global behavior, to modify the organism's shape, or to automatically repair defective parts by tmehselves.

Sörös and colleagues [32] presented an industrial robot supervision system inspired by the research results of CogInfoCom. The concept of cognitive robot control embeds human intelligence into the control loop to supervise the process. The human operator's assignment is to give appropriate instructions to the remote manufacturing system, which independently performs the ordered tasks using its own artificial intelligence. The system was designed to be independent of the geographical distance between the user and the manipulated environment. It was successfully tested to establish industrial robot control loops spanning countries.



REAL FUSION MEASUREMENT

Available Sensors

Sensor ID	Parent	RSSI	Temperature	Humidity	Battery	Time	Details
52	0	-61	4.7	81	4698	2011-02-14 13:58:53	Details
76	0	-37	1.8	85	4827	2011-02-14 13:52:48	Details
105	0	-82	0.1	66	4852	2011-02-14 13:59:23	Details
112	0	-43	3.3	84	4711	2011-02-14 13:49:08	Details
115	0	-88	2.9	90	4883	2011-02-14 14:01:32	Details
120	0	-43	1.9	85	4824	2011-02-14 13:55:42	Details
122	0	-61	0.6	73	4822	2011-02-14 13:45:58	Details
130	0	-45	3.2	79	4815	2011-02-14 13:02:11	Details
136	0	-67	2.1	84	4946	2011-02-14 13:04:47	Details

Fig. 2. Developed WSAN-based IoT application for distant monitoring of the vegetable storage conditions: top – remote user's GUI; middle – installation facility; bottom – position ofwireless sensor network (WSN) nodes.

Solvang and Sziebig [33] discussed how an industrial robot control could be shifted to more human- friendly interactions on the shop floor by using CogInfoCom-aided solutions. They also presented a shop-floor control architecture with various programming interfaces. In their approach, all actions in a manufacturing cell should be performed according to the STEP-NC standard, with tactile feedback assuming a significant role.

We have earlier presented our CogInfoCom-related experiences in mobile and industrial robot control and supervision [8]-[10]. Our experiences show that inter-cognitive communication is an important element in the development of engineering applications where natural and artificial cognitive systems need to work together efficiently. This simplifies human-robot interaction and may help even inexperienced operators to utilize robots with maximum efficiency.

B. Examples in Social Domain

The WSAN-based experiment on indoor air quality [34] confirms the importance of energy efficiency as a critical design parameter. In order to improve people's health, safety, and comfort, it is important to observe indoor air quality. Poor quality of the indoor air can cause headaches, dizziness, nausea, and eye and throat irritation. Previously, only carbon dioxide concentration was commonly controlled; however, in recent years, volatile organic compounds have also been used to characterize air quality. Another potential hazard is the toxic gases (e.g., carbon monoxide and methane) and substances leaks into the air. This emphasizes the need for the indoor toxic gas sensors capable of triggering an alarm to notify the people. The use of WSANs for this purpose enables to simplify the deployment and to reduce the costs as no power wiring or backbone infrastructure is required. The only downside is the limited energy available to these nodes. To prevent the frequent changes of battery, the ultra-low power nodes are required.

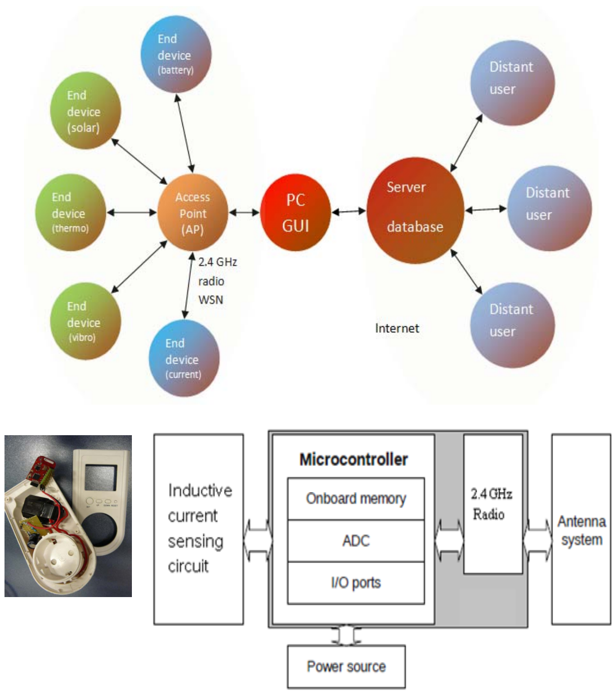


Fig. 4. The WSAN based IoT demonstrator for smart home: top – the structure of the demonstration, bottom – the prototype of a WSAN node for electric power consumption measurement.

In the Real Fusion project we have developed a home automation IoT solution depicted in Fig. 3 revealing the support for the specific home automation interfaces and the usage of different heterogeneous network connections. The demonstration featured a prototype for monitoring electric power consumption which can be used with the broad range of household devices. The power consumption is characterized by measuring the current inducted in the secondary circuit by the current of the primary circuit. This method's main advantage is that it does not require breaking the primary circuit for inserting measurement devices and thus does not add to the power consumption. The developed prototype (Fig. 4) was implemented as an electric CEE 7/4 socket and thus can be used for any type of electric household device. The prototype node was integrated with the WSAN node and was tested with various energy harvesting options (i.e., temperature, vibration, and light) for node's power supply.

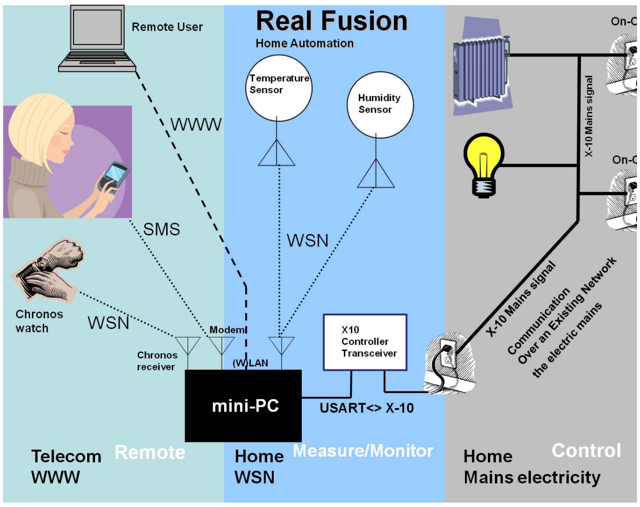


Fig. 3. The architecture of the IoT solution example for home automation.

The IoT allows the interconnection of smart objects and human beings by using different communication protocols and by developing a multimodal, heterogeneous dynamic network. The smart objects can be mobile robots, wireless sensors, etc. The IoT also opens up new social possibilities. Turcu and Turcu [35] introduced a social IoT model by integrating the RFID based cognitive robots within a social network. The proposed model enables extending the IoT's social potential from a local to a global level by merging local devices and social Web data.

We have earlier demonstrated easy guiding methods for co-worker robots. Our experiences include both industrial and service robot cases [8]-[10]. Our demonstrations show a variety of ways how inter-cognitive communication between human and artificial cognitive systems can be utilized in robotics. With service robots used in homes, the interaction may often be even more difficult than that with industrial robots, because of the dynamic social environments. Inexperienced users often do not understand the robots' internal states, intentions, actions, and expectations.

C. Examples in Environmental Domain

The WSANs used in geographic space that detect, monitor, and track environmental phenomena and processes are called geosensor networks and have its own specifics [36]. Quite often, the nodes composing the environmental WSAN are distributed over huge areas; this emphasizes the need for an effective localization of the nodes and geospatial data management. The Open Geospatial Consortium (OGC) standard components are introduced to collect, to handle, and to browse geosensor information [37]. In OGC standard, Extensible Markup Language (XML) is a key part of this infrastructure and all the services and content models are specified in XML schemas. Second, the low rate of the environment parameters (e.g., temperature or humidity) changing stresses the importance of the extremely low energy consumption of the nodes in sleep mode.

Our experimental results with geosensors [38]-[40] have demonstrated that the contemporary smartphones are a very effective and convenient solution for displaying the environmental data. Earlier paper describes how mobile devices can also act as a gateway between sensor nodes and the server of sensor observations service as well as log and store data. The approach of using a very lightweight protocol for the communication between a Bluetooth sensor and a mobile device combined with the sensor Web enablement protocol for publishing the data is a novel and has many benefits. Mobile phone with its processing capabilities could process messages and necessary protocol changes and included standard Web fields over lightweight proprietary protocol. On the one hand, the data collected by mobile devices is automatically converted to the universal format and becomes available for the sensor Web users. On the other hand, the users can use a wide range of the already developed and convenient for them applications to display or analyze the data on their mobile devices. These resent experimental results show that nowadays phones have enough capacity to fulfill these requirements to be used as a cognitive part of this system, both for protocol conversion and to visualization of sensor values for users. With these experimental studies, we have utilized mobile phone with its connections: near communication with Bluetooth, data storage and processing on the phone and database connection over cellular radio or WiFi. Locational awareness for sensor data could be covered by sensor added GPS-functionality [38] or complete message on the phone with its integrated GPS-chip [39].

For agriculture applications [41] we have demonstrated a system which obtained the data from various sources: farm equipment (agricultural vehicles) and soil measurements with a wireless geosensor network. For the data presentation, we have used the appropriate standards, namely ISO 11783 (also known as ISOBUS) for agricultural data and OGC standards [37] for soil measurements. Part 10 of the ISOBUS standard defines the data interchange between the farm management information system and the task controller process of the vehicle (tractor and implement device). The standard precisely defines the standardized data transfer and data transfer file in the XML format. The transfer of the actual XML files is not desirable when wireless radio communication methods are used since the larger data amount has the disadvantage of increased operational costs or a disturbingly long time spent on the data transfer. The binary format XML compression methods based on the OGC's SensorML standard and BXML, demonstrated in [17], are achievable for this purpose allowing the use of WSAN based radio communication. Our suggestion is to use the compressed XML data format to achieve convenient wireless transfer media while simultaneously minimizing resource and cost requirements. Another possible origin of spatial data comprises external sources such as meteorological databases or weather stations. Beyond the intra-cognitive communication from various spatial systems or devices, the precision agriculture case also has different inter-cognitive requirements due to the need for presenting the data to farmers and other stakeholders. We developed different user interfaces for farmers (or farming advisors) permitting those to handle, update, and analyze farm- specific or field-specific data. Besides, we developed the special interface for the other users, enabling those only to view specific data (e.g., crop yield or nutrient balance maps).

V. DISCUSSION AND CONCLUSION

The WSANs are the key enabler for the various IoT solutions in different application domains. The CogInfoCom aspects should be included when developing these solutions. Since the IoT is a very complex heterogeneous system utilizing variety of wired and wireless communication protocols, even the architectural choices and integration of different networks and interfaces require an in-depth understanding of the intra-cognitive communication aspects among these cognitive artifacts. The integration of the systems is beneficial and opens new perspectives when the system allows collaboration of objects with different capabilities.

When considering WSAN-enabled IoT systems and solutions, energy efficiency and reliability of wireless communications are the essential design aspects. The adaptive reactions to the changes in available energy sources and energy harvesting or congestion of radio channels show the importance of intra-cognitive communication allowing automated local decision-making policies without cognitive human users. Meanwhile, the user's inter-cognitive feedback is inevitably required to optimize the operation of the WSAN and to find the correct tradeoff between the consumed resources and the provided quality of service.

The role of infocommunications is more crucial and evident when examining experiences in and designs of IoT solutions in different domains or applications. Industrial robotic applications require intra-cognitive communication among individual members of a swarm of robots, as well as effective and intuitive inter-cognitive human-robot communication. In the social domain, home automation and its anticipated deeper integration with home security and infotainment devices require incorporating both intra-cognitive communication among devices and a simple, effective, and consistent user interface for inter-cognitive communication. The examples in the environmental domain reveal the need to design multiple inter-cognitive communication interfaces due to the wide variety of the requirements, expectations, and access rights of different human user groups.

ACKNOWLEDGMENT

The authors acknowledge everyone who participated in the development of our demonstration examples This work was carried out within the projects supported by the EU Structural Funds, the TE Centre for Northern Ostrobothnia, the Council of Oulu Region, the Finnish Funding Agency for Technology and Innovation (Tekes), Ylivieska Region, Nivala-Haapajärvi Region, and Haapavesi-Siikalatva Region.

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