Modular Wireless Sensor and Actuator Network Nodes with Plug-and-Play Module Connection

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***Abstract*—In the paper we introduce the new concept of the modular Wireless Sensor and Actuator Network (WSAN) Nodes with Plug-and-Play(P&P) module connection capability. Unlike the state-of-the-art solutions, our platform features modularity in both hardware and software domains, and supports automatic discovery and identification of the modules, which combined, enable automatic P&P modules identification and take in use. According to our vision, the new generation of the WSAN nodes might be built by stacking together the hardware P&P modules encapsulating various power supply sources, processing units, wired and wireless transceivers, sensors and actuators, peripheral devices or the sets of those. Once a node is assembled, the processing unit of the node identifies all attached modules, and downloads the necessary software drivers for working with those and the applications out of the network. In the paper, we introduce the concept, discuss the related challenges, present our hardware architecture solution, and report the first results on the implementation of the hardware testbed platform.**

Keywords*—*wireless sensor and actuator networks, WSN, WSAN, module, plug-and-play, dynamic structure, platform, Internet of Things

I. Introduction

In the recent years the advances in the sensors, actuators, low power embedded systems and wireless communication technologies boosted development and proliferation of Distributed Measurement and Control (DMC) applications based on the Wireless Sensors and Actuator Networks (WSANs). The low installation and maintenance costs, good scalability and high flexibility - are the major reasons making WSANs one of the key technologies for the future [1].

The contemporary WSANs are subject to the two opposite trends. On one hand, many WSAN applications require hundreds or even thousands of nodes being installed throughout the area of interest in order to reliably detect and classify the observed phenomena. In this case, the high efficiency, low cost of manufacturing, deploying and further service, are critical for the success of the application. For achieving this, engineers often rely on the point solutions, based on the use of specialized hardware, custom software and proprietary communication protocols optimized for the particular use-case scenarios. This results in low interoperability, flexibility and extensibility of the resulting systems. On the other hand, the nodes featuring universal architecture, communication and information encoding mechanisms, might be somewhat less effective, but enable easy extension, modification, and seamless integration of the different systems and applications. This is especially important for multidisciplinary and multipurpose systems, which are one of the corner stones of the emerging Internet of Things (IoT) concept [2].

In this study, we attempt to reconcile both trends. The specifics and the main contributions of this paper are 1) the suggested modular WSAN node concept with *plug-and-play (P&P) connection of the modules* and 2) the proposed hardware architecture and mechanisms enabling its implementation. We aim at enabling one to build the WSAN nodes with the desired functionality by combining together the P&P hardware *modules*, containing the different sensors, actuators, communication interfaces, power sources or other *peripherals*. Moreover, the solution provides the WSAN node's main processing unit with a universal mechanism for controlling the power consumption of the peripherals, which are available on the connected modules. This feature is especially beneficial for WSAN-based DMC applications, in which the nodes are often restricted in the available energy and require an effective energy management mechanism.

In the current paper we focus specifically on the concept and the hardware (HW) architectural solutions. In the further works we plan to discuss in details the other aspects related to the software (SW) architecture, communication mechanisms, networking aspects, and the algorithms for inter- and intranode optimizations based on the data about nodes' modules and peripherals.

II. Related works

Although the most widely used today HW WSAN platforms have the static structure (e.g., refer to [3]), few solutions featuring dynamic structure have been presented as well: [4]–[19]. To enable dynamic reconfiguration of the WSAN node's HW structure, the presented in [4]–[17] platforms are assembled out of the functional modules, number of which ranges between two (in [16]) and eight (in [13]). The different modules featuring the specific functionalities (e.g., temperature sensing, energy harvesting or additional memory) are attached to one or several core modules hosting the main processor and, optionally, a radio and a primary power source. By modifying the set of its modules, the functionality of a WSAN node can be adapted to address the needs of the particular application. Although this approach makes hardware assembly of a WSAN node much easier and enables easy re-use of the modules in different applications, the development of embedded SW for such nodes is still overly complex. The two major reasons causing this are: a) the absence of the module identification mechanisms for the reported platforms, and b) the wide diversity of the wired communication interfaces

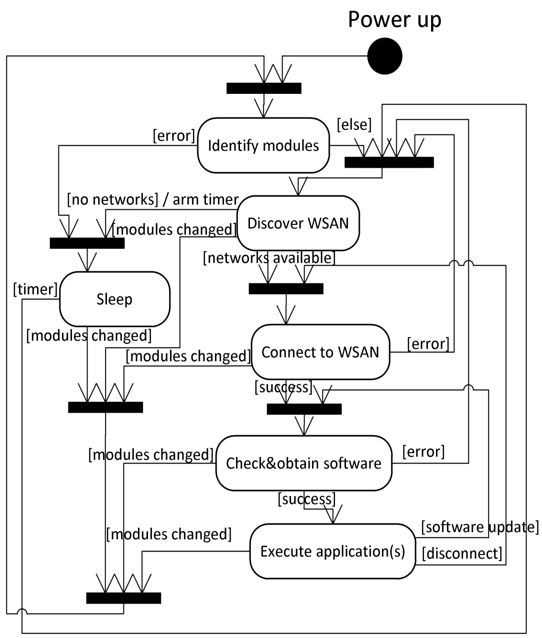

Fig. 1. Simplified state diagram of modular node's operation

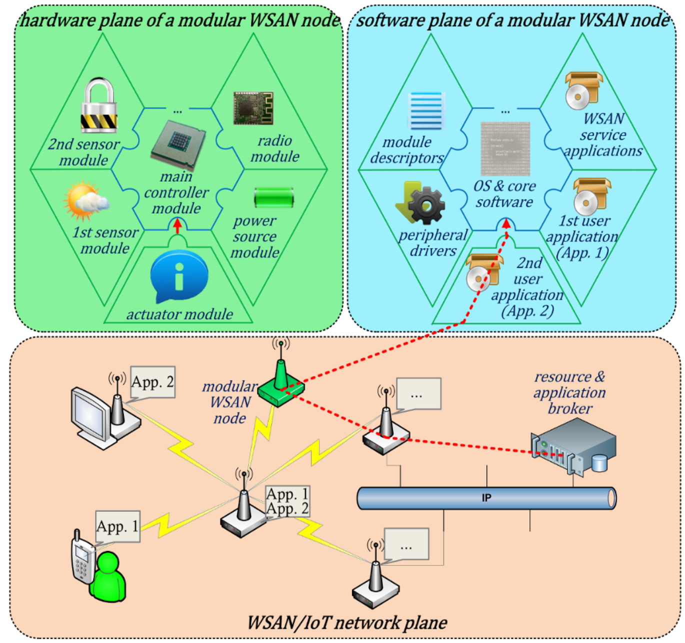

Fig. 2. Modular WSAN node concept

required for different modules. In the attempt to address this, the authors in [17] and [18] utilized the IEEE 1451 smart transducer interface. In [17] the authors divided the three major functionalities (namely communication, processing and interfacing to sensors/actuators) of a IEEE 1451 Transducer Interface Module (TIM) between the three hardware modules. In [18] the authors proposed to extend the IEEE 1451 by introducing the Energy Electronic Datasheet (EEDS), which would enable using IEEE 1451 not only for transducers, but also for the various power sources.

Unlike these works, in this paper we propose the modular WSAN nodes architecture featuring the P&P connectivity of the modules in terms of both HW and SW.

III. Proposed concept

According to our vision, the new generation of WSAN nodes might be built by stacking together the *HW P&P modules* encapsulating one or more *peripherals*, i.e., the power supply sources, processing units, wireless transceivers, sensors and actuators, or other devices (e.g., additional memory, encryption or localization engines, mobile chasis) or the sets of those. Once a node is assembled, the main processing unit (MPU) of the node automatically detects all attached modules, discovers the peripherals available on each module and their data communication interfaces. In the case if MPU does not possess the SW necessary for working with a specific peripheral (i.e., the peripheral "driver"), it can either try to get it from the module, or obtain it from the WSAN (see Fig. 1). The node should also feature the possibility of reporting its structure to the other nodes and network sink, discover the structures of the neighboring nodes, and support SW application downloading from WSAN. The key components of the proposed concept are depicted in Fig. 2.

Fig. 2 reveals that unlike the state-of-the art solutions, which are focusing mainly on the HW modularity, our approach brings together the HW and SW modularity to enable full-featured P&P module connectivity. Inevitably, this requires development of more complex mechanisms and introduces multiple new challenges to be solved. The three most significant are listed below.

The first challenge is the development of the HW architecture of the main board (hosting the MPU), the modules and the interface between those. The solution should enable all the discussed functionalities, but must be lightweight and effective enough to enable its use on WSAN nodes. Our solution for this problem is presented in Section IV.

The second problem is the SW architecture, and the mechanisms enabling SW downloads from a WSAN. Note the especial importance of ensuring the security and reliability of SW downloads.

Finally, the third set of challenges is related to the networking aspects of WSANs containing the modular nodes. We envision, that the major difference of these networks compared to the state-of-the-art ones would be the high diversity of the nodes in terms of the resources and capabilities available on various nodes. This inevitably requires the development of the new media access, routing and clustering solutions adapted to this scenario. Besides, the downloading of the SW drivers and applications from the WSAN also imposes some requirements on the architecture of the network.

Although we mostly leave the two latter points out of discussion in this paper, some related data can be found in Sections V and VI.

IV. Proposed hardware architecture

The simplified structural diagram of the proposed HW architecture is presented in Fig. 3. As one can see from Fig. 3, for connecting the main board and the modules we have introduced the new interface named Intelligent Modular

Periphery (IMP) Interface (IMPI). Functionally, the lines of IMPI can be divided into three major groups. First come the power supply lines, which are used for a) getting the power from the power source modules (*Vin* line) to the main board, and b) powering the other connected modules (*Vout* line). The second set of lines is reserved for the IMP-bus, which is intended for a) detecting the connected modules and their connection order b) enabling their identification and control over those. For this reason, each module is equipped with the special Module Control and Identification Unit (MCIU) which can be accessed through IMPI. The MCIUs store all the relevant information about the module and the set of peripherals available on the module. Optionally, MCIU can also provide MPU with the means enabling basic control over the peripherals, e.g., powering those on/off. Physically, the MCIU can be implemented on a microcontroller, programmable logic device (PLD) or any other digital device.

The IMP-bus is implemented as a daisy chain interface based on the efficient Serial Peripheral Interface (SPI) bus [20]. On one hand, this enables to simplify the implementation of the IMP bus by enabling one to use for this the SPI HW transceivers, which are an inevitable component of the contemporary microcontrollers. On the other hand, this enables easy discovery of the connected modules and their connection sequence. Using the designed communication protocol (which we leave aside due to the lack of space) and the IMP-bus, the MPU first detects the number of connected modules, their connection order, and reads out the number of peripherals on each module. Then the MPU retrieves from the MCIUs the peripheral description data (PDD) for each peripheral. The PDD is composed of two major blocks, namely the peripheral connection descriptor (PCD) and the peripheral service data (PSD). The former one lists all the communication interfaces used by a peripheral. The PSD provides the additional information about the peripheral (e.g., name, identifier, manufacturer, description, calibration data, SW drivers). Using the data from PCD, the MPU maps particular data interfaces (e.g., analog or GPIO pins, serial interfaces) to the specific modules and peripherals. Note, that this approach enables both reserving the interfaces for particular modules, and sharing the interfaces between different modules. To give an example, the first peripheral module depicted in Fig. 3 reserves 2 GPIO lines and UART, and shares SPI. Once all the data interfaces are mapped, the MPU can disable the IMP-bus and start communicating with the desired peripherals using the respective communication interfaces. Note, that to reduce the energy consumption, the MCIUs stay in the low-power sleep mode for most of the time and are activated by the MPU using the *SEL* line.

Although the proposed solution is somewhat similar to the one of IEEE 1451, there are a few crucial differences. First, our solution is not limited to any specific type of modules/peripherals and can be used for transducers, wired and wireless transceivers, power sources, etc. Second, our solution enables the modules containing multiple peripherals of different types (e.g., a single module might contain a radio, a battery and few transducers). On one hand this enables to reduce the number of the modules required for an application, on the other hand this also reduces the cost and power consumption of the modules. Third, our solution enables to control the power consumption of the peripherals via the IMP bus. Finally,

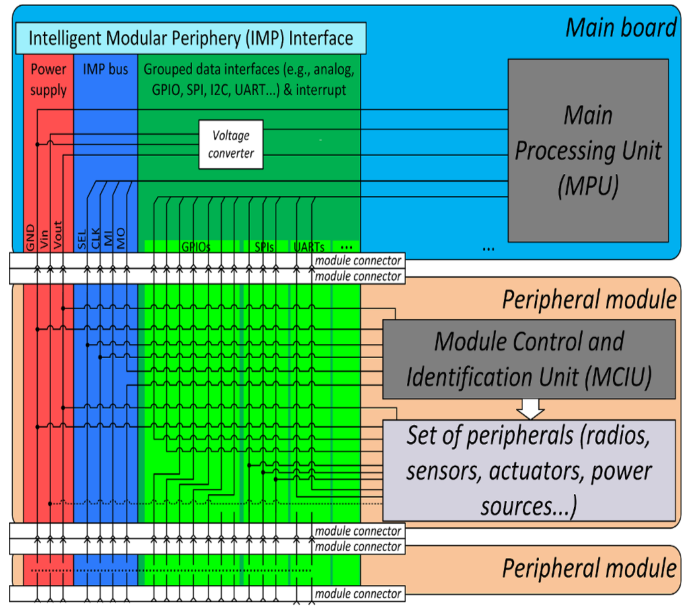

Fig. 3. Hardware architecture of the proposed modular WSAN platform

the separation of the data communication interfaces from the identification and control bus enables the MPU to parallelize the communication with different peripherals, thus simplifying the design and reducing the cost of modules.

V. Implementation

In order to test the proposed architecture under the real-world conditions, we have prototyped the main board and few peripheral modules (see Fig. 4). As the MPU on the main board we use the STs STM32F207 ARM-based 32-bit microcontroller running FreeRTOS operation system. Besides the MPU, the main board contains a voltage regulator circuitry, an SRAM, a real-time clock, few basic sensors, USB and JTAG connectors, and two 30-pin IMPI connectors. Note, that all the peripherals installed on the main board are considered by the MPU as ”virtual” modules (i.e., the PDD for those are pre-stored in the non-volatile memory of the MPU), which enables MPU SW to handle those exactly in the same way as the ”real” HW modules connected via IMPI.

Each IMPI connector features eight GPIO lines, one SPI, one I2C and one UART interface. The IMPI connectors are placed on the opposite sides of printed circuit board (PCB), which enables stacking the modules both upwards and downwards. Besides the main board, we have designed various peripheral module boards encapsulating the batteries, solar energy harvesting, IEEE 802.15.4 and proprietary radio transceivers, multi-channel analog-to-digital converter (ADC), various relays and sensors. As the MCIU on module boards we currently use low-cost and low-power TI MSP430G2453 microcontroller, which implements the the required IMPI functionalities in the SW and has the peripherals’ PDDs stored in its internal FLASH memory.

At a time, we have already implemented and tested the MPU SW implementing the IMPI communication, modules discovery, PDD access, and the control over peripherals (on/off

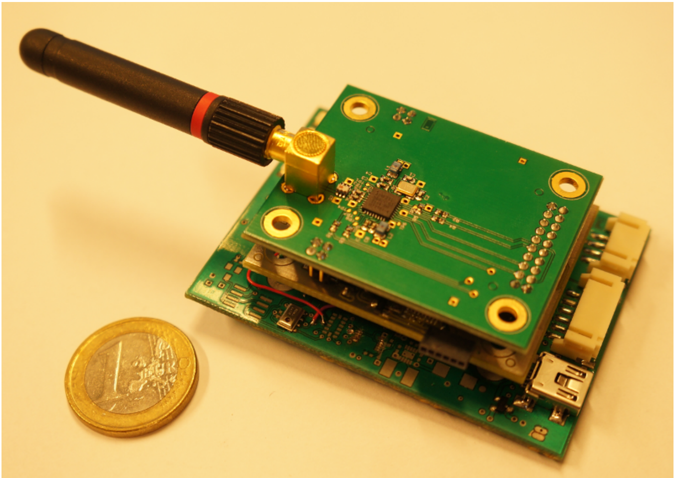

Fig. 4. Prototype of a modular WSAN node with radio and adapter modules attached to the main board

powering). Currently, we continue extending the core SW and are developing the peripheral drivers to be used with the different modules.

VI. Conclusions and further work

In the paper we have introduced the new concept of the modular WSAN node with plug-and-play(P&P) connection of the modules. Unlike the state-of-the-art solutions, our platform features modularity in both hardware and software domains, and supports automatic discovery of the modules, which combined, enable automatic P&P modules identification and take in use. In the paper, we have discussed in sufficient details the concept, proposed the new WSAN node hardware architecture, and reported the first results of the implementation of our platform.

The current work is just a first step on the way towards enabling the fully smart and autonomous WSAN/IoT nodes assembled out of P&P modules, and much work is still required. We plan to continue the work in multiple directions. First, we will continue developing the MPU software and will consider porting the core code to a microcontroller platform, more suitable for the applications featuring low energy consumption and computation load (e.g., Atmel AVR or TI MSP430). Second, we will continue with the design of the novel hardware modules and pay special attention to hardware miniaturization and cost reduction. Third, we intend to start the studies of the networking aspects related to the proposed modular platform and its use. Namely, these studies will focus on routing and clustering in the heterogeneous WSANs, and the mechanisms for obtaining and utilizing the data about the structure of the nodes on link, network and application layers.

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