Petracca et al. EURASIP Journal on Embedded Systems (2017) 2017:32
DOI 10.1186/s13639-017-0080-z

EURASIP Journal on Embedded Systems

RESEARCH Open Access

AMBER: Advanced Mother Board for Embedded systems pRototyping

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Abstract

The proliferation of low-cost embedded system platforms has allowed the creation of large communities of developers, as well as the development of new advanced applications. Even though some of these applications can be of industrial relevance, their immediate application to real products is not straightforward since most of them require a complete and expensive hardware redesign of the considered embedded solution. To speed up the technological transfer of custom embedded solutions while overtaking the limits imposed by a complete hardware redesign, the article presents AMBER, an innovative embedded platform leveraging on a design based on System-on-Modules (SOM) and Extender modules. AMBER decouples the processing part of the system, which is fully contained on the SOM, from the peripherals, which are contained on the main board and Extender modules. This allows a smooth industrial-oriented redesign of the embedded solution. In the article, AMBER is first presented starting from its philosophy and design choices while highlighting its main features. Then, an application of AMBER as an enhanced gateway to be used in the Industrial Internet of Things (IIoT) scenario is reported by considering a monitoring and actuation use case. The IIoT-oriented AMBER solution is hardware and software configured to support real-time communications with actuators compliant with the Powerlink standard, as well as to interact with sensors compliant with Bluetooth Low Energy. Performance results show the effectiveness of the proposed solution in the selected industrial scenario while promoting a fast and immediate transfer in new embedded products targeted to IIoT applications.

Keywords: Embedded system design, Fast prototyping, Industrial internet of things, IIoT gateway design

1 Introduction

In the last several years, the continuous progress in the electronic field, as well as the continuous decrease in prices of electronic components, has led to the introduction on the market of sophisticated and powerful embedded system platforms able to be used by a wide range of users. Platforms like Arduino [1], RaspberryPi [2], and BeagleBone [3] have allowed people to easily use and control an embedded platform with the aim of creating innovative and possibly high-value applications. Although this wide availability of popular embedded platforms has fostered the continuous development of communities of developers, with hundreds of applications developed and published, the use of such devices is still limited over the time to hobby purposes only. Most commercial products based on embedded devices usually do not use such boards as they are, as a complete hardware redesign is performed, even though software solutions made available by large communities of developers is often used. Concerning embedded devices based on microprocessors, in many cases, the hardware redesign is a necessary step to overtake the limits of a Single-Board Computer (SBC) design based approach that is at the base of such popular embedded platforms. On the other hand, to effectively enable fast prototyping of embedded devices for commercial purposes starting from popular development boards, an industrial-oriented design of such platforms is necessary, thus allowing companies reuse as much as they can the hardware components and exclusively prototyping non-critical parts only.

By following the aforementioned approach, this article presents an innovative Advanced Mother Board for Embedded systems pRototyping, the AMBER solution. AMBER [4] is an open embedded platform targeted to *modularity*, *flexibility*, and *scalability*, three main features

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which enable its use in a wide range of applications. Moreover, by adding an industrial-oriented design leveraging on new embedded system design trends, AMBER aims at filling the gap between solutions that can be used by technology enthusiasts and research laboratories and the industry. In this direction, AMBER enables a fast prototyping of industrial embedded solutions where only non-critical parts of the system can be redesigned. In this article, the AMBER board is first presented starting from its philosophy, then the main choices behind its realization are detailed. Finally, an application of AMBER as an enhanced gateway to be used in the Industrial Internet of Things (IIoT) [5] scenario is reported by considering a monitoring and actuation use case. In particular, the AMBER solution is hardware and software configured to read environmental data from Bluetooth Low Energy (BLE) [6] devices, while controlling actuators through a wired connection based on Powerlink [7].

The article is structured as follows: in Section 2, the most popular embedded platforms based on an SBC approach are presented like related works to be considered as a starting point to build an industrial-oriented platform. Section 3 details the AMBER solution starting from its philosophy, then its prototyped version with the main design choices is described. In Section 4, AMBER is presented as an IIoT gateway able to manage both wireless distributed sensors and industrial communication solutions based on the Powerlink standard. Conclusions and final remarks are reported in Section 5.

2 Related work

Single-board computer platforms can be considered microcomputers where a microprocessor, memory, peripherals, and possibly general purpose input/output pins (GPIOs) are embedded in a single printed circuit board. The use of a microprocessor-based architecture gives the possibility of running operating systems, thus allowing high-level programming of the device, enabling users to stay focused on the application instead of low-level programming. During the last few years, a large number of SBC platforms have been developed and commercialized. Most of these platforms fall into two categories based on the microprocessor architecture used: ARM and Intel x86.

Among SBCs based on ARM processors, the first platform to be cited is the RaspberryPi [2] which was first launched on the market in 2012. The latest version, released in 2016, is the RaspberryPi 3 [8], a platform based on a 64-bit ARMv8 microprocessor, and embedding 1 GB of RAM. Moreover, the platform integrates WiFi and BLE modules for applications requiring connectivity features. Several GPIOs are available to create possible extensions. Another popular platform is the BeagleBone [3] and in particular the BeagleBone Black [9] version. This board, released in 2013 embeds an AM335x ARM® Cortex®-A8 processor, 512 MB of RAM, 4 GB eMMC flash storage, and a large number of GPIOs. BeagleBone can be extended using custom boards commonly called capes by the community. Several capes have been developed over the years to add both wireless (e.g., WiFi, BLE, ZigBee) and wired (e.g., CAN, RS485) communication capabilities. Among other boards that have been introduced to the market but have not reached the popularity of the previous two are the Gumstix Poblano 43c [10] and the PandaBoard [11]. The Poblano 43c exploits the use of advanced processors, the AM4378 ARM® Cortex®-A9 while mounting 512 MB of RAM, WiFi module, and several connectors for additional modules. The Pandaboard platform in its ES release leverages on Cortex®-A9 MPCore capabilities by mounting 1 GB of RAM, wireless devices and several headers on which conventional communication buses are exported. Another SBC system to be cited is the Cubieboard [12], which mounts in its fifth and latest version an ARM® Cortex®-A7, 2 GB of RAM, 8 GB eMMC flash storage, an embedded communication module for WiFi and BLE, and a total of 70 GPIOs. Among boards with a new generation of microprocessors that must be cited is the SABRE Lite [13], officially released in 2011, which mounts an ARM® Cortex®-A9 microprocessor, the NXP i.MX6, 1 GB of RAM, and 2 GB of flash. No wireless modules are embedded, but they can be added by using the exported GPIOs. Latest powerful boards to be cited are the DragonBoard [14] and the NVIDIA Jetson TK1 [15]. The former is the first SBC device exploiting the new generation of microprocessors developed for the mobile market. In fact, the board mounts an ARM® Cortex®-A53 processor, which is on the basis of the Qualcomm Snapdragon 400 chipset used in a wide range of mobile phones. Moreover, the DragonBoard embeds 1 GB of RAM, 8 GB of eMMC flash memory, and an onboard integrated WiFi/BLE module. GPIOs are exported on a particular connector. Regarding the latter, the Jetson TK1, this is a solution introducing the possibility of performing GPU in the embedded domain. In fact, along with an ARM® Cortex®-A15 microprocessor, the board mounts an NVIDIA Kepler GPU. Several buses exported on GPIOs enable the connection of additional modules.

Regarding SBC platforms based on the Intel x86 architecture, only a few examples can be cited, since few solutions have been proposed over the years. The first platform to be cited is the ALIX, released in several versions as a solution to be used in advanced networking applications. In its sixth series, the Alix6f2 [16] hosts an AMD Geode LX800 processor, 256 MB of RAM, and several standard sockets to connect wireless communication modules. No GPIOS are made available, thus reducing the potential use of this device in other application domains.

Another platform recently proposed to the public, but not yet available on the market, is the UDOO x86 [17] which embeds, in its most powerful version, an Intel Pentium CPU, 8 GB of RAM, and 32 GB of flash memory. To build possible add-ons, 20 GPIOs multiplexed among several interfaces are available.

All reported boards are summarized in Table 1 where, along with the name of the device, all key features are detailed. As previously discussed, all these popular platforms are based on an SBC approach with the primary objective of attracting a large community of potential developers by following a mass production strategy to lower the final cost of the device. The result is the broad availability of software and application solutions in which companies can be interested. Although the software and the custom hardware prototypes made available by the community can be easily used to create new real products based on embedded devices, such hardware solutions exploiting new features based on additional and custom-developed modules cannot be used as they are. A complete hardware redesign is necessary to include new features (e.g., a sensor or a new communication module), thus facing on possible hardware design problems. To overcome these limitations and enable companies to reuse the hardware used in the prototyping step, this article presents the AMBER solution. By overtaking the limits of an SBC-based approach, AMBER exploits the new development trend based on System-on-Modules (SOMs) by enhancing this concept to reach advanced modularity features, while providing at the same time flexibility and scalability properties.

3 The AMBER solution

In this section, AMBER is presented starting from its philosophy, while highlighting its key features in enabling a fast prototyping of industrial embedded solutions. All provided features allow reusing as much as possible the custom hardware add-ons developed by the community with the corresponding developed software. After presenting the AMBER philosophy, the section analyzes and reports the hardware design choices behind the first prototype of the envisioned solution. The AMBER Board Support Package (BSP), the basic support code (i.e., bootloader, operating system, toolchain) to be used as starting point to create advanced high-level applications, is introduced in the last part of the section.

3.1 The philosophy

In today's scenario, most of the embedded solutions are based on an SBC design. Such platforms are composed of a single printed circuit where the microprocessor, the memory, and several peripherals are installed. While the computational part of the system is completely embedded on the platform, some extensions can be created by using available GPIOs. In this case, the development of a new and extended platform enabling new features requires redesigning the most critical part of the system: the processing part. For instance, considering the BeagleBone Black solution, analyzed in Section 2, several add-ons, the capes, have been created by the community. The development of an industrial-oriented solution fully integrating a developed cape would require a complete redesign of the system, including the processor and memory which require significant design due to the high-frequency buses used. To overcome the limits of an SBC-based design, AMBER aims at decoupling the processing components from the peripherals. Such approach is realized considering a System-on-Module based design concept. A SOM is a board level circuit that integrates primary system functions in a single module to be installed on a hosting mother board. The AMBER solution embraces this design concept and pushes them towards new levels introducing the possibility of creating board level circuits for additional peripherals: Extender modules to be plugged into the main board of the system. In a nutshell, AMBER can be defined as an advanced mother

Table 1 Popular SBC devices based on ARM and x86 architectures

SBC name	Processor	Cores	RAM [MB]	Flash [MB]	Ethernet [Mb/s]	Price [€]
RaspberryPi 3	ARM® Cortex®-A53	4	1024	0	100	35
BeagleBone Black	AM335x ARM® Cortex®-A8	1	512	4096	100	45
Poblano 43c	AM4378 ARM® Cortex®-A9	1	512	0	1000	180
PandaBoard ES	ARM® Cortex®-A9 MPCore	2	1024	0	100	170
Cubieboard5	ARM® Cortex®-A7	8	2048	8192	100	95
SABRE Lite	i.MX6 ARM® Cortex®-A9	4	1024	2048	1000	190
DragonBoard	ARM® Cortex®-A53	4	1024	8192	-	70
Jetson TK1	ARM® Cortex®-A15	4	2048	16384	1000	170
ALIX6f2	AMD Geode LX800	1	256	0	100	95
UDOO x86 ultra	Intel Pentium	4	8192	32768	1000	245

board for embedded systems prototyping aiming at filling the gap between solutions that can be used by technology enthusiasts, research laboratories, and the industry. The proposed AMBER approach, on the one hand, allows reaching an extreme *modularity* while, on the other hand, enables a fast prototyping of industrial solutions. In fact, by leveraging on SOMs, no critical parts of the system must be redesigned. SOMs with different features and prices are widely available on the market. Moreover, if an Extender module has been carefully designed and developed in a prototyping step, only the hosting main board solution needs to be developed to meet the industrial requirements, thus requiring an industrial-oriented customization of the AMBER solution. In its philosophy, AMBER proposes to leverage on Extender modules pluggable into sockets populated with a large number of communication buses. This approach allows AMBER to provide an extreme *flexibility* since a large number of electronic devices provided by different vendors can be used. Moreover, another interesting feature of the AMBER solution is the *scalability*. This feature is mainly enabled by the exploited SOM-based approach. In fact, SOM solutions exploiting multi-core architectures allow the use of AMBER in a large set of applications requiring different computational capabilities. The AMBER philosophy based on *System-on-Modules* and *Extender modules* is shown in Fig. 1 where a socket able to host the SOM, two sockets populated with Extender modules, and a third socket available for additional modules are reported.

In addition to the three main AMBER characteristics reported above: *modularity*, *flexibility*, and *scalability*, a fourth to be added is the *openness*. In fact, since AMBER aims at fostering the development of industrial solutions starting from systems developed by technology enthusiasts and research laboratories, it has been envisioned since the beginning as a fully open solution.

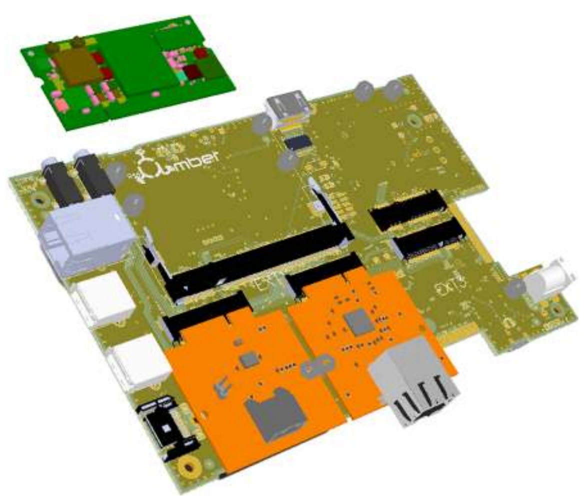

Fig. 1 AMBER conceptual model

3.2 The hardware design choices

Moving from design philosophy to real embedded solutions, several design choices must be done to reach tradeoffs among final costs, interest from the community, the lifetime of the solution, and ability to be updated. In this respect, the first implementation choice has been focused on the System-on-Module. The Variscite SOMs [18], and in particular those based on the NXP i.MX6 [19] family of microprocessors, have been selected among available solutions on the market. Such a choice is the result of analysis related to advantages and drawbacks in early standardization efforts, available architecture, prices, and product longevity. Moreover, Variscite is a worldwide leader in SOM design and manufacturing, thus being able to provide a broad range of solutions at low cost while guaranteeing more than 10 years of longevity. Although Variscite products do not support the recent released Qseven standard [20] aiming at standardizing the form factor and the communication buses to be exported on the SOM socket, the provided solutions embed on the SOM popular communication modules (e.g., WiFi, BLE). Moreover, thanks to a SOM design enhancing a full compatibility among solutions exploiting the same microprocessor architecture, multi-core capabilities can be easily exploited (i.e., a new SOM with the same pinout and embedding a microprocessor with a greater number of cores can work in a plug&play manner). All these characteristics make Variscite solutions very appealing to those customers willing to focus their attention on the software side of their products while using already embedded popular communication systems.

Concerning the Extender modules, instead, the attention has been mainly focused on the Extender socket definition, since the design of a new Extender module is something that should be realized by people willing to add a new feature. In any case, a correct and simple design of the Extender socket is necessary to foster and facilitate the development of new Extender modules. For this reason, a popular and low-cost socket connector has been considered, while exporting 50 GPIOs related to the following communication buses: I2C, SPI, UART, and USB. GPIOs related to MiniPCIe and Ethernet have not been exported on the Extender socket since they are considered conventional buses and interfaces to be hosted on the main board. AMBER hosts three Extender sockets to let developers combine several functionalities. Moreover, their number allow keeping the AMBER dimensions reasonable, thus allowing its installation in real laboratory testbeds.

The AMBER board in its prototype and finalized design is reported in Fig. 2. In the picture can be recognized the three Extender sockets able to host Extender modules, the SOM, in particular, the Variscite VAR-SOM-SOLO/DUAL CPU, and the MiniPCIe socket. In the Extender socket number 1 can be noticed a simple Extender module exporting all available buses and GPIOs, thus enabling a fast laboratory prototyping of new Extender modules from the community.

3.3 The BSP availability

The BSP plays a key role in the success and spread of a new embedded solution. If, on the one hand, the BSP must be an effective and powerful implementation of specific support code letting a complete software customization of the system, on the other hand, it must also be managed by non-expert users. The AMBER BSP enables a user to easily create a customized Linux distribution based on the 4.1.15 kernel version and the 2015.04 version of U-boot. Even though the selected Linux kernel is not one of the latest officially released, it is maintained by both NXP and Variscite, thus taking advantage from both communities of developers. Regarding the Linux distribution, two of them are supported in the AMBER BSP: Debian Jessie and Yocto with Morty core. The former is a popular distribution with a large availability of software packages for the ARM architecture, thus being a suitable solution for hobbyists and research laboratories willing to focus their attention on applications. The latter enables an advanced and optimized customization of the system. Yocto permits to create a custom Linux distribution by selecting necessary packages and recompiling them. Companies mainly use Linux distributions created through Yocto for the final commissioning of a developed solution. In addition to the two Linux distributions reported above, the Android Nougat 7.1.1 has been recently released. As for the hardware implementation, also the choice for the maintained BSP (U-boot, Kernel version, Linux distribution, Android version) goes in the direction of fostering an easy reuse of applications and functionalities to foster an immediate industrial reuse.

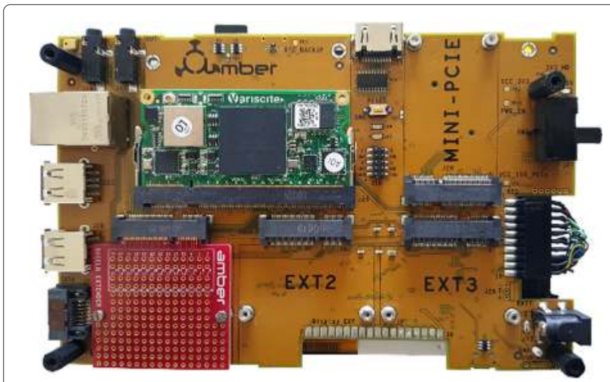

Fig. 2 AMBER prototype front side

4 AMBER as an IIoT gateway solution

In this section, AMBER is presented as an advanced gateway targeted to IIoT solutions, thus showing the key role that it can play in the development of innovative industrial systems leveraging on advanced Internet of Things (IoT) technologies. After an introduction related to IIoT, and the AMBER role in such a context, an industrial monitoring and control use case based on BLE and Powerlink technologies is described by detailing the whole system design and implementation. In the hardware and software implementation, a new developed Extender module is presented, thus showing how the main AMBER features can really foster an easy development of industrial solutions starting from research laboratory prototype. To prove the effectiveness of the implemented solution based on AMBER, time delay performance in monitoring and actuation are measured and reported from a laboratory testbed.

4.1 Industrial Internet of Things and AMBER role

In recent years the Internet popularity has experienced exponential growth, thus fostering in the academic and industrial communities the so-called IoT paradigm [21]. According to such a paradigm, in the near future, billion of devices will be part of the global Internet network to create smart environments in a significant number of scenarios, thus improving human lifestyle and efficiency in their working activities.

The use of IoT technologies in industrial environments is at the pillars of the fourth industrial revolution, known in the literature as Industry 4.0 [22, 23]. IIoT systems can be successfully used to create effective smart factories in which enhanced levels of efficiency can be reached. IoT devices can be pervasively used to collect data on the field with the aim of improving productivity through advanced automatic processes [24] and safety through a deeper knowledge of worker position [25] and reducing equipment faults through fast event detection capabilities [26]. Through the use of wireless and wired devices with monitoring and actuating capabilities, advanced applications avoiding the human-in-the-loop constraints can be created, thus moving towards effective cyber-physical-systems.

An advanced IIoT system with sensing and actuation capabilities is composed of three primary layers, from the bottom to the top: (i) the sensing and actuation layer, (ii) the gateway layer, and the (iii) server layer. Such architecture, depicted in Fig. 3, is a generalization of what is reported in [27] considering the whole intelligence distributed in all the components of the system, thus exploiting the so-called Fog Computing approach [28].

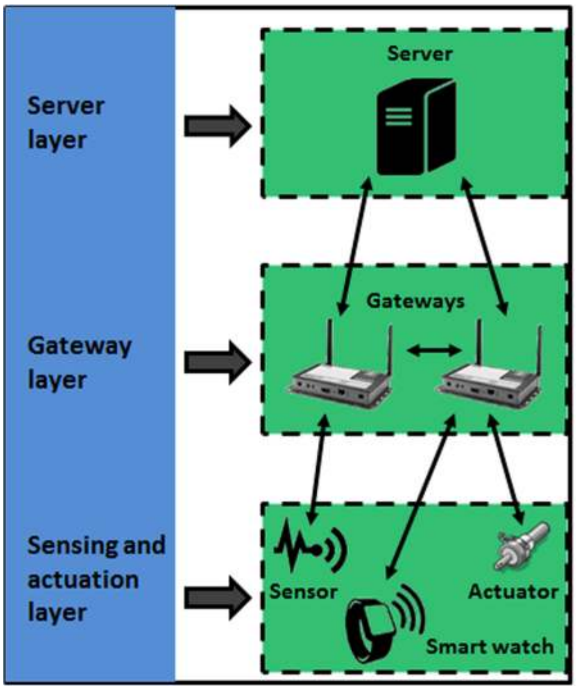

Fig. 3 Three layer IoT architecture

At the lowest layer, sensors, actuators, and other devices are considered to be smart objects, that is devices able to sense/actuate, process, and communicate, thus implementing part of the intelligence of the system according to their capabilities. At the gateway layer, instead, powerful devices are necessary to manage multiple communication technologies, both wired and wireless, as well as to perform advanced data analysis (i.e., machine learning algorithms, big data analysis) on a reduced time window, and real-time controls by leveraging on connected sensors and actuators. The greater the intelligence of the system implemented in the gateway, the faster the reaction against the occurrence of certain events. The upper layer is composed of server units able to store data collected by the two levels below, as well as to process them to extract advanced knowledge (i.e., long-term analysis). Ideally, such servers can reside in the cloud.

In the reported architecture, AMBER can be successfully used as an IoT gateway, since, how it has been reported in [29], it has all the necessary and required characteristics. Moreover, it can be easily and successfully used in an industrial scenario to develop advanced industrial control systems fully supporting the architecture depicted in Fig. 3. In fact, along with the capabilities of supporting multiple wireless technologies by developing specific Extender modules, AMBER is a suitable choice to control devices through wired field buses requiring real-time constraints. Thanks to proper Extender modules and low-level software adaptations, a wide number of industrial buses based on twisted pairs can be supported (e.g., Profibus, ModBus), as well as real-time Ethernet field buses (e.g., Powerlink, EtherCAT, Profinet).

4.2 Use case, system design, and implementation

In this article, AMBER is proposed as an IIoT gateway solution targeted to an industrial control system where the thermal control of critical equipment installed in the environment is necessary. An example is a production line in which several machines must be controlled in real-time, and afterwards, an additional thermal control making use of new generation wireless sensors is required to be installed. In this scenario, the gateway of the system must be able to manage and control all the installed actuators in real-time. Moreover, at the same time, it must receive data from wireless temperature sensors to react and take the proper action in the lowest amount of time (i.e., when the temperature of a sensor is above a certain threshold a motor in production line must be turned off to reach a safe condition). To notify of dangerous conditions in real-time to actuators compliant with new generation field buses based on Ethernet technology the Powerlink [30] standard has been selected. Moreover, battery-powered temperature sensors based on the Bluetooth Low Energy [31] technology have been considered to implement the monitoring part of the system.

Powerlink is an open-source industrial protocol designed and developed to reach reliable and deterministic real-time communications for automation. The main idea behind Powerlink is to avoid collisions over the Ethernet channel by introducing a master-slave approach. The bus master is the Managing Node (MN), while all the other nodes participating in the network are called Control Nodes (CN). The Powerlink standard acts cyclically with a bus cycle, is determined at configuration time, and divided into two phases. The former is the isochronous phase in which time critical information is sent from MN to CNs in a scheduled manner, thus avoiding collisions and meeting real-time constraints. The latter, instead, is the asynchronous phase in which all nodes can communicate to each other by using the standard Ethernet protocol. This phase is used to send non time-critical data. Bluetooth Low Energy is a wireless technology mainly developed to reach ultra low-power performance, thus being a suitable choice for a wide range of applications in which battery-powered devices require to be connected in a network. BLE applications range from healthcare, fitness, domotic to industrial applications, where new devices can be installed for retrofitting purposes. The BLE standard specifies the functionality for enabling bidirectional communications between two devices possibly acting as master or slave. Master nodes (e.g., laptop, smartphone, system gateways) usually scan for other devices, while a slave node sends data (e.g., sensor devices) whenever it is necessary. A slave is usually a battery-powered device in a sleep mode state, and it periodically wakes up to be discovered by a master.

In the considered use case, AMBER is configured as an IIoT gateway acting as MN node in the Powerlink network and master node in the wireless segment of the system. Moreover, to follow the architecture reported in Fig. 3, AMBER is wired connected to the Internet (i.e., connection towards the server layer) in order to publish possible events, or data, in remote servers. The high-level system design is depicted in Fig. 4 where at the center of the picture has been reported the AMBER with the necessary hardware modifications, some Powerlink actuators connected through Ethernet on the left, and BLE sensors on the right. From a hardware point of view, a new Extender module has been designed in order to enable an additional Gigabit Ethernet communication on AMBER. Such LAN Extender module is reported at the bottom of Fig. 5, while the top shows the IIoT AMBER mounting the extender. This additional Ethernet peripheral is used by AMBER to control Powerlink actuators, while the Texas Instruments Wilink WL183xMOD [32] module embedded in the selected Variscite SOM, the VAR-SOM-SOLO/DUAL based on a dual-core architecture, is used to interact with BLE sensors. Regarding the actuators, no real hardware solutions have been used in the laboratory implementation of the system since they are closed solutions in which no software customizations are possible to add special functions to be used for performance evaluation purposes (e.g., execution time measurements). To overcome this limitation, a laptop with a Linux OS has been used. Conversely, for the BLE segment of the system, real devices have been selected, in particular the TI Sensortag [33] device. Such a device is based on a new generation of microcontrollers, the TI CC2650 [34], implementing a double protocol stack: BLE [6] and IEEE802.15.4 [35]. Moreover, the device embeds several sensors (i.e., temperature, humidity, accelerometer, light, pressure), thus being a suitable solution to be used in a wide range of IoT applications. From a software point of view, AMBER runs a Debian Jessie distribution in which the openPowerlink [36] stack has been ported. Moreover, an application reading data from BLE sensors and sending actuation controls (AMBER is configured as a MN Powerlink node) upon the occurrence of a certain event (i.e., temperature value above a certain threshold) has been developed. The openPowerlink stack is executed even on the laptop acting as CN node in the Powerlink network. Regarding the BLE sensors, no software customizations have been developed, and the official TI code released with the devices have been used, thus focusing all development efforts on the AMBER application in charge of reading data from these sensors. Since the Powerlink stack runs as a microprocessor application, the LAN Extender is completely agnostic to the enhanced protocol mechanisms and it can be successfully used to support other real-time Ethernet field buses such as EtherCAT and Profinet.

Although in the described use case BLE sensors have been considered, thanks to the AMBER modularity and flexibility features, the envisioned IIoT system can be easily extended. In the industrial environment, a common standard used in wireless communications is the IEEE802.15.4. Such a standard is at the basis of WirelessHART [37] and 6LoWPAN-based [26] industrial monitoring solutions. To support IEEE802.15.4 based communications, while enhancing the monitoring part of the system, an additional extender can be plugged into available slots. The IEEE802.15.4 Extender reported in Fig. 6 leverages on AMBER modularity and flexibility by using an additional socket in which necessaries communication buses have been connected to support the selected transceiver.

Since additional IIoT interfaces and managing processes require additional computational resources, more powerful SOMs can be used, thus enabling scalability features in the proposed solution. For instance, the presented AMBER configuration targeted to IIoT scenarios can be

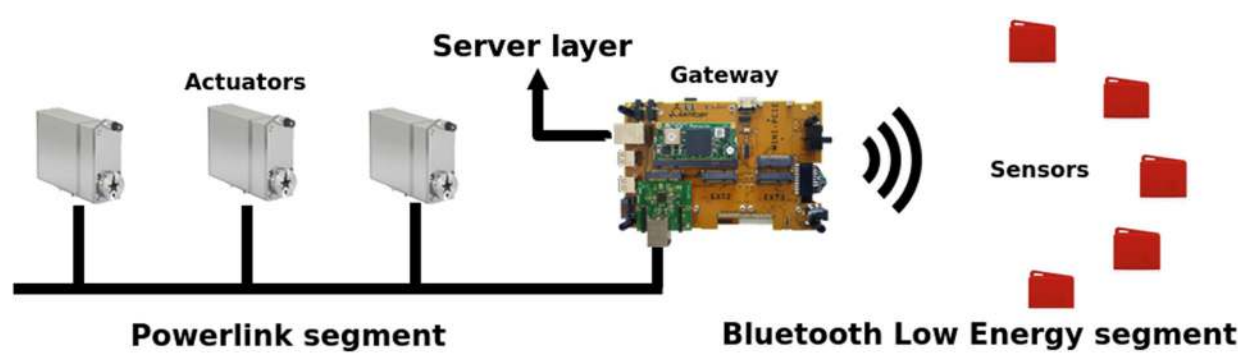

Fig. 4 IIoT solution system design

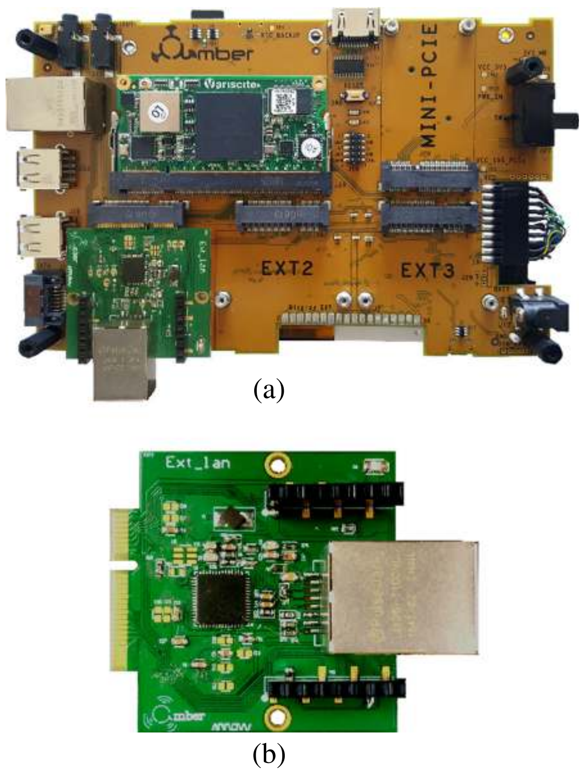

Fig. 5 IIoT AMBER components. **a** Amber with LAN extender. **b** LAN Extender

upgraded by using a quad core SOM, the Variscite VAR-SOM-MX6. Moreover, thanks to the AMBER modularity, higher scalability levels can be reached by considering Extenders embedding additional microprocessors or microcontrollers, thus exploiting hardware and software Asymmetric Multi-Processor (AMP) solutions [38].

4.3 Performance evaluation

Since the whole system has been targeted to a monitoring and control IIoT use case in which a thermal criticality triggers an actuation event, a key parameter to evaluate is the actuation time delay. This key performance parameter, evaluated as the time from which the temperature data request is sent until the actuation is performed, is a global indication of the system responsiveness. To measure the actuation time delay, all the components of the system (i.e., AMBER and the laptop emulating the actuator) have been synchronized by means of an external NTP (Network Time Protocol) server. Moreover, the Powerlink network has been configured with a cycle time of 100 ms (isochronous plus asynchronous phases). More than 1000 experiments have been executed, and all results are summarized by the histogram reported in Fig. 7. The reported actuation time delay includes the time to perform the temperature request to a particular sensor, the time to compare such a value with a priori imposed threshold, and the time in which the actuation notification reaches the laptop emulating the actuator node of the Powerlink network. In a real application, an additional delay due to the actuator response time must be considered. For instance, considering electromechanical actuators characterized by response times less than 12 ms [39], such a value can be added to results in Fig. 7 to perform a worst case analysis of the system.

The actuation time delay distribution presents a Gaussian shape with a mean value close to 235 ms. A worst case analysis of the reported results shows that the highest delay is lower than 268 ms. Such a value proves the high degree of responsiveness of the system, as well as the likely choice of using AMBER as IIoT gateway solution. It must be stressed again that despite the fact that the presented system has been developed for laboratory experimentation, the developed LAN Extender module and all the software can be easily reused to enable a fast prototype of a powerful and integrated industrial solution.

Fig. 6 IEEE802.15.4 Extender

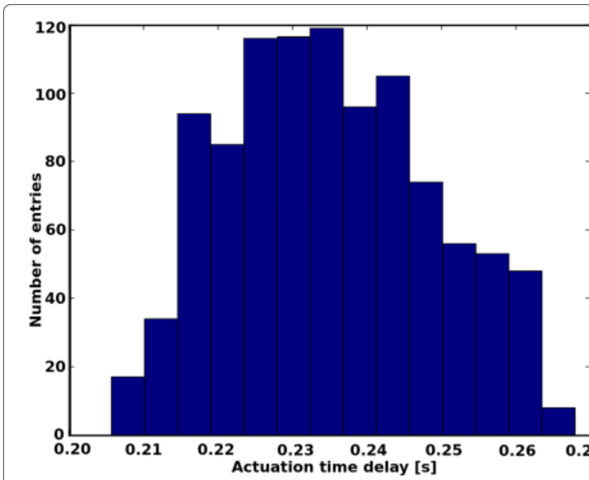

Fig. 7 Actuation time delay distribution

5 Conclusions

The continuous decrease in prices of the electronic components has fostered the spread of several embedded platforms mainly used by hobbyists and research laboratories to create new customized applications. Such a solution do not allow an immediate technology transfer towards the industry since an expensive redesign of the hardware components is required. To overcome these limitations, the article presents AMBER, an innovative embedded platform leveraging on System-on-Modules and Extender modules design. By decoupling the processing part of the system hosted in the SOM from the peripherals, hosted on the main board and the Extender modules, an industrial redesign of the whole system can be easily allowed, thus fostering an industrial reuse of results provided by developers communities and research laboratories. Thanks to its envisioned philosophy and design choices, AMBER provides modularity, flexibility, and scalability features. All these characteristics make AMBER an effective choice in a wide range of applications.

Considering the new, exciting, and challenging IIoT scenario, the article presents the AMBER as an innovative gateway solution to be used to interact with both wireless sensors and wired actuators that require real-time constraints. In the paper, the IIoT AMBER is presented as an effective solution able to control actuators compliant with the Powerlink standard, as well as to read data from Bluetooth Low Energy sensors, thus implementing a thermal monitoring and control use case. For the envisioned application, a new Extender module has been developed, and a real laboratory testbed has been created with the aim of evaluating the actuation time delay, a key parameter to determine the responsiveness of the system in the selected scenario. Performance results show that the whole system based on AMBER is able to trigger an actuation event against a critical situation in less than 268 ms. Such a value proves the capabilities and the potentialities of AMBER in industrial scenarios. Moreover, thanks to its design, all the hardware and software developed to create the IIoT AMBER used in the laboratory testbed can be easily reused to enable a fast prototype of a powerful, integrated, and effective industrial solution.

Authors' contributions
The authors contributed equally to every part of this work. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

Publisher's Note

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Received: 22 April 2017 Accepted: 5 September 2017
Published online: 13 September 2017

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