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A Review of Low-End, Middle-End, and High-End Iot Devices

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ABSTRACT Internet of Things (IoT) devices play a crucial role in the overall development of IoT in providing countless applications in various areas. Due to the increasing interest and rapid technological growth of sensor technology, which have certainly revolutionized the way we live today, a need to provide a detailed analysis of the embedded platforms and boards is consequential. This paper presents a comprehensive survey of the recent and most-widely used commercial and research embedded systems and boards in different classification emphasizing their key attributes including processing and memory capabilities, security features, connectivity and communication interfaces, size, cost and appearance, operating system support, power specifications, and battery life and listing some interesting projects for each device. Through this exploration and discussion, readers can have an overall understanding on this area and foster more subsequent studies.

INDEX TERMS Internet of Things, embedded systems, hardware platform, microcontrollers, microprocessors, operating systems.

I. INTRODUCTION

It is not news that Internet of things (IoT) has enormous potential for value creation and is being signalled as the next stage in the hyper-digitization of our world. It is a growing trend where all devices that can benefit from a connection will be connected to one another in a smart, energy-efficient and cost-effective manner, thereby revolutionizing ways in which individuals and organizations interact with the physical world as well as among themselves. IoT has great potential to impact our lives, where its application domains stems from various sectors such as health care systems, smart grids, transportation systems, industrial and automation, agriculture, just to mention a few [1]–[4].

According to GSMA Intelligence,[1] it is forecasted that there will be about 25 billion IoT devices by 2025. The practical realization of this vision, requires the development of a number of new versions of IoT devices, platforms and technologies. IoT devices play a crucial role in the overall development of the IoT as they are typically small in size, combining microcontrollers and microprocessors with other components, such as memory, I/O, peripherals and wireless connectivity chips in a pre-built, ready to program package.

IoT devices can be open source hardware or proprietary. The existence of well-established IoT standards have intrigued manufactures to create open hardware platforms. The specifications such as PCB schematics are publicly available for everyone to study, reproduce and modify to suit their various purpose in the open source hardware whereas proprietary IoT boards schematics are usually a guarded secret, in which users are not allowed to have access to the design details. This is a major difference between the open source hardware and proprietary hardware. The open source hardware devices have active communities, and are supported by majority of the operating systems (OS).

IoT devices can range from smartphones to RFID readers, wearable devices to tablets, gadgets, just to mention a few. Within the context of this paper, we will only focus on embedded systems and boards that facilitate the provision of extracting information from the environment routing over the network to the cloud. This article classify IoT devices into three categories: Low-end IoT devices, Middle-end IoT devices, High-end IoT devices.

[1] https://www.gsmaintelligence.com/

TABLE 1. Classes of low-end devices.

Specifications	Class 0	Class 1	Class 2
RAM	$\ll$ 10kB	$\approx$ 10kB	$\approx$ 50kB
Flash	$\ll$ 100kB	$\approx$ 100kB	$\approx$ 250kB
RTOS support	Devices do not support RTOS	RTOS could be implemented in these devices	RTOS can be operated
Communication protocols	No protocol stack embedded, use gateways for communication	Communicate via lightweight protocols such as CoAP (Constrained Application Protocol). They can communicate with other devices without the help of gateways	Communication protocols such as HTTP are supported
Security Vulnerabilities	Data compromise will result in a basic threat	Data compromise will result in medium threat	Data compromise will result in medium/high threat

1) LOW-END IOT DEVICES

Low-End IoT devices are devices that are constrained in terms of resources. The term constrained devices [5] was introduced to define a group of connected devices that are resource challenged. Low-end IoT devices are too constrained in terms of resources to run traditional OS such as Linux or Windows 10 IoT Core. Their Random Access Memory (RAM) and flash are of tens or hundreds of kilobytes and the processing unit is a 8-bit or 16-bit architecture with some state-of-the-art devices supporting 32-bit architecture. These devices are primary manufactured for basic sensing and actuating applications, and are programmed either by using low-level firmware or a very low functionality Wireless Sensor Networks (WSN) OS. An example of a low-end IoT device is the OpenMote-B and Atmel SAMR21 Xplained-Pro. These devices have been involved in various IoT applications [6], [7]. The Internet Engineering Task force (IETF) standardized the classification [5] of such devices into three subcategories.[2] Table 1 shows the classes of low-end IoT devices.

2) MIDDLE-END IOT DEVICE

Middle-end IoT devices are devices with less constrained resources compared to a high-end IoT device described in Section I-.3, but providing more features with greater processing capabilities opposed to low-end IoT devices. There are some processing capabilities in the middle-end IoT device such as image recognition by running low-level computer vision algorithms. Furthermore, middle-end IoT devices can house more than one communication technologies unlike many of the low-end devices. The devices in this category usually have their clock speed and RAM in the range of hundreds of MHz and KB respectively compare to low-end devices that have their clock speed and RAM in tens of MHz and KB respectively. An example of the middle-end IoT devices are the Arduino Yun, Netduino devices etc. Interesting projects have been developed through middle-end IoT devices [8]–[10].

[2]The classification by IETF are based on memory capacity, however, other classifications are described in Table 1

3) HIGH-END IOT DEVICE

High-end IoT devices are devices, mostly Single Board Computers (SBC) that have enough resources, such as a powerful processing unit, a lot of RAM and a possible high storage volume with a possible Graphical Processing Unit, to run a traditional OS such as Linux, Windows 10 IoT Core etc. In addition, these devices can perform tentative computations such as executing heavy Machine Learning algorithms. An example of such a device is the Raspberry Pi. These devices are well-known for their on-board connectivity including FastEthernet/GigaEthernet interfaces, Wi-Fi/BT chipset, HDMI out interface, more than one full USB 2.0 ports. Moreover, with the increasing usage of multimedia applications, majority of these devices come with camera interfaces such as Camera Serial Interface (CSI) and Display Serial Interface (DSI). Various interesting projects [11]–[13] demonstrate the usage of high-end IoT devices. These devices are often used as IoT gateways because of their high level of resources, making them to accommodate new services such as intelligent analytics at the edge of the network. We are only focusing on embedded systems and boards as smartphones are also regarded as high-end IoT devices. Figure 1 illustrates the classification of IoT devices.

Despite the key role of IoT devices in the development of IoT, there are very few works in the literature that have demonstrated about the underlying hardware that enables the IoT applications, since most attention for IoT has been focused on its application domains, its services, cloud solutions, business solutions, IoT technologies as well as IoT security [14]. This article presents a comprehensive survey of the recent and most-widely used embedded systems and boards, focusing on key attributes including processing and memory capabilities, security features, connectivity and communication interfaces, size, cost and appearance, OS support, power specifications and battery life and listing some interesting projects for each device. These features are essential in choosing the appropriate IoT device, thus enabling designers and developers to make the right choice. A list of abbreviations is provided in Table 2 whereas Table 3 provides a comparison of this study and already existing surveys on IoT devices.

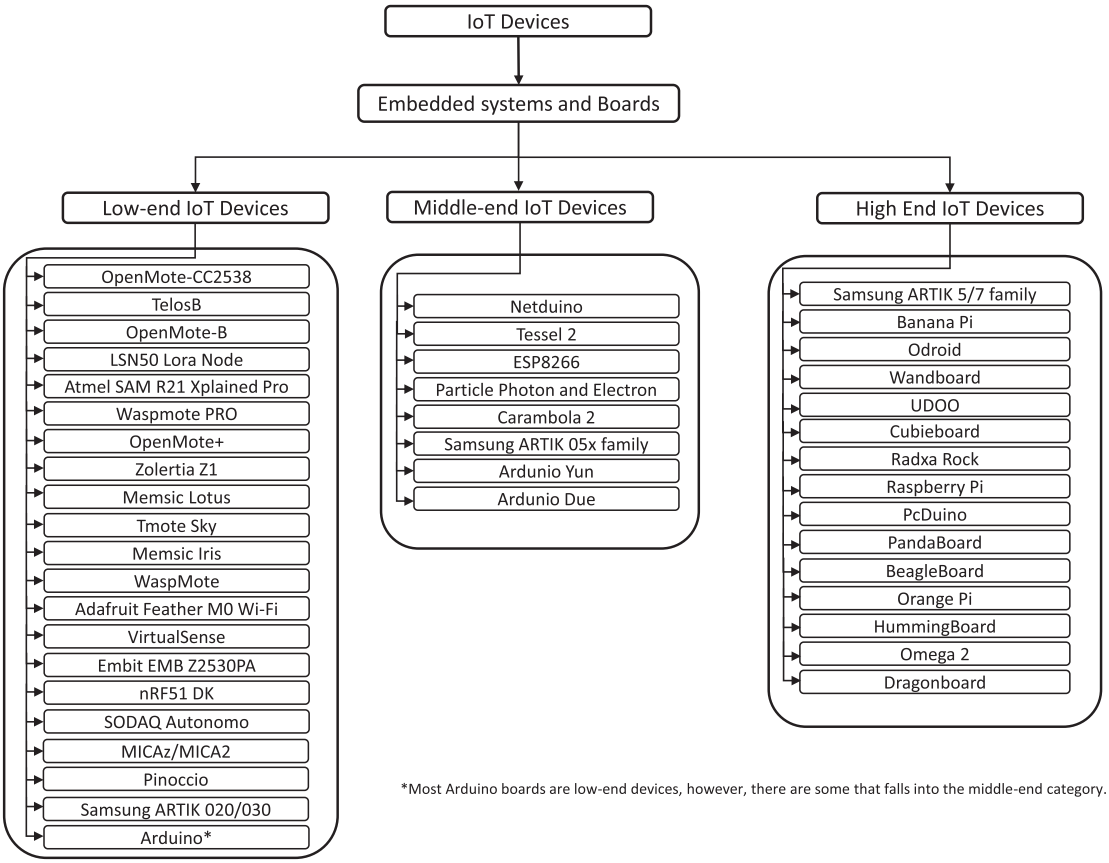


FIGURE 1. IoT hardware classification.

IoT devices can also be differentiated based on microprocessor-based devices and microcontroller-based devices. Microprocessor-based devices are considered as a specialized computer with a lot of processing power that can run a full operating system. They have a lot of memory and can run several programs simultaneously with easy Internet connectivity and are relatively easy to program with different languages and tools. However, they are very expensive with high power consumption. Example of these devices are Beaglebone, Odroid etc.

Microcontroller-based board is a single integrated circuit (IC) that houses several components such as processing unit, memory, programmable I/O peripherals. They are often cheap with limited processing power, memory and connectivity. An example is Arduino MKR1000. It is relevant to mention that microcontroller depending on the form factor (dimension), RAM, flash, power, etc., can be produced in hundreds of different versions. For instance, STM32 comprises of hundreds of different versions.

The remainder of this paper is organized as follows: Section II describes the related work. Section III discusses the major concerns in IoT hardware design. Section IV reviews the recent and most widely used low-end IoT devices capturing the comparison between them illustrating their used cases. In Section V, we look into a broad range of middle-end and high-end IoT devices with comparison in terms of computing, connectivity, communication among others. We discuss about the open research issues and future directions in Section VI and finally in Section VII, we conclude the paper with some final remarks.

II. RELATED WORKS

The number of survey papers related to IoT devices is very limited despite IoT versatility in various areas. This work is unique as there are no surveys that focus entirely on the recent and the most widely used low-end, middle-end, high-end IoT devices. We compare our work to the existing body of research, then we see the following. There are limited survey papers that focuses on low-end IoT devices [15]–[18]. The work in [15] is identified as the pioneering work that provided a comparative study of sensor nodes presenting their energy management techniques, battery types, processing unit and radio devices. Healy *et al.* [16], Johnson *et al.* [17] followed the same approach by providing a survey on the sensor nodes and analyzing the sensor nodes under different parameters including processing ability, expected lifetime and measurements. However, a survey of selected sensor nodes that are widely used in agriculture is presented in [18]. Hahm *et al.* [19] provided the basic requirements for a low-end IoT device, with notable few mentions. Their work

TABLE 2. List of abbreviations.

Symbols	Description
ACE	AXI Coherency Extensions
ADC	Analog-to-Digital Converter
AMBA	Advanced Microcontroller Bus Architecture
ARM	Advanced RISC Machines
AV	Audio Visual
AXI	Advance Extensible Interface
BLE	Bluetooth Low Energy
BT	Bluetooth
CoAP	Constrained Application Protocol
CSI	Camera Serial Interface
CPU	Central Processing Unit
DAC	Digital-to-Analog Converter
DDR	Double Data Rate
DSI	Display Serial Interface
DSP	Digital Signal Processor
eDP	Embedded DisplayPort
EEPROM	Electrically Erasable Programmable Read-Only Memory
eMMC	embedded Multi-Media Controller
FPGA	Field Programmable Gate Array
GCC	GNU Compiler Collection
GPIO	General Purpose Input/Output
GPS	Global Positioning System
GPU	Graphics Processing Unit
HDMI	High-Definition Multimedia Interface
HMP	Heterogeneous Multiprocessing
HTTP	Hypertext Transfer Protocol
I/O	Input/Output
I2C	Inter-Integrated Circuit
I2S	Inter-IC Sound
IC	Integrated Circuit
IETF	Internet Engineering Task Force
LiPo	Lithium Polymer
LPDDR	Low Power Double Data Rate
LVDS	Low-Voltage Differential Signaling
MiniDP++	Mini DisplayPort
MIPI	Mobile Industry Processor Interface
MIPS	Million Instructions Per Second
MQTT	Message Queuing Telemetry Transport
NFC	Near Field Communication
PCB	Printed Circuit Board
Pmod	Peripheral Module Interface
PWM	Pulse Width Modulation
PRU	Programmable Real-Time Unit
RISC	Reduced Instruction Set Computer
RTC	Real Time Clock
RTOS	Real-Time Operating System
SATA	Serial Advanced Technology Architecture
SBC	Single Board Computer
SD	Secure Digital
SDRAM	Synchronous Dynamic Random Access Memory
SIMD	Single Instruction stream, Multiple Data stream
SISO	Single-Input Single-Output System
SMP	Symmetric Multiprocessing
SoC	System on Chip
SPDIF	Sony/Philips Digital Interface
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory
SSL	Secure Sockets Layer
TLS	Transport Layer Security
TTL	Transistor-Transistor Logic
UART	Universal Asynchronous Receiver Transmitter
USB	Universal Serial Bus
USB OTG	USB On-The-Go
VOIP	Voice Over Internet Protocol
WiSOC	Wireless System-On-A-Chip
WKP	Wake Up Pin
WLAN	Wireless Local Area Network
XADC	Xilinx Analog Mixed Signal Module

deliberates more on the OS for low-end IoT devices. However, a new set of survey is long overdue due to many contemporary features that have been introduced.

There are several articles that covered specific hardware boards such as Raspberry Pi, Beagleboard, Odroid [20]–[22]. Maksimović textitet al. [20] focused on Raspberry Pi by making a comparative study of its performance and constraints in terms of power, memory and flexibility. Nayyar and Puri [21] provided a comprehensive review of the Beaglebone technology, with surveys of the Beaglebone boards in terms of their features and specifications to show insight for application developers. In [22], several experiments were carried out on Odroid-XU3 board, to demonstrate its performance in terms of power and energy consumption. The works in [20]–[22] only covered specific boards and moreover majority of the used boards are outdated, and many new features have been introduced. Hence, the need for this survey to update the previous study.

There are very few works [23]–[25] that provided a set of survey for IoT hardware platforms. Isikdag [23] presented the different types of SBCs that can be used for acquiring and presenting indoor information. Inácio *et al.* [24] and Singh and Kapoor [25] provided various IoT device attributes of IoT hardware platforms including processing, memory, OSs. The work in [23]–[25] only provided few and limited hardware domains and not in detail, and moreover, many new features have been introduced for IoT devices.

To fill this gap, in this paper, we provide a comprehensive survey of low-end, middle-end and high-end IoT devices. This is a survey that studies both SBC and microcontroller-based boards. We classify, detail and compare these devices based on communication, connectivity, interfaces, computing, security, OSs, size among others. We hope that our discussion and exploration can give readers an overall understanding on this area and foster more subsequent studies.

III. MAJOR CONCERNS IN IOT HARDWARE DESIGN

In this section, we give an overview of the diverse requirements IoT devices should aim to satisfy.

A. PROCESSING AND MEMORY CAPABILITIES

Processing unit and memory capabilities are the basic essential features embedded devices must possess to perform the basic task required for a IoT device. The processing unit and memory capabilities for an embedded device is largely influenced by the type of sensing, communication, processing for the target IoT applications [27]. For example, high complex systems require high computational processing for performing high-resolution sound or video streams while limited amount of processing is required to perform the basic function such as temperature and pressure monitoring.

Similarly, for the processing capabilities, the amount and type of memory of an embedded board impacts the performance of the IoT device. IoT device memory are of different types: Traditional External Flash Memory (NAND flash and NOR flash), Embedded flash memory, multichip package

TABLE 3. Overview of comparison between this study and available surveys.

Contributions	This paper	Vieira et.al [15]	Healy et.al [16]	Johnson et.al [17]	Hahm et.al [19]	Isikday [23]	Inacia et.al [24]	Singh et.al [25]	Karray et.al [26]
Year		2003	2008	2009	2016	2015	2017	2017	2018
IoT Overview	✔	≃	≃	≃	✔	✘	✔	✘	✔
IoT Hardware Requirements	✔	≃	≃	≃	✔	✘	✔	✘	✔
Review of low-end IoT devices	✔	✔	✔	✔	✔	✘	✘	✘	✔
Review of middle and high-end IoT devices	✔	✘	✘	✘	✘	✔	✔	✔	✘
List of projects	✔	✘	✘	✘	✘	✘	✘	✔	✘
Open Challenges, Recommendation and Future technologies	✔	✘	✘	✘	✘	✘	✔	✘	✔

✔: Topics covered ≃: Topics partially covered ✘: Topics not covered

memory and multimedia cards [28]. NAND flash is suited for data heavy application such as wearable devices because of its flexibility, capacity and density. NOR flash on the other hand supports execution in place (XIP) with frequently changing small data storage. Embedded flash memory is becoming very common in the IoT, given its high levels of performance and density, which is compatible with most microcontroller applications. Multichip Package Memory (MCM) offer more density for IoT devices as it combines the CPU, GPU, memory and flash storage in one chip. Lastly multimedia cards specifically use designed controllers, allowing for better integration into application systems. They come at reasonable costs with excellent performance and low power operation. We briefly describe some definitions of terms that will be relevant in the rest of the paper.

Random Access Memory (RAM) is a volatile memory, which means that the stored information is lost after the device is switched off, it is used by the processing unit to store information that needs to be accessed.

Static RAM (SRAM) is a type of RAM that holds data in a static form as long as power is being supplied. It is fast and expensive as it is mostly used as integrated RAM in microcontrollers or as L1/L2 cache in microprocessors.

Synchronous Dynamic RAM (SDRAM) is a type of dynamic RAM that is synchronized with the clock speed of the microprocessor, which increases the number of instructions per second that can be performed.

Double Data Rate (DDR) is the newer version of SDRAM. The main difference between SDRAM and DDR is the amount of data it can send. DDR transmits data twice in a clock-cycle while it only occur once per clock-cycle in SDRAM.

Embedded Multimedia Card (eMMC) is an internal storage technology for smartphones and tablets using the Multimedia Card standard. Supporting error correction in hardware an eMMC chip contains a controller and flash memory.

B. COMMUNICATION AND CONNECTIVITY INTERFACES

Communication and Connectivity Interfaces are very important in choosing the IoT device to use [29]. IoT devices interact with the physical world through peripherals that enable sensor input or actuator output. For example, in determining the sensitivity of a motion, your device must contain an accelerometer or a gyro. The choice of I/O components or peripherals is related to the type of information they are associated with. IoT hardware platforms use several common interfaces. These interfaces define a method of communicating between a peripheral and the processing unit. Any device not being part of the board can be attached by interfacing with peripherals. Sensors such as pressure, temperature, heat etc., and actuators such as relay, motor etc., or any other devices such as RFID tag reader, display can be attached to a board with the use of peripherals. GPIO, PWM, USB, I2C, SPI, UART, ADC, DAC are widely used interfaces found in IoT hardware platforms [30]. We briefly describe some definitions of terms used in this section.

General Purpose Input/Output (GPIO) provides low-level general input and output through digital pins directly connected to the processor. Each pin can be freely set to function as either an input or an output. For instance, as an input port, it can be used to communicate to the CPU, the digital readings received from sensors. As an output port, it can be used to drive outside operations based on CPU instructions. GPIO interface is flexible and simple as possible to allow for easy implementation and maximum portability.

Pulse Width Modulation (PWM) is a method for generating an analog signal using a digital source. A PWM signal consists of two main components that define its behaviour: a duty cycle and a frequency. The duty cycle describes the amount of time the signal is in a high (on) state as a percentage of the total time it takes to complete one cycle. The frequency determines how fast the PWM completes a cycle (i.e. 1000 Hz would be 1000 cycles per second), and therefore how fast it switches between high and low states. In other words, PWM is a way of controlling analog devices with a digital output. PWM are used for a wide variety of control applications. They are often used to control valves, pumps, hydraulics, and other mechanical parts.

Analog to Digital Conversion (ADC) is a system that converts an analog voltage to a digital value. The analog voltage such as sine waves etc. varies among a theoretically infinite number of values whereas the digital value has a defined level or state.

Digital to Analog Conversion (DAC) converts digital value to analog voltage. It is often less common because it often results to degradation of the signal, which can be minimized by using good quality hardware and efficient algorithms.

Serial Peripheral Interface (SPI) is a synchronous serial communication interface for short range communications, e.g. processing unit with peripherals, with only one bit at the time to be transmitted. The SPI introduces the terms of master and slave devices, where the master device is responsible for reading and writing to the slave device.
Inter-Integrated Circuit (I2C) is a type of bus for connecting integrated circuits, where all the chips are connected to the same bus and each chip can become a master by initiating a communication.
Universal Asynchronous Receiver-Transmitter (UART) is a computer hardware component that is responsible for the asynchronous serial communications. The speed of data transmission is configurable and UART is mostly used for managing the serial ports.

In terms of connectivity, reliable connectivity to the Internet is very essential to ensure good QoS for IoT applications. With technologies evolving every day, various connectivity interfaces are available to give better performance and end-to-end results. Wi-Fi, Bluetooth, Ethernet, Zigbee are wireless/wired technologies that play a crucial role in providing IoT with Internet connectivity [31]. Some IoT devices are also equipped with mobile wireless technologies such as 3G, 4G.

C. OS SUPPORT

Operating system (OS) is an essential feature for the IoT to be fully functional by allowing IoT devices to integrate across heterogeneous networks [32]. An OS multiplexes hardware resources and provides an abstraction of the underlying hardware to make application programs simpler and more portable [33]. Due to the constrained resources, such as Processing Unit, memory and power requirements, the usage of a traditional OS is not possible for some category of IoT devices. To address this problem, an OS for low-level hardware is necessary for a high-end application developer to create high level applications. These OSs must be lightweight in terms of memory (RAM and flash) [34], with very low power consumption. Examples of these OSs are ContikiOS [35] and RIOT [36]. However, as IoT is a very broad term, there are devices that support OS with more functionalities, like SBCs. The OSs for these devices can handle more tentative computations as the power derived from the hardware is much more [37]. Most SBC run Linux OS and offer Android and Chrome OS compatibility. An essential feature an OS should possess is the efficient implementation of real-time capabilities and security features. For many IoT applications, it is crucial that the OS will support real-time functionalities for time critical applications [38].

D. SECURITY

Security issues of IoT devices occur in different instances which include technological, ethical and privacy concerns [39]. Preliminary research indicates that IoT devices are easily vulnerable to many threats and security attacks. The embedded devices are connected to the internet which makes them vulnerable to security attacks such as Denial of Service (DoS). Secondly, due to the resource constrained of IoT devices, which makes them not only vulnerable to attacks and less capable to cope with security attacks, it also makes them less capable in adopting security measures and solutions because of their limitations in terms of memory, communication etc. IoT devices security cannot be optional, thus its design requires careful consideration and special techniques. Embedding security into the hardware will reduce the impact of security attacks. As described [40], security microcontroller or security controller (SC) is a way of embedding security measures at the hardware level. SC is a dedicated IC that provides a defined set of cryptographic operations. It can be used to secure the client authentication step during Transport Layer Security (TLS) handshake procedure and also providing authenticity and confidentiality of cryptographic credentials in use and at rest.

In addition, ARM TrustZone is a way of hardware security to ARM processors. ARM TrustZone technology is a system-wide approach to embedded security option for the ARM Cortex-based processor systems. It begins in the hardware of the ARM processor chip, which is the basis of secure boot and has been implementing in some ARM Cortex-A and Cortex-M processors [41].

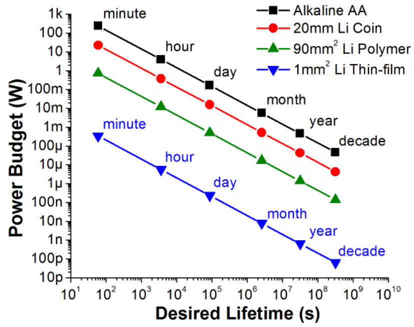


FIGURE 2. Shows the average power draw constraint as a function of lifetime and battery type. Figure from [42].

E. POWER SPECIFICATIONS/BATTERY LIFE

There is no equivalent forecast to battery life which could be compared to Moore' law prediction for size and energy efficiency. The type of communications protocol, radio transceiver, sensors, processor type are criteria that significantly affects the battery life of an IoT device. One important management design is the ability to balance power consumption and device performance. Previous research has indicated that reducing the average current drawn while keeping the voltage fixed or scaling the supply voltage does not minimize the average power consumption [43]. Figure 2 shows the average power draw constraint as a function of lifetime and battery type.

Generally, most IoT devices that will be connected to the IoT ecosystem will run on small batteries. However, in remote locations, or in harsh environments, where battery replacement can be difficult, it is necessary to find alternate source of energy such as energy harvesting. With this, least amount of power and voltage is substantial for the sensors, processor and embedded memory to be low in standby and operating mode.

In addition, the radio interface is typically the most power-hungry component for the transmission of data when dealing with wireless devices [44]. Recent radio transceivers that are manufactured exhibit similar current consumption for data transmission and listening for incoming communications. The problem is that in this scenario an IoT device does not know when to expect to receive data, and thus must perform energy-draining scanning to detect the presence of a packet. Hence, there is a consistent amount of power dissipated in listening mode while no data is received. The recent development of wake-up radios makes a huge impact in terms of reducing the power consumption. Wake-up radios are radio receivers with near-zero power consumption, which are used in listening to incoming transmissions to wake up the main radio when needed [45].

A battery lifetime of 10 years is desirable to bring the down the maintenance and replacement costs [46]. Battery life is calculated based on the capacity of the battery in milliampere Hours (mAh) divided by the load current in mA. In this article, we examine the supply voltage, the type of battery and the current consumption of each device, which is an essential attribute in determining the battery life of a device.

F. SIZE AND COST

The significant drop in the cost of IoT devices and development boards has contributed enormously to the improvement of IoT technology. The cost of an IoT device is related to its embedded computational features. The higher the computational features such as memory and processing features, the higher the cost.

IoT devices are generally small in size with low cost, which makes the embedded technology to be small. It is significant to minimize the silicon area of these devices. In addition, amount of space required for memory must not only be kept to a minimum, but should also minimize any additional wafer processing cost due to extra masks or processing steps. The more silicon wafer is required, the more the cost [47]. Form factors of IoT hardware (low-end, middle-end and high-end IoT devices) have shrunk to millimeter levels, with intriguing features mounted on it to meet the computational needs of IoT applications. Moore's law [48] is applicable to device size, where silicon chips are consistently crammed onto chips, while increasing its complexity. There should be a balance in size and performance.

The appearance of the device is also an essential requirement. Environmental conditions in which these devices would be used play an important role in the physical design appearance of the device. With the majority of the IoT devices being deployed outdoor or in harsh condition environments, it is crucial to equip these devices with the appropriate level of protection, e.g. waterproof and/or shockproof protection. For example, a device that is installed on the underside of a truck as part of a fleet monitoring application would need to be shielded to ensure it continues to operate under harsh conditions. It would need to be waterproof and resistant to dirt, shock, and vibration.

IV. SURVEY OF LOW-END DEVICES

Low-end devices are devices with minimal resource constrained to run a traditional OS. They require low power wireless technologies such as Zigbee, NFC, Bluetooth and RFID standards for communication. They are portable and battery operated. This section reviews the widely used low-end IoT devices in the industry. Figure 3 shows examples of low-end IoT devices.

A. OPENMOTE-CC2538

The OpenMote-CC2538 is an open-hardware platform designed to facilitate the prototyping and technology adoption of IEEE 802.15.4-2015 networks, and it is fully supported by OpenWSN. It is based on the popular platform of Texas Instruments CC2538 housing a Cortex-M3 MCU, clocked up to 32MHz with a 32-bit architecture, 32KB of RAM and 512KB of flash making it a state-of-the-art microcontroller [49]. In addition, the MCU provides an integrated radio module for IEEE 802.15.4 2.4GHz band. The device itself provides I2C, SPI etc., interfaces which gives the opportunity to connect any kind of sensors. The OpenMote offers alongside with the OpenMote-CC2538 mote two modules, the OpenBase and the OpenBattery. OpenBase is a module with JTAG, micro USB Type-A for flashing a mote, an extender header for the OpenMote-CC2538 mote and power supply through the micro USB Type-A ports. On the other hand, the OpenBattery has a built in support for 2-AAA batteries, a SHT21 temperature/humidity sensor, a ADXL346 3-axis accelerometer sensor, a MAX4409 light sensor, four led lights and two buttons. Regarding the OS support for the OpenMote-CC2538, there is a wide range of WSN OS like OpenWSN, ContikiOS, Thingsquare, FreeRTOS, RIOT. The energy consumption in the sleep mode is 0.4μA and $13m$A in the run mode despite its powerful MCU.

B. TELOSB

TelosB is 2.4GHz low energy mote compliant. It is based on a 16-bit RISC architecture Texas Instruments MSP430 MCU clocked at 8MHz, paired with 10KB of RAM and 48KB of flash storage [50]. Sensors that support I2C, SPI interfaces can be used with this device. TelosB supports OS like OpenWSN, RIOT, ContikiOS, TinyOS 1.1.11 or higher, Nano-RK, Mantis, LiteOS and MoteWorks. At the communication level we have a IEEE 802.15.4 compatible radio with a data-rate of 250Kbps. TelosB can be powered by 2-AA batteries and the energy consumption is estimated at $< 23m$A (active MCU and TX/RX) and $< 1\mu$A at MCU sleep state. Its total footprint is of 65mm$\times$31mm$\times$6mm and weighs 23g (without batteries).

C. OPENMOTE-B

OpenMote-B [51] is the first board that fully supports the IEEE 802.15.4g standard including MR-OFDM modulations

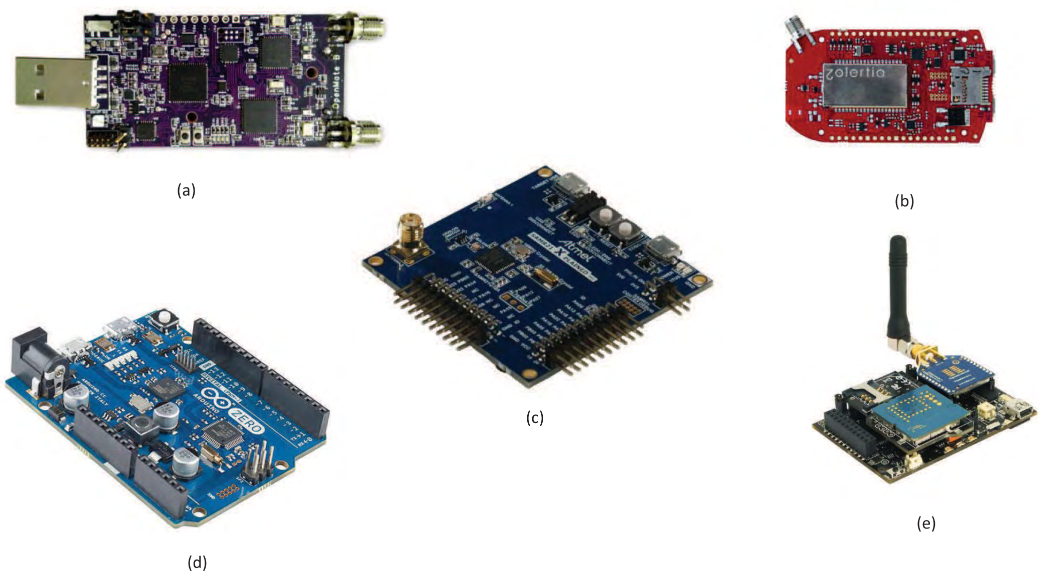


FIGURE 3. Examples of low-end IoT devices. (a) OpenMote-B (source from Openmote.com). (b) Zolertia ReMote (source from Zolertia.io). (c) Atmel SAM R21 (source from microchip.com). (d) Arduino Zero (source from Arduino.cc). (e) Waspmote (source from libelium.com).

in Sub-GHz and 2.4GHz bands for robust indoor communications. It is based on the popular platform of Texas Instruments CC2538 housing a Cortex-M3 MCU, clocked up to 32MHz with a 32-bit architecture and 32KB of RAM and 512KB of flash making it a state-of-the-art microcontroller. The radio of the OpenMote-B consists of two modules, the integrated radio in the CC2538 compatible in 2.4GHz band, and the based on the Atmel AT86RF215 SubGHz radio module. The device itself provides I2C, SPI interfaces which gives the opportunity to connect any kind of sensors. The OpenMote-B unlike the OpenMote-CC2538 comes with an integrated USB 2.0 port for firmware upgrade and power supply for the OpenMote-CC2538 mote and has a built in support for 2-AA batteries, a temperature/ humidity sensor, four led lights and two buttons. It is supported by OpenWSN, RIOT & ContikiOS. The OpenMote-B differs from the OpenMote-CC2538 mostly with the support of the IEEE802.15.4g and the simultaneous dual radio operation.

D. LSN50

LSN50 LoRa [52] sensor node is an open source hardware. LSN50 is gaining momentum in the IoT industry because of its long-range unique attributes. It is designed for outdoor use and powered by Li/SOCI2 battery for long term use. It is designed to facilitate developers to quickly deploy industrial level LoRa and IoT solutions [53]. LSN50 features a STM32L072CZT6 MCU with a SX1276/78 Wireless Chip, which allows user to send data and reach extremely long ranges at low-data rates. It uses ARM Cortex-MO+ 32bit core operating at a 32MHz frequency, equipped with 20KB of RAM, 6KB of EEPROM and 192KB of flash memory. It comes 18×digital I/Os including I2C, ADC, DAC, USART, USB. It supports 433/688/915/920MHz band. LSN50 LoRa sensor node is supported with IP66 Waterproof Enclosure and is implemented in various IoT applications such as long range irrigation systems, industrial monitoring and control, smart metering, home and building automation.

E. ATMEL SAM R21 XPLAINED PRO

The SAMR21 by Atmel is a 2.4GHz low energy consumption mote based on the ATSAMR21G18A, a MCU integrated with the radio module. The MCU is a Cortex-ARM M0+ clocked up to 48MHz and feature a two-stage pipeline, single-cycle I/O access, single cycle 32×32 multiplier, event system, and a fast, flexible interrupt controller [54]. SAMR21 comes with a 32KB RAM and 256KB of flash, while the radio module is a AT86RF233. The offered development boards from Atmel house only two buttons and two leds, however, the ATSAMR21G18A provides several I2C, SPI, etc. interfaces making the integration of several sensors easy. It supports various OS such as OpenWSN, ContikiOS, Thingsquare, FreeRTOS, RIOT, Mbed. The energy footprint of the SAMR21 is 70mA at active state and 3.5μA at sleep mode. Interesting IoT projects have emerged from Atmel SAMR21 including [7].

F. WASPMOTE PRO

The Waspmote PRO [55] uses the Atmel Atmega1281 MCU clocked at 14MHz and paired with 8KB of RAM and 128KB of lash, with an additional micro-SD card support up to 2GB. The built-in sensors are a temperature sensor and an accelerometer, while through the expansion header XBEE/ IEEE802.15.4, GSM/GPRS/3G, GPS. Sensing modules can be attached to the board, as well as other components through the digital and analogue pins. Some of the standards supported by the Waspmote PRO are SPI, UART, PWM, I2C, etc. Waspmote PRO can be programmed through the Waspmote IDE provided by Libelium in a C/C++ style. The board can be powered by a USB cable, battery pack or by solar energy. The energy footprint in the sleep mode and operational mode is 0.06μA and 15mA respectively. The energy consumption is not accurate as it depends on the expansion modules attached on the mote. The small form factor of the device is 73.5mm$\times$51mm$\times$13mm and 20g weight, making it perfect for a wide range of IoT applications.

G. OPENMOTE+

The OpenMote+ [56] is a prototype board that shares a lot of similarities with the OpenMote-B, like the I/O, on-board sensors, way of re-programming and power supply. Unlike the previous two OpenMote devices, the plus model is equipped with an EZR32WG System-on-Chip (SoC) from Silicon Labs, an ARM Cortex-M4 MCU paired with 32KB of RAM and 256KB of flash storage. Furthermore, in OpenMote+, we have a dual radio support: an EZRadioPRO and AT86RF233 radio modules. The former is a SubGHz radio for communications over long distances, in the range of kilometers, with data rates up to 1Mbps while the latter is used for short distance communications, compliant with the IEEE 802.15.4-2011 standard. Some of the operating systems that support this platform are ContikiOS, RIOT, OpenWSN. The energy footprint of the device is $\leq$ 18mA and $\leq$ 13.8mA for the EZRadioPRO and the AT86RF233 radio modules respectively.

H. ZOLERTIA REMOTE

Zolertia Remote is based on the Texas Instruments CC2538 ARM Cortex-M3 SoC, with an on-board 2.4 GHz IEEE 802.15.4 RF interface, running up to 32MHz with 512KB of programmable flash and 32KB of RAM, bundled with a Texas Instruments CC1200 868/915 MHz RF transceiver to allow dual band operation. The MCU communicates with the CC1200 over an SPI interface. Operating at 863-950 MHz, the CC1200 provides long distance communications. Zolertia Remote [57] has 3 ADC, 1 SPI, 1 I2C and 2 UART interfaces. In addition to the interfaces, there is a programmable LED. The power footprint is as low as 0.4μA at Power Mode 3 for the CC2538 while it can reach up to 20mA at active mode. The energy consumption for the CC1200 is as low as 0.12μA at wake-up radio (eWOR) while it can reach up to 46mA at transmission mode. The input voltage ranges between 3.5-16VDC with support of solar panels as well. The small form factor of the device is 73mm$\times$40mm.

I. MEMSIC LOTUS

Memsic Lotus [58] uses the NXP LPC1758 MCU, a 32-bit Cortex-M3 clocked up to 100MHz paired with 64KB of RAM and 512KB of flash. The board itself does not provide any sensing capabilities but the 51-pin expansion header provides connectivity with light, temperature, relative humidity, barometric pressure, acceleration/seismic, acoustic, magnetic and other Memsic sensor boards by exploiting standards like SPI, I2C, UART (the device supports up to 3 UART), I2S, GPIO and ADC. At the networking side, Lotus uses the Atmel RF231; IEEE802.15.4 radio module which provides a data rate of 250Kbps, a nominal range of around 100 meters and 16 channels at the 2.4GHz band. Lotus is using an RTOS OS but is also supported by MoteRunner and TinyOS. The energy footprint of the device is low as it consumes 10μA in the sleep mode and while in the active mode at 100MHz, it can consume up to 50mA. The size of the board is small as well with the dimension being 76mm$\times$34mm$\times$7mm and weighing only 18g.

J. TMOTE SKY

The Tmote Sky [59] is an ultra low-power 2.4GHz WSN module. The MCU of the Tmote Sky is a Texas Instruments MSP430F1611 clocked at 8MHz paired with 10KB of RAM and 48KB of flash. The development board comes with optional sensors like temperature/humidity sensor, light sensor, total solar radiation sensor, photo-synthetically active radiation sensor, a 10-pin expansion and a 6-pin expansion connectors. Furthermore, the board provides an on-board JTAG controller and a USB 2.0 port. The radio module of Tmote Sky is a CC2420 module, which provides IEEE 802.15.4 connectivity with a data rate up to 250Kbps. Tmote Sky is a low energy device with a power consumption as low as 5.1μA with the MCU on standby mode, while the maximum energy footprint of the device being less than 23mA. The device is compatible with TinyOS and ContikiOS.

K. MEMSIC IRIS

Memsic Iris mote is designed specifically for deeply embedded sensor networks. It uses the XM2110CA MCU that is based on the Atmel ATmega1281 low-power MCU, 8-bit RISC architecture paired with 8KB RAM and 128KB of flash. Memsic Iris [60] does not provide any sensing capabilities but the 51-pin expansion header provides connectivity with light, temperature, relative humidity, barometric pressure, acceleration/seismic, acoustic, magnetic and other Memsic sensor boards by exploiting standards like SPI, I2C, UART, I2S, GPIO and ADC. The device supports IEEE802.15.4 standard with a data rate up to 250Kbps. The energy consumption in the sleep mode is 8μA while the maximum footprint of the device is 8mA.

L. ADAFRUIT FEATHER M0 WI-FI

Adafruit Feather M0 WiFi w/ATWINC1500 is an 'all-in-one' Arduino compatible platform [61]. The Feather M0 uses the Atmel ATSAMD21G18 Cortex-M0+ MCU clocked at 48MHz and paired with 32KB of RAM and 256KB of flash. The microcontroller has 20 GPIO pins, 8 PWM pins, 10 ADC pins, 1 DAC pin, 3 user available Serial Communication Module (SERCOM) with support for SPI, I2C and UART. The network connectivity of the Feather M0 is achieved through the integrated ATWINC1500 module that allows IEE802.11b/g/n connectivity. The Wi-Fi module supports the WEP, WPA and WPA2 encryption algorithms with TLS 1.2 and ad-hoc network functionality. The ATWINC has much lower power usage, about 12mA for the WINC and 10mA for the ATSAMD21 with auto-power management on for the Wi-Fi and no power management for the ARM. The size of the device is 53.65mm$\times$23mm$\times$8mm. The device supports RIOT OS and can be reprogrammed using the Arduino IDE.

M. VIRTUALSENSE

The VirtualSense Mote [62] is a modular ultra-low power WSN device. The module has a square shape with dimension 53mm$\times$53mm and the height depends on the number of layers. The modules are connected through the four 14-pin header connectors. VirtualSense [63] is a highly modular mote with various possible configuration. The provided hardware are the MCU layer, the Network and Sense layer, the Programming layer, the Ultrasonic Wake-up and Distance measurement layer and the Power Supply layer. The MCU layer contains a 16-bit RISC architecture MSP430F5418A clocked at 25MHz and paired with 16KB of RAM and 128KB of flash storage. The Network and Sense layer provide the IEEE 802.15.4 support. This layer consists of a TI CC2520 RF transceiver capable of handling all the communication such as data buffering and frame handling. Temperature, pressure and a luminosity sensor are also included in this layer. The Programming layer provides an easy and quick way to reprogram the device as the user can reprogram the board through a USB port without the need for a dedicated JTAG external programmer. Furthermore, this layer converts the 5V current from the USB port to 3.3V in order to power on the device through the USB port. The overall power consumption of the device in hibernate/sleep mode does not exceed 1.5μW while in TX and RX mode, its footprint is 10mW and 60mW respectively. The OS used in this device is containerized, as it uses a small footprint Java VM for the applications that run on the mote, and the network operations are taking place on the lower layer which is ContikiOS.

N. EMBIT EMB-Z2530PA

The Embit EMB-Z2530PA [64] mote is equipped with a Texas Instruments CC2530 MCU based on the 8051 CPU in an 8-bit architecture clocked at 32MHz and paired with 8KB of RAM and 256KB of flash. The energy consumption of the mote at sleep mode (MCU and radio) is less than 1.1mA, while the maximum footprint of the device is $\leq$ 154mA. The device supports several protocols like UART, SPI, I2C which allows several sensors and devices to be connected. The programming can be done by TI flash tools like SmartRF. The mote is quite small with dimension 29.50mm$\times$22.60mm$\times$3.6mm

O. NORDIC SEMICONDUCTOR NRF51 DK

The Nordic Semiconductor nRF51 DK [65] is a low-cost, versatile single-board development kit for Bluetooth Smart, ANT and 2.4GHz proprietary applications using the nRF51 Series SoC. This kit supports development for nRF51822 [66] and other SoCs. The kit is hardware compatible with the Arduino UNO Revision 3 standard, making it possible to use 3rd-party shields. It supports the standard Nordic Software Development Tool-chain using Keil, IAR and GCC. There is also support for the ARM mbed tool-chain for rapid prototyping and development using mbed's cloud-based IDE and tool-chain with an extensive range of open-source software libraries. Program/Debug options on the kit are Segger J-Link OB for standard tool-chain and Cortex Microcontroller Software Interface Standard-Debug Access Port for mbed. The kit gives access to all I/Os and interfaces via connectors and has 4 LEDs and 4 buttons which are user-programmable. In addition to standard nRF51 Series development, the development kit can be used as a useful and highly cost-effective Bluetooth Smart packet sniffer using Nordic nRF Sniffer software allowing detailed data related to Bluetooth Smart communication to be captured and analyzed. Using the Master Emulator firmware and the Master Control Panel Software, it enables setting up of a peer device that can be used to test the connection of the application.

P. SODAQ AUTONOMO

The Autonomo [67] by SODAQ is an arduino compatible board, which is based on ATSAMD21J18 featuring an ARM Cortex-M0+ MCU clocked up to 48MHz in a 32-bit architecture. Autonomo comes with a 32KB RAM and 256KB of flash, and houses two leds for user configurable and charging. It comes with 16 GPIO pins, 12 PWM, UART, I2C and SPI, making the integration of several sensors easy. The device is compatible with OpenWSN, ContikiOS and RIOT. The SODAQ Autonomo has a solar power charge controller with a named charging rate of 500mA for a 3.7V LiPo battery, but it can also be powered by a 5V USB power supply. The total footprint of the device is 58.5mm$\times$33.5mm.

Q. MICAZ/MICA2

MICAz/MICA2 is a 2.4GHz mote module from Crossbow technology. It is based on the Atmel ATmega 128L, a low energy microcontroller, 8-bit architecture clocked at 8MHz, which is capable to execute an application and in parallel the network stack, paired with 4KB of RAM and 128KB of flash storage [68]. It is a modular device as it is equipped with a 51-pin extension header, where sensors like temperature/humidity, light, and other sensors supporting I2C, SPI interfaces. MICAz is also versatile on the OS support as it supports OpenWSN, RIOT, ContikiOS, TinyOS, Nano-RK, Mantis, LiteOS and MoteWorks. At the communication level we have an 802.15.4 compatible radio with a data-rate of 250Kbps and capable of AES-128 encryption. As a device made for WSN, the MICAz can be powered by 2-AA batteries and the energy consumption is estimated at $<$ 20mA (active MCU and TX/RX) and $<$ 15μA at MCU sleep state and its total footprint is of 58mm$\times$32mm$\times$7mm and 18g (without batteries). MICAz uses the CC2420 radio chip where MICA2 uses the CC1000 radio chip.

TABLE 4. A comparison of low-end IoT devices in terms of computing.

Mote Platform	Processing Unit	Clock speed	RAM	On-board Storage	Supply Voltage / Battery	Radio Transceiver	Onboard Sensors	Cost ($) Starting at
OpenMote-CC2538	Cortex-M3	32MHz	32KB	512KB	2V to 3.6V, 2×AAA	CC2538	temperature, humidity, light, accelerometer	104.00 as of 2016
TelosB / Tmote SKY	TI MSP430F1611	8MHz	10KB	48KB	2.1V to 3.6V, 2×AA	CC2420	temperature, humidity, light	104.00
OpenMote-B	Cortex-M3	32MHz	32KB	512KB	2.1V to 3.6V, 2×AAA	Atmel AT86RF215 + TI CC2538	temperature, humidity, light, accelerometer	116.26
LSN50	Cortex-M0+ / STM32L072CZT6	32MHz	20KB	192KB	2.1V to 3.6V, Li/SOCl2	SX1276/SX1278	—	45.00
Atmel R21 Xplained Pro	Cortex-M0+	48MHz	32KB	256KB	1.8V to 3.6V	ATSAMR21G18A	—	57.70
Waspmote PRO	Atmel ATmega 1281	14.7456MHz	8KB	128KB	Battery (3.3V – 4.2V) or Solar (6V - 12V)	NS	Accelerometer (on-board sensor), Temperature Sensor and light (through dedicated sockets)	280.00
Openmote+	Cortex-M4 / EZR32WG	48MHz	32KB	256KB	1.8V to 3.6V	Atmel AT86RF233	—	NS
Zolertia ReMote	Cortex-M3	32MHz	32KB	512KB	3.3V to 16V	CC2538 & CC1200	accelerometer, temperature	115.60
Memsic Lotus	Cortex-M3	10-100 MHz	64KB	512KB	1.8V to 3.6V, 2×AA	Atmel AT86RF231	—	NS
Memsic Iris	Atmel ATmega1281	16MHz	8KB	128KB	1.8V to 3.6V, 2×AA	Atmel AT86RF230	—	NS
VirtualSense	MSP430F5418A	25MHz	16KB	128KB	1.8V to 3.8V, 2×AAA	CC2520	temperature, light and pressure	NS
Embit EMB-Z2530PA	8051	32MHz	8KB	256KB	2V to 3.6V	CC2530	—	24.00
MICAz	Atmel ATmega 128L	8MHz	4KB	128KB	2.1V to 3.6V, 2×AA	CC2420	—	NS
Mica2	Atmel ATmega 128L	8MHz	4KB	128KB	2.1V to 3.6V, 2×AA	CC1000	—	NS
Pinoccio	ATmega256RF2	16MHz	32KB	256KB	5V via micro-USB, Li-Po Battery	in-built radio supporting IEEE 802.15.4 standard	temperature	49.00
Adafruit Feather M0 Wi-Fi	ATSAMD21G18 ARM Cortex-M0+	48MHz	32KB	256KB	3.3V via micro-USB, Li-Po Battery	ATWINC1500	—	34.95
nRF51 DK with nRF51822	ARM Cortex-M0	48MHz	32KB	256KB	1.8V to 3.6V, 3V coin-cell battery	in-built Bluetooth v4.1-compliant 2.4GHz multiprotocol radio	temperature	40.00
SODAQ Autonomo	ATSAMD21J18 Cortex M0+	48MHz	32KB	256KB	1.8V to 3.6V	NS	—	50.00
Arduino MKR1000	ATSAMW25 (SAMD21 Cortex-M0+ 32-bit ARM MCU)	48MHz	32KB	256KB	5V via micro-USB	Wi-Fi radio	—	36.00

NS:Not Specified

R. PINOCCIO

Pinoccio [69] is an open source hardware with built-in 2.4GHz radio communication module using the IEEE 802.15.4 standard aimed at developing IoT projects. Pinoccio board is based on the Atmel ATmega256RF2 [70] MCU clocked at 16MHz paired with 256KB of flash storage, 32KB of SRAM and 8KB of EEPROM. It also includes 17 digital I/O pins, including four with PWM, 8 ADC pins, 2 UART serial ports, an SPI, a dedicated I2C port, on-board temperature sensor, Wi-Fi, micro-SD slot, on-board RGB LED and a rechargeable Li-Po battery (550mAh). The Pinoccio platform is compatible with Arduino, which supports Arduino IDE packages for the development of IoT projects. The specifications of the above-discussed boards are compared and depicted in Table 4 and Table 5.

V. IOT HARDWARE PLATFORMS

This section reviews the most used middle-end and high-end IoT device.

A. SAMSUNG ARTIK

Samsung ARTIK [98], [99] is an integrated platform for the development and management of IoT products. Samsung Artik modules are based on ARM processors with attributes of their reduced complexity and low power consumption making them suitable for IoT applications. Samsung ARTIK modules implement Wi-Fi, ZigBee, Thread, and/or Bluetooth radios, moving data with SSL/TLS-protected TCP-IP, MQTT, CoAP, BLE, and other protocols. Samsung ARTIK provides a range of modules: Artik 0, Artik 5 and Artik 7, which comes in different sizes and capabilities. The modules can be accompanied by development boards, but can also be directly deployed to develop a target product.

Artik 0 module family is very economical, tiny, with very low-power and flexible. It is recommended to choose ARTIK 020 for Bluetooth Applications, ARTIK 030 for ZigBee and Thread applications and ARTIK 053 for Wi-Fi and enhanced security applications. Samsung Artik 020 and 030 are based on a 32-bit ARM Cortex-M4 [100] CPU running at 40MHz with flash memory of 256KB and 32KB RAM, Samsung

TABLE 5. A comparison of low-end IoT devices in terms of communication, connectivity and dimension.

Mote Platform	OS Support	Size (L×W) or (L×W×H) mm	Interfaces						Project(s)
			GPIO	UART	I2C	SPI	ADC	DAC	
OpenMote-CC2538	OpenWSN, ContikiOS, Thingsquare, FreeRTOS, RIOT	75.5×56.4 for openbase, 52.9×25.0 for openbattery	32	2	1	2	8×12 bit	—	[71], [72]
TelsoB	OpenWSN, RIOT, ContikiOS, TinyOS, Nano-RK, Mantis, LiteOS, SOS, Mote-Works	65×31×6	48	2	1	2	8×12 bit	12 bit	[73], [74]
Openmote-B	ContikiOS, RIOT, OpenWSN	NS	32	2	1	2	8×12 bit	—	[6]
LSN50	LoRaWAN	65×50×50	18	1	1	NS	2×12 bit	12 bit	[75]
Atmel R21 Xplained Pro	OpenWSN, ContikiOS, Thingsquare, FreeRTOS, RIOT, Mbed	66.5×66.5	28	4	5	5	8×12 bit	—	[7]
Waspmote PRO	RIOT, Libelium OTA	73.5×51×13	8	2	1	1	7 bit	—	[76], [77]
Openmote +	ContikiOS and OpenWSN	NS	NS	NS	NS	NS	NS	NS	NS
Zolertia ReMote	ContikiOS, RIOT, OpenWSN, OpenThread	73×40	48	2	1	2	8×12 bit	12 bit	[78]
Tmote Sky	ContikiOS, TinyOS, MantisOS	65×31×6	48	2	1	2	8×12 bit	12 bit	[79], [80]
Memsic Lotus	MoteRunner, TinyOS, MEMSIC Kiel, FreeRTOS	76×34×7	NS	NS	NS	NS	12 bit	—	[81]
Memsic Iris	MoteRunner/MoteWorks, TinyOS	58×32×7	54	2	1	3	16×10 bit	—	[82], [83]
VirtualSense	ContikiOS	53×53	NS	1	1	2	7×12 bit	12 bit	[90]
Embit EMB-Z2530PA	TI SmartRF	29.5×22.6×3.6	21	1	NS	1	8×12 bit	—	[91]
MICAz /MICA2	OpenWSN, RIOT, ContikiOS, TinyOS, Nano-RK, MantisOS, LiteOS, MoteWorks	58×32×7	53	2	1	1	8×10 bit	—	[84]–[86]
Pinoccio	RIOT, Arduino Software (IDE), Pinoccio API	58.5×33.5	17	2	1	1	8	—	[87]
Adafruit Feather M0 Wi-Fi	RIOT, Arduino Software (IDE)	53.65×22.8×8	20	1	1	1	10×12 bit	10 bit	[88], [89]
nRF51 DK with nRF51822	RIOT, ContikiOS, nordic proprietary	Not specified	31	2	1	1	8×10 bit	—	[92]–[94]
SODAQ Autonomo	OpenWSN, ContikiOS, RIOT	58.5×33.5	16	1	1	1	6×12 bit	10 bit	[95]
Arduino MKR1000	Arduino Software (IDE)	61.5×25.0	8	1	1	1	7× 8/10/12 bit	10 bit	[96], [97]

NS:Not Specified

ARTIK 053/053s on the other end are based on a 32-bit ARM Cortex-R4 CPU with 32KB I-Cache and 32KB D-Cache running at 320MHz, paired with a flash memory of 128KB and 1280KB of RAM. ARTIK 0 modules are mostly used in in health and fitness application, industrial, home and building automation, lighting etc.

Samsung ARTIK 5 module family is bigger than ARTIK 0 in terms of size, power and capabilities. Samsung ARTIK 5 family are very reliable for smart things because of their ideal balance of power and performance for gateways or devices with video and processing requirements. There are two modules belonging to the ARTIK 5 family, which are ARTIK 520 and ARTIK 530. Samsung ARTIK 520 module utilizes a dual core ARM Cortex-A7 [101] processor running at 1GHz packaged with 512MB LPDDR3 and 4GB flash memory with a wide range of wireless communication options such as BLE, 802.15.4/ZigBee and IEEE 802.11a/b/g/n/ac. On the other hand, Samsung 530/530s combines a quad core ARM Cortex-A9 [102] processor packaged with 512MB or 1GB DRAM and 4GB flash memory with a wide range of communication options such as as BLE, 802.15.4/ZigBee and IEEE 802.11a/b/g/n/ac [103]. The last family is ARTIK 7, which has a great performance for high-end gateways with local processing and analytics, and for multimedia applications. Samsung ARTIK 710/710s is the only module belonging to this family, which utilizes an octa core 64-bit ARM Cortex A-53 [104] processor paired with 1GB RAM and 4GB flash with Wi-Fi, Bluetooth, ZigBee, Thread to serve effectively as a gateway for large buildings or a factory and the ability to run local analytics to improve latency and responsiveness. Image of Samsung ARTIK 710 is shown in figure 5. Samsung Artik 1020 is no longer in production and has been replaced by Samsung ARTIK 710. Limited stocks of ARTIK 1020 modules and developer kits are still available for experimentation and small-scale projects at the time of this writing. Table 6 summarizes the different characteristics of the Samsung ARTIK modules.

B. ARDUINO

Arduino [105] offers a wide variety of open source boards from simple microcontroller boards to advanced boards with enhanced features. Arduino can be used to develop various projects which can be stand-alone or communicate with software running on a computer. Moreover, it has impacted the education sector in redefining the learning procedure,

TABLE 6. A comparison of samsung ARTIK modules.

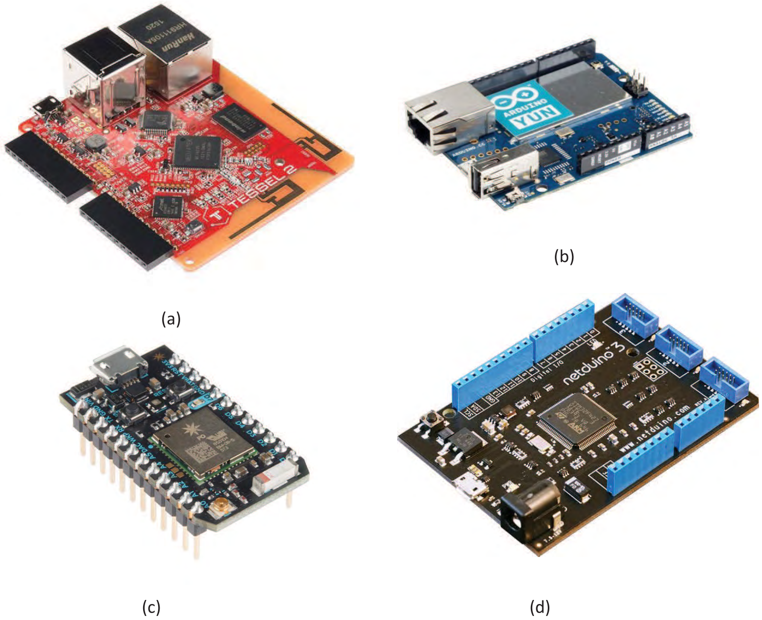
Specifications	ARTIK 020	ARTIK 030	ARTIK 053/053s/055s	ARTIK 520	ARTIK 530/530s	ARTIK 710/710s
Processing Unit	ARM Cortex-M4	ARM Cortex-M4	ARM Cortex -R4 with 32KB I-Cache and 32KB D-Cache	dual core ARM-Cortex-A7	quad core ARM-Cortex-A9	octa core ARM-Cortex-A53
Clock Speed	40MHz	40MHz	320MHz	1.0GHz	1.2GHz	1.4GHz
GPU	—	—	—	ARM MALI 3D Graphics accelerator	ARM MALI 3D Graphics accelerator	ARM MALI 3D Graphics accelerator
RAM (Memory)	32KB	32KB	128KB	512MB LPDDR3	512MB for 530, 1GB for 530s LPDDR3	1GB LPDDR3
On-board storage	256KB	256KB	8MB	4GB eMMC flash, SD	4GB eMMC flash, SD	4GB eMMC flash, SD
On-board connectivity	Bluetooth support	ZigBee support	802.11b/g/n	Bluetooth 4.1, BLE, 802.15.4/Zigbee, 802.11a/b/g/n/ac, Ethernet support	Bluetooth 4.2 (BLE+Classic), 802.15.4/ Zigbee, 802.11a/b/g/n, Ethernet support	Bluetooth 4.1 (BLE+Classic), 802.15.4/ Zigbee, 802.11a/b/g/n/ac, Ethernet support
Media (Audio and Display)	—	—	—	1-channel PCM and I2S audio interface, 2-lane MIPI DSI	I2S audio interface, 4-lane MIPS DSI and HDMI/LVDS display	I2S audio interface, 4-lane MIPS DSI and HDMI/LVDS display
Size L×W×H or L×W (mm)	12.9×15.0×2.2	13.0×15.0	15.0×40.0×3.9 for 053/053s, 15.0×26.0×3.9 for 055s	25.0×30.0	36.0×49.0	36.0×49.0
Supply Voltage	1.85 - 3.8V	1.85 - 3.8V	5-12V for 053/053s and 3.3V for 055s	1.85 - 3.8V	1.85 - 5V	1.85 - 3.8V
Cost ($)	5.22	7.32	8.93 for 053/053s and 9.73 for 055s	59.18	44.13 for 530/530s	58.17 for 710 and 61.18 for 710s
Interfaces	25×GPIO pins including UART, I2C, SPI, I2S	25×GPIO pins including UART, I2C, SPI, I2S	60 and 58×GPIO pins for 053/053s 055s respectively including UART, I2S, I2C, PWM, SPI, ADC	100×GPIO pins including UART, I2C, SPI, I2S, JTAG	100×GPIO pins including UART, I2C, SPI, I2S, JTAG for 530/530s	108×GPIO pins SPI, I2S, I2C, UART, USB, GMAC, PWM

TABLE 7. A comparison of Arduino Boards for the last 6 years.

Specifications	MKR1000	101	Zero	Due	Yun	Leonardo
Processor	ATSAMW35	Intel Curie	ATSAMD21G18A	ATSAM3X8E	Atmega32U4 / Atheros AR9331	ATmega32U4
Clock Speed	48MHz	32MHz	48MHz	84MHz	16MHz/400MHz	16MHz
RAM (Memory)	32KB	24KB	32KB	96KB	2.5KB/64MB	2.5KB
On-board Storage	256KB	196KB	256KB	512KB	32KB/16MB	32KB
On-board connectivity	2.4GHz IEEE 802.11b/g/n Wi-Fi support	Bluetooth LE support	—	—	IEEE 802.3 10/100Mbps Ethernet and 2.4GHz IEEE 802.11b/g/n Wi-Fi support	IEEE 802.3 10/100Mbps Ethernet support
Size L×W (mm)	61.5×25.0	68.6×53.4	68.6×53.3	101.6×53.3	68.6×53.3	68.6×53.3
Operating Voltage	3.3V	3.3V	3.3V	3.3V	5V/3.3V	5V
Cost ($) Starting at	34.99	39.95	42.90	37.40	59.00	17.60
Low-level peripherals	8×GPIO pins, 12×PWM pins, 7×ADC, 1×DAC, 1×UART, 1×SPI and 1×I2C	14×GPIO pins, 4×PWM pins, 6×ADC 1×UART, 1×SPI and 1×I2C	14×GPIO pins, 12×PWM pins, 6×ADC, 1×DAC, 1×UART, 1×SPI and 1×I2C	54×GPIO pins, 12×PWM pins, 12×ADC, 2×DAC, 4×UART and 1×SPI	20×GPIO pins, 7×PWM pins, 12×ADC, 1×UART, 1×I2C	20×GPIO pins, 7×PWM pins, 12×ADC, 1×UART, 1×SPI and 1×I2C
Release Date	April 2016	October 2015	June 2015	October 2012	September 2013	July 2012

by helping students to learn and develop various IoT projects. Arduino boards come in many versions. Table 7 shows the comparison of Arduino boards released over the last 6 years. We briefly look at some of the Arduino boards worth mentioning.

Arduino Due [106] is the first Arduino that makes use of an ARM Processor. It uses an ATSAM3X8E Cortex-M3 32-bit architecture MCU clocked at 84MHz and paired with 96KB of RAM and 512KB of flash. Arduino Due houses more digital, analog pins than the previous versions of Arduino boards and it provides a USB-OTG functionality and a JTAG programming interface header. The Arduino MKR1000 was released in 2016 and the main use of this device is for IoT purposes. It is based on the ATSAMW25 [107] SoC which uses a SAMD21 32-bit architecture low-power MCU clocked at 48MHz and paired with 32KB of RAM and 256KB of flash. Part of the ATSAMW25 is also the WINC1500 module which provides Wi-Fi connectivity to the device at the 2.4GHz band and the ECC508 Crypto-Authentication module. MKR1000 supports USB-OTG and



(a) (b) (c) (d)

FIGURE 4. Examples of middle-end IoT devices. (a) Tessel 2 (source from tessel.io). (b) Arduino Yun (source from Arduino.cc). (c) Particle Photon (source from particle.io). (d) Netduino N3 (source from wildernesslabs.co).

has an input voltage of 5V. The Arduino Yun was released in 2013. It uses an Arduino AVR microcontroller-based on the ATmega32U4 running at 16MHz paired with 2.5KB of RAM and 32KB of flash, and a microprocessor-based on Atheros AR9331 of MIPS architecture clocked at 400MHz paired with 64MB of DDR2 RAM and 16MB of flash. The ATmega32U4 is responsible for the Arduino pin header used for more intensive processing tasks while the Atheros AR9331 is responsible for the Ethernet and Wi-Fi Connectivity, the micro-SD card slot and the full USB 2.0 port. Image of Arduino is shown in Figure 4.

Other boards worth mentioning are MKR WAN 1300 [108], which combines the functionality of the MKR Zero and LoRa connectivity. This makes it an ideal solution for people with minimal previous networking experience to design IoT projects having a low power device. Arduino MKR WAN 1300 is based on the Atmel SAMD21 and a Murata CMWX1ZZABZ LoRa module.

C. ODROID

Odroid boards [109] are energy efficient devices that can run various flavours of Linux distributions and Android. Odroid boards support CPU frequency scaling, thereby reducing the power requirements when the CPU load is not high. The recent models of Odroid boards include Odroid-XU4, Odroid-C2, Odroid-C1+. Odroid-XU4 is a SBC which features an octa core Samsung Exynos 5422 processor, with an advanced Mali GPU and Gigabit Ethernet port. The Samsung Exynos 5422 SoC has a (big) Cortex-A15 quad core CPU clocked at up to 2.0GHz and a (LITTLE) Cortex-A7 quad core CPU clocked at up to 1.4GHz. The Samsung Exynos 5422 SoC implements the big.LITTLE architecture with heterogeneous multiprocessing (HMP). The HMP can simultaneously use all eight cores, compared to previous big.LITTLE systems that could only utilize combinations of up to four cores out of a total of eight cores.

Each core has a 32KB L1 data cache and a 32KB L1 instruction cache, which is organized as 2-way (Cortex-A15 [101]) or 4-way (Cortex-A7 [101]) set-associative cache with a fixed cache line length of 64bytes. The four A-15 cores share a 2MB L2 cache, while the A7 cores share a 512 KB L2 cache. Both quad core CPU are connected to each other and to a 2GB LPDDR3 RAM clocked at 933MHz with an 128-bit AMBA ACE Coherent Bus interface. All cores support the NEON extension with the 128-bit SIMD instruction set, which can greatly speed up the GF(28) operations [110].

Odroid-XU4 comes with 1 USB 2.0 port, 2 USB 3.0 ports, an HDMI connector for 720p and 1080p monitors, and a 5V/4a DC power connector. In addition to these standard inputs, the Odroid-XU4 also includes a 40-pin HDMI port, an external RTC battery connector, a USB-UART serial console port, an eMMC module connector and a dedicated slot for a micro-SD card. Odroid-XU4 is an ARM device, and can serve as a general purpose computer for web browsing, and used in various IoT projects such as BEMOSS [111].

D. WANDABOARD

Wandboard [112] is a development board capable of running several Linux distributions and Android. As a SoC, it contains an ARM Cortex processor with USB ports and one Gigabit LAN port. Wandaboard is about using a system-on-module approach that works with an easy-to-design baseboard that

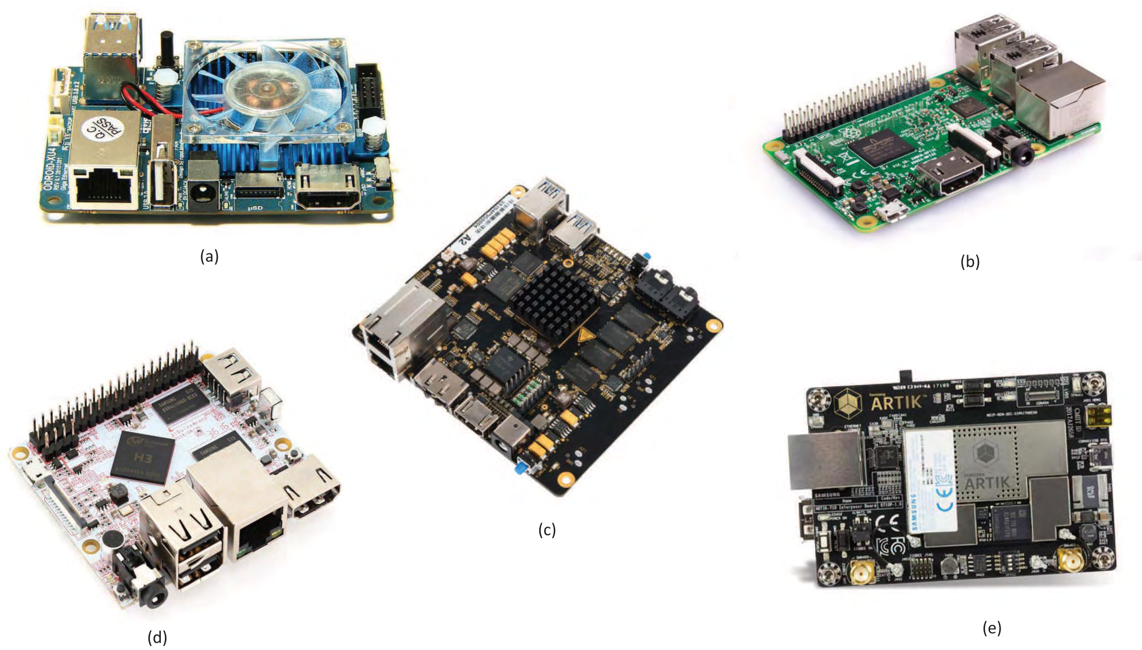


FIGURE 5. Examples of high-end IoT devices. (a) Odroid-XU4 (source from hardkernel.com). (b) Raspberry Pi 3 B+ (source from raspberrypi.org). (c) BeagleBone-X15 (source from beagleboard.org). (d) pcDuino4 Nano (source from linksprite.com). (e) Samsung ARTIK 710 (source from artik.io).

anyone can design and build with simple engineering knowledge. The wandboard community recently launched the release of WandPi-8M (the recent version of Wandboard). It is the top performer of all the Wandboards and very powerful with an ARM Cortex-A53 [104] + M4 running a NXP iMX8M Quad processor and comes with a memory of 2GB DDR4.

E. UDOO

UDOO [113], [114] is an open hardware, a SBC belonging to the family of open source Arduino-powered mini PC that supports several Linux distributions and Android. UDOO boards are developed with the objective of supporting education in terms of simulating the teaching of computer science in schools and also a platform to run IoT applications [115]. UDOO comes in different versions: UDOO DUAL/QUAD, UDOO NEO, UDOO x86 and UDOO Bolt. UDOO DUAL/QUAD is a low-cost computer equipped with a NXP i.MX 6 Atmel SAM3X8E processor with the dual core for the DUAL version and the quad core for the QUAD version. They are ideal for prototyping applications that requires multimedia capabilities maintaining the benefits offered by the low-power consuming ARM processors.

UDOO DUAL/QUAD features a 1GB RAM with HDMI interface, USB ports and integrated graphics and they have been used in the widest range of scopes including 3D printers, self-driving rovers etc. UDOO NEO is a low cost version among the UDOO products. It features a NXP i.MX 6Solo X processor with an embedded ARM Cortex-A9 core and a Cortex-M4 Core. The board also features a micro HDMI interface, an Ethernet port, an integrated 2D/3D graphics controller, a 512MB DDR3 RAM for the basic version and 1GB RAM for the extended/full version. With the Bluetooth 4.0 module, embedded 9-axis motion sensors and on-board Wi-Fi, the board is ideal to create robots, drones and many IoT projects. UDOO x86 is available in three variants with the basic version equipped with Intel Atom X5-E8000; the advanced version equipped with Intel Celeron N3160 and the ultra version equipped with Intel Pentium N3710. The board can output its screen via HDMI and via MiniDP++ which can work simultaneously. UDOO x86 has on-board memory up to 8GB and up to 32GB for the eMMC Drive, also coupled with BLE, Wi-Fi, and Ethernet for communication. The board is equipped with 20 GPIO pins and can run several Linux distributions, Windows and Android. Lastly, UDOO BOLT is a portable, breakthrough supercomputer with AMD Ryzen Embedded V1000 SoC that goes up to 3.6GHz, also with an integrated Arduino-compatible platform. UDOO has been ivolved in various IoT projects in health sector [116], [117], and in agriculture [118].

F. CUBIEBOARD

Cubieboard is a widely considered IoT node platform [23], [119] produced by Cubietech. It uses Allwinner processor and can run several Linux distributions and Android. Cubieboard has a broad range of boards such as Cubieboard 1, Cubieboard 2, with Cubieboard 7 as the latest Cubieboard at the time of writing this article. For example Cubieboard 5 is generally considered an improvement on the Pi. Cubieboard 5 is implemented around an Allwinner SoC H8, which contains an

ARM-Cortex-A7 octa core CPU that goes up to 2.0GHz. The 2GB DDR3 memory is clocked at 480MHz, i.e., substantially slower than the ODROID-XU4. Cubieboard 5 comes with an advanced PowerVR SGX544 GPU clocked up to 700MHz and also supports OpenGL ES 2.0/1.1, OpenCL 1.1, DX 9_3. It is also enhanced with some features such as 2GB DDR3 memory, Wi-Fi + BT on board, Li-battery and RTC battery support. The board packs considerably more connectivity, including two USB 2.0 ports and one USB 2.0 OTG port, a FastEthernet port, on-board infra-red receiver, input and output jacks for analog audio, an HDMI connector and a SATA 2.0 connector. Cubieboard has been used for captivating projects such as Hadoop cluster [120], Cubieboard cluster [121]. Further information about these boards can be obtained from the Cubieboard Web Site [122].

G. RADXA ROCK

Radxa Rock [123] is a powerful single-board that comes with a quad core ARM processor, and Mali400-mp4@533MHz, OpenGL ES 2.0 as a graphics processing unit. Radxa Rock can run Android and several Linux distributions. Radxa Rock PRO is one of the latest version of Radxa, based on ARM Cortex-A9 processor running up to 1.6GHz, and comes with built-in intelligent power management system. The board also includes many peripherals such as Wi-Fi,Bluetooth, Ethernet connection, HDMI connection etc. Interesting projects have been developed through Radxa Rock, including a real-time speed-limit sign recognition [124].

H. RASPBERRY PI

Raspberry Pi [125], [126] is one of the most used SBC platforms with a variety of usage. It is a small, powerful, education-oriented computer board designed for scientists, students, academicians, and enthusiasts to develop IoT projects. It has a shape of a credit card with many features, and it has evolved over the years with major and minor updates as technology evolves day by day. The main features common to all Raspberry Pi version are the 5V power input via MicroUSB or GPIO header, the GPU (Broadcom VideoCore IV @ 250MHz, OpenGL ES 2.0), a CSI interface for connecting a camera module and the HDMI output.

There are various versions of Raspberry Pi boards, including Raspberry Pi 1 being the first Raspberry Pi board and Raspberry Pi 3+ being the latest Raspberry Pi board as of the time of writing. We will focus on the latest Raspberry Pi, as the reference for other Raspberry Pi. Raspberry Pi 3 Model B+ [127] released in March, 2018 is the latest product in the Raspberry Pi 3 range. It features a Broadcom BCM2837B0 SoC with a 64-bit quad core Cortex-A53 (ARMv8) processor running at 1.4GHz. It includes a 1GB LPDDR2 SDRAM with an integrated 2.4GHz and 5GHz IEEE 802.11b/g/n/ac wireless LAN, Bluetooth 4.2, BLE and a Gigabit Ethernet over USB 2.0. The board also includes an extended 40-pin GPIO header, full-size HDMI, 4 USB 2.0 ports, CSI camera port, DSI display port, 4-pole stereo output and composite video port, a micro-SD port and supports a Power-over-Ethernet.

Raspberry Pi boards can run many operating systems, including Raspbian Linux, Windows 10 IoT Core, Ubuntu Mate and Snappy Ubuntu Core. It also supports many programming languages such as JavaScript, C/C++ and Python. Raspberry Pi has a large community where people come together to learn about digital making with Raspberry Pi. Various interesting projects have emerged through Raspberry Pi, including a patient monitoring system [128] and home automation system [129].

I. OMEGA2

Omega2 [130], [131] is a SBC, cloud integrated, designed for building Internet of Things projects. It is advertised as the world's smallest Linux Server as it combines the power-efficiency of the Arduino, with the flexibilities of the Raspberry Pi. Omega2 comes with Mediatek MT7688 SoC chip which features a 580MHz MIPS CPU equipped with 64MB of DDR2 memory and 16MB of flash memory. In terms of connectivity, the board has an inbuilt Wi-Fi and supports 10/100Mbps wired Ethernet network. Omega2 comes in two version, the basic Omega2 and Omega2 plus. The board costs $5 USD where Omega Plus costs $9 USD because of its added features of having 128MB RAM and 32MB memory with a micro-SD slot.

Omega2 comes with 15 GPIO pins, 2 PWM, 2 UART, I2C and SPI. It is powered by 3.3V with average power consumption of 0.6W. It is modular and support many coding languages with simple drag and drop programming, with the ability to run Apache and FreeBSD. Omega2 will foster IoT application development and innovation, owing to its simple and easy use platform that comes at an affordable price.

J. NETDUINO

Netduino [132] board is an open source development platform based on the cortex-M microprocessor and uses the .NET MicroFramework to run its applications. It is similar to the Arduino platform but differs in its programmability using the Microsoft .NET development environment. Applications in Netduino boards are written in C#, which provides threading, automatic garbage collection, just to mention a few, to the toolbox. Netduino boards are compatible with Arduino boards. The board has built-in Ethernet and Wi-Fi for connectivity. Netduino boards comes with 22 GPIO pins, 6 of which supports PWMs, 4 UARTs (serial communication), I2C and SPI. Currently, the Netduino family consists of the Netduino 3, Netduino 2 and the original Netduino. The original Netduino (1st generation) and Netduino Mini (also 1st generation), have been replaced by the much more powerful Netduino 2 and Netduino 3. For example, the Netduino N2 plus comes with Cortex-M4 clocked at 168MHz paired with 384KB of flash and 100+ KB of RAM. Netduino provides a robust hardware reference platform that allows easy experimentation and rapid prototyping for academicians, students, enthusiast. Interesting projects have been developed through Netduino, including a Water level meter [8].

K. PANDABOARD

PandaBoard [133], [134] is a low cost, low power SBC development platform based on the OMAP4430 applications processor from Texas Instruments. It features a dual core Cortex-A9 MPCore with symmetric Multiprocessing (SMP) at 1GHz each. This allows for 150% performance increase over previous ARM Cortex-A8 cores. In addition, by providing expandability via on-board connectors, PandaBoard supports development of additional capabilities. Pandboard ES is the latest version which delivers extra MIPS with up to 1.2GHz dual core Arm CortexâĂ"A9 MPCOre performance, enabling software developers access to open OMAP4460 processor-based development platform. In addition to all the existing features of the OMAP4430 processor-based PandaBoard, PandaBoard ES also has a DSI expansion header, Bluetooth low energy-capable WiLink 6.0 combo connectivity module and a switch to control boot order. PandaBoard supports Android and Ubuntu distributions. Various IoT projects have been developed through PandaBoard, including a Prototype monitoring system for power line [135].

L. BEAGLEBOARD

Beagleboards [136] are low-cost, open source platforms for developers, students, innovators and enthusiasts in building IoT projects. The boards are community supported and run various Linux distributions and Android. Beagleboard comes in various models which include BeagleBone Black, Green, Blue, BeagleBoardâĂ"X15, BeagleBoardâĂ"xM, Beaglebone Enhanced and PocketBeagle. BeagleBone Black uses a 32-bit RISC architecture Cortex-A8 clocked up to 1GHz and paired with 512MB of DDR3 RAM and 4GB of eMMC Flash. The platform provides several interfaces like Ethernet, a full USB 2.0 port, a USB Type-A port for providing power supply and communication, a 5V barrel Power-Jack, a SD card slot, two 46-pin interfaces, an HDMI port, etc. The device is being supported by several operating systems like Ubuntu, Android, Debian, etc. The board was released in 2013. BeagleBone Blue is an all-in-one device running Linux and developed mainly for robotic use cases. It uses the Octavo OSD3358 microprocessor, which includes an ARM Cortex-A8 processor clocked at 1GHz. It is a powerful board which provides on-board sensors including accelerometer, gyros, magnetometer, barometer, and thermometer. BeagleBone Green is a joint product of the BeagleBone community and the Seeed Studio. It is based on the same hardware design of the BeagleBone Black with small modifications, and comes in two versions: Beaglebone Green and BeagleBone Green wireless. The wireless version is a slightly enhanced version of the basic Green version, which provides additional features in terms of WLAN and Bluetooth. Beaglebone Green Wireless features a WLAN baseband processor and RF transceiver supporting IEEE 802.11b/g/n and Bluetooth 4.1 but lacks an Ethernet port.

Beagleboard-xM was one of the earliest boards from BeagleBone community, with the objective of fast development for hobbyists and innovators. It is based on ARM processor and provides many intriguing features. PocketBeagle features an incredible low cost, slick design and simple usage, making PocketBeagle the ideal development board for beginners and professionals alike. SamCloud BeagleBone Enhanced is an ultra-powered embedded computer with the hardware design of BeagleBone Black with enhanced features. It is jointly produced by the Beaglebone community and SanCloud. The enhanced features a 1GB on-board DDR3 RAM (doubled the BeagleBone Black), 3 additional USB ports, on-board sensors which include accelerometer/gyro/compass, Barometer and temperature sensor, SPI flash for bootloader, Gigabit Ethernet and additional plug in Wi-Fi/Buetooth card (uses 1 USB port). Lastly, BeagleBoard-X15 is the most powerful among the beagleboards. It uses the Sitara AM5728 Processor, a dual Cortex-A15 clocked at 1.5GHz, two Cortex-M4 clocked at 212MHz and 2 CC66 DSPs clocked at 700MHz. The main processor is paired with 2GB DDR3 RAM and a dedicated 2D/3D graphics processor which can support up to two displays. Regarding the connectivity we have two Gigabit Ethernet ports, 3 USB 3.0 ports, full HDMI port, Audio I/O, TF card slot, extension header, camera port, eSATA interface. The BeagleBoard-X15 board is powered by a 12V Power Jack. Beaglebone boards have been used in achieving various IoT projects such as Smart Museum [137]. Beaglebone introduced The CryptoCape as the BeagleBone's first dedicated security daughterboard [138]. The cape adds specialized ICs that perform various cryptographic operations allowing the addition of a hardware security layer to one's BeagleBone project. Table 8 shows the comparison of Beagleboards.

M. TESSEL

Tessel [139] is an embedded system based on ARM cortex-M microprocessor designed for IoT applications. Tessel board is an open source hardware that runs JavaScript for controlling a wide variety of IoT devices. The recent version Tessel 2 [140], is a completely an open source project where all of its hardware and software materials are made available online. Tessel 2 is a robust IoT and robotics development platform that combines a microcontroller with a more powerful microprocessor. It is based on Atmel SAMD21 microcontroller with Cortex-MO+ processor running up to 48MHz. It comes with a 580MHz Mediatek MT7620n Wi-Fi System-on-Chip (WiSOC), a chip commonly used in access point and router platforms. The board comes with 68MB DDR2 RAM & 32MB flash sufficient to store applications [141]. In terms of connectivity, it has an improved Wi-Fi (IEEE 802.11b/g/n) compared to Tessel 1 and also features 10/100Mbps Ethernet for ultra-reliable wired connection. Tessel 2 runs JavaScript, supports Node package manager (whereas Tessel 1 was JavaScript-based and not compatible with the libraries from the Node.js ecosystem). The board has two USB ports, one micro-USB for power and programming, and two primary

TABLE 8. A comparison of Beagleboard in terms of computing, communication and connectivity.

Specifications	BeagleBoard-X15	BeagleBone Black	BeagleBone Blue	BeagleBone Green	BeagleBoard-xM	BeagleBone Enhanced	PocketBeagle
Processor	Sitara AM5728 dual core ARM Cortex-A15	AM335x single core ARM Cortex-A8	Octavo OSD335 single core ARM Cortex-A8	AM335x single core ARM Cortex-A8	AM37x single core ARM Cortex-A8	Sitara AM3358BZCZ100 single core ARM Cortex-A8	Octavo Systems OSD3358 single core ARM Cortex-A8 with NEON Floating Point Accelerator
Clock Speed	1.5GHz	1GHz	1GHz	1GHz	1GHz	1GHz	1GHz
GPU	PowerVR SGX544 3D graphics accelerator	PowerVR SG530 3D graphics accelerator	PowerVR SG530 3D graphics accelerator	SGX530 3D, 20M Polygons/S 3D graphics accelerator	PowerVR SGx 3D graphics accelerator	SGX530 3D, 20M Polygons/S 3D graphics accelerator	SGX530 3D, 20M Polygons/S 3D graphics accelerator
RAM (Memory)	2GB DDR3	512MB DDR3	512MB DDR3	512MB DDR3	512MB DDR2	1GB DDR3	512MB DDR3
Onboard storage	4GB eMMC flash, micro-SD	4GB eMMC flash, micro-SD	4GB eMMC flash, micro-SD	4GB eMMC flash, micro-SD	No NAND flash memory, micro-SD card supported	4GB eMMC flash	4KB I2C EEPROM, micro-SD
On-board connectivity	Dual Gigabit Ethernet	Fast Ethernet	802.11b/g/n, Bluetooth 4.1 and BLE	Fast Ethernet	Fast Ethernet (via USB hub with Ethernet)	Gigabit Ethernet and Wi-Fi/Bluetooth card via additional plug in	Wi-Fi via donlge or USB-Wi-Fi adapter
Size L×W (mm)	107.0×102	86.4×53.3	88.9×54.6	86.4×53.3	78.74×76.2	86.44×54.54	56.0×35.0
Media (Audio and Video/Display)	HDMI, add-on boards with parallel video data in/out, 3.5mm stereo in/out jacks	microHDMI, cape add-ons for both Video and Audio	SPI displays for video and add-ons, bluetooth for Audio	Via Cape only for video/display, Via cape or USB audio sound card for audio	DVI-D, S-Video, 3.5mm audio jack	HDMI for video, audio via HDMI interface, stereo	SPI displays
Cost ($) Starting at	249.00	49.00	79.00	44.00	149.00	52.96	25.00
I/O	157 digital pins, 3 PWM channels including 7×UART, 1×SPI and 1×I2C	65 digital pins, 8 PWM channels, 7 analog inputs including 4×UART, 2×SPI and 2×I2C	8×GPIOs via JST-SH, UARTs, SPI, I2C, 2-cell LiPO, analog, buttons, LEDs, 2×SPI and 1×I2C	65 digital pins, 8 PWM channels, 7 analog inputs including 6×UART and 1×SPI 1×I2C	GPIO, PWM, UART, I2C, JTAG	69 digital pins, PWM, analog inputs including 3×UART, 1×SPI and 1×I2C	44 digital pins, 4 PWM, 8 analog inputs, including 3×UART, 2×SPI and 2×I2C
Release Date	September 2016	April 2013	March 2016	NS	September 2010	NS	September 2017

NS:Not Specified

sets of ports. The board has planned support for Rust and other languages.

N. ESP8266 WI-FI MODULE

ESP8266 [142] is a small, cheap and powerful Wi-Fi module chip to build IoT projects. It is capable of either hosting an application or offloading all Wi-Fi networking functions from another application processor. ESP8266 is based on 32-bit L106 RISC Tensilica running at 80MHz and comes with 1MB of built-in flash memory. It supports 802.11b/g/n protocol, Wi-Fi Direct and soft-access point. The board features 16 GPIO pins, SPI, I2C, UART and ADC. The module comes in various models such as ESP8266 Olimex module. ESP8266 Olimex module is an improved version, which can be easily mounted on a breadboard and can easily access all the pins of the ESP8266 compare to the generic ESP8266 module where the number of accessible GPIO pins is quite limited, and also difficult to plug into a standard breadboard. ESP8266 Olimex board has an integrated USB-to-Serial converter as well as an on-board power supply.

ESP12 is another version of ESP8266 version which gives access to all the pins of the ESP8266. It is made to be integrated on PCBs. ESP8266 can function autonomously, using the on-board processors, or it can be program using the Arduino board. ESP32 is a recent version of the ESP series that features two independently controlled CPU cores with adjustable clock frequency ranging from 80MHz to 240MHz, with classic Bluetooth for legacy connection. The board supports Bluetooth Low Energy and includes peripherals such as capacitive touch sensors, hall sensors, SD card interface, Ethernet, high speed SPI, UART, I2S and I2C. ESP8266 has been involved in various IoT projects such as Wireless Gardening [143], cloud controlled ESP8266 Robot [143] and ambient monitoring [144].

O. PCDUINO

pcDuino [145] is a high performance mini PC platform that can run many operating systems, including Raspbian Linux, Android. It combines the benefit of an ARM based mini PC and Arduino ecosystem (pc + Arduino). pcDuino is backward compatible with Arduino shields to be installed on pcDuino with a simple translation board (T-board). It also provides support for programming languages such as Java, C/C++, python and more. pcDuino boards are good for Internet of Things projects as it provides less power compared to other Pi-boards. It outputs its screen to HDMI enabled TV or monitor via the built in HDMI interface. pcDuino baoard comes with 14 digital pins for GPIO, one UART RX, one UART TX, two PWM pins, two I2C pins, four SPI pins and six ADC pins. PcDuino is an established board which has come up with many interesting projects such as Human Gesture Controlled Robot [146]. Moreover, pcDuino comes in many models such as pcDuino4 Nano, pcDuino 1 Lite Wi-Fi, pcDuino2 and many more.

P. PARTICLE PHOTON & ELECTRON

Particle Photon & Electron is a microcontroller-based board that combines a powerful ARM Cortex M3 [100] microcontroller running at 120MHz. Particle Photon [147] contains a Wi-Fi chip in a tiny thumbnail-sized module which supports wireless data rates up to 65Mbit/s. Particle Electron [148] on the other hand, is the cellular version of Particle Photon with built-in cellular attributes in building cellular IoT products. Particle Photon and Electron have the same configuration in terms of memory and storage capacity which are 128KB of RAM and 1MB of flash memory. In terms of connectivity and I/O interfaces, Particle Photon connects to the Internet using the single band 2.4GHz IEEE 802.11b/g/n Wi-Fi. In addition, the board has 18 mixed-signal GPIO, 8 analog ADC inputs, 2 analog DAC outputs, 2 SPI, one each for 12S, I2C I/O, 9 PWM output pins and 1 micro-USB port [149]. In the case of Particle Electron, it uses U-blox SARA modules for 2G, 3G, LTE cellular connectivity and also includes 36 total pins: 28 GPIO pins (18 digital I/0 pins, 8 D0-D13,A0-A13), 1 pin for TX/RX, 2 GNDs, 1 pin each for VIN, VBAT, WKP, 3V3, RST [150]. Particle Electron comes with an on-board Li-Po charging, where this is absence in Particle Photon. Both Particle supports a real-time operating system (RTOS).

Q. CARAMBOLA2

Carambola2 [151] is a surface, single sided, Wi-Fi enabled Linux module, bundled with an open source development board for IoT projects. Caramobola2 is based on AR9331 SoC, which is clocked at 400MHz, and also featuring a 16MB of flash memory and 64MB DDR2 of RAM. Its operating voltage is 3.3V with its average power consumption to be 0.5W. It is Linux friendly with OpenWRT flash image and source code available at [152]. The board features an inbuilt IEEE 802.11b/g/n Wi-Fi, with 1×1 SISO with 150Mbps as the maximum data rate and 21dB output power. The length and width of Carambola 2 are 28mm and 38mm respectively, which is small and easy to embed. The board also features a USB port with one serial port, 2 Ethernet ports, one i2S, SLIC, SPDIF and 23 GPIO pins. Carambola board comes with all necessary hardware/software pieces to create 802.11s mesh network and IoT projects. The cost of the board is about $25 in 2018. Carambola2 has been involved in IoT projects including a Fleet Management System [153].

R. INTEL GALILEO AND EDISON

Intel Galileo development board is the first initiative of Intel in providing IoT projects [154]. Intel Galileo is an open hardware designed for students, academician, or researcher to develop useful projects or products. It is designed to be compatible with a wide range of Arduino being an Arduino-certified development board powered by Intel Quark SoC × 1000 at 400MHz, with 512MB RAM built in. It is designed to support shields that operate at either 3.3V or 5V with the core voltage operating at 3.3V. The board has 14 digital input/output pins, of which 6 can be used as PWM outputs. Other features include I2C bus, SPI, UART, VIN, USB port, micro-SD card slot. In terms of connectivity, the board has built-in Ethernet with support for Power over Ethernet (PoE). Intel Galileo comes in two versions: Intel Galileo and Intel Galileo Gen 2 [155]. The difference between both versions is that Intel Galileo have to operate at exactly 5V due to the lack of on-board regulator whereas Galileo Gen 2 has on-board regulator, so it may be powered with any suitable supply providing 7-15 VDC.

Intel Edison is an ultra-small computing platform powered by Intel ATOM SoC dual core CPU running at 500MHz coupled with an Intel Quark core at 100MHz including a 1GB LPDDR3 RAM and 4GB of flash storage. It also includes an integrated Wi-Fi, Bluetooth 4.0 LE, and support for Yocto Linux, python, Node.js and Wolfram. Intel also designed a development kit for the Edison that is compatible with Arduino and Breakout Board. The kit for Arduino has 20 GPIO pins, of which 6 can be used as analog inputs. The Intel Edison kit for Breakout Board consists of power supply, battery recharger, USB OTG power switch, UART to USB bridge and I/O header. Intel Galileo and Edison boards have been used in various IoT projects such as IoT based smart healthcare kit [156], Assisted living implementation in smart home [157]. Unfortunately, Intel Galileo and Edison are no longer in production, but the boards are still available.

S. BANANA PI

Banana Pi [159], [160] is a SBC in the category of Raspberry Pi. Banana Pi also can run NetBSD, Android, Ubuntu, Debian, Arch Linux, Raspbian operating systems. There are various models of Banana Pi, and the most recent have increased functionalities compare to the basic one. Banana PI BPI-M2 Berry (BPI-M2B) is one of the recent boards of Banana Pi. It is an open source hardware platform, using Allwinner V40 SoC and supports Wi-Fi and Bluetooth on board. It features a 64-bit quad core ARM Cortex-A7 processor running at 1.2GHz with 1GB DDR3 SDRAM and a Gigabit Ethernet port. It has the same size as Raspberry Pi 3 and includes 40 Pins Header, 28×GPIO, some of which can be used for specific functions including UART, I2C, SPI, PWM, I2S. Some other models of Banana Pi can be found on the Banana Pi website [159].

T. ORANGE PI

Orange Pi [161] is a SBC similar to Raspberry Pi. It has the capability of running Linux based operating systems and Android. It uses AllWinner processor with Gigabit Ethernet and Sata Port. The recent models of Orange Pi are Orange Pi Pc Plus, Orange Pi Plus 2, Orange Pi 4G-IoT, Orange Pi Mini 2 and Orange Pi zero. For example. Orange Pi Pc Plus uses Allwinner H3 quad core ARM Cortex-A7 1.6GHz, a Mali400MP2 600MHz as the graphics processing unit, 1GB DDR3 SDRAM, and 40 pins header compatible with Raspberry Pi B+. Further information about these models can be obtained from the Orange Pi website [161]. Orange

TABLE 9. A comparison of middle-end and high-end IoT devices in terms of computing.

Hardware Platform	Processing Unit	Clock speed	RAM	On-board Storage	GPU	Supply Voltage/Battery	Cost ($) Starting at	Project(s)
Samsung ARTIK 710/710s	octa core ARM Cortex-A53	1.4GHz	1GB DDR3	4GB eMMC	ARM MALI, 3D Graphics accelerator	3.7–5.0V via VIN	58.17 for 710 and 61.18 for 710s	[170]
Arduino Yun	ATmega32u4 and Atheros AR9331	16MHz and 400MHz	64MB DDR2	32KB and 16MB & micro-SD	N/A	5V via micro-USB	59.00	[171]
Odroid-XU4	Samsung Exynos5422 octa core (Quad ARM Cortex-A15 and Quad ARM Cortex-A7)	2GHz for A15, 1.4GHz for A7	2GB LPDDR3	micro-SD	ARM Mali-T628 MP6 @ 600MHz supports OpenGL ES 3.1/2.0/1.1 and OpenCL 1.2 full profile	5V/4A	59.00	[111]
WandPi 8M Pro	NXP iMX8M quad core ARM Cortex-A53 + ARM Cortex-M4	1.3GHz for A-53 & 266MHz for M4	2GB DDR4	8GB eMMC	Vivante GC7000Lite	5V via USB-C	179.00	[172]
UDOO NEO	NXP iMX 6SoloX with ARM Cortex-A9 core and a Cortex-M4 core	1GHz and 200MHz	512MB DDR3 (Basic) or 1GB DDR3 (extended and full)	micro-SD	Vivante, GC420 Integrated 2D/3D graphics accelerator	1×DC Micro USB 5V, 1×DC Power Jack 6-15V, 1× RTC Battery Connector	49.00	[173], [174]
Cubieboard 5	AllWinner SOC H8, octa core ARM Cortex-A7	2GHz	2GB DDR3	8GB NAND flash, micro-SD, 1×SATA 2.0 port	PowerVR SGX544 @ 700MHz supports OpenGL ES 2.0/1.1, OpenCL 1.1, DX 9_3	5V/2.5A DC, Lithium battery support	99.00	[175]
Radxa Rock Pro	quad core ARM Cortex-A9	1.6GHz	2GB DDR3	8GB NAND flash, micro-SD	Mali400-MP4@533MHz supports OpenGL ES 2.0	5V via DC jack or USB OTG input	99.00	[124], [176]
Raspberry Pi 3 Model B+	Broadcom BCM2837B0, quad core ARM Cortex-A53	1.4GHz	1GB LPDDR2	Micro-SDHC slot, USB Boot Mode	VideoCore IV @ 300/400MHz; OpenGL ES 2.0; H.264, MPEG-4 decode (1080p30); H.264 encode (1080p30)	5V/2.5A DC via micro USB connector, 5V DC via GPIO header	35.00	[128], [129], [177]
Onion Omega2	Mediatek MT7688 MIPS32 (24KEc)	580MHz	64MB DDR2	16MB & micro-SD	—	3.3V via GPIO header	5.00	[178]
NetDuino N3	ARM Cortex-M4	168MHz	164+KB	384KB for N3, 1.4MB for N3 Ethernet and N3 Wi-Fi	—	7.5-12 VDC	39.95 for N3, 45 for N3 Ethernet, 50 for N3 Wi-Fi	[8]
PandaBoard ES	OMAP4430 dual core ARM Cortex-A9	1.2GHz	1GB DDR2	SDHC	PowerVR SGX540 supports OpenGL ES 2.0, ES 1.1, OpenVG 1.1 and EGL 1.3	5V via micro-USB or DC jack	182.00	[135]
BeagleBoard-X15	TI AM5728 Dual ARM Cortex-A15 + Dual ARM Cortex-M4 + Quad PRU	1.5GHz	2GB DDR3	4GB eMMC	Dual PowerVR SGX544 3D Graphics accelerator	12V jack	249.00	[137]
Tessel 2	Mediatek MT7620n/Atmel SAMD21	580MHz /48MHz	68MB DDR2	32MB	—	3.3V	44.95	[179]
ESP 8266	L106 32-bit RISC	80MHz	160KB	512KB-16MB	—	3.3-3.6V	6.95	[143], [144]
pcDuino4 Nano	AllWinner H3 quad core ARM Cortex-A7	1.2GHz	1GB DDR3	micro-SD	Mali-400MP2@600MHz supports OpenGL ES2.0, OpenVG 1.1	5V/2A DC via micro-USB, 5V via VDD pin on 4-pin serial header	30.00	[146]
Particle Photon	STM32F205 ARM Cortex-M3	120MHz	128KB	1MB	—	via VIN (3.6VDC-5.5VDC) pin, USB Micro B connector	19.00	[180], [181]
Particle Electron	STM32F205RGT6 ARM Cortex-M3	120MHz	128KB	1MB	—	via VIN (3.9V-12VDC) pin, USB Micro B connector, LiPo battery	49.00	[182]
Carambola 2	Atheros AR9331	400MHz	64MB DDR2	16MB	—	2.97V-3.63V	25.00	[153]
Intel Galileo Gen 2	Intel Quark X1000 x86 Quark	400MHz	256MB DDR3	8MB, EEPROM 8KB, & SD	—	7-15V via DC jack or PoE	79.00	[156], [157], [183]
Intel Edison	Atom 2 core (Silvermont)	500MHz	1GB DDR3	4GB eMMC & SD	—	7-15V via DC jack	50.00	[184], [185]
Banana Pi M2 Berry	AllWinner V40 quad core ARM Cortex-A7	1.2GHz	1GB DDR3	micro-SD	Mali400MP2 @500MHz supports OpenGL ES 2.0, OpenVG	5V/2A via micro-USB	36.00	[186]
Orange Pi PC Plus	AllWinner H3 quad core ARM Cortex-A7	1.536GHz	1GB DDR3	8GB eMMC, micro-SD	Mali400MP2 @600MHz supports OpenGL ES 2.0	5V DC or GPIO header	23.99	[162], [186]
ZedBoard	ZYNQ™-7000 SOC XC7Z020-CLG484-1 dual core ARM Cortex-A9 + NEON FPU	667MHz	512 MB DDR3	256MB QSPI flash, SD/MMC port	—	12V DC	449.00	[187]
HummingBoard Gate	NXP i.MX6Q quad core ARM Cortex-A9	1.2GHz	4GB DDR3	micro-SD	Vivante GC2000, OpenGLIES 1.1/2.0,OpenCL 1.1E 3D GPU Support	7V-36V	83.00	[188]
DragonBoard 410c	quad core ARM Cortex-A53 (32/64-bit)	1.2GHz	1GB LPDDR3	8GB eMMC & SD 3.0	Qualcomm Adreno 306 GPU including OpenGLIES 3.0,OpenCL, DirectX	8V-18V	75.00	—

Pi have been used in various IoT projects including a High-Security Energy-Efficient Gateway for IoT Fog Computing Applications [162]. The specifications of the above-discussed boards are compared and depicted in Table 9 and Table 10.

There are other boards such as HummingBoard Gate [163], which is the first SBC to include an integrated mikroBUS™ socket offering an easy hardware configuration to MikroElektronika's wide range of click boards™ add-on modules. HummingBoard Gate can run several Linux distributions and Windows 10 IoT Core. Zedboard [164], [165] is another board worth mentioning, which is a low-cost development board based on the Xilinx Zynq-7000 All Programmable SoC. It provides a complete ARM based high-performance Processing System (PS) featuring a Dual

ARM Cortex-A9 MPCore with integrated memory controllers, floating point operations support and full Linux OS compatibility. The PS side of the board is tightly integrated with the Programmable Logic (PL, with Field-Programmable Gate Array (FPGA) capabilities). It has been involved in various IoT projects [166], [167]. Other families of zedboard belonging to the Zynq family includes MicroZed, PicoZed, UltraZed, Ultra96 and MiniZed [168]. These boards are manufactured by AVNET.

DragonBoard 410c [169] is the first development board based on a Qualcomm Snapdragon 400 series processor featuring advanced processing power, Wi-Fi, Bluetooth connectivity, and GPS, all packed into a board the size of a credit card.

VI. OPEN RESEARCH ISSUES AND RECOMMENDATIONS

The most important question for Internet of Things users and architecture developers is choosing the appropriate IoT device for one use. The previous sections provided deep understanding about different possibilities. Table 4, Table 5, Table 9 and Table 10 gives a summary about the platform detailed in this paper. There is no such thing as a 'best' IoT device. If there was, all the manufacturers would make that, and there wouldn't be any choice left. Instead, one must make tradeoffs between competing interests: The fastest chips tend to use more power than the slowest ones. The boards with the most I/O pins are bigger (and usually cost more) than ones with fewer features. For each application, there is a sufficient device to use. For instance, multimedia applications, real time applications etc, high performance platforms are advised. In this section, we pinpoint some specific research directions related to IoT device with some recommendation.

A. OPERATING SYSTEM

OS provides a layer of abstraction for the hardware by managing the resources on each IoT device [189]. A suitable execution model is required for an OS for handling concurrent application on IoT devices, because most IoT devices are resource constrained. The execution model must provide memory efficiency and energy efficiency to the communication components, which is a difficult task for an OS [190]. In addition, an OS must provide a full file system interface to efficiently map data into sectors thereby making writing and reading of data more efficient. This is essential for some IoT devices having less flash storage. Communication protocols must also be memory and energy efficient during device synchronization. Resource management are techniques to address this situation when considering the resource scarcity of IoT devices [38], [191]. Memory protection are areas where further research needs to be carried out in order to ensure reliability of IoT device especially in remote location [38].

B. SECURITY

With emergence of Internet of Nano-Things (IoNT), Internet of Everything (IoE) and Internet of Bio-Nano-Things (IoBNT), it becomes crucial to investigate on ways on providing security measures on the IoT device. As described in [192], software security alone has proven insufficient to protect devices against many known threats including DoS, distributed DoS, malware among others. Thus, it is essential for all IoT devices to be equipped with encryption chip on-board to resist very determined attackers that do not run commercial OS. The encryption chip essentially gives a trusted environment, which acts like a sort of strong foundation for which IoT systems can be built. IoT device security cannot be optional, thus, this area requires extensive research to provide minimum IoT device security. We can arguably predict that all future IoT devices will be equipped with encryption chips on-board.

C. MEMORY SPECIFICATIONS

Phase-change memory is a new-based non-volatile memory technology and considered as the top contender for realizing storage-class memory. It can provide high read and write speed, endure at least 10 million write cycles while avoiding the loss of data [193]. Recently, Intel released a 3D Xpoint universal memory technology called Optane [194], which is envisioned to replace DRAM owing to its performance and endurance. It uses byte addressing, which can endure write cycles 1000 times more than NAND flash and has 1000 times faster I/Os. Moreover, with the emergence of RRAM, this promises high-capacity, non-volatile data storage, with improved speed, energy efficiency and density compared to dynamic random-access memory (DRAM). Compatibility with IoT devices is an area where more research needs to be carried out. UFS [195] memory is considered as an alternative to eMMC by offering 600MB/s and 30% to 55% power reduction compared to 200MB/s of eMMC.

D. POWER SPECIFICATIONS/ BATTERY LIFE

Energy efficiency is an essential requirement that needs to be addressed. New models should be designed to facilitate and preserve the battery life. For instance, the usage of flash technology can offer power savings. Recent development of wake-ups radio also makes a huge impact in terms of reducing power consumption, but more research is required in this area. In addition, Embedded memory can play an important role in meeting energy requirements, as lower power and lower voltage operation, monolithic integration, faster read and write times, non-volatility, and higher capacity are ways that memory technology can help IoT devices achieve greater energy efficiency. For instance, to reduce the frequency of data transmissions designers must make greater use of local data buffering (storage), as batching data for transmission allows the frequency of transmissions to be significantly reduced.

E. SIZE

IoT devices are generally small in size with low cost, which makes the embedded technology to be small. The idea of shrinking transistor sizes onto microcontrollers and computer processors to enhance performance as well as to reduce

TABLE 10. A comparison of middle-end and high-end IoT devices in terms of communication, connectivity and dimension.

Hardware Platform	Size L×W×H or L×W (mm)	Media (Audio and Video/Display)	OS/IDE support	On-board connectivity	Low-level peripherals	Peripheral Interfaces (Camera/USB)	Release Date
Samsung ARTIK 710/710s	36.0×49.0	I2S audio interface, 4-lane MIPS DSI and HDMI/LVDS display, 4-lane MIPI CSI	Linux distributions, Arduino IDE, Artik SDK	Bluetooth 4.1 (BLE+Classic), 802.15.4/ Zigbee, 802.11a/b/g/n/ac, Ethernet support	108×GPIO pins SPI, I2S, I2C, UART, USB, GMAC, PWM	2×USB 2.0, 1×USB OTG	October, 2016
Arduino Yun	68.6×53.3	—	Supports OpenWrt Linux distribution and Linino OS	10/100Mbps Ethernet, IEEE 802.11b/g/n Wi-Fi support	20×GPIO pins including 7×PWM pins, 12×ADC, 1×UART, 1×I2C	1×USB 2.0	September, 2013
Odroid-XU4	83.0×59.0×18	On-board Audio codec, HDMI &DP 1080P, HDMI monitor	Linux (Ubuntu, Kali Linux), Android	10/100/1000Mbps Ethernet	expansion ports for GPIO, UART, I2C, I2S, SPI, PWM, ADC	1×USB 2.0, 2×USB 3.0	July, 2015
WandPi 8M Pro	85.0×56.0×25.0	HDMI display, I2S audio	Linux, Yocto, Ubuntu, Android	10/100/1000Mbps Ethernet, 802.11 a/b/g/n/ac Wi-Fi, Bluetooth 4.1 (BR+EDR+BLE)	40 pins header including GPIO, PWM, UART, SPI, I2C, I2S	1× USB 2.0	April, 2018
UDOO NEO	89.0×59.0	1×Micro HDMI/LVDS interface + touch (I2C signals), HDMI audio transmitter, 1×S/PIDF & I2S	Android, Linux UDOObuntu2 (14.04LTS)	10/100Mbps Ethernet for basic and full version, (802.11b/g/n Wi-Fi, BLE 4.0 for only for extended and full version)	32×GPIO extended (A9 dedicated) with 22×GPIO Arduino (M4 dedicated), 8×PWM pins, 6×ADC, 1×DAC, 3×UART, 1×SPI, 3×I2C, 2×CAN bus	1× USB 2.0, 1×USB OTG	October, 2015
Cubieboard 5	112.0×82.0×18.0	HDMI &DP 1080P @ 60Hz display output, HDMI audio out, 1×s/PIDF	Android, Ubuntu and Linux distributions	10/100/1000Mbps Ethernet, 802.11b/g/n Wi-Fi, BT 4.0	70×GPIO, including 2×PWM pins, 1×ADC, 2×UART, 1×SPI, 1×I2C	1× USB 2.0, 1×USB OTG	March, 2016
Radxa Rock Pro	100×80×30	S/PDIF, headphone jack, HDMI/LVDS	Android, Ubuntu	10/100Mbps Ethernet, Bluetooth 4.0, 802.11 b/g/n Wi-Fi	80×GPIO including UART, I2C, SPI, PWM, ADC, LCD	2× USB 2.0, 1×USB OTG	November, 2011
Raspberry Pi 3 Model B+	85.6×56.5×17.0	HDMI, MIPI DSI display port, MIPI CSI camera port, 4 pole stereo output and composite video port	Raspbian, Windows 10 IoT, OpenELEC, OSMC, Pidora, Arch Linux, RISC OS, Ubuntu	2.4GHz and 5GHz IEEE 802.11.b/g/n/ac wireless LAN, Bluetooth 4.2, BLE, 10/100/1000Mbps Ethernet	17× GPIO pins including UART, SPI, I2S, I2C	4×USB 2.0	March, 2018
Omega2	42.9×26.40	—	OpenWRT	IEEE 802.11 b/g/n Wi-Fi	15×GPIO including UART, I2C, SPI	1× USB 2.0	November, 2016
Netduino N3	79.5×53.3×12.3	—	.Net MicroFramework	10/100Mbps Ethernet for N3, IEEE802.11b/g/n Wi-Fi for N3 Wi-Fi	22×GPIO, 6×PWM pins, 6×ADC, 4×UART, 1×SPI, 1×I2C	1 micro-USB	December, 2016
PandaBoard ES	114.3×101.6	LVDS/HDMI display, analog audio via 3.5mm jack	Linux, Android, OpenBSD, FreeBSD, Firefox OS	10/100Mbps Ethernet, 802.11b/g/n Wi-Fi, Bluetooth 2.1 + Bluetooth EDR	14-pin JTAG, GPIO, UART, I2C	2× USB 2.0, 1×USB OTG	November, 2011
BeagleBoard-X15	107.0×102.0	HDMI, add-on boards with parallel video data in/out, 3.5mm stereo in/out jacks	Debian, Android, Ubuntu, Cloud9 IDE	Dual 10/100/1000Mbps Ethernet	157×GPIO pins including 7×UART, LCD, GPMC, 1×SPI, 1×I2C, 1×CAN bus	3×USB 3.0 Type A Host, 4×USB 2.0 Host, 1×micro-USB Type B	September, 2016
Tessel 2	76.2×50.8	—	OpenWRT	10/100Mbps Ethernet, IEEE 802.11b/g/n Wi-Fi	16×GPIO, including 4×PWM pins, 10×ADC, 1×DAC, 2×UART, 2×I2C	2× USB 2.0, 1 micro-USB	April 2016
ESP 8266	18×20	—	Zerynth, Arduino IDE	802.11 b/g/n Wi-Fi	16×GPIO, 10×ADC, 1×UART, 1×SPI, 1×I2S, 1×I2C	—	August, 2014
pcDuino4 Nano	64.0×56.0	LVDS/HDMI display, HDMI audio, analog audio via 3.5mm jack, I2S audio	Ubuntu MATE, Debian	10/100Mbps Ethernet	40-pin Raspberry Pi compatible header with UART, SPI, I2C, PWM, GPIOs	3× USB 2.0, 1×USB OTG	September, 2016
Particle Photon	36.58×20.32×6.86 (with headers), 36.58×20.32×4.32 (without headers)	—	FreeRTOS, Zerynth	IEEE 802.11b/g/n Wi-Fi	18×GPIO, 9×PWM pins, 8×ADC, 2×DAC, 2×SPI, 1×I2C 1×I2S	micro-USB	March, 2015
Particle Electron	50.8×20.32×12.7 (with headers), 50.8×20.32×7.62 (without headers)	—	RTOS, Zerynth	U-blox SARA-U260/U270 (3G) and G350 (2G) cellular module	30×GPIO, 13×PWM pins, 12×ADC, 2×DAC, 3×UART, 2×SPI, 1×I2C, 1×I2S, 2×CAN bus	micro-USB	January, 2016
Carambola 2	28.0×38.0	—	OpenWRT Linux	2×Ethernet, IEEE 802.11b/g/n Wi-Fi	23×GPIO including, UART, SPI, I2S	1×USB 2.0, 1× mini USB	March, 2013
Intel Galileo Gen 2	123.8×72.0	—	Linux, Windows IoT Core	10/100Mbps Ethernet	20×GPIO, 6×PWM pins, 12×ADC, 6×UART, 1×SPI, 1×I2C	1 ×mini-USB, 1× USB 2.0	April, 2013
Intel Edison	35.5×25.0×3.9	—	Yocto Linux	802.11 b/g/n Wi-Fi, Bluetooth 4.0	20×GPIO, 6×PWM pins, 6×ADC, 1×UART, 1×SPI, 1×I2C	1 ×micro-USB, 1× USB 2.0	September, 2014
Banana Pi M2 Berry	92.0×60.0	4-lane MIPI DSI display, RGB/LVDS panel, HDMI 1.4 1080P60, HDMI audio, I2S audio, analog audio via 3.5mm jack	Android, Linux, OpenBSD, NetBSD	10/100/1000Mbps Ethernet, 802.11b/g/n Wi-Fi, BT 4.0	28×GPIO including PWM, UART, SPI, I2C, I2S	4× USB 2.0, 1×USB OTG	May, 2017
Orange Pi PC plus	85.0×55.0	3.5mmJack /HDMI audio, CVBS/HDMI display/video	Android 4.4, Debian (Armbian, DietPi, Raspbian), Ubuntu, Lubuntu, OpenMediaVault, Kali, OpenWRT	10/100Mbps Ethernet, IEEE 802.11b/g/n Wi-Fi	40 pins header including GPIO, UART, SPI, I2C, I2S, CSI	3× USB 2.0, 1×USB OTG	April, 2016
ZedBoard	160.02×134.62	3.5mmJack, 24-bit stereo audio codec, HDMI output display/video, VGA connector	Linux distributions	10/100/1000 Ethernet, IEEE 802.11b/g/n Wi-Fi	PS & PL I/O expansion (FMC, Pmod, XADC)	1×USB OTG	October, 2012
HummingBoard Gate	102×69	HDMI output display/video LVDS, HDMI 1.4, DSI, Parallel	Linux, Windows 10 IoT core, Android	10/100/1000Mbps Ethernet, IEEE 802.11b/g/n Wi-Fi	36×GPIO, 3×PWM pins, 3×SPI, 1×I2C	4× USB 2.0	June, 2014
DragonBoard 410c	85mm×54mm	HDMI output display/video, 4-lane MIPS DSI, 2-lane + 4-lane MIPI CSI	Linux, Windows 10 IoT core, Android, Open Embedded	IEEE 802.11b/g/n Wi-Fi, Bluetooth 4.1	12×GPIO, 1×UART, 1×SPI, 4×I2C, 1×I2S	2× USB 2.0, 1×micro USB	August, 2015

size and cost has become more complex following the twilight of Moore's law. Significant research attention has been dedicated to address this problem. French microelectronics laboratory LETI, developed a new process of stacking thin layers of semiconductor material containing transistors, without degrading performance of the transistors. This result into the development of monolithic 3D chips, which behave like a single device, having the same size as the 2D chips, at the same time generating less hear and consuming less power. The bottom line, however, is that several electronics devices have reached a near-optimal form factor already and stretching further to get a cutting-edge miniaturization will be very expensive.

F. MOBILITY SUPPORT

Mobility and robotics are trending areas for the next generation of Internet of Things. This requires new models to support the mobility of IoT devices.

VII. CONCLUSION

The goal of the IoT is the reduction of human-machine interaction by enabling a smart, energy efficient and cost-effective way in its communication. This paper provides a systematic analysis on the IoT devices presenting their features along with their relevant use cases and limitations. The contributions are multi-fold. First, the IoT device concept, and its classification were provided, with the motivation to study and survey on various Internet of Things devices. Secondly, the basic concerns in IoT device design were discussed. Thirdly, a comprehensive survey of the recent and most-widely used embedded systems and boards in different classification are provided while focusing on key attributes including processing and memory capabilities, security features, connectivity and communication interfaces, size, cost and appearance, OS support, power specifications and battery life and listing some interesting projects for each device. Finally, open research issues and recommendations with future directions are provided. We believe this survey will stimulate the research community and pave the way towards more efficient and robust low-end, middle-end and high-end IoT devices.

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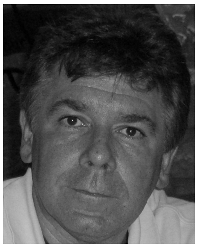

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