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A Survey of IoT Key Enabling and Future Technologies: 5G, Mobile IoT, Sematic Web and Applications

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Abstract The Internet of Things (IoT) is the communications paradigm that can provide the potential of ultimate communication. The IoT paradigm describes communication not only human to human (H2H) but also machine to machine (M2M) without the need of human interference. In this paper, we examine, review and present the current IoT technologies starting from the physical layer to the application and data layer. Additionally, we focus on future IoT key enabling technologies like the new fifth generation (5G) networks and Semantic Web. Finally, we present main IoT application domains like smart cities, transportation, logistics, and healthcare.

Keywords Internet of Things · 5G · Semantic Web · LTE · Smart City

1 Introduction

Internet of Things (IoT) is the new communications paradigm that will expand the current Internet and enable communication through machine to machine (M2M). Until recently, the Internet connected devices were directly controlled by humans and they were mostly computers, tablets and mobile phones. The IoT will enable to connect to the Internet every kind of device, including sensors and smart tags. This new era of ubiquity means that any device is connected to the network, anytime, anywhere, for anybody [76, 126]. The world of information and communication technologies has an additional dimension. This

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dimension means that from anytime and any place connectivity for anyone, the definition is extended to connectivity for anything. Figure 1 shows this new dimension.

The IoT current technologies cover the whole protocol stack starting from the physical layer to the application layer. Additionally, new IoT designed data layers emerged. In this paper, we try first to give a brief overview of all these technologies. For short range applications these among others include Radiofrequency identification (RFID) [134], Bluetooth Low-Energy (BLE) [46], Near Field Communication (NFC) [135], fourth generation of cellular systems (4G), IEEE 802.15.4 [65], and the recent IEEE 802.11ah [11]. For long range applications namely the Low Power Wide Area (LPWA) technologies include the LoRaWAN protocol [87] and the future cellular IoT. Moreover, Semantic Web technologies will also be a key enabler for IoT. In this paper, we elaborate on the future enabling technologies for IoT like fifth generation (5G) of cellular systems and Semantic Web.

Figure 2 shows the integration of current and future enabling technologies with IoT. These include the NB-IoT [1], the Semantic Web of Things (SWoT) [113], the Cognitive Internet of Things (CIoT) [136], and the CloudIoT [22] paradigms. Combination of all or some of the above paradigms is also an interesting option. The IoT paradigm will evolve, will move forward and will interact with the above-mentioned technologies. Additionally, the other technologies will benefit from IoT integration and will also evolve and expand.

The IoT era means a whole new world of applications and services. These include the Smart City application where a set of smart sensors and IoT devices monitors everyday city activities and helps in forecasting, reducing energy consumption, and among others avoiding traffic congestion. Additional application domains for IoT systems include the transportation, logistics, and the healthcare. In this paper, we review all the above domains and discuss technology enablers and testbed cases.

The rest of the paper is organized as follows. Section 2 provides a brief overview of all current IoT technologies. Section 3 highlights and reviews key future enabling technologies like 5G and Semantic Web. The IoT basic application domains are examined in Sect. 4, where technologies and testbeds are presented. Finally, the conclusions are being enlightened in Sect. 5.

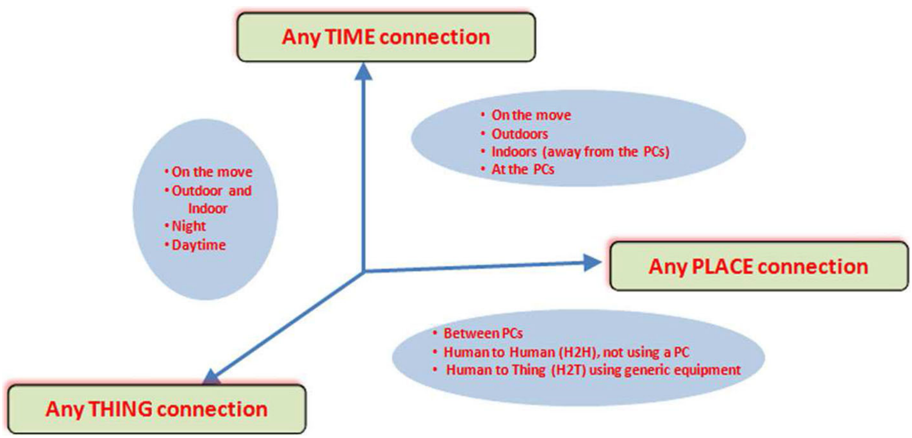

Fig. 1 A new dimension in the world of information and communication technologies [126]

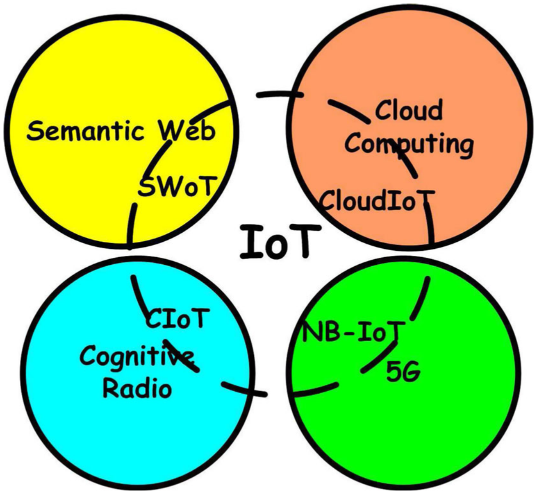

Fig. 2 Enabling technologies and IoT integration

2 Current IoT Technologies

In this section we provide a brief description of the key technologies and elements for IoT. A sample protocol stack for servers and IoT nodes is depicted in Fig. 3. We notice that the IoT stack is different from the common host stack in Internet. The protocol stack for IoT nodes consists of constrained or compressed versions of common protocols. There are several options for the physical layer, while for MAC layer the most common option is IEEE 802.15.4. The network layer requires the use of an adaptation protocol like 6LoWPAN in order to compress and fragment the IPv6 headers. In the transport layer UDP is used, while in the application layer a constrained version of HTTP Constrained Application Protocol (CoAP) is utilized. The data layer uses the compressed XML format the Efficient XML Interchange (EXI) protocol.

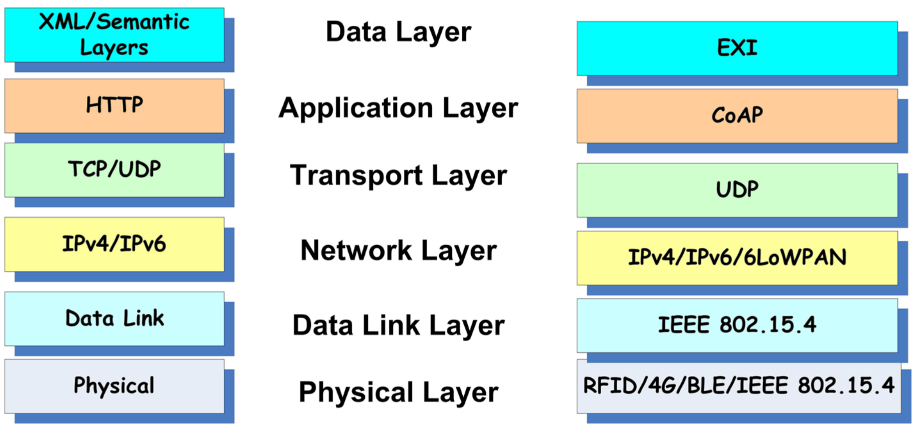

Fig. 3 Protocol stacks for hosts (*left*) and (*right*) for IoT nodes

2.1 Physical and Data Link Layer Technologies

Among others the physical layer technologies used in IoT nodes include Radiofrequency identification (RFID), Bluetooth Low-Energy (BLE), IEEE 802.15.4, IEEE 802.11ah, Near Field Communication (NFC), and will include the future fifth generation (5G) of mobile communications. RFID [134] has gained considerable growth in the last decade and remains in the front end of the general research and development sector concerning the remotely receiving and transmitting data using RF waves. The information stored in the RFID tag is unique identification number called Electronic Product Code (EPC). EPCs can be 96-bit or 64-bit long. A performance analysis of the current EPCglobal Gen 2 RFID protocol versus a CDMA approach can be found in [130].

Nowadays the RFID technology providing automated wireless identification and tracking capability and being more robust than the barcode system, has shown a commercial worldwide deployment following frequency allocation in the UHF band, ranging from 860 to 950 MHz [107]. An ordinary RFID system comprises of at least, a reader (Interrogator) with a reader antenna, tags (transponders) which are microchips combined with an antenna in a compact package, a host computer and middleware including software and data base. An overview of criteria for RFID tag antenna design and an analysis of practical application aspects can be found in [45, 107].

NFC is a set of short-range wireless protocols, that work at close range of about 10 cm or less [135]. The operating frequency for NFC is 13.56 MHz and the data rates are small ranging from 106 kbit/s to 424 kbit/s. NFC defines two entities an initiator and a target; the initiator actively generates an Electromagnetic field that be used for powering the passive target. Thus, NFC targets can be very simple devices like unpowered tags, stickers, or cards. Moreover, NFC permits peer-to-peer communication, however, in that case both devices should be powered. Bluetooth low energy (BLE) [46] is a new wireless personal area network technology designed by the Bluetooth Special Interest Group. BLE provides considerably reduced power consumption and cost while maintaining a similar communication range. BLE provides also high-speed and IP connectivity, which makes it suitable for IoT nodes [4, 76].

The IEEE 802.15.4 5 defines the operation for both physical and data-link (media access control) layers for low-rate wireless personal area networks. (LR-WPANs). products. IEEE 802.15.4 provides low-cost and low-power wireless connectivity within short ranges of up to 20 m. Thus, it is suitable for use in WSNs, M2M and IoT. Another IEEE 802.15.4 advantage is the fact that it supports a large node number (about 65,000). However, it lacks support for QoS. A standard which is a competitor of IEEE 802.15.4 is IEEE 802.11ah [11], which is a new WiFi standard targeting at IoT nodes using a low power consumption and larger range. A feasibility study of IEEE 802.11ah radio technology for IoT and M2M use cases can be found in [56]. The authors in [98] compare performance of IEEE 802.15.4 and IEEE 802.11ah. They conclude that IEEE 802.11ah performs betters in cases of congested networks; however 802.15.4 outperforms the IEEE 802.11ah in terms of energy consumption.

2.1.1 Antenna Design Challenges for IoT Technologies

One of major challenges in today s RFID technologies that could potentially impede their practical implementation is the design of small size tag antennas with high efficiency and effective impedance matching to ICs with typically capacitive reactance. These antenna requirements are essential to optimize the RFID system power performance, especially for passive configurations where the only energy source is the incoming reader energy. Several RFID design cases for both passive and active tags can be found in the literature. Among others, these include covered slot antenna design [28], circular patch antenna analysis [99], planar inverted F-antenna [61], folded dipole antenna [138], U-shaped antenna [6], compact strip dipole [71], and patch antennas [63, 146].

The most commonly used shapes for RFID tags are those of meander line [2, 17, 24, 102], and spiral line [5, 16] due to the characteristics of high gain, omnidirectionality, planarity and relatively small surface size. Additionally, printed fractal antenna configurations exhibit similar attributes and recently several types of them have been proposed as efficient tag antennas [82, 94].

There are several antenna design challenges for IoT and 5G applications. RFID antenna tag design for IoT applications is more complex than a regular antenna. Instead of matching the tag input impedance to a constant value like 50 Ω the tag antenna input impedance is required to be conjugate matched to the IC input impedance. The chip input impedance has relatively low real part value and high capacitive imaginary part value. Thus, the RFID antennas input impedance should have an inductive imaginary part of equal value. Additionally, the second design requirement for a tag antenna is to be of small size. However, this requirement is difficult to fulfill when high antenna gain is also needed. Therefore, two main optimization objectives for RFID tag design can be gain maximization and conjugate matching. These objectives can be combined in one objective function as in several papers, which can be described by [49–51]

$$F_1(\bar{x}) = -G(\bar{x}) + \Xi \times |\max\{0, |\Gamma| - 0.3\}| \tag{1}$$

where $\bar{x}$ is the vector of the unknown parameters of the antenna geometry, G is the antenna Gain calculated, Ξ is a very large number, and Γ is the (load dependent) reflection coefficient of the tag antenna-load system which is computed by:

$$\Gamma = \frac{Z_{in,chip} - Z^*{}_a}{Z_{in,chip} + Z_a} \tag{2}$$

where $Z_{in,chip} = R_{in,chip} + jX_{in,chip}$ is the chip input impedance and $Z_a = R_a + jX_a$ the tag input impedance respectively.

Moreover, another important parameter of the RFID system performance, is the read range. That is the maximum distance at which RFID reader can detect the backscattered signal from the tag antenna. As reader sensitivity is typically high in comparison with the tag, the read range is defined by the tag response. Therefore, we can define the read range using the Friis free-space formula as [107]:

$$R = \frac{\lambda}{4\pi}\sqrt{\frac{P_{EIRPrd} e D_{tag} p_{loss} \tau}{P_{in,chip}}} \tag{3}$$

where P_{EIRPrd} is the effective isotropically radiated power by the reader, D_{tag} is the tag directivity, e is the tag efficiency, p_{loss} is the polarization loss factor (represents the loss of EM power because of polarization mismatch $0 \le p_{loss} \le 1$), $P_{in,chip}$ is the power absorbed by the chip given by:

$$P_{in,chip} = \left(1 - |\Gamma|^2\right) P_{tag} \tag{4}$$

where P_{tag} is the available power at the input of the tag antenna, and τ is the power transmission coefficient given by:

$$\tau = \frac{4R_a R_{in,chip}}{\left|Z_{in,chip} + Z_a\right|^2} \tag{5}$$

More details about the RFID antenna design can be found in [51, 107].

Additionally, IoT devices will use the future 5G cellular network. One of characteristics of the future 5G framework of cellular systems will probably be the use of millimeter wave frequencies. These frequencies will allow the use of the wide available spectrum compared with the current 4G systems. The expectation is to offer to users multi-Gigabit-per-second (Gbps) services. The Antenna design for the new mobile devices seems to be also a challenging task. A possible solution for this case is expected to be the use of microstrip patch antennas. Such antennas have several advantages like low profile, low cost and ease of fabrication. Several design efforts have been already carried out on this field achieving good performance in mm-wave frequency band. Shaped apertures have been also proposed to feed the antenna elements, providing dual band operation, high gain, wide bandwidth and dual polarization characteristics to the antenna [18, 66, 67, 147].

A possible solution could be as in [52] to use E-shaped patch antennas that allow dual band operation. These E-shaped patch antennas [70, 143] extend the rectangular patch functionality and bandwidth by incorporating slots in the patch to introduce multiple resonances. They are suitable for dual-band or wide-band designs. The design in mm-wave frequencies could be employed using aperture coupled feeding [106]. Another design implication for this case is that the feeding should be modified in order to allow dual band operation. One solution is the modification of the aperture shape to enable dual band operation [52]. This can be accomplished using a H-shaped aperture that resonates in two operating frequencies. The geometrical parameters of both the patch and the aperture need to be determined in order to satisfy the performance requirements at the desired frequencies. The geometry of an aperture coupled E-shaped patch antenna consists of two parallel slots that are incorporated into the rectangular patch. The aperture is modified to an H-shaped, which introduces two possible lengths to generate different resonant frequencies. The antenna geometry complexity makes it difficult or even impossible to estimate the effect of each design parameter in order to achieve the desired antenna performance. Thus, an optimization technique should be employed for this antenna design case [52].

2.2 Network Layer Technologies

The Internet Protocol version 4 (IPv4) is the main technology at network level that Internet hosts support. The IPv4 addressing principle requires a global unique IP address for every interface connected to the Internet. The IP address space is managed by the Internet Assigned Numbers Authority (IANA) globally. IANA has recently announced the exhaustion of IPv4 address blocks. This is one of the reasons for the deployment of an IPv4 successor protocol the IPv6. The IPv6 standard [148] uses 128-bit IP addresses, therefore it is possible to assign a unique IPv6 address to any possible node in the IoT network.

However, IPv6 header introduces overheads that could be a problem in small data rate capabilities of IoT nodes. IPv6 datagrams require a minimum MTU of 1280 bytes. This size is impossible to handle over a IEEE 802.15.4 MAC with maximum frame size of 127 bytes. Therefore, an additional adaptation layer is required to fit IPv6 packets into shorter IEEE 802.15.4 frames. A solution to this problem comes with the introduction of 6LoWPAN (Low power Wireless Personal Area Networks). 6LoWPAN works at network level and it is an adaptation layer that fits IPv6 packets into smaller IEEE 802.15.4 frames [64, 100]. This is accomplished by compressing the IPv6 header. 6LoWPAN compresses the IPv6 header by removing the not needed fields, by removing fields that have always the same content and by compressing the IPv6 addresses by inferring them from link layer addresses. An example of 6LoWPAN operation is depicted in Fig. 4. One may notice that without IPv6 header compression there only 33–54 maximum bytes left for payload. The smaller number corresponds to IEEE 802.15.3 security options. Using 6LoWPAN the 40-bytes IPv6 header is compressed to 2–3 bytes, thus leaving 71–92 bytes for payload. Additionally, 6LoWPAN defines a header encoding scheme to support fragmentation for large IPv6 datagrams. In case of fragmentation, the 6LoWPAN header size is 4–5 bytes and it consists of the fields datagram size (11 bits that hold the size of the datagram being fragmented), the datagram tag (16 bits that is the number of the fragment), and datagram offset (8 bits that show the offset withing the original datagram).

Thus, 6LoWPAN standard uses header compression in order to reduce the transmission overhead, fragments the IPv6 packets to meet the IPv6 Maximum Transmission Unit (MTU) requirement, and forwards packets to data link-layer to support multi-hop delivery [80, 93]. A possible implementation of 6LoWPAN in a Smart City could involve the use of a border router like in [141]. The border router is directly connected to the 6LoWPAN network and transparently performs the conversion between the IPv6 and 6LoWPAN networks. Therefore, it translates any IPv6 packet intended for a node in the 6LoWPAN network into a packet with 6LoWPAN header compression format, and operates the inverse translation in the opposite direction.

2.3 Transport and Application Layer Technologies

Transmission Control Protocol (TCP) is the most commonly used transport layer protocol in the Internet today. TCP is connection-oriented and uses flow control and congestion control mechanisms. The above requires additional header overhead, thus making it not well suited for IoT nodes. An alternative solution to TCP is User Datagram Protocol (UDP), which uses a minimum header overhead and it is connectionless. Therefore, UDP is the common solution for transport layer protocol in IoT nodes.

HTTP is one of the most commonly used application layers. However, HTTP is quite complex and verbose, thus it is not suitable for use on IoT nodes. Additionally, HTTP lies

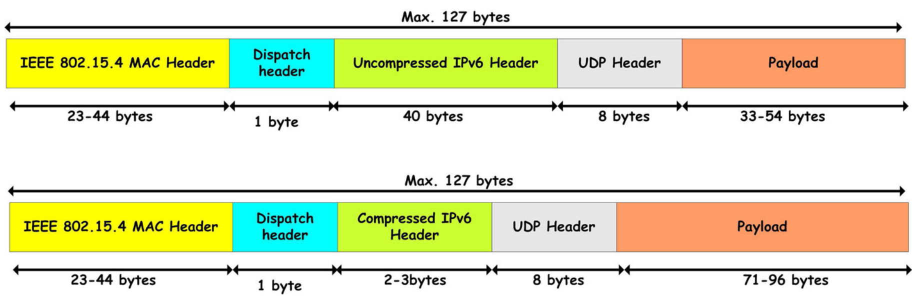

Fig. 4 6LoWPAN frames without and with IPv6 header compression

above TCP so the combination is very resource consuming for IoT nodes. The solution to overcome this problem is the use of the Constrained Application Protocol (CoAP) on IoT nodes [21, 118]. CoAP is an HTTP equivalent protocol for low power devices over UDP. The CoAP defines a web transfer protocol based on REpresentational State Transfer (REST) on top of HTTP functionalities. REST represents a simpler way to exchange data between clients and servers over HTTP. The CoAP interaction model is client/server similar to HTTP. CoAP proposes a binary format over UDP and handles only the re-transmissions strictly required to provide a reliable service. The main CoAP header is four bytes long. Additionally, the total header size followed by options is 10–20 bytes long. CoAP uses the well-known from HTTP methods like GET, PUT, POST, and DELETE. The CoAP response codes are encoded in a single byte e.g. the "404 page not found" response becomes 4.04 in CoAP. The CoAP uses two layers the Message layer and the Request/Response layer as it is depicted in Fig. 5a. The bottom Message layer works with UDP. The Message layer provides reliability over UDP by marking a message as Confirmable (CON). The Request/Response layer deals with communication between client and server using Request/Response messages, which include either a Method Code or a Response Code, respectively. Moreover, CoAP can interoperate with HTTP. The communication between IoT nodes and the rest the Internet hosts can be accomplished with the

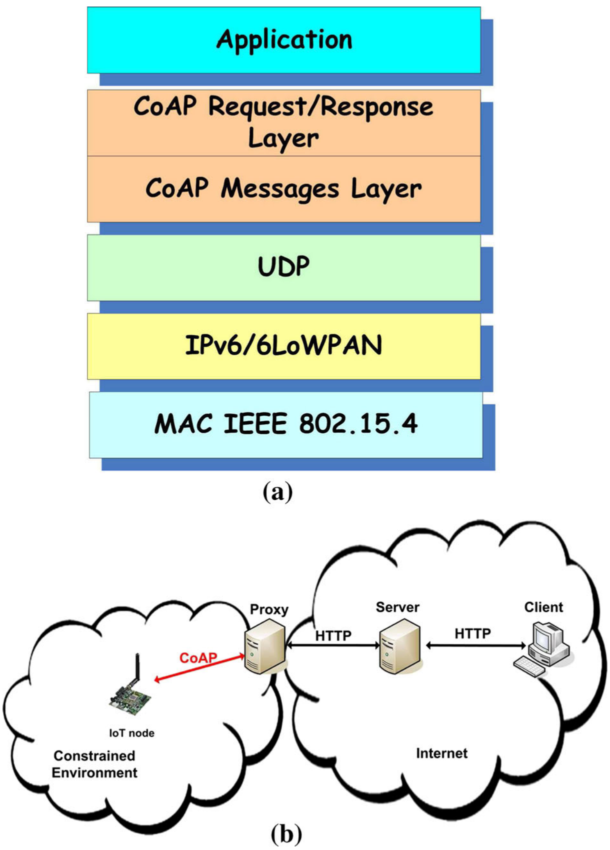

Fig. 5 **a** CoAP protocol stack and **b** CoAP and HTTP web architecture

use of a so called cross proxy that translates HTTP to CoAP and vice versa. That way the communication between IoT devices and the rest of the Internet hosts is transparent and straightforward. Figure 5b shows an example of such a web architecture.

The next evolution of IoT is the Web of Things (WoT) [54]. WoT evolves the IoT with a common stack based on web services.

2.4 Data Layer Technologies

Efficient XML Interchange (EXI) is a binary XML format for exchange of data defined by the World Wide Web consortium (W3C) [73]. EXI is significant because it is designed to optimize XML applications for resource-constrained environments. The main task of EXI is to encode XML documents in a binary data format, rather than plain text. Therefore, EXI reduces the verbosity of XML documents and it is suitable for low power devices and limited bandwidth environments. Additionally, EXI minimizes the required storage size.

W3C developed EXI around five key design principles. The EXI format had to be general, minimal, efficient, flexible, and interoperable. The first two features general and minimal resolve to the non-invasiveness of EXI. Efficiency is provided by several components such as the compact nature of EXI streams and the fact that EXI uses information from the XML schema to improve compactness and processing efficiency. EXI provides flexibility by handling documents that contain arbitrary schema extensions or deviate from their schema. EXI is interoperable by integrating well with existing XML technologies, thus minimizing the changes required to those technologies. Moreover, EXI is compatible with the XML Information Set. EXI represents the contents of an XML document as an EXI stream. The EXI streams consist of an EXI header and a EXI Body. Figure 6a depicts the format of an EXI stream. The EXI header contains the encoding properties that are needed to decode the EXI body. A minimal EXI header can be have the size of a single byte. The EXI body consists of a sequence of EXI events. The XML items are encoded into one or more EXI events.

An EXI Processor performs the EXI compression at the highest level. This processor could have the role of either an EXI Encoder or an EXI Decoder. A typical EXI data processing workflow of an XML document is shown in Fig. 6b. EXI has the capability to compress XML documents into a structured sequence of bytes without the verbose tagged structure. The compression ratio could vary from 1.4:1 to 100:1 for typical XML documents. EXI is a knowledge based encoding that uses a set of grammars to determine which events are most likely to occur at any given point in an EXI stream and encodes the most likely alternatives in fewer bits. EXI defines two encoding types; schema-less and schema-

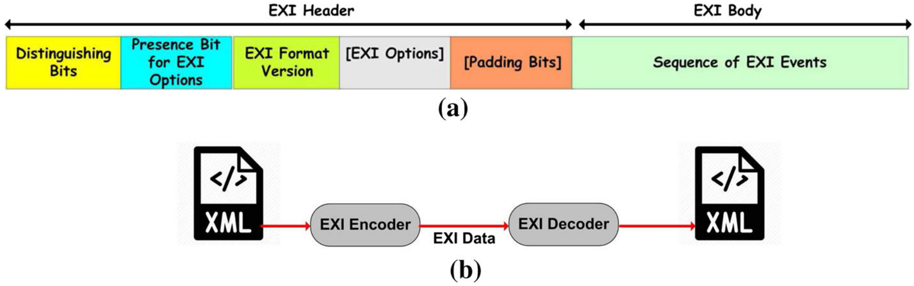

Fig. 6 **a** EXI stream and **b** EXI dataflow

informed. In the first type when no XML schema information is available, EXI uses a set of built-in grammars to encode XML documents and XML fragments. In case of known schema information [i.e. known XML Schema Definition (XSD)], then the EXI grammars can be further improved. All the above-mentioned reasons make EXI suitable for data exchange from IoT nodes.

3 Future and Enabling Technologies for IoT

This section describes future enabling technologies that will play an important role in IoT deployment. Among others, we will present the future cellular IoT technologies and the use of Semantic Web in IoT.

3.1 Low Power Wide Area for Mobile IoT Technologies

Low Power Wide Area (LPWA) technologies support the use of low power, low data requirements and long range operation devices. These include a proprietary solution from LoRa Alliance LoRaWAN [87], and the current and future cellular technologies. LoRaWAN defines the communication protocol and system architecture for the network while the LoRa physical layer enables the long-range communication link. LoRaWAN operates at unlicensed frequency bands below 1 GHz, which are different for each world region. In Europe the LoRa Alliance defines operation at 867–869 MHz, the uplink and the downlink bandwidth is 250 and 125 KHz respectively.

LoRaWAN technology is quite recent so we havent been able to find a large number of papers dealing with it in the literature. We have found a total of 16 papers in the scopus database ranging from 2015 to 2017. Most of them are conference papers. The authors in [92] analyze the LoRa protocols in Europe frequency bands by obtaining uplink throughput and data transmission time for a single LoRaWAN node. They have shown that the capacity of the uplink channel available to a LoRaWAN node strongly depends on the distance from the base station and does not exceed 2 kbit/s. Moreover, the LoRa performance and scalability is the subject of another recent paper [20] where the authors study the capacity limits of LoRa networks. They have developed models that describe LoRa communication behavior and use these models in a simulation to study scalability. Additionally, in [129] the authors study the MAC layer of the LoRaWAN protocol, and more specifically the on-the-air activation procedure. In [105] the authors evaluate the LoRa performance using measurements. They used commercially available equipment that operated at 868 MHz and they had measured the packet success delivery ratio to be 96.7%.

Fourth generation (4G) technology includes the Long Term Evolution-Advanced (LTE-A) standard [48]. LTE Advanced is a major enhancement of the Long Term Evolution (LTE) standard. LTE-A added support for bandwidth extension up to 100 MHz, support for downlink and uplink spatial multiplexing using MIMO, and obtains higher throughput and lower latencies compared to LTE. A search in scopus database reveals 178 total papers regarding LTE and IoT. Figure 7 depicts the paper numbers over the recent years since 2010. We notice that the number of LTE and IoT related papers rises almost exponentially.

LTE-A has been utilized in [31] for convergence between a LTE-A network and a wireless sensor network (WSN). The main objective of the authors was to build a machine-to-machine (M2M) network capable of meeting Quality of service (QoS) issues. Moreover, the authors in [85] optimize the discontinuous reception/transmission (DRX/DTX)

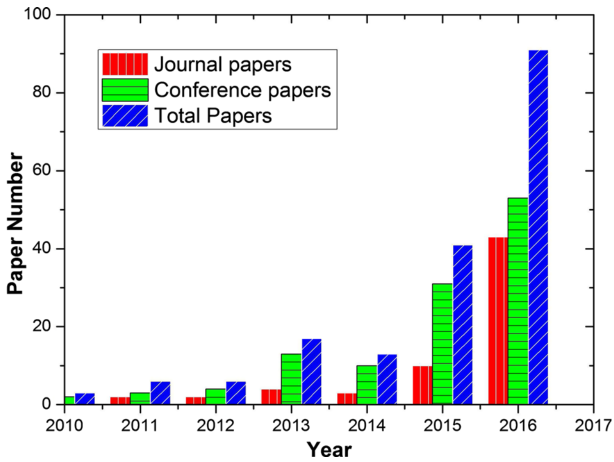

Fig. 7 Number of papers for LTE and IoT

mechanism of LTE-A that allows devices to turn off their radio interfaces and go to sleep. The optimization is performed in terms of energy cost.

However, current LTE-A devices are not specifically made to meet the requirements to support the IoT nodes. As a result, 3GPP focuses on standardization efforts for IoT capable cellular devices. The main requirements for such devices as it is reported in a recent white paper from Nokia [97] are long battery life, low device cost, low deployment cost, extended coverage, and support for a massive number of devices. The two main new technologies that will lead to new standards are eMTC (enhanced Machine Type Communication, often referred to as LTE-M) and NB-IoT (NarrowBand-Internet of Things) [36, 53, 108–111, 127]. LTE-M or LTEM2M was released in LTE Advance Pro Release 12 in 2014, while additional specifications are included In rel 13 [36, 97, 109, 111, 127]. LTE Release 12 introduced a new user equipment type called (UE) Category 0. That UE includes features like reduced peak data rate, half duplex operation with relaxed RF requirements, and a single receive antenna [111]. Additionally, eMTC introduced a set of physical layer features with the objective reduce the cost and power consumption. These features include narrowband operation, low cost, simplified operation, transmission of downlink control information, extended coverage, and frequency diversity by RF retuning [111].

An overview of the additional features in the latest LTE release 13 is given in [111]. The authors in [62] present a brief look into the future LTE Release 14. The main new features according to the authors will be including latency reductions, enhancements for machine-type communication, operation in unlicensed spectrum, massive multi-antenna systems, broadcasting, positioning, and support for intelligent transportation systems. Moreover, the authors in [9] provide a comprehensive review of the most prominent existing and novel M2M technologies, and discuss about the first real-world deployment experiences.

The M2M technologies in LTE-A is the subject of another review paper [90], where the authors present network architectures and reference models for M2M communication and also give an overview of the future M2M services that are expected in 5G networks. Additionally, the authors in [58] propose a traffic-aware Access Class Barring (ACB) scheme to improve the scalability of M2M networks. Their simulations results show that the proposed scheme outperforms the traditional ACB scheme. The introduction of a new connection-less communication protocol for IoT systems over LTE mobile networks is given in [72], where the authors present simulation results to prove its effectiveness. The problem of uplink resource and power allocation problem for energy conservation in LTE-A networks is addressed in [26]. The authors minimize the total energy consumption subject to QoS constraints.

NB-IoT is expected to be the main IoT over LTE technology in the next years. The bandwidth in NB-IoT is decreased to 180 kHz compared to eMTC. However, as a result of the bandwidth reduction the device complexity is also reduced and the peak data rate is also further reduced (around 50 kb/s for uplink and 30 kb/s for downlink). Additionally, NB-IoT UEs can only support limited mobility procedure and low data rates. On the other hand, eMTC supports applications with higher data rate and mobility requirements. NB-IoT [110] can be deployed in three different operation modes. These are stand-alone as a dedicated carrier, in-band within the occupied bandwidth of a wideband LTE carrier, and within the guardband of an existing LTE carrier (Fig. 8). NB-IoT uses a bandwidth of 200 KHz in stand-alone operation mode (GSM channel), while in the two other operating modes NB-IoT it will operate on a one physical resource block of LTE with a bandwidth of 180 kHz. NB-IoT latest specification was in Rel. 13 in June 2016. Initially, the NB-IoT was firstly introduced in Rel. 13, June 2016 while in the forthcoming Rel. 14 (June 2017) the NB-IoT will be finalized. This date fully coincides with the first commercially available products (Fig. 9). Additionally, a new standard supporting older 2G GSM networks has emerged. EC-GSM-IoT (Extended Coverage GSM for IoT) is based on eGPRS and designed as a high capacity, long range, low energy and low complexity technology. EC-GSM-IoT networks will co-exist with current mobile networks. The pilot trials for this new protocol have begun, while the first commercial products will be launched in 2017.

3.2 5G and IoT

The next fifth generation (5G) Radio Access technology will be a key component of the Networked Society. 5G will support massive numbers of connected devices and meet the real-time, high reliability communication needs of mission-critical applications. 5G will provide wireless connectivity for a wide range of new applications and use cases, including wearables, smart homes, traffic safety/control, critical infrastructure, industry processes and very-high-speed media delivery. As a result, it will also accelerate the development of the IoT. The 5G technology will become a key driver for global IoT. The main features of the new 5G technology are reviewed and presented in [3, 47, 96, 125]. These new features include very high data rates (typically of Gbps order), extremely low latency, a huge increase in base station capacity, and significant improvement in users' perceived quality of service (QoS). We have searched the Scopus database and found a total of 167 papers

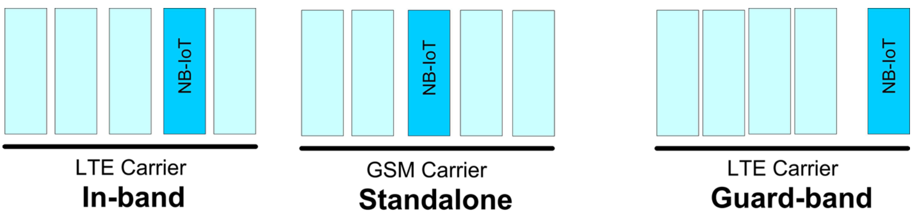

Fig. 8 NB-IoT different deployment cases [97]

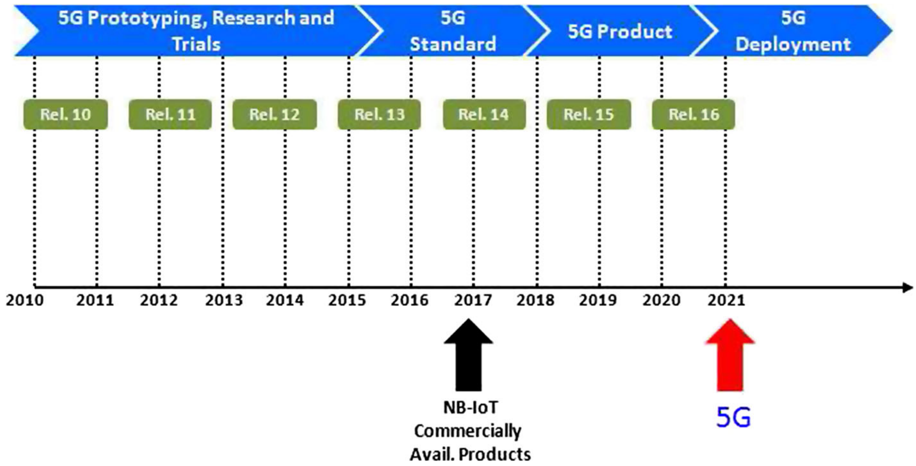

Fig. 9 3GPP roadmap and NB-IoT time relation (estimation) [1]

about 5G and IoT from 2012 to 2017. The paper number is increasing over the recent years. Figure 10 shows the paper number for 5G and IoT papers (Tables 1, 2).

The authors in a recent paper, [101], analyze in detail the potential of 5G technologies for the IoT, by considering both the technological and standardization aspects. Additionally, they present the new massive business shifts that a tight link between IoT and 5G may cause in the operator and vendors ecosystem. Moreover, in [137] the key findings of the European research project 5GNOW are presented, which include new proposed physical layer technologies. The integration of 5G and IoT is also the subject of several recent papers, [30, 43]. In [121] the authors propose a four layer model that is applicable to a Smart City or smart home infrastructure and connects the elements using technologies like 5G, Internet of Things, cloud of things, and distributed artificial intelligence. The end to end (E2E) platform of the Centre Tecnologic de Telecomunicacions de Catalunya (CTTC) that integrates 5G technologies with distributed cloud resources and IoT is presented in

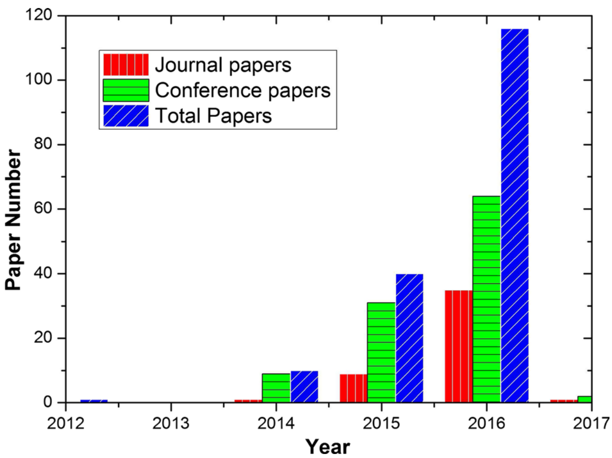

Fig. 10 Number of papers for 5G and IoT

Table 1 A comparison of current and future long range technologies for IoT [97]

	LoRa	GSM (Rel.8)	EC-GSM-IoT (Rel.13)	LTE (Rel.8)	eMTC (Rel.13)	NB-IoT (Rel.13)
LTE user equipment category	N/A	N/A	N/A	Cat.1	Cat.M1	Cat.NB1
Range	<15 km	<35 km	<35 km	<100 km	<100 km	<35 km
Spectrum	Unlicensed <1 GHz	Licensed GSM bands	Licensed GSM bands	Licensed LTE bands in-band	Licensed LTE bands in-band	Licensed LTE in-band guard-band stand-alone
Bandwidth	<500 kHz	200 kHz	200 kHz	LTE carrier (1.4–20 MHz)	1.08 MHz (1.4 MHz carrier bandwidth)	180 kHz (200 kHz carrier bandwidth)
Max. data rate	<50 kbps (DL/UL)	<500 kbps (DL/UL)	<140 kbps (DL/UL)	<10 Mbps (DL) <5 Mbps (UL)	<1 Mbps (DL/UL)	<170 kbps (DL) <250 kbps (UL)

Table 2 A comparison of features for different LTE UE [97]

UE category	Category 4	Category 1	Category M1 (eMTC)	Category NB1 (NB-IoT)
Downlink peak rate	150 Mbps	10 Mbps	1 Mbps	170 kbps
Uplink peak rate	50 Mbps	5 Mbps	1 Mbps	250 kbps
Number of antennas	2	2	1	1
Duplex mode	Full duplex	Full duplex	Full/half duplex	Half duplex
UE receive bandwidth	1.08–18 MHz	1.08–18 MHz	1.08 MHz	180 kHz
UE transmit power	23 dBm	23 dBm	20/23 dBm	20/23 dBm
Multiplexed within LTE	Yes	Yes	Yes	Yes/No
Modem complexity	10,000%	8000%	2000%	1500%

[95]. Moreover, the authors in [33] present the mobile access system technology developed to counter increasing data traffic and describe the centralized base band unit supporting LTE-Advanced and indoor femtocell base stations developed by Fujitsu. They also discuss the technological trends for 5G and describe activities to realize such technology.

The authors in [74] deal with the problem of handling different traffic types in future 5G networks. They introduce a random access within the standard acquisition procedures to support sporadic traffic and thus enabling IoT devices. Furthermore, according to [39] the IoT applications can be classified in two categories the Massive IoT and the Critical IoT.

3.2.1 Massive IoT

Massive IoT refers to services that typically span over a very large number of devices, usually sensors and actuators. Sensors are extremely low cost and consume very low

Table 3 Vertical markets for massive IoT technology [39]

Massive IoT
Transport and logistics (fleet management and goods tracking)
Agriculture (climate/agriculture monitoring, livestock tracking)
Environment (flood monitoring/alerts, environmental monitoring)
Industrial (process monitoring and control, maintenance monitoring)
Consumers (wearables kids/senior tracker, medical monitoring)
Utilities (smart metering, smart grid management)
Smart cities (parking sensors, smart bicycles, waste management, smart lightning)
Smart buildings (smoke detectors, alarm systems, home automation)

amounts of energy in order to sustain long battery life. Clearly, the amount of data generated by each sensor is normally very small, and very low latency is not a critical requirement. While actuators are similarly limited in cost, they will likely have varying energy footprints ranging from very low to moderate energy consumption (Table 3).

Sometimes, the mobile network may be used to bridge connectivity to the device by means of capillary networks. Here, local connectivity is provided by means of a short-range radio access technology, for example Wi-Fi, Bluetooth or 802.15.4/6LoWPAN. Wireless connectivity beyond the local area is then provided by the mobile network via a gateway node.

3.2.2 Critical IoT

Critical IoT refers to applications such as traffic safety/control, control of critical infrastructure and wireless connectivity for industrial processes. Such applications require very high reliability and availability in terms of wireless connectivity, as well as very low latency. On the other hand, Low Device cost and energy consumption is not as critical as for Massive IoT applications. While the average volume of data transported to and from devices may not be large, wide instantaneous bandwidths are useful in being able to meet capacity and latency requirements (Table 4).

There is much to gain from a network being able to handle as many different applications as possible, including mobile broadband, media delivery and a wide range of IoT applications by means of the same basic wireless-access technology and within the same spectrum. This avoids spectrum fragmentation and allows operators to offer support for new IoT services for which the business potential is inherently uncertain, without having to deploy a separate network and reassign spectrum specifically for these applications.

Table 4 Vertical markets for critical IoT technology [39]

Critical IoT
Automotive (V2I, V2V, V2P, V2C, car entertainment)
Industrial (remote control, automated fabrication, collaborative robots)
Medical (e-health, remote surgery, biomedical sensors)
Public sector (smart grid, video surveillance)

3.3 Semantic Web and IoT

The use of Semantic Web, [15], and Semantic Web Services, [42], technologies to enable the interoperability of systems and applications is gaining momentum worldwide. The state-of-the art technology in a web environment is adding semantic meaning to web recourses. Currently these resources are usually only human understandable: the hypertext mark-up language (HTML) only provides information for textual and graphical information intended for human consumption. Semantic Web aims for machine understandable information that can be processed and shared by both computers and humans. [15] provides the definition of the Semantic Web as "an extension of the current one [Web], in which information is given well-defined meaning, better enabling computers and people to work in cooperation."

Data representation in a Semantic Web environment is given in layers as shown in Fig. 11a [89]. These layers include XML [23], RDF (Resource Description Framework) [88], Ontology (OWL) [35], and Logic. OWL is an ontology language for the Semantic Web, developed by the World Wide Web Consortium (W3C) Web Ontology Working Group [117]. In OWL, an ontology is a set of definitions of classes and properties. OWL has the ability of applying constraints on the way those classes and properties can be employed. OWL DL (Description Logic) is an OWL sublanguage that supports those users who want the maximum expressiveness while retaining computational completeness.

A search in the scopus database shows that there are 358 total papers from 2009 to 2017 that deal with Semantic technologies and IoT. These contain 264 conference papers and 92 journal papers. Figure 11b shows the chart with the paper numbers. We notice a significant growth over the last 3 three years.

Semantic technologies use machine-interpretable representations that describe objects, share and integrate information, and infer knowledge. Thus, it would be beneficial to apply such technologies to IoT applications that could deal with M2M communication and integration. However, the resource-constrained nature of the IoT requires special design considerations to be taken into account to effectively apply the semantic technologies on the real world data [12]. Several information technologies exist for the creation of web-based IoT applications. Barnaghi et al. review [12] the applications of semantic technologies to IoT. The combination of IoT and Semantic Web is also called Semantic Web of Things (SWoT). The main idea is add semantic annotations real-world objects, locations and events. The authors in [113] give a general framework for the Semantic Web of Things, which is based on an evolution of classic Knowledge Base models and present architectural solutions for information storage, communication and processing. Moreover, in [68] the author also study the SWoT and analyze the impact to resource performance of the use of semantic-annotations. A new paradigm for applying intelligence to IoT is given in [136] called by the authors Cognitive Internet of Things (CIoT). The authors present the definition and propose an operational framework of CIoT.

The authors in [79] present the LinkSmart middleware platform for IoT that combines service-oriented architecture, peer-to-peer networking, and Semantic Web services technologies. The LinkSmart platform uses semantic binding of networked devices using ontologies and knowledge-based inference mechanisms. Moreover, in [83] the authors present a smart home system using IoT and semantic integration of web services. A semantic modelling and linked data approach is used in [34] to create an information framework for IoT. The authors describe a platform that can publish instances of the IoT related resources and entities and link them to the Web. Additionally, in [81] a Linked

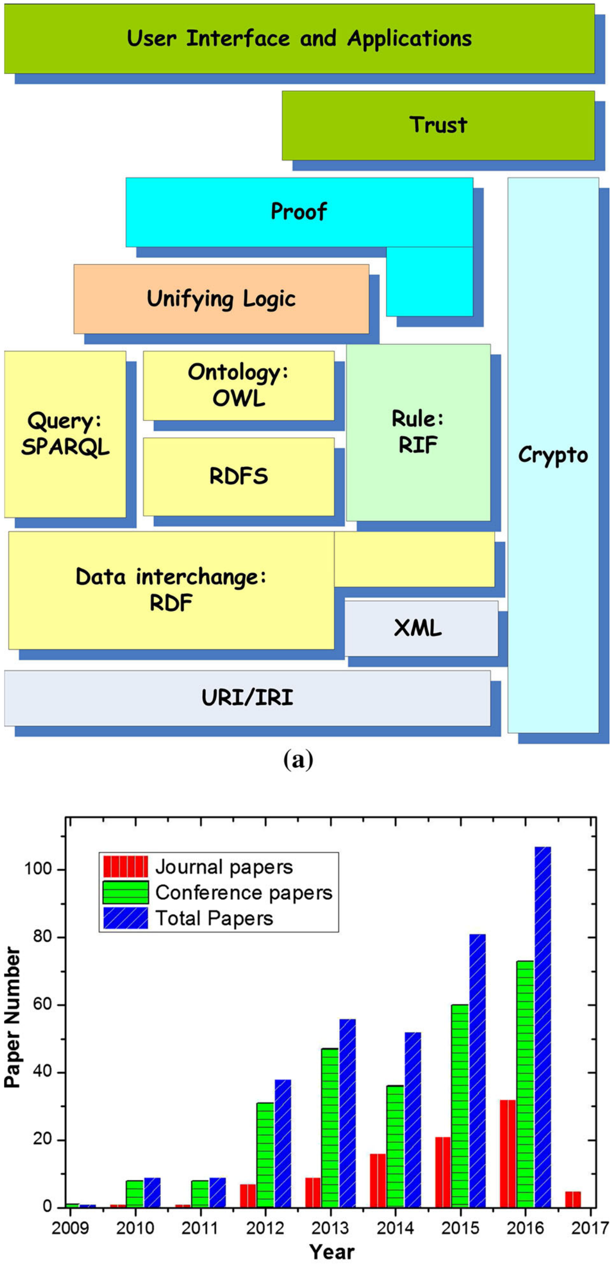

Fig. 11 **a** Semantic Web "layer cake" and **b** number of papers for Semantic Web and IoT

Stream Middleware is described that integrates time-dependent data taken from IoT devices with semantic descriptions. In [77] the authors present novel semantic level interoperability architecture for pervasive computing and IoT. The proposed model is evaluated using reference applications developed by the authors. Additionally, in [124] the authors present an extensible and active semantic information organization model for IoT. Wang et al. [132] present the design of a comprehensive description ontology for knowledge representation in the IoT domain and discuss how its usage towards service discovery, testing and dynamic composition. In [120] a novel architecture model for IoT with the help of Semantic Fusion Model (SFM) is presented. The authors call this architecture Smart Semantic framework that encapsulates the processed data from IoT nodes. Several additional case studies that involve applications of semantic technologies to IoT can be found in the literature [78, 104, 112, 114].

4 Applications of IoT

IoT allows the development of a huge number of applications. However, out of these applications only a small number is currently available. A list of application domains for current and future IoT applications can be found in [10]. Figure 12 depicts some of these application domains [10]. These applications have the potential to improve the quality of living and they can be found everywhere in everyday life. These among others include smart cities, smart homes, smart transportation and logistics, and smart healthcare. The basic idea is to install in these environments IoT nodes that can communicate with each other and elaborate the received information. In this paper, we will further discuss the IoT applications in three different domains, namely the smart cities domain, the transportation and logistics domain, and the healthcare domain.

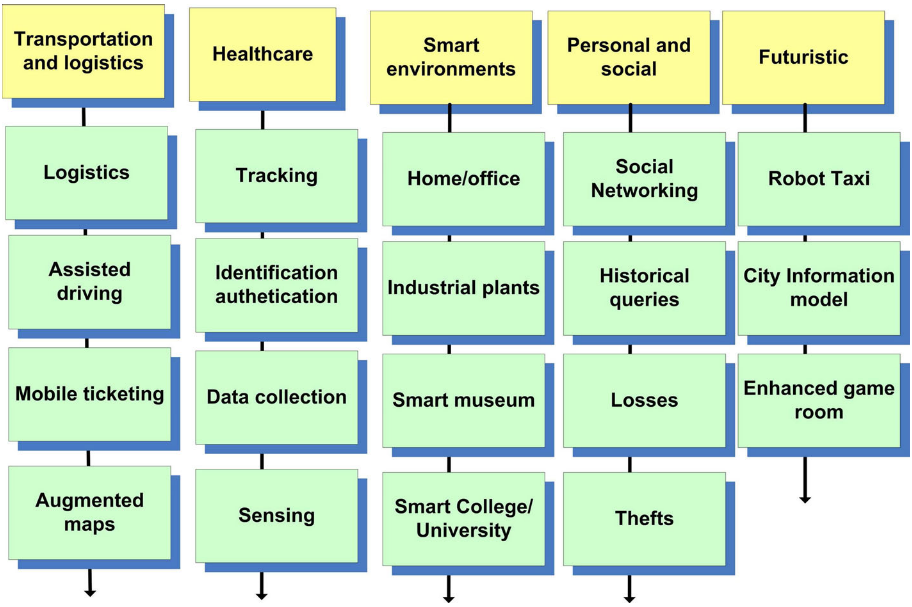

Fig. 12 Current and future application domains for IoT [10]

4.1 Smart Cities

Smart cities are among the most common IoT applications. The main idea is to install IoT nodes (sensors) for everything, and connecting them to the internet through specific protocols. Their main operation is information exchange and communications, in order to achieve intelligent recognition, location, tracking, monitoring and management. With the technical support from IoT, a Smart City needs to have three features of being instrumented, interconnected and intelligent. Only then a Smart City can be formed by integrating all these intelligent features at its advanced stage of IoT development. Another definition for a Smart City can be found in [141] "...Smart City vision, which aims at exploiting the most advanced communication technologies to support added-value services for the administration of the city and for the citizens"

The explosive growth of Smart City and IoT applications creates many scientific and engineering challenges. These call for ingenious research efforts from both academia and industry, especially for the development of efficient, scalable, and reliable Smart City based on IoT. New protocols, architectures, and services are in dire needs to respond for these challenges.

There are several papers in the literature that deal with smart cities. [7, 14, 19, 22, 27, 29, 32, 41, 55, 60, 69, 84, 104, 115, 122, 131, 141]. After a search in the scopus database we found 653 total papers from 2011 to 2017. These can be further grouped into 462 conference papers and 163 journal papers. Figure 13 shows the growth of Smart City papers from 2011 to 2017. We notice how the paper number rises almost exponentially from 2011 to 2016.

The authors in [141] present an urban IoT system that supports the Smart City paradigm. The authors first present the enabling technologies, protocols, and architecture for an urban IoT. Then they give the technical solutions and the best-practice guidelines that were adopted in the Padova Smart City project. The services for the Padova Smart City can be grouped into the following categories; Structural Health of Buildings, Waste management, Air quality monitoring, Noise monitoring, Traffic congestion, City energy consumption, Smart parking, Smart lighting, Automation and Salubrity of Public Buildings. Their conclusion is the deployment of Smart City testbeds will clear any doubts about the maturity of the current technologies and has the potential to lead to a further and massive

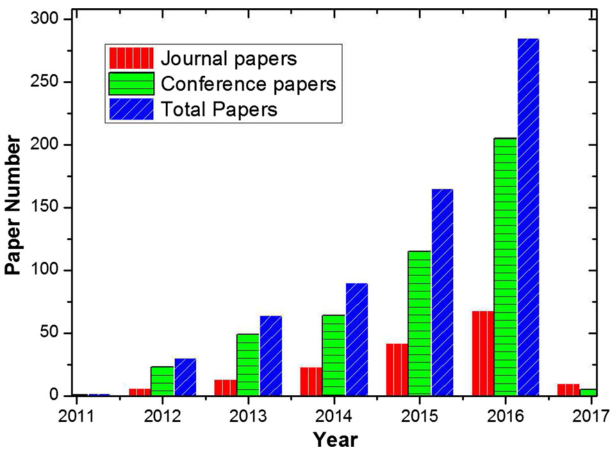

Fig. 13 Number of papers for smart cities

adaption of Smart City paradigms. Another Smart City testbed is given in [115]. The authors present the European project SmartSantander, which comprises of a larger number of IoT nodes deployed in several urban scenarios and all connected into a testbed. The authors also present the technological solutions adopted and they conclude that SmartSantander is a suitable platform for large scale experimentation and evaluation of IoT concepts under real-life conditions. Additionally, in [60] the authors present the building blocks of the SmartSantander EU project. A survey of smart cities software architecture can be found in [32]. An additional example of IoT application in the concept of a Smart City is the design of a smart museum given in [29], where the Cultural Heritage is integrated into digital ecosystem of a Smart City. The authors present a real testbed placed in a temporary art exhibition of sculptures in the Maschio Angioino Castle, located in Naples, Italy.

Several papers exist in the literature that deal with new technologies and their application to smart cities. In a recent paper [22], the authors provide a literature survey on the integration of Cloud and IoT, which they call the CloudIoT paradigm. They present services and applications based on CloudIoT, which include among others the Smart City. In the same concept, the authors in [19] present the Fog Computing an extension of the Cloud Computing paradigm. Fog Computing has the potential to enable a new set of applications and services. The authors claim that Fog Computing is a technology enabler for IoT, which can applied for Connected Vehicle, Smart Grid, and Smart Cities. Moreover, Cloud Computing and IoT is also the topic of another paper [122], that proposes a new platform for using cloud computing capacities for provision and support of ubiquitous connectivity and real-time applications and services for smart cities' needs.

Additionally, in [69] the authors give a information framework for creating Smart Cities using IoT. They provide the whole set of protocols from physical layer to application layer and they apply this framework to a noise mapping case study. Moreover, the authors in [104] study the concept of sensing as a service and how it fits with the IoT. The authors try to investigate the concept of sensing as a service model in technological, economical and social perspectives and identify the major open challenges and issues.

A cognitive management framework for IoT is proposed in [131]. The basic idea is to change dynamically real-world objects which are represented in a virtualized environment, and where cognition and proximity are used to select the most relevant objects. The authors give a proof of concept by applying the above framework in a Smart City case study. The role of advanced sensing in IoT and Smart Cities is investigated in [55]. The authors present an overview of the state of the art with regards to sensing in smart cities. Among others the topics studied by the authors include sensing applications in smart cities, sensing platforms and technical challenges associated with these technologies. Moreover, in [14] the authors propose a solution to integrate and opportunistically exploit MANET and WSN to boost urban data harvesting in IoT for smart cities applications. The authors in [84] study the big data collected from IoT nodes in a Smart City. They propose a strategy to deal with this big data based on the cloud computing and data mining.

4.2 Transportation and Logistics

Transportation and Logistics is another application domain for IoT that has attracted several researchers [44, 59, 75, 86, 119, 123, 133, 142, 144, 145]. The transportation domain includes smart vehicles like cars, trains, buses as well as bicycles along with roads and/or rails, which are equipped with IoT sensors. On the other hand both the roads and the transported goods use IoT nodes to inform about traffic, to find the least congested route, to

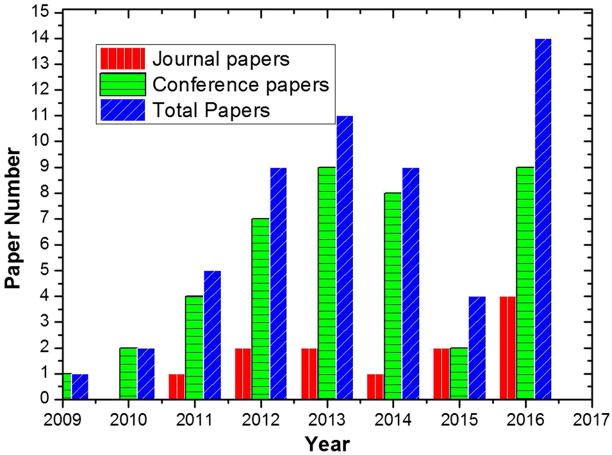

Fig. 14 Number of papers for transportation and logistics using IoT technologies

manage the depots and to monitor the status of the transported goods throughout the supply chain and provide tourist with appropriate transportation information. Additional achieved monitoring all perishable goods from production to the place of consumption, so as to avoid uncertainty as to the level of quality. Posters or signs are provided with a tag via of which anyone can receive all the required information. The obtained results searching the scopus database reveal a total number of 55 papers, ranging from 2009 to 2016. These papers can be analyzed to 43 conference papers and 12 journal papers. Figure 14 shows the variation of the papers over the years. We notice that 2016 was the year with the largest number of published papers with a total of 14 papers.

In [59] the authors present a multilayered vehicular data cloud platform by using cloud computing and IoT technologies. They also present two vehicular data cloud services, an intelligent parking cloud service and a vehicular data mining cloud service. Moreover, in [133] the authors focus on smart transportation including intelligent information service, vehicle identification, vehicle navigation and positioning; the best path selection, traffic information release. The authors in [144] develop a framework integrating IoT and a mobile platform for transportation process monitoring of car-carrier, which reduces logistics cost and improves the utility of the logistics management.

Several papers also deal the logistics and IoT topic. The authors in [44] integrate two technology paradigms like Cloud Computing and Agents in order to implement a smart objects-oriented IoT framework. The RFID technology is the main enabler in several logistics papers [75, 119, 123, 144]. The application of IoT to agricultural supply chain optimization is discussed in [142]. Additionally, the application of IoT in the logistics in forest industry is presented by the authors in [145]. The authors in [86] apply IoT technologies for monitoring the process of logistics of dangerous chemical cargoes.

4.3 Healthcare

A domain that gains advantages by the IoT is the healthcare domain [8, 13, 25, 37, 38, 57, 91, 103, 112, 116, 128, 139, 140]. The benefits of this can be grouped in tracking of people and things in motion that includes positioning in real time, monitoring of patients and the improvement of the flow work in hospitals. Moreover, it will include the identification and authentication of patients and the automatic data collection and transfer that targets reduction of the treatment period, the process automation and the optimization of stock medical management. Under the healthcare domain the Active and Assisted Living (AAL) solutions are included, aiming to provide intelligent home infrastructures that support independent living if senior citizens with chronic diseases and frailty conditions. The benefits of such solutions span from the social contribution to the financial impacts. Seniors can enjoy a better Quality of Life in a safe and independent living, while on the same time the institutionalization costs can be significantly reduced. Currently there are many successful R&D initiatives targeting the healthcare domain, nevertheless there are very few integrated approaches that have succeeded. The reason is the combination of a highly regulated environment with multiple stakeholders, including policy makers, national health systems, doctors, formal/informal caregivers and of course the patients in the center of focus. Therefore, innovation and excellence in AAL solutions needs to be blended with flexible business models and persuasive technologies.

The scopus database contains 452 papers that use IoT technologies for healthcare applications. These papers contain 302 conference papers and 142 journal papers. Figure 15 shows how the number of healthcare IoT papers has increased over the recent years.

A flagship EC research project initiative in the Healthcare domain, namely eWALL, deploys a cloud infrastructure and connects homes of seniors, aiming to contribute to their active and independent living. The platform leverages best-of-breed future internet technologies (cloud, IoT, BigData) and transforms homes into Home Caring Environments. eWALL is envisaged as holistic infrastructure model and an affordable, prefabricated, easy to install system that can be mounted on the existing wall and that will fade into the background. The concept of eWALL resides at the intersection of the concepts of Ambient Assisted Living (AAL), Enhanced Living Environments (ELEs) and Ambient Intelligence (AmI) [91]. The eWALL has been engineered, based on a multidisciplinary approach to determine the requirements of senior citizens wth chronic diseases and to create a smart caring home environment capable of sensing and learning. eWALL Cloud platform can support any number of Sensing Environments based in primary user home

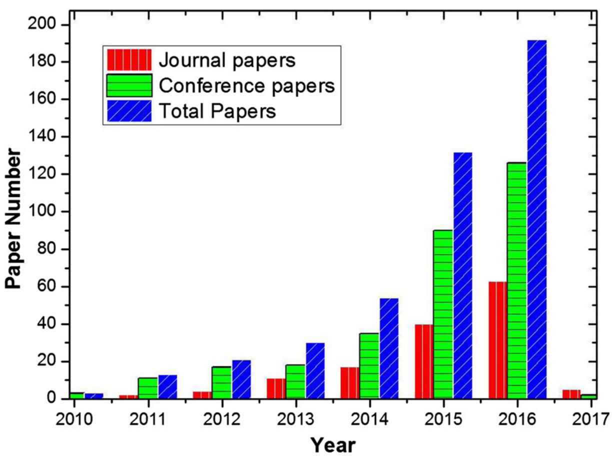

Fig. 15 Number of papers for healthcare using IoT technologies

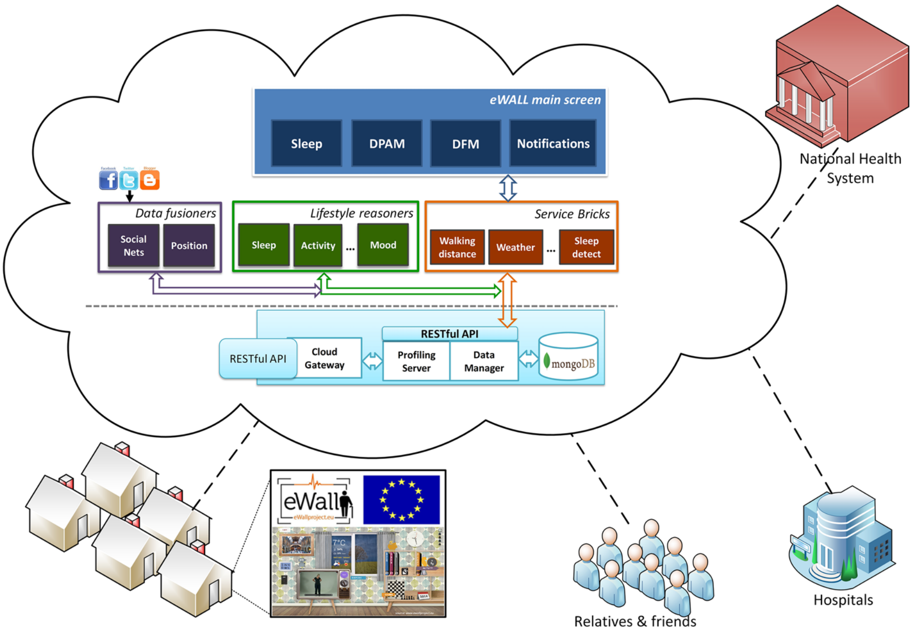

Fig. 16 The eWALL reference architecture, consisting of a cloud environment and an urban IoT network for the home part

and responsible for explicit and implicit interaction with the primary user, as shown on Fig. 16. The eWALL platform has been released as open-source for creating an ecosystem of developers, vendors and service providers; thus creating a reference AAL architecture [40].

Additionally, the authors in [37] present an Ambient Assisted Living (AAL) application which uses a combination of several IoT technologies like NFC, and RFID. The use of RFID technology and IoT for healthcare is the topic of another paper [8]. Moreover, in [139] an IoT-based system for emergency medical services is presented. The authors in [25] describe a smart hospital system (SHS) that uses different IoT technologies.

5 Conclusion

IoT is a key communications paradigm for future smart applications and services. Current IoT existing technologies enable the application development in several domains. The existing Smart City applications and testbeds show that the technology is mature and thus the number of applications is growing exponentially. Future technologies like 5G that will bring IoT as a common 5G application will give an extra boost to IoT expansion. Semantic web technologies, which are still growing and maturing, will enable the context-aware IoT. Other technologies like Cloud Computing and Cognitive Radio Networks will also be combined with IoT to provide new services.

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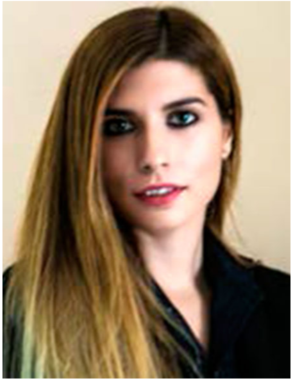

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