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Review

The Internet of Things vision: Key features, applications and open issues

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A R T I C L E I N F O

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A B S T R A C T

The Internet of Things (IoT) is a new paradigm that combines aspects and technologies coming from different approaches. Ubiquitous computing, pervasive computing, Internet Protocol, sensing technologies, communication technologies, and embedded devices are merged together in order to form a system where the real and digital worlds meet and are continuously in symbiotic interaction. The smart object is the building block of the IoT vision. By putting intelligence into everyday objects, they are turned into smart objects able not only to collect information from the environment and interact/control the physical world, but also to be interconnected, to each other, through Internet to exchange data and information. The expected huge number of interconnected devices and the significant amount of available data open new opportunities to create services that will bring tangible benefits to the society, environment, economy and individual citizens. In this paper we present the key features and the driver technologies of IoT. In addition to identifying the application scenarios and the correspondent potential applications, we focus on research challenges and open issues to be faced for the IoT realization in the real world.

1. Introduction

Due to the huge advancements in the fields of electronics and the deployments of wireless communication systems, mobile devices and ubiquitous services (providing anytime-anywhere connectivity to the users) spread rapidly over the past decade. Today, however, the role played by devices is no longer limited to connect users to the Internet, but it has been expanding becoming an opportunity to interlink the physical world with the cyber world [1], leading to the emergence of Cyber-Physical Systems (CPS) [2,3]. The notion of CPS refers to a next generation of embedded ICT systems where computation and networking are integrated with physical processes and they control and manage their dynamics and make them more efficient, reliable, adaptable and secure [4–9]. Information about physical processes, for example gathered through sensors, are transferred, processed, and used in the digital world, but they may also affect physical processes through feedback loops, for example by using actuators [1]. The peculiarity of CPS is that the ICT system is designed together with the physical components to maximize the overall efficiency, thus being in contrast with classic embedded systems where the goal is to include electronics/computing/communication/abstraction in an already operating physical world.

CPS will have a great impact on the future society and humans, and their social networks, will play a central role in bridging the cyber, physical and social worlds [10–13]. Through their interactions with ICT devices, they will gain access to the virtual world affecting the way information is distributed and they will give their contribution to build/modify the cyber infrastructure.

The economic value associated with the CPS will also be large. In the 2013 report,[1] McKinsey Global Institute has identified twelve technologies that, by 2025, will have massive, economically disruptive impact, driving profound changes in many dimensions: in citizens' lives, in business and across the global economy. Specifically, four technologies fall within CPS: (i) automation of knowledge work, (ii) Internet of Things, (iii) advanced robotics, and (iv) autonomous/near-autonomous vehicles. Among them, the Internet of Things (IoT), with an estimated value of 36 trillion of dollars, is considered the CPS paradigm with the highest economic impact [14].

IoT refers to an emerging paradigm consisting of a continuum of uniquely addressable *things* communicating one another to form a worldwide dynamic network. The origin of IoT has been attributed to members of the Auto-ID Center at MIT, the development community of the Radio-Frequency Identification (RFID), around 2000 [15]. Their idea was visionary: they aimed at discovering information about a tagged object by browsing an Internet address or a database entry corresponding to a particular RFID. To address the above idea,

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[1] http://www.slideshare.net/brandsynapse/mgi-disruptive-technologiesfullreport may2013?related=1.

http://dx.doi.org/10.1016/j.comcom.2014.09.008
0140-3664/

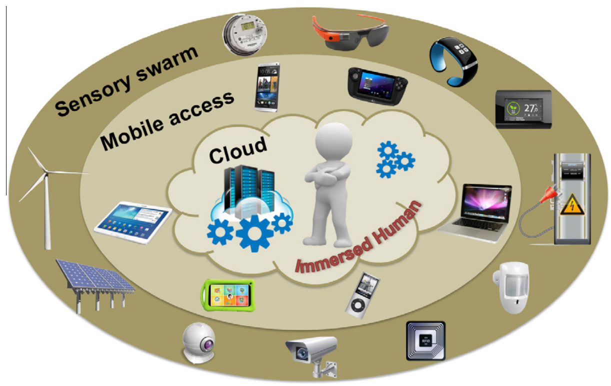

Fig. 1. The emerging IoT scene.

they worked on the development of the *Electronic Product Code (EPC)*, i.e., a universal identifier that provides a unique identity for every physical object [16], with the aim of spreading the use of RFID in worldwide networks. Today, the concept of *thing* is more general and is not limited to RFID only. A *thing* can be any real/physical object (e.g., RFID, sensor, actuator, spime,[2] smart item[3]) but also a virtual/digital entity, which moves in time and space and can be uniquely identified by assigned identification numbers, names and/or location addresses. Therefore, the *thing* is easily readable, recognizable, locatable, addressable and/or controllable via Internet. Moreover, this new generation of devices is *smart* thanks to the embedded electronics allowing them to sense, compute, communicate, and integrate seamlessly with the surrounding environment. The association "one device/one function" disappears, but the whole set of objects becomes the place where the function is activated, resulting all widely distributed. The emerging IoT scenario is depicted in Fig. 1 [17]. Smart devices will form the so-called *sensory swarm* and will be the majority of the system. They will be extremely heterogeneous in terms of resource capabilities, lifespan and communication technologies. They will exceed classic devices such as smartphones and tablets, which, on the contrary, will form a way for accessing Internet [18]. At the core, instead of having traditional computation systems, the *Cloud* will provide the abstraction of a set of computers and will offer computation and storage services. It is envisaged that the number of connected things[4] will exceed 7 trillion by 2025 [19], with an estimate of about 1000 devices per person. A part of them will be wearable [20], but the majority will be in the infrastructure. In this vision, humans will be completely immersed in the world of technology, leading to the so-called *Immersed human*.

To make the concept of IoT more concrete, let us consider the city ecosystem as an example and how the city of the future will look like [21]. The city is the economic and social life core of a nation. Today, half of the global population is concentrated in the cities and consume its resources (e.g., light, water) every day. Urban population is constantly growing and this implies an inevitable increase in the resource consumption that undermines the environment. Quality, sustainability and security are crucial and unavoidable issues for the city. The realization of sustainable and secure cities requires intelligent solutions that ensure the efficiency at multiple levels aiming to: (i) a more aware and optimized usage of the offered resources, (ii) a minimization of environmental impact, for example by reducing CO_2 emissions, and (iii) a tangible increase in the life quality in terms of safety, health, and wellness. Indeed, a smart city is a city that operates simultaneously on two levels: one physical and one virtual. The smart city provides a management of its services (e.g., transport, energy, lighting, waste management, entertainment) through the widespread usage of ICT technologies. Such technologies provide a logical/virtual infrastructure that controls and coordinates the physical infrastructure in order to adapt the city services to the actual citizen needs, while reducing waste and making sustainable the city [21]. IoT will be essential to turn a traditional city into a *smart city* and the traditional and more emerging sectors such as mobility, buildings, energy, living, governance will also benefit of it. For example, smart mobility services will be created to provide effective tools to the citizens to accurately plan their journeys with public/private transportations, bike/car/van sharing services or multimodal transport systems. Intelligent traffic lights and static/mobile sensors spread in the city can be used to automatically manage the traffic, to monitor/predict situations of traffic jam and to warn drivers about the presence of critical situations, also proposing them alternative routes/means in real time. At the same time, data gathered by sensors [22,23] will help municipalities to monitor the condition of the roads (e.g., presence of potholes, slippery, not draining roads), to plan the waste collection service (e.g., volumetric sensors may measure filling level of trashcans and report to sanitation headquarters when full/close to full), to perform environmental monitoring and territorial prevention by measuring water level, air pollution, presence of a certain component (i.e., percentage of allergenic pollen or radiation in the air) [24]. Energy management will also be optimized by using a smart grid for monitoring and modify consumes in town and buildings through actuators and by using renewable energies for the production [25–28]. Fig. 2 provides a schematic representation of the smart city. It will be equipped with a network of sensors, cameras, screens, speakers, smart meters, and thermostats that will collect information. The gathered information, the so-called "Big Data" (the name refers to its large volume and its heterogeneity in terms of content and data representation), will not be used for the improvement of just a single service/application, but it will be shared among different services [15]. To this aim, a common platform for operational management of the city – a sort of City Operating System – will be responsible for managing, storing, analyzing, processing, and forwarding it where needed within the city to improve services and adapting to human needs. This management layer, no longer vertical but horizontal, will ensure interoperability, coordination, and optimization of individual services/applications through the analysis of information flows. Citizens/authorities will access the services offered by the platform through their applications, will consume them and will actively participate by creating additional content that will be provided as further input to the City Operating System.

As also highlighted by the above example, IoT will bring tangible benefits to the environment, the society, individuals and business with the creation of new intelligent applications, services and products in various domains whilst ensuring the protection and privacy of information and content exchanged [29]. The economic value associated with IoT will be large and the benefits enormous: for example, it is envisioned a US GDP increase by 2–5% by 2025 with a faster productivity growth and an increase of job creation [30]. IoT will offer a potential to affect the economic activity across industries, influencing their strategic decisions, their investments and their productivity. Currently, about 20% of the GDP comes from industries working in the digital, while the majority of the GDP (about 80%) comes from primarily physical industries. IoT will bring

[2] Spimes are objects that can be tracked in space and time and during their entire lifespan univocally through an identifier and the use of technologies such as RFID and GSM. They are very economical and eco-friendly (i.e., they can be recycled) and can be improved over time. For example, the recording of their entire life cycle can be used to revise and modify the object itself or some specific behavior.

[3] Smart items have very advanced features such as to adopt autonomous and proactive behavior. For instance, they are able to generate traffic autonomously for certain purposes, or execute data processing or perform communication in a collaborative form.

[4] From now on we will use the terms *thing* and *object* interchangeably.