IoT & Environmental Analytical Chemistry: towards a profitable symbiosis.

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Abstract: In a constantly evolving world, where the rising population and increased social awareness have led to a higher concern for the environment, research in this field (most notably in Environmental Analytical Chemistry) should take advantage of the great opportunities offered by new technologies such as Internet of Things (IoT) and Cloud-based services. Both of them are especially suitable when chemical sensors and related devices are used in the continuous in-line monitoring of environmental parameters. In this sense, it is very important to obtain spatially distributed information of these parameters as well as their temporal evolution.

In this work, a friendly approach to IoT world for environmental applications is carried out. To get a global vision of these concepts, the starting point is their historical evolution. New trends are also identified along with associated challenges and potential threats. A revision of the recent literature relating IoT with environmental issues has also been performed, the most relevant contributions being discussed. Finally, the need of a mutual cooperation between IoT and Environmental Analytical Chemistry is outlined and commented in detail. Ignoring the new capabilities offered by Cloud computing and IoT environments

is no further an option. The wiser course is to embrace these opportunities consciously for mutual profit.

Keywords: Environmental Analytical Chemistry; Internet of Things; Cloud Computing, Future trends, Ambient Intelligence, Advanced sensing systems

1. Introduction

It is clear that monitoring the environment is increasingly important, since it is one of the greatest concerns in our society. In this sense, more and more systems work –in one way or another– to control environmental parameters (with growing requirements). It is thus not surprising that Environmental Analytical Chemistry should explore the benefits that can get from new technologies such as Internet of Things (IoT) and cloud computing, due to their unique features, especially spatial and temporal distribution. For its part, IoT also faces a series of challenges, which will be commented later. The solution adopted obviously depends on the application, and therefore this paper discusses those corresponding to Environmental Analytical Chemistry.

IoT can be defined in many ways. According to the International Telecommunications Union[1] (ITU), defines it as “A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies”. On the other hand, the standardization Committee ISO/IEC JTC 1 SWG 5 [2] describes it as “An infrastructure of interconnected objects, people, systems and information resources together with intelligent services to allow them to process information of the physical and the virtual world and react.”

These definitions highlight the existence of a communications infrastructure that interconnect the so-called intelligent objects. This concept closely resembles another one: Cloud Computing; these communication abilities are then used to offer services located in a set of servers (Cloud) to connected clients. Both approaches are obviously complementary; IoT refers to low-cost devices (and therefore limited resources) interacting with the real world, whereas Cloud Computing deals with highly scalable systems, which provide services at a virtual level. This combined approach is straightforward with a lot of advantages. A deeper knowledge about those concepts may be obtained from a historical perspective, which is provided in section 2. Section 3 discusses the state-of-the-art in IoT and Cloud Computing applications in Analytical Chemistry; finally, section 4 offer the authors' opinion on future trends regarding the symbiosis of Analytical Chemistry and IoT+Cloud.

2. What is behind the "Internet of Things" term?

In our view, the best way to enter IoT world is by studying the evolution of the technologies leading to the rise of IoT. (Figure 1).

The first computers gave rise to the need of their communication, initially through wired networks and later by means of wireless networks. This was the starting point of Computer Networks and (using them) the so-called Distributed Systems (a set of computers that were interconnected to carry out a certain application, usually distributed in the space and –from the user's point of view- acting as a single system). An example of this in Analytical Chemistry may be the distributed expert systems for the monitoring and control of food parameters along an alcoholic fermentation process [3].

The nineties of the last century saw an impressive advance in consumer electronics and, simultaneously, in the world of computers. The latter have increased their power and reduced energy consumption as well as size and price. Computer-based systems begin then to "inundate" day-to-date life.

A similar evolution has taken place in environmental analysis systems. The old-fashioned system where samples were manually taken and transported to the laboratory for their off-line analysis [4] (Figure 2a) gave way to automatic systems in which analyses were carried out either at-line or on-line (Figure 2b). The last stage was the in-line analysis (Figure 2c) followed soon by a new paradigm based on cloud technologies: the cloud gathers and stores all data corresponding to the measured values (Figure 2d). Both cases rely upon the use of a communication network.

Subsequently, computer networks start their interconnection, until reaching a single global network that is known today as Internet.

In this way, we arrive at a point where, for instance, all laboratories are connected to the Internet (and therefore among them as well), with an ever-increasing number of applications exchanging information through this ‘network of networks’. In this sense, the decrease in size, consumption, and price of computer systems lead to the emergence of new philosophies regarding the particular world of sensorization, namely the so-called WSN (Wireless Sensor Networks) [5] and/or WSAN (Wireless Sensor and Actuator Networks) [6]. They transform traditional (expensive and using manual analysis devices) monitoring systems based on a few sensors into genuine smart, sensorization systems that are able to provide an impressive amount of information.

The next transformation was the application of this idea of sensor (an element capable of obtaining information from the surrounding world) to the concept of integrating it into anything of day-to-day life, the latter being connected to the Internet. This gave rise to the increasingly popular ‘Internet of Things’ (IoT), which can be considered as an ecosystem where a great deal of technologies coexist, from sensor networks to embedded systems that are integrated into the cloud in order to provide new services. IoT as an enabling technology arose in the 90’s, when Mark Weiser [7] already predicted the “disappearance” of the computers, since the computing power would integrate itself into everyday objects. Later on, Kevin Ashton [8] introduced the term “Internet of Things”, remarking a world where all objects will be connected to the Internet. Additionally, these objects will interact with one another in an intelligent way to provide human beings with a higher quality of life without intervening directly.

This concept has been a utopia for many years, until the great advances in electronics and the democratization of communications have made it feasible. In fact, nowadays it is possible to find processors that are a thousand times more powerful than early computers, and as small as 1 cm^2 in size. Communication possibilities are then enormous, with a coverage of nearly 100 % of the territory in the western world. And last but by no means least, prices in both electronics and communications are really low, which permits (a) to purchase a great amount of devices, (b) to implement fault-tolerance mechanisms based on redundancy, and (c) to cover large surfaces with high spatial resolution levels. All in all, the huge potential of IoT may be deducted from Gartner's report [9], according to which, eight of 2019 technology trends are directly related to IoT, and the other two have application in IoT.

Nowadays we can often find mobile devices, such as smart phones, that are able to provide full connectivity as well as user applications with advanced services. Nevertheless, the last frontier consists of the fact that these devices –embedded in everyday objects- need to be able to provide their users with unrequired services and in cooperation with other devices and/or intelligent objects.

For this purpose, it is necessary: (a) to provide these devices with the ability to detect and anticipate the users' needs. This can only be achieved through the integration of sensor devices that interact with the real world, thus giving them a safe, constant information of the environment. The great advances of the so-called wireless sensor networks have permitted a step forward in this field; (b) what is required is a real integration of the devices that exceeds the simple communication, support being found for a collaborative intelligence to be able to efficiently process the data obtained by these sensors. Bearing all that in mind, all necessary measures will be adopted to provide the user with an increased security and convenience.

Nevertheless, whichever approach is taken, it is still needed to receive the data. This requirement can be addressed in two ways. The classic approach would be to incorporate code into your applications, such as a laboratory information management system (LIMS)[10,11] for an analytical laboratory or a supervisory control and data acquisition (SCADA) [12] for a process control system.

Simultaneously, but within the concept of IoT, new and more revolutionary applications based on the use of Internet are developed. An example could be the term ‘ubiquity’, since the users begin to employ a great deal of different computing devices (personal computers, smartphones, wearable peripherals, smart homes applications, etc.) in many places. This gives rise to the need of creating a ‘single’ access to the information, wherever they may be and regardless of the computer they use. This makes it necessary to establish a common place to store the information and then the concept of ‘cloud’ appears. But if data are hosted in the Cloud, why not run the applications in the Cloud as well? It could be a clear advantage, and then the concept of ‘Cloud Computing’ emerges. On the other hand, as everything is connected to the Internet, a great amount of information is increasingly available, which makes it essential to develop new technologies that are able to extract suitable information from a great deal of data; this gives rise to the so-called ‘big data’. Finally, if a large amount of information has been provided by IoT and big data, it must be used in such a way as to generate smart environments. In this sense, the new term ‘Ambient Intelligence’ (AmI) [13] proposes the creation of intelligent environments (smart-houses, autonomous cars, smart-cities, …) that adapt to the needs, preferences and interests of the people who live there, with the aim of improving living standards for all of us.

Smart and distributed sensing systems can then be considered as a major technological cornerstone of IoT [14], applicable to many fields, such as wearable sensors, industrial smart metering, and environmental monitoring. Today, one of the major challenges of using smart wireless sensors in real deployments is related to energy consumption, cost, and guaranteeing adequate lifetime. The support for the remote management (reception, storage, processing, and sharing) of these data will be provided by the aforementioned Cloud Computing technology. It consists of the presence of Internet servers –clusters– which offer data carrier services through the Internet, including:

- SAAS (Software as a Service) [15]: it provides the end user with final applications of Internet-accessible data.

- PAAS (Platform as a Service) [16]: it allows for the development of applications that take advantage of the environment (ubiquity, high availability …).
- IAAS (Infrastructure as a Service) [17]: it permits to obtain computer resources in the form of virtual machines, which gives rise to a seemingly endless scalability.

Figure 3 shows the different elements combined in a Cloud-based IoT platform. All devices in the platform are able to exchange information between them through the communication infrastructures. For this purpose, and as shown in the figure, it can be said that each device has two sides: one of them is specific to the device (with its own functionality), whereas the other one (the so-called "ICT side" (ICT - Information and Communication Technologies) is in charge of all ICT-related issues (communications, processing, power supply management, ….). The environment to be analyzed is shown at the bottom of the figure. The analysis is carried out using an array of sensorization devices; apart from the aforementioned ICT side, all of them have another side ("Environmental Analytical side"), aimed at performing the analysis of the environmental parameter(s) under monitoring. The analytical chemist should play here a major role, especially taking into account the restrictions imposed by this type of sensorization devices. The cloud is located at the top of the figure; it consists of a set of devices providing services (along with the ICT side) that complement the information obtained by the sensorization nodes. This information can be stored on distributed databases that are utilized by several applications (running in the Cloud) in order to provide an added value. In this sense, the data carrier provided by the Cloud also includes their processing, i.e. the combination of different data to produce a new knowledge. Sometimes this is an easy process (for example, the search for conventional statistical information or basic operations), but it is not always so; in other cases, the great amount of data to be stored on these Cloud systems require the application of Big Data techniques (the processing of a large volume of information in order to achieve added value). In this sense, Big Data allows for predictive analysis, search for trends, and data correctness assessment.

These platforms foster innovation in the collaborative intelligence applied to the data obtained by the devices. This large volume of data makes it necessary to utilize advanced processing techniques -such as Data Science techniques- that allow for extracting the relevant information. This discipline is arousing a great deal of interest, which is growing exponentially, thanks mainly to the large amount of data obtained through the Internet. On the other hand, the utilization of these relevant data for the well-being of users has led to the development of new artificial intelligence techniques, for example Deep Learning.

However, the inexorable rise of these new technologies face serious challenges, which should be solved in a satisfactory way, so that they may be employed using their full potential. Among these problems, we can remark: (a) privacy [18,19] (not all data can be accessed freely), (b) security (improper access or use, or malfunctioning may cause damage), (c) integrity (data can be incorrect or manipulated), and so on. Furthermore, the lack of standardization of these new technologies as well as the consequent uncertainty, slow down their application. Companies innovating in this field develop *ad-hoc* applications that are often mutually incompatible, what gives rise to interoperability problems.

Despite these issues, a major, unstoppable transformation is currently taking place in the society. There is an exponential increase in the number of computer systems as well as in their applications in all areas. This creates new conceptions in all fields, so that we are slowly redirecting our way of thinking and our daily activity towards this new reality. The concept of IoT is not unaffected by this transformation, and we are gradually adapting us to this revolutionary technology. This forces researchers to be one step ahead in its use, their investigation being mainly focused on its practical applications.

3.- Applications of IoT and Cloud Computing in Environmental Analytical Chemistry

In the field of Environmental Analytical Chemistry, IoT prepares the way for a future based on millions of smart connected devices, which sense their surroundings and, combined with cloud computing services, will provide information on scales ranging from the microscopic to global. In this section, the most relevant, recent contributions of IoT and Cloud Computing in this field will be discussed.

Dinh et al. [20] developed a location-based interactive model of IoT and cloud integration (IoT-cloud) for mobile cloud computing applications; it then can be easily compared to the periodic sensing model. If sensors are required to report their data periodically (be they necessary or not), this certainly leads to unnecessary energy loss due to redundant transmission. Rather, in this model IoT-cloud provides sensing services on demand based on interest and location of mobile users, which is very important in the continuous monitoring of environmental parameters. In this case, sensing scheduling of sensors is controlled by the cloud, which knows when and where sensor data are required. It means that, when there is no demand, sensors are put into a standby mode to save energy. This location-based model has turned out to be a significant improvement in terms of network lifetime compared to the periodic model.

The team of Kassal and co-workers [21] have pioneered the development and characterization of an ultra low-power radio-frequency identification (RFID) wireless sensor tag with potentiometric input for use with pH and ISEs (ion-selective electrodes). They claim that this type of tags will be critical to the practical realization of IoT. The tag is able to measure and store electrode potential in its internal memory, and then transfer logged data wirelessly by RFID to a nearby reader or by near field communication (NFC) to a smart phone. This sensor tag is straightforward with ultra low-power consumption, potentiometric sensing ability, autonomous data logging, and RFID/NFC compatible air interface. These characteristics make the tag suitable for utilization in environmental analysis, since in the continuous monitoring of certain parameters, pH or other ISEs are deployed as stand-alone chemical sensors or as part of larger chemical sensor networks that will support the IoT. The authors successfully compare the performance of this tag in the pH determination in solution to the one carried out with a commercial laboratory pH-meter.

On November 16, 2017, the American Chemical Society hosted a webinar, featuring Dr. Wendy A. Warr taking a look at technological advances that have significantly changed chemical research, as well as what the future might hold [22]. She pointed out that environmental analytical chemists now also have the option of cloud computing, instead of hosting computational power in-house; in this sense, the cloud allows smaller organizations that do not have Information Technology departments to compute using online tools.

There is also an interesting review [23] of the state-of-the-art related to the feasibility of making sensing devices (for instance, those utilized in environmental analysis) ubiquitous, flexible and conformable to any object or surface, since it will also allow them to become part of the core of the IoT revolution, which demands systems' mobility and self-powering functionalities to meet the requirements of most Environmental Analytical chemists.

On the other hand, the fact that IoT devices are frequent targets of attack makes security a critical issue; nevertheless, care must be taken when addressing it, since there should always be a compromise between security demands and ease of assembly, use, and maintenance. In this sense, Chamberlain et al [24] describes the industrial deployment experience of the EZConnect™ security infrastructure implemented by BECS Technology, Inc., a company specialized in water chemistry monitoring.

NO_2 (along with other nitrogen oxides) interacts with water, oxygen and other chemicals in the atmosphere to form acid rain. That is why its continuous monitoring is of capital importance in environmental analysis. For this purpose, a three-dimensional (i.e. a high specific surface area), superhydrophobic, reduced graphene oxide with unique hierarchical structures was synthesized by spark plasma sintering in one step for highly selective NO_2 detection [25]. The resulting sensor demonstrated the practical capability to detect 50 μg L^{-1} NO_2, with a very low theoretical limit of detection of 9.1 μg L^{-1}. The good tolerance to environmental changes such as humidity and temperature makes this sensor suitable for reliable application in the IoT under ambient conditions. Unfortunately, this paper does not contribute to the IoT research. Only a LabView software is detailed to control the sensors but nothing about IoT protocols or communication issues are detailed.

As part of environmental pollution monitoring, there is a growing need of autonomous sensors for unattended, continuous nutrient monitoring in water. Both institutions and industries require frequent water quality control, but it is usually time-consuming and expensive. Autonomous sensors permit frequent, unattended data collection, although sometimes at an unreasonable prices; that is why the development of low-cost sensors is essential to realize the concept of IoT. Nevertheless, much work still needs to be done in this field. Duffy and Regan [26] have reviewed the current literature on the research and development of deployable autonomous sensors for PO_4^{3-} and NO_3^-, emphasis being put on analytical performance and cost. Furthermore, some recent sensing approaches that could be automated in the short to medium term are included, along with an overview of approaches to the monitoring of both anions. They are compared with standard laboratory procedures as well as with commercially available sensors for both inorganic species. The role of sensor networks in decision making is also discussed. From IoT perspective, this paper only highlights the necessity of low-cost sensors. Without low cost sensors, IoT deployments will be impossible. Additionally, authors identify Wireless Sensor Networks as a basic technology for the success of IoT. Unfortunately, nothing about IoT research is accomplished by the authors.

There is an increasing research interest in chemoresistive gas sensors based on two-dimensional (2D) materials (including graphene-based materials), mainly due to their potential use in new technologies such as IoT. Major features of these sensors are high selectivity, high sensitivity, and reversible response and recovery. In this sense, an easy solution process has recently been proposed [27]. The resulting chemically fluorinated graphene oxide sensors developed show improved sensitivity, selectivity, and reversibility upon exposure to NH_3 with a really low theoretical detection limit of ~6 μg L^{-1} at room temperature. The authors point out that the remarkable NH_3 sensing properties offered by this type of sensors and research by first-principles calculations would enlarge the possibility of functionalized 2D materials for practical gas sensing applications such as IoT. From this perspective, this paper doesn't make any contribution in IoT technology.

Simultaneous progress in chemical sensing and wireless communication technologies has given rise to the development of wireless chemical sensors (WCSs). These hybrid devices enable wireless determination, collection and distribution of chemical analytical information in a way that is significantly impacting the Sensor IoT with applications in the environment, and other fields. Challenges and examples for each of the major chemical sensor and major radio technologies related to different application areas are reviewed over the period 2007–2017 [28], including the latest trends emerging from wearable sensors. Special attention is paid to radio-based WCSs, showing that ubiquitous wireless technologies such as Bluetooth, ZigBee, radio-frequency identification (RFID) and near-field communication (NFC) clearly contribute to make analytical chemical sensing suitable and realistic for market needs, especially for electrochemical and optical sensors. Although this paper shows an in-depth review of existing wireless chemical sensors, it does not include the most actual and promising IoT protocols such as Sigfox [29] , Lora [30] or 5G [31]. Modern IoT proposals for environmental chemical solutions must include and in-depth study and consider the use of these protocols. Presented solutions use wireless technologies from a few years ago, based on wireless sensors networks and gateways or sinks to upload data to internet. Most solutions only upload data to internet but do not offer real IoT solutions for accessing data.

Wireless chemical sensors are increasingly important in environmental analysis as well as in the rapidly emerging area of the Sensor IoT. In such wireless scenarios, the application of fluorescence-based sensors is lagging behind other types of transduction mechanisms. Kassal *et al* developed a new low-cost and highly portable wireless fluorimeter for optical chemical fluorescence intensity measurements [32]. It has been a major step forward, since fluorescence-based sensors are not so frequently used in wireless sensor networks. This device is then programmed and communicates wirelessly with mobile devices or personal computers by either radio-frequency identification or near-field communication. It is easily adaptable for utilization with different fluorescent sensor chemistries and analytes. This highly versatile fluorimeter has been successfully tested in the laboratory by means of different essays with fluorescein and a paper-immobilized quinine sulphate fluorescent indicator. The authors then conclude that their system could significantly contribute to some emerging areas of mobile chemical sensor research, including the Sensor IoT. Unfortunately, the presented solutions cannot be classified as a IoT application as only connect the chemical sensor via RFID or NFC to a mobile device that it's connected to Internet.

It is commonly accepted that the aquaculture of oysters represents a major source of income in some coastal areas. Nevertheless, the growth rate of oysters heavily depends on several environmental parameters, such as temperature, salinity, turbidity, pH and dissolved oxygen. In this sense, Viegas and co-workers have proposed a cloud-based platform to obtain the values of water quality parameters that affect oysters' growth [33]. The paper describes in detail the hardware and software of the measurement system, as well as the storage and processing of the obtained data; it also includes several experimental results about the aforementioned parameters. This solution is a real cloud-based platform that uses the 4G cellular network technology to communicate the information. It uses the ThingSpeak platform [34]: an IoT analytics platform service that allows the aggregation, visualization, and analysis of data streams in the cloud.

The real-time monitoring of water quality in real time has always been of great importance for researchers and regulatory agencies worldwide. A typical method consists of employing the sensor network in the setting of IoT to detect and measure water quality parameters and share the resulting data by means of the Internet. Bearing that in mind, sensitive and selective sensors based on interdigitated microelectrode array (IDA) electrodes have been developed [35] for the detection of residual chlorine (in the form of hypochlorite ion). IDA sensors with an ion-sensitive coating show higher sensitivity of about 600 mV with [$HClO^-$] increasing from 0 to 10 mg L^{-1} more than the traditional sensing method. Both the response mechanism and selectivity have been dealt with. Furthermore, several material components that affect the sensing process were tested. On the other hand, the stability/repeatability and linearity have been significantly improved. The authors claim that micro-IDA chips with improved ISE membrane show a strong potential for residue chlorine detection for applications in water monitoring, but is not limited to this species, since they also show high selectivity to other common ions in water, such as sulphate, carbonate, and chloride. Other advantages also include small size, low cost, rapid response, and low power consumption, which is particularly suitable for IoT. Nevertheless, further details regarding reliability and standardization are missing in this paper.

It is often believed that environmental analysis still has to take full advantage of the benefits of low-cost data gathering by IoT sensors. In this sense, however, a recent work [36] has focused on some hands-on experience of using those IoT sensor devices in the environment. Additionally, this research contributes to lower computing costs by integrating Edge and Cloud Computing in the process of data gathering. Ultimately, it also means a reduction in the global cost of the distributed IoT sensor networks.

Alreshaid and his team [37] analyzed the process of integrating chemical and liquid/gas detecting sensors into the IoT. Using recently developed sensors that are integrated into wireless platforms as a starting point, a microfluidic sensor to detect different types of liquids is presented along with gas sensors that are able to signal the presence of targeted gases in really small amounts; these species include dimethyl methyl phosphonate, diethyl ethyl phosphonate, and ammonia.

The optimization of data transmission is one of the key points in the success of the application of IoT technology in environmental analysis. For this purpose, several compression techniques have been explored. One of them, compressive sensing (CS), is a really attractive model to be incorporated in the development of IoT platforms. CS is a new signal acquisition and compression theory that benefits from the “austere” behavior of most natural signals and IoT architectures to obtain power-efficient, real-time platforms that can lead to interesting IoT applications. A recent, comprehensive review has dealt with the incorporation of CS in IoT applications with the help of the existing bibliography [38]. Furthermore, the authors remark some major emerging trends in future CS-based IoT research.

Another interesting review covering the period 2013-2018 [39] critically discusses biosensor and chemosensor technologies and concepts utilized in an IoT setting or considered IoT-ready. The authors select these analytical chemical devices due to (a) their ability to be remotely located, (b) their adaptability to the dynamics of the environment, and (c) the fact that they easily function in networks (very important in case of continuous monitoring of environmental parameters). Besides, as the authors highlight, they have made the greatest progress toward IoT integration. The paper is completed with a revision of present and future challenges regarding a full integration into a global analytical concept.

Capella *et al* [40] have recently proposed a new approach for the development of better sensors based on Cloud services and IoT. Their proposal has been applied to the development of a potentiometric sensor for the determination of bicarbonate in water. The data obtained by this sensor are uploaded to the Cloud so that any user can access them. Furthermore, and taking advantage of the sensor connection to the network, this device makes use of the information available in the Cloud (mainly pH values), which leads to a virtual bicarbonate smart sensor with a better performance (lower cost and energy consumption). From a chemical point of view, the results obtained were straightforward with a highly satisfactory accuracy and precision. A complete experimentation was performed to compare the proposed device with other classical sensors.
Moreover, the authors point out that this work allows for the implementation of a new generation of smart sensors and, at the same time, joins the recent IoT waves. In this sense, it must be borne in mind that IoT proposes to decouple information sources and consumers, in such a way that (a) any application or device may use the information provided by other environments, and (b) the information generated by any application or device is available for others.

Finally, Muñoz et al [41], coinciding with the conclusions shown in [40], present the development of an IoT-based water management architecture to be applied in agro-industrial districts. This proposal includes desalination plants, connection to the public utility network, and several consumer agents. They provide a detailed description of the design of an IoT environment to carry out the optimal management of the heterogeneous resources required by the elements that make up these environments. In spite of the fact that only simulation results are presented, their approach demonstrate the benefits as well as the need for a coordinate research between IoT techniques and Environmental Analytical Chemistry.

4. Conclusions and future trends

In previous sections, IoT environments and their contributions have been commented. Now it is the turn to critically discuss the benefits of IoT and Cloud in Environmental Analytical Chemistry and what this discipline may offer to those technologies. Taking the need for a migration from the laboratories to the real environment as a starting point, we believe that this symbiosis is very important, supported by the development of low-size, inexpensive and low-consumption sensors that are able to work nonstop based on energy harvesting technologies.

a) What advantages may Environmental Analytical Chemistry obtain from IoT?

The starting point is the aforementioned Gartner's report [5], according to which "in 2020 95 % of newly designed electronic products will be equipped with IoT technology". This means that chemical analysis instruments will be developed to integrate themselves into IoT ecosystems that will be hosted in the Cloud. It will then be necessary to equip laboratories with the required communications infrastructure.

Thanks to the availability (in the Cloud) of this huge amount of data, new perspectives will be opened up in many fields of Environmental Analytical Chemistry. In the near future, trends show the possibility of obtaining nearly any measured data (regardless of its source) on a common platform, and accessible for any application –be it public or private– that needs them.

The manufacturers of sensing devices will be able to know –in real time- how their products are working, which will lead to the development and implementation of better sensors and transducers. On the other hand, the information on the environment (where the device is working) will be immediately available, thus allowing for the suitability of the sensor to the environment as well as the implementation of devices with extreme working ranges.

At a given moment, any device (or user) in the Cloud will be able to consult and utilize this information for his/her own benefit. In this sense, the approaches considering the information in the Cloud as a new virtual sensor (consulted -rather than obtained- measurements) are extraordinarily interesting, since they permit to supplement the functionality of real sensors. Thanks to these virtual sensors, it is then possible to apply redundancy techniques, fault tolerance, or interference rejection without incorporating new devices (no extra cost). As an example, our research group is now working on the determination of bicarbonate concentration in aqueous media using a classical CO_2 sensor, additional information required (pH) being obtained from the Cloud, whereas the obtained concentration values are stored in the Cloud.

The integration in the Cloud will allow for the evolution of the old model of Wireless Sensor Networks, according to which a set of predetermined nodes monitored a parameter in a continuous way, into new collaborative sensorization networks, where heterogeneous sensors with different purposes integrate their measurements into a common IoT platform. In this sense, even denser networks could be created, for example, by integrating these sensors into the smartphone of laboratory personnel. This information, as a whole, could also be offered to provide new services; initiatives such as open data from New York City or Valencia (our hometown in Spain) already gather and offer a great amount of data, both from the public domain or provided by private agents.

IoT ecosystems generate a great amount of data whose treatment can only be dealt with through Cloud Computing, where high scalability makes the resources nearly unlimited. Significant advances have taken place in the field of Data Science; Gartner forecast that “by 2020, more than 40 % of data science tasks will be automated”. That is why that Environmental Analytical Chemistry cannot ignore the impact of these new techniques in scientific research.

b) What benefits could bring Environmental Analytical Chemistry to IoT and Cloud Computing?

Although Internet of Things is going to become an intelligent environment (capable of interacting one on one with the human being), it needs senses. Taking into account that (a) computer vision and image processing are -in some way- the sense of sight of IoT and (b) personal assistants can be considered as the ears, Environmental Analytical Chemistry is destined to become IoT's taste and smell.

There are many parameters that can only be quantified (and therefore incorporated into smart environments) using techniques provided by Environmental Analytical Chemistry. If major variables such as cholesterol, city pollutants, or food toxicity are to be determined, an effort should be made to develop the suitable transducers, i.e. low cost, small size, and low power consumption. In this sense, relevant contributions could be, for example, the use of smartphone cameras in photometric analyses or the addition of pollution sensors to anti-pollution fitness masks). The field of wearables also offers a wide range of opportunities for these applications. In both cases, the usefulness of the obtained values would increase several-fold thanks to the incorporation of individual data –conveniently anonymized- into Cloud applications. For example, in this way runners could avoid the most polluted areas of the city.

A growing demand also expected in the miniaturization of sensors and transducers. The implementation of increasingly smaller devices would lead to a great amount of them in intelligent objects, thus offering new opportunities to electronic noses and tongues, redundancy or interference rejection techniques; all of them would increase both reliability and durability of sensors.

All in all, the symbiosis between Environmental Analytical Chemistry and ICTs opens up enormous prospects within the IoT & Cloud ecosystem.

There is scarcely any doubt that Environmental Analytical Chemistry (as well as many other disciplines) will soon benefit from the important aforementioned advantages of Cloud computing and IoT. Nevertheless, to date a detailed search in the literature has resulted in only a few relevant, major contributions, hence the importance of the present work as a somewhat pioneering contribution in this application field.

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FIGURE CAPTIONS:

Figure 1: The way towards IoT (Internet of Things).

Figure 2: Scheme of (a) off-line analysis, (b) at-line/on-line analysis, (c) in-line analysis, (d) data retrieved from the Cloud.

Figure 3: Different elements combined in a Cloud-based IoT platform.

Figure 1

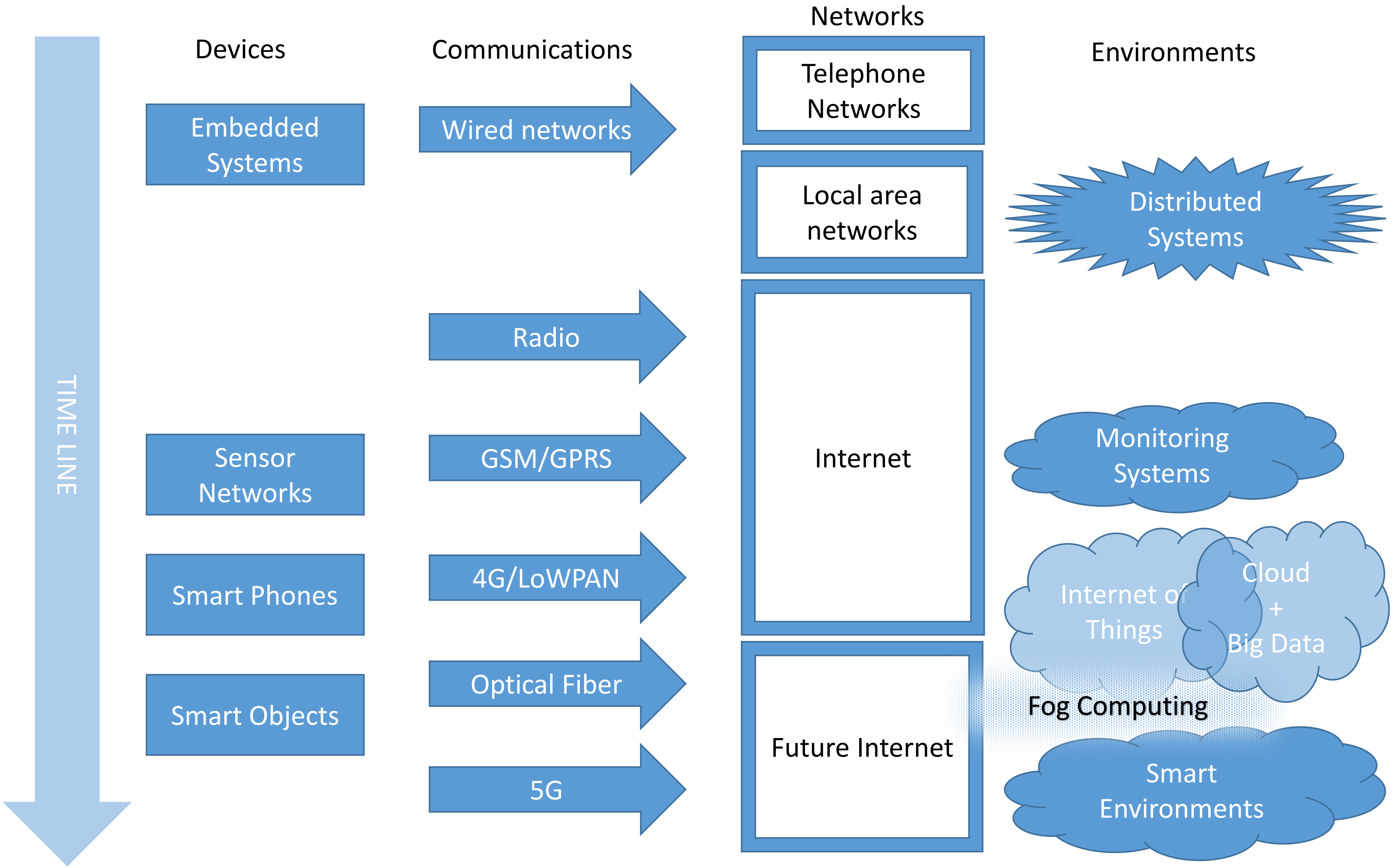
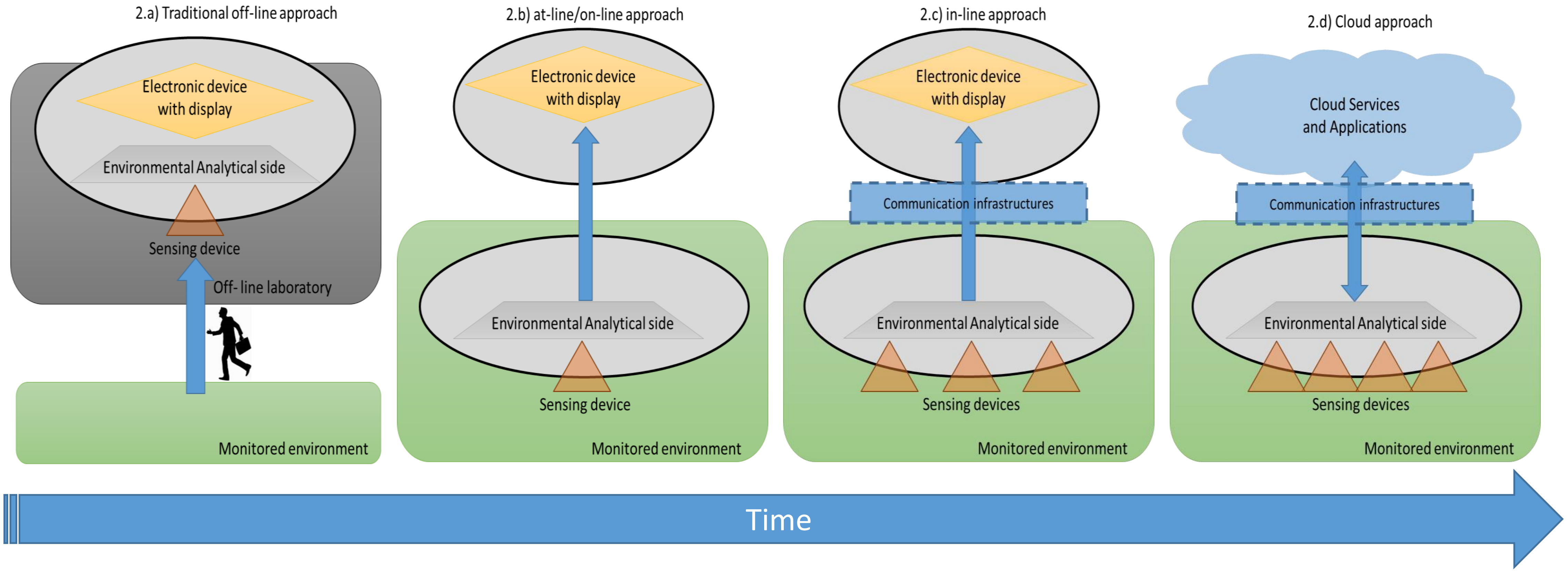
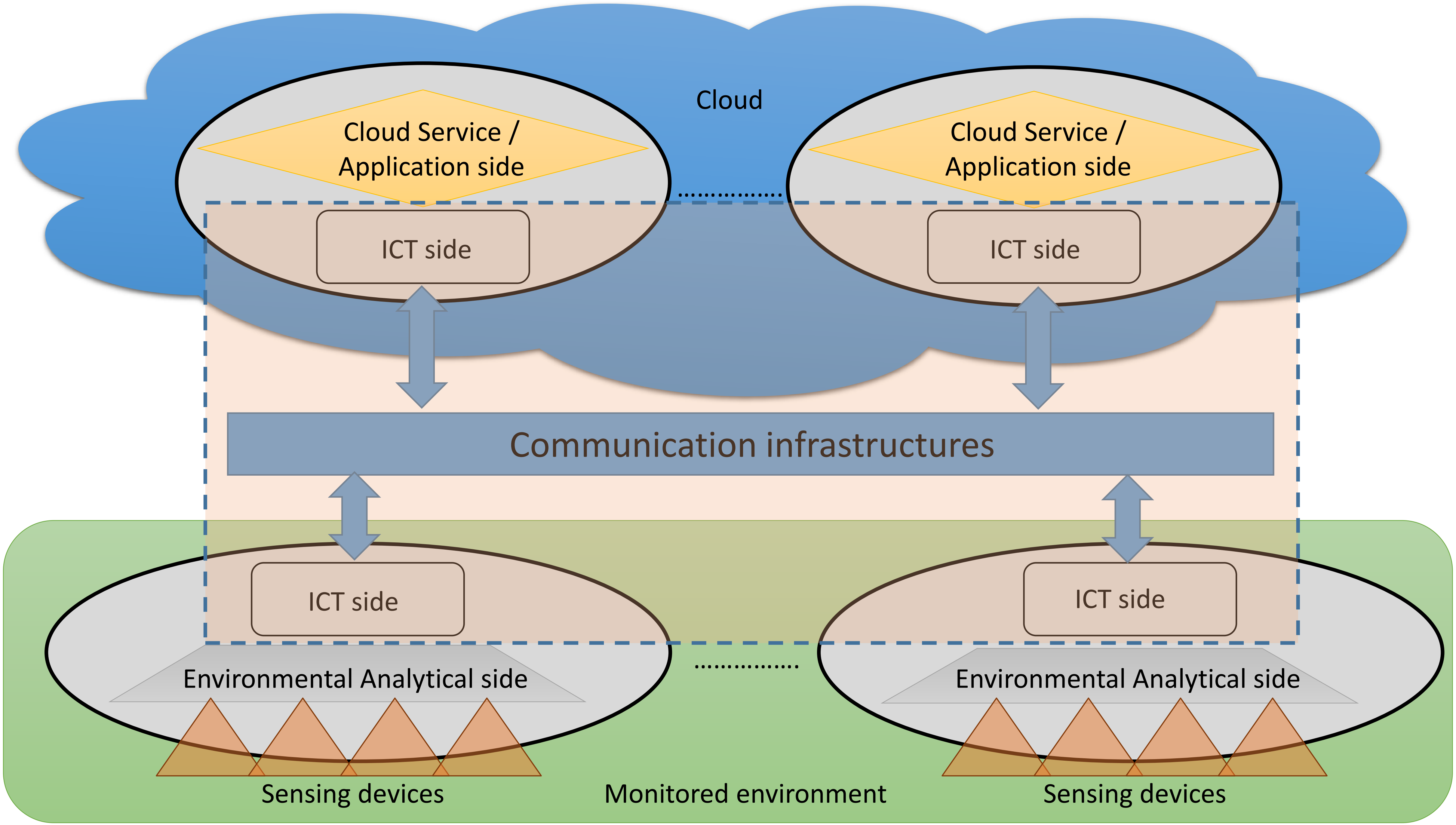

TIME LINE
Devices
Communications
Networks
Environments
Embedded Systems
Wired networks
Telephone Networks
Local area networks
Distributed Systems
Radio
Internet
Sensor Networks
GSM/GPRS
Monitoring Systems
Smart Phones
4G/LoWPAN
Internet of Things
Cloud + Big Data
Smart Objects
Optical Fiber
Fog Computing
5G
Future Internet
Smart Environments

Figure 2



2.a) Traditional off-line approach
Electronic device with display
Environmental Analytical side
Sensing device
Off- line laboratory
Monitored environment
2.b) at-line/on-line approach
Electronic device with display
Environmental Analytical side
Sensing device
Monitored environment
2.c) in-line approach
Electronic device with display
Communication infrastructures
Environmental Analytical side
Sensing devices
Monitored environment
2.d) Cloud approach
Cloud Services and Applications
Communication infrastructures
Environmental Analytical side
Sensing devices
Monitored environment
Time

Figure 3


Cloud
Cloud Service / Application side
Cloud Service / Application side
ICT side
ICT side
Communication infrastructures
ICT side
ICT side
Environmental Analytical side
Environmental Analytical side
Sensing devices
Monitored environment
Sensing devices