All for One, All at Once: A Pluggable and Referenceable Architecture for Monitoring Biophysical Parameters Across Intertwined Domains

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Abstract. An architecture capable of monitoring biophysical parameters from both the human, veterinary, and environmental domains is described, which focuses on the intersection of Internet of Things (IoT) and Edge Computing. The main features of the architecture - pluggability, cross-referenceability, and measures accuracy and reliability - were developed to deal with the characteristics of the One Digital Health framework. The potential benefits of a pluggable and referenceable architecture have been emphasized for different kinds of stakeholders, as described in two different use-cases from the human/animal and the environmental domains. Potential benefits for the stakeholders from deploying the architecture compared to market and applied research solutions have been discussed.

Keywords: Edge Computing · Internet of Things · Use-cases · eHealth · One Digital Health

1 Introduction

In the last twenty years, the Internet of Things (IoT) has experienced a diffusion over many areas of society and a number of application fields, among which eHealth, Home Automation, Smart Cities and Industry 4.0 are the most emblematic [1, 2]. IoT applications are able to collect data in real time through sensors, to communicate with other devices and to implement services that aim to improve the quality of life. Edge computing (EC) is a distributed computing model in which data processing occurs the closer as possible to where the data is generated. A common ground in human, animal and environmental health projects is often the need for the institution stakeholder to be provided with a solution able to (i) allow cross-referenceability of different data sources, and (ii)

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be pluggable into any kind of Information System already on duty. Furthermore, some stakeholders may be forced to make use of certified devices which, far from being the goal of the research themselves, are instead able to produce data to support research objectives [3].

Herein, an architecture is introduced that allows collection, real-time transmission and processing of data using EC and IoT concepts. Such pervasive data monitoring infrastructure is supposed to be: (i) pluggable in any kind of Information System already in use in various possible fields of application, without requiring redesign or refitting of the existing solutions; and (ii) referenceable in that it allows to cross-reference the data gathered in automatic and unified way from different kind of sensors and contexts. Aim of the present work is to evaluate the applicability of the introduced cloud-edge architecture to different health-related scenarios, centered on a human/animal (health informatics/veterinary health informatics) or a green subject (environmental informatics). The scope is to test its capability to support the comprehensive monitoring of biophysical parameters in intertwined scenarios, according to the specifics of a One Digital Health (ODH) Intervention [4–6].

After the introduction and a brief analysis of the literature, the proposed architecture is described from a technical viewpoint, along with the two mentioned application use-cases. Some discussion and conclusions are then provided, especially for what concerns the role of the architecture within the specifics of the ODH framework.

2 Background

2.1 From Cloud to Edge

The most widespread architecture adopted for providing services through the Internet follows the Cloud Computing model, in which a localized cluster of Data Centers is tasked with receiving, processing, storing data and transmitting results. This cluster, called Data Center Network (DCN), is seen as a single, scalable and ever available service, and is strongly oriented to the client-server paradigm. Digital communications technology leaders have made evident how the number of connected devices is increasing, especially mobile and IoT devices, whose traffic is increasingly machine-to-machine, as devices communicate without human interaction [7]. Accordingly, the summation of the data created, captured or replicated is expected to grow from 33 Zettabytes in 2018 to 175 Zettabytes in 2025 [8]. This growth has raised two main concerns: (i) since each DCN is localized, time-critical applications are affected by degraded performance based on the client's geographical position; (ii) the amount of data transmitted worldwide is outgrowing the Internet infrastructure enhancement. To overcome these issues, the most straightforward idea is to move the service closer to the client, in order to require shorter transmission paths, decreasing both service delays and the network load, a concept later evolved in EC.

2.2 Edge and IoT, as a Whole

The IoT is the extension of the Internet to devices that communicate among themselves without human intervention, often organized as nets of sensors, actuators and wearables that produce and consume data in order to implement real world services. These devices need to transmit measurements occurring several times each second, therefore installing multiple sensors can add a severe bandwidth consuming load on the network. Also, the sensors usually need to be cheap and to have a long-lasting battery, thus they only support a Low-Power Wireless Personal Area Network (LoWPAN) [9]. Both those characteristics have usually led IoT infrastructures to include IoT Gateways, tasked to retrieve data from data producers, make decisions, actuate devices and send data to Cloud structures. This kind of infrastructure naturally overlaps with an EC application one, thus making it an enabler for sophisticated IoT applications like Smart Cities for environmental monitoring, Telemedicine, and Industry 4.0 [5, 9, 10].

With specific reference to the healthcare sector, data can be e.g., taken by means of IoT devices during an ongoing rehabilitation process far from the medical department, allowing for shorter hospitalization and cost reduction [11]; furthermore, non-invasive observations can be held and processed continuously in order to allow timely intervention or prevention [12], and the same data can be useful when consulted by medical staff when treatment is needed, even when they are not characterized by a medical grade accuracy [13]. Since that data is taken remotely, healthcare can be fairer in case of geographical limitations [11]. Yacchirema et al. [14] presented a system able to detect falls with 91.67% accuracy. Their architecture, embedding a smart IoT Gateway, can detect falls based on a decision tree updated and supplied by the Cloud Node. P-Ergonomics Platform, shows how EC enabled IoT health monitoring can take place in occupational wellbeing and can help mitigate work-related disease such as musculoskeletal disorders [15]. This platform uses an Infrastructure-as-a-Service (IaaS) EC platform such as well-known providers (e.g., Amazon, Google, Microsoft).

3 Proposed Architecture

While EC is all about bringing resources closer to the edge, implementations may differ greatly, having as common ground the presence of three main layers: *Edge Devices Layer, Cloud Layer* and *Edge Node Layer* (Fig. 1).

The proposed implementation of the architecture is shown in Fig. 2. It has been evaluated for the use in public projects where entities, covering the role of the customer, requested a pervasive data monitoring infrastructure without having a bleeding-edge Information System.

The *Edge Devices Layer* features devices connecting from the edge (or Endpoints), requesting a service. For the proposed architecture it is made up of sensors that can leverage low power PAN connection technologies in order to have a long-lasting battery life. Non-invasive devices could become set-and-forget.

For the deployed architecture it has been chosen to add a *Gateway* between the Edge Devices Layer and the Edge Node Layer. The choice was driven by the willingness of either, keeping most of the network load confined in the PAN and, allowing for quick responses for time-critical applications. The gateway is therefore responsible for managing a star-shaped network of sensors for, on the one side, performing data aggregation and, for the other side, routing both internally and through the Internet. In addition, gateways perform local analysis to react to field state changes while adapting its behavior

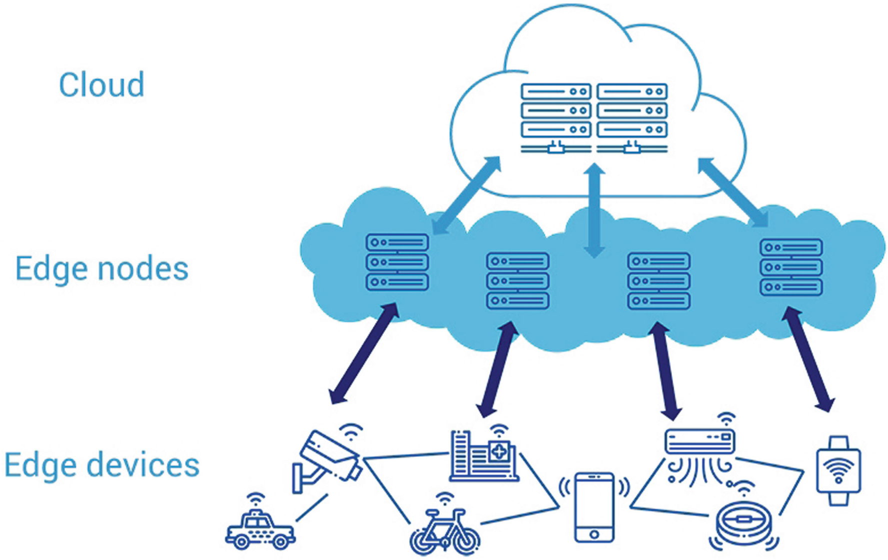

Fig. 1. Edge Computing general structure

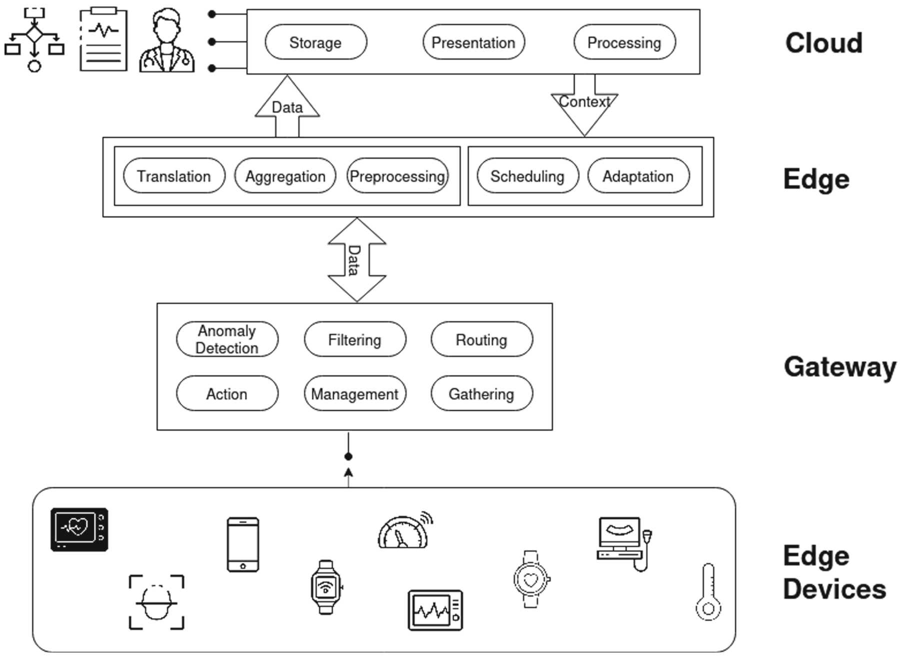

Fig. 2. General structure of the proposed architecture

depending on the context. Sensor values and policies requested by the customers shape such context so that a coordinator on the layer above is prescribed.

The *Edge Node Layer* features servers that are generically described as lying between the Cloud Node Layer and the Edge Devices Layer. Communication among layers is mainly composed of traffic between the Endpoints and one or more Edge Nodes. For the proposed architecture, most of the Internet load is between the Gateways and the Edge Nodes. The Node can be placed and replicated based on the client's requirements. The Edge Node supervises a set of gateways, providing them with a configuration depending on the policies dictated by the Cloud Node. Furthermore, the Edge Node takes a role in data-processing, sending results to the Cloud Node. This processing can be of different nature such as applying mathematical algorithms and taking decisions. However, the processing should not need to identify a subject and does not store sensitive data, thus leaks and data correlation attacks result in unprofitable efforts.

The *Cloud Layer* features a Data Center Network, or Cloud Node, and it has a central role in applying intensive processing and storing massive amounts of data. However, managed data have the property of being needed both centrally for data processing, and globally by the endpoints. In the proposed architecture, the customer is interested in receiving a set of data from both the Gateway and the Edge Node. The Cloud Node is installed directly into the customer's facilities in order to respect data protection regulations and policies. This Node can elaborate and store data being able to apply complex processing thanks to the chance of cross-referencing the data ever harvested. One main focus is allowing different kinds of agents, both algorithms and human staff, to consult and operate on data, which will differ in nature, from diagnostic imaging to time series.

4 Use Cases

4.1 Human Domain

A scenario has been figured out within a research project with a University Hospital, where elderly people have undergone a home care treatment in which data monitoring and Assisted Physical Activity have been used to implement a tele-rehabilitation prototype program. Patients have been provided with a set of medical IoT (IoMT) devices, and instructed to perform exercises and simply take measurements of some among their biophysical parameters, the way they were already used to; data is therefore automatically collected, processed and then included in the medical records managed by the existing Electronic Health Records (EHR) framework used in the hospital, and currently hosted in the Cloud Node.

The sensors currently included in the application fall into two categories: some can be considered "set-and-forget", such as a fitness tracker, a speed sensor embedded in the mini-cyclette provided for the Assisted Physical Activity (APA), or an inertial sensor that can be installed on the beddings in order to estimate heart rate and sleep quality; others need some interaction due to their nature, like a thermometer, a pulse oximeter, a blood pressure monitor and a scale. In order to deploy the latter category of sensors into the application, the instruments needed to look familiar and work like their non-smart counterpart: this means that patients would only be required to operate the device starting a measurement and any consequent setup or connection would be handled by the gateway. To act as the gateway, an appliance equipped with an ARM-based SoC and the Android operating system has been deployed. Many low-cost devices adhere to this description and some of them even support general purpose I/O ports, thus allowing the connection of custom inputs as screens or sensors. A framework running on such gateways features the appropriate interface to communicate with every BLE sensor to manage and retrieve data. The framework aggregates different kinds of data, both in the form of measurements and events e.g., devices moving out of range. The gateway behavioral policies are defined by the Edge Node, which provides it with a suitable configuration that can be updated during the operation time, whenever needed. Such a process makes it possible to (i) define new targets for data streams, (ii) change the scheduling of operations, and (iii) update security credentials, without requiring any user interaction. The gateway does not have enough computational resources for an effective data processing, so it can either transmit the data gathered from the devices to the Cloud Node (i.e., in case data do not need further processing), or it can send them to the Edge Node otherwise. However, gateways can make simple decisions based on non-medical interpretation of sensor readings, such as what to do on the occurrence of particular events, or when a value with a particular meaning has been gathered. For instance, the gateway can trigger a notification on the fitness tracker when a value exceeds a particular threshold. The installation of the gateway requires no more than a power cable and a LAN cable. In this regard, a cabled connection to the patient's home router has been chosen to let the gateway access the Internet without further configuration. A WiFi connection would have instead required little gateway configuration by means of a HID device. Each gateway at its first boot asks the Edge Node for a valid configuration to know the sensors it shall connect to. Authors refer to the "Gateway + sensors" set as "Kit". The role of an edge node can be fulfilled by a machine equipped with the computational power that can be commonly found in consumer electronics, and by open source software. What has been implemented in this case is a machine with two main aims: (i) communicating with the gateways via a message queue-based interface; and (ii) providing a REST service for the Cloud Node. The data received from the gateway needs non-medical and non-identifying processing, like unit conversion, data filtering, data aggregation and compression. The Edge Node receives from the Cloud Node via the REST interface new policies. Gateways will be updated with new configurations and schedules originated by the mentioned policies. As an example, some policies relate to the Kit composition and the sensors' sampling settings. The edge node is responsible for storing sensors' unique identifiers therefore setting up Kits and defining behaviors for the gateways. The Cloud Node exposes interfaces on two sides too: on the one side it receives data from both the Edge Node and the gateways; on the other side it should expose a set of interfaces that are appropriate to feed data to: medical staff, algorithms, and data visualization graphical interfaces. However, the Cloud Node has been left to the stakeholder to implement or commission, since as said it mainly hosts a EHR framework. What results is that medical staff have been provided with a unified user interface that aggregates (i) locally hosted data about patients, and (ii) data coming from the edge, gathered from the Kits patients are associated with. When a new patient needs to be included in the remote monitoring plan, the medical staff register their data on the platform and associate them with a Kit. The patient is instructed as to how to use the sensors of their Kit; no configuration or maintenance is needed besides basic battery management.

While the monitoring system operates normally and standard policies are set on the Cloud Node, the gateways receive measurements all-day-long from different Edge Devices as soon as they are made available from the equipment. Data collection happens simultaneously from all the devices operated by the patient so that, for instance, it is possible to retrieve weight from a scale while measuring temperature with a thermometer, thanks to the technicalities of the BLE protocol. Some of the Edge Devices have an embedded memory that allows multiple parameters to be stored for days, e.g. smartwatches and portable ECGs. When the devices are available in range, the whole memory content is retrieved by the gateway and processed to: (i) reduce redundancy, and (ii) update the Edge Node only on new data. As an example of a particular situation that has come across during the APA project, physicians decide to impose a policy at Cloud Node level for which each patient that had a severe cardiac episode must have their SpO2 and Heart Rate (HR) sampled while pedaling during their training sessions. Cloud Node provided, alongside the policy, a list of related Kit IDs to the Edge Node. The simultaneous sampling of both cycling rate and SpO2 and HR from the pulse oximeter was already possible but the Edge Node also imposed a subsequent policy: during bike sessions, all the devices capable of measuring SpO2 and HR - e.g. smartwatch - had to enable real-time sampling for the whole session as to have benchmarks. Policy group is then translated into a configuration sent to the interested gateways.

4.2 Green Environment Domain

A second scenario has been devised collaborating with the Municipal Administration of a metropolitan city in South Italy, for a research project aimed to establish a remote pervasive monitoring system for the urban greenery. The objective was to allow specialists, employed by the Municipal Administration, to remotely infer on the damages either unpredictable (e.g. broken branches caused by extreme weather conditions), too widespread to be monitored effectively (e.g. drying trees caused by high temperatures), or anthropic-related. The deployed system harvests, refines and feeds the cloud information system hosted in the eGovernment framework with biophysical parameters of the greenery including wind speed, temperature and humidity of both air and soil, acceleration and orientation of branches and trunks.

The application needed sensors to be installed non-intrusively on green subjects over a large area in open air, both at heights and near the roots, thus several requirements have been identified for the outdoor components. Since their particular placement on green subjects lowers the maintainability of the whole system, sensors needed to be durable, low-cost and require low maintenance. As for the latter, green computing strategies have been adopted to optimize longevity and power consumption of the sensors while still providing a suitable range for wireless communication. While a water and dust-resistant shell addresses the most immediate concern about exposure, an accurate choice of SoC with BLE support has been made aiming to maximize battery life, allowing for year-long maintenance cycles. The deployed sensors feature an additional signal amplification setting that can be remotely tuned to achieve a proper balance between power consumption and transmission range. A custom Gateway Station has been built using a dust and water-resistant shell that exposes the solar panel and an anemometer, in a compact package, that can be easily installed where suitable exposure to sunlight and wind is provided (e.g. lamp post). Cautions about power saving relate to gateways as well. The minimum hardware for the task has been identified in an ESP-32 microcontroller equipped with a GSM modem for internet connection, with long-term deployment being ensured by a 12Ah 12V battery and a solar panel that recharges it via a voltage controller module. In this Use Case, authors define as "Kit" each set featuring the gateway and exclusively the sensors it manages. The management tasks include: getting new configurations from the Edge Node, pushing sensor settings (e.g. signal attenuation and polling rate), gathering measurements from sensors and sending them to the Edge Node. In order to minimize the time in which the equipped GSM modem is turned on, the gateway buffers measurements in compressed units and turns the modem on only when needed. Additionally, the gateway acts as a local weather station, measuring parameters as a common context for the field. In case new sensors are declared on the Edge Node, they are dynamically added to the Kit of the geographically closest gateway, the configuration of which is timely updated. On the other hand, if a gateway is added to the greenery, a reassignment is performed to match each sensor to the closest gateway now that a new one is present in the field. The Edge Node is, again, made up of consumer electronics and open-source software. While, on one side, the Edge Node is tasked with operating on data and managing the gateways, on the other, it exposes a REST interface for communication with the Cloud Node. Data operation starts by decompressing the mentioned data unit. The measurements need then to be processed depending on the sensor's installation parameters that are stored in the Edge Node. This makes it possible to infer branches' and masts' inclinations time series. Finally, data is sent to the Cloud Node. Gateway management is a dynamic process that produces a configuration that minimizes power consumption and considers the policies received from the Cloud Node. Sensors declaration, administration and policies are received from the Cloud Node through the REST interface. The Cloud Node receives data from the Edge, while providing a sensible interface for the domain's experts to use. Authors did not implement the Cloud Node, as it lies in the Information System of the Municipal Administration along with its established framework which is subject to restrictive policies. However, a graphical user interface is available on the Cloud Node, which allows remote kit administration and locally saved data visualization.

The system, when the standard policies are in place on the Cloud Node, yields values of wind speed, acceleration, temperature and humidity with different frequencies, depending on the meaning of each of these parameters. For instance, branch acceleration measurements fluctuate faster than those of the trunks; temperature and humidity vary on a larger time scale. Based on this, sensors can be fine-tuned in order to improve battery life and reduce storage redundancy. However, policies can be specified to address specific scenarios improving precision botany intervention. In a first example, in order to measure the soil response to the water fed and actuate an efficient irrigation strategy, agronomy specialists have compiled an irrigation timesheet on the Cloud Node; the system reacts by increasing the humidity sampling rate. Another example pertains to anthropic risk during extreme windy conditions: when the wind speed exceeds a threshold, the trees' oscillations time series needs an increased definition, thus the polling rate is set to the maximum. In both examples, the policies are filled out on the Cloud Node through a graphical interface, then are sent to the Edge Node layer, from which configurations are calculated and delivered to the interested gateways, according to positioning within the greenery area. Gateways, then, dynamically orchestrate the sensors, even making choices and schedules based on the configuration received.

5 Discussion

The design of the proposed architecture was driven by the need to develop specific features to deal with the ODH paradigm [4], which brings in a syndemic scenario new questions, new solutions to be found. In this regard, in projects spanning at different extents human, animal, and environmental health, a frequently encountered requirement involves as said delivering solutions to institutional stakeholders, which make it possible to (i) seamlessly integrate into any existing Information System currently in use, and (ii) facilitate cross-referenceability across diverse data sources. Accuracy and reliability of measures is a further objective of utmost importance to be accounted for. Experiences moving in such directions can be either found for instance in [16, 17] for Veterinary medicine, and in [18] involving green subjects. In particular, the former shows how the human-based case study reported in this work can be extended to the animal domain as the logic underlying the two kinds of business processes are comparable [19]. Table 1 summarizes the main differences between the proposed architecture, the solutions currently existing on the market, and those developed in applied research.

Table 1. Features supported by different kinds of implementations.

	Market Vendors	Applied Research	Proposed Architecture
Pluggability	N	Y	Y
Cross-referenceability	Y	Y	Y
Accuracy and reliability of measures	Y	N	Y

Big vendors' solutions usually lack pluggability-related features for mere commercial reasons. There is little interest in developing solutions integrable with other systems, as the purpose is to sell a closed, single-package (although customizable within certain limits) to the final client. It is on the other hand highly likely that referenceability-related features are deployed, because in many cases it is noted that different devices from the same vendor show aggregated information via a single, shareable interface - e.g., websites/smartphones apps. Moreover, as big vendors aim to produce and commercialize devices that can be certified, accuracy and reliability of the measurements as well are at their best. Pluggable- and referenceable-related features can be detected in solutions developed in applied research-focused contexts: the devices embedded in such solutions are in fact mostly experimental in nature, and aimed at rapid prototyping, therefore they are highly customizable [13]. This makes it therefore possible to achieve high-level results in terms of both pluggability and referenceability. On the contrary, the major emphasis on the aspects of device integration simplicity and ease of platform creation may hinder a timely development of the aspects of measurement accuracy and reliability.

In our case, according to the principles of implementation of an ODH Intervention [5], the Edge Node Layer hosts those digital functionalities/digitalities that are operationalized to deliver specific activities (Specialities), by means of the IoT-based Edge Devices (Technologies). The sensors used in the *IoT* devices do not need significant throughput, but only require connectivity capable of being supported by backup batteries, and low-cost hardware. The study of this category of low-cost and low-energy devices has mainly focused on those communication protocols that enable the most effective strategies for this purpose, resulting in fertile ground for Bluetooth Low-Energy (BLE) [20]. Since the Bluetooth specifications prescribe hardware and connectivity protocols, but not the content of the transmitted packets, many sensors use proprietary data protocols and representations, requiring proprietary programs or smartphone applications to access said data: as previously stated, this was not favorable for the application. Finding different kinds of certified sensors capable of both producing *reliable and accurate measures* and to connect to a single gateway has been a lengthy task, and usually the manufacturer was requested to provide either the protocol documentation, or a library implementation of the communication interface. Many project stakeholders requested, similarly, data collection applications with low-cost non-invasive sensors, in which they would study, process and cross-reference the data using their Information System already on duty [21]. An IoT EC application can be connected to said Information System, not only letting IoT and EC complement each other, but resulting in easy adoption. Moreover, embodying characteristics of *pluggability* makes the adoption of the biophysical parameters monitoring solution, either within the same domain (yet in different application contexts), and in different but intertwined domains, easier and less traumatic for stakeholders within a real-world scenario.

In this sense, it is possible to agree that deploying an ODH Intervention by means of the proposed architecture, can (i) address One Health–related challenges; and (ii) ensure both economic and practical convenience for stakeholders. Likewise, the design and deployment of an ODH intervention also requires from the generated data, at each step, to be [22, 23]: (i) "Findable," as the digitalities involved contribute to the study and collection of all data pertinent to the interconnection between systems' needs; (ii) "Accessible" through standardized protocols, leveraging common substrates of data, information, and knowledge derived from digital biodiversity; (iii) "Interoperable," as a result of the deliberate establishment of an ecosystem capable of facilitating seamless and secure health data exchange and processing, addressing shared risks between animal and human populations; (iv) "Reusable," enabling a systematic, continuous, and intelligent integration of extensive, intelligent, and multidimensional data exchanges facilitated by the digitalities involved. At the semantic level, it is imperative that the nomenclature employed for (meta)data and the delineation of variables along with their attributes, aligns seamlessly with a controlled vocabulary [24]. The need to use data collected across scientific disciplines and related to different communities is in our case possible, as the proposed architecture has been designed with a focus on *referenceability*:

data collection from Edge devices is in fact accomplished by exploiting low-level communication protocols, thus leaving the authors full control of the (multi-terminology) thesaurus to be specifically designed [25]. In this way, data from different sources across the three One Health domains can essentially share common vocabulary and background knowledge - which matches with the requirements of Interoperability, actually critical to achieve data cross-referenceability.

Additionally, to all of the above, it is also possible to agree that deploying an ODH Intervention by means of the proposed architecture, can (i) achieve One Health–related important and strategic outcomes for clinical follow-up and practice, such as for technology improvements needed; and (ii) achieve FAIR uses of digital technologies by trying to be environmentally-respectful by design [26].

6 Conclusions

In the present paper the design of a Cloud Edge architecture embedding IoT devices was introduced, which consists of four layers of nodes in increasing distance from the data source. The main features of the architecture - pluggability, cross-referenceability, and measures accuracy and reliability - were developed to deal in the most appropriate way with the issues descending from the implementation of the One Digital Health framework. Two use cases were described to showcase the deployment of the architecture in human- and environment-centered scenarios, respectively. In the application of a ODH framework many opportunities can be found, as stakeholders may have non-bleeding edge Information Systems while subject to restrictive and complex privacy policies. However, having access to cross-referenceable data coming from different domains, collected by sensors that are both certified and already available on the market, makes stakeholders able to perform complex and precise data analysis having access to large amounts of data. Such amounts of data are of increasing importance if Artificial Intelligence-based approaches are also to be considered, and it certainly suggests a direction for future developments in One Health-focused scenarios of critical importance such as urban aquatic ecosystems, called to serve as vital connectors between people, animals, and plants, fostering biodiversity and sustainability in cities [27].

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