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SEMANTIC CHALLENGES IN THE INTERNET OF THINGS FOR WELL-BEING, AGING AND HEALTH

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Contents

1. Introduction

The World Health Organization (WHO) defined universal health coverage (UHC) [1] as its priority objective in ensuring that all people have access to the health services they need, including prevention, promotion, treatment, rehabilitation and palliative care, of sufficient quality to be effective, while ensuring that the use of these services does not expose the beneficiary to financial difficulties. WHO also defined e-health as “the cost-effective and secure use of information and communications technologies (ICT) in support of health and health-related fields, including healthcare services, health surveillance, health literature, and health education, knowledge and research” [2]. With the greater involvement of electronic systems and ICT in the provision of health services, major international organisations, such as the European Union (EU), the International Telecommunication Union (ITU) and the European Space Agency (ESA), have officially adopted the term “e-health”. It refers to the utilisation of modern information and communication technologies in order to meet the needs of citizens, patients, healthcare professionals and policy makers [3].

The Global Observatory for e-Health (GOe), WHO initiative dedicated to the study of e-health, its evolution and impact on health in countries, has reported back in 2016 that “it has become increasingly clear that universal health coverage (UHC) cannot be achieved without the support of e-health” [4]. The United Nations (UN) 2030 Agenda for Sustainable Development highlights that “the spread of ICT and global interconnectedness has great potential to accelerate human progress, to bridge the digital divide and to develop knowledge societies” [5]. The vision of the WHO Global strategy on digital health 2020-2025 is “to improve health for everyone, everywhere by accelerating the development and adoption of appropriate, accessible, affordable, scalable and sustainable person-centric digital health solutions to prevent, detect and respond to epidemics and pandemics, developing infrastructure and applications that enable countries to use health data to promote health and well-being, and to achieve the health-related Sustainable Development Goals (SDGs)” [6].

Regarding the more recent term “digital health”, in 2018 the World Health Assembly (WHA) adopted a resolution on digital health [7], which recognised the potential of digital technologies to play an important role in improving public health. The resolution has urged the Member States to prioritise the development and greater utilisation of digital technologies in health care as a way of promoting UHC and advancing the SDGs. The relationship between the terms “e-health” and “digital health” still seems unclear, with some ongoing debate: while the WHO treated them as synonyms, some sources [8] provide different perspectives and broader definitions of digital health as “the convergence of genomics, big data, and digital technologies to provide personalised healthcare at lower cost” and “cultural transformation of traditional healthcare”. In this work, “digital health” will be used as the latter. Thanks to the accelerated development of artificial intelligence (AI) models in recent years, it is necessary to include machine learning (ML), deep learning (DL) and generative AI models in the above-mentioned digital technologies convergence statement.

Given the notion of cyberspace as a "global domain within the information environment consisting of the interdependent network of information systems infrastructures including the Internet, telecommunications networks, computer systems, and embedded processors and controllers" [9], the term initially introduced by short fiction writer William Gibson in his 1982 short story "Burning Chrome" and criticized later by the author himself, clarifications are needed to be given for terms cyberhealth and cybercare. Cyberhealth refers to cybersecurity health or hygiene, as the practices and procedures that individuals and organizations use to maintain the health and security resilience of their systems, devices, networks, and data [10]. The main goal of cyber hygiene is keeping sensitive data secure and protected from cyberattacks and breaches. Cybercare refers to "healthcare in cyberspace", e. g. doctor’s consultations with patients via videoconferencing, or patients receiving care locally by using IT such as telemedicine, smartphones, and wearable sensors to link to medical specialists [11].

Wearable sensors belong to the Internet of Things (IoT). IoT is a term coined by the computer scientist Kevin Ashton back in 1999, while working at Procter & Gamble, where he introduced radio-frequency identification (RFID) chips on products to track them through a supply chain [12]. Today the term encompasses a variety of ICT and network protocols joined in the "network of uniquely identifiable connected things (also known as devices, objects, and items) offering intelligent computing service" [13]. The continuous spread of IoT worldwide shows that the number of global IoT connections grew by 18% in 2022 to 14.3 billion active IoT endpoints [14], while predictions state the global number of connected IoT devices in 2023 to grow another 16%, to 16.7 billion active endpoints, and to more than 29 billion IoT connections by 2027 [14]. The growing demand for applications around the world in manufacturing, transportation, healthcare, retail, energy and utilities, and residential has had direct impact on the IoT growth [15].

IoT technologies have been applied to healthcare and well-being for a growingly ageing society in seek of care in order to "increase the quality of healthcare and overall well-being while reducing related costs and overheads" [16] by providing innovative solutions, such as IoT-enabled residential environments to provide assisted living for dementia suffers, well-being monitoring and intervention powered by low-cost sensing devices, and quantification of the self [16]. The term "well-being, aging and health" (WBAH) has been coined to cover application areas that "not only support healthcare, but also foster well-being, encourage patients and the population in general to live according to healthy lifestyle recommendations, and address the specific needs of an aging population" [17]. WBAH aspects are being addressed at the policy level by recent global initiatives, such as The UN Decade of Healthy Ageing (2021-2030) [18], a global collaboration aligned with the last decade UN SDGs, aiming to foster healthy aging and improve the lives of older people and their families and communities.

IoT represents a share of heterogeneous networked computing resources, along with the cloud, fog/edge computing, and mobile devices, all unified into a seamless and integrated continuum, a novel computing paradigm named distributed computing continuum (DCC) [19], as shown in Fig. 1.1. A part of this hybrid model integrating edge devices with centralized cloud services (and in some sources the whole continuum) is named edge-to-cloud continuum (ECC), enabling perpetual connectivity, pervasive computing, and precision control in virtually all industries [20]. In a DCC computations are performed by distributing the workload across multiple devices in the system and combining the final results, in order to make the processing faster and increase scalability. The resources are allocated "based on factors like resource proximity, computational capability, and prioritizing time-sensitive tasks" so "real-time responses may be offloaded to edge devices, while complex analytics may be conducted in the cloud by default" [19]. There are several classes of computing devices in DCC: computers (desktop, laptop, embedded), IoT (sensors, actuators), mobile devices (smartphones, smartwatches, tablets, etc.), servers (web, e-mail, file, and database servers, etc.) and supercomputers.

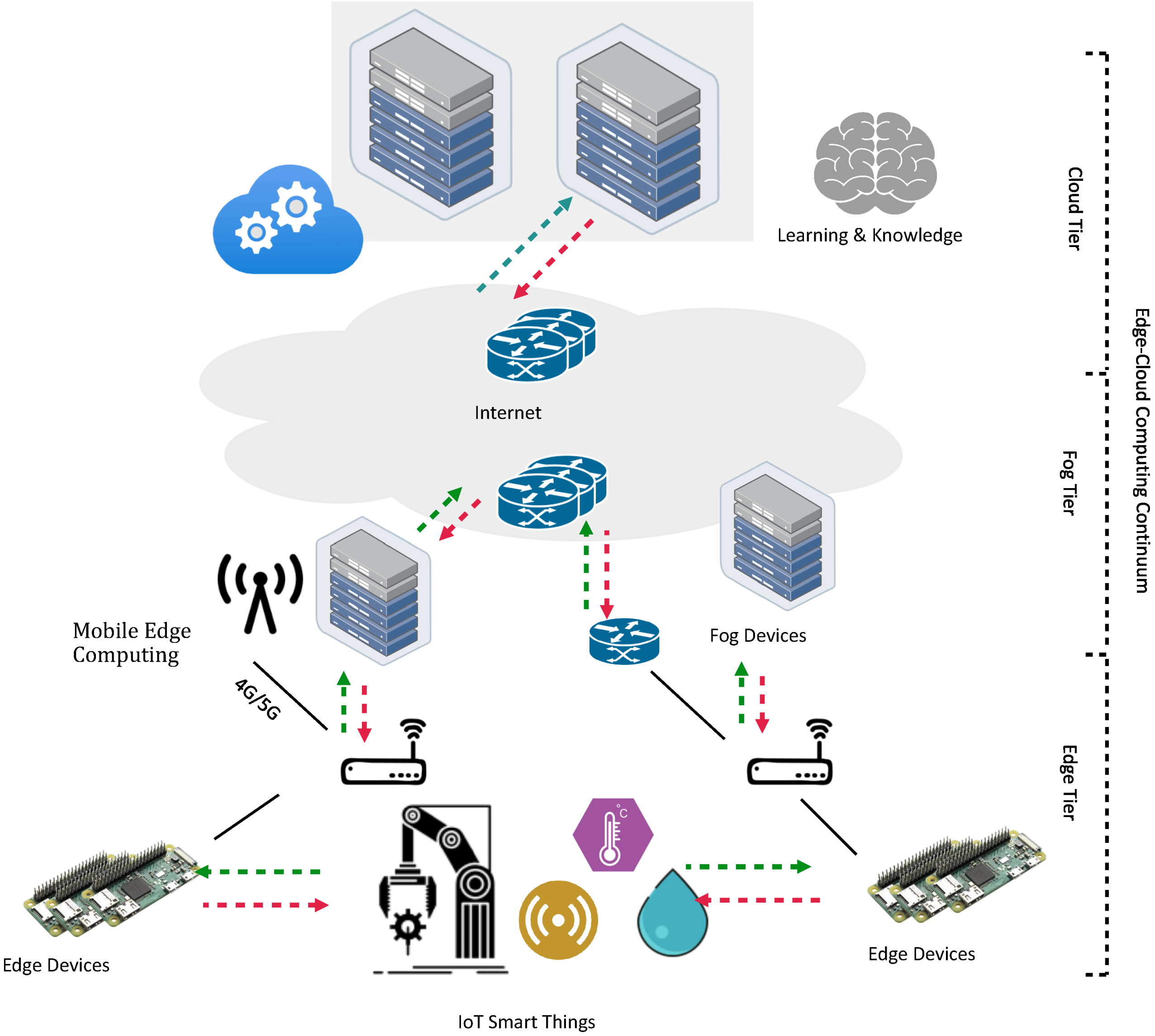


Figure 1.1. General architecture for distributed computing continuum (DCC) systems [19]

In order to conduct complex tasks on different levels of DCC, from data collection and processing by the devices via computations on the edge, fog and cloud to providing business functions to a variety of applications and users across various domains, a series of challenges have to be overcome, such as: interoperability, complexity of governance, data synchronization, sustainability and energy efficiency, privacy and security [19]. Dynamic nature of these environments ask for "adaptive solutions to accommodate diverse use cases and application requirements" and "standardized frameworks and protocols to foster interoperability and seamless integration" [21].

One of the challenges is establishing, maintaining and enhancing semantic interoperability, which "ensures that the precise format and meaning of exchanged data and information is preserved and understood throughout exchanges between parties" [22] and it covers both semantic (meaning and relationships) and syntactic (exact format) aspects. As semantic interoperability is already recognized as being of "fundamental importance across countless industries and will constitute one of the driving forces of the fourth industrial revolution" [23], the standardization plays a critical role, especially with "the application of ontology-based semantic technologies" [23] aiming to achieve and improve interoperability throughout the DCC.

This work is organized as follows: Chapter 2. provides state of the art for IoT, as well as current challenges affecting the variety of technologies involved in the IoT ecosystem, Chapter 3. describes principles and practice for WBAH, Chapter 4. tackles semantic interoperability approaches for IoT, while Chapter 5. provides possible research directions regarding semantic challenges in IoT for WBAH.

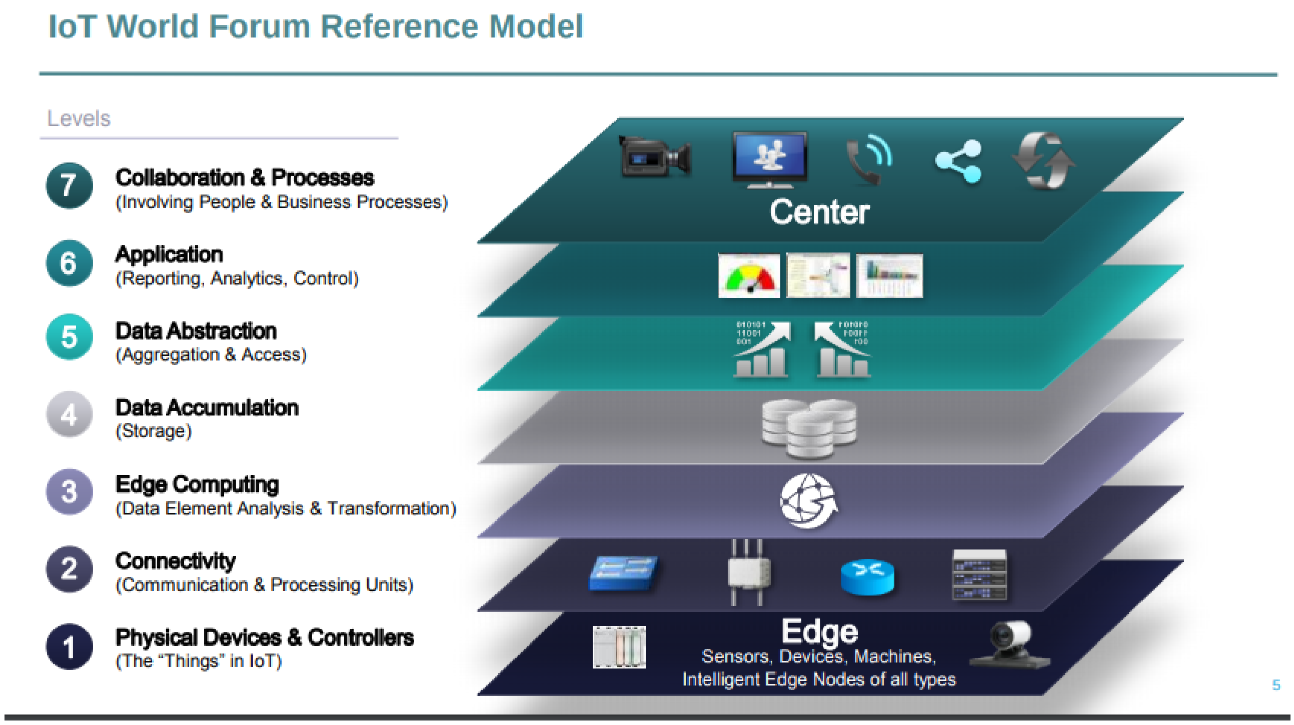
2. Internet of Things: State of the Art and Challenges

IoT is not one, but a variety of technologies, used to connect physical and virtual world in order to provide a range of services to applications and systems, and consequently to living beings. As defined by ITU-T in 2012, IoT is "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" [24]. Along with the definition, two notes have been provided, describing IoT from a broader perspective as a "vision with technological and societal implications", while making full use of things (physical or virtual, and capable of being identified and integrated into communication networks) to offer services to various applications "through the exploitation of identification, data capture, processing and communication capabilities," and fulfilling given security and privacy requirements.

As there is not only one definition of IoT, there is also no single, globally accepted IoT architecture, but the models vary in number of layers and complexity depending on a business need. The IoT World Forum (IWF) reference model has been presented in 2014 [25], in order to be used as a common framework to "help educate CIOs, IT departments, and developers on deployment of IoT projects, and accelerate the adoption of IoT" [26]. It consists of seven layers (or levels), as shown in Fig. 2.1, with each layer providing additional information for establishing a common terminology:

1. Physical Devices and Controllers (Device Layer): composed of physical devices and controllers of objects (things) that receive (sensors) and send information or react to stimuli from the environment (actuators),
2. Connectivity (Network Layer): composed of network devices (e. g. switches, routers) that enable internet connectivity among things and communication with application platforms,
3. Edge Computing (Edge/Fog Layer): composed of network elements (e. g. gateway) and protocols for routing to higher layers of cloud and transforming larger data flows into information suitable for storage and further processing,
4. Data Accumulation (Cloud Layer): composed of storage elements suitable for storing different data types and formats coming from heterogeneous processors,
5. Data Abstraction (Big Data Analytics Layer): composed of methods and procedures for aggregating and formatting the stored data to make it accessible by applications more efficiently,

6. Application (Application Layer): composed of applications that use IoT input data or control IoT devices by interpreting incoming information,
7. Collaboration and Processes (Business Layer): composed of application-supported processes and personas that exchange IoT data and control information across the Internet.



IoT World Forum Reference Model

Levels

7 **Collaboration & Processes**
(Involving People & Business Processes)

6 **Application**
(Reporting, Analytics, Control)

5 **Data Abstraction**
(Aggregation & Access)

4 **Data Accumulation**
(Storage)

3 **Edge Computing**
(Data Element Analysis & Transformation)

2 **Connectivity**
(Communication & Processing Units)

1 **Physical Devices & Controllers**
(The "Things" in IoT)

Figure 2.1. The standardized architectural model proposed at the IoT World Forum 2014 [25]

2.1. IoT Protocols

In the over two decades, IoT ecosystem has been advancing not only in terms of devices and platforms but also a variety of communication protocols used. An obvious classification of IoT communication protocols is between wireless and wired communication protocols [27]. Some studies focus only on certain type of IoT communication protocols, such as IoT application layer communication protocols [28]. This work will follow above-presented IWF architectural model and map the protocols to each of seven layers, classified into three classes: infrastructure protocols, service discovery protocols and application protocols, as shown in Fig. 2.2.

2.1.1. Infrastructure Protocols

IoT infrastructure protocols can be divided into network and internet protocols, with the first one consisting of a physical/device layer and link layer protocols, and the second one consisting of a transport layer, routing protocols, and network-layer protocols.

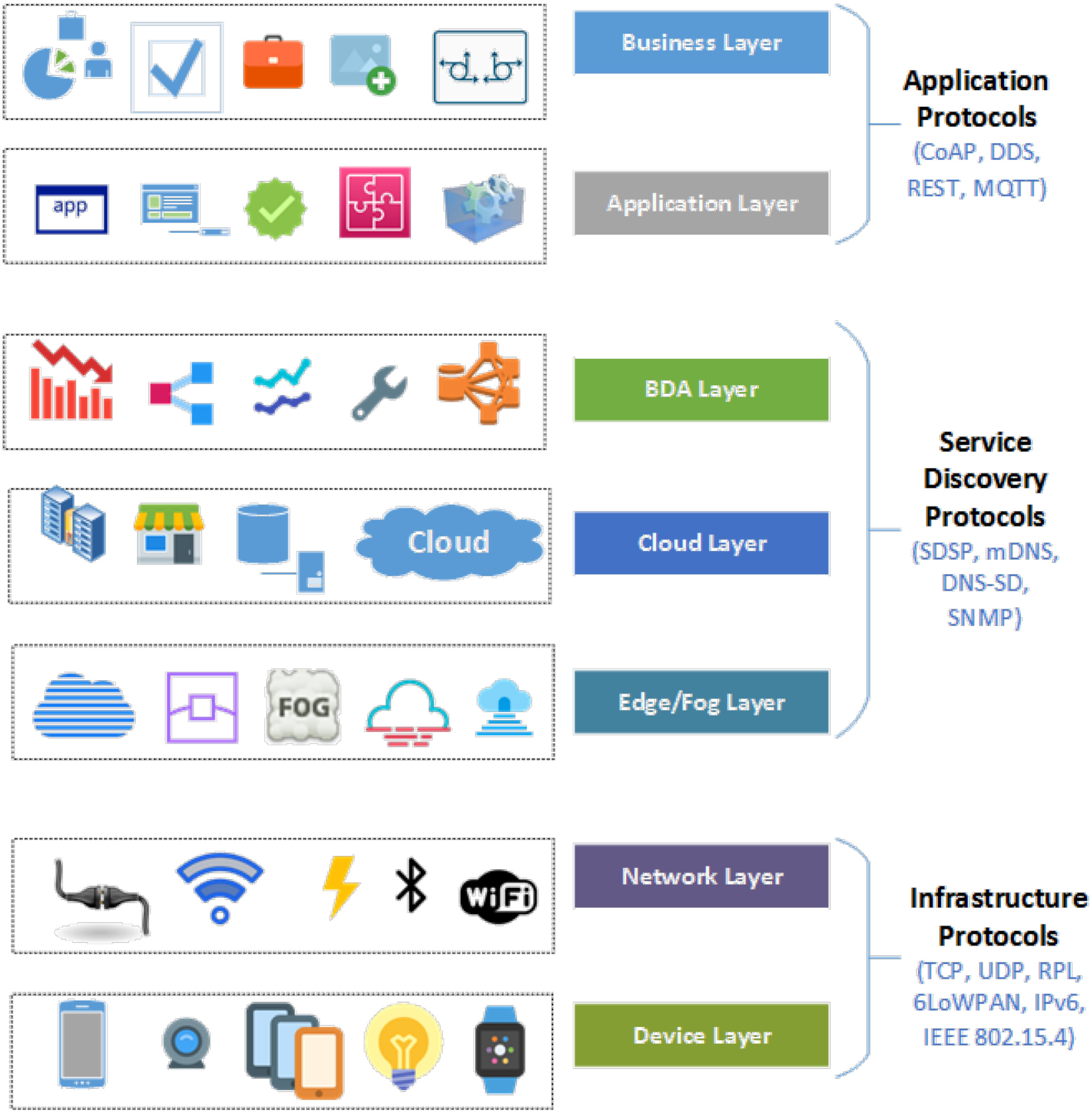


Figure 2.2. IoT protocol categorization of IWF layers [29]

Some of the most used IoT network protocols are:

- Bluetooth Low Energy (BLE): designed to operate wirelessly in short-range (20-200 meters) with low battery consumption (0.01-10 mW) and provide the latency 15 times shorter then the classic Bluetooth [30]. Also named Bluetooth 4.0 or Smart Bluetooth, it is available in most smartphone models,
- Near Field Communication (NFC): short-range (up to 10 cm), high frequency (13.56 MHz) wireless technology based on RFID [31]. It supports not only data transmission but also wireless charging, which is particularly useful for small, portable devices, like wearables, earbuds and other compact IoT devices,
- IEEE 802.15.4: designed to operate a low-rate wireless personal area network (LR-WPAN) [32], with basically a 10-meter communications range with line of sight at a transfer rate of 250 kbps. It serves as a basis for the Zigbee, 6LoWPAN,etc., each of which further extends the standard by developing the upper layers,
- Long-Range Wide-Area Network (LoRaWAN): designed as a low power wide area network (LPWAN) network technology, it is medium access control (MAC) and open protocol that uses spread spectrum technology to enable data transmission over long distances [33]. It offers high energy efficiency, wide coverage, and the ability to send data through obstacles,
- Zigbee: designed to operate in the 2.4 GHz frequency range with 250 kbps transfer rate, best suited for intermittent data transmissions from a sensor or input device, by using the IEEE 802.15.4 standard [34]. It is typically used in low data rate applications with long battery life and secure networking (128-bit AES encryption).

Some of the most used Internet protocols in IoT architectures are:

- Internet Protocol v6 (IPv6): designed to provide improved remote access and large-scale IoT device management by using 128-bit IP addresses [35]. It contributes to scalability, connectivity and security of IoT ecosystems, providing the necessary interoperability for the Device-to-Device (D2D) IoT by using gateways to translate between the incompatible protocols,
- IPv6 over Low Power Wireless Personal Area Network (6LoWPAN): designed as an adaption layer for IPv6 over IEEE 802.15.4 links [36], by creating a low power wireless mesh network where every node has its own IPv6 address. It operates like network encapsulation protocol, in the 2.4 GHz frequency range only with a 250 kbps transfer rate,
- Routing Protocol for Low Power and Lossy Networks (RPL): designed as a light IPv6 network routing protocol susceptible to packet loss and implemented in Contiki OS for usage on microcontrollers and sensor nodes. A reliable and energy-efficient version of RPL obtains decent links for information routing and provides optimal transmission power [37],

- User Datagram Protocol (UDP): designed as a connectionless and lightweight communication protocol, with low latency, but lacking reliability. For use in IoT applications there are reliable UDP-based transport protocols, such as Reliable Dynamic Buffer UDP (RDBUDP or RUBDP), UDP-based Data Transfer (UDT) and Performance Adaptive UDP (PA-UDP) [38].

2.1.2. Service Discovery Protocols

Service discovery in IoT ecosystems aims to automatically find appropriate services among many heterogeneous objects that offer different services. The following service discovery protocols are typically used in this process:

- DNS-Service Discovery (DNS-SD): designed to use standard DNS messages to discover services of an IoT network and connect devices without external administration or configuration [39]. Resolved host names of the service providers are then paired with the local IP addresses by using mDNS,
- Multicast DNS (m-DNS or mDNS): originally designed for service discovery among resource-rich devices and then adapted into light versions for IoT ecosystems [40], it resolves host names to IP addresses in a local network without using a DNS server. It operates on multicast UDP packets, where a node acquires terms of all nodes in the local network,
- Simple Service Discovery Protocol (SSDP): a network protocol used in small-scale networks (e.g. home networks) to advertise and discover network services primarily supported by the Universal Plug-and-Play (UPnP) architecture [41]. It is an HTTPU-based textual protocol that uses XML and does not use any server-based configuration mechanism such as DHCP or DNS.

2.1.3. Application Protocols

IoT application protocols are designed to provide application programming interfaces (APIs) to developers via IoT messaging abstractions for devices-service communication. Some of the best suited application protocols for internet data messaging are:

- Advance Message Queuing Protocol (AMQP): initially designed for enterprise messaging, it then became an open standard for asynchronous messaging by wire, maintained by OASIS [42]. With its queue-based architecture and a publish-subscribe model, it enables encrypted and interoperable messaging between organizations and applications, being especially popular for IoT device management that uses client–server messaging,
- Constrained Application Protocol (CoAP): designed for local area networks and later standardized by IETF, it is a web protocol for constrained devices that exchanges messages in

asynchronous mode [43]. It relies strictly on UDP which made it susceptible to data loss across lossy inter-networks. Uniform resource identifier (URI) support is enabled with minimum complexity in this RESTful protocol,

- Data Distribution Service (DDS): designed to be a high speed, low latency middleware protocol, it became a standard, maintained by the OMG, for machine-to-machine communication that enables data exchange through the publish–subscribe model [40]. Unlike MQTT and CoAP, it uses a broker-less architecture, with a data bus that directly connects producers and subscribers, and by employing multi-casting techniques for data transmission,

- Message Queue Telemetry Transport (MQTT): firstly designed for telemetry applications using low power data rates, this publish/subscribe messaging transport protocol is an open standard maintained by OASIS and used for lightweight applications that require a small code footprint and low bandwidth [44]. Most implementations today rest on the MQTT 3.x specification, with the MQTT 5 specification slowly taking over support to hyperscale clouds (such as AWS),

- Extensible Messaging and Presence Protocol (XMPP): initially designed for the resource-rich Internet devices, this application protocol uses a lightweight publish/subscribe scheme for resource-constrained IoT devices to perform data exchange either periodically or upon any value change [45]. It is an open standard, maintained by IETF, that uses XML to realize the message-oriented middleware and applications.

2.2. IoT Applications

Today there are almost as many connected IoT devices as there are people worldwide, and by 2030 their number in expected to increase to more than 25 billion [46]. The good part of consumer market for IoT applications typically consists of "wearables, voice-enabled assistants for the home, and smart-car technologies", while industrial market "encompasses processes that help manufacturing, industry, and energy sectors perform more efficiently and lessen operational expenses" [46]. It is estimated there are over 900 applications for IoT in the enterprise market, with a 93% IoT technology adoption rate among enterprises, while industries that lead in IoT spending include discrete manufacturing, fleet management and logistics, and energy utilities [46].

While IoT usage is getting more and more widespread, the number of challenges regarding "energy efficiency, interoperability, security, and other issues are restricting the number of use-cases and ways the technology can be used" so a "cross-layer approach in standard architectures is necessary" [47], in order for a reliable and effective information propagating and processing from one layer to the another, by using distributed intelligence approach, to significantly improve overall performances. Before analysing IoT challenges, the following subsections elaborate more on each of the eight groups of recognized IoT application domains.

2.2.1. Smart Cities / Home / Environments

Along with the sensing ability, IoT systems may also have actuators and cameras that monitor and measure any kind of information from the surroundings, as well as react in the given circumstances in the physical world, therefore having great application in the smart cities and smart home environments. With the growth of connected devices in smart environments, the extraction of meaningful information and the correlation of the data from the collected data seem to be the key factors for successful implementation [48]. Autonomy and affordability of IoT devices can contribute to the implementation of smart home scenarios, such as automated and sensor-monitored smart windows [49], remotely controlled by a mobile or Web app. Personal air quality and thermal comfort conditions are also considered and studied as vital aspects of smart and high-performance buildings [50].

2.2.2. Healthcare, Medicine and Assisted Living

One of significant IoT research interests have been healthcare and assisted living domains, "where major contributions are aimed at developing effective approaches for the analysis of the collected data for a fast and reliable monitoring of patients and recommendation of appropriate treatments" [51]. Some of application areas include emergency services, patient and hospital monitoring, medical equipment monitoring and medicine monitoring. The study [52] has introduced a Health Monitoring Observer Network by using wearable technology that enable not only remote health monitoring but also environmental monitoring for better integration and comprehension of patient health data. The methodology for economic value calculation has also been introduced, in order to decrease the cost of efficient health management and improve quality of life.

2.2.3. Smart Energy and Utility Management

One of the IoT application domains is the energy sector where it is used to enhance the performance of power grid so it is usually named smart energy or smart grid in research literature. One of the studies has analysed the IoT usage in reducing the losses and improving the voltage profile within the power grid, and consequently enhancing managing and controlling uncertainty of distributed generation sources [53]. In order to achieve both energetic and financial efficiency by monitoring the energy consumption by the end consumers while providing useful information about the energy quality, IoT-based smart energy meter for smart grids has been introduced as one of the solutions [54]. Smart metering and grid management are only few examples of IoT applications in utility managements, while some other include asset monitoring and management, and demand response allowing utilities to adjust energy consumption based on real-time data [55].

2.2.4. Smart Agriculture and Water Management

Small-size and low-cost IoT sensor nodes have found their application in the digital transformation of agriculture. The study [56] proposed energy-efficient operation of a LoRaWAN sensors network intended for precision agriculture, more precisely to be used for crop condition monitoring by measuring essential environmental parameters. Another study [57] has demonstrated the ability of ML algorithms to use simple multispectral reads for efficient classification of maize leaf rolling, by predicting states of plants assessed by using sensors in drought and heat conditions. IoT sensors infrastructure can be used for coastal flooding assessment induced by barometric pressure, wind-generated waves and tidal-induced oscillations [58], in order to trigger a real-time early warning system.

2.2.5. Retail and Supply Chain Management

A systematic review on IoT applications in retail sector has revealed the rise in the numbers of papers and their citations, as well as the "most of the research related to IoT in retail was led in India and China and was multi-authored" [59]. Some of the examples of IoT implementations in retail include: advanced inventory management (with RFID tags for product tracking and smart shelves with weight sensors), supply chain optimization (with GPS tracking for shipments and temperature monitoring sensors), in-store navigation (with BLE beacons), maintenance and equipment monitoring (with asset tracking and management) and check-out optimization (with self-checkout systems and mobile payment integration) [60]. Transportation and Logistics, as the activities that usually contribute to supply chain management and are heavily used in retail have been described separately in the following subsection.

2.2.6. Transportation and Logistics

Transportation is one of crucial activities that link clients and customers to supply chain stakeholders and processes, and contribute to logistics by providing the right goods and services at the right locations in a timely manner. Means of transportation include various vehicles that, supported by IoT, can be monitored "with respect to their movement, location, whether it is running or stopped, or at any risk etc." and "the indoor conditions of the truck like temperature,humidity, light conditions etc." [61]. Automating payments, navigation and vehicle controls can be supported by IoT. Advancements can also be made in the area of IoT sensors to get them low-power and cost-effective, as the implementation of novel vehicle presence detectors for smart parking systems [62]. Smart logistics and transportation can integrate IoT and Blockchain in order to ensure trusted, secure and decentralized systems [63]. "The implementation of drones in the logistic chain has become one of the leading tasks today" for global giant companies that have designed their own UAVs [64].

2.2.7. Industrial Control Systems and Automation

Usage of information technology (IT), and ICT, including mobile applications, various sensor networks and other embedded solutions, has to be enforced for IoT applications to become efficient and useful, but carefully balanced when considering ethics and privacy. One of the advancements shaping the future of the IoT industry is "the implementation of Industrial IoT (IIoT) as part of the Fourth Industrial Revolution" [46]. Aiming to move from laboratory surroundings and research purposes only into real-life use in enterprise or industrial settings, in order to achieve full potential and cover a widen scale of IIoT applications, the notion of operational technology (OT) has to be taken into account. OT is defined as "hardware and software that detects or causes a change, through the direct monitoring and/or control of industrial equipment, assets, processes and events" [65]. As introducing IIoT systems inevitably transforms existing and establishes new processes, IT and OT environments are converging and have to be analysed, modeled and implemented comprehensively.

2.2.8. Safety and Security

IoT has been applied to a certain degree in the field of public safety, due to its "architecture advantages and technical features" [66]. The study published by the Alliance for IoT and Edge Computing Innovation (AIOTI) states that IoT can "drastically extend the limits and scope of traditional public safety services and provide new means and intelligence for improved situation awareness, prevention, mitigation, response and recovery supporting automated notifications, actuation, optimum knowledge sharing, improved decision making and advanced interactions with citizens, public safety agencies and first responders" [67]. These IoT applications can easily be part of smart city and smart home solutions, but its mission-critical nature that aims at saving lives makes it worth of having it in a separate IoT applications category. The systematic review found that "Industry 4.0 can increase safety levels in warehouse and logistic, with the storage of products based on specific classes" by managing the issues related to "safety of products, storage places, transports, environment and operators" [68]. When it comes to IoT applications in security, numerous examples can be found also in the smart home field, like smart home automation systems.

2.3. IoT Challenges

Reaching a quarter of a century since the very term has been introduced, IoT "continues to play a pivotal role in reshaping industries and daily life" [69], with IoT devices' rapid growth and integration advancing connections and interactions with physical objects, making processes more efficient and data-driven. Along with immense opportunities IoT applications offer, as seen in the previous section, there are significant IoT challenges that industries and practitioners face, "from data privacy concerns and lack of standardization to interoperability issues and the ever-evolving cyber threats" [69].

One of the publications presents a curated selection of research studies and reviews on various dimensions of IoT challenges, such as: complexities of implementing IoT in smart buildings, critical aspects of Quality of Service (QoS) and energy management, security mechanisms specific to BLE, providing insights into protecting IoT ecosystems from emerging threats, and the educational impact of IoT on health [70]. Some authors describe IoT as a Complex Adaptive System (CAS) "that will continue to evolve hence requiring new and innovative forms of software engineering, systems engineering, project management, as well as numerous other disciplines to develop it further and manage it the coming years" [71]. The following subsections elaborate more on each of the eight groups of recognized IoT challenges.

2.3.1. Heterogeneity, Interoperability and Compatibility

As shown in previous sections, various IoT devices may use different communication protocols and industry standards to connect different platforms, operating systems and services, and controlling them not being compatible can be is one of the biggest challenges for IoT application development companies [72]. Multimodality of sensors and the usage of cross-domain IoT platforms shape heterogeneity which poses interoperability and design challenges and limits the possibility of reusing sensor data to develop new applications and integrating automated solutions based on sensor data [73]. Using open standards of layered protocols, like MQTT or CoAP, may lead to enhancements in interoperability [72]. "As the IoT continues to grow, the need for services that work with multiple IoT applications will continue to increase to realize the promised efficiency gain of the IoT" [74]. For IoT devices to maintain compatibility, they need to be regularly updated and patched, because of various functionality, performance and security issues that can occur when communicating with different software versions.

2.3.2. Data and Network Management, and Scalability

By increasing the number of connected IoT devices exponentially, IoT network infrastructure management has become challenging, so different management strategies and infrastructure upgrades are required in order "to control network congestion, handle growing data volumes, and ensure dependable connectivity" [61]. "IoT networking protocols can be divided into smart device networks and traditional networks, which is used to increase data rates" [74]. Each of the IoT network classes - cellular, LAN/PAN, LP-WAN or mesh, has its specific challenges in terms of bandwidth, power management, data signalling and communication, etc. With the big data streams coming to growing number of IoT devices for collection and processing, scalability as a property of an IoT application to handle a growing amount of work becomes one of the major challenges [72]. Including cloud platforms and microservices in the architectural design, along with some of the techniques like load balancing and auto-scaling, may increase scalability [72].

2.3.3. Device Management and Cost Constraints

IoT sensors, as crucial components of IoT solutions responsible for extracting information from their environments, "have to be developed to support specific requirements and reliable real-time operation" [75]. IoT solutions have to implement "the most structured and capable device management, monitoring, troubleshooting, and updating mechanisms" by also making sure "to opt for the over-the-air (OTA) updates to keep your device's firmware up to date" [72]. Business-oriented IoT implementations can have initial higher costs because of the infrastructure setup, devices deployment and data management processes installment, so "clear understanding of the return on investment (ROI) and long-term viability" is needed in order to "defend their IoT investments and benefit from the installed systems" [61]. One of the important challenges represents a lack of understanding how IoT advantages can enable economic benefits, in addition to the "high financial outlay for upgrading existing systems with no clear standards in place to regulate interoperability" [46].

2.3.4. Cybersecurity, Reliability and Resilience

For IoT solutions to serve their purpose, it is expected from them to work properly for a given time period, without any issues and shortcomings, so that they prove to be reliable, Even more, mission-critical IoT systems are expected to recover from an unexpected event and continue functioning properly, by proving to be resilient. IoT reliability consists of "device reliability, data quality, network reliability and anomaly detection, all of which represent key areas for improvement" [76] and fully satisfying end-to-end IoT reliability still remains the challenge. IoT devices vulnerability may lead to "major security issues like unauthorized access, data breaches, and manipulation of devices" [72]. The top IoT cybersecurity concerns stated in the report [77] are the "attacks on IoT devices that impact critical operations", while the other two top concerns are the lack of skilled personnel to implement IoT security and protecting sensitive data generated by an IoT device (encryption, tokenization, etc.). Prioritizing the security of both devices and the controlling applications is crucial, and "IoT app developers must diligently apply secure coding principles to mitigate potential vulnerabilities" [78].

2.3.5. Energy Efficiency and Environmental Impact

As a wide range of IoT devices requires more energy for their operation, one of the issues remains device's battery life. Some of the power-saving approaches include regularly optimizing the device's firmware and implementing low-power communication protocols [72]. "Energy-efficient designs, low-power communication protocols, and effective power management techniques must be used to increase the energy efficiency of IoT devices and systems" [61]. Not only empty batteries, but the IoT devices themselves, no matter their size, represent e-waste, which is another challenge to tackle.

2.3.6. Ethical and Social Implications, and Privacy

Being a data-intensive set of technologies, IoT solutions should also address challenges like "ownership, transparency, accountability, and the formation of ethical frameworks in order to ensure responsible and trustworthy IoT deployments" [61]. There are smart city scenarios where privacy can be threatened and data leakage can occur by a passive side-channel attack at large distances on the LoRaWAN smart parking device revealing information about vehicle presence, such as occupied parking lot [79]. Therefore, "IoT systems should meet the privacy requirements of each country's regulations and make sure user privacy is protected" [75].

2.3.7. Regulatory and Legal Compliance

Continuously on ethical and social implications, as well as privacy challenges, IoT solutions have to be aligned with "regulations governing data protection, privacy, and industry-specific regulations" [61]. Ensuring regulatory compliance asks for disciplined approach to data processing, user privacy protection and establishing trust within IoT implementations, e.g. aligning with the General Data Protection Regulation (GDPR) requirements in the EU or with the American Data Privacy and Protection Act (ADPPA) in the USA. "This demands continuous vigilance, proactive measures, and a comprehensive understanding of the legal landscape to mitigate potential legal and financial ramifications" and "to ensure responsible and sustainable growth of IoT ecosystems" [69].

2.3.8. IoT App Integration and User Experience Design

In order to ensure the prerequisites for users' full adoption of an IoT app, both web and mobile, their integration with other platforms, services, and systems have to result in needed and useful functionalities, as well as a high-performance, reliable, secure and trustworthy app. "Crafting the IoT apps on the adaptive platforms and frameworks make the integration much easier and hassle-free for the developers, ensuring the development of performance mobile apps" [72]. Also, user experience (UX) has to be designed and implemented "to enable the users to easily navigate and make faster decisions" and "to enable the users to easily navigate and make faster decisions" [72].

3. Well-Being, Aging and Health: Principles and Practice

Throughout 2020, 2021 and 2022 the global COVID-19 pandemic has impacted all aspects of people’s well-being, with health being one of them. As reported by the OECD [80], the new SARS-CoV-2 coronavirus has had devastating impacts on both physical health and mortality, with averaged 16% excess deaths in 33 OECD countries between March 2020 and early May 2021 compared to 2015-2019 period, which resulted in a 7-month fall in OECD 29-average life expectancy in 2020. Also, mental health deteriorated for almost all population groups on average in 2020, with older people much more likely suffering severe outcomes or death due to the infection, making reduced social contact an especially important precaution for them, while younger adults have experienced some of the largest declines in mental health, social connectedness and life satisfaction both in 2020 and 2021.

Confronting such a global, not only public health but also economic and social crisis, with both short and potentially long term consequences, showed all the seriousness of dealing with well-being, aging, and health (WBAH) as important aspects of life that affect everybody [81]. Well-Being, Aging and Health (WBAH) can be defined as a "multidimensional concept covering well-being, aging and health aspects of persons, communities and societies in the appropriate contexts including the environment properties, the entities engagement and interactions, as well as past and current WBAH status of each of the entities observed in order to achieve and maintain WBAH at the satisfactory level and gain resilience against factors that pose risk to degrade WBAH" [82].

3.1. Definitions of Terms

Health is "one of the greatest resources for achieving and maintaining personal quality of life, advancement of communities and development of societies around the world" [83]. The WHO has defined it as "a state of complete physical, mental and social well-being and not merely the absence of disease and infirmity" [84]. Its implications for policies and practices made it a topic of scientific and professional debates, questioning its applicability to the new challenges in health systems, especially regarding the term "complete". A study [85] claims the WHO definition to be adequate, with the qualitative meaning of "complete" as holistic approach to health, not stating health has to be "perfect" at all. "The necessity for a plural approach to health depending on the application seems reasonable, while still no alternative definition of health has reached the worldwide consensus" [86].

The OECD defines current human well-being as a term encompassing the different areas that matter for people's lives and covering well-being outcomes at the individual, household or community level, focusing on material conditions, quality of life factors and community relations through the following 11 dimensions of The OECD Well-Being Framework: Income and Wealth, Work and Job Quality, Housing, Health, Knowledge and Skills, Environment Quality, Subjective Well-Being, Safety, Work-Life Balance, Social Connections and Civil Engagement [87].

Health and well-being of all people and communities as essential to a thriving, equitable society has been also recognized as one of the fundamental principles of the Healthy People 2030 Framework [88] by the Office of Disease Prevention and Health Promotion (ODPHP) of the U.S. Department of Health and Human Services. In order to achieve health and well-being of all people, the framework states it is essential to involve diverse stakeholders as active partners from across the public, private, and nonprofit sectors. As a process of getting older, aging represents the accumulation of changes in a human being over time and can encompass physical, psychological, and social changes [89].

The exact phrase "well-being, aging and health" (WBAH) can rarely be found in the research literature before 2020 and is only addressing certain well-being aspects, such as sexual well-being [90] or psychological well-being [91]. In the study [90] that aimed at older women and men, subjective sexual well-being refers to the cognitive and emotional evaluation of an individual's sexuality. The research [91] examines how the ups and downs of daily life influence long-term health and aging, aiming to contribute to the development of strategies for promoting psychological and physical well-being across the adult lifespan.

3.2. WBAH-Related Principles

There is much research done in the related areas of active and healthy aging (AHA), as well as health and well-being (HWB), stating mainly two of three terms of well-being, aging and health. In order to justify a conceptual formulation of WBAH given at the beginning of this chapter, the interrelationships with already established areas need to be addressed, namely: Ambient Assisted Living (AAL), AHA and HWB. Fig. 3.1 illustrates these interrelationships by using Venn diagram.

3.2.1. Ambient Assisted Living

AAL or innovative ICT-enabled assisted living relates to intelligent systems of assistance for a better, healthier and safer life in the preferred living environment and covers concepts, products and services that interlink and improve new technologies and the social environment, with the aim of enhancing the quality of life (related to physical, mental and social well-being) to for all people (with a focus on older persons) in all stages of their life [92].

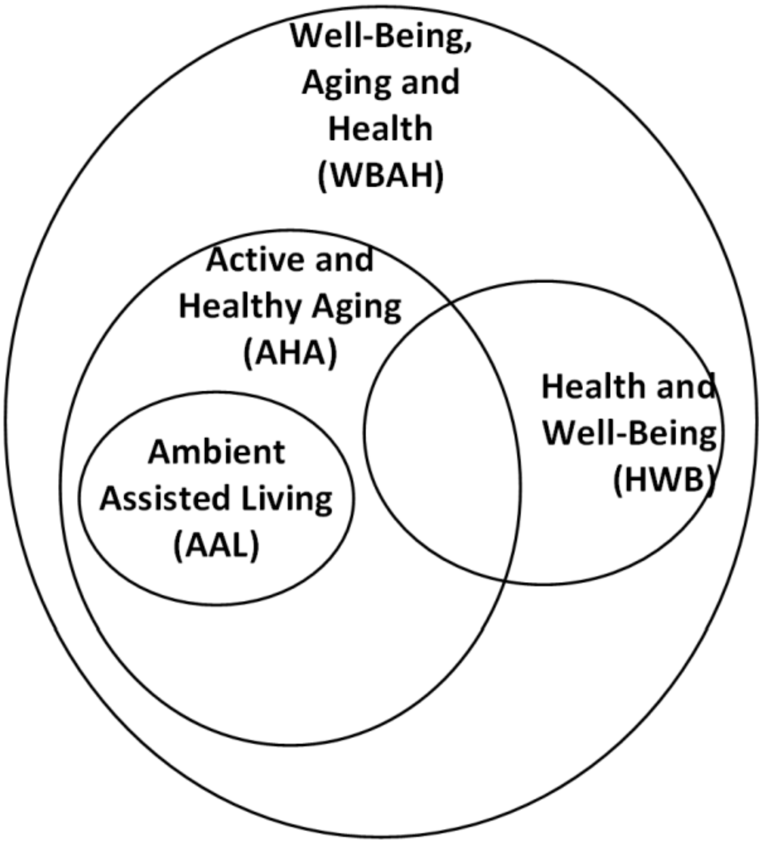


Figure 3.1. Venn diagram for AAL, AHA, HWB and WBAH [73]

3.2.2. Active and Healthy Aging

AHA is a complex and multi-dimensional concept with marked heterogeneity, with the conceptual AHA framework that includes three key domains (1. Physical and cognitive capability across the life course; 2. Psychological and social well-being, mental health and quality of life across the life course; 3. Functioning of underlying physiological systems across the life course, preventing or delaying onset of chronic diseases, frailty and disability) and three key influencing factors (4. Education, lifelong learning, working and caring; 5. Lifetime lifestyles; 6. Lifetime social, economic and physical environment) [93].

3.2.3. Health and Well-Being

"HWB comprise physical health, psychological and emotional stability, and social engagement. Physical wellness involves self-care and a temperate lifestyle. Emotional well-being is psychological well-being encompassing subjective experience and positive emotionality. A stable mood—emotional equanimity—enhances countering negative emotions and physician burnout. Social engagement revolves around interpersonal and social relations. Physician engagement entails a doctor's commitment to studying, enhancing expertise, and skills toward safe and high-quality patient care." [94].

3.3. WBAH Practice

WBAH aspects are being addressed at the policy level by recent global initiatives. The United Nations (UN) Decade of Healthy Ageing (2021-2030) aims to foster healthy aging and improve the lives of older people and their families and communities, by addressing four areas for action: (1) Age-friendly environments; (2) Combating ageism; (3) Integrated care, and (4) Long-term care [95]. In order to respond to mental health challenges risen during COVID-19 pandemic, the WHO Comprehensive Mental Health Action Plan 2013–2030 [96] has been updated with implementation options and indicators, and the WHO European Framework for Action on Mental Health 2021-2025 has been endorsed, providing "a coherent basis for intensified efforts to mainstream, promote and safeguard mental well-being as an integral element of COVID-19 response and recovery; to counter the stigma and discrimination associated with mental health conditions; and to advocate for and promote investment in accessible quality mental health services" [97]. WBAH is a complex concept of interleaving terms, underlying aspects and containing dimensions.

3.3.1. WBAH Stakeholders 4P Model

"No matter which business processes have to be digitally transformed and what technologies will bee used, a driving force for innovation are people, the stakeholders. Each of the stakeholders in healthcare, or even in integrated care including social aspects of care and well-being of patients, are motivated by their needs and opportunities and bound by the legal, organizational and operational contexts. Changing the mindset from staying limited to become empowered is important prerequisite for each innovation to occur" [83].

"Stakeholders that have to be included in the innovation pathway for well-being, aging and health can be organized in four dimensions of the 4P model proposed here and shown in Fig. 3.2: (1) patient, (2) policy makers, (3) population, and (4) providers. Patient can be a person with illness or other health/medical condition, an aging person in a need for care, a person with complex needs, etc. Policy makers include government bodies, health insurance payers, public health authorities, medicinal products and medical devices authorities, social care authorities and others" [83].

"Population perspective also has to be taken into account from patient organizations, various advocate groups, aging population, non-governmental organizations (NGOs), media, general public, etc. Finally, no care is delivered without healthcare or social care providers, health professionals and social workers, as well as health-related businesses which develop solutions and the knowledge providers which conduct research and provide scientific evidence" [83].

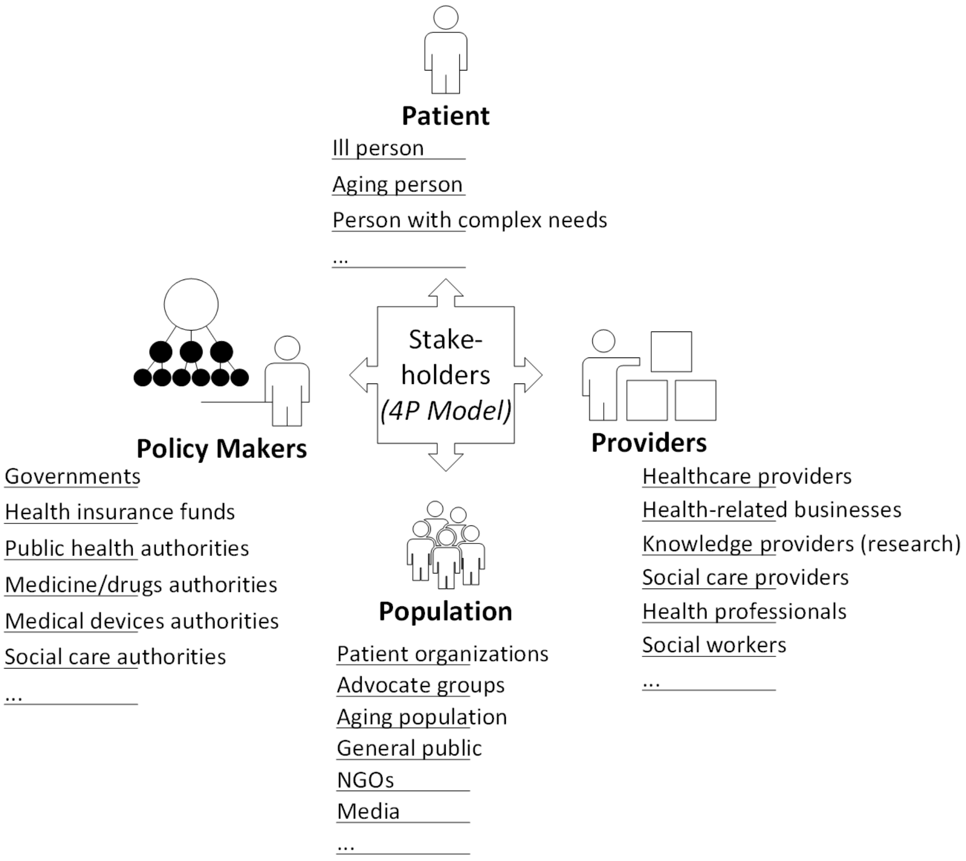


Figure 3.2. WBAH stakeholders 4P model [83].

3.3.2. WBAH Innovation Map

As defined by the European Institute of Innovation and Technology (EIT) [98], innovation pathway for digital health consists of four phases: (1) ideation, (2) development, (3) market entry, and (4) adoption, offering a continuous, often reiterative and cyclical pathway for ICT-based solutions that focus on healthcare interventions related to patients' or users' health. Within the pathway phases there are the following stages: (1.1) need, (1.2) idea, (2.1) proof of concept, (2.2) proof of feasibility, (2.3) proof of value, (3.1) initial clinical trial, (3.2) validation of solution, (3.3) approval and launch, (4.1) clinical/cost assessment, (4.2) reimbursement, (4.3) standard of care, and (4.4) obsolescence, "where certain steps can be revisited or repeated to support continuous research and development, and the design and development of new innovations" [98].

"In order to widen the scope from healthcare interventions to include social innovations and innovations for the aging population, some adjustments have to be made to the presented innovation pathway in order to optimise it: stage (3.1) has to allow other trials and pilots to be conducted methodically to enable further validation, approval and launch; stage (4.1) has to allow assessments in the context of other institutions than clinical, as well as in out-institutional surroundings, such as home care and community care; stage (4.2) has to also allow fee-free solutions, potentially to be delivered by social enterprises measuring and maximising their social impact" [83].

"Such a WBAH-enabled innovation pathway has become more integrative (by addressing social care and well-being) and inclusive (by including aging population and sensitive user groups). In order to provide more insight in innovation for WBAH options and scenarios, the WBAH innovation map has been assembled, as shown in Fig. 3.3" [83].

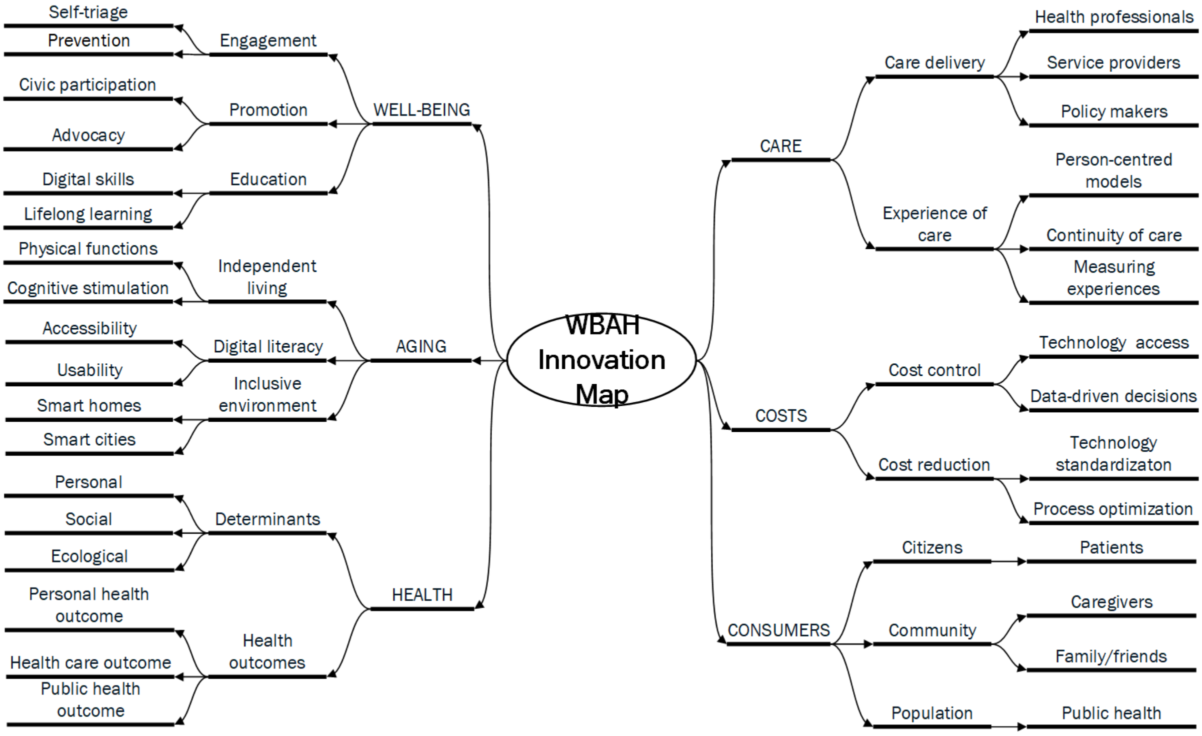


Figure 3.3. WBAH Innovation Map [83].

3.4. WBAH Innovation Pathway Optimization

"Innovation pathway represents a generic framework of phases and stages common to implement innovations and accomplish their market reach, while fulfilling certain milestones on the way, starting with the need and idea, progressing through development, market entry, and eventually adoption. Depending on the area where innovations aim to be applied, a high-level optimisation process may be applied in order to derive the innovation pathway with more precise steps and guidance towards successful innovation adoption" [83].

"In order to widen the scope from healthcare interventions to include social innovations and innovations for the aging population, some adjustments have to be made to the presented innovation pathway in order to optimise it: stage (3.1) has to allow other trials and pilots to be conducted methodically to enable further validation, approval and launch; stage (4.1) has to allow assessments in the context of other institutions than clinical, as well as in out-institutional surroundings, such as home care and community care; stage (4.2) has to also allow fee-free solutions, potentially to be delivered by social enterprises measuring and maximising their social impact" [83].

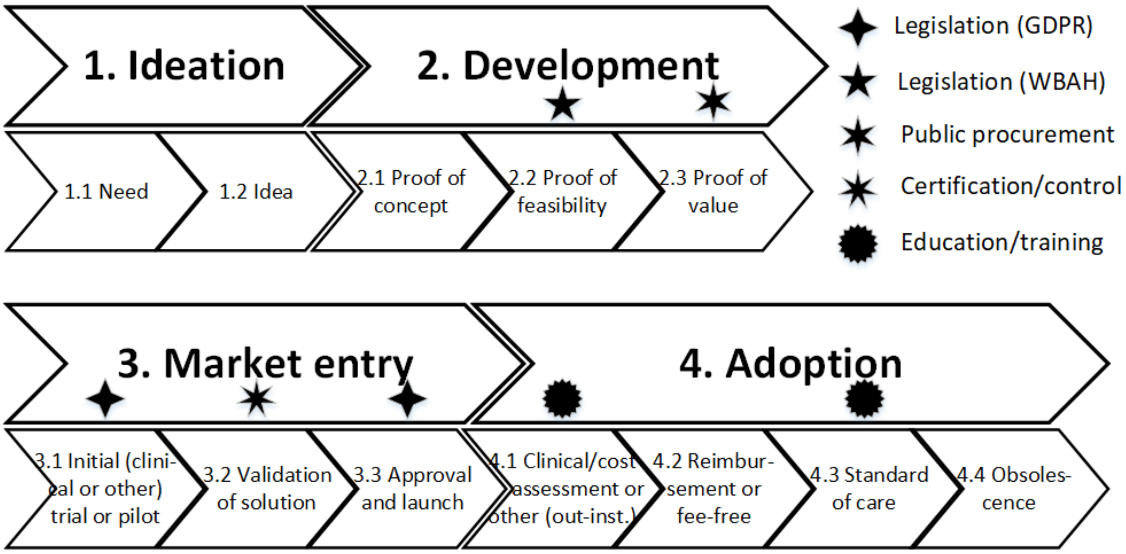


Figure 3.4. Optimised Innovation Pathway for WBAH.

"The application of even optimised innovation pathway for WBAH varies depending on the contexts, including regional presence, legal norms, industry regulations and market development" [83]. To add just one example of the context dependence - "innovation pathways for pharmaceuticals are best-known and well-regulated, while innovation pathways for digital therapeutics still have to be more researched and better regulated" [83].

"There are other aspects not included in the scope of this work for the reasons of clarity and conciseness, but not of less importance for achieving full success during the optimised innovation pathway for WBAH" [83], such as public procurement, risk assessment, product evaluation, payment schemes, user experience, etc.

3.4.1. One Well-Being, Aging and Health

WBAH can be expanded to the concept of One Well-Being, Aging and Health (OWBAH), which includes all these aspects for people, animals, plants, and their shared environment, in order to ensure a more compassionate and healthy age-friendly society [73]. It has been composed based on the already known definition of one health (OH). OH is defined by the WHO One Health High Level Expert Panel as "an integrated, unifying approach that aims to sustainably balance and optimise the health of people, animals, and ecosystems. It recognizes the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and inter-dependent. The approach mobilizes multiple sectors, disciplines and communities at varying levels of society to work together to foster well-being and tackle threats to health and ecosystems, while addressing the collective need for clean water, energy and air, safe and nutritious food, taking action on climate change, and contributing to sustainable development" [99].

4. Semantic Interoperability for IoT

IoT deals with large amounts of data traditionally being collected on IoT devices and processed centrally in the cloud, while DCC in the recent years introduced hybrid architectures that allow breaking down workloads and sharing processing on various levels. As stated by Gartner [100], steps for success in tackling this crucial part of so-called "IoT jigsaw (puzzle)" include: embracing hybrid architectures, planning for disaggregation and resiliency, and focusing on monitoring and manageability. Due to the multi-proprietary nature of DCC, the infrastructure resources, including nodes, as well as their associated middleware layers, may belong to different organizations, therefore have different semantics [19].

According to the comprehensive survey [101], there are three categories of approaches to the development of IoT solutions "towards providing seamless and meaningful communications among heterogeneous devices, technologies, and platforms": ontology (heavy-weight, light-weight, domain-specific, unified), middleware (semantically centralized, semantically distributed), and Semantic web (heterogeneous data, homogeneous data). Based on the classification framework, a comparative analysis of different components of semantic models has been provided in the study. In order to tackle challenges involving semantic interoperability for IoT, together with already existing information models, as well as analyse related industry-based standards, the following section focuses on IoT ontologies, while the other two provide more details on the semantic middleware and Semantic Web.

4.1. Ontology-Driven Approach

As originally defined back in 1992 for the areas of computer and information sciences [102], ontology defines a set of "classes (or sets), attributes (or properties), and relationships (or relations among class members) with which to model a domain of knowledge or discourse" and includes "information about their meaning and constraints on their logically consistent application" [103]. In order to efficiently handle data acquisition from heterogeneous IoT devices, information processing from various IoT networks, and knowledge management in these multidimensional and multi-domain environments, usage of ontologies represent an appropriate approach to enable data interoperability through common semantics [104]. Even more, ontology standards "for various subject matters and vertical sectors are paramount to breaking the data silos across sectors" [104].

A brief overview of ontologies for IoT has been given in [73], in order to represent sensor knowledge and describe acquired data semantics. The study from 2017 shown "no existing ontology is comprehensive enough to document all the concepts required for semantically annotating an end-to-end IoT application as ontologies are often restricted to a certain domain" and "there are no concrete methods for evaluating an ontology, and developers must always follow the best practices while publishing a new ontology in order to enhance readability, usability, extensibility, and interoperability" [105].

The overview [73] on numerous ontologies has been provided from the Linked Open Vocabularies for Internet of Things (LOV4IoT) ontology catalog for IoT [106], with currently 802 ontology-based IoT projects listed in and 29 IoT application areas analyzed. Also, the IoT ontology landscape report from December 2021 [107] included 30 ontologies from different application areas of IoT, assessing "the technology readiness level (TRL), ranging from technology validated in the lab (very light) to actual system proven in operational environment (dark)" for each ontology. Six ontologies are listed as generic (horizontal), while others fitted in one or more of the following application areas: Home/Building (6), Industry (6), Mobility (3), Health (1), Energy (3), Cities (3), Wearables (2), Farming/Agrifood (4) and Water/Environment (3).

Developing ontologies is a non-trivial process, due to not only complex nature of knowledge acquisition and management but also heterogeneity of ontologies themselves, which is in the nature of the semantic web. There are different kinds of heterogeneity problem: (1) syntactic - when using different ontology languages (e.g. XML, OWL); (2) terminological - different terms refer to the same concept or same term describes different concepts; (3) conceptual (semantic) - difference in granularity, coverage, perspective; (4) semiotic (pragmatic) - different interpretations regarding different context. Designing ontologies for IoT services aims to provide semantic structure needed for further data processing and usage in IoT-based applications, as well as to overcome interoperability issues, when it comes to multimodality of sensors and the usage of cross-domain IoT platforms. Still, having multiple ontologies within the same domain only emphasises the semantic heterogeneity problem.

Finding the potential correspondences between semantically related entities of such ontologies is called ontology matching [108]. Ontology matching can be based on many different techniques and done iteratively towards improved performance, while still many challenges lie ahead, like multilingualism, uncertainty, matching with background knowledge, user involvement etc. Ontology matching is the process of determining correspondences between concepts in ontologies [109]. Ontology alignment is the result of ontology matching expressing declaratively matching relations.

Some of the results of the systematic mapping study from 2019 [110] "propose semantic integration approaches, presenting steps such as a mapping among ontologies". Likewise, comparing ontologies is not always expedient, because each of the ontologies have been developed with specific motivation in mind, from specific background knowledge and for specific purpose. While modelling the same or similar domains, different ontologies may reflect different tasks and requirements of applications and follow different conventions and restrictions as well.

4.2. Semantic Middleware

The term "middleware" seems to be as old as the term "software engineering" itself, based on the report [111] from the Working Conference on Software Engineering, sponsored by the NATO Science Committee in 1968 and held in Garmisch, Germany. This is the place from where the term "software engineering" gained its worldwide popularity, and it is considered as a landmark point for this discipline. "Middleware" has been introduced by Alex d'Agapeyeff, a founder and a chairman of a British software house "Computer Analysts and Programmers Ltd" (CAP), while presenting the model of "d'Agapeyeff's Inverted Pyramid", stating the need for the middle layer between "the manufacturer's software" and "application programs" [111].

From then until today, middleware has been used in many contexts, not describing and meaning only one, specific concept. There are multiple definitions of middleware, depending on the field of research and practice: for DevOps engineers it is a layer "gluing" together different system components, for network engineers it is a communication management software, while for data engineers it is a technology responsible for "coordinating, triggering, and orchestrating actions to process and publish data from various sources, harnessing big data and the IoT" [112]. The latter is also seen as the semantic middleware, "used to provide common services for applications and simplicity for application development by integrating heterogeneous devices and data" while supporting "semantic interoperability by converting the raw sensor data into RDF using ontology within the diverse applications and services domains" [101].

In 2018 the efforts were made to propose a reference model for IoT middleware [113], consisting of the following modules: Interoperability, Persistence and Analytics, Context, Resource and Event, Graphical User Interface, Security. In order to increase security in IoT middleware, four fundamental aspects have also been proposed: 1) Per Device Authentication; 2) Devices Should Use Different Credentials to Publish and Consult Data From the Middleware; 3) Devices Should Access Other Device Data Using Their Own Credentials; 4) Middleware Should Know Device Habits and Store Their MAC and IP Address [113]. However, there is no implementation of this high-level reference model, and "no objective way of comparing different middleware" [113].

Two years later, another approach to reference model for IoT middleware targeted specifically large scale IoT, "that could be decoupled with the public internet and leverage big data for large scale enterprises and could be entirely hosted at on-premise intranet" [114]. The model has three main modules: 1) Data Ingestion and Device Management; 2) Streaming Message Analytics; 3) Storage. The prototype has been implemented by reusing existing software solutions and evaluated for performance, with Apache NiFi, Apache Kafka and Apache Spark cluster chosen that run on Linux with minimal configuration. This study aimed at "building an edge computing architecture with the proposed reference model that is highly scalable for enterprises that uses huge amount of data" [114], which is inline with the DCC ecosystem approach.

In order to reduce the heterogeneity among IoT devices, the study [115] proposed a "multi-layer semantic middleware for cross-domain IoT", which used knowledge graphs based on Web of Things (WoT) to represent various resources and capture the knowledge. The model introduced a new middleware layer for cross-domain access, with Apache Jena as a semantic web framework and Apache Fuseki a a SPARQL server, which is integrated with TDB, a component for RDF storage and query. The evaluation has been done by test the system response time, i.e., Round-Trip Time (RTT), to verify the feasibility of the proposed solution.

Another study [116] proposed "a semantic middleware for IoT applications based on service composition" which supported "semantic description of IoT resources, including services and user requests, and provides a modular, end-to-end, and loosely coupled request resolution process that comprises a context-aware service discovery, a semantic service selection, and an automatic lightweight service composition". One of the recent research studies [117] proposed a novel semantic IoT middleware for secure data management by utilizing "the security and decentralised advantages of blockchain to manage and store semantic annotations, ensuring data integrity and protection from unauthorised modifications" and "AI-driven feedback mechanisms "to continuously refine and optimise the middleware's operational efficiency".

4.3. Semantic Web

The Semantic Web, also known as Web 3.0, is a standardized extension of the World Wide Web (WWW), set by W3C with a goal to make Internet data directly and indirectly machine-readable. The term was coined in 1999 by Tim Berners-Lee, the inventor of WWW and relating technologies: HTML, URL, HTTP. As stated in the comprehensive survey [101], Semantic web is used to "acquire heterogeneous sensory data, extracting the meaning of them to make accessible from the Internet for providing overall interoperability". After the first few years of slow adoption of the Semantic Web, it got the faster pace after launching of schema.org, a global shared vocabulary of schemas for structured data on the Internet. Schema.org "currently consists of 811 Types, 1484 Properties 14 Datatypes, 89 Enumerations and 495 Enumeration members" [118].

Decade and a half ago the concept of the Web of Things (WoT) was introduced [119] and later adopted by the W3C, aiming to tackle the fragmentation of the IoT by utilizing standardized Web technologies. To describe devices taking part in a smart application with their capabilities [120], the concept of Thing Description (TD) has been proposed by the W3C Web of Things Working Group. TD ontology is one of the concrete representations of the TD model, the building blocks of the Web of Things (WoT). This ontology can be used instead of the standard JSON representation format for TD documents, and can also process contextual information on Things, as well as be used for alignments with other WoT related ontologies [121]. Representation of the TD model has been also done through Semantic Web standards, such as OWL, in order to get general, high-level ontology for the formalization of Web Thing profiles [120].

In order to emphasise the difference between IoT and Web of Things (WoT), IoT describes how physical objects are being connected to the Internet in order to be explored, controlled, monitored or interacted with [122], while WoT aims at enabling interoperability across IoT platforms and application domains by using Web protocols and standards [123]. Furthermore, aiming at adoption the Semantic Web standards, such as Unicode and URI to identify resources, RDF to encode information and RDFS and OWL to bind a meaning to every information atom, the Semantic Web of Things (SWoT) has been proposed [120]. Due to the overlapping of these terms usage, it can be deduced if an IoT ontology is formulated by using SW standards in each of the stated steps, it can be comprehended as SWoT ontology.

The systematic mapping study from 2019 [110] showed the majority of results dealing with approaches that use Semantic Web technologies and discussing limitations and challenges to ensure semantic interoperability for IoT. Efforts to achieve end-to-end interoperability from the devices, like sensors and actuators, to the SWoT are complex and heavyweight, still not succeeding in full interoperability. Some of the limitations deal with data heterogeneity, especially the differences in naming conventions, domain specificities, vendor-dependent platforms and communication protocols. If linked data from the databases and semi-processed data from the middleware are added to the sensor data, the data publishing challenge still remains, as well as visualisation of heterogeneous data [101].

In further advancements of Semantic Web technologies, there are several future trends that need to be pointed out, such as "emergence of personal advisors utilizing semantic technology, the integration of blockchain with semantic web principles to ensure secure data management, and the development of AI-driven search engines that provide context-aware and precise results" [124]. Additionally, semantic matchmaking, as a mapping between concepts or entities which focuses on similarity of their semantic meaning and identifies the relationship between them, is "especially useful for large-scale IoT" in the context of ECC environments, "since the large number of connected devices/Things need to effectively communicate between each other and with other services, to reach its full potential" [125].

Even more foundational than Semantic Web and a novel concept is semantic communication (SemCom), which focuses on transmitting the meaning, therefore essential information required for understanding rather than the raw data. Various approaches, like Large Language Models (LLM), can interpret and summarize data contextually, which reduces the amount of data transmitted. This can be processed by intelligent devices in the edge network, making the concept of Large Language Models Edge Intelligence (LLM EI, or LLM-based EI) achievable [126]. Capabilities of 6G networks, that include ultra-high data rates, ultra-low latency and enhanced connectivity, may "create an environment in which LLM-based EI can thrive, enabling such sophisticated applications that were previously unattainable" [126].

5. Research Directions

IoT technologies have been applied to healthcare and well-being for a growingly ageing society in seek of care in order to "increase the quality of health care and overall well-being while reducing related costs and overheads" [16] by providing innovative solutions, such as IoT-enabled residential environments to provide assisted living for dementia suffers, well-being monitoring and intervention powered by low-cost sensing devices, and quantification of the self [16].

As stated in the comprehensive survey [101], an IoT semantic model consists of ontology, semantic middleware and semantic web, where "ontologies are highly used to provide semantic annotation to raw sensor data" while "middleware converts aggregated data to semantic data with the help of an ontology model" by implementing "a query processor that supports the SPARQL query", but achieving full semantic interoperability acquiring data in RDF format, that is by "transformation of sensory data into triplet format with the help of ontologies is still an open issue". The semantic web has a role of providing the graphical representations of the semantically structured data to support "decision making based on semantics".

Some of the firm statements in [101] show "none of the existing surveys address the more recent trend of semantic models like light-weight ontology, semantically distributed IoT middleware, or semantic web to support heterogeneous data" and "the process of converting raw sensor data into RDF using ontologies" which is "important for real-time IoT applications such as smart health, intrusion detection system, smart surveillance, etc.".

5.1. Core IoT Ontology

Back in 2012 the World Wide Web Consortium (W3C) started working on the Semantic Sensor Network (SSN) ontology and published it as a W3C Recommendation, as well as an OGC implementation standard, in cooperation with the Open Geospatial Consortium (OGC). SSN is "an ontology for describing sensors and their observations, the involved procedures, the studied features of interest, the samples used to do so, and the observed properties, as well as actuators" [127]. Based on a modular architecture, SSN also includes a self-contained core ontology named SOSA (Sensor, Observation, Sample, and Actuator) for its elementary classes and properties.

SSN and SOSA set of ontologies "support a wide range of applications and use cases, including satellite imagery, large-scale scientific monitoring, industrial and household infrastructures, social sensing, citizen science, observation-driven ontology engineering, and the Web of Things" [128]. The latest corrections to the SSN ontology were made in 2017. Some shortcomings of SSN include real-time data collection issues, providing a taxonomy for measurement units, context, quantity kinds (the phenomena sensed), and exposing sensors to services [105].

5.1.1. SAREF Core IoT Ontology

Another major effort in IoT ontology standardisation is made by the European Telecommunications Standards Institute (ETSI) in 2020, by introducing the Smart Applications REFerence (SAREF) ontology, shown in Fig. 5.1, "intended to enable interoperability between solutions from different providers and among various activity sectors in the Internet of Things (IoT), thus contributing to the development of the global digital market" [127]. SAREF is a core IoT ontology currently offering extensions for ten domains (Energy, Environment, Building, Smart Cities, Industry and Manufacturing, Smart Agriculture and Food Chain, eHealth/Ageing-well, Wearables, Water, Smart Lifts), while the extension for the Automotive domain is still under development [129]. SAREF core IoT ontology aims to "enable interoperability between solutions from different providers and among various activity sectors in the IoT, thus contributing to the development of the global digital market" [129].

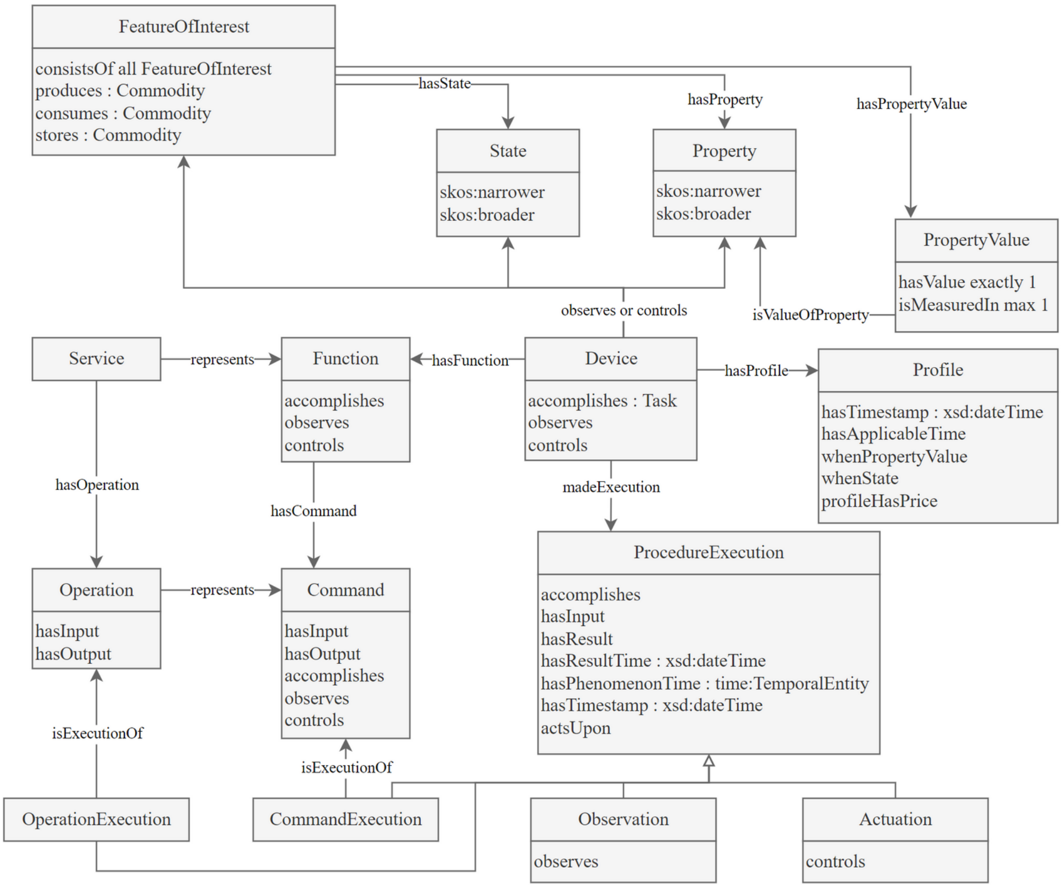


Figure 5.1. Overview of the SAREF ontology [129].

5.1.2. SAREF4EHAW Extension

The only WBAH-related IoT ontology listed in the recent report on ontologies standards [67] is SAREF4EHAW [104]. SAREF4EHAW in an extension of the core SAREF ontology for "eHealth Ageing Well" (EHAW) vertical, specified and published by the ETSI in 2020 and originally focused "on monitoring and supporting healthy lifestyles and early warning systems for cardiovascular accidents" [130]. Part of the semantic model for SAREF4EHAW ontology classes and properties is given in Fig. 5.2.

There are several use cases of SAREF4EHAW provided in the research literature: (1) developing a mobile application monitoring different activities of elderly people [131]; (2) knowledge-driven symptom monitoring that includes "real-time detection of symptoms during headache attacks, which is useful for classifying and diagnosing headaches, and headache attack triggers" [132]; (3) Data Analytics for Health and Connected Care (DAHCC) ontology set consisting of five ontologies (ActivityRecognition, SensorsAndActuators, MonitoredPerson, SensorsAndWearables, CareGiver), out of which ActivityRecognition, MonitoredPerson and CareGiver import SAREF4EHAW ontology [133].

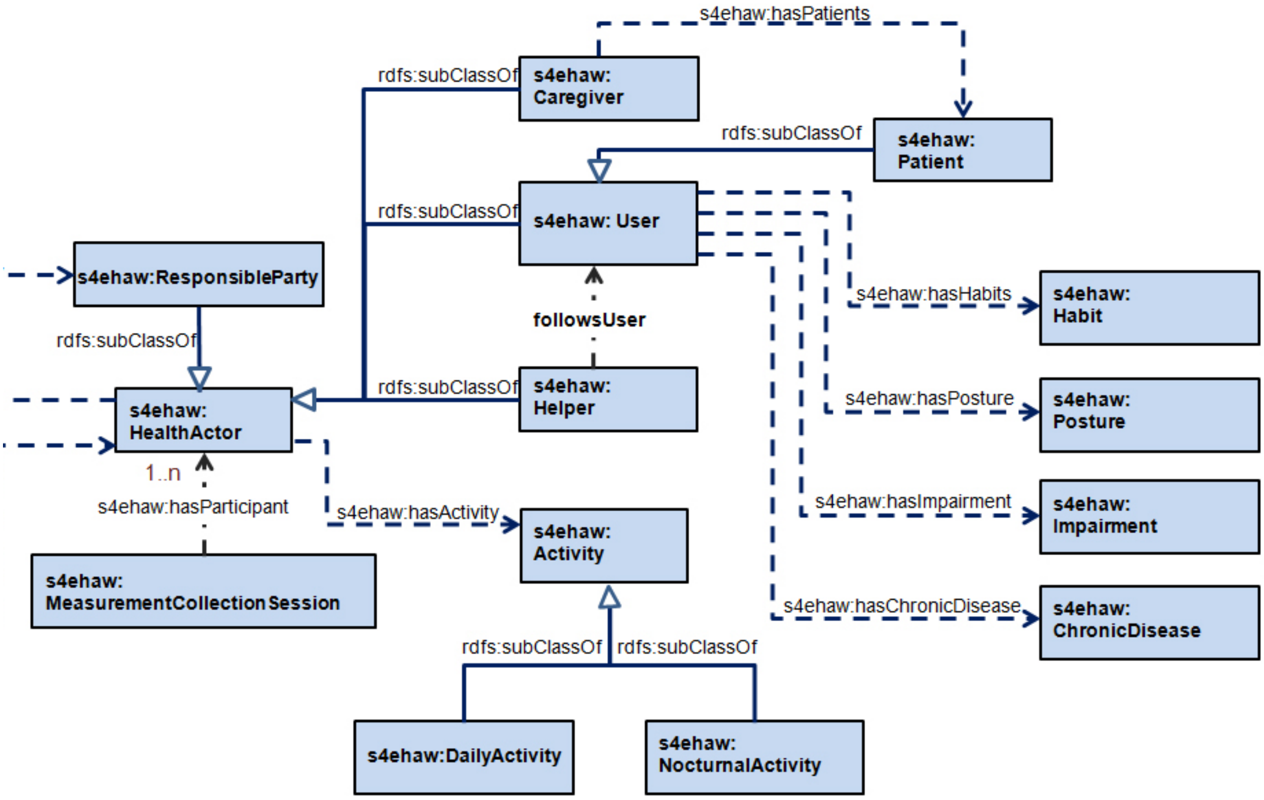


Figure 5.2. Part of the semantic model for SAREF4EHAW ontology [130].

5.1.3. SAREF4WEAR Extension

SAREF4WEAR in an extension of the core SAREF ontology for the wearables domain, which based on a limited set of use cases and from available existing data models, in close collaboration with AIOTI, the Horizon 2020 (H2020) Large Scale Pilots, ETSI (in particular TC SmartBAN) and oneM2M [129]. As shown in Fig. 5.3, the ontology covers equipping The Feature of Interest (saref:FeatureOfInterest), such as living organisms (s4wear:LivingOrganism) and software (s4wear:Software), with a Wearable device (s4wear:Wearable) which transmits information related to the connected saref:LivingOrganism. A wearer class (s4wear:Wearer) describes those living organisms that wear some wearable, so it defines any saref:LivingOrganism for which the s4wear:featureIsMeasuredByDevice property subsists [134].

Besides the above mentioned (DAHCC) ontology [133], there are few more use cases of SAREF4WEAR provided in the research literature: (1) integrating health monitoring in public transport, providing passengers with quality transport services and ensuring continuous health monitoring [135]; (2) IoT concepts and future directions for cross-coalition Command Control (C2) infrastructure [136]; (3) the utilization of ontologies for a more comprehensive understanding of the progression and etiology of neurodegenerative diseases (NDs) [137]. As the point of interest of this work is IoT-enabled WBAH, which can be efficiently supported by wearables, and as SAREF4EHAW also reuses SAREF4WEAR, the latter is also included in this work to be analyzed.

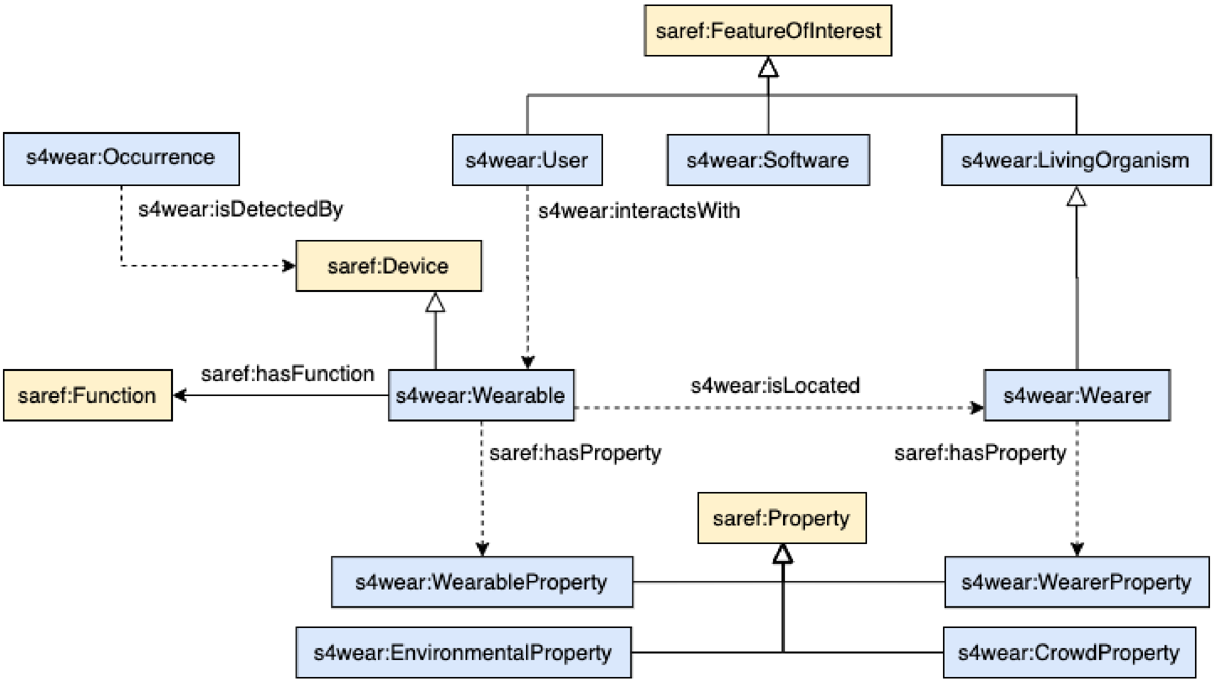


Figure 5.3. SAREF4WEAR overview of ontology classes and properties [134].

5.2. IoT Ontology Development Process

Design of the IoT ontology development process "has to be domain-independent, technology-agnostic, scientifically rigorous and user-friendly, in order to provide a generic and neutral, but also efficient and effective approach to the development of new and comprehensive IoT ontologies. Having in mind this is about both reliable, component-based software development and innovative, knowledge-based services design, the approach has to include new research achievements and state of practice from both software engineering (SE) and human-computer interaction (HCI) disciplines" [138].

Such an ontology development methodology has to provide method and tool support for the following important processes, proposed by [138]:

- ontology modeling - efficient conceptualization and modular ontology modeling, having available the ontology design patterns and other best practices, such as tool-supported model checking where possible,
- ontology verification - enabling intended ontology model checking against the models of the axiomatization of the ontology, in order to find and rectify inconsistencies and flaws,
- ontology validation - enabling audits of the developed ontology by providing iterative expert and domain user feedback, in order to prevent misalignment with user expectations and affirm the ontology adoption,
- ontology evolution - enabling developed and adopted ontology to be adapted to changes in the corresponding domain, while maintaining both the consistency of the ontology itself as well as the consistency of depending resources,
- ontology reuse (aligning, merging) - enabling either ontology alignment with mappings among ontologies while preserving the original ontologies, or by ontology merging resulting in the new ontology from the combination of the input ontologies,
- non-ontological resources reuse - enabling reuse of glossaries, dictionaries, lexicons, classification schemes, taxonomies, thesauri, etc.

There is a number of recognized challenges concerning the desired IoT ontology development to comprehensively serve the IoT ecosystem in the WBAH-enabled environment, and some suggestions to tackle them [138]:

- multidimensional nature of the domain, or multi-domains: stepwise and incremental approach is needed, because the first version of the IoT ontology will not support the WBAH purposes completely, due to the inherent complexity of the knowledge representation from the domain(s),

- IoT ontologies selection: relying only on public IoT ontology catalogues and notable libraries as reliable sources of additional IoT ontologies to be used for the baseline ontology extension,
- collaboration with the standardization body: open-sourcing each version of the resulting IoT ontology for WBAH, in order to provide transparency towards the research community as well as the standardization body representatives,
- semantic middleware performance: implementing the resulting IoT ontology for WBAH in the concrete system providing WBAH services and conducting performance tests in order to assess the quality of provided WBAH services.

"For every development methodology it is also crucial to include privacy-by-design and security-by-default, guiding the IoT ontology development towards innovative services that will provide high level of data protection, especially when it comes to personal data, and will implement appropriate cybersecurity methods and techniques, without excluding user safety. These are indispensable ingredients in achieving user's trust in the services, which is a necessary condition for full adoption of the services" [138].

6. Conclusion

Being large and mature field of research and practice for more then half a century, information management (IM) remains full of challenges when dealing with structured, semi-structured and unstructured data, processing information and acquiring knowledge in any realm of human activities. According to the Systems Engineering Body of Knowledge (SEBoK), IM is a "set of activities associated with the collection and management of information from one or more sources and the distribution of that information to one or more audiences" [139]. Three decades ago a DIKAR (Data, Information, Knowledge, Action and Result) model has been introduced [140], describing the value-chain consisting of data maintained in IT infrastructure that has to be interpreted in order to provide information, which has to be understood in order to emerge as knowledge, which then allows decision makers to take effective decisions that lead to appropriate actions expected to deliver meaningful results.

The emergence of IoT has brought further complexity to IM strategies, as stated by Gartner [100]: "Organizing and managing highly distributed data is by itself a significant challenge; but ensuring the distribution and consistency of business rules are applied to the data, and monitoring the execution of those business rules, adds additional layers of complexity". One of the biggest challenges is achieving data and information integration by establishing semantic interoperability. As concluded in the recent study [141], setting up a semantic layer by "using vocabularies and ontologies... can establish a common understanding of relevant data, by defining concepts as well as their properties and relationships" which is crucial not only for establishing interoperability within organizations or between organizations, but also in cross-border settings, which is a part of the EU-level vision of Common European Data Spaces [142].

Developing a proper, fully interoperable semantic model for the domain of interest, or even in cross-domain settings, is very challenging due to many reasons stated so far in this work, adding diverse knowledge models, scalability and quality of service to the list. A systematic literature review [143] stated that SWoT, "combined with a set of best software development practices, presents a promising solution to ease the development of semantically interoperable IoT environments". The following tools can provide a solid support: Protégé [144] and NeOn Toolkit [145] ontology editors, TripleChecker [146] and OOPS! (OntOlogy Pitfall Scanner!) [147] validation tools, PerfectO [148] ontology improvement tool, Node-RED [149] low-code programming tool for event-driven applications, WebVOWL (Web-based Visualization of Ontologies) [150] visualization tool, LODE (Live OWL Documentation Environment) [151] documentation maker, Drools [152] rule engine, etc.

Achieving efficient data acquisition from the IoT sensors, also data integration, as well as the proper interpretation of the derived information, is a prerequisite for seamless usage of IoT solutions and achieving WBAH-enabled environment in its full potential. IoT ontologies serve to facilitate the IoT activities, e. g. tracking and information discovery, storage, information exchange, and object addressing. Providing IoT-based support in the WBAH-enabled environments means implementing and maintaining IoT solutions, in a coordinated and harmonized manner, that not only support healthcare, but also foster well-being, encourage patients, citizens and the general population to live according to healthy lifestyle recommendations, and address the specific needs of an aging population.

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Labels:

AAL	Ambient Assisted Living
ADPPA	American Data Privacy and Protection Act
AES	Advanced Encryption Standard
AHA	Active and Healthy Aging
AI	Artificial Intelligence
AIoT	Artificial Intelligence of Things
AIOTI	Alliance for the Internet of Things Innovation
AMQP	Advance Message Queuing Protocol
API	Application Program Interface
BDA	Big Data Analytics
BLE	Bluetooth Low Energy
CAS	Complex Adaptive System
CIO	Chief Information Officer
CoAP	Constrained Application Protocol
D2D	Device-to-Device
DCC	Distributed Computing Continuum
DDS	Data Distribution Service
DHCP	Dynamic Host Configuration Protocol
DIKAR	Data, Information, Knowledge, Action and Result
DL	Deep Learning
DNS	Domain Name Service
DNS-SD	DNS-Service Discovery
ECC	Edge-to-Cloud Continuum
EIT	European Institute of Innovation and Technology
ESA	European Space Agency
ETSI	European Telecommunications Standards Institute
EU	European Union
GDPR	General Data Protection Regulation
GOe	Global Observatory for e-Health
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
HTTPU	HTTP UDP
HWB	Health and Well-Being
IACS	Industrial Automation and Control Systems
ICS	Industrial Control Systems
ICT	Information and Communication Technologies
IEC	International Electrotechnical Commission
IETF	Internet Engineering Task Force
IIoT	Industrial Internet of Things

IM	Information management
IoHT	Internet of Health Things
IoMT	Internet of Medical Things
IoT	Internet of Things
IP	Internet Protocol
IT	Information Technology
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
IWF	IoT World Forum
JSON	JavaScript Object Notation
LLM	Large Language Model
LLM EI	Large Language Model Edge Intelligence
LODE	Live OWL Documentation Environment
LoRaWAN	Long Range Radio Wide Area Network
LOV4IoT	Linked Open Vocabularies for Internet of Things
LPWAN	Low Power Wide Area network
LRWAN	Low Power Wide Area Network
LR-WPAN	Low-Rate Wireless Personal Area Network
M2M	Machine to Machine
MAC	Medium Access Control
m-DNS	Multicast DNS
ML	Machine Learning
MQTT	Message Queue Telemetry Transport
NB-IoT	Narrow Band-IoT
NFC	Near Field Communication
NGIoT	Next-Generation Internet of Things
OASIS	Organization for the Advancement of Structured Information Standards
OECD	Organisation for Economic Co-operation and Development
OOPS!	OntOlogy Pitfall Scanner!
OMG	Object Management Group
OSI	Open System Interconnection
OWBAH	One Well-Being, Aging and Health
OWL	Web Ontology Language
OWL2	Web Ontology Language 2
OT	Operational Technology
OTA	Over-the-Air
PA-UDP	Performance Adaptive UDP
QoS	Quality of Service
RDBUDP (RUBDP)	Reliable Dynamic Buffer UDP
RDF	Resource Description Framework

REST	Representational State Transfer
RFID	Radio-Frequency Identification
RIF	Rule Interchange Format
ROI	Return on Investment
RPL	Routing Protocol for Low Power and Lossy Networks
RTT	Round-Trip Time
SAREF	The Smart Applications REFerence
SAREF4EHAW	The Smart Applications REFerence eHealth Ageing Well
SAREF4WEAR	The Smart Applications REFerence Wearables
SCADA	Supervisory Control and Data Acquisition
SDGs	Sustainable Development Goals
SEBoK	Systems Engineering Body of Knowledge
SemCom	Semantic Communication
SHAFE	Smart Healthy Age-Friendly Environments
SML	Sustainability and Maintainability Level
SPARQL	SPARQL Protocol and RDF Query Language
SSDP	Simple Service Discovery Protocol
SW	Semantic Web
SWoT	Semantic Web of Things
TD	Thing Description
TRL	Technology Readiness Level
TTN	The Things Network
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
UDT	UDP-based Data Transfer
UHC	Universal Health Coverage
URI	Uniform resource identifier
URL	Uniform Resource Locator
UPnP	Universal Plug-and-Play
W3C	World Wide Web Consortium
WAN	Wide Area network
WBAH	Well-Being, Aging and Health
WebVOWL	Web-based Visualization of Ontologies
WHA	World Health Assembly
WHO	World Health Organization
WoT	Web of Things
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
WWW	World Wide Web
XML	Extensible Markup Language
XMPP	Extensible Messaging and Presence Protocol

SEMANTIC CHALLENGES IN THE INTERNET OF THINGS FOR WELL-BEING, AGING AND HEALTH

Abstract:

Health is one of the greatest resources for achieving and maintaining personal quality of life, advancement of communities and development of societies around the world. In order to achieve universal health coverage and meet the needs of citizens, patients, healthcare professionals and policy makers, strategic, systematic and continuous support of information and communications technologies in health and health-related fields is necessary. The presence of cybercare along with providing healthcare services on-site allow for usage of advanced technologies like smartphones, wearable sensors and medical devices. Wearable sensors belong to the Internet of Things - the network of uniquely identifiable, heterogeneous and connected devices offering intelligent computing service. Internet of Things is a variety of technologies, which have been applied to healthcare and well-being in order to increase the quality of healthcare and overall well-being while reducing costs and overheads by providing innovative solutions, such as remote patient monitoring, residential environments to provide assisted living for dementia suffers, etc. The term "well-being, aging and health" has been coined to cover application areas that not only support healthcare, but also foster well-being, encourage patients and the population in general to live according to healthy lifestyle recommendations, and address the specific needs of an aging population. In order to conduct complex tasks, from data collection and processing by the devices to providing business functions to a variety of applications and users, one of the greatest challenges to overcome is semantic interoperability. Semantic interoperability for Internet of Things should ensure the precise format and meaning of exchanged data and information is preserved and understood throughout exchanges between parties, which comes with a series of challenges. In order to tackle them, three approaches have been proving valid: ontology-driven approach, semantic middleware and Semantic Web. All three approaches have ontologies as a fundamental building block, each defining classes, attributes, and relationships with which to represent sensor knowledge and describe acquired data semantic. No existing ontology is comprehensive enough to document all the concepts required for semantically annotating an end-to-end IoT application as ontologies are often restricted to a certain domain. Further research will include design and development of an IoT semantic model consisting of ontologies, representing semantic middleware and providing Semantic Web interoperability across IoT platforms and application domains by using Web protocols and standards. ETSI-standardized core Internet of Things ontology named SAREF has been assessed, along with its SAREF4EHAW and SAREF4WEAR extensions, as candidates for seamless usage of Internet of Things solutions and providing Web-ready services for well-being, aging and health needs.

Keywords:

IoT, semantics, ontology, well-being, aging, health, e-health, distributed computing continuum, information management, semantic web.

SEMANTIČKI IZAZOVI INTERNETA STVARI ZA DOBROBIT, STARENJE I ZDRAVLJE

Sažetak:

Zdravlje je jedan od najvećih resursa za postizanje i održavanje kvalitete osobnog života, napretka zajednica i društvenog razvoja diljem svijeta. Kako bi se postigla univerzalna zdravstvena zaštita i zadovoljile potrebe građana, pacijenata, zdravstvenih djelatnika i kreatora politika, nužna je strateška, sustavna i kontinuirana podrška informacijsko-komunikacijskih tehnologija u zdravstvu i sa njim povezanim područjima. Prisutnost kibernetičke skrbi zajedno s pružanjem zdravstvenih usluga na licu mjesta omogućuje korištenje naprednih tehnologija poput pametnih telefona, nosivih senzora i medicinskih uređaja. Nosivi senzori pripadaju Internetu stvari - mreži jedinstveno prepoznatljivih, heterogenih i povezanih uređaja koji nude inteligentne računalne usluge. Internet stvari je niz tehnologija koje su primijenjene na zdravstvo i dobrobit kako bi se povećala kvaliteta zdravstvene skrbi i opće dobrobiti uz smanjenje troškova pružanjem inovativnih rješenja, kao što je daljinsko praćenje pacijenata, stambena okruženja za potpomognuti život oboljelih od demencije, itd. Pojam "dobrobit, starenje i zdravlje" skovan je kako bi pokrio područja primjene koja ne samo da podržavaju zdravstvenu skrb, već i potiču dobrobit, tj. pacijente i stanovništvo općenito na život u skladu s preporukama zdravog načina života i rješavanja specifičnih potreba starećeg stanovništva. Kako bi se izvršili složeni zadaci, od prikupljanja podataka i obrade na uređajima do pružanja poslovnih funkcija različitim aplikacijama i korisnicima, jedan od najvećih izazova za prevladati je semantička interoperabilnost. Semantička interoperabilnost za Internet stvari trebala bi osigurati da se točan format i značenje razmijenjenih podataka i informacija očuvaju i razumiju tijekom razmjene između strana, što dolazi s nizom izazova. Kako bi se uhvatili u koštac s njima, tri su se pristupa pokazala valjanima: pristup vođen ontologijom, semantički međusloj i semantički web. Sva tri pristupa imaju ontologije kao temeljni građevni blok, od kojih svaki definira klase, atribute i odnose s kojima se predstavlja znanje senzora i opisuje semantika stečenih podataka. Nijedna postojeća ontologija nije dovoljno sveobuhvatna da dokumentira sve koncepte potrebne za semantičko označavanje aplikacije Interneta stvari s kraja na kraj jer ontologije su često ograničene na određenu domenu. Daljnja istraživanja uključuju dizajn i razvoj semantičkog modela Interneta stvari koji se sastoji od ontologija, predstavljajući semantički međusloj i pružajući interoperabilnost semantičkog weba preko platformi Interneta stvari i aplikacijskih domena korištenjem web protokola i standarda. ETSI standardizirana temeljna ontologija Interneta stvari pod nazivom SAREF procijenjena je, zajedno sa svojim proširenjima SAREF4EHAW i SAREF4WEAR, kao kandidat za besprijekornu upotrebu rješenja Interneta stvari i pružanje Web usluga za dobrobit, starenje i zdravlje.

Ključne riječi:

internet stvari, semantika, ontologija, dobrobit, starenje, zdravlje, e-zdravstvo, kontinuum raspodijeljenog računarstva, upravljanje informacijama, semantički web.