Article

Comprehensive List of Topics Describing the IoT Ecosystem

Gaetanino Paolone [1], Paolino Di Felice [2,*] 0000-0003-3552-0199, Danilo Iachetti [3], Francesco Pilotti [4], Romolo Paesani [4], and Martina Marinelli [4]

[1] B2B S.r.l., 64100 Teramo, Italy; g.paolone@b2binformatica.it
[2] Department of Industrial and Information Engineering and Economics, University of L'Aquila, 67100 L'Aquila, Italy; paolino.difelice@univaq.it
[3] Meccatronica S.r.l., 64100 Teramo, Italy; d.iachetti@meccatronica.design
[4] Gruppo SI S.c.a.r.l. , 64100 Teramo, Italy; f.pilotti@softwareindustriale.it
[4] Gruppo SI S.c.a.r.l. , 64100 Teramo, Italy; r.paesani@softwareindustriale.it
[4] Gruppo SI S.c.a.r.l. , 64100 Teramo, Italy; m.marinelli@softwareindustriale.it
* Correspondence: paolino.difelice@univaq.it; Tel.: 3204232540

Abstract: Internet of things (IoT) is a complex ecosystem of connected devices that exchange data over a network and whose final aim is to provide services. The total number of installed connected devices is expected to grow exponentially in the near future. Analogously, the number of IoT-related studies published every year is constantly increasing. This huge knowledge asset has generated a fragmented picture about IoT systems, their basic constituents, their qualities, and in some cases even inconsistent terminologies and definitions. This paper aims at providing a holistic view of the topics characterizing the IoT ecosystem by taking into account a technology perspective and a business one; then a definition of IoT ecosystem is given.

Keywords: Internet of Things; IoT Taxonomy; IoT Ecosystem; Systematic Mapping Study.

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1. Introduction

Ref. [1] conducted a bibliometric study of 3,523 IoT-related publications published in 2000–2019. This huge knowledge asset has generated a fragmented picture about IoT systems, their basic constituents, their qualities, and in some cases even inconsistent terminologies and definitions. A long list of surveys have been written with the aim of overcoming the issue. Most of these studies suffer of two severe drawbacks: (a) they are structured according to a limited number of research questions; (b) their scope does not cover all the aspects connected with the IoT domain. This paper aims at grouping the main topics which characterize the IoT ecosystem by taking into account a technology perspective and a business one, the latter complementing the former.

The remaining part of the paper is structured as follows. Section 2 describes firstly the articulation of the research process and, secondly, the bibliographic search we have carried out. 119 reviews were selected from 62 distinct Scopus indexed journals. Section 3 reports on the way the eighteen topics extracted from the 119 reviews were classified. Section 4 introduces a definition of IoT ecosystem that merges the technology perspective and the business one. Section 5 ends the paper.

2. The Research Methodology

The present paper classifies the IoT-ecosystem's topics identified through a systematic mapping study. Such a domain is very broad and, moreover, a long list of systematic reviews have been already published, therefore "a systematic mapping study is more appropriate than a systematic review", [2], p.5. Specifically, the search was devoted to download review studies. The research process was articulated in the following steps:

a: querying the Scopus database,

b: download the search results (PDF files containing for each paper: title, authors, abstract, keywords, and the DOI),
c: reading of the abstracts,
d: elimination of not relevant items,
e: classification of the remaining items,
f: downloading of those papers,
g: reading the full-text of those papers,
h: analysis of the references in each read article. Download of relevant references not yet been downloaded,
i: applying iteratively steps e, g, and h to those papers.

We queried the largest scientific database, namely the Elsevier's Scopus repository. All major publishers (e.g., ACM, Elsevier, IEEE, Springer, ...) are indexed in Scopus. The initial search string was: `IoT OR IOT OR "Internet Of Thing" OR "Internet Of Thing (IOT)" OR "Internet Of Things" OR "Internet Of Things (IOT)" OR "Internet Of Things (IoT)" OR "Internet Of Things (IOT)".`

As output, we got 148,773 documents. This set was resized by adding the filters: (a) Document type: `Review`; (b) Source type: `Journal`; (c) Language: `English`. The number of items returned by the search was 3,286. Through the "Source title" item exposed by Scopus, we found that the 3,286 reviews came from 160 distinct journals. Since a large number of them have focuses distant from the IoT ecosystem, the initial search was restricted to the 62 journals listed below:

ACM Computing Surveys; Annals of Emerging Technologies in Computing; Applied Sciences; Array; Blockchain: Research and Applications; Communications of the ACM; Computer & Security; Computer Communications; Computer Networks; Computer Science Review; Computer; Computers and Electronics in Agriculture; Computers and Security; Computers in Industry; Digital Communications and Networks; Digital Signal Processing; Future Generation Computer Systems; Future Internet; Health and Technology; IEEE Access; IEEE Cloud Computing; IEEE Communications Magazine; IEEE Communications Surveys and Tutorials; IEEE Internet Computing; IEEE Internet of Things Journal; IEEE Pervasive Computing; IEEE Transactions on Industrial Informatics; IEEE Wireless Communications; Industrial Marketing Management; Information Sciences; Information Systems; Information; Intelligent Systems with Applications; International Journal of Distributed Sensor Networks; International Journal of Environmental Research And Public Health; International Journal of Wireless Information Networks; Internet of Things Netherlands; Journal of Ambient Intelligence and Humanized Computing; Journal of Business Research; Journal of Healthcare Engineering; Journal of Industrial Information Integration; Journal of Management Analytics; Journal of Medical Internet Research; Journal Of Network and Computer Applications; Journal of Open Innovation: Technology, Market, and Complexity; Journal of Parallel and Distributed Computing; Journal of Retailing and Consumer Services; Journal of Retailing; Journal of Sensor and Actuator Networks; Journal of Systems Architecture; Journal of Theoretical and Applied Information Technology; Mobile Networks and Applications; Pervasive and Mobile Computing; Proceedings of the IEEE; Security and Communication Networks; Sensors; Smart Cities; Sustainable Cities and Society; Telematics and Informatics; Trends in Food Science and Technology; Wireless Communications and Mobile Computing; Wireless Personal Communications.

Five journals (namely: Journal of Business Research, Industrial Marketing Management, Journal of Open Innovation: Technology, Market, and Complex, Journal of Retailing and Consumer Services, and Journal of Retailing), among the set of the 62 listed above, are business-oriented. They have been selected in order to complement the IoT technology perspective with the IoT business one.

953 items were returned by the new search. Next, we downloaded title, authors' name, keywords, abstract and DOI for each article belonging to the set of items returned by Scopus. Such a number confirms the great ferment of research about the IoT ecosystem, interest substantiated by the large number and heterogeneity of the topics with a more or

Table 1. Dimensions and topics of the IoT ecosystem.

Functional Blocks	Qualities	Other Topics
Identification	Security	Application Domains
Sensing	Privacy	Business Models
Networking	Interoperability	Customers
Computation	Scalability	Servitization
Services	Latency	Digital Twins
Analytics	Reliability	Software Engineering

less connection with such a domain. Given that the objective of this work is to classify the main topics characterizing the IoT ecosystem (Section 1), we carried out a further filter. It consisted in restricting the attention to the review papers appeared from 2019 to April 2022. As a result, 119 articles were retrieved.

3. Classification of IoT Topics from Recent IoT Review Studies

The topics covered in the 119 review articles were grouped as three distinct dimensions (Table 1): (a) *Functional Blocks* (sometimes also called the constituent components) of the IoT systems, (b) their *Qualities* – i.e., their non-functional characteristics, and (c) *Other Topics*. The six functional blocks are as in [3], the six qualities come from [4], while the six items in the last column complete those in the other two columns of the table.

3.1. IoT Functional Blocks

This section briefly describes the six functional blocks in Table 1.

- **Identification** IoT systems are complex systems composed of physical entities, sensors, actuators, network components, and software components. So, it is mandatory that each entity is distinguishable from each other. The identification of the entities is done by attaching tags to them. In this way, a unique identification code is associated unambiguously to the "things" [5].
- **Sensing** IoT networks sense, aggregate, and broadcast data from smart objects located in the environment. A wide range of sensors are today available on the market place and used in IoT applications [6,7].
- **Networking** IoT networks are a combination of heterogeneous smart devices, communication technologies, and protocols that all together perform application-specific tasks. There are a bulk of technologies for IoT communication [8].
- **Computation** Standard computation is performed by the CPU and is managed by the operating system. Such a paradigm is not suitable in the IoT domain where, as the number of IoT devices grows, a different approach is required. Today, Edge/Fog/Cloud computing are the most relevant IoT computing models [9–11].
- **Services** Services are usually implemented as software. IoT systems can provide an increasing number of ubiquitous services with different performances and functionalities [12,13].
- **Analytics** IoT systems sense and convey a huge volume of heterogeneous data that has to be stored and later processed by efficient algorithms to get benefit from it. The processing of this data consumes a lot of energy to reach its goal with required quality of service. Unfortunately, IoT devices are restricted by limited resources. Therefore the optimal use of energy is a big issue for these devices that has recently been attracting much attention and become a relevant research direction [14].

Ref. [3] is a literature review that proposes an IoT technological stack which has the merit of decoupling the enabling technologies, the underlying infrastructure, and vendor implementations concerning the IoT ecosystem. In the paper, the IoT functional blocks are investigated at each layer of the stack and are associated to the pertinent technologies.

3.2. IoT Qualities

Quality aspects are non-functional characteristics of IoT systems. As said at the beginning of Section 3, the IoT qualities we refer to come from [4]. With respect to the original taxonomy, we merged Trust into Security (similarly to what is done in [15]).

- **Security** is a major concern of IoT systems because they are distributed and involve a large number of distinct components. Security functions in IoT systems assure the authenticity, availability, confidentiality, and integrity of information travelling the networks. An increasing number of scholars are studying security improvements that can be achieved in IoT systems using a blockchain-based approach (e.g., [16–19]).
- **Privacy** characterizes aspects related to the protection of the data of an IoT system. The privacy requirement spans all layers of IoT systems, that is from the sensing of data, to its storage, to the processing [20].
- **Interoperability** (called heterogeneity in [15]) is the ability of IoT systems to seamlessly communicate and use each other's services. Middleware is the core component of the IoT systems devoted to enhance the interoperability.
- **Scalability** It is important that the IoT system continues to function effectively despite its growth. Ref. [21] distinguishes among functional scalability, heterogeneous scalability, and network scalability.
- **Latency** concerns the time an IoT system needs before responding to an external stimulus (e.g., a user request via a smartphone) [3,4].
- **Reliability** is a property of consistent, intended behavior and results [15]. Reliability is relevant with respect to communications, data, and computing [4].

3.3. Other Topics

The larger becomes the domain of the IoT applications, the more relevant become the topics concerning Business Models, Customers, and Servitization. The Digital Twin (DT) is an emerging approach that promotes the softwarization of physical things, into logical ones. At present, DT promises to change the way products and systems are made and used. From the Software Engineering perspective, IoT applications are distributed over heterogeneous devices, operate in dynamic and uncertain environments. It follows that to be able to provide IoT users (either humans or machine) with robust IoT applications is a serious challenge.

Below, we introduce these six topics.

- **Application Domains** IoT is becoming popular due to its wide range of applications in healthcare, retail, smart parking, transportation, agriculture, public safety, smart lighting, smart home, smart buildings, manufacturing, logistics, disaster management, just to mention a few.
- **Business Models** are conceptual tools that explain the logic of an organization, the way it operates, and hence, how it creates value. Till now, "a practical and effective IoT business model is yet to emerge" [22].
- **Customers** "Today consumers increasingly buy experiences rather than goods or services" [23]. The adoption of the IoT technology is becoming mandatory for industries and retailers to meet this goal, indeed the IoT has the potential to provide personalized services to customers (since IoT is able to bridging the gap between the digital world and the real world). The other side of the coin concerns the protection of the customer identity and personal data. In [24], Pinto, da Silva, and Moro conjecture that in the near future there will be an acceleration in the proposal of reliable people-centered IoT solutions based on Distributed Ledger Technology.
- **Servitization** Moving from product to service is called servitization. *Revenue growth and profitability* and *Improved customer outcomes* are two relevant reasons why manufacturers and retailers should implement the servitization paradigm. In the present time, with digitalization advancing rapidly, more and more companies are understanding the benefits of making the final step, that is implementing the so-called Digital servi-

tization [25]. The notion of digital servitization coincides with the notion of Smart service adopted in [26]: "Smart service is a service whose value and efficiency extends beyond classic, digital service and is delivered through a smart product."

- **Digital Twins** Many definitions of the notion of DTs have been proposed. One of them follows: A DT is composed of three parts: (a) the physical object in the real space; (b) the virtual object in the virtual space, and (c) connected data that ties the physical and virtual together [27]. IoT sensors continuously collect the data necessary for companies to derive value from physical things. This feed of real-time data is what ensures that a DT maintains an actual live copy of an asset, process, or ecosystem.
- **Software Engineering** The development of IoT applications differs from the development of traditional applications because they execute on a network consisting of hundreds to thousands heterogeneous devices (e.g., sensors, actuators, storage, and user interface devices), operate in dynamic and uncertain environments, and can fail to provide their services without notice. Another difference with the development of traditional software resides in the multitude of involved stakeholders. MontiThings is a modeling infrastructure that facilitates the development of IoT applications by increasing abstraction, separating concerns, and their deployment to heterogeneous devices [29].

4. Definition of IoT Ecosystem

The prevalent number of definitions of the IoT-ecosystem notion comes from a technology perspective [30,31], while [32] proposed a definition of IoT business ecosystem (i.e., a definition of IoT ecosystem from the business perspective). In light of this study, we are now able to give a definition of the IoT ecosystem which merges the technology perspective of the IoT domain with the business one: "An IoT ecosystem connects resource-constrained heterogeneous devices in a handled way to build an efficient and secure system, whose final aim is to deliver services of practical utility to a community comprising a multitude of stakeholders." At a high level of abstraction, the involved stakeholders are: the industries providing the IoT technology, the developers of IoT solutions, and the customers (either individuals, companies, or machines).

This widening of the perimeter of the definition of the IoT ecosystem is motivated by the fact that, from a commercial point of view, the IoT represents a huge opportunity for most companies to enter new markets and generate revenues increasing.

5. Conclusions

The aim of the paper was to introduce the reader to the IoT ecosystem by providing him with a broad-spectrum description of the many topics that can be traced back to it. A systematic mapping of the state of the art made it possible to identify 3 distinct dimensions for a total number of 18 topics covering both the technology perspective and the business one. Such a classification represents our own taxonomy of the IoT ecosystem. A long list of alternative taxonomies are already available as it emerges, for example, from [4].

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References

1. Wang,J.; Lim,M.K.; Wang,C.; Tseng, M.L. The evolution of the Internet of Things (IoT) over the past 20 years *Computers & Industrial Engineering* **2021**, 155, 107174, https://doi.org/10.1016/j.cie.2021.107174
2. Kitchenham, B.; Charters, S. Guidelines for performing Systematic Literature Reviews in software engineering. *EBSE Technical 1472 Report EBSE-2007-01*, **2007**, 525444systematicreviewsguide.pdf (accessed on july, 2022)

3. Ali, O.; Ishak, M.K.; Bhatti, M.K.L.; Khan, I.; Kim, K.-I. A Comprehensive Review of Internet of Things: Technology Stack, Middlewares, and Fog/Edge Computing Interface. *Sensors*, **2022**, 22, 995. https://doi.org/10.3390/s22030
4. Alkhabbas, F.; Spalazzese, R.; Davidsson, P. Characterizing Internet of Things Systems through Taxonomies: A Systematic Mapping Study *Internet of Things*, **2019**, 7, 10, 0, 084
5. Kassab, W.; Darabkh, K.A. A–Z survey of Internet of Things: Architectures, protocols, applications, recent advances, future directions and recommendations. *Journal of Network and Computer Applications* **2020**, 163, 102663
6. Stavropoulos, T. G.; Papastergiou, A.; Mpaltadoros, L.; Nikolopoulos, S.; Kompatsiaris, I. IoT Wearable Sensors and Devices in Elderly Care: A Literature Review. *Sensors*, **2020**, 20, 2826, doi:10.3390/s20102826
7. Laghari, A.A.; Wu, K.; Laghari, R.A.; Ali, M.; Khan, A.A. A Review and State of Art of Internet of Things (IoT). *Archives of Computational Methods in Engineering*, **2022**, 29:1395–1413, https://doi.org/10.1007/s11831-021-09622-6
8. Sobin, C.C. A Survey on Architecture, Protocols and Challenges in IoT *Wireless Personal Communications*, **2020**, 112:1383–1429, https://doi.org/10.1007/s11277-020-07108-5
9. Jin, X.; Lib, L.; Dang, F.; Chen, X.; Liu, Y. A survey on edge computing for wearable technology *Digital Signal Processing* (in press)
10. Laroui, M.; Nour, B.; Moungla, H.; Cherif, M.A.; Afifi, H.; Guizani, M. Edge and fog computing for IoT: A survey on current research activities & future directions. *Computer Communications*, **2021**, 180, 210–231
11. Firouzi, F.; Farahani, B.; Marinšek, A. The convergence and interplay of edge, fog, and cloud in the AI-driven Internet of Things (IoT). *Information Systems*, **2022**, 107, 101840, https://doi.org/10.1016/j.is.2021.101840
12. Achir, M.; Abdelli, A.; Mokdad, L.; Benothman, J. Service discovery and selection in IoT: A survey and a taxonomy. *Journal of Network and Computer Applications*, **2022**, 200, 103331
13. Yu, J.; Wang, M.; Liu, J.; Abnosian, K. Service management mechanisms in the internet of things: an organized and thorough study. *Journal of Ambient Intelligence and Humanized Computing*, **2022**, 13, 75–86
14. Khamesi, A.R.; Silvestri, S.; Baker, D.A.; De Paola, A. Perceived-Value-driven Optimization of Energy Consumption in Smart Homes. *ACM Transactions on Internet of Things* 1, 2, April 2020, Article 13, https://doi.org/10.1145/3375801
15. ISO/IEC 30141:2018, Internet of Things (IoT) – Reference Architecture https: //standards.iso.org/ittf/PubliclyAvailableStandards/c065695_ISO_IEC_30141_2018(E).zip (Accessed on May 25, 2022)
16. Kaur, M.; Khan, M.Z.; Gupta, S.; Alsaeedi, A. Adoption of Blockchain With 5G Networks for Industrial IoT: Recent Advances, Challenges, and Potential Solutions *IEEE Access*, **2022**, 10, 10.1109/ACCESS.2021.3138754
17. Pal, S.; Dorri, A.; Jurdak, R. Blockchain for IoT access control: Recent trends and future research directions. *Journal of Network and Computer Applications*, **2022**, 203, 103371, https://doi.org/10.1016/j.jnca.2022.103371
18. Lone, A.H.; Naaz, R. Applicability of Blockchain smart contracts in securing Internet and IoT: A systematic literature review. *Computer Science Review*, **2021**, 39, 100360
19. Schiller, E.; Aidoo, A.; Fuhrer, J.; Stahl, J.; Ziörjen, M.; Stiller, B. Landscape of IoT security. *Computer Science Review*, **2022**, 44, 100467
20. Strous, L.; Solms, S.; Zúquete, A. Security and privacy of the Internet of Things. *Computers & security*, **2021**, 102, 102148, https://doi.org/10.1016/j.cose.2020.102148
21. Zhang, J.; Ma, M.; Wang, P.; Sun, X.-D. Middleware for the Internet of Things: A survey on requirements, enabling technologies, and solutions. *Journal of Systems Architecture*, **2021**, 117, 102098 https://doi.org/10.1016/j.sysarc.2021.102098
22. Cranmer, E.E.; Papalexi, M.; tom Dieck, M.C.; Bamford, D. Internet of Things: Aspiration, implementation and contribution *Journal of Business Research*, **2022**, 139, 69–80
23. Batat, W. *Experiential marketing: Consumer Behavior, Customer Experience and the 7Es*. Routeledge, Taylor & Francis Group, London & New York, **2019**
24. Pinto, F.; da Silva, C.F.; Moro, S. People-centered distributed ledger technology-IoT architectures: A systematic literature review *Telematics and Informatics*, **2022**, 70, 101812
25. Favoretto, C.; Mendes, G.H.S. Oliveira, M.G.; Cauchick-Miguel, P.-A.; Coreynen, W. From servitization to digital servitization: How digitalization transforms companies' transition towards services. *Industrial Marketing Management*, **2022**, 102, 104–121
26. Fischer, M; Heim, D.; Hofmann, A. Christian Janiesch, Christoph Klima, Axel Winkelmann. A taxonomy and archetypes of smart services for smart living. *Electronic Markets*, **2020**, 30:131–149, https://doi.org/10.1007/s12525-019-00384-5
27. Grieves, M. *Product Lifecycle Management: Driving the Next Generation of Lean Thinking*. New York, NY, USA: McGraw-Hill, **2006**
28. Bucchiarone, A.; Cabot, J.; Paige, R.F.; Pierantonio, A. Grand challenges in model-driven engineering: an analysis of the state of the research. *Software and System Modeling*, **2020**, 19 (1), 5–13
29. Kirchhof, J.C; Rumpe, B.; Schmalzing, D.; Wortmann, A. MontiThings: Model-Driven Development and Deployment of Reliable IoT Applications. *The Journal of Systems and Software*, **2022**, 183, 111087
30. Bansal, S.; Kumar, D. IoT Ecosystem: A Survey on Devices, Gateways, Operating Systems, Middleware and Communication *International Journal of Wireless Information Networks*, **2020**, 27:340–364, https://doi.org/10.1007/s10776-020-00483-7
31. Raj, A.; Shetty, S.D. IoT Ecosystem, Layered Architectures, Security and Advancing Technologies: A Comprehensive Survey *Wireless Personal Communications*, **2022**, 122:1481–1517, https://doi.org/10.1007/s11277-021-08958-3
32. Mazhelis, O.; Luoma, E.; Warma, H. Defining an Internet-of-Things Ecosystem. In: Andreev, S., Balandin, S., Koucheryavy, Y. (eds) *Internet of Things, Smart Spaces, and Next Generation Networking*. ruSMART NEW2AN 2012. Lecture Notes in Computer Science, vol 7469, 1–14, **2012**, Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-32686-8_1