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*Editors*

# Enabling Things to Talk

Designing IoT solutions with the  
IoT Architectural Reference Model



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 Springer

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# Foreword

Dear Reader,

The book that you are holding now in your hands is the result of a European success story and we want to share with you our feeling of being proud of it. Since 2007, the concept “Internet of Things” has clearly been driven by research and policy initiatives in Europe.

The Internet of Things (IoT) is an emerging network superstructure that connects physical resources and people together with software. It will enable an ecosystem of smart applications and services that will improve and simplify the life of the citizen and will contribute to sustainable growth, provided it combines and guarantees trust and security for people and businesses. At the same time, the IoT will bring hyper-connectivity to our society, using augmented and rich interfaces and characterised by higher semi-autonomous system behaviour than today.

Following a workshop in February 2008, co-organised with the European Technology Platform on Smart Systems (EPoSS),<sup>1</sup> a corresponding research call was developed where in particular Internet of Things architectural questions were pivotal. IoT-A has been the project in the past years in giving an answer by elaborating the Architectural Reference Model (ARM).

Whereas in the first run the IoT referred to the advent of barcodes and Radio Frequency Identification (RFID), helping to automate inventory, tracking and basic identification, the second, current wave of IoT is characterised by a strong verve for connecting sensors, objects, devices, data and applications. The next wave could be called a “cognitive IoT”, facilitating object and data re-use across application domains, leveraging on hyper-connectivity, interoperability solutions and semantic enriched information distribution. We consider it being very important for Europe to be able to leverage each wave and to turn the research results into relevant innovation and products.

The Architectural Reference Model provided aims to connect vertically closed systems, architectures and application areas for creating open systems and integrated

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<sup>1</sup> [www.smart-systems-integration.org](http://www.smart-systems-integration.org)

environments and platforms. It constitutes the platform from which Europe can capitalise on the benefits of developing consumer-oriented platforms that closely involve the telecom, hardware, software and service industries. Innovative Internet ecosystems going beyond the smart phone must be created, and new multiple application sectors including potential new players and service providers need to collaborate in order to take advantage together of the technological progress.

By just accomplishing the goals of the Architectural Reference Model, a success would be achieved that would far overshadow everything previously created for the individual application areas. And it really can no longer be doubted that this would be achievable in the near future with a determined improvement of available engineering capabilities and with motivated pan-European, multidisciplinary teams ready to put thorough and serious scientific and technological effort to tackle the practical treatment of the IoT challenges, although we must not underestimate the extent of the difficulties that still have to be overcome. This will be the goal of the Internet of Things Objective in Horizon 2020 to build upon success stories like the Architecture Reference Model in order to rise up to today's and tomorrow's societal challenges.

European Commission Vice-President Neelie Kroes is committed to embody and promote a strong leadership presence in IoT technologies and applications in Europe, given the great opportunities they offer to both EU businesses and citizens in areas of general interest like the prediction, monitoring and alerting of natural hazards, the automation of processes in healthcare, utilisation of home metering solutions to assist in independent living, and support of the disabled persons. The Commission will continue to support research and innovation in this domain in the context of "Horizon 2020", the forthcoming EU research and innovation framework programme starting in 2014.<sup>2</sup>

If you start entering complex subjects you need both a framework and an explanation on how to advance and gain rapidly benefits. This "cookbook" provides you with all what you need for starting your IoT endeavour or refocus your current IoT activities. You will find the IoT Architectural Reference Model and compelling use cases – it is now in your hand to use this book and to expand the knowledge of the worldwide IoT community.

We enthusiastically invite you to read this book and opt-in to the Internet of Things! With your engagement, motivation and interactions, the future of the Internet of Things in Europe will be bright and successful.

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Directorate General CONNECT, European Commission  
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<sup>2</sup> <http://ec.europa.eu/research/horizon2020>

# Acknowledgements

Many thanks are due to Gerrit Muller, Buskerud University College and the Embedded Systems Innovations by TNO, for joining us in a one-day intense discussion on architecture methodology and architecture propaedeutics in January 2013. This event helped us with assessing the quality of our work and also it opened our eyes to ways of improving the accessibility of this document with rather simple measures. Many of the structural changes in this manuscript were triggered by our discussion with Gerrit Muller. One of these changes is the introduction of a “red-thread” example that now nits the many parts of the IoT Architectural Reference Model (ARM) together.

Special thanks goes to Miguel-Ángel Monjas from Ericsson who, as part of the BUTLER project, did a deep analysis of the ARM, also taking into account related documents from other IoT-A work packages. He provided a large number of review comments, including for example the proposal to provide some examples for interactions between applications and different functional components to realize a use case, which we have taken up as part of the Guidelines section.

We would also like to thank Cosmin-Septimiu Nechifor from Siemens who greatly supported our reverse mapping activities in the context of the IERC AC1 discussions at NEC in Heidelberg in April 2013. Also, we would like to thank Ivana Trickovic from SAP who guided our Business Process Model and Notation extensions in a way that they have a chance of becoming part of the official standard. Patrick Garrell and Yves David from Groupe Casino have contributed significantly to the final definition of the cold chain use case that implements many of the features and architectural constructs developed in IoT-A.

Furthermore, we would like to thank Stefan Ferber for the opportunity of organizing a workshop at Bosch in Waiblingen. The attendees from different Bosch departments engaged in interesting discussions and valueable feedback towards the ARM.

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# Chapter 1

## Introduction to the Internet of Things

Thorsten Kramp, Rob van Kranenburg, and Sebastian Lange

The expression “Internet of Things” (IoT), coined back in 1999 by Kevin Ashton, the British technology pioneer who cofounded the Auto-ID Center at the Massachusetts Institute of Technology, is becoming more and more mainstream. In opening the IoT Week 2013<sup>1</sup> with a pre-recorded video message,<sup>2</sup> Ashton insisted on the realization that IoT is here *now*; it is not the *future* but the *present*. While Gartner identifies IoT as one of the top ten strategic technology trends,<sup>3</sup> Cisco forecasts 50 billion devices connected by 2020,<sup>4</sup> a potential market in excess of \$14 trillion,<sup>5</sup> and also claims that IoT is actually already here.<sup>6</sup> Similarly, it is not only companies with a technological focus, such as Ericsson, Bosch or Siemens that use IoT to advertise their cutting edge technologies – media companies such as the BBC are conducting research activities and have plans for IoT deployment. In short, we are currently on the verge of witnessing the emergence of a “mega-market”, where markets such as home and building automation, electricity generation and

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<sup>1</sup> <http://www.iot-week.eu>

<sup>2</sup> <http://kevinjashton.com/2013/06/17/pre-recorded-opening-talk-for-internet-of-things-week-helsinki-june-17-2013/>

<sup>3</sup> <http://www.gartner.com/newsroom/id/2209615>

<sup>4</sup> <http://share.cisco.com/internet-of-things.html>

<sup>5</sup> <http://iotevent.eu/cisco-sees-14-trillion-opportunity-in-iot/>

<sup>6</sup> <http://newsroom.cisco.com/press-release-content?type=webcontent&articleId=1158640>

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distribution, logistics, automotive, as well as telecommunications and information technology will steadily converge. As yet, we do not know the consequences of connecting all of these smart objects (smart meter, e-vehicle, cargo container, fridge etc.) to the Internet.<sup>7</sup>

At the same time, the Internet of Things (IoT) is not something you will experience as such itself. What you will see is that more and more objects become connected. If you are selling products, you will be negotiating with providers of connectivity. If you are building, selling or inventing models or tools for providing services or applications, you will notice that the convergence of IoT, big data and energy efficiency, combined with cheap hardware, software, data storage and analytics, favours open standards, innovation and interoperability. Daily activities that were distinct become interwoven in new formats and business models.

Thus, in effect, the Internet of Things is a combination of a technological *push* and a human *pull* for more and ever-increasing connectivity with anything happening in the immediate and wider environment – a logical extension of the computing power in a single machine to the environment: *the environment as an interface*. This push-pull combination makes it very strong, unstoppable, fast and extremely disruptive.

Mireille Hildebrandt, a Dutch professor working on the implications of emerging technologies and the rule of law, states that “we may need to develop an *Ambient Law* that is embodied in the algorithms and human machine interfaces that support Ambient Intelligence and for this we will have to break through our paralysis, ready to become literate in terms of a new script.”<sup>8</sup> In a speech to the Pittsburgh Technology Council in 2009, Eric Schmidt, an American software engineer and executive chairman of Google, focused on the negative effects of (what he called) institutional fragmentation on innovation and integration. He wondered whether governments – and the very process of policy and policymaking itself – could benefit from the iterative cycles of measuring success and failure that characterize the engineering and design prototyping cycles. With this amount of real-time tracking and aggregated data and information rather than heuristics, the act of governing itself could benefit. Specific laws could take effect for 3 months and be evaluated and adjusted and then, based on real data rather than estimates, be adjusted again. It is this process that can lead to combinatorial and system innovation.

Two dominant characteristics unite these different perspectives: firstly, a sense that Internet connectivity is becoming increasingly ubiquitous and pervasive; and secondly, the idea that eventually everything – including mundane physical artefacts – will be connected.

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<sup>7</sup> On the LinkedIn Group “Internet of Things” [strueker@iig.uni-freiburg.de](mailto:strueker@iig.uni-freiburg.de).

<sup>8</sup> Hildebrandt, Mireille and Koops, Bert-Jan, *The Challenges of Ambient Law and Legal Protection in the Profiling Era*, *Modern Law Review*, Vol. 73, Issue 3, pp. 428-460, May 2010.

**IoT Application Example 1: Transport/Logistics**

In transport logistics, IoT improves not only material flow systems but also the global positioning and automatic identification of freight. It also increases energy efficiency and thus decreases energy consumption.

In conclusion, IoT is expected to bring profound changes to the global supply chain via intelligent cargo movement. This will be achieved by means of continuous synchronisation of supply chain information and seamless real-time tracking and tracing of objects. It will make the supply chain transparent, visible and controllable, enabling intelligent communication between people and cargo/goods.

**IoT Application Example 2: The Smart Home**

Future smart homes will be conscious about what happens inside a building, mainly impacting three aspects: resource usage (water conservation and energy consumption), security and comfort. The goal is to achieve better levels of comfort while cutting overall expenditure.

Moreover, smart homes also address security issues by means of complex security systems for detecting theft, fire or unauthorized entry. The stakeholders involved in this scenario constitute a very heterogeneous group.

Different actors will cooperate in the user's home, such as Internet companies, device manufacturers, telecommunications operators, media service providers, security companies, electricity utility companies, etc.

**IoT Application Example 3: Smart Cities**

While the term smart city is still a fuzzy concept, there is general agreement that it is an urban area which creates sustainable development and high quality of life. Giffinger et al.'s model elucidates the characteristics of a smart city, encompassing economy, people, governance, mobility, environment and living.<sup>9</sup> Outperforming in these key areas can be achieved through strong human or social capital and/or ICT infrastructure. For the latter, an initial business analysis concludes that several sectors/industries will benefit from more digitalised and intelligent cities (examples for a city of one million people):<sup>10</sup>

(continued)

<sup>9</sup> [http://www.smart-cities.eu/download/smart\\_cities\\_final\\_report.pdf](http://www.smart-cities.eu/download/smart_cities_final_report.pdf)

<sup>10</sup> <http://de.slideshare.net/rlnicholson2/smart-cities-proving-ground-for-the-intelligent-economy>

**(continued)**

- (a) Smart metering, 600,000 m, \$120 million opportunity
- (b) Infrastructure for charging electric vehicles, 45,000 electric vehicles, \$225 million opportunity
- (c) Remote patient monitoring (diabetes), 70,000 people, \$14 million opportunity
- (d) Smart retail, 4,000 stores, \$200 million opportunity
- (e) Smart bank branches, 3,200 PTMs, \$160 million opportunity

**IoT Application Example 4: Smart Factory**

In a global supply chain, companies will be able to track all of their products by means of radio frequency identification (RFID) tags. As a consequence, companies will reduce their operating expenses (OPEX) and improve their productivity due to tighter integration with enterprise resource planning (ERP) and other systems. Also, maintenance of machinery will be facilitated by connected sensors, allowing for real-time monitoring of the health and performance of the factory equipment.

Generally, IoT will provide automatic procedures that imply a drastic reduction in the number of employees needed. Workers will be replaced by bar code scanners, readers, sensors and actuators, and in the end by complex robots as efficient as a human being.

Without any doubt, these technologies will bring opportunities for white-collar workers and a large number of technicians will be required to program and repair these machines. This is synonymous to a transfer to maintenance jobs, but it also constitutes a new challenge for providing all blue-collar workers with an opportunity to move toward these types of jobs and to avoid unemployment.

As the developments got closer to the market and the everyday lives of citizens, the need for non-technical research in the area of machine to machine (M2M) communication and the Internet of Things was acknowledged in the 1996 EU Call for Proposals of  $i^3$ : Intelligent Information Interfaces, an Esprit Long-Term Research initiative. The aim of  $i^3$  (pronounced “eye-cubed”) was to develop new, human-centred interfaces for interacting with information, aimed at the future broad population. This approach was also the starting point and rationale for the EU-funded proactive initiative “*The Disappearing Computer*”, a cluster of 17 projects conducted by interdisciplinary research groups. Its mission was “to see how information technology can be diffused into everyday objects and settings, and to see how this can lead to new ways of supporting and enhancing people’s lives

that go above and beyond what is possible with the computer today.”<sup>11</sup> The third research iteration of this approach was Convivio (2003–2005), a thematic network of researchers and practitioners developing a broad discipline of human-centred design of digital systems for everyday life. The coordinator of Convivio stated that human-centred design “still has little influence either on governmental and super-national policies or on industrial strategies. As a result, it also has little impact on the quality of ICT in public and private life.”<sup>12</sup>

However, in 2013, some 50 % of respondents<sup>13</sup> to a European Commission Public Consultation fell into the “interested citizen” category rather than belonging to a particular industrial, academic or other sector.<sup>14</sup>

Andreas Kirsch in the IoT Expert Group commented that the main point that emerged from the work of the subgroup on privacy was that everyone will be affected by IoT but many people will not realise it. It is vital that this realization is handled well. By default, the Internet of Things may involve function creep or have unintended consequences: “It was noted that most people use the same concepts when discussing IoT as when discussing the Internet in general. There is a significant difference, however. IoT involves objects talking to each other without user consent, with possibly un-envisaged functionalities. Cameras, for example, might take on functions that are different from their overt primary functions. These possibilities, once perceived, may cause user anxieties to rise. Moreover, what is the role of user consent if objects may be able to talk to each other spontaneously? It will be very difficult to backtrack after the deployment of million of chips employing a passive approach to connectivity.”

Privacy, security and ideas in society about data storage and tracking could stall adoption when, for example, by combining the analysis of supply and demand, energy enterprises are able to supply more efficient demand shaping. They will not just give incentives to consumers; they will actually turn off devices that are not needed (e.g. turn off the freezer for 20 min). Furthermore, these actions must take place automatically. In IoT we always face a heterogeneous scenario involving diverse stakeholders. The main actors are of course energy utility companies, but public entities will also be important players. These services need to be coupled with educational programs that explain what is happening in reality.

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<sup>11</sup> The Disappearing Computer II (DC) Proactive Initiative <http://cordis.europa.eu/ist/fet/dc2-in.htm>

<sup>12</sup> Letter to the Convivio community, Giorgio De Michelis, Convivio network coordinator, <http://daisy.cti.gr/webzine/Issues/Issue%201/Letters/index.html>

<sup>13</sup> Additional responses have been received since the last report, with the total number rising from 500 to more than 600. These additional responses did not affect the statistics for the exercise as a whole.

<sup>14</sup> Tenth Meeting of the Internet of Things Expert Group, Brussels, 14 November 2012. Tom Wachtel, rapporteur.

**IoT Application Example 5: Retail**

IoT realises both customer needs and business needs: price comparison of a product; looking for other products of the same quality at lower prices; with shop promotions, giving information not only to customers but also to shops and businesses. Having this information in real time helps enterprises to improve their business and to satisfy customer needs.

Obviously, big retail chains will take advantage of their dominant position to enforce the future IoT retail market, as was the case with RFID adoption, which was enforced by Walmart in 2004 (Wu et al. 2006). In particular, companies with controlling positions, such as Carrefour, Metro, Migros, Walmart, etc. will be able to push the adoption of IoT technology due to their sizable market shares.

**IoT Application Example 6: E-Health**

Control and prevention are two of the main goals of future health care. Already today, people have the option of being tracked and monitored by specialists even if the patient and specialist are not in the same place. Tracing peoples' health history is another aspect that makes IoT-assisted e-health very versatile. Business applications could offer the possibility of medical services not only to patients but also to specialists, who need information to proceed in their medical evaluation. In this domain, IoT makes human interaction much more efficient because it permits not only localization, but also tracking and monitoring of patients. Providing information about the state of a patient makes the whole process more efficient, and also makes people much more satisfied.

The most important stakeholders in this scenario will be public and private hospitals and institutes such as the Institute of Applied eHealth at Edinburgh Napier University, which participated in the first stakeholder session of IoT-A. It is worth mentioning that telecommunications operators are quite active in e-health (for instance, O2 UK).

The IoT Expert Group claims that, "As IoT will introduce new difficulties for contextual integrity, the principle whereby information supplied for use in one context (e.g. a meeting with one's doctor) is not expected by the owner of the data to be used in a different context (e.g. the doctor applying for a mortgage). There will be a social contract between people and objects, and the ethical ramifications of a contract of this kind must be considered".<sup>15</sup>

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<sup>15</sup> Internet of Things Expert Group (E02514), Commission Decision of 10 August 2010 setting up the Expert Group on the Internet of Things. OJ C 217, 11.8.2010, p. 10–11, <http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetail&groupID=2514>

All current computing and IoT paradigms position connectivity and content-centric networking centrally as an ecology of devices, protocols, services and networks, such as RFID, active sensors, biometrically-related smart camera data, 2D and 3D bar codes and 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks) or ZigBee. At the core of this ecology there is a seamless flow between:

- The **BAN** (body area network): e.g. the ambient hearing aide, the smart T-shirts
- The **LAN** (local area network): e.g. the smart meter as a home interface
- The **WAN** (wide area network): the bike, car, train, bus
- The **VWAN** (very wide area network): the smart city as e-government services everywhere; no longer tied to physical locations

Traceability, sustainability and security linking the gateways of these different area networks cannot be ensured without interoperability at architectural, domain-specific and application level. (see also the box on page 9 – The hierarchy of networks)

It is also highly likely that monitoring mechanisms will be built into devices themselves: for example, “if a guest is charging their electric car at a friend’s house, we should consider applications that will understand that the charge should appear on the guest’s electric bill and not that of the friend.”<sup>16</sup> But there is a clear deadlock: clients do not know what they can expect, nor do they know what they could ask.

M2M vendors cannot interface their sensor capabilities beyond an optimizing function. No one is *asking* for an Internet of Things. People have no idea about what they can expect and why they should hand over their washing machines to a local grid to ensure energy efficiency, for example. Is a positive outcome feasible?

A successful IoT means the best possible feedback on our physical and mental health, the best possible deals based on real-time monitoring for resource allocation, the best possible decision-making based on real-time data and information from open sources, and the best possible alignments of our local providers with the global potential of wider communities.

Now that we have introduced the basic ideas of the Internet of Things concept and pointed out some aspects of the current discussion taking place in the Internet of Things community, you can see that the whole field is very much “in motion”. New ideas, concepts and new technologies are appearing constantly, whereas others are disappearing, being ruled out as incompatible or not feasible. In the IoT concept, which is itself disruptive, other potential “disruptive” technologies (e.g. Google Glass etc.) strongly influence the direction of technological development as well as the related societal and political discussion.

Despite the high-level discourse that is necessary to assess the socio-economic impact of IoT in general, in this book we will focus on the underlying technological concepts, network architecture approaches and connectivity and interoperability requirements that are required to provide and realise the fundamental connectivity that will ultimately allow for the emergence of the Internet of Things to the benefit of mankind in general.

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<sup>16</sup> <http://tools.ietf.org/id/draft-roychowdhury-6lowappsip-00.txt>

With a strong focus on network architectures, architecture models and guidelines for building a truly interoperable Internet of Things, this book summarises the results of the IoT-A<sup>17</sup> project, funded by the European Union and conducted between 2010 and 2013. More than 50 scientists and researchers contributed to the development of an “Architectural Reference Model” (ARM) for the Internet of Things.

This book is in two parts (I and II). Part I (Chaps. 2, 3, 4) introduces, on a more general level, the concepts developed over the course of the IoT-A project. It is targeted at a general audience including end users who want to employ IoT technologies, managers interested in understanding the opportunities generated by the new technologies, and system architects who are interested in an overview of the models developed. In Chap. 2 we explain the history behind and origin of the IoT-A project. In Chap. 3 we introduce the ARM as enabler, its terminology and methods for employing it. Chapter 4 then highlights use cases that exemplify how the ARM has been used in real life scenarios.

Part II (Chaps. 5, 6, 7, 8, 9, 10, 11, 12) contains Chap. 5, which provides an overview on guidance to the ARM, followed by Chap. 6 with very detailed and elaborate description of a process to generate concrete architectures. In Chap. 7 the IoT Reference Model is aiming at establishing a common grounding. Based on this, in Chap. 8 the IoT Reference Architecture is presented. Chapter 9 provides reference manuals with guidelines how to use the various Models and Perspectives presented in creating a concrete architecture. In Chap. 10 an interaction analysis on some selected scenarios is given to provide a general understanding on the interactions to be considered. The best practices and guidelines relating to how system engineers or other end users can use the ARM to develop specific IoT architectures for dedicated IoT solutions and how users can apply the concepts presented to develop a dedicated IoT architecture for a specific application case are illustrated in Chap. 11 and exemplified in reverse mapping exercises of existing standards and platforms to the IoT ARM up to a business case evaluation in Chap. 12.

In contrast to Part I, Part II addresses the topic on a very scientific and technical level and is targeted at the knowledgeable scientific or technical reader.

### **IoT Application Example 7: Smart Energy/Smart Grid**

This field has many overlaps with other scenarios, such as smart home and smart city. The key issue in these scenarios is to detect ways to save energy. We are basically referring to what is known as a smart grid. In this application area, initiatives that imply a more distributed energy production must be highlighted, as many houses today have a solar panel, for example. As a vital constituent, smart metering is considered a prerequisite for enabling intelligent monitoring, control and communication in grid applications. The use of IoT platforms in smart metering will provide the following benefits:

(continued)

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<sup>17</sup> [www.iot-a.eu](http://www.iot-a.eu)

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- a. An efficient network of smart meters allows for faster outage detection and restoration of service. Such capabilities abound to the benefit of customers.
- b. Customers will have greater control over their energy or water consumption, providing them with more choices for managing their bills.
- c. IoT deployment of smart meters is expected to reduce the need for building power plants. Building power plants that are necessary only for occasional peak demand is very expensive: a more economical approach is to enable customers to reduce their demand through time-based rates or other incentive programs, or to use automatic recording of consumption to temporarily turn off devices which are not in use.

Finally, by combining the analysis of supply and demand, energy enterprises will be able to supply more efficient demand shaping. They will not just give incentives to consumers, but will actually turn off devices that are not needed (e.g. turn off the freezer for 20 min). Furthermore, these actions must take place automatically. Here, we again face a heterogeneous scenario involving diverse stakeholders. The main actors are of course energy utility companies, but public entities will also be important players.

**The Hierarchy of Networks: BAN (Body Area Network): The Ambient Hearing Aide, the Smart T-shirts**

Control and prevention are two of the main goals of future health care. Already today, people have the option of being tracked and monitored by specialists even if patient and specialist are not in the same place. Tracing peoples' health history is another aspect that makes IoT-assisted e-health very versatile. Business applications could offer the possibility of medical services not only to patients but also to specialists, who need information to proceed in their medical evaluation. In this domain, IoT makes human interaction much more efficient because it permits not only localization, but also tracking and monitoring of patients. Providing information about the state of a patient makes the whole process more efficient, and also makes people much more satisfied. Trust is a key issue in this relationship. Patient to patient networks become more empowered as well.

**LAN (local area network): the smart meter as a home interface**

Future smart homes will be conscious about what happens inside a building, mainly impacting three aspects: resource usage (water conservation and energy consumption), security and comfort. The goal is to achieve better levels of comfort while cutting overall expenditure. Moreover, smart homes

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also address security issues by means of complex security systems to detect theft, fire or unauthorized entry. The stakeholders involved in this scenario constitute a very heterogeneous group. Different actors will cooperate in the user's home, such as Internet companies, device manufacturers, telecommunications operators, media service providers, security companies, electricity utility companies, etc.

**WAN (wide area network): the bike, car, train, bus, . . .**

In transport logistics, IoT improves not only material flow systems but also global positioning and automatic identification of freight. It also increases energy efficiency and thus decreases energy consumption.

Prof. Dr. Michael ten Hompel, Managing Director at Fraunhofer-Institut for "Materialfluss und Logistik", describes the consequences for something as "solid" as logistics: "The logical consequence of the Internet of Things is not just a new philosophy of how we can control our production and logistics. It completely changes the paradigms of conventional supply chain management. Within the Internet of Things the supply chain will be created in real time: *Entities*, consisting of objects and a piece of (agent based) software, generates the resulting supply chain 'on the move.' Therefore the sequences of operations are not predicted. This leads to a new understanding of how to handle our logistic management which won't be a supply chain (!) anymore."

IoT is thus expected to bring profound changes to the global supply chain via intelligent cargo movement. This will be achieved by means of continuous synchronisation of supply chain information and seamless real-time tracking and tracing of objects. It will make the supply chain transparent, visible and controllable, enabling intelligent communication between people and cargo.

**VWAN (very wide area network): the smart city as e-government services *everywhere*; no longer tied to physical locations**

While the term smart city is still a fuzzy concept, there is general agreement that it is an urban area which creates sustainable development and high quality of life. Giffinger et al.'s model elucidates the characteristics of a smart city, encompassing economy, people, governance, mobility, environment and living (Giffinger 2007). Outperforming in these key areas can be achieved through strong human or social capital and/or ICT infrastructure. There are a number of critics who question whether the smart city as it is conceived now can be inclusive and educational.

**Part I**  
**General Concepts of the Architecture**  
**Reference Model (ARM)**

# Chapter 2

## The Need for a Common Ground for the IoT: The History and Reasoning Behind the IoT-A Project

Alessandro Bassi and Sebastian Lange

The Internet of Things concept has evolved rapidly in recent years. It can be seen as an umbrella term for interconnected technologies, devices, objects and services. Nevertheless, after many years of heavy discussion, there is still no clear and common definition of the concept. And yet the application scenarios and market opportunities offered by objects communicating actively and autonomously extend far beyond the foreseeable horizon.

Looking at websites such as [kickstarters.com](http://kickstarters.com) and [indiegogo.com](http://indiegogo.com), new applications and services envisaged by innovators and researchers are astonishing and clearly show the vast opportunities our future society will be confronted with.

The concept of IoT as introduced in Chap. 1 emerged primarily from the convergence of different technological developments and fields. In particular, it builds on the emergence of innovative enabling functionalities that stem from identification technologies such as RFID and bar codes, as well as from the development of networked sensors and actuators. In the early 2000s, RFID technology was developed and rolled out mainly across the logistics sector for tracking and tracing goods. At the same time, research was conducted on sensor networks and miniaturized smart systems. Sensors were becoming increasingly small and computing power dramatically increased. Nevertheless, innovative solutions were always developed for specific application cases, and there was no true interoperability and interconnectivity between different application areas.

For instance, in some fields such as manufacturing and logistics, communication and tagging solutions are well-established as they provide a clear business benefit in terms of asset tracking and supply chain management. However, the same solutions

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do not apply for other fields such as domotics, where business synergies could provide services with clear added-value benefits.

As the IoT domain covers such a wide spectrum of application fields with very little in common, the development cycles and technologies used can be completely different. Often, early technological developments are driven by visionary small and medium-sized enterprises (SME) that are able to innovate faster and to catch emerging trends. However, the target is usually a product or service with a narrow scope, and as the focus and window of opportunity are slim, the solutions developed are usually non-interoperable, and while successful, they do not produce a common abstract infrastructure capable of marking significant progress in the whole field. The same holds true for large industry companies that often develop specialized solutions for dedicated business opportunities without implementing generally applicable concepts.

Therefore, current solutions can still be seen as island solutions, implementing some sort of “**INTRAnet of Things**” rather than an “**INTERNet of Things**”.

While quite logical at this point, in the long term, this situation is unsustainable. Today, we can observe a similar situation to that in the networking field, where several solutions emerged at its infancy but were subsequently abandoned in favour of a unified communication infrastructure, the **TCP/IP protocol suite**.

The emergence of a common “lingua franca” for the IoT domain, representing the narrow central point in the Internet protocol suite, is a prerequisite for quick and pervasive development of innovative solutions that can leverage different technologies developed for different targets in different application domains.

After much discussion about the core concepts of the IoT for several years, in 2009 a group of researchers from more than 20 large industrial companies and research institutions joined forces to lay the foundation for the much needed common ground or a common “architecture” for the Internet of Things: the **IoT-Architecture project (IoT-A)** was born. IoT-A has become the European Commission’s flagship project in the European Union’s Seventh Framework Program for Research and Development with respect to establishing an architecture for the Internet of Things.

Leaving aside business considerations, and considering only the technical point of view, it was clear for the project partners that the existing solutions did not address the scalability requirements of a future IoT, both in terms of communication between smart devices and the orchestration and management of complex services. Furthermore, the IoT domain comprises several different governance models, which are often incompatible. This leads to a situation where privacy and security are treated on a per case and per legislation basis, retrofitting solutions to existing designs – this severely hampers portability, interoperability and deployment.

Of course, the spread of the IoT domain is so huge that it would be naive to consider a “one-size-fits-all” protocol, such as IP, or even a single layer where interoperability between all sorts of smart device communication can take place. However, it soon became clear that within this area, there was a need for a common ground in a more abstract layer.

We are convinced that different classes of devices will always co-exist. Taxonomies can be created according to different principles, such as critical or non-critical, or distributed or centralised. These classes can foster different profiles according to the specific needs and requirements of applications and domains.

As it is impossible to specify one single design pattern that can satisfy all application domains, the common ground has to be found at a more abstract level. We believe that the identification of a **reference model for the entire IoT domain** will provide the common ground. By **reference model** we mean an abstract framework that comprises a minimal set of unifying concepts, axioms and relationships for understanding significant relationships between the entities of an environment. This framework should enable the development of specific architectures which may have different levels of abstraction. At this level of abstraction we are independent of specific standards, technologies, implementations, or other concrete details.

This high-level work then drives the realisation of a framework for identifying specific **reference architectures** that subsequently describe both essential building blocks as well as design choices for dealing with conflicting requirements regarding functionality, performance, deployment and security. Interfaces need to be standardised, and best practices need to be provided in terms of functionality and information usage.

The central decision of the IoT-A project was to base its work on the current state of the art, rather than applying a clean slate approach. As a result, common traits have been derived to form the baseline of the **IoT Architectural Reference Model (ARM)**. This has the major advantage of ensuring that the model is backward-compatible, as well as the adoption of established, working solutions for various aspects of the IoT.

It is no longer possible to build architectures in the lab or without real world input. IoT-A acknowledged this new reality, where the lines between R&D, innovation and emergent technologies are blurred, at a very early stage. With the help of end users, organised into the IoT-A stakeholders group, new requirements for IoT have been collected and introduced in the main model-building process. This stakeholder group was one of the most important sources for obtaining external input as well as feedback on the current status of project work. Thus far, the stakeholder contributions have been a main feature of the project, as the stakeholder requirements collected in an initial workshop formed the basis for the initial draft of the ARM, particularly the domain model and the functional decomposition. Each building block of the ARM was then developed to meet all requirements and enable the IoT-A holistic approach. Further stakeholder workshops and questionnaires were employed to review the progress of the ARM development and to fine tune the concepts and models.

Currently, the prevailing practice domain for stakeholder engagement is largely characterized by complex and dynamic environments that cover a wide range of stakeholders, from hostile to conciliatory, from obstructive to collaborative.

This is an apt characterisation of the Internet of Things: complex and dynamic environments containing a wide range of stakeholders. As such, it is an open and

ongoing ecology of environments, characterized by change and real-time combinatorial innovation.

For all their different backgrounds – automotive, health, logistics, retail. . . – the stakeholders were surprised to see that their requirements were often very similar. In their real world cases, the same principles and same abstract level required that “in this IoT world things become active participants”; the goal is a seamless chain of real-time tracking and tracing, in which the elite of expensive high-level item tracking and the multitude of low-level items should be balanced for cost efficiency. Interoperability was validated by the stakeholders in the independently generated use cases as the number one requirement.

The next chapter introduces the ARM in detail, its language and terminology, as well as its beneficial role in the IoT application development process.

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# Chapter 3

## The IoT Architectural Reference Model as Enabler

Martin Bauer and Joachim W. Walewski

As identified in the previous chapter, IoT-A has created an “Architectural Reference Model” (IoT ARM) as the common ground for the Internet of Things. The core idea is that the IoT ARM provides a common structure and guidelines for dealing with core aspects of developing, using and analysing IoT systems. The first part of this chapter provides a non-exclusive list of the beneficial uses of the IoT ARM. In the second part we focus on the role of the IoT ARM in the architecture development process.

### 3.1 Using the IoT ARM

In the following we present a non-exclusive list of the beneficial uses of the IoT ARM. The order in which they are discussed does not imply any ranking – we list them according to their degree of abstraction and remoteness from the product: i.e. the first usage type is concerned more with generic enabling (abstract and remote), while the last usage type concerns how the IoT ARM can be used for procuring system solutions (concrete, close to business). The usage type that is more important to any specific use of the IoT ARM depends on the perspective of the actors involved. A manager of an IoT development process, for instance, is more likely to favour the enabling aspects of the IoT ARM, while a procurement department is more likely to favour concrete advantages that are closer to the business process itself.

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### ***3.1.1 Cognitive Aid***

When it comes to product development and other activities, an architectural reference model is of fourfold use.

Firstly, it helps to guide discussions, since it provides a language everyone involved can use, and which is intimately linked to the architecture, the system, the usage domain, etc.

Secondly, the high-level view provided in such a model is of high educational value, since it provides an abstract but also rich view of the domain. Such a view can help people new to the field to “find their way” and to understand the special features and intricacies of IoT.

Thirdly, the IoT ARM can assist IoT project leaders in planning the work at hand and the teams needed. For instance, the Functionality Groups identified in the IoT Functional View of the IoT system can also be understood as a list of independent teams working on an IoT system implementation. The Process Chapter (Chap. 6) provides more insight on how the IoT ARM can support the architecture generation process and also about how to separate it into different activity “islands”. This type of approach is particularly interesting for enterprise architecture frameworks that incorporate system-architecting processes. Typically, these enterprise frameworks provide institutional rules and prescriptions for how the system-architecting process is to be conducted. The IoT ARM can inform such institutional rules and prescriptions. An example of the latter is the Zachman framework (Zachman 1987).

Fourthly, the IoT ARM helps to identify independent building blocks for IoT systems. This constitutes very valuable information when dealing with questions such as system modularity, processor architectures, third-vendor options, re-use of components already developed, etc.

### ***3.1.2 Reference Model as a Common Ground***

Establishing a common ground for a field is not an easy task. In order to be effective, it has to capture as many pertinent vantage points as possible. Establishing the common ground for the IoT encompasses defining IoT entities and describing their basic interactions and relationships with each other. The IoT ARM provides exactly such a common ground for the IoT field.

### ***3.1.3 Generating Architectures***

One of the main benefits is the use of the IoT ARM for generating compliant architectures for specific systems. This is done by providing best practices and

guidance for translating the IoT ARM into concrete architectures. For an overview on this, see Chap. 5. The benefit of this type of generation scheme for IoT architectures is not only a certain degree of automation in this process, and thus lower R&D efforts, but also that the decisions made follow a clear, documented pattern as described in Chap. 6.

### ***3.1.4 Identifying Differences in Derived Architectures***

When using the aforementioned IoT ARM-based architecture process, any differences in the derived architectures can be attributed to the special features of the use case in question and the design choices related to this case (Shames and Yamada 2004). When applying the IoT ARM, a list of system function blocks, data models, etc., together with predictions of system complexity, etc. can be derived for the architecture generated. Furthermore, the IoT ARM defines a set of tactics and design choices for meeting qualitative system requirements (for more details, see Chap. 6, Design choices). All of these facts can be used to predict whether two derived architectures will differ and where they will do so.

The IoT ARM can also be used for reverse mapping. System architectures can be cast in the “IoT ARM” language and the resulting “translation” of the system architectures is then stripped of incompatible language and system partitions and mappings. The differences that remain are then true differences in architecture.

### ***3.1.5 Achieving Interoperability***

As we explain later on in this book (see Chap. 6 on design choices), fulfilling qualitative requirements through the architecting process inevitably leads to design challenges. Since there is usually more than one solution to each of the design challenges (we refer to these solutions as design choices), the IoT ARM cannot guarantee interoperability between any two concrete architectures, even if they have been derived from the same requirement set. Nevertheless, it is an important tool in helping to achieve interoperability between IoT systems. This is facilitated by the design-choice process itself. During this process, one identifies and tallies the design choices made. By comparing the design choices made when deriving two architectures, one can readily identify where in the architecture measures are necessary to achieve interoperability. Interoperability may be achieved a posteriori by integrating one IoT system as subsystem in another system, or by building a bridge through which key functionalities of the respective other IoT system can be used. Notice though that these workarounds often fall short of achieving full interoperability. Nevertheless, building bridges between such systems is typically much more straightforward than completely re-designing either system and usually fair interoperability can be achieved.

### ***3.1.6 System Roadmaps and Product Life Cycles***

Above we discussed how the design choices made in order to derive a particular architecture, and also the features selected, are instrumental in describing the difference between two architectures. As well as identifying the differences between two “foreign” architectures, this approach can also be used to map the evolution of architectures. For instance, design choices are tied to qualitative requirements. Let us assume that during the requirements process (see Chap. 6, Sect. 6.4), two disjoint “design choice” islands are identified, i.e. groups of design choices that lead to non-interdependent functionalities, data models, etc. In this case, it is possible to embody only one “design choice” island in the systems produced and to embody the full set of design choices in the next product generation. Thus, the IoT ARM can be used to devise system roadmaps that lead to minimum changes between two product generations while still guaranteeing a noticeable enhancement in system capability and features. This approach also helps the designer to formulate clear and standardised, requirements-based rationales for the system roadmap chosen and the product life cycles that result from the system roadmap.

### ***3.1.7 Benchmarking***

Another important use of the IoT ARM is benchmarking. For example, NASA used a reference architecture that described its envisaged exploration vehicle in order to receive better benchmarking tenders during a public bidding process for the said exploration vehicle (Tamblyn et al. 2007). While the reference model prescribed the language to be used in the systems/architectures to be assessed, the reference architecture stated the minimum (functional) requirements for the systems/architectures. By standardising the description and also the ordering and delineation of system components and aspects, this approach also provided the benchmarking process with a high level of transparency and inherent comparability. Using this approach, besides just “ticking” off the minimum features each tender has to fulfil, even more insight can be gained into the proposed system. For instance, the number and “richness” of functional components belonging to the system and their interaction patterns allow an appreciation of the system complexity both in terms of composition and structure but also in terms of interaction. This information can be gleaned from the IoT Functional View (functional decomposition, interactions), the IoT Information View (data flow, data complexity) and the IoT Deployment View. It makes judging the overall system complexity easier during the tender review phase.