6LoWPAN: The Wireless Embedded Internet

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6LoWPAN

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Foreword

You are holding (or perhaps reading online or in an e-book) a remarkable volume. I have been a proponent of IPv6 and an enthusiastic adopter of sensor networks for some time. I am using a commercially available 6LoWPAN system to monitor my home and especially the wine cellar. You may imagine my positive reaction to the book you are reading now. It is stunningly thorough and takes readers meticulously through the design, configuration and operation of IPv6-based, low-power, potentially mobile radio-based networking.

In reading through this book, I was struck also by the thoughtful framing of issues that reach beyond the specifics of 6LoWPAN and go to the heart of many aspects of Internet protocol design. For example, general problems, such as packet fragmentation, are explained in the context of the standard Internet protocols and then, more particularly, in the context of 6LoWPAN. This technique helps to place issues into broader contexts and takes advantage of knowledge that readers may have already of the Internet Architecture.

Sensor network utility seems to me indisputable and consequently, this book has wide-ranging implications for anyone thinking about the proliferation of sensor networks, the need for significant address space to support them, and their integration into the present IPv4 Internet and the future IPv6 Internet. The special requirements imposed by battery-powered operation, radio-based communication and potentially mobile operation motivate the need for books of this caliber. Whoever said "the devil is in the details" might well have had 6LoWPAN in mind!

I found the sections on mobility particularly helpful and the term "micro-mobility" especially illuminating. Mobility in the Internet's design has long been a problem area and I had been puzzled by this since the original Internet included two mobile packet radio networks (in the San Francisco Bay area and Fort Bragg, North Carolina). It is clear that the mobility conferred by these networks was confined to mobility *within* a given packet radio system, in other words, micro-mobility as defined by the authors. That's the easy kind. The hard kind is when the IP address of the mobile node has to change to reflect a new topological access point into the Internet. It is that kind of mobility that has not been well served by present-day Internet protocols. There is still much work to be done to handle this better. The need for a *Home Agent* is a reflection of the awkwardness of IP mobility in general. The 6LoWPAN design does the best it can to deal with this, within the present-day IPv6 architecture.

Routing in low-power, lossy environments has been taken up by the ROLL working group in the Internet Engineering Task Force. In addition, the Mobile Ad-Hoc Network (MANET) working group has also tackled aspects of this problem. These sections of the book are extremely valuable for their pedagogical utility to say nothing of the practical consideration they give to this vexing problem area.

I found the sections on Applications (Chapter 5) especially interesting since that is where all the real action is. Figure 5.3 is a beautiful example of using simple diagrams to localize problem areas and issues. This chapter highlighted for me the importance of matching the applications to the underlying capability of the network(s) through which the application must operate. If end-to-end connectivity is not guaranteed, applications need to incorporate awareness of this if they are to operate successfully and effectively, for example. Blindly layering protocols accustomed to reliable, speedy and sequenced delivery on critical network components that cannot provide such guarantees will generally produce unsatisfactory results.

As we enter into a period where sensors networks become an integral part of energy management, building automation, and other applications, it is highly desirable to standardize application infrastructure to enable interoperability among systems from many vendors. In Chapter 5, we encounter ideas that enable the experience obtained from the proprietary ZigBee space to be adapted to operate in the UDP/IP/6LoWPAN space. It is encouraging to see such efforts at synthesizing commonality to increase interoperability and to enable competitive offerings. The so-called CAP protocol is the key element at work and strikes me as an important contribution to the Internet protocol library. The chapter finishes with a very useful compendium and summary of a variety of proprietary protocols that ultimately will have to be adapted to work in a more standard Internet environment to be broadly useful.

The convergence of ZigBee protocols with Internet-oriented ones, in the 6LoWPAN context, and the creation of the IP for Smart Objects (IPSO) alliance are healthy indications that the ad hoc solutions for low-power networking are beginning to coalesce into interoperable designs that can become the core of the Internet of Things. I cannot see all the ramifications of this emerging consensus but it is fair to say that it will deliver an information-rich environment in which to invent new applications and provide feedback that will enable wiser choices leading to an environmentally smarter society.

Vint Cerf
Vice-president and Chief Internet Evangelist, Google

Preface

The *Internet of Things* is considered to be the next big opportunity, and challenge, for the Internet engineering community, users of technology, companies and society as a whole. It involves connecting embedded devices such as sensors, home appliances, weather stations and even toys to Internet Protocol (IP) based networks. The number of IP-enabled embedded devices is increasing rapidly, and although hard to estimate, will surely outnumber the number of personal computers (PCs) and servers in the future. With the advances made over the past decade in microcontroller, low-power radio, battery and microelectronic technology, the trend in the industry is for smart embedded devices (called smart objects) to become IP-enabled, and an integral part of the latest services on the Internet. These services are no longer cyber, just including data created by humans, but are to become very connected to the physical world around us by including sensor data, the monitoring and control of machines, and other kinds of physical context. We call this latest frontier of the Internet, consisting of wireless low-power embedded devices, the *Wireless Embedded Internet*. Applications that this new frontier of the Internet enable are critical to the sustainability, efficiency and safety of society and include home and building automation, healthcare, energy efficiency, smart grids and environmental monitoring to name just a few.

Standards for the Internet are set by the Internet Engineering Task Force (IETF). A new set of IETF standards for IPv6 over low-power wireless area networks (6LoWPAN) will be a key technology for the Wireless Embedded Internet. Originally WPAN stood for wireless Personal area network, a term inherited from IEEE 802.15.4, which is no longer descriptive for the wide range of applications for 6LoWPAN. In this book we use the term low-power wireless area network (LoWPAN). This book is all about 6LoWPAN, giving a complete overview of the technology, its application, related standards along with real-life deployment and implementation considerations. The low-power networking industry, from ZigBee ad hoc control to industrial automation standards like ISA100, is quickly converging to the use of IP technology, and IPv6 in particular. 6LoWPAN plays an important role in this convergence of heterogeneous technologies, interest groups and applications behind Internet technology.

This book is meant to be an introduction and reference to understanding and applying 6LoWPAN for use by experts in embedded systems, networking or Internet applications, by both undergrad and postgrad engineering students as well as by lecturers. The book has been designed, along with its accompanying material, to be directly used as the basis for an intensive short course on 6LoWPAN, or as a module in a full course.

Please visit the official web-site of the book at http://6lowpan.net. There you will find accompanying material for the book, including course material and 6LoWPAN programming exercises. An interactive 6LoWPAN blog by the authors, along with other 6LoWPAN material is also available at the site. We would love to hear your comments, ideas and advice.

In order to get the most out of this book it is recommended that the reader has background understanding of the Internet architecture [RFC1958, RFC3439], IPv6 [RFC2460, RFC4291, RFC4861] along with wireless communication basics. The book makes wide use of references to Internet Engineering Task Force (IETF) Request For Comments (RFC) [RFCxxxx] and Internet-Draft (I-D) [ID-xx-xx-xx] documents, which are accessible freely and easily at http://www.ietf.org. Keep in mind that Internet-Drafts are a work in progress as part of the IETF standardization process, and change frequently before possibly becoming an RFC.

The book is organized as follows. Chapter 1 gives an overview of the Wireless Embedded Internet, 6LoWPAN and its architecture. Chapter 2 introduces the 6LoWPAN format, features and addressing in detail, and explains how it works in practice. Chapter 3 looks at bootstrapping 6LoWPAN networks using Neighbor Discovery, and security issues related to these networks. Chapter 4 looks at the important topic of mobility issues and routing, both inside 6LoWPAN networks and with the Internet. Application protocols are considered in Chapter 5. Finally implementation issues related to using 6LoWPAN in embedded devices and routers are covered in Chapter 6 and several examples of systems using 6LoWPAN are given in Chapter 7 including the ISA100 standard. Conclusions and future challenges are discussed in Chapter 8. For ease of reference, appendices are included with basic information on IPv6 (Appendix A) and IEEE 802.15.4 (Appendix B).

As telecommunications and Internet engineering is a mine field of special terminology, many terms often conflicting, we have included a glossary of the most important terms for understanding the subject as a reference at the end of the book. The relevant IETF documents also include terminology sections in the beginning which can be useful for understanding.

Finally, we make use of IETF style packet header diagrams, which for historical and practical reasons are (even today) drawn using ASCII art! This makes it much easier for the reader to reference IETF documents for further reading on protocol details. An explanation of this format is included in Appendix A.

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We would first like to thank the people that have collaborated with us on this book. Special acknowledgment goes to Geoff Mulligan, co-chair of the 6LoWPAN working group at the IETF and chairman of the IPSO Alliance, who has collaborated with us since the beginning of this project. Geoff was key in encouraging and helping develop the concept for the book, provided comments on the manuscript and contributed Section 7.1 (ISA100 Industrial Automation) of the book. We give thanks to Anthony Schoofs, Oliver Laumann, Pascal Thubert, and Vint Cerf, who have given us very helpful comments during the preparation of the manuscript.

The good people at Wiley have been critical for making this a smooth project. We especially thank Tiina Ruonamaa for giving us the courage to turn a rough idea into a book proposal and finally a book.

The unique culture and resourceful constituency of the Internet Engineering Task Force have made this technology possible in the first place, and have given both of us great experiences over the years. We would like to thank the dedicated and highly motivated people in the 6LoWPAN and ROLL working groups, who have spent the past few years, and several GB of email traffic, developing the concepts and protocols for 6LoWPAN. We would especially like to thank Dominique Barthel, Anders Brandt, Ian Chakeres, Samita Chakrabarti, David Culler, Mischa Dohler, Carles Gomez, Jonathan Hui, Dominik Kaspar, Eunsook "Eunah" Kim, Nandakishore Kushalnagar, Philip Levis, Jerry Martocci, Gabriel Montenegro, Bob Moskowitz, Charlie Perkins, Kris Pister, Anthony Schoofs, Pascal Thubert, JP Vasseur, Thomas Watteyne and Tim Winter. Carsten would like to single out the support he got, and the immense technical input, from IETF area directors Thomas Narten, Margaret Wasserman, Mark Townsley, Jari Arkko, and most recently Ralph Droms, from the 6LoWPAN WG advisor Erik Nordmark and 6LoWPAN WG secretary Christian Peter Pii Schumacher, and especially (again) from his esteemed co-chair Geoff Mulligan.

Zach would like to thank his colleagues at Sensinode, the Center for Wireless Communications, the Technical Research Center of Finland and in the SENSEI project. The people active in the IP Smart Object Alliance also deserve thanks; IPSO has been great for the success of embedded IP in the marketplace. He would especially like to thank Prof. Petri Mähonen and Prof. Carlos Pomalaza-Raez for bringing him under their wings and for their endless encouragement and inspiration. He sends warm thanks to his family, especially to his wife Sari for putting up with this project, and two little girls Selna and Alme who already expect embedded gadgets to do anything possible. Special thanks to Marketta, without whose help this book would not have been possible.

Carsten would like to thank his colleagues at Universität Bremen TZI and at the companies NetCS, Tellique and Lysatiq for sharpening his view on what is a viable, implementable and successful protocol and for fostering the space in which this work could prosper. He especially would like to thank Prof. Jörg Ott, with whom he has had many extremely rewarding interactions about protocol design. Infinite thanks to Prof. Ute Bormann, who has helped him on so many levels, both as a colleague at TZI and as a wonderful wife.

1

Introduction

The Internet has been a great success over the past 20 years, growing from a small academic network into a global, ubiquitous network used regularly by over 1.4 billion people. It was the power of the Internet paradigm, tying heterogeneous networks together, and the innovative World Wide Web (WWW) model of uniform resource locators (URLs), the hypertext transfer protocol (HTTP) and universal content markup with the hypertext markup language (HTML) that made this possible. Grass-roots innovation has however been the most powerful driver behind the Internet success story. The Internet is open to innovation like no other telecommunication system before it. This has allowed all groups involved, from Internet architects to communication engineers, IT staff and everyday users to innovate, quickly adding new protocols, services and uses for Internet technology.

As the Internet of routers, servers and personal computers has been maturing, another Internet revolution has been going on – *The Internet of Things*. The vision behind the Internet of Things is that embedded devices, also called *smart objects*, are universally becoming IP enabled, and an integral part of the Internet. Examples of embedded devices and systems using IP today range from mobile phones, personal health devices and home automation, to industrial automation, smart metering and environmental monitoring systems. The scale of the Internet of Things is already estimated to be immense, with the potential of trillions of devices becoming IP-enabled. The impact of the Internet of Things will be significant, with the promise of better environmental monitoring, energy savings, smart grids, more efficient factories, better logistics, better healthcare and smart homes.

The Internet of Things revolution started in the 1990s with industrial automation systems. Early proprietary networks in industrial automation were quickly replaced by different forms of industrial Ethernet, and Internet protocols became widely used between embedded automation devices and back-end systems. This trend has continued in all other automation segments, with Ethernet and IP becoming ubiquitous. Machine-to-machine (M2M) telemetry made a breakthrough already in the early 2000s, with the use of cellular modems and IP to monitor and control a wide range of equipment from vending machines to water pumps. Building automation systems have gone from legacy control to making wide use of wired IP communications through the *Building Automation and Control Network* (BACnet) and

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Open Building Information Exchange (oBIX) standards. More recently, automatic metering infrastructures and smart grids are being deployed at a rapid rate, largely depending on the scalability and universal availability of IP technology. Finally, mobile phones have become almost universally IP-enabled embedded devices currently making up the largest body of devices belonging to the Internet of Things.

An equally important development has been happening in the services that are used to monitor and control embedded devices. Today these services are almost universally built on Internet technology, and more commonly are implemented using web-based services. *Web Service* technologies have completely changed the way business and enterprise applications are designed and deployed. It is this combination of Internet-connected embedded devices and Web-based services which makes the Internet of Things a powerful paradigm.

Hundreds of millions of embedded devices are already IP-enabled, but the Internet of Things is still in its infancy in 2009. Although the capabilities of processor, power and communications technology have continuously increased, so has the complexity of communications standards, protocols and services. Thus, so far, it has been possible to use Internet capabilities in only the most powerful embedded devices. Additionally, low-power wireless communications limits the practical bandwidth and duty-cycle available. Throughout the 1990s and early 2000s we have seen a large array of proprietary low-power embedded wireless radio and networking technologies. This has fragmented the market and slowed down the deployment of such technology.

The Institute of Electrical and Electronics Engineers (IEEE) released the 802.15.4 low-power wireless personal area network (WPAN) standard in 2003, which was a major milestone, providing the first global low-power radio standard. Soon after, the ZigBee Alliance developed a solution for ad hoc control networks over IEEE 802.15.4, and has produced a lot of publicity about the applications of wireless embedded technology. ZigBee and proprietary networking solutions that are vertically bound to a link-layer and application profiles only solve a small portion of the applications for wireless embedded networking. They also have problems with scalability, evolvability and Internet integration. A new paradigm was needed to enable low-power wireless devices with limited processing capabilities (see Figure 1.1) to participate in the Internet of Things, forming what we call the *Wireless Embedded Internet*.

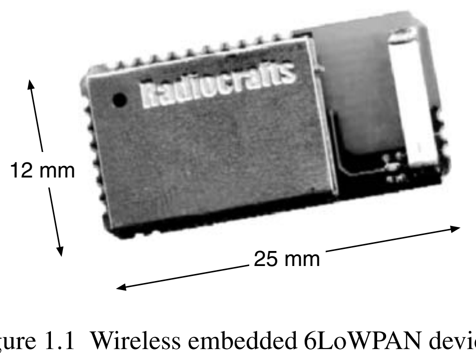

Figure 1.1 Wireless embedded 6LoWPAN device.

This book introduces a set of Internet standards which enable the use of *IPv6 over low-power wireless area networks* (6LoWPAN)[1], which is the key to realizing the Wireless Embedded Internet. 6LoWPAN breaks down the barriers to using IPv6 in low-power, processing-limited embedded devices over low-bandwidth wireless networks. IPv6, which is the newest version of the Internet Protocol, was developed in the late 1990s as a solution to the rapid growth and challenges facing the Internet. The further growth of the Internet of Things will be made possible thanks to IPv6.

In this chapter we give an overview of 6LoWPAN. First the Internet of Things is introduced, followed by the ideas behind 6LoWPAN, IETF standardization, related trends and applications of 6LoWPAN technology in Section 1.1. The overall 6LoWPAN architecture is then introduced in Section 1.2. A comprehensive overview of 6LoWPAN basic mechanisms and the link-layer are given in Section 1.3, followed by a 6LoWPAN network example in Section 1.4.

1.1 The Wireless Embedded Internet

What is the Internet of Things in practice? Maybe the simplest definition is that the Internet of Things encompasses all the embedded devices and networks that are natively IP-enabled and Internet-connected, along with the Internet services monitoring and controlling those devices. Figure 1.2 shows an illustration of the Internet of Things vision.

Today's Internet is made up of a *core Internet* of backbone routers and servers, including millions of nodes (any kind of network device) in total. The core Internet changes rarely and has extremely high capacity. The vast majority of today's Internet nodes are in what is sometimes called the *fringe Internet*. The fringe Internet includes all the personal computers, laptops and local network infrastructure connected to the Internet. This fringe changes rapidly, and is estimated to have up to a billion nodes. In 2008 it was estimated that the Internet had approximately 1.4 billion regular users, and Google announced that over a *trillion* unique URLs existed in their search indexes. The growth of the fringe is dependent on the number of Internet users and the personal devices used by them. The Internet of Things, sometimes referred to as the *embedded fringe*, is the biggest challenge and opportunity for the Internet today. It is made up of the IP-enabled embedded devices connected to the Internet, including sensors, machines, active positioning tags, radio-frequency identification (RFID) readers and building automation equipment to name but a few. The exact size of the Internet of Things is hard to estimate, as its growth is not dependent on human users. It is assumed that the Internet of Things will soon exceed the rest of the Internet in size (number of nodes) and will continue growing at a rapid rate. The long-term potential size of the Internet of Things is in trillions of devices. The greatest growth potential in the future comes from embedded, low-power, wireless devices and networks that until now have not been IP-enabled – the Wireless Embedded Internet. In 2008 the IP Smart Objects (IPSO) Alliance [IPSO] was formed by industry leaders to promote the use of Internet protocols by smart objects and the Internet of Things through marketing, education and interoperability.

The Wireless Embedded Internet is a subset of the Internet of Things, and the main subject of this book. We define the Wireless Embedded Internet to include resource-limited

[1] The 6LoWPAN acronym has been redefined on purpose in this book, as "Personal" is no longer relevant to the technology. WPAN originally referred to IEEE 802.15.4 Wireless Personal Area Network.