

# 6LoWPAN: The Wireless Embedded Internet

**Zach Shelby**

*Sensinode, Finland*

**Carsten Bormann**

*Universität Bremen TZI, Germany*



A John Wiley and Sons, Ltd, Publication



6LoWPAN

## WILEY SERIES IN COMMUNICATIONS NETWORKING & DISTRIBUTED SYSTEMS

Series Editor: David Hutchison, *Lancaster University, Lancaster, UK*  
Serge Fdida, *Université Pierre et Marie Curie, Paris, France*  
Joe Sventek, *University of Glasgow, Glasgow, UK*

The 'Wiley Series in Communications Networking & Distributed Systems' is a series of expert-level, technically detailed books covering cutting-edge research, and brand new developments as well as tutorial-style treatments in networking, middleware and software technologies for communications and distributed systems. The books will provide timely and reliable information about the state-of-the-art to researchers, advanced students and development engineers in the Telecommunications and the Computing sectors.

### Titles in the series:

Wright: *Voice over Packet Networks* 0-471-49516-6 (February 2001)  
Jepsen: *Java for Telecommunications* 0-471-49826-2 (July 2001)  
Sutton: *Secure Communications* 0-471-49904-8 (December 2001)  
Stajano: *Security for Ubiquitous Computing* 0-470-84493-0 (February 2002)  
Martin-Flatin: *Web-Based Management of IP Networks and Systems* 0-471-48702-3 (September 2002)  
Berman, Fox, Hey: *Grid Computing. Making the Global Infrastructure a Reality* 0-470-85319-0 (March 2003)  
Turner, Magill, Marples: *Service Provision. Technologies for Next Generation Communications* 0-470-85066-3 (April 2004)  
Welzl: *Network Congestion Control: Managing Internet Traffic* 0-470-02528-X (July 2005)  
Raz, Juhola, Serrat-Fernandez, Galis: *Fast and Efficient Context-Aware Services* 0-470-01668-X (April 2006)  
Heckmann: *The Competitive Internet Service Provider* 0-470-01293-5 (April 2006)  
Dressler: *Self-Organization in Sensor and Actor Networks* 0-470-02820-3 (November 2007)  
Berndt: *Towards 4G Technologies: Services with Initiative* 0-470-01031-2 (March 2008)  
Jacquet, Bourdon, Boucadair: *Service Automation and Dynamic Provisioning Techniques in IP/MPLS Environments* 0-470-01829-1 (March 2008)  
Minei/Lucek: *MPLS-Enabled Applications: Emerging Developments and New Technologies, Second Edition* 0-470-98644-1 (April 2008)  
Gurtov: *Host Identity Protocol (HIP): Towards the Secure Mobile Internet* 0-470-99790-7 (June 2008)  
Boucadair: *Inter-Asterisk Exchange (IAX): Deployment Scenarios in SIP-enabled Networks* 0-470-77072-4 (January 2009)  
Fitzek: *Mobile Peer to Peer (P2P): A Tutorial Guide* 0-470-69992-2 (June 2009)  
Shelby: *6LoWPAN: The Wireless Embedded Internet* 0-470-74799-4 (November 2009)  
Stavdas: *Core and Metro Networks* 0-470-51274-1 (February 2010)

# 6LoWPAN: The Wireless Embedded Internet

**Zach Shelby**

*Sensinode, Finland*

**Carsten Bormann**

*Universität Bremen TZI, Germany*



A John Wiley and Sons, Ltd, Publication

This edition first published 2009  
© 2009 John Wiley & Sons Ltd

*Registered office*

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ,  
United Kingdom.

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at [www.wiley.com](http://www.wiley.com).

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

*Library of Congress Cataloging-in-Publication Data*

Shelby, Zach.

6LoWPAN : the wireless embedded internet / Zach Shelby and Carsten Bormann.  
p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-74799-5 (cloth)

1. Wireless Internet. 2. Wireless communication systems—Standards. 3. Low voltage systems. I. Bormann, Carsten. II. Title.

TK5103.4885.S52 2009

621.384—dc22

2009026837

A catalogue record for this book is available from the British Library.

ISBN 9780470747995 (H/B)

Set in 10/12pt Times by Sunrise Setting Ltd, Torquay, UK.

Printed in Great Britain by Antony Rowe, Chippenham, Wiltshire.

# Contents

<b>List of Figures</b>	<b>ix</b>
<b>List of Tables</b>	<b>xiii</b>
<b>Foreword</b>	<b>xv</b>
<b>Preface</b>	<b>xvii</b>
<b>Acknowledgments</b>	<b>xix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 The Wireless Embedded Internet . . . . .	3
1.1.1 Why 6LoWPAN? . . . . .	4
1.1.2 6LoWPAN history and standardization . . . . .	6
1.1.3 Relation of 6LoWPAN to other trends . . . . .	8
1.1.4 Applications of 6LoWPAN . . . . .	9
1.1.5 Example: facility management . . . . .	11
1.2 The 6LoWPAN Architecture . . . . .	13
1.3 6LoWPAN Introduction . . . . .	15
1.3.1 The protocol stack . . . . .	16
1.3.2 Link layers for 6LoWPAN . . . . .	17
1.3.3 Addressing . . . . .	19
1.3.4 Header format . . . . .	20
1.3.5 Bootstrapping . . . . .	20
1.3.6 Mesh topologies . . . . .	22
1.3.7 Internet integration . . . . .	23
1.4 Network Example . . . . .	24
<b>2 The 6LoWPAN Format</b>	<b>27</b>
2.1 Functions of an Adaptation Layer . . . . .	28
2.2 Assumptions About the Link Layer . . . . .	29
2.2.1 Link-layer technologies beyond IEEE 802.15.4 . . . . .	29
2.2.2 Link-layer service model . . . . .	30
2.2.3 Link-layer addressing . . . . .	31
2.2.4 Link-layer management and operation . . . . .	32

2.3	The Basic 6LoWPAN Format . . . . .	32
2.4	Addressing . . . . .	34
2.5	Forwarding and Routing . . . . .	37
2.5.1	L2 forwarding (“Mesh-Under”) . . . . .	38
2.5.2	L3 routing (“Route-Over”) . . . . .	40
2.6	Header Compression . . . . .	41
2.6.1	Stateless header compression . . . . .	43
2.6.2	Context-based header compression . . . . .	45
2.7	Fragmentation and Reassembly . . . . .	52
2.7.1	The fragmentation format . . . . .	55
2.7.2	Avoiding the fragmentation performance penalty . . . . .	59
2.8	Multicast . . . . .	59
<b>3</b>	<b>Bootstrapping and Security</b>	<b>63</b>
3.1	Commissioning . . . . .	64
3.2	Neighbor Discovery . . . . .	66
3.2.1	Forming addresses . . . . .	67
3.2.2	Registration . . . . .	69
3.2.3	Registration collisions . . . . .	73
3.2.4	Multihop registration . . . . .	77
3.2.5	Node operation . . . . .	80
3.2.6	Router operation . . . . .	81
3.2.7	Edge router operation . . . . .	82
3.3	Security . . . . .	83
3.3.1	Security objectives and threat models . . . . .	84
3.3.2	Layer 2 mechanisms . . . . .	85
3.3.3	Layer 3 mechanisms . . . . .	87
3.3.4	Key management . . . . .	89
<b>4</b>	<b>Mobility and Routing</b>	<b>91</b>
4.1	Mobility . . . . .	92
4.1.1	Mobility types . . . . .	92
4.1.2	Solutions for mobility . . . . .	94
4.1.3	Application methods . . . . .	96
4.1.4	Mobile IPv6 . . . . .	97
4.1.5	Proxy Home Agent . . . . .	100
4.1.6	Proxy MIPv6 . . . . .	100
4.1.7	NEMO . . . . .	102
4.2	Routing . . . . .	104
4.2.1	Overview . . . . .	104
4.2.2	The role of Neighbor Discovery . . . . .	107
4.2.3	Routing requirements . . . . .	108
4.2.4	Route metrics . . . . .	109
4.2.5	MANET routing protocols . . . . .	111
4.2.6	The ROLL routing protocol . . . . .	114
4.2.7	Border routing . . . . .	119



4.3	IPv4 Interconnectivity . . . . .	120
4.3.1	IPv6 transition . . . . .	121
4.3.2	IPv6-in-IPv4 tunneling . . . . .	122
<b>5</b>	<b>Application Protocols</b>	<b>125</b>
5.1	Introduction . . . . .	126
5.2	Design Issues . . . . .	127
5.2.1	Link layer . . . . .	129
5.2.2	Networking . . . . .	130
5.2.3	Host issues . . . . .	130
5.2.4	Compression . . . . .	131
5.2.5	Security . . . . .	131
5.3	Protocol Paradigms . . . . .	132
5.3.1	End-to-end . . . . .	132
5.3.2	Real-time streaming and sessions . . . . .	132
5.3.3	Publish/subscribe . . . . .	133
5.3.4	Web service paradigms . . . . .	134
5.4	Common Protocols . . . . .	134
5.4.1	Web service protocols . . . . .	135
5.4.2	MQ telemetry transport for sensor networks (MQTT-S) . . . . .	137
5.4.3	ZigBee compact application protocol (CAP) . . . . .	139
5.4.4	Service discovery . . . . .	141
5.4.5	Simple network management protocol (SNMP) . . . . .	142
5.4.6	Real-time transport and sessions . . . . .	143
5.4.7	Industry-specific protocols . . . . .	144
<b>6</b>	<b>Using 6LoWPAN</b>	<b>149</b>
6.1	Chip Solutions . . . . .	150
6.1.1	Single-chip solutions . . . . .	150
6.1.2	Two-chip solutions . . . . .	151
6.1.3	Network processor solutions . . . . .	151
6.2	Protocol Stacks . . . . .	152
6.2.1	Contiki and uIPv6 . . . . .	153
6.2.2	TinyOS and BLIP . . . . .	153
6.2.3	Sensinode NanoStack . . . . .	154
6.2.4	Jennic 6LoWPAN . . . . .	155
6.2.5	Nivis ISA100 . . . . .	155
6.3	Application Development . . . . .	156
6.4	Edge Router Integration . . . . .	159
<b>7</b>	<b>System Examples</b>	<b>163</b>
7.1	ISA100 Industrial Automation . . . . .	164
7.1.1	Motivation for industrial wireless sensor networks . . . . .	164
7.1.2	Complications of the industrial space . . . . .	165
7.1.3	The ISA100.11a standard . . . . .	166
7.1.4	ISA100.11a data link layer . . . . .	169

7.2	Wireless RFID Infrastructure . . . . .	170
7.2.1	Technical overview . . . . .	172
7.2.2	Benefits from 6LoWPAN . . . . .	173
7.3	Building Energy Savings and Management . . . . .	174
7.3.1	Network architecture . . . . .	174
7.3.2	Technical overview . . . . .	174
7.3.3	Benefits from 6LoWPAN . . . . .	175
<b>8</b>	<b>Conclusion</b>	<b>177</b>
<b>A</b>	<b>IPv6 Reference</b>	<b>181</b>
A.1	Notation . . . . .	181
A.2	Addressing . . . . .	182
A.3	IPv6 Neighbor Discovery . . . . .	184
A.4	IPv6 Stateless Address Autoconfiguration . . . . .	188
<b>B</b>	<b>IEEE 802.15.4 Reference</b>	<b>191</b>
B.1	Introduction . . . . .	191
B.2	Overall Packet Format . . . . .	192
B.3	MAC-layer Security . . . . .	194
	<b>List of Abbreviations</b>	<b>195</b>
	<b>Glossary</b>	<b>203</b>
	<b>References</b>	<b>209</b>
	<b>Index</b>	<b>219</b>

# List of Figures

1.1	Wireless embedded 6LoWPAN device . . . . .	2
1.2	The Internet of Things vision . . . . .	4
1.3	The relation of 6LoWPAN to related standards and alliances . . . . .	7
1.4	Example of a personal fitness monitoring application . . . . .	10
1.5	Example of an industrial safety application . . . . .	11
1.6	An example of a facility management system including an automatic metering infrastructure (AMI) . . . . .	12
1.7	The 6LoWPAN architecture . . . . .	14
1.8	IP and 6LoWPAN protocol stacks . . . . .	16
1.9	IPv6 edge router with 6LoWPAN support . . . . .	17
1.10	6LoWPAN header compression example . . . . .	21
1.11	6LoWPAN/UDP compressed headers (6 bytes) . . . . .	21
1.12	Standard IPv6/UDP headers (48 bytes) . . . . .	22
1.13	A 6LoWPAN example . . . . .	24
2.1	Uncompressed IPv6 packet with 6LoWPAN header . . . . .	33
2.2	Composition of an EUI-64 . . . . .	35
2.3	Composition of an IPv6 address from an EUI-64: U is the inverted L bit . . . . .	36
2.4	Interface identifier for 16-bit short addresses . . . . .	37
2.5	The IP routing model . . . . .	38
2.6	The LoWPAN routing model (L3 routing, “Route-Over”) . . . . .	38
2.7	DLL mesh forwarding below the LoWPAN adaptation layer . . . . .	39
2.8	LoWPAN adaptation layer mesh forwarding . . . . .	39
2.9	Mesh addressing type and header . . . . .	40
2.10	Hop-by-hop header compression with two different header compression methods . . . . .	42
2.11	HC1-compressed IPv6 packet: without and with HC2 . . . . .	43
2.12	IPv6 header: non-address fields . . . . .	44
2.13	Best-case HC1-/HC2-compressed IPv6 packet . . . . .	46
2.14	LOWPAN_IPHC header . . . . .	47
2.15	LOWPAN_IPHC traffic class and flow label compression . . . . .	48
2.16	LOWPAN_NHC base header for UDP . . . . .	50
2.17	LOWPAN_NHC base header for IPv6 extension headers . . . . .	50
2.18	LOWPAN_NHC port number compression . . . . .	51
2.19	Best-case LOWPAN_IPHC IPv6 packet . . . . .	52
2.20	Globally routable best-case LOWPAN_IPHC IPv6 packet . . . . .	52

2.21	Fragmentation fields in the IPv4 Header . . . . .	53
2.22	IPv6 fragment header . . . . .	55
2.23	Non-initial 6LoWPAN fragment . . . . .	56
2.24	Initial 6LoWPAN fragment . . . . .	56
2.25	The LOWPAN_BC0 broadcast header . . . . .	60
2.26	IP multicast address to 16-bit short address mapping . . . . .	61
3.1	6LoWPAN information option . . . . .	68
3.2	Router Advertisement dissemination . . . . .	68
3.3	6LoWPAN summary option . . . . .	69
3.4	Basic router discovery and registration process with an edge router . . . . .	70
3.5	Node registration/confirmation message format . . . . .	70
3.6	Address option format . . . . .	71
3.7	Example: Node Registration with two address options . . . . .	73
3.8	Example: Node Confirmation with two address options . . . . .	74
3.9	Example: the second address option in a refresh NR message . . . . .	74
3.10	The transaction ID (TID) sequence number lollipop . . . . .	76
3.11	Router performing ICMP relay on the NR/NC messages . . . . .	78
3.12	The registration process: multihop operation . . . . .	78
3.13	Extended LoWPAN operation as a binding moves to a new edge router . . . . .	83
3.14	Owner interface identifier option . . . . .	83
3.15	Encapsulating security payload (ESP) packet format . . . . .	88
3.16	ESP payload encrypted with AES/CCM . . . . .	89
4.1	An industrial asset management application where mobility is common . . . . .	92
4.2	The difference between micro-mobility and macro-mobility . . . . .	94
4.3	Network mobility example . . . . .	95
4.4	Example of Mobile IPv6 used with 6LoWPAN . . . . .	99
4.5	Example of a proxy Home Agent located on an edge router . . . . .	101
4.6	Example of PMIPv6 with 6LoWPAN . . . . .	102
4.7	Example of the basic NEMO protocol working with 6LoWPAN . . . . .	103
4.8	Stack view of forwarding inside the LoWPAN and across the edge router . . . . .	105
4.9	Topology view of forwarding inside the LoWPAN and across the edge router . . . . .	106
4.10	Example of reactive distance-vector routing . . . . .	113
4.11	The ROLL architecture . . . . .	117
4.12	Examples of upstream and downstream forwarding with ROLL . . . . .	118
4.13	Border routing example . . . . .	121
4.14	Configured IPv6-in-IPv4 tunneling example . . . . .	123
5.1	Applications process communication occurs through Internet sockets . . . . .	126
5.2	The relationship of common IP protocols . . . . .	128
5.3	Application design issues to consider and where they occur in a LoWPAN . . . . .	129
5.4	End-to-end and proxied application protocol paradigms . . . . .	133
5.5	Typical structure of web service content over HTTP/TCP . . . . .	135
5.6	The MQTT-S architecture used over 6LoWPAN . . . . .	138
5.7	The MQTT-S message structure . . . . .	138

5.8	The CAP protocol stack . . . . .	140
5.9	The RTP base header . . . . .	143
6.1	An example embedded device using a modular two-chip (MSP430+CC2420) design . . . . .	149
6.2	Single-chip solution architecture . . . . .	150
6.3	Two-chip solution architecture . . . . .	151
6.4	Network processor solution architecture . . . . .	152
6.5	The Contiki architecture . . . . .	154
6.6	The NanoStack architecture . . . . .	155
6.7	Example use of a socket-like API . . . . .	157
6.8	Edge router with a 6LoWPAN network interface . . . . .	160
7.1	The ISA100 network architecture . . . . .	168
7.2	Forwarding at the link-layer through the ISA100 protocol stack . . . . .	168
7.3	The Idesco Cardea system architecture . . . . .	171
7.4	The wireless communications between Cardea components . . . . .	173
7.5	The typical network architecture of a LessTricity deployment . . . . .	175
7.6	The Jennic 6LoWPAN stack with the LessTricity application . . . . .	176
A.1	IPv6 packet header . . . . .	181
A.2	IPv6 packet header in box notation . . . . .	182
A.3	IPv6 link-local address . . . . .	183
A.4	IPv6 global unicast address . . . . .	183
A.5	IPv6 multicast address . . . . .	184
A.6	Flag values for IPv6 multicast addresses . . . . .	184
A.7	General format of ICMPv6 messages . . . . .	185
A.8	General format of an ICMPv6 message option . . . . .	185
A.9	IPv6 Router Advertisement message . . . . .	186
A.10	IPv6 Router Solicitation message . . . . .	187
A.11	IPv6 ND prefix information option . . . . .	187
B.1	Overall structure of the IEEE 802.15.4 data packet . . . . .	193
B.2	The security subheader in an IEEE 802.15.4 data packet . . . . .	194



# List of Tables

2.1	The two most-significant bits in the dispatch byte . . . . .	33
2.2	Current and proposed dispatch byte allocations . . . . .	35
2.3	Address ranges for 16-bit short addresses . . . . .	37
2.4	HC1 SAE and DAE values . . . . .	44
2.5	HC1 NH values . . . . .	44
2.6	S/SAM values, and D/DAM values when $M = 0$ . . . . .	49
2.7	EID values in LOWPAN_NHC base header . . . . .	49
2.8	D/DAM values for $M = 1$ . . . . .	61
3.1	Information content of a Node Registration binding . . . . .	75
3.2	Processing rules for NR messages . . . . .	77
4.1	Non-exhaustive summary of requirements identified for ROLL . . . . .	110
4.2	Routing metrics identified for ROLL . . . . .	111
7.1	Classes of sensor and control applications . . . . .	166
A.1	IPv6 addresses in hexadecimal notation . . . . .	183
A.2	Scope values for IPv6 multicast addresses . . . . .	184
B.1	Frequency ranges and channels for IEEE 802.15.4 . . . . .	192
B.2	Fields in the fixed header/trailer of the IEEE 802.15.4 data packet . . . . .	193
B.3	Addressing modes in the IEEE 802.15.4 MAC header . . . . .	193
B.4	Key identifier modes (KIM) in the IEEE 802.15.4 security subheader . . . . .	194
B.5	Security level (LVL) in the IEEE 802.15.4 security subheader . . . . .	194





# 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.

Zach Shelby and Carsten Bormann  
*Sensinode, Finland and Universität Bremen TZI, Germany*

# Acknowledgments

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 Mähönen 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, Telligence 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

*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*.

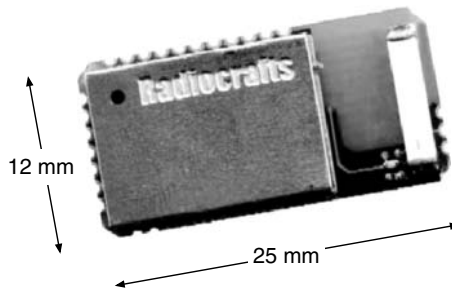


Figure 1.1 Wireless embedded 6LoWPAN device.



This book introduces a set of Internet standards which enable the use of *IPv6 over low-power wireless area networks* (6LoWPAN)<sup>1</sup>, 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

---

<sup>1</sup>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.