Interconnecting Smart Objects with IP
Interconnecting Smart Objects with IP
The Next Internet

Jean-Philippe Vasseur
Adam Dunkels
Dedication

To the best gift life offered me: my wife Bojilte, who gave me three exceptional children: Nana, Eleonore and Louis, who I love so much. I would also like to dedicate this book to my wonderful parents.

J.P. Vassar

Dedicated to my wonderful wife Mania and our three fantastic sons Morgan, Castor, and Olof - you bring so much love into my life!

/ADAM
About the Authors

_JP Vasseur_ is a Cisco Distinguished Engineer where he works on IP/MPLS architecture specifications, focusing on IP, Traffic Engineering, network recovery and Sensor networks. Before joining Cisco, he worked for several Service Providers in large multi-protocol environments. He is an active member of the IETF (co-author of more than 30 IETF RFCs/Drafts), co-chair of the IETF PCE (Path Computation Element) and the ROLL (Routing Over Low power and Lossy networks (ROLL) Working Groups. JP is also the chair of the Technology Advisory Board of the IPSO (IP for Smart Object Alliance). JP is a regular speaker at various international conferences, he is involved in various research projects in the area of IP/Sensor Networks and the member of a number of Technical Program Committees. He has filed a number of patents in the area of IP/MPLS and Sensor Networks. He is the coauthor of “Network Recovery” (Morgan Kaufmann, July 2004) and “Definitive MPLS Network Designs” (Cisco Press, March 2005).

_Adam Dunkels_, PhD, is a senior scientist at the Swedish Institute of Computer Science where he has worked with IP networking for embedded and low-power wireless systems for eight years. He is the author of the open source Contiki operating system for networked embedded devices and the open source uIP and lwIP embedded TCP/IP stacks that are currently used in thousands of embedded systems in space, on earth, and on the seven seas. He has authored over 40 papers on embedded IP, wireless sensor networks and embedded programming, and has received prestigious awards for his work. Adam has also developed the Operating System for Smart object that become a de-facto standard.
# Contents

Foreword............................................................................................................................................. xvii  
Preface.................................................................................................................................................. xix  
Acknowledgements........................................................................................................................... xxiii

## PART 1 THE ARCHITECTURE

### CHAPTER 1 What Are Smart Objects? .............................................................. 3
  1.1 Where Do Smart Objects Come From? ................................................................. 4  
      1.1.1 Embedded Systems ............................................................................................. 6  
      1.1.2 Ubiquitous and Pervasive Computing ................................................................. 7  
      1.1.3 Mobile Telephony ............................................................................................... 9  
      1.1.4 Telemetry and Machine-to-machine Communication ........................................... 10  
      1.1.5 Wireless Sensor and Ubiquitous Sensor Networks ........................................... 11  
      1.1.6 Mobile Computing ............................................................................................ 12  
      1.1.7 Computer Networking ....................................................................................... 13  
  1.2 Challenges for Smart Objects ..................................................................................... 14  
      1.2.1 Node-level Challenges ...................................................................................... 15  
      1.2.2 Network-level Challenges ................................................................................. 15  
      1.2.3 Standardization .................................................................................................. 18  
      1.2.4 Interoperability .................................................................................................. 19  
  1.3 Conclusions ................................................................................................................ 19

### CHAPTER 2 IP Protocol Architecture .............................................................. 21
  2.1 Introduction ................................................................................................................ 21  
  2.2 From NCP to TCP/IP ................................................................................................. 21  
  2.3 Fundamental TCP/IP Architectural Design Principles .............................................. 22  
  2.4 The Delicate Subject of Cross-layer Optimization .................................................... 25  
  2.5 Why Is IP Layering also Important for Smart Object Networks? ............................. 27  
  2.6 Conclusions ................................................................................................................ 28

### CHAPTER 3 Why IP for Smart Objects? ........................................................... 29
  3.1 Interoperability .......................................................................................................... 30  
  3.2 An Evolving and Versatile Architecture .................................................................... 32  
  3.3 Stability and Universality of the Architecture ........................................................... 33  
  3.4 Scalability .................................................................................................................. 34
3.5 Configuration and Management ................................................................. 34
3.6 Small Footprint ....................................................................................... 35
3.7 What Are the Alternatives? ...................................................................... 36
3.8 Why Are Gateways Bad? .......................................................................... 37
  3.8.1 Inherent Complexity ......................................................................... 37
  3.8.2 Lack of Flexibility and Scalability ................................................... 38
3.9 Conclusions ............................................................................................. 38

CHAPTER 4 IPv6 for Smart Object Networks and the Internet of Things .......... 39
  4.1 Introduction ............................................................................................ 39
  4.2 The Depletion of the IPv4 Address Space ............................................. 41
    4.2.1 Current IPv4 Address Pool Exhaustion Rate .................................... 42
  4.3 NAT: A (Temporary) Solution to IPv4 Address Exhaustion .................... 45
  4.4 Architectural Discussion ........................................................................ 47
  4.5 Conclusions ............................................................................................ 48

CHAPTER 5 Routing ...................................................................................... 51
  5.1 Routing in IP Networks .......................................................................... 51
    5.1.1 IP Routing and QoS ......................................................................... 51
    5.1.2 IP Routing and Network Reliability ................................................ 53
  5.2 Specifics of Routing in LLNs .................................................................. 54
    5.2.1 What Makes the Routing in LLNs Different? .................................... 55
  5.3 Layer 2 Versus Layer 3 “Routing” .......................................................... 58
    5.3.1 Where Should Path Computation Be Performed? ........................... 58
  5.4 Conclusions ............................................................................................ 62

CHAPTER 6 Transport Protocols ................................................................. 63
  6.1 UDP ........................................................................................................ 63
    6.1.1 Best-effort Datagram Delivery ......................................................... 63
    6.1.2 The UDP Header ............................................................................. 64
  6.2 TCP .......................................................................................................... 64
    6.2.1 Reliable Stream Transport .............................................................. 65
    6.2.2 The TCP Header ............................................................................. 67
    6.2.3 TCP Options ................................................................................... 68
    6.2.4 Round-trip Time Estimation ............................................................ 68
    6.2.5 Flow Control .................................................................................. 69
    6.2.6 Congestion Control ....................................................................... 69
    6.2.7 TCP States ..................................................................................... 70
  6.3 UDP for Smart Objects ............................................................................ 72
  6.4 TCP for Smart Objects ............................................................................ 73
  6.5 Conclusions ............................................................................................ 74
CHAPTER 7  Service Discovery ................................................................. 75
 7.1 Service Discovery in IP Networks ..................................................... 76
 7.2 Service Discovery Protocols .............................................................. 76
    7.2.1 SLP ......................................................... 76
    7.2.2 Zeroconf, Rendezvous, and Bonjour ........................................... 78
    7.2.3 UPnP ...................................................... 78
 7.3 Conclusions .................................................................................. 79

CHAPTER 8  Security for Smart Objects .................................................. 81
 8.1 The Three Properties of Security ...................................................... 82
    8.1.1 Confidentiality .................................................. 82
    8.1.2 Integrity ....................................................... 83
    8.1.3 Availability .................................................... 83
 8.2 “Security” by Obscurity ................................................................. 83
 8.3 Encryption .................................................................................. 84
 8.4 Security Mechanisms for Smart Objects ......................................... 86
    8.4.1 Security Policies for Smart Objects ............................................ 86
    8.4.2 Link Layer Encryption ......................................................... 87
 8.5 Security Mechanisms in the IP Architecture ................................... 88
    8.5.1 IPsec ......................................................... 88
    8.5.2 TLS ......................................................... 89
 8.6 Conclusions .................................................................................. 89

CHAPTER 9  Web Services for Smart Objects .......................................... 91
 9.1 Web Service Concepts ................................................................. 92
    9.1.1 Common Data Formats ...................................................... 94
    9.1.2 Representational State Transfer .............................................. 95
 9.2 The Performance of Web Services for Smart Objects ...................... 98
    9.2.1 Implementation Complexity .................................................. 98
    9.2.2 Performance ......................................................... 100
 9.3 Pachube: A Web Service System for Smart Objects ...................... 102
    9.3.1 Interaction Model ....................................................... 104
    9.3.2 Pachube Data Formats ..................................................... 105
    9.3.3 HTTP Requests ....................................................... 106
    9.3.4 HTTP Return Codes ...................................................... 106
    9.3.5 Authentication and Security ................................................ 107
    9.3.6 Triggers ......................................................... 108
 9.4 Conclusions .................................................................................. 108

CHAPTER 10  Connectivity Models for Smart Object Networks ............... 111
 10.1 Introduction .............................................................................. 111
 10.2 Autonomous Smart Object Networks Model .................................. 111
PART 2 THE TECHNOLOGY

CHAPTER 11 Smart Object Hardware and Software.................................119
  11.1 Hardware ...............................................................................................119
    11.1.1 Communication Device .................................................................121
    11.1.2 Microcontroller ..............................................................................122
    11.1.3 Sensors and Actuators .................................................................123
    11.1.4 Power Sources ..............................................................................123
    11.1.5 Outlook: Systems on a Chip, Printed Electronics, and Claytronics..125
  11.2 Software for Smart Objects .................................................................127
    11.2.1 Operating Systems for Smart Objects ............................................128
    11.2.2 Multi-threaded Versus Event-driven Programming .....................132
    11.2.3 Memory Management ..................................................................135
    11.2.4 Outlook: Macroprogramming, Java .............................................137
  11.3 Energy Management ............................................................................138
    11.3.1 Radio Power Management Mechanisms ......................................140
    11.3.2 Asynchronous Duty Cycling .......................................................141
    11.3.3 Synchronous Duty Cycling .............................................143
    11.3.4 Examples of Radio On-times ......................................................144
  11.4 Conclusions .........................................................................................144

CHAPTER 12 Communication Mechanisms for Smart Objects..............147
  12.1 Communication Patterns for Smart Objects .......................................147
    12.1.1 One-to-one Communication .......................................................148
    12.1.2 One-to-many Communication .....................................................148
    12.1.3 Many-to-one Communication .....................................................149
  12.2 Physical Communication Standards ..............................................151
  12.3 IEEE 802.15.4 ..........................................................152
    12.3.1 802.15.4 Addresses .................................................................153
    12.3.2 The 802.15.4 Physical Layer ......................................................154
    12.3.3 MAC Layer ..................................................................................156
    12.3.4 The 802.15.4 Frame Format ......................................................156
    12.3.5 Power Consumption .................................................................157
  12.4 IEEE 802.11 and WiFi ..............................................................158
    12.4.1 Network Topology and Formation ............................................159
    12.4.2 Physical Layer ..............................................................................160
    12.4.3 MAC Layer ..................................................................................160
    12.4.4 Low-power WiFi ........................................................................161
12.5 PLC .................................................................................................................................................. 163
12.5.1 Physical Layer.............................................................................................................................. 164
12.5.2 MAC Layer .................................................................................................................................. 164
12.5.3 Power Consumption .................................................................................................................. 165
12.6 Conclusions ..................................................................................................................................... 165

CHAPTER 13 uIP — A Lightweight IP Stack .................................................................................. 167
13.1 Principles of Operation .................................................................................................................... 169
13.1.1 Input Processing ............................................................................................................................. 169
13.1.2 Output Processing .......................................................................................................................... 173
13.1.3 Periodic Processing ....................................................................................................................... 174
13.1.4 Packet Forwarding .......................................................................................................................... 174
13.2 uIP Memory Buffer Management ................................................................................................... 175
13.3 uIP Application Program Interface ............................................................................................... 176
13.4 uIP Protocol Implementations ......................................................................................................... 178
13.4.1 IP Fragment Reassembly ............................................................................................................. 179
13.4.2 TCP .................................................................................................................................................. 179
13.4.3 Checksum Calculations ................................................................................................................. 180
13.5 Memory Footprint ............................................................................................................................. 181
13.6 Conclusions ..................................................................................................................................... 181

CHAPTER 14 Standardization ........................................................................................................ 183
14.1 Introduction ...................................................................................................................................... 183
14.2 The IETF ........................................................................................................................................... 184
14.2.1 The IETF Mission .......................................................................................................................... 184
14.2.2 The IETF Organization ................................................................................................................ 185
14.2.3 IETF Standard Tracks .................................................................................................................. 186
14.2.4 The IETF Standard Process ......................................................................................................... 188
14.2.5 The IAB ........................................................................................................................................... 189
14.3 IETF Working Groups Related to IP for Smart Objects ................................................................. 191
14.3.1 The IPv6 Over Low-power WPAN Working Group ................................................................. 192
14.3.2 The ROLL Working Group ......................................................................................................... 193
14.4 Conclusions ..................................................................................................................................... 198

CHAPTER 15 IPv6 for Smart Object Networks — A Technology Refresher .......... 199
15.1 IPv6 for Smart Object Networks? ................................................................................................. 199
15.2 The IPv6 Packet Headers ................................................................................................................. 200
15.2.1 IPv6 Fixed Header ....................................................................................................................... 200
15.2.2 Extended Headers ........................................................................................................................ 201
15.2.3 The Hop-by-hop Option Header .................................................................................................. 202
15.2.4 The Routing Header .................................................................................................................... 202
15.2.5 The Fragment Header .................................................................................................................. 203
15.2.6 The Destination Option Header .................................................................................................. 205
15.2.7 The No Next Header .................................................................................................................... 205
**Contents**

15.3 IPv6 Addressing Architecture ................................................................. 206  
15.3.1 Notion of Unicast, Anycast, and Multicast ........................................ 206  
15.3.2 Representation of IPv6 Addresses ......................................................... 206  
15.3.3 Unicast Addresses ............................................................................... 207  
15.3.4 Anycast Addresses ............................................................................... 209  
15.3.5 Multicast Addresses ............................................................................ 210  
15.4 The ICMP for IPv6 .................................................................................. 211  
15.4.1 ICMPv6 Error Messages ..................................................................... 212  
15.4.2 ICMP Informational Messages .............................................................. 212  
15.5 Neighbor Discovery Protocol ................................................................. 212  
15.5.1 The Neighbor Solicitation Message ...................................................... 214  
15.5.2 The NA Message ................................................................................ 214  
15.5.3 The Router Advertisement Messages .................................................. 215  
15.5.4 The Router Solicitation Message ......................................................... 218  
15.5.5 The Redirect Message ....................................................................... 219  
15.5.6 Neighbor Unreachability Detection (NUD) ........................................ 219  
15.6 Load Balancing ....................................................................................... 219  
15.7 IPv6 Autoconfiguration ........................................................................... 220  
15.7.1 Building the Link-local Address .......................................................... 220  
15.7.2 The Stateless Autoconfiguration Process ........................................... 220  
15.7.3 Privacy Extensions for Stateless Address Autoconfiguration in IPv6 .... 223  
15.8 DHCPv6 .................................................................................................. 224  
15.8.1 Stateful Autoconfiguration ................................................................. 224  
15.8.2 Stateless DHCP ................................................................................. 225  
15.9 IPv6 QoS .................................................................................................. 225  
15.9.1 The Diffserv Model ......................................................................... 225  
15.9.2 The IntServ Model ......................................................................... 226  
15.10 IPv6 over an IPv4 Backbone Network .................................................. 227  
15.11 IPv6 Multicast ....................................................................................... 228  
15.11.1 IPv6 Multicast Addressing ................................................................. 230  
15.12 Conclusions ........................................................................................ 230  

CHAPTER 16 The 6LoWPAN Adaptation Layer .............................................. 231  
16.1 Terminology ........................................................................................... 231  
16.2 The 6LoWPAN Adaptation Layer ........................................................... 232  
16.2.1 The Mesh Addressing Header .............................................................. 234  
16.2.2 Fragmentation ................................................................................... 237  
16.2.3 6LoWPAN Header Compression ......................................................... 237  
16.3 Conclusions ........................................................................................... 250  

CHAPTER 17 RPL Routing in Smart Object Networks ..................................... 251  
17.1 Introduction ............................................................................................ 251  
17.2 What Is a Low-power and Lossy Network? ............................................. 251  
17.3 Routing Requirements ............................................................................. 252
## Contents

### 17.4 Routing Metrics in Smart Object Networks
- 17.4.1 Aggregated Versus Recorded Routing Metrics .......................................................... 255
- 17.4.2 Local Versus Global Metrics .................................................................................. 256
- 17.4.3 The Routing Metrics/Constraints Common Header ........................................... 256
- 17.4.4 The Node State and Attributes Object .................................................................... 256
- 17.4.5 Node Energy Object .............................................................................................. 257
- 17.4.6 Hop-count Object .................................................................................................... 257
- 17.4.7 Throughput Object .................................................................................................. 257
- 17.4.8 Latency Object ....................................................................................................... 257
- 17.4.9 Link Reliability Object .......................................................................................... 257
- 17.4.10 Link Colors Attribute ......................................................................................... 258

### 17.5 The Objective Function ......................................................................................... 258

### 17.6 RPL: The New Routing Protocol for Smart Object Networks ...................... 259
- 17.6.1 Protocol Overview ............................................................................................... 259
- 17.6.2 Use of Multiple DODAG and the Concept of RPL Instance ................................. 263
- 17.6.3 RPL Messages ........................................................................................................ 263
- 17.6.4 RPL DODAG Building Process ........................................................................... 267
- 17.6.5 Movements of a Node Within and Between DODAGs ......................................... 270
- 17.6.6 Populating the Routing Tables Along the DODAG Using DAO Messages ...................................................... 271
- 17.6.7 Loop Avoidance and Loop Detection Mechanisms in RPL ..................................... 273
- 17.6.8 Global and Local Repair ....................................................................................... 276
- 17.6.9 Routing Adjacency with RPL ................................................................................ 280
- 17.6.10 RPL Timer Management ...................................................................................... 280
- 17.6.11 Simulation Results ............................................................................................... 282

### 17.7 Conclusions ............................................................................................................ 287

### CHAPTER 18 The IP for Smart Object Alliance ...................................................... 289
- 18.1 Mission and Objectives of the IPSO Alliance ......................................................... 289
- 18.2 IPSO Organization .................................................................................................... 291
- 18.3 A Key Activity of the IPSO Alliance: Interoperability Testing ................................. 292
- 18.4 Conclusions .............................................................................................................. 294

### CHAPTER 19 Non-IP Smart Object Technologies .................................................... 295
- 19.1 ZigBee ...................................................................................................................... 295
  - 19.1.1 ZigBee Device Types ......................................................................................... 296
  - 19.1.2 Layers in the ZigBee Stack ................................................................................ 297
  - 19.1.3 PHY and MAC Layers ...................................................................................... 298
  - 19.1.4 NWK ................................................................................................................ 298
  - 19.1.5 APS Sublayer .................................................................................................... 299
  - 19.1.6 AF ..................................................................................................................... 299
  - 19.1.7 Network Setup ............................................................................................... 300
  - 19.1.8 ZigBee Is Migrating to IP ............................................................................... 301
PART 3 THE APPLICATIONS

CHAPTER 20 Smart Grid ................................................................. 305

20.1 Introduction ........................................................................... 305
20.1.1 How Can We Define the Smart Grid? ......................... 308
20.2 Terminology ........................................................................... 309
20.3 Core Grid Network Monitoring and Control ...................... 310
  20.3.1 Use Case 1: Secondary Substation Monitoring and Control ... 310
  20.3.2 Use Case 2: Substation CBM ............................................ 311
  20.3.3 Use Case 3: Line Dynamic Rating ................................. 312
  20.3.4 Technical Characteristics and Challenges ..................... 313
20.4 Smart Metering (NAN) ......................................................... 316
  20.4.1 Applications and Use Cases ......................................... 316
  20.4.2 Technical Challenges and Network Characteristics .......... 317
20.5 HAN ....................................................................................... 319
  20.5.1 Applications and Use Cases ......................................... 319
  20.5.2 Technical Challenges and Network Characteristics .......... 322
  20.5.3 Summary of the Technical Challenges ......................... 323
20.6 Conclusions ........................................................................... 323

CHAPTER 21 Industrial Automation .............................................. 325

21.1 Opportunities ....................................................................... 325
21.2 Challenges ........................................................................... 327
21.3 Use Cases ............................................................................ 329
  21.3.1 Condition Monitoring .................................................. 329
  21.3.2 Wireless Control .......................................................... 330
  21.3.3 Mobile Workforce ......................................................... 331
21.4 Conclusions ........................................................................... 333

CHAPTER 22 Smart Cities and Urban Networks ......................... 335

22.1 Introduction ......................................................................... 335
22.2 Urban Environmental Monitoring ...................................... 336
  22.2.1 Urban Ecosystem Monitoring ................................. 336
  22.2.2 Natural Hazards Monitoring and Early Detection .......... 338
  22.2.3 Technical Characteristics and Challenges .................. 340
22.3 Social Networks ................................................................. 342
  22.3.1 Extension of Web-based SNSs ............................. 342
  22.3.2 Monitoring the Elderly and Kids ......................... 344
  22.3.3 Technical Characteristics and Challenges ................ 345
22.4 Intelligent Transport Systems ................................................................. 346
22.4.1 Traffic Monitoring and Controlling .................................................... 347
22.4.2 Automatic Charging and Fining ......................................................... 349
22.4.3 Technical Characteristics and Challenges ........................................... 350
22.5 Conclusions ......................................................................................... 351

CHAPTER 23 Home Automation ................................................................. 353
23.1 Introduction .......................................................................................... 353
23.2 Main Applications and Use Cases ........................................................... 354
  23.2.1 Lighting Control ............................................................................. 354
  23.2.2 Safety and Security ........................................................................ 355
  23.2.3 Comfort and Convenience .............................................................. 355
  23.2.4 Energy Management ..................................................................... 356
  23.2.5 Remote Home Management ............................................................ 356
  23.2.6 Aging Independently and Assisted Living ....................................... 357
23.3 Technical Challenges and Network Characteristics ................................ 357
  23.3.1 Type of Topology and Traffic Matrix ................................................ 357
  23.3.2 Number of Devices ......................................................................... 358
  23.3.3 Degree of Mobility ......................................................................... 358
  23.3.4 Robustness and Reliability .............................................................. 358
  23.3.5 Requirements for Quality of Service ............................................... 358
  23.3.6 Battery Operation .......................................................................... 359
  23.3.7 Operating Environment ................................................................. 359
  23.3.8 Security .......................................................................................... 359
  23.3.9 Ease of Installation and Setup .......................................................... 360
23.4 Conclusions ......................................................................................... 360

CHAPTER 24 Building Automation ............................................................... 361
24.1 BAS Reference Model ........................................................................... 362
24.2 Emerging Building Automation Applications ........................................ 363
  24.2.1 Occupancy and Shutdown ............................................................... 363
  24.2.2 Energy Management ..................................................................... 364
  24.2.3 Demand Response .......................................................................... 364
  24.2.4 Fire and Smoke Abatement ............................................................. 364
  24.2.5 Evacuation ..................................................................................... 365
24.3 Existing Building Automation Systems ................................................ 365
  24.3.1 Existing Control Protocols ............................................................... 367
24.4 Building Automation Sensors and Actuator Characteristics .................. 368
  24.4.1 Area Control .................................................................................. 368
  24.4.2 Zone Control .................................................................................. 369
  24.4.3 Building Control ............................................................................ 370
24.5 Emerging Smart-Object-based BAS ................................................... 371
  24.5.1 Emerging Sensors, Actuators, and Protocols .................................... 371
  24.5.2 IP-based Enterprise Protocols ......................................................... 371
24.6 Conclusions ......................................................................................... 372
Foreword

Vinton G. Cerf

The Internet has been around in concept since 1973 and in operation since 1983. Its usage exploded when the World Wide Web application became broadly available with the arrival of the commercial Netscape Navigator browser and server applications around 1994. Since that time, an avalanche of content and new applications have poured into the Internet, which has grown to include nearly 2 billion people and possibly that many servers, laptops, desktops, and mobile units. But the system is about to experience yet another explosive period of growth as smart devices become a part of the Internet environment. The trend has already become visible as sensor networks connect to the Internet along with some fraction of the 4 billion mobiles thought to be in use around the world. To these devices appliances of all kinds (home, office, portable, fixed and mobile sensors, etc.) will be added.

What will this “Internet of Things” be like? For one thing, many of these “Internet-enabled” devices will be using the relatively new IPv6 protocol for access. IPv6 was standardized by the Internet Engineering Task Force around 1996, but implementation has been sparse. It is expected to accelerate, partly to accommodate the huge number of potential devices that will be connected to the Internet and also to cope with the anticipated exhaustion of the original IPv4 address space. The latter provided for approximately 4.3 billion unique terminations. A combination of relatively sparse assignment practices and reuse of “private address space” through Network Address Translation (NAT) boxes has allowed operation of the limited IPv4 address space through the present, but it is expected that the last of the IPv4 addresses will be allocated by the Internet Corporation for Assigned Names and Numbers by mid-2011, and the Regional Internet Registries that assign address space to Internet Service Providers will exhaust their supplies not long thereafter. There are 340 trillion trillion IPv6 addresses, and it is hoped that this will suffice for the foreseeable future.

Many of the “things” on the Internet will be appliances that can accept control inputs remotely or can report status information remotely. Sensor systems are good examples. I have a monitoring system in my home that tracks temperature, humidity, and light levels in every room in the house every 5 minutes. This information is captured and stored in a local database at home but is accessible remotely from anywhere on the Internet. One can easily envision security systems and a wide range of appliances that might be able to report their status and accept control information. The Smart Grid project in the United States is prototypical of the ideas behind the Internet of Things. For example, devices can not only report their energy usage but also be provided by users, or others on their behalf, with profiles to moderate energy usage during times of peak loads in exchange for reduced charges.

How often have you gone off on a trip, only to wonder whether a particular appliance was on or off, a light switch was set on or off, or some other home or office device was properly configured for your absence? The Smart Grid may provide a means to answer such questions remotely and securely and even allow remote interaction.

Standards to permit the interoperation of smart, Internet-enabled devices will also be essential. Such standards will also promote competitive provision of devices and services associated with them. Such potentially large-scale systems will make demands on designers to cope with billions of devices interacting in various subsets with each other. Emergent properties may well appear unexpectedly. Security and strong authentication of identity and authority will play key roles in making such systems safe to use.
Our ability to model, understand, and successfully operate such large-scale infrastructure will be challenged, and within that challenge there may dwell many Ph.D. dissertations as well as new and unexpected businesses. The law and policy will not escape the impact of this gigantic network with its billions of components. The potential for mischief, interference, and even significant infrastructure failures (deliberate or accidental) will be made even more complex by the global scope of the Internet and its connections. New frameworks for dealing with liability, risk, vulnerability, and criminal activity will be needed along with multilateral agreements to secure the benefits and protect users from harm.

The authors of this book offer a rich and thoughtful exploration of this new Internet canvas on which the twenty-first century will unfold. Predictions will be hard; we are all just going to have to live through it to find out what happens!

Vinton G. Cerf
Woodhurst
January 2010
Preface

The digital revolution of the 21st century will be much, much larger than previous digital revolutions. During the 20th century, the world underwent two major digital revolutions: computers were developed and found their way into offices and homes, and the Internet interconnected the computers and fundamentally changed the way we interact with the digital world.

We now stand before the digital revolution of the 21st century: smart objects – the Internet of Things – that interconnect the digital world with the physical world. Industry predicts the number of smart objects to be counted in billions within the next ten years. Over the course of the forthcoming decade, we will see this fundamentally change the way we interact with both the digital and the physical world.

A smart object is a small micro-electronic device that consists of a communication device, typically a low-power radio, a small microprocessor, and a sensor or actuator. The sensors give the smart objects the ability to sense the physical world, for example by measuring its temperature. Actuators make it possible for the smart objects to change the physical world, for example by controlling an engine.

We already see a number of emerging applications of smart objects. The power grid is about to be equipped with sophisticated smart objects networks to help better manage the grid, handle renewable sources of energy, and recharge electric cars. Office buildings can become more energy-efficient with temperature sensors that monitor the actual temperature in the building so that controllable radiators and air conditioners can better control the temperature. Cities will support intelligent transport systems, environmental monitoring, energy management, and even social networking using smart objects. Freighter containers can measure the climate inside the containers to make sure that food-stuffs are kept in a good environment.

But we are only beginning to scratch the surface of what smart objects can do; the emerging applications we see today are just the start. The true innovative power of smart objects comes from their interconnection. When innovators can begin to easily and rapidly build applications and systems that connect the physical and the digital world, a new level of serendipity begins.

The network architecture for the smart objects must be extremely open to future innovation. We cannot possibly know what the future holds for smart objects, as the field is still in its infancy. Innovation must be allowed to occur both in how we use smart objects and in the way the smart object technology itself is designed. The overall architecture is the fundament and must be extremely flexible to support new applications in the future, just like the Internet did over that past three decades.

So far, however, smart objects have largely been isolated islands whose interconnection has been made difficult because of a number of proprietary solutions, usually optimized for one specific application, that have not been possible to integrate.

**OBJECTIVES**

In this book, we explain why the Internet Protocol, IP, is the protocol of choice for smart object networks, providing an open and standard based technology for the endless number of applications to come. IP has already successfully showed that it can interconnect billions of digital systems on the global Internet and in private IP networks. Once smart objects can be easily interconnected, a whole
new class of smart object systems can begin to evolve. Developers can build systems that integrate information physical-world phenomena with digital information from on-line sources. Businesses can make use of physical information both to make their own business more efficient but also to explore completely new business opportunities.

The interconnection of smart objects is not without significant technical challenges. First, the sheer number of potential devices that can be connected provides challenges for communication mechanisms, routing protocols, and communication architecture. Deployments of hundreds or thousands of smart objects are not uncommon. Second, the requirement for low-power operation affects every layer of the system, from hardware through software and to the data management architectures. To meet lifetime requirements, smart objects must be able to operate with power consumptions of less than one milliwatt. Third, the requirements for a small physical size, low power consumption, and low cost mean that each device must make very efficient use of their limited resources. Smart objects may have only a few kilobytes of memory. Still, IP-based smart object networks are being designed and deployed. This book tells you how this is achieved. But this is just the beginning of an exciting journey: the future of interconnected smart objects has just begun.

**STRUCTURE OF THE BOOK**

We spent a good amount of time thinking of the most appropriate structure for this book, in order to make it a reference for engineers and researchers but also provide materials valuable for non-expert in the field. We decided to organize the book around three main parts: the book starts with one part devoted to discussing the architectural foundation of the IP smart object networks, before the second part takes a deep dive into protocols and algorithms, and the third part concludes the book with a detailed review of seven important use cases and applications for IP-based smart objects.

Part I demonstrates why the IP architecture is well suited to smart object networks by contrast with non-IP based sensor network or other proprietary systems interconnect to IP networks (e.g. the public Internet of private IP networks) by means of hard to manage and expensive multi-protocol translation gateways that scale poorly. We start Part I with a description of smart objects. After a review of the architectural principles of IP, we explain why IP and in particular IPv6, that uses the same architecture as IPv4, is particularly well suited for smart objet networks. Several key networking features are reviewed from an architectural angle such as routing, transport, service discovery, security, and web services. Part I concludes with a discussion on potential connectivity models of IP smart objects to (private and public) IP networks.

The second part is a deep technology dive into the technologies. Part II starts with a detailed discussion on smart objects (hardware architecture, lightweight operating systems) and several of the low power link layers technologies used in these networks. Then follows a chapter devoted to standardization, a must for any technology to be widely adopted: this chapter discusses in details the standardization process of the standardization body in charge of IP protocols: the IETF (Internet Engineering Task Force). Then follows two chapters explaining in details two key areas of IP smart object networks: the 6LoWPAN adaptation layer specified to carry IPv6 packet over the IEEE 802.15.4 link layer and the newly defined routing protocol (called RPL) used in IP smart object network. This second part concludes with an overview of the IPSO (IP for Smart Object alliance) followed by a discussion on two non-IP technologies.
IP smart object networks will unavoidably change and improve our day-to-day quality of life, in a number of ways: these networks will radically increase the efficiency of power grids allowing for new sources of energy generation and energy savings, they will help better manage buildings and homes, make our cities smarter and these are only a few examples. Thus, instead of providing a few examples here and there, we decided to devote an entire part of this book to the applications of IP smart object networks: "What will IP smart object network be used for?" in a very near future. Each chapter in Part III of the book describes the use of smart object networks as opposed to the technology itself and follows a similar structure: for each use case, we start with a detailed description of the various applications (for example, how to enable new services in a smart city such as urban environmental monitoring, social networking, and intelligent transport systems) followed by a discussion on the technical challenges. Part III discusses in detail seven major applications: smart grid, industrial automation, smart cities and urban networks, home automation, building automation, structural health monitoring, and container tracking.
Acknowledgements

There are number of persons to acknowledge in this section for their tremendous help in writing this book.

Our warm thank to Vinton Cerf, Internet Pioneer, for having accepted to write the foreword of this book.

We are extremely grateful to our reviewers, Paul Bertrand (Founder and Vice-President of Watteco) and Mijeom Kim (Senior Research Engineer, Korea Telecom) for their detailed review of the book.

Considering how broad the set of use cases for IP smart objects network is, we greatly benefited from the expertise of several world-wide experts in several of the uses cases discussed in Part III. The following people wrote the bulk of several of the chapters in Part III:

- Jonas Neander, Ewa Hansen, Tomas Lennvall, and Mikael Gidlund, (ABB AB, Corporate Research) – Chapter 21, Industrial Automation;
- Lin Zhang (Professor, Tsinghua University, China) – Chapter 22, Smart Cities and Urban networks;
- Bernd Grohmann (VP Marketing & Business Development, eQ-3 AG) – Chapter 23, Home Automation;
- Jerry Martocci (Lead staff engineer, Wireless communications, Johnson Controls) – Chapter 24, Building Automation;
- Jukka Manner (Professor, Aalto University School of Science and Technology) and Jaakko Hollmen (Chief Research Scientist, Aalto University School of Science and Technology) – Chapter 25, Structural Health Monitoring.

We are also extremely grateful to the number of people who reviewed chapters of the book: Danny Cohen, Julien Abeille, Jonathan Hui, Tim Winter, Pascal Thubert, Joakim Eriksson, Nicolas Tsiftes, Akiba, and Eric Sandberg.

Needless to say that this book would not have been possible without the tremendous support and professionalism of our editor Rick Adams, our development editor Heather Scherer and our project manager Andre Cuello.

SPECIAL ACKNOWLEDGMENTS

I would like to thank my company, Cisco Systems, for years of exiting work and opportunities and I would address very special thanks to several individuals: my former managers, Joel Bion and Bruce Davie for their support when I first started to work on IP Smart Objects networks several years ago while this was still a concept, of course my manager Alain Fiocco for his constant support and inspiration in many areas, but also Dave Oran for our fruitful discussion over the past decade and finally close collaborators I have been closely working with over past few years: Navneet Agarwal, Amit Phadnis, Mathilde Durvy, Julien Abeille and Pascal Thubert. Special thank to Patrick Wetterwald with whom I spend long hours working on IP smart objects for the last few years.
I would like to warmly thank several Cisco executives who supported the work over the years: Marthin De Beer, Laura Ipsen, Ben Fathi, Win Elfrink and Guido Jouret.

A particular thank to Jaudelice De Oliveira (Professor at Drexel University) for years of friendship and fruitful collaboration, and to Joydeep Tripathi for the collaboration to write a sensor network simulator that we used to provide several simulation results provided in the Chapter 17 of this book.

JP Vasseur

First and foremost, I would like to thank the large number of people who have contributed to the success of the Contiki operating system and of the uIP and lwIP TCP/IP stacks. In particular, I would like to thank the members of the Contiki core team, who have all put in a tremendous effort to make Contiki what it is today: Oliver Schmidt, Niclas Finne, Joakim Eriksson, Fredrik Österlind, Nicolas Tsiftes, Mathilde Durvy, and Julien Abeillé. I would also like to thank all members of my research group at the Swedish Institute of Computer Science: Joakim Eriksson, Niclas Finne, Zhitao He, Marcus Lundén, Luca Mottola, Shahid Raza, Nicolas Tsiftes, Thiemo Voigt, Dogan Yazar, and Fredrik Österlind, for conducting top-quality research, and for being such inspiring people to work with. Likewise, I am also in debt to all collaborators in the numerous research projects I am involved in and have been involved in over the years. Being surrounded by so many great people is a tremendous gift.

I would like to thank my current and former lab managers, Sverker Janson and Bengt Ahlgren, SICS CEO Staffan Truvé, and SICS business manager Janusz Launberg, for their support and their confidence in my work with IP-based smart objects over the past ten years.

Finally, I would like to thank my wife Maria for her great support and patience with me during the writing of this book.

Adam Dunkels