INTRODUCTION TO IoT

Sudip Misra | Anandarup Mukherjee | Arijit Roy

Introduction to IoT

Internet of Things, as a research field, piques the interest of a growing community of academics and scholars across the world. It has witnessed massive adoption and large-scale deployment in industries and other spheres of everyday life. Considerable theoretical information about IoT as well as tutorials, courses, implementations, use-cases, etc., is available across the web. However, all this available information is so scattered that even professionals in the field have trouble obtaining concise information on IoT and connecting the dots between the various technologies relating to it. This book serves as a textbook and also as a single point of reference for readers interested in the subject. Written by leading experts in the field, this lucid and comprehensive work provides a clear understanding of the operation and scope of IoT. It discusses the basics of networking, network security, precursor technologies of IoT and the emergence of IoT. It gives an overview of various connectivity, communication, and interoperability protocols prevalent in the field. While providing a dedicated overview and scope of implementation of various analytical methods used for IoT, the book discusses numerous case studies and provides hands-on IoT exercises, enabling readers to visualize the interdisciplinary nature of IoT applications and understand how they have managed to gain a foothold in the technology sector. The book also serves curious, non-technical readers, enabling them to understand necessary concepts and terminologies associated with IoT.

Sudip Misra is a professor in the Department of Computer Science and Engineering at the Indian Institute of Technology Kharagpur. He has published over 300 research papers and 11 books in allied areas of IoT. He is Associate Editor of *IEEE TMC, TVT* and *IEEE Network*. He is a Fellow of the National Academy of Sciences (India), IET (UK), and BCS (UK), and is a distinguished lecturer of the IEEE Communications Society. His current research interests include wireless sensor networks and IoT.

Anandarup Mukherjee is the co-founder and director of Sensor Drops Networks Pvt. Ltd., an IoT startup incubated at the Indian Institute of Technology Kharagpur. He has published more than 30 research papers. He works in the domain of IoT and unmanned aerial vehicle swarms.

Arijit Roy is the co-founder and director of Sensor Drops Networks Pvt. Ltd. He is a senior researcher in the Smart Wireless Applications and Networking (SWAN) lab at the Indian Institute of Technology Kharagpur. His primary research areas include IoT, sensor networks, and sensor-cloud.

Introduction to IoT

Sudip Misra
Anandarup Mukherjee
Arijit Roy

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314 to 321, 3rd Floor, Plot No.3, Splendor Forum, Jasola District Centre, New Delhi 110025, India

79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108842952

First published 2021

Printed in India

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging-in-Publication Data

Names: Misra, Sudip, author. | Mukherjee, Anandarup, author. | Roy, Arijit, author.
Title: Introduction to IoT / Sudip Misra, Anandarup Mukherjee, Arijit Roy.
Description: United Kingdom ; New York : Cambridge University Press, 2020. | Includes bibliographical references and index.
Identifiers: LCCN 2020037656 (print) | LCCN 2020037657 (ebook) | ISBN 9781108842952 (hardback) | ISBN 9781108959742 (paperback) | ISBN 9781108913560 (ebook)
Subjects: LCSH: Internet of things.
Classification: LCC TK5105.8857 .I567 2020 (print) | LCC TK5105.8857 (ebook) | DDC 004.67/8–dc23
LC record available at https://lccn.loc.gov/2020037656
LC ebook record available at https://lccn.loc.gov/2020037657

ISBN 978-1-108-84295-2 Hardback
ISBN 978-1-108-95974-2 Paperback

To Our Families

Contents

Figures

Tables

Foreword

The Internet of Things (IoT) paradigm has grown by leaps and bounds in the past decade. Nowadays, IoT is a common presence in households, transportation, markets, retail, banking, industries, education, and logistics. Yet regular innovative developments in IoT continue to flood the market. IoT has given rise to many interesting applications and resulted in the development of new networking and communication technologies that are designed specifically for IoT-oriented tasks. Manually intensive, yet crucial, domains of healthcare, agriculture, and transportation now rely heavily on IoT applications. The inclusion of IoT applications in these domains has resulted in facilitating their automation, enhanced safety, and precision of operations and allowed the inclusion of scientifically optimized practices. It is popularly considered that the rapid rise of IoT resulted from the inclusion of the beneficial features from the paradigms and technologies of Internet computing, cloud computing, wireless sensor networks (WSN), cyber-physical systems (CPS), and machine-to-machine (M2M) communications. All through its development, IoT has been supported by the popular networking paradigms in distributed systems, namely of cloud computing and edge and fog computing. These have allowed the massive, yet affordable, deployment of IoT across various domains. The emergence of the recent paradigm of edge computing can be directly attributed to IoT. IoT has also motivated the development of numerous connectivity and communication protocols and technologies such as IPv6, MQTT, 6LoWPAN, and LoRA, amongst others.

Unlike other books on IoT, already available on the market, this book provides detailed and interlinked coverage of topics related to IoT networks. The authors have designed this book carefully so that it acts as a guide and a single point of reference to IoT networks for beginners, as well as those already familiar with the technologies connected to IoT. With applications in the domains of agriculture, healthcare, electronics, power sector, industries, households, consumer electronics, computing, analytics, environment, transportation, logistics, security, military, surveillance, and many others, it is no wonder that the demand for deeper insights into IoT technologies is increasing day by day. The involvement of people from diverse backgrounds makes it necessary to create a concise repository of information on this new technology. The Internet hosts much information on IoT (theory, tutorials, courses, and implementations). However, they are so scattered that even professionals in this field have trouble obtaining connected and concise information.

This book has been purposefully designed by the authors as a textbook; it gradually exposes the readers to the technical details of IoT by first providing a primer on crucial networking technologies, which will help new readers in this domain to comfortably adopt and absorb the technical details of core IoT network technologies and its associated domains. Thereafter, the book gradually shifts focus to IoT networking technologies covering the emergence of IoT, addressing strategies in IoT, sensing and actuation, processing topologies, connectivity technologies, communication protocols, and interoperability. Later, this book expands its focus to cover the popular paradigms of cloud and fog computing, along with their applications in real life. The authors also provide real-life case studies on agriculture, healthcare, and vehicular IoT, aiming to get new learners motivated in the practical applicability of IoT in real-world applications. The authors have also provided chapters on IoT hardware projects and common analytical methods/tools used in IoT.

This book is divided into five parts: 1) Introduction, 2) Internet of Things, 3) Associated IoT Technologies, 4) IoT Case Studies, and 5) IoT Hands-on. I especially found the following features quite attractive in this book:

(a) *Preliminary and background information* on networking technologies.

(b) *Self-descriptive illustrations* help in visualizing complicated concepts.

(c) *Exercises at the end of chapters* test the learner's understanding of contents.

(d) *Conceptual questions* at the end of the book test the understanding of learners.

(e) *Real-life use cases* of IoT motivates new learns to delve deeper into IoT.

(f) A descriptive guide to building *IoT-based hardware projects.*

The authors of this book are globally acclaimed researchers, all of whom have published a number of research papers in this domain in highly impactful journals/magazines such as the *IEEE Communications Magazine, IEEE Transactions on Communications, IEEE Transactions on Mobile Computing, IEEE Transactions on Sustainable Computing, IEEE Transactions on Vehicular Technology, IEEE Internet of Things Journal, Elsevier Computer Networks, IEEE Systems Journal*, and many more. Sudip is well known in the community for his research achievements in the broad domain of Internet of Things. He has published more than a dozen books, which are published by globally renowned publishers such as Cambridge University Press, Wiley, Springer, World Scientific, and CRC Press. Due to his significant research contributions, his work has been recognized with different fellowships and awards such as the highly prestigious Abdul Kalam Technology Innovation National Fellow (India), the Fellow of the National Academy of Sciences (India), the Fellow of IETE (India), IET (U.K.), RSPH (U.K), IEEE Communications Society Outstanding Young Researcher Award, Humboldt Fellowship (Germany), Faculty Excellence Award (IIT Kharagpur), Canadian Governor General's Academic Medal, NASI Young Scientist Award, IEI Young Engineers Award, SSI Young Systems Scientist Award and so on. He serves as the Editor of *IEEE Transactions on Vehicular Technology*, and the Associate Editor

of *IEEE Transactions on Mobile Computing*, *IEEE Transactions on Sustainable Computing*, *IEEE Systems Journal*, and *IEEE Networks*. He is also the IEEE Communications Society Distinguished Lecturer for the year 2020 through 2021. Besides Sudip, the other authors, Anandarup and Ariit, are distinguished senior researchers in Sudip's Smart Wireless Applications and Networking (SWAN) Lab at IIT Kharagpur. Both of them were awarded the Gandhian Young Innovation Award (GYTI) by the President of India in 2018 for their socially relevant innovation. They also serve as co-founders and directors of their entrepreneurial venture Sensor Drops Networks Pvt. Ltd.

On a concluding note, I expect this book to be quite useful to a diverse variety of readership. I am convinced that this book serves as a guide for the readers on their journey of exploring the amazing depth of concepts, technologies, and impacts of the Internet of Things.

Professor Schahram Dustdar
IEEE Fellow & ACM Distinguished Scientist
Vienna University of Technology (TU Vienna), Austria
Co-Editor-in-Chief, *ACM Transactions on IoT*

Preface

Overview and Goals

Internet of Things (IoT) is rapidly gaining a foothold in the technology sector; it has managed to emerge as a highly sought-after field of study and research in computing sciences and electronics. The vastly interdisciplinary nature of the areas to which IoT can be applied has managed to pique the interest of the whole world. IoT finds diverse use in domains spanning industrial, military, as well as regular consumer applications. The versatility of IoT and its ability to connect anything make it one of the most demanded technologies of the modern age. The involvement of people from vastly diverse and distinct backgrounds, all point to the need for a concise repository of information on this new technology.

The Internet hosts much information on IoT, which is in the form of theory, tutorials, courses, implementations, and others. However, these discussions are so scattered that even professionals in this field have trouble obtaining integrated and concise information on IoT.

IoT is a new paradigm for connecting "things" in order to automate a system. In the context of IoT, "things" include computers, cell phones, medical devices, vehicles, wearables, and other appliances and devices for daily use. These "things" tend to be heterogeneous, which results in the development and existence of a vast number of communication solutions and protocols, which vary distinctly from each other. Consequently, communications among these "things" is a challenging issue in IoT. Another major challenge in IoT is the dynamic nature of "mobile things," which generally follow a decentralized architecture. Due to this decentralized communication and control structure, the connectivity and data transmission dynamically changes with time, in turn resulting in a new set of challenges.

Pedagogical Aids

We have included various pedagogical aids to help the reader swiftly grasp the contents and the treatment of the various topics covered in this book. We have provided a set of conceptual questions at the end of this book. For solving these questions, the reader must have completely grasped the concepts covered in this book.

Additionally, we provide visual presentations of the chapters covered in this book so that it can be used as a teaching aid in colleges and universities. Each chapter of this book has the following pedagogical components:

- *Learning outcomes*, which gives an initial glimpse into the chapter.
- *Self-descriptive illustrations,* which are easy to understand.
- *Check yourself* exercises, which encourage readers and learners to explore additional topics on their own. This will gradually enable the readers to easily find terminologies, technologies, and concepts on their own as they start understanding the more complicated parts of this book.
- *Summary*, which provides a concise outcome for each chapter.
- *Exercises*, which allow the readers of this book to brush up their knowledge at any point in the future and also enable them to test their understanding of the concepts/technologies covered in this book.

Organization and Features

This book holistically covers the significant aspects of IoT in detail, including legacy and new technologies. These technological concepts form the core of IoT, the knowledge of which is indispensable for architecting an IoT-based solution. The entire book is written in a lucid and elementary manner, which provides readers with a clear understanding of the scope and operation of each topic. This book is an excellent guide for beginners, enabling them to start architecting IoT-based solutions confidently. Keeping the need of the beginners in mind, the authors have provided an overview of the background knowledge required for working with IoT. This background information is supplied in Part I, which includes topics covering basics of networking, basics of security, and predecessor technologies of IoT.

Part II of this book describes in detail the emergence of IoT and basic IoT enabling components, including sensors, connectivity protocols, communication protocols, and others. Each chapter in Part II describes and illustrates the various components of an IoT architecture: sensors, actuators, processing, connectivity, communication, and interoperability features. Physical quantifications of environmental effects and phenomena, which are carried out by sensors, constitute one of the essential components of IoT. These sensors can be heterogeneous and are classified according to their functionalities and usage as scalar, multimedia, hybrid, and virtual sensors, which are used to sense various parameters in an IoT architecture. The planned deployment of sensor nodes in an area of interest is one of the crucial issues in IoT, which aims to minimize the energy consumption of these devices and facilitate the quick processing of sensor data. Other tasks include the geographical representation of sensor placement and connectivity establishment among them, which is also referred to as the topology. Thus, this book sheds some light on the different sensor types and the working procedure, which are commonly used in an IoT architecture.

The sensed data needs to be stored and continually updated in memory locations for further processing. As per requirement, a user has the option of utilizing the sensed information as either structured or unstructured data. In IoT, the *where* and *how* of processing is another critical issue. Therefore, the correct processing technique needs to be selected accordingly. This book covers the processing techniques required for IoT. The transmission of this processed IoT data between devices is mostly dependent on various communication and connectivity protocols. The authors illustrate and discuss these connectivity protocols in detail, which is lucid to both experts as well as novice audiences. Some of these discussed protocols have been developed, primarily due to various developments in IoT and its architectures. After successful establishment of connectivity between two or more IoT nodes, the subsequent steps involve establishing communication between these nodes. These nodes may be tasked with either sensing, actuation, or both functions with specific requirements concerning packetization, addressing, reliability, security, and other such measures. The authors discuss these needs by describing a significant number of communication protocols in a separate chapter dedicated to these communication protocols. Finally, Part II discusses the various types of interoperability and their importance concerning IoT and its technologies. As IoT involves the inclusion of legacy, present, and upcoming technologies, the primary challenge lies in the integration of hardware and software platforms, which are provided by various original equipment manufacturers (OEMs) following their proprietary solutions and technologies. Consequently, the inclusion of these devices into a single platform is a non-trivial task. Therefore, the establishment of connectivity among these diverse devices in IoT becomes a challenging issue. The paradigm of device and software interoperability is introduced to the readers, which highlights the urgency of equipment, technology, communication, and protocol standardization in the context of IoT. The authors discuss the challenges of interoperability along with its other aspects resulting in the shaping of the readers' perspective; this would enable them to come up with IoT solutions and architectures, keeping the present and future interoperability challenges in mind.

In a traditional IoT architecture, there is the option to store the sensed data from heterogeneous sensor nodes in various locations such as locally on the devices, on a remote server, on a fog, or a cloud. Part III of this book primarily covers cloud, fog, and edge computing. An IoT architecture consists of a large variety of different, multipurpose, and multifunctional devices. The authors of this book ensure that each of these storage schemes is described individually. Cloud computing, yet another crucial technology, plays a vital role in handling the massive amounts of data generated by these IoT devices. A cloud enables the features of enormous storage capabilities, processing resources, and unification of data on a single platform. This book elucidates the idea of cloud computing in a simplified manner. A few topics of cloud computing, primarily focused on its applicability in the context of IoT, are discussed. Additionally, various service models are briefly discussed as they are used with traditional cloud computing. To mitigate the issues of latency in data processing

in a cloud, which can be crucial for applications such as healthcare, the authors also include brief overviews of fog and edge computing. The authors cover the different aspects of fog computing, starting from fundamental issues to issues relating to its architecture along with suitable use-cases in this book.

After discussing the technical details of IoT and its backbone technologies, the authors highlight different application domains of IoT, such as agriculture, vehicular, and healthcare. These typical application domains of IoT are discussed in Part IV of this book as case-studies. Each chapter covers the application domains one-by-one employing real-life use-cases. These use-cases provide a clear idea about the real implementation of IoT in each application domain. This part is designed to enable both beginners, as well as advanced readers, to understand the needs, implementation, technologies, solutions, and implications of sustainable IoT architectures and solutions described in Parts I–III. Finally, the last chapter of this part concludes the various theoretical and practical aspects of IoT, its components, and architectures, with a discussion on newly emerging paradigms and various enabling ones.

Finally, Part V of this book is designed to further strengthen the readers' grasp on concepts through hands-on experience with IoT applications. The authors make use of commonly available hardware, including sensors, actuators, and processor boards, to demonstrate various sample integrations. These sample integrations are designed to enable readers to envision complicated device integrations and form complex IoT network architectures. Basic knowledge of Arduino and Python programming is required for pursuing this part. However, for readers with no prior experience in these languages, the hands-on section provides sample codes and explains the functionality of the integrations and its various aspects. Another chapter focuses on data informatics and analytics popularly used in IoT. The various types of analytics and terminologies associated with them are outlined; this chapter provides new readers and knowledge-seekers a starting point into IoT analytics.

All the chapters in this book are accompanied by a set of basic questions on the topics covered in that chapter. However, the last part of this book contains a consolidated set of conceptual questions, which will require the readers to access various sources, besides this book, to be able to address them. This exercise will train the readers to selectively choose from the vast amount of information available elsewhere, and sieve the ones most crucial to their current problem.

Target Audience

This book primarily targets the undergraduate and postgraduate technical readers who are either looking to delve into the growing domain of IoT or are taking IoT targeted introductory as well as advanced courses. This book is additionally designed to address the curious, non-technical reader, as well as working professionals from non-computer science and electronics domains, enabling them to pick up the necessary concepts and terminologies associated with IoT. This multifaceted book

can also be used as a quick reference introducing the concepts and challenges in IoT research, which may be of significant use to working professionals, academicians as well as researchers across various industries.

Suggested Use of This Book

This book has been designed to be used both as a textbook as well as a reference book. Undergraduate students taking an introductory course on IoT will need to first go through the introductory part, which consists of the basics of networking, security, and similar technologies preceding IoT. The solving of the exercises at the end of each chapter and the conceptual questions at the end of this book would serve as a good indicator of the undergraduate reader's progress in grasping the concepts covered in this book. Working professionals in other domains and new learners (not familiar with networking and the nuances of computing sciences) can follow the same approach.

Postgraduate and research students in electronics, computer sciences, electrical engineering, and other similar domains can use this book directly from the second part, as they would already be aware of the introductory concepts. Working professionals in the allied domains of electronics and computer sciences can also follow the same protocol for this book as the postgraduate students. This book will also serve as a ready reference for the numerous topics included in it and which are commonly encountered in designing IoT-based solutions.

Finally, the curious reader who aims to work on IoT, without having any prior knowledge of this domain and computer sciences, should first peruse the fourth part of this book, which covers various real-life case studies of IoT in various domains. This will help the reader understand the usability of IoT in the context of the unique challenges faced for each domain. The reader can also gain additional exposure to IoT through the last part, which presents a hands-on approach to building IoT-based solutions through a set of very concise and interesting experiments. The experiments are aimed at both new as well as advanced learners.

Acknowledgment

The authors would like to thank Ms. Nidhi Pathak and Mr. Pallav Deb, who are doctoral research scholars at the Indian Institute of Technology Kharagpur, India. They have been instrumental in helping with various hardware and software implementations used in this book. Additionally, the authors would like to thank the various scholars/researchers in the Smart Wireless Applications and Networking (SWAN) Lab. for taking time out to go through this work and suggest improvements. The authors sincerely acknowledge the role of various, regular as well as online, students of Professor Misra's course *Architecting Protocols for the Internet of Things* and

his popular MOOC *Introduction to IoT*, which is hosted online by NPTEL (India). Finally, the authors are grateful to their families for being understanding and patient.

PART ONE
INTRODUCTION

Chapter 1

Basics of Networking

Learning Outcomes

After reading this chapter, the reader will be able to:

- Understand the basic principles of computer networking
- List the basic terminologies and technologies
- Relate new concepts of IoT with the basics of networking
- Discuss various network configurations and topologies
- Explain various OSI (open systems interconnections) and TCP/IP (transmission control protocol/Internet protocol) layers and their associated uses
- Describe basics of network addressing

1.1 Introduction

In the present era of data- and information-centric operations, everything—right from agriculture to military operations—relies heavily on information. The quality of any particular information is as good as the variety and strength of the data that generates this information. Additionally, the speed at which data is updated to all members of a team (which may be a group of individuals, an organization, or a country) dictates the advantage that the team has over others in generating useful information from the gathered data. Considering the present-day global scale of operations of various organizations or militaries of various countries, the speed and nature of germane information are crucial for maintaining an edge over others in the same area. To sum it up, today's world relies heavily on data and networking, which allows for the instant availability of information from anywhere on the earth at any moment.

Typically, networking refers to the linking of computers and communication network devices (also referred to as hosts), which interconnect through a network

(Internet or Intranet) and are separated by unique device identifiers (Internet protocol, IP addresses and media access control, MAC addresses). These hosts may be connected by a single path or through multiple paths for sending and receiving data. The data transferred between the hosts may be text, images, or videos, which are typically in the form of binary bit streams [1].

Points to ponder

- The data generated from a camera sensor tells us more about a scene compared to the data generated from, say, a proximity sensor, which only detects the presence of people in its sensing range.
- Furthermore, the simultaneous data generated from multiple cameras focusing on the same spot from various angles tell us even more about the scene than a single camera focused at that scene.

As the primary aim of this chapter is to provide the reader with an overview of networking, we have structured the text in such a manner that the general concepts are covered. Additional *Check yourself* suggestions to review various associated technologies are provided along with the topics.

We start our discussion with the different types of networks, followed by an overview of two popularly used layered network models: ISO-OSI (the open systems interconnection developed by the International Organization of Standardization) and TCP/IP (transmission control protocol/Internet protocol) suite. Subsequently, we will touch upon the various types of addressing mechanisms and set up the basic premise of how a message is transmitted between two devices/computers/hosts.

1.2 Network Types

Computer networks are classified according to various parameters: 1) Type of connection, 2) physical topology, and 3) reach of the network. These classifications are helpful in deciding the requirements of a network setup and provide insights into the appropriate selection of a network type for the setup.

1.2.1 Connection types

Depending on the way a host communicates with other hosts, computer networks are of two types—(Figure 1.1): *Point-to-point* and *Point-to-multipoint*.

(i) **Point-to-point**: Point-to-point connections are used to establish direct connections between two hosts. Day-to-day systems such as a remote control for an air conditioner or television is a point to point connection, where the connection has the whole channel dedicated to it only. These networks were

designed to work over duplex links and are functional for both synchronous as well as asynchronous systems. Regarding computer networks, point to point connections find usage for specific purposes such as in optical networks.

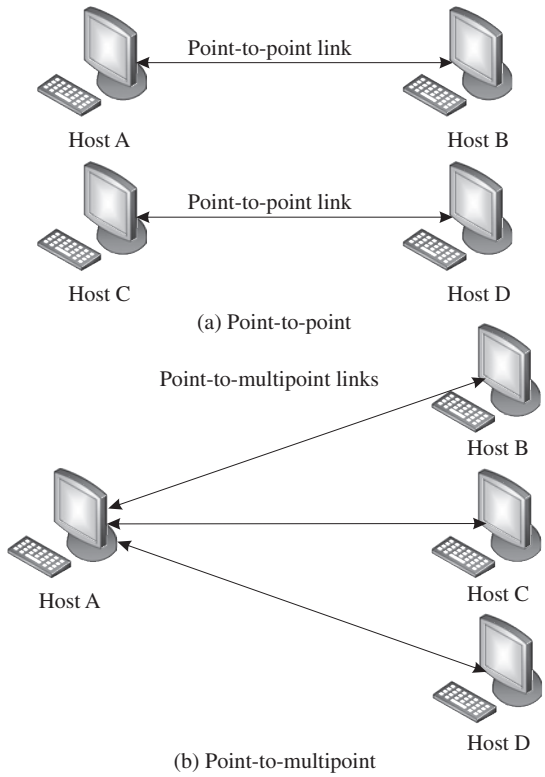

Figure 1.1 Network types based on connection types

Point-to-point Requests for Comments (RFCs)

The following requests for comments (RFCs) are associated with point-to-point communication and its derivatives. **RFC 1332**: point-to-point (PPP) Internet protocol control protocol (IPCP); **RFC 1661**: PPP; **RFC 5072**: IP Version 6 over PPP; **RFC 2516**: PPP over Ethernet; **RFC 1963**: PPP serial data transport protocol; **RFC 1962**: PPP compression control protocol (CCP); **RFC 1990**: PPP multilink protocol (MP); **RFC 2615**: PPP over SONET/SDH (synchronous optical networking/synchronous digital hierarchy).

(ii) **Point-to-multipoint**: In a point-to-multipoint connection, more than two hosts share the same link. This type of configuration is similar to the one-to-many connection type. Point-to-multipoint connections find popular use in wireless networks and IP telephony. The channel is shared between the various hosts,