ALGORITHMS AND PROTOCOLS FOR WIRELESS AND MOBILE AD HOC NETWORKS

Edited by

Azzedine Boukerche, PhD
University of Ottawa
Ottawa, Canada
ALGORITHMS AND PROTOCOLS FOR WIRELESS AND MOBILE AD HOC NETWORKS
WILEY SERIES ON PARALLEL AND DISTRIBUTED COMPUTING

Editor: Albert Y. Zomaya

A complete list of titles in this series appears at the end of this volume.
ALGORITHMS AND PROTOCOLS FOR WIRELESS AND MOBILE AD HOC NETWORKS

Edited by

Azzedine Boukerche, PhD
University of Ottawa
Ottawa, Canada
This book is dedicated to my parents and my family who have always been there with me.
Love you all.

Azzedine Boukerche
CONTENTS

Preface ix
Contributors xiii
About the Editor xvii

1. Algorithms for Mobile Ad Hoc Networks 1
   Azzedine Boukerche, Daniel Câmara, Antonio A.F. Loureiro,
   and Carlos M.S. Figueiredo

2. Establishing a Communication Infrastructure in Ad Hoc Networks 21
   Michel Barbeau, Evangelos Kranakis, and Ioannis Lambadaris

3. Robustness Control for Network-Wide Broadcast in Multihop
   Wireless Networks 51
   Paul Rogers and Nael B. Abu-Ghazaleh

4. Encoding for Efficient Data Distribution in Multihop
   Ad Hoc Networks 87
   Luciana Pelusi, Andrea Passarella, and Marco Conti

5. A Taxonomy of Routing Protocols for Mobile Ad Hoc Networks 129
   Azzedine Boukerche, Mohammad Z. Ahmad, Damla Turgut,
   and Begumhan Turgut

6. Adaptive Backbone Multicast Routing for Mobile Ad Hoc Networks 165
   Chaiporn Jaikaeo and Chien-Chung Shen

7. Effect of Interference on Routing in Multihop Wireless Networks 187
   Vinay Kolar and Nael B. Abu-Ghazaleh

8. Routing Protocols in Intermittently Connected Mobile
   Ad Hoc Networks and Delay-Tolerant Networks 219
   Zhensheng Zhang

9. Transport Layer Protocols for Mobile Ad Hoc Networks 251
   Lap Kong Law, Srikanth V. Krishnamurthy, and Michalis Faloutsos

10. ACK-Thinning Techniques for TCP in MANETs 277
    Stylianos Papanastasiou, Mohamed Ould-Khaoua, and Lewis M. MacKenzie
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Authors</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.</td>
<td>Reputation-and-Trust-Based Systems for Ad Hoc Networks</td>
<td>Avinash Srinivasan, Joshua Teitelbaum, Jie Wu, Mihaela Cardei, and Huigang Liang</td>
<td>375</td>
</tr>
<tr>
<td>15.</td>
<td>Performance Issues in Vehicular Ad Hoc Networks</td>
<td>Maria Kihl and Mihail L. Sichitiu</td>
<td>433</td>
</tr>
<tr>
<td>16.</td>
<td>Cluster Interconnection in 802.15.4 Beacon-Enabled Networks</td>
<td>Jelena Mišić and Ranjith Udayshankar</td>
<td>459</td>
</tr>
</tbody>
</table>

Index                                                                                       481
With the recent technological advances in wireless communication and the increasing popularity of portable computing devices, wireless and mobile ad hoc networks are expected to play an increasingly important role in future civilian and military settings where wireless access to wired backbone is either ineffective or impossible. Mobile ad hoc networks (MANETs) are composed of a set of stations (nodes) communicating through wireless channels, without any fixed backbone support. Applications of MANETs include, but are not limited to, military operations, security, emergency, and rescue operations, among other applications where intense utilization of a communication network is available for a very limited time. However, frequent topology changes caused by node mobility make routing in wireless ad hoc networks a challenging problem. In addition, limited capabilities of mobile stations require a control on node congestion due to message forwarding and limited battery consumption. Mobility of mobile hosts introduces also new challenging problems that were not encountered in the design and implementation of conventional wireless and wired networks. A critical and challenging problem of mobile ad hoc networking and computing is how to fully cope with the special characteristics of the wireless and mobile ad hoc environment, make balanced use of computation and communication resources, and take advantage of and support the user’s mobility. Most of the available literature in this emerging technology concentrates on physical and networking aspects of the subject. However, in most of the these studies, they have neglected the description of the fundamental design of distributed algorithms and have not discussed how to apply them to wireless and mobile ad hoc and network setting environments. An important requirement for successful deployment of wireless and mobile ad hoc network-based applications is the careful evaluation of performance and investigation of alternatives algorithms, prior to their implementation. In light of this, the purpose of this book is to focus on several aspects of mobile ad hoc networking and computing and, in particular, algorithmic methods and distributed computing with mobile communication and computation capabilities.

This book is organized as follows. In Chapter 1, we address the design challenges of distributed algorithms and discuss several important algorithmic issues arising in wireless and mobile networks. Algorithms for MANETs must self-configure and must adjust to environment and data communication where they run, and goal changes posed from the user and application. Chapter 2 presents several techniques for enabling communication infrastructure and maintenance in ad hoc networks. Network-Wide Broadcast (NWB) algorithms provide a mechanism to deliver information to nodes in multihop and networks without depending on routing state. This makes them
ideal for initial self-configuration or for operation under mobility where the routing state becomes stale. Chapter 3 presents a classification of existing NWB algorithms, focusing on their robustness characteristics representing different points of the space under different network densities, loss rates, and routing and mobility characteristics. The heterogeneity of portable devices to be interconnected, along with the large spectrum of communication requirements, has helped the design of a new set of multihop ad hoc network technologies, which are known as opportunistic networks, and they represent one of the most interesting scenarios for the application of the encoding techniques. Several studies have been devoted to possible applications of network coding over multihop networks. Chapter 4 describes the basic encoding techniques upon which network coding is based, and then it presents encoding techniques for efficient data distribution in multihop ad hoc networks.

Because of the frequent changes of mobile nodes, routing has always been one of the most challenging problem for MANET’s designers. Chapter 5 provides a comprehensive taxonomy of existing ad hoc routing protocols, and it discusses the advantages and disadvantages of each of the routing protocols. Chapter 6 presents a set of well-known mobility-adaptive multicast routing protocols for MANETs. Traditional IP multicast and routing protocols are inappropriate for mobile ad hoc networks. This is mainly because multicast trees could easily break due to dynamic topologies of MANET. Chapter 7 discusses the evolution of multihop wireless network routing protocols from the perspective of accounting for link quality, and then it provides an overview of recent efforts to model and analytically derive near-optimal routing configurations. Chapter 8 provides an overview of the state of the art on routing protocols in intermittently connected mobile ad hoc networks and delay-tolerant networks.

The Transmission Control Protocol (TCP) is an efficient transport layer protocol designed for wired networks (such as the Internet). However, many studies have shown that it performs badly in the wireless and mobile ad hoc network (MANETs) environments. Chapter 9 provides a thorough understanding of the problems of traditional TCP over wired networks and presents the principles behind the proposed traditional TCP enhancements for mobile ad hoc networks. As a follow-up, Chapter 10 identifies the main challenges faced by TCP when used over a diverse ad hoc network environment, and it discusses recent ACK-thinning techniques that have been proposed for MANET environments.

Transmission power control in wireless ad hoc networks is concerned with the selection of transmit power for packet transmission at each node to achieve some desired performance targets. The transmit power level affects many aspects of the operation of wireless ad hoc network. Chapter 11 discusses some basic principles that can be used as a guideline for the design of efficient power control protocols and presents several well-known power control algorithms and protocols while highlighting their impacts on the layers of the protocol stack. In recent years, we have been witnessing a growing interest to WLAN mesh networks. This is mainly because they are viewed as a cost-effective way of deploying outdoor coverage in metro-area Wi-Fi hot zones. In a WLAN mesh, multihop relaying is used to reduce the infrastructure cost of providing wired network connections to each WLAN mesh node. However, before these multihop networks become a commodity for outdoor mesh deployments, we must
ensure that there are continuous electrical power connections to mesh nodes. Chapter 12 discusses the design and resource allocation for solar-powered IEEE 802.11 WLAN mesh networks.

Wireless communication networks, in general, and mobile ad hoc networks (MANETs), in particular, have undergone tremendous technological advances over the last few years. However, due to the nature of MANETs, nodes are vulnerable to a variety of security threats. Unless we take these security issues seriously, mobile ad hoc networks will never be fully deployed and adopted by the regular users. Indeed, security and trust have been widely recognized as an important factor affecting consumer behavior. Chapter 13 presents a detailed understanding of reputation-and-trust-based systems for wireless network in general, as well as of mobile ad hoc networks in particular.

In these last few years, we have seen the development of a number of research studies investigating the use of ad hoc networks as a communication technology for vehicle-specific applications within the wider concept of Intelligent Transportation Systems (ITS). In this kind of network, vehicles have communication capability, which allows them to exchange messages with each other using vehicle-to-vehicle communication (V2V) and to exchange messages with a roadside network infrastructure using roadside-to-vehicle communication (R2V). Chapter 14 identifies the main features that distinguish vehicular ad hoc networks from traditional ad hoc networks, and it also presents a summary of the enabling technologies that are expected to support this emerging technology, while Chapter 15 presents the routing techniques that are suitable for vehicular ad hoc networks and highlights the transport and security issues for these networks. Last but not least, Chapter 16 discusses the main design and performance issues of cluster interconnection for beacon-enabled 802.15.4 clusters, an emerging technology for multihop wireless networks, and then highlights the pros and cons for each of the proposed approaches.

It is our belief that this is the first book that covers the basic and fundamental algorithms and protocols for wireless ad hoc and multihop networks, making their design and analysis accessible to all levels of readers.

Special thanks are due to all contributors for their support and patience, as well as to the reviewers for their hard work and timely reports, which make this book truly special. Last but not least, we wish to extend our thanks to Paul Petralia and Whitney Lesch from John Wiley & Sons for their support, guidance, and certainly their patience in finalizing this book.

AZZEDINE BOUKERCHE

University of Ottawa
CONTRIBUTORS

Nael B. Abu-Ghazaleh, Computer Science Department, Binghamton University, Binghamton, NY 13902

Mohammad Z. Ahmad, School of Electrical Engineering and Computer Science, University of Central Florida, Orlando, FL

Maen M. Artimy, Internetworking Atlantic Inc., Halifax, Nova Scotia, Canada, B3J 1L1

Michel Barbeau, School of Computer Science, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

Brahim Bensaou, Department of Computer Science and Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong

Azzedine Boukerche, School of Information Technology and Engineering, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada

Daniel Câmara, Department of Computer Science, Federal University of Minas Gerais, Belo Horizonte, Brazil

Mihaela Cardei, Department of Computer Science and Engineering, Florida Atlantic University, Boca Raton, FL 33431

Marco Conti, IIT-CNR, Via G. Moruzzi 1, Pisa 56124, Italy

Michalis Faloutsos, Computer Science Department, University of California, Riverside, California, 92521 USA

Carlos M.S. Figueiredo, FUCAPI—Analysis, Research, and Technology Innovation Center, Belo Horizonte, Brazil

Chaiporn Jaikaeo, Department of Computer Engineering, Kasetsart University, Bangkok, Thailand

Maria Kihl, Department of Electrical and Information Technology, Lund University, Sweden

Vinay Kolar, Computer Science Department, Binghamton University, Binghamton, NY 13902, USA

Evangelos Kranakis, School of Computer Science, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada
Srikanth V. Krishnamurthy, Computer Science Department, University of California, Riverside, California, 92521 USA

Ioannis Lambadaris, Department of Systems and Computer Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

Lap Kong Law, Trapeze Networks, Pleasanton, CA, 94588-4084

Antonio A.F. Loureiro, Department of Computer Science, Federal University of Minas Gerais, Belo Horizonte, Brazil

Huigang Liang, Department of Management Information Systems, East Carolina University, Greenville, North Carolina 27858

Lewis M. MacKenzie, Department of Computing Science, University of Glasgow, Glasgow G12 8RZ, Scotland

Jelena Mišić, Department of Computer Science, University of Manitoba, Winnipeg, Manitoba, Canada

Farid Naït-Abdesselam, IRCICA/LIFL—INRIA POPS, University of Lille 1, Lille, France

Mohamed Ould-Khaoua, Department of Computing Science, University of Glasgow, Glasgow G12 8RZ, Scotland

Stylianos Papanastassiou, Department of Computing Science, University of Glasgow, Glasgow G12 8RZ, Scotland

Andrea Passarella, IIT-CNR, Via G. Moruzzi 1, Pisa 56124, Italy

Luciana Pelusi, IIT-CNR, Via G. Moruzzi 1, Pisa 56124, Italy

William J. Phillips, Department of Engineering Mathematics and Internetworking, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 4R2

William Robertson, Internetworking Program, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 4R2

Paul Rogers, Computer Science Department, Binghamton University, Binghamton, NY 13902

Amir A. Sayegh, Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada

Chien-Chung Shen, Department of Computer and Information Sciences, University of Delaware, Newark, DE 19716

Mihail L. Sichitiu, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695

Mohammed N. Smadi, Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada
Avinash Srinivasan, Department of Mathematics, Computer Science, and Statistics, Bloomsburg University, Bloomsburg, PA 17815

Joshua Teitelbaum, Microsoft, Redmond, Seattle 98052

Terence D. Todd, Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada

Begumhan Turgut, Department of Computer Science, Rutgers University, Piscataway, NJ

Damla Turgut, School of Electrical Engineering and Computer Science, University of Central Florida, Orlando, FL 32816-2450

Ranjith Udayshankar, Department of Computer Science, University of Manitoba, Winnipeg, Manitoba, Canada

Jie Wu, Department of Computer Science and Engineering, Florida Atlantic University, Boca Raton, FL 33431

Zhensheng Zhang, San Diego Research Center, San Diego, CA 92121

Junhua Zhu, Department of Computer Science and Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong
Azzedine Boukerche is a Professor and holds a Canada Research Chair position at the University of Ottawa. He is the Founding Director of Paradise Research Laboratory at the University of Ottawa. Prior to this, he held a Faculty position at the University of North Texas, and he was working as a Senior Scientist at the Simulation Sciences Division, Metron Corporation, located in San Diego. He was also employed as a faculty member at the School of Computer Science, McGill University, and he taught at Polytechnic of Montreal. He spent a year at the JPL/NASA-California Institute of Technology, where he contributed to a project centered around the specification and verification of the software used to control interplanetary spacecraft operated by JPL/NASA Laboratory. His current research interests include wireless ad hoc and sensor networks, wireless networks, mobile and pervasive computing, wireless multimedia, QoS service provisioning, large-scale distributed interactive simulation, parallel discrete event simulation, and performance evaluation and modeling of large-scale distributed and mobile systems. Dr. Boukerche has published several research papers in these areas. He was the recipient of and/or nominated for the Best Research Paper Award at IEEE/ACM PADS ’97, IEEE/ACM PADS ’99, ACM MSWiM 2001, ICC’08, and MobiWac’06, and he was the co-recipient of the 3rd National Award for Telecommunication Software 1999 for his work on distributed security systems on mobile phone operations.

Dr. A. Boukerche is a holder of an Ontario Early Research Excellence Award (previously known as Premier of Ontario Research Excellence Award), an Ontario Distinguished Researcher Award, and a Glinski Research Excellence Award. He is a Co-Founder of QShine International Conference on Quality of Service for Wireless/Wired Heterogeneous Networks (QShine 2004) and has served as a General Chair for the 8th ACM/IEEE Symposium on Modeling, Analysis, and Simulation of Wireless and Mobile Systems, the 9th ACM/IEEE Symposium on Distributed Simulation and Real-Time Application, and the 6th IEEE/ACM MASCOT ’98 Symposium; he has also served as the Vice General Chair for the 3rd IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS ’07), Program Chair for IEEE Globecom 2007 and 2008 Ad Hoc, Sensor and Mesh Networking Symposium, and a Program Co-Chair for ICPP 2008, the 2nd ACM Workshop on QoS and Security for Wireless and Mobile Networks, ACM/IFIPS Europar 2002 Conference, IEEE/SCS Annual Simulation Symposium ’02, ACM WWW ’02, IEEE MWCN 2002, IEEE/ACM MASCOTS ’02, IEEE Wireless Local Networks 03-04, IEEE WMAN 04-05, and ACM MSWiM 98-99.
1.1 INTRODUCTION

In the fourth century B.C., the Greek writer Aeschylus wrote the play *Agamemnon*, which provides a detailed description of how fire signals were supposedly used to communicate the fall of Troy to Athens over a distance of more than 450 km. This very same idea is present in the third movie of the trilogy “The Lord of the Rings,” where fire signals were used to call for help of an ally army. In both cases, as well as in others found mainly in the literature and movies, the problem with a fire signal is that there is only one meaning associated with it—in the examples above, the fall of Troy and the call for help, respectively. This limitation of using fire signals to relay a message was realized by Polybius, one of the most famous ancient Greek historians who lived 200 years after Aeschylus in the second century B.C. To overcome this limitation, Polybius proposed a very simple fire signal mechanism based on fire torches that could be used to relay different messages. He described the procedure a person should follow before they start transmitting a message to another one (i.e., how a connection could be established between a pair of communicating entities), and he also described how messages could be coded using fire torches. Since this was basically a visual communication system, other people could see the same message (broadcast) and the people responsible for relaying messages could be mobile.
Polybius can probably be considered the first data communication engineer for mobile ad hoc networks. What it is more amazing is that his ideas were used during the next 2000 years for relaying messages among people in scenarios similar to the ones described above.

A mobile ad hoc network (MANET)\(^1\) is comprised of mobile hosts that can communicate with each other using wireless links. It is also possible to have access to some hosts in a fixed infrastructure, depending on the kind of mobile ad hoc network available. Some scenarios where an ad hoc network can be used are business associates sharing information during a meeting, emergency disaster relief personnel coordinating efforts after a natural disaster such as a hurricane, earthquake, or flooding, and military personnel relaying tactical and other types of information in a battlefield.

In this environment a route between two hosts may consist of hops through one or more nodes in the MANET. An important problem in a mobile ad hoc network is finding and maintaining routes since host mobility can cause topology changes. Several routing algorithms for MANETs have been proposed in the literature, and they differ in the way new routes are found and existing ones are modified.

Mobile ad hoc networks can be realized by different networks such as body area network (BAN), vehicular ad hoc network (VANET), wireless networks (varying from personal area network to wide area network), and wireless sensor network (WSN). Furthermore, MANETs can be realized by different wireless communication technologies such as Bluetooth, IEEE 802.11, and Ultra-Wide Band (UWB). However, each one of these networks combined with the communication technologies pose various challenges in the design of algorithms for them as discussed in the following.

### 1.2 DESIGN CHALLENGES

The design of algorithms for MANETs poses new and interesting research challenges, some of them particular to mobile ad hoc networks. Algorithms for a MANET must self-configure to adjust to environment and traffic where they run, and goal changes must be posited from the user and application.

Data communication in a MANET differs from that of wired networks in different aspects. The wireless communication medium does not have a foreseeable behavior as in a wired channel. On the contrary, the wireless communication medium has variable and unpredictable characteristics. The signal strength and propagation delay may vary with respect to time and environment where the mobile nodes are. Unlike a wired network, the wireless medium is a broadcast medium; that is, all nodes in the transmission range of a transmitting device can receive a message.

The bandwidth availability and computing resources (e.g., hardware and battery power) are restricted in mobile ad hoc networks. Algorithms and protocols need to save both bandwidth and energy and must take into account the low capacity and

\(^1\)Ad hoc is a Latin expression that means “for the particular end or case at hand without consideration of wider application”. An ad hoc network means that the network is established for a particular, often extemporaneous service customized to applications for a limited period of time.
limited processing power of wireless devices. This calls for lightweight solutions in terms of computational, communication, and storage resources.

An important challenge in the design of algorithms for a mobile ad hoc network is the fact that its topology is dynamic. Since the nodes are mobile, the network topology may change rapidly and unexpectedly, thereby affecting the availability of routing paths. Figure 1.1 depicts a snapshot of a MANET topology.

Given all these differences, the design of algorithms for ad hoc networks are more complex than their wired counterpart.

1.3 MANETs: AN ALGORITHMIC PERSPECTIVE

1.3.1 Topology Formation

**Neighbor Discovery.** The performance of an ad hoc network depends on the interaction among communicating entities in a given neighborhood. Thus, in general, before a node starts communicating, it must discover the set of nodes that are within its direct communication range. Once this information is gathered, the node keeps it in an internal data structure so it can be used in different networking activities such as routing. The behavior of an ad hoc node depends on the behavior of its neighboring nodes because it must sense the medium before it starts transmitting packets to nodes in its interfering range, which can cause collisions at the other nodes.
Node discovery can be achieved with periodic transmission of beacon packets (active discovery) or with promiscuous snooping on the channel to detect the communication activity (passive discovery). In PRADA [1], a given source node sends periodically to its neighboring nodes a discovery packet, and in turn their neighbors reply with a location update packet (that might include, for instance, the node’s geographical location). PRADA adjusts dynamically its communication range, called topology knowledge range, so it leads to a faster convergence of its neighboring nodes.

**Packet Forwarding Algorithms.** An important part of a routing protocol is the packet forwarding algorithm that chooses among neighboring nodes the one that is going to be used to forward the data packet. The forwarding algorithm implements a forwarding goal that may be, for instance, the shortest average hop distance from source to destination. In this case, the set of potential nodes may include only those in direct communication range from the current node or also the set of possible nodes in the route to the destination. The forwarding goal may also include some QoS parameters such as the amount of energy available at each node.

The following forwarding algorithms consider only nodes that are in direct communication range of the node that has a data packet to be forwarded, as depicted in Figure 1.2. The Most Forward within Radius (MFR) forwarding algorithm [2] chooses the node that maximizes the distance from node $S$ to point $p$. In this case, as depicted in Figure 1.2, it is node 1. On the other hand, the Nearest Forward Progress (NFP) forwarding algorithm [3] chooses the node that minimizes the distance from node $S$ to point $q$. In this case it is node 2. The Greedy Routing Scheme (GRS) [4] uses the nodes’ geographical location to choose the one that is closest to the destination node $D$.

![Figure 1.2. Strategies used by some forwarding algorithms.](image-url)
In this case it is node 3. The compass-selected routing (COMPASS) algorithm [5] chooses the node that minimizes the angle $\alpha$ but considers the nodes that are closer to node $D$. In this case it is node 4. The random process forwarding algorithm [6], as the name suggests, chooses a random node that is in direct communication range from $S$.

The Partial Topology Knowledge Forwarding (PTKF) algorithm [1] chooses a node using a localized shortest path weighted routing where routes are calculated based on the local topological view and consider the transmission power needed to transmit in that link.

1.3.2 Topology Control

Topology control algorithms select the communication range of a node, and they construct and maintain a network topology based on different aspects such as node mobility, routing algorithm, and energy conservation [7]. Broadly speaking, topology control algorithms for ad hoc networks can be classified in hierarchical or clustering organization, as well as in power-based control organization [7, 8]. Furthermore, these algorithms can be either centralized, distributed, or localized.

Clustering Algorithms. The clustering process consists in defining a cluster-head node and the associated communication backbone, typically using a heuristic. The goal is to avoid redundant topology information so the network can work more efficiently. Clustering algorithms are often modeled as graph problems such as the minimum connected dominating set (MCDS) [9]. This problem asks for the minimum subset of nodes $V'$ in the original graph $G = (V, E)$ such that $V'$ form a dominating set of $G$ and the resulting subgraph of the MCDS has the same number of connected components of $G$. It means that if $G$ is a connected graph, so is the resulting subgraph. MCDS is an NP-complete problem [10], and thus we must look for approximate solutions [7]. In the case of the clustering algorithm, nodes in the dominating set represent the cluster heads and the other nodes are their neighbors. An inherent characteristic of an ad hoc network, which makes this problem much more difficult, is that its topology is dynamic.

The cluster heads can be elected using either deterministic or nondeterministic approaches. A deterministic solution is similar to a distributed synchronous algorithm in the sense that it runs in rounds. In this case there is just one round, and after finishing it the cluster heads are chosen. Suppose we have a node and its neighboring nodes—that is, its one-hop neighborhood. The lowest ID solution selects the node with the lowest identifier among them to create the minimal dominating set (MDS) [10]. The max degree solution selects the node with the highest degree among them [11, 12]. The MOBIC solution examines the variations of RSSI (received signal strength indicator) signal among them to select the cluster head [13].

A nondeterministic solution runs multiple incremental steps to avoid variations in the election process and to minimize conflicts among cluster heads in their one-hop neighborhood. Examples of this approach are CEDAR [11], SPAN [14], and solutions based on a spanning tree algorithm [9].
Power-Based Control Algorithms. A mobile node in a MANET must rely on a energy source (typically a battery) to execute all its tasks. Batteries need to be recharged to provide a continuous energy supply for a node. To extend the lifetime of nodes in an ad hoc network, we need algorithms to determine and adaptively adjust the transmission power of each node so as to meet a given minimization goal and, at the same time, maintain a given connectivity constraint. Some possible minimization goals are to control the maximum or average power and define a maximum or average connectivity degree. Some connectivity constraints are a simplex communication or a full-duplex communication (biconnected). Ramanathan and Hain [2] propose a topology control algorithm that dynamically adjusts its transmission power such that the maximum power used is minimized while keeping the network biconnected.

1.3.3 Routing

The main goal of an ad hoc network routing algorithm is to correctly and efficiently establish a route between a pair of nodes in the network so a message can be delivered according to the expected QoS parameters [15, 16]. The establishment of a route should be done with minimum overhead and bandwidth consumption. In the current wired networks, there are different link state [17] and distance vector [18] routing protocols, which were not designed to cope with constant topology changes of mobile ad hoc environments. Link-state protocols update their global state by broadcasting their local state to every other node, whereas distance-vector protocols exchange their local state to adjacent nodes only. Their direct application to a MANET may lead to undesired problems such as routing loops and excessive traffic due to the exchange of control messages during route establishment.

An ad hoc network has a dynamic nature that leads to constant changes in its network topology. As a consequence, the routing problem becomes more complex and challengeable, and it probably is the most addressed and studied problem in ad hoc networks. This reflects the large number of different routing algorithms for MANETs proposed in the literature [15].

Ideally, a routing algorithm for an ad hoc network should not only have the general characteristics of any routing protocol but also consider the specific characteristics of a mobile environment—in particular, bandwidth and energy limitations and mobility. Some of the characteristics are: fast route convergence; scalability; QoS support; power, bandwidth, and computing efficient with minimum overhead; reliability; and security. Furthermore, the behavior of an ad hoc routing protocol can be further complicated by the MAC protocol. This is the case of a data link protocol that uses a CSMA (Carrier Sense Multiple Access) mechanism that presents some problems such as hidden stations and exposed stations.

In general, routing algorithms for ad hoc networks may be divided into two broad classes: proactive protocols and reactive on-demand protocols, as discussed in the following.

Proactive Protocols. Proactive routing algorithms aim to keep consistent and up-to-date routing information between every pair of nodes in the network by proactively
propagating route updates at fixed time intervals. Usually, each node maintains this information in tables; thus, protocols of this class are also called table-driven algorithms. Examples of proactive protocols are Destination-Sequenced Distance Vector (DSDV) [19], Optimized Link-State Routing (OLSR) [20], and Topology-Based Reverse Path Forwarding (TBRPF) Protocols [21].

The DSDV protocol is a distance vector protocol that incorporates extensions to make its operation suitable for MANETs. Every node maintains a routing table with one route entry for each destination in which the shortest path route (based on the number of hops) is recorded. To avoid routing loops, a destination sequence number is used. A node increments its sequence number whenever a change occurs in its neighborhood. When given a choice between alternative routes for the same destination, a node always selects the route with the greatest destination sequence number. This ensures utilization of the route with the most recent information.

The OLSR protocol is a variation version of the traditional link state protocol. An important aspect of OLSR is the introduction of multipoint relays (MPRs) to reduce the flooding of messages carrying the complete link-state information of the node and the size of link-state updates. Upon receiving an update message, the node determines the routes (sequence of hops) to its known nodes. Each node selects its MPRs from the set of its neighbors such that the set covers those nodes that are distant two hops away. The idea is that whenever a node broadcasts a message, only those nodes present in its MPR set are responsible for broadcasting the message.

The Topology-Based Reverse Path Forwarding is also a variation of the link-state protocol. Each node has a partial view of the network topology, but is sufficient to compute a shortest path source spanning tree rooted at the node. When a node receives source trees maintained at neighboring nodes, it can update its own shortest path tree. TBRPF exploits the fact that shortest path trees reported by neighbor nodes tend to have a large overlap. In this way, a node can still compute its shortest path tree even if it receives partial trees from its neighbors. In this way, each node reports part of its source tree, called reported tree (RT), to all of its neighbors to reduce the size of topology update messages, which can be either full or differential. Full updates are used to send to new neighbors the entire RT to ensure that the topology information is correctly propagated. Differential updates contain only changes to RT that have occurred since the last periodic update. To reduce further the number of control messages, topology updates can be combined with Hello messages so that fewer control packets are transmitted.

**Reactive Protocols.** Reactive on-demand routing algorithms establish a route to a given destination only when a node requests it by initiating a route discovery process. Once a route has been established, the node keeps it until the destination is no longer accessible, or the route expires. Examples of reactive protocols are Dynamic Source Routing (DSR) [22] and Ad Hoc On-Demand Distance Vector (AODV) [23].

The DSR protocol determines the complete route to the destination node, expressed as a list of nodes of the routing path, and embeds it in the data packet. Once a node receives a packet it simply forwards it to the next node in the path. DSR keeps a cache
structure (table) to store the source routes learned by the node. The discovery process is only initiated by a source node whenever it does not have a valid route to a given destination node in its route cache. Entries in the route cache are continually updated as new routes are learned. Whenever a node wants to know a route to a destination, it broadcasts a route request (RREQ) message to its neighbors. A neighboring node receives this message, updates its own table, appends its identification to the message and forwards it, accumulating the traversed path in the RREQ message. A destination node responds to the source node with a route reply (RREP) message, containing the accumulated source route present in the RREQ. Nodes in DSR maintain multiple routes to a destination in the cache, which is helpful in case of a link failure.

The AODV protocol keeps a route table to store the next-hop routing information for destination nodes. Each routing table can be used for a period of time. If a route is not requested within that period, it expires and a new route needs to be found when needed. Each time a route is used, its lifetime is updated. When a source node has a packet to be sent to a given destination, it looks for a route in its route table. In case there is one, it uses it to transmit the packet. Otherwise, it initiates a route discovery procedure to find a route by broadcasting a route request (RREQ) message to its neighbors. Upon receiving a RREQ message, a node performs the following actions: checks for duplicate messages and discards the duplicate ones, creates a reverse route to the source node (the node from which it received the RREQ is the next hop to the source node), and checks whether it has an unexpired and more recent route to the destination (compared to the one at the source node). In case those two conditions hold, the node replies to the source node with a RREP message containing the last known route to the destination. Otherwise, it retransmits the RREQ message.

Some Comments. An important question is to determine the best routing protocol to be used in a MANET. This is not a simple issue, and the identification of the most appropriate algorithm depends on different factors such as QoS guarantees, scalability, and traffic and mobility pattern. Reactive protocols tend to be more efficient than proactive protocols in terms of control overhead and power consumption because routes are only created when required. On the other hand, proactive protocols need periodic route updates to keep information updated and valid. In addition, many available routes might never be needed, which increases the routing overhead. Proactive protocols tend to provide better quality of service than reactive protocols. In this class of protocols, routing information is kept updated; thus, a route to a given destination is available and up-to-date, which minimizes the end-to-end delay. Royer and Toh [15] present a comparison of these protocols in terms of their complexity, route update patterns, and capabilities.

The above classification is very broad, and there are other taxonomies to categorize routing protocols [24]. For instance, there are protocols that use a hybrid scheme to route messages; that is, they try to combine the advantages of some protocols, whereas there are protocols that use the node’s geographical location to route messages.

It is interesting to observe that some IETF MANET Internet Drafts [mobile ad hoc networks (MANETs)] have reached a reasonable level of maturity, analysis, and
implementation experience and became IETF standards. This includes the proactive protocols Optimized Link-State Routing (OLSR) [20] and Topology Dissemination-Based Reverse Path Forwarding (TBRPF) [21] and the reactive protocols Distributed Source Routing (DSR) [22] and Ad Hoc On-Demand Distance Vector (AODV) [23].

1.3.4 Multicasting and Broadcasting

An important aspect in the design of a routing protocol is the type of communication mode allowed between peer entities. Routing protocols for a MANET can be unicast, geocast, multicast, or broadcast. Unicast is the delivery of messages to a single destination. Geocast is the delivery of messages to a group of destinations identified by their geographical locations. Multicast is the delivery of messages to a group of destinations in such a way that it creates copies only when the links to the destinations split. Finally, broadcast is the delivery of a message to all nodes in the network.

Notice that, broadly speaking, there are two types of physical transmission technology that are largely used: broadcast links and point-to-point links. In a network with a single broadcast channel, all communicating elements share it during their transmissions. In a network that employs a wireless medium, which is the case of a mobile ad hoc network, broadcast is a basic operation mode whereby a message is received by all the source node’s neighbors. In a MANET, the four communication modes that can be implemented by a routing protocol are realized by a wireless broadcast channel.

A multicast routing protocol is employed when a mobile node wants to send the same message or stream of data to a group of nodes that share a common interest. If there is a geographical area (location) associated with the nodes that will receive the message or stream of data, we use a geocast protocol. Thus, a geocast protocol is a special type of multicast protocol, such that nodes need their updated location information along the time to delivery a message. In a multicast communication, nodes may join or leave a multicast group as desired, whereas in a geocast communication, nodes can only join or leave the group by entering or leaving the defined geographical region.

In a MANET, a multicast communication can possibly bring benefits to the nodes such as bandwidth and energy savings. However, the maintenance of a multicast route, often based on a routing tree or mesh, is a difficult problem for mobile ad hoc multicasting routing protocols due to the dynamic nature of a MANET. In particular, the cost of keeping a routing tree connected for the purpose of multicast communication may be prohibited. In a multicast mesh, a message can be accepted from any router node, as opposed to a tree that only accepts packets routed by tree nodes. Thus, a multicast mesh is more suitable for a MANET because it supports a higher connectivity than a tree. The method used to build the routing infrastructure (tree or mesh) in a mobile ad hoc network distinguishes the different multicasting routing protocols.

Some of the route-tree-based multicast protocols for MANETs are AMRoute (Adhoc Multicast Routing Protocol) [25], DDM (Differential Destination Multicast) [26], and MAODV (Multicast Ad-hoc On-Demand Distance Vector routing) [27]. AMRoute uses an overlay approach based on bidirectional unicast tunnels
to connect group members into the mesh. DDM is a stateless multicast protocol in the sense that no protocol state is maintained at any node except for the source node. Intermediate nodes cache the forwarding list present in the packet header. When a route change occurs, an upstream node only needs to pass to its downstream neighbors the difference to the forwarding nodes since the last packet. MAODV is the multicast version of the AODV protocol [23]. It uses a multicast route table (MRT) to support multicast routing. A node adds new entries into the MRT after it is included in the route for a multicast group. MAODV uses a multicast group leader to create an on-demand core-based tree structure.

Different from the previous route-tree-based multicast algorithms, LGT (Location-Guided Tree Construction Algorithm for Small Group Multicast) [28] uses the location information of the group members to build the multicast tree without the knowledge of the network topology. Two heuristics are proposed to build the multicast tree using location information: the Location-Guided \textit{k}-ray tree (LGK) and the Location-Guided Steiner tree (LGS).

Some of the mesh-based multicast routing protocols for MANETs are CAMP (Core-Assisted Mesh Protocol) [29], FGMP (Forwarding Group Multicast Protocol) [30], and ODMRP (On-Demand Multicast Routing Protocol) [31]. CAMP generalizes the notion of core-based trees introduced for Internet multicasting. It uses core nodes for limiting the control traffic needed for the creation of a multicast mesh avoiding flooding. On the other hand, both FGMP and ODMRP use flooding to build the mesh. In the FGMP protocol, the receiver initiates the flooding process, whereas in the ODMRP the senders initiates it.

1.3.5 Transport Protocols

The Transmission Control Protocol (TCP) is by far the most used transport protocol in the Internet. It is the typical protocol for most network applications. TCP is a reliable connection-oriented stream transport protocol that has the following features: explicit and acknowledged connection initiation and termination; reliable, in-order, and not duplicated data delivery; flow control; congestion avoidance; and out-of-band indication of urgent data.

An important design issue of TCP is that it uses packet loss as an indication of network congestion, and it deals with this effectively by making corresponding transmission adjustment to its congestion window. In wired networks, error rates are quite low and the TCP’s congestion avoidance mechanism works very well.

The mobile multihop ad hoc network introduces new challenges to the TCP protocol due to the frequent change in network topology, disconnections, variation in link capacity, and high error rate. In fact, issues present in the physical, MAC, and network layers can affect the performance of the TCP protocol. In a wireless mobile ad hoc network, packet losses are usually not caused by network congestion, but by error transmissions and frequent disconnections due to mobility, resulting in backoff mechanisms being inappropriately invoked. This reduces the network throughput and increases the delay for data transmission. The variation in link capacity, the presence of asymmetric links, and delayed acknowledgment of messages can seriously affect the