POLICY-DRIVEN MOBILE AD HOC NETWORK MANAGEMENT

RITU CHADHA • LATHA KANT

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Policy-Driven Mobile Ad hoc Network Management

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To my father, Indrajit Singh Chadha, who has been my inspiration throughout my life.
Thank you for being my mentor, supporter, cheerleader, and guide!
Ritu Chadha

To my Wonderful Family: my parents for having taught me perseverance and sincerity by example; my son and husband for their understanding, love, and support; and my brother for his confidence in me!
Latha Kant

FOREWORD

This book provides a comprehensive overview of policy-based network management as applied to mobile ad hoc networks (MANETs), including technical foundations, lessons learned, standards initiatives, state-of-the-art approaches, and new research directions.

The challenge of network management is to synthesize coherent system-level behaviors from a large set of individual network elements. In policy-driven management approaches, a network operator's high-level statement of objectives is used to manage low-level control interfaces exposed by component software in the network elements. For traditional networks, policy-based approaches hold out the potential of automation leading to higher availability, superior performance, and tremendous cost savings. For MANETs, automation is a necessity and not just a desirable goal.

Mobile ad hoc networks are the linchpin of strategies for providing ubiquitous connectivity and computing in the absence of infrastructure. Defense applications for "network-centric operations" are a driving motivator, although closely related civilian applications are recently emerging in emergency response, monitoring and control, telematics, and home networking.

In the long run, simple and reliable multihop wireless transactions are likely to become an increasingly important fraction of all communications at the network edge. Even so, the technical obstacles to creating and operating adaptive, efficient, and assurable multiphop radios are nearly overwhelming. Techniques and protocols that have long sufficed in infrastructure-based settings break down when applied to MANETs.

The first and most obvious casualty of network node mobility was traditional routing, and much of the early work on MANETs focused on new adaptive routing protocols. However, recently it has become clear that mobility in wireless networks has a deep impact on more than just the routing layer. The combined peculiarities of mobility and radio-frequency communication are now driving a deep reexamination of wider assumptions behind conventional networking.

For instance, researchers have recently demonstrated "cross-layer" designs that offer performance improvements by breaking down the separation of concerns implicit in conventional layered network models. Thus the conventional ISO-OSI 7-layer model may not be the most appropriate basis for a MANET software architecture. In addition, hop-by-hop mechanisms for congestion control appear to be better at avoiding hotspots and queue instability in wireless networks than end-to-end protocols. Thus the end-to-end designs that have been the basis for progress in the Internet may not be sufficient for MANETs. And finally, although the balance of evidence in favor of network coding has not yet tipped, it is possible that future wireless networks may even do altogether away with the traditional idea of packet routing and forwarding in favor of algebraically based information diffusion.

Researchers have much to do before the job is done, but unfortunately the need for MANETs is immediate and we do not have the luxury of waiting for theory to catch up with practice. And herein lies the importance of this book, which approaches the problem of MANETs from an entirely different angle: that of the network operator. Never mind that today's MANET designs are still evolving; there are, nevertheless, people tasked with the job of designing and operating such networks with minimal manual intervention. These are the people that will necessarily have an interest in policy-driven MANETs.

How does an operator view MANETs? Principally as a challenge in network management, with attention to subtopics such as fault management, configuration, accounting, performance, and security. Network operators have always faced the unenviable task of making up for shortfalls in design. The best example is fault tolerance, where operators are the last line of defense against software and hardware flaws, and good operating practices can go a long way to providing reliable solutions based on unreliable components. Policy-based network management is an emerging framework whereby operators can provide flexibility and adaptivity even to software systems that are not inherently adaptive; security to software that was not necessarily created with authorization and authentication in mind; and performance to software that leaves open many degrees of freedom.

Thus operators work from the top down to make the best of whatever solutions are available while at the same time researchers and software engineers work from the bottom up to provide inherently adaptive MANET solutions. Policy-based systems will define the boundary between these two activities: between territory that is theoretically well understood and territory that is not. This boundary is concretely defined by the network's sensing and configuration parameters, which are exposed by software developers precisely because there is no a priori understanding of how to tune these to the operating scenario at hand. Whenever a configuration parameter exists, it is because the software developer is passing a responsibility to the network operator.

A modern network has typically hundreds or thousands of parameters that need to be managed by the operator, and these parameters are rife with feature interactions. It should be no surprise that configuration is one of the

largest of operating expenses for traditional telecommunication providers, that misconfiguration ("human error") is one of the most substantial sources of network downtime, and that misconfiguration is at the core of many security vulnerabilities. The challenge is even harder because these configuration parameters are an uncoordinated accident arising from the fact that every network is a system comprising many independent parts, often created by independent designers and manufacturers.

It is no secret that even traditional network operators find tasks daunting, even with the luxury of months or years to plan networks that will ultimately be highly static and predictable in nature. What then can be expected of mobile ad hoc networks that need to be deployed and operated in even more challenging and volatile conditions? MANETs exponentiate the difficulty of network management.

Manual management techniques that are barely tolerable in wired networks are entirely unworkable for MANETs, so we need an entirely new approach. The approach explored in this book is that of policy-driven management. Policy-based network management provides an architectural framework for bridging the gap between what software designers provide and how operators will use that software.

It is clear that at least three communities should find this book of practical and immediate interest. The first are those systems architects who must present the operator with a manageable overall system. The second is the community of operators, who must understand and use the high-level configuration capabilities of their policy-based MANET to meet the immediate needs of the users. And third, anyone developing component technologies for MANETs needs to understand the context in which their systems will be coordinated with other systems.

Moreover, this book should also be immensely interesting to those trying to decide what MANET research is worth undertaking and why. MANET protocol designers and theoreticians will be fascinated by this material because they will be able to see precisely what kinds of configuration parameters are not considered by operators and systems architects to be adequately handled by the fundamental MANET algorithms. Research might be undertaken to reclaim responsibility for parameters that are currently left in the hands of operators, and this book provides a roadmap of such concerns. Perhaps even more parameters associated with adaptation could lend themselves to direct and optimal algorithmic control, simplifying the remaining tasks for policy-based management. Conversely, wherever the policy enforcement algorithms are adequate, there may be little point in creating specialized protocols.

Beyond direct algorithmic control, there is the wider question of overall "design for manageability" that is really a software engineering problem in its own right, independent of any application in networks. What techniques, especially at the system level, will dramatically simplify the task of operators and therefore also simplify complexity of the policy-based framework? Within networking, current lines of research on "optimization decomposition" and

"network utility maximization" hint at techniques for co-design of the exposed parameters and algorithms for automated adaptation. These techniques are interesting because they cross component boundaries and result in new, more manageable designs overall. There are doubtless many design patterns and techniques that component designers and system architects could use to simplify the remainder of policy issues. One productive perspective from which to study this book is to consider those opportunities.

Although the material in this book is of primary interest to those with a charter to create effective mobile ad hoc networks, the implications of successful MANET designs can be expected to have wider application. MANETs may be a niche, but it is often the case that niche solutions are the basis for disruptive innovation in much wider context. In this case, it is well known that network management is a substantial problem for all operators; any successful technique for automated management that is able to handle the particularly challenging case of MANETs has a substantial potential to be useful in less challenging instances as well. A solution to the hard problem may also address the "easy" problem.

At one point in the twentieth century, it seemed as though a large fraction of the population would need to serve as telephone switchboard operators if the growth in telecommunications continued. The invention of mechanical and digital switching changed the nature of the game. As anyone who manages even a small home network knows, we will similarly need to find new solutions to network management if the ideal of ubiquitous, reliable, secure computing and communications is to be realized. MANETs are at the leading edge of a revolution in adaptive networking protocols, and policy-based architectures are at the leading edge of a revolution in automated management.

For researchers, practitioners, entrepreneurs, and investors who are asking whether the effort to understand and conquer specialized MANET challenges is worthwhile, the answer must depend on whether MANETs are truly a specialized one-off niche, or simply the most pointed evidence that longstanding problems in network management must be solved in order to make overall progress in telecommunications. There is little doubt that the management issues which are taken to an extreme by MANETs are the same management issues that plague the operators of simpler networks. And there is little doubt that a future which truly does offer ubiquitous, secure, and reliable communications and computing will presuppose solutions to the self-configuration challenges brought into sharp relief by MANETs.

Washington, DC J. CHRISTOPHER RAMMING

About the writer: Chris Ramming is presently a program manager in the Defense Advanced Research Projects Agency (DARPA) Strategic Technology Office. His primary charter is to vastly improve wireless network performance, self-management, and intrinsic security. Prior to joining DARPA, the bulk of Mr. Ramming's career was with AT&T/Bell Labs Research. He has a broad

interest in telecommunications technology and has performed work on multimedia softswitches, WWW service creation, networking, provisioning, domain-specific programming languages, decision analysis, and large-scale software engineering. Mr. Ramming holds degrees in computer science from Yale College and the University of North Carolina, Chapel Hill, The views expressed in this foreword are his personal views only and do not necessarily reflect the official views of DARPA or the U.S. government.

PREFACE

Mobile ad hoc networks (MANETs) are rapidly gaining in importance, in both the commercial and the military arenas. In order to deploy and maintain these networks effectively, it is imperative that appropriate network management techniques and tools be used. While a significant amount of research has been dedicated to the development of *networking technologies* for MANETS over the past decade, not much attention has been paid so far to the unique *management needs* of these networks. This is mostly due to the fact that since MANET technologies are relatively new, the bulk of the research efforts in the area of MANETs were concentrated on solving fundamental problems in MANET networking, such as routing, mobility management, transmission schemes, and so on. However, now that technologies for implementing and deploying MANETs are becoming more mature, it is time to turn our attention to the effective *management of MANETs*.

MANETs differ fundamentally in both functionality and capability from their static wireline network counterparts due to a variety of reasons, including random node mobility, unpredictable network dynamics, fluctuating link quality, limited processing capabilities, power constraints, and so on. All of these characteristics give rise to a need for dynamic changes in both the functioning and management of the underlying network. Furthermore, unlike wireline networks, the dependencies or relationships between network elements are not fixed. Due to node mobility, network links are dynamic and of unpredictable quality, resulting in intermittent connectivity. Finally, an underlying problem is the scarcity of wireless network bandwidth. Unlike today's wireline networks, where bandwidth is plentiful and links are reliable, mobile ad hoc networks typically have very limited bandwidth and are relatively less reliable, due to environmental effects.

A great deal of work has been done in the area of network management under the auspices of standards bodies such as the ITU-T (International Telecommunication Union—Telecommunication Standardization Sector) and the IETF (Internet Engineering Task Force). The developed standards have resulted in valuable architecture definitions, abstractions, protocols, and process

models for managing different types of networks. However, one aspect that has not been adequately addressed is the automation of network management and the integration of different management functions. The traditional network management functions include Fault, Configuration, Accounting, Performance, and Security (FCAPS) management. To see why these functions need to be performed in coordination with each other, consider the following illustrative examples. Statistics collected for fault and performance management can be processed and analyzed by various management applications, leading to diagnoses of network problems. In order to fix such problems, there may be a need for repairing or replacing faulty equipment (in the case of network faults); or it may be necessary to reengineer the network to add more capacity to deal with severe network congestion problems; and so on. Such requirements need to be addressed manually, due to the need to physically install or repair equipment in the field. However, many performance and some fault problems can be handled by network reconfiguration. For example, if a network link is severely congested, it may be possible to alleviate the problem by sharing the traffic load with another underutilized link, or by reducing the amount of management traffic, and so on. This can be accomplished simply by appropriately reconfiguring the network. Today, this is done manually by experienced network operators who examine outputs from fault and performance management systems and decide how to reconfigure the network appropriately. This is the fundamental problem with network management today: *There is too much human intervention required to run a network*. In order to reduce the cost of network operations, it is critical that human intervention be minimized by creating a feedback loop between fault/performance monitoring systems and configuration systems and by specifying policies that regulate how the system should be reconfigured in response to various network events.

Clearly, the above points are as valid for wireline networks as they are for MANETs; in other words, the lack of automation in network management is a problem for both wireline networks and MANETs. However, the critical point to note here is that *this lack of automation poses a much greater problem for MANETs than for wireline networks*. This is because *the characteristics of MANETs result in a requirement for much more frequent network reconfiguration and much more stringent monitoring* than needed in wireline networks. The characteristics of MANETs, such as the lack of fixed infrastructure, dynamic topology, power and processing constraints, intermittent connectivity, varying security requirements, scarce bandwidth, and the existence of high-loss, unreliable links, result in a need for much more network management control than is typically needed in a static wireline network, where network elements can be configured in a certain way and rarely need to be reconfigured. The heightened need for network management control stems from the fact that the network must be maintained in a functional state in spite of the dynamic nature of the network. Additionally, this increased network management control must be automated as far as possible, because otherwise the amount of manual intervention required to keep the network functioning

optimally would result in prohibitive cost, making MANETs uneconomical and impractical to deploy.

This book discusses the management challenges associated with ad hoc networks, and it provides an in-depth description of how policy-based network management can be used for increasing automation in the management of mobile ad hoc networks. It describes the required components of a network management solution for such networks, using a policy-based management framework that integrates the traditional network management components (FCAPS, i.e., Fault, Configuration, Accounting, Performance, and Security management).

WHY IS THIS BOOK NEEDED?

The field of mobile ad hoc networking is gaining momentum in both the commercial and the military arenas. The IETF has several working groups devoted to various ad hoc networking issues, namely autoconf (ad hoc network autoconfiguration) and MANET (mobile ad hoc networks), and several books devoted to mobile ad hoc networking have appeared recently (e.g., see Murthy and Manoj [2004], Aggelou [2004], Mohapatra and Krishnamurthy [2004], Toh [1997, 2002], Ilyas [2002], and Santi [2005]). However, relatively little work has been done in the area of network management that is specifically targeted at mobile ad hoc networks. Even in the area of traditional network management, there are very few textbooks that provide a comprehensive view of network management. Most of the books in the area of network management have a very narrow focus and primarily discuss SNMP [Case et al., 1990] and related MIBs (management information bases). There are no books currently on the market that address network management for mobile ad hoc networks. This can partly be explained by the fact that ad hoc networking is a relatively new field, and therefore the networking issues were the first ones that needed to be addressed by the networking community. However, now that the basics of ad hoc networking have been ironed out and standards for ad hoc networking are emerging, there is a void in the area of network management techniques for these networks. This book is the first of its kind in the marketplace and fills this void.

TARGET AUDIENCE

This book is targeted at professionals, researchers, and advanced graduate students in the field of IP network management who are interested in mobile ad hoc networks in particular. Not only does it open up key challenges in the areas of ad hoc networking and ad hoc network management, it also highlights important research aspects in this area that can be of potential interest to advanced researchers in the field of IP networking and network management,

as well as to graduate students. Furthermore, there is a growing research community that is interested in mobile ad hoc networks. In particular, the U.S. military is spending billions of dollars on deploying mobile ad hoc networks for enhancing its warfighting capabilities, as well as hundreds of millions of dollars on building management systems for these networks. In fact, since a detailed understanding of the salient aspects of ad hoc networking has only recently been ironed out, there is now a critical need to turn the attention to managing the ad hoc networks that are being deployed.

To sum up, this book provides readers with an understanding of:

- Mobile ad hoc networking.
- Network management requirements for MANETs, with an emphasis on the differences between the management requirements for MANETs and those for static, wireline networks.
- The use of policies for managing mobile ad hoc networks to increase automation and to tie together management components via policies.
- Policy conflict detection and resolution.
- The aspects of mobile ad hoc networking that need to be configured and reconfigured at all layers of the protocol stack, including a discussion of interdomain policy management.
- Methodologies for providing service survivability in the face of both hard (deterministic) and soft (stochastic) failures in MANETs.
- The components of a quality of service (QoS) management solution for MANETs based on differentiated services (DiffServ).
- The intricacies of managing security in an ad hoc network environment.
- Important open research issues in the area of MANET management.

ABOUT THE AUTHORS

Ritu Chadha is Chief Scientist and Director of the Policy Management research group in Applied Research at Telcordia Technologies, where she has been working since 1992. She was the program manager for the U.S. Army CERDEC DRAMA (Dynamic Re-Addressing and Management for the Army) project, which focused on the design, prototyping, and field demonstration of a policy-based network management system for mobile ad hoc networks. She is also the Chief Engineer for Telcordia's Future Combat Systems (FCS) Network Management System project and is responsible for delivering Policy Management, FCAPS functionality, QoS, and Mobility Management for FCS. Dr. Chadha is a well-known expert in the area of policy management and has published over 50 refereed papers in journals and conferences. She was part of the IETF and DMTF teams that created the Policy Framework standards, and she co-authored IETF RFC 3460 [Moore, 2003], which describes exten-