Preface

The constant improvement in communication technologies and the related dramatic increase in user demand to be connected anytime and anywhere, to both the wealth of information accessible through the Internet and other users and communities, have boosted the pervasive deployment of wireless and wired networked systems.[1] These systems are characterized by the fact of their being *large* or *very large*, highly *heterogeneous* in terms of communication technologies, protocols, and services, and very *dynamic*, due to continual changes in topology, traffic patterns, and number of active users and services.

Intelligent and *autonomic* management, control, and service provisioning in these complex networks, and in the future networks resulting from their integration and evolution, require the definition of novel protocols and techniques for all the architectural components of the network.

In this book we focus on the *routing* component, which is at the very core of the functioning of every network since it implements the strategies used by network nodes to discover and use paths to forward data/information from sources to destinations. An effective design of the routing protocol can provide the basic support to unleash the intrinsic power of the highly pervasive, heterogeneous, and dynamic complex networks of the next generation. In this perspective, the routing path selection must be realized in a fully *automatic* and *distributed* way, and it must be *dynamic* and *adaptive*, to take into account the constant evolution of the network state, which is defined by multiple concurrent factors such as topology, traffic flows, available services, etc.

The literature in the domain of routing is very extensive. Routing research has fully accompanied the evolution of networking to constantly adapt the routing protocols to the different novel communication technologies and to the changes in user demand. In this book we review routing protocols and algorithms which have been specifically designed taking inspiration from, and reverse engineering the characteristics of, processes observed in nature in general and in *insect societies* in particular.

[1] The author would like to sincerely thank Gianni Di Caro for his time and effort in co-authoring this preface.

This class of routing protocols is indeed relatively large. The first notable examples date back to the beginning of the second half of the 1990s, and a number of further implementations rapidly followed the first ones and gained the attention of the scientific community.

The fact that insect societies have and, in general, nature has served as a major source of inspiration for the design of novel routing algorithms can be understood by noticing that these biological systems are characterized by the presence of a set of distributed, autonomous, minimalist units that, through local interactions, self-organize to produce system-level behaviors which show life-long adaptivity to changes and perturbations in the external environment. Moreover, these systems are usually resilient to minor internal failures and losses of units, and scale quite well by virtue of their modular and fully distributed design. All these characteristics, both in terms of system organization and resulting properties, meet most of the necessary and desired properties of routing protocols for next-generation networks. This fact makes it potentially very attractive to look at insect societies to draw inspiration for the design of novel routing protocols featuring *autonomy, distributedness, adaptivity, robustness*, and *scalability*. These are desirable properties, not only in the domain of network routing, but also in a number of other domains. As a matter of fact, in the last 20 years, collective behaviors of insect societies related to operations such as *foraging, labor division, nest building and maintenance, cemetery formation*, etc. have provided the impetus for a growing body of scientific work, mostly in the fields of telecommunications, distributed systems, operations research, and robotics. Behaviors observed in colonies of *ants* and of *termites* have fueled the large majority of this work. In this book, however, we focus our attention on *bee colonies* that since the beginning of our research have been attracting a growing interest.

All the algorithms that will be discussed in the book are characterized by the fact of their being composed by a potentially very large number of *autonomous* and *fully distributed* controllers, and of having been designed according to a *bottom-up* approach, relying on basic *self-organizing* abilities of the system. These characteristics, together with the biological inspiration from behaviors of *insect societies*, are the very fingerprints of the *Swarm Intelligence* (SI) paradigm.

These peculiar design guidelines contrast with those of the more common *top-down* approach followed for the design of the majority of "classical" routing protocols. In typical top-down design a centralized algorithm with well-known properties is implemented in a distributed system. Clearly, this requires us to modify the original algorithm to cope with the intrinsic limitations of a distributed architecture in terms of full state observability and delays in the propagation of the information. The main effect of these modifications is that several properties of the original algorithm do not hold anymore if the network dynamics is non-stationary, which is the most common case. Still, it is relatively easy to assert some general formal properties of the system.

On the other hand, with the bottom-up approach, the design starts with the definition of the behavior and interaction modalities of the individual node with the objective of obtaining the wanted global behavior as the result of the joint actions of all nodes interacting with one another and with the environment at the local level. It

is, in general, "easier" to follow a bottom-up approach, and the resulting algorithm is usually more flexible, scalable, and capable of adapting to a variety of different situations. This is precisely the case for SI protocols and our bee-inspired routing protocols that we will discuss in this book. The negative aspect of this way of proceeding is that it is usually hard to state the formal properties and the expected behavior of the system.

In this book we follow a presentation style that nurtures the cognitive faculties of a reader in such a manner that he becomes a curious traveler in an adventurous journey that takes him from nature to *networks*. We expect him to ask himself questions during this adventure: (1) What is the correlation between nature and *networks*? (2) How do *bees* in nature provide inspiration for *bee agents*? (3) What are the peculiar characteristics of *bee agents*? (4) Can we utilize tools of mathematics to model behavior of *bee agents*? (5) How do we develop testing theaters to appreciate the role of *bee agents* in different acts? (6) How can we engineer nature to develop systems that can be deployed in the real world? We feel most of these questions will be answered sooner or later in the book. We believe that the book will also reveal unconventional design philosophies to classical networking researchers and engineers, who will appreciate the importance of cross-fertilization of concepts from nature for *engineering*. We call this discipline *Natural Engineering*, in which nature and its principles are used as a driving impulse to raise the awareness and the consciousness of a designer. This principle is also at the center of *Bionics* research.

Acknowledgements

First, I would like to emphasize that the dedication to my father should not be considered as a traditional dedication because my father is not a person but an institution. He retired as a senior bank executive. The financial experts could imagine the stress related to such a job. He used to teach me at least for two to three hours daily in my primary school after coming home from his tiring job routine. I still remember that once when he was posted in a rural town of Saudi Arabia, I was unable to go to any school for two years because of the unavailability of any English or Urdu medium school. However, I had the honor of being educated by my father. He taught me everything from science to mathematics and from drawing to literature during these two years. I just used to go to the Dhahran province at the end of the academic year to take my final examination in an Urdu medium school. Some of you might be surprised to know that I stood second in both grades 5 and 6 and missed the top position by only a couple of marks. I think that without his tremendous hard work I would not have been successful in my life. I believe that the world would be a better place for many children if their fathers could give them only 20% of the time that my father gave to me. I thank you and salute you my teacher, tutor and father. This book is in fact your book and this success is of course your success. My mother is a housewife and she gave me all that a mother could give to her child. Without her strong encouragement and prayers, I would not have achieved this success in my life. I am thankful to God that He gave me parents like mine.

After my parents, I thank Prof. Dr. Horst F. Wedde (LS III, TU Dortmund), who showed his confidence in me by allowing me to tread on a labyrinthine research path many other professors would have not even dared to. He always encouraged me and remained patient while I was reading the two masterpieces: *The Dance Language and Orientation of Bees* and *The Wisdom of the Hive*. Finally, his patience and confidence was generously rewarded once our paper won the best paper award at the ANTS conference in Brussels in 2004. Currently, we are working on two projects that are inspired by the bee behavior: *BeeHive* deals with routing in fixed networks and *BeeAdHoc* deals with routing in Mobile Ad Hoc Networks (MANETs). The projects have received enormous attention from nature-inspired routing algorithm groups around the world. Moreover, my special gratitude goes to Prof. Wedde for the way he thoroughly read the draft version of this manuscript. Last but not least, he pushed a lazy person like me to limits to finish the writing of this manuscript in time. I would also like to thank Prof. Dr. Heiko Krumm and Dr. Thomas Bartz-Beielstein for their valuable comments and suggestions on an earlier version of the book. These helped in improving the quality of the book.

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current manuscript. She is a gynecologist and I wish that a day would come when I could do something for her as well. Yousouf kept me busy in everything except my *BeeHive* and *BeeAdHoc* projects. He showed me that there are more important things in life than *BeeHive*, e.g., *Teletubbies* and *Barney*. I now remember their names by heart (Tinky Winky, Dipsy, Laa-Laa and Po) because we saw them almost daily during the time period when I was writing the first half of the book. In the meantime, God has blessed us with a daughter, Hajra. Her cute smiles were the best source of stress therapy for me, when I was writing the second phase of the book that consists of Chapters 6 to 8.

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