1.2 Fundamentals of Complex Networks

The interest of the research and industrial communities, as well as the public sense for networks, has grown substantially, especially in the last decade. Their drastic and vast proliferation and technological penetration has increased the observed public awareness in any type of form in which networks emerge. Networks are nowadays omnipresent and have been identified as highly crucial in most of their application frameworks. For example, protein interaction networks in biology, which essentially implement a molecule signaling and control toolbox, are highly important for human body operation. In computer networks and telecommunications, mobile networks have enabled pervasive communication between people across continents, diverse conditions, and degrees of importance and criticality.

Similar observations to the above, and many more others observed in natural and daily social lives, lead to the fact that if one needs to characterize modern societies in a couple of words, these terms must be *connected*, *interconnected*, and *inter-dependent*. In addition, even though these terms represent the bigger picture only from a narrow perspective, they are very successful in providing the essential elements dominating our everyday lives.

Another key observation of emerging networks in our lives, widely accepted in both the research and industrial communities, is that the complexity of most interconnected (inter-networked) systems is not in the behavior/operation of a single unit or larger component among the many constituting a realistic system, but rather in the cumulative behavior/operation exhibited by the interconnection and communication of such individual units. Namely, the inter-networking of such units/modules is more important for achieving more beneficial analysis and control of such systems at a lower cost. Such interdependence of nodes is closely related to the notion of collaboration as well, where nodes might be working together for achieving a more complex objective that would be otherwise impossible to achieve individually by a single network entity. Inter-dependence and collaboration are critical aspects of almost all types of networks, and will be widely considered in the rest of the chapters of this book.

The main research efforts in the past were centered in the understanding and analysis of the behavior of individuals units and components of them and the achieved progress has been fascinating. However, as the level of understanding increases and daily demands for added-value knowledge and services increase, the inter-dependent behavior of such basic modules gains interest and sometimes it becomes essential in order to achieve the desired level of control and flexibility over these structures.

Researchers involved in different capacities in the study of emerging networks have lately used a new term, namely complex networks, in order to cumulatively refer to all network research in diverse and multiple disciplines, namely [6], [115].

Definition 1 *(Complex networks) A complex network is one that exhibits*

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emergent behaviors that cannot be predicted a priori from known properties of the network's constituents.

The above definition does not explain the notion of a network, which will be analyzed in more detail in the following subsection. It rather focuses on the characterization of networks as "complex." It considers especially that the observed behaviors can be diverse and completely different, even within the same discipline (e.g., social networks), but could also exhibit unexpected similarities even when observed across diverse disciplines (e.g., malware propagation in wireless multihop networks resembling the virus propagation in animal species or humans).

The corresponding field of complex networks covers a very broad span of network types and emerging features, problems, and mechanisms of broader scientific interest. The proper definition, study, and classification of the corresponding diverse types of involved network structures will provide a solid basis for identifying and revealing common emerging problems. It will also reveal the most suitable approaches that can be exploited from different scientific fields, i.e., other than complex communications networks (such as systems biology, finance, and sociology), in order to address the involved problems more efficiently and develop more feasible/practical solutions.

By considering the various networks involved in the study of complex networks and their emerging behaviors, in general, three dominating features are characteristically observed. The first one is that when it comes to modeling the interactions between network elements, this is achieved by links connecting these entities. Links may represent various forms of interactions or relations. The second element is that nodes exchange different types of resources across such links. The resources can be rather diverse, e.g., in communications networks, nodes exchange data in bit form, protein networks exchange aminoacids, pipeline networks transfer various types of fluids (blood for veins, oil for oil pipes, water for water utility networks), and others. As before, the resources could be of different and diverse natures and quantities and convey diverse meanings. Finally, the third element is that nodes interact through the direct links defined. Thus, two nodes cannot interact directly unless they share a common link between them. This type of interaction refers to a physical inter-connection of the nodes linked directly, e.g., two people being best friends in a group of humans. However, interactions can also be implicit, for instance, in the case of two people being linked to each other in a social network, without physically knowing each other, but rather simply because they shared another third link with a person who happened to be friend with both in reality. Thus, in this book we are mainly involved with direct interactions between network entities, especially in the more specific parts of the presented frameworks. In any other case that interactions are implicit, this is explicitly noted and relevant considerations are made.

Regarding the current information-based and network-dependent societies, another two prominent features may be observed. The first is the diversity of

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the emerging network structures arising almost holistically in every application aspect that one could possibly think of. For instance, network structures emerge in biology, societies, engineering, nature, and practically all other aspects of artificial operation (initiated and dominated by humans). The second is that such networks consist of participating entities of various potentials and intelligences. Different computational and decision-making capabilities by such entities lead to nonpredictable cumulative behaviors. The latter is the main reason that the corresponding interest has risen so much lately and has attracted the attention of various scientific disciplines.

It has been observed and in some cases formally quantified, e.g., in communications networks, that most of the important networks surrounding us are becoming larger, increasing in the scales of millions or billions of users/actors/players/entities/etc. Some of these characteristic networks in accordance with their projected current order[1] estimate (as documented in various sources of the bibliography and the Internet) are provided in Table 1.1.

A more complete network taxonomy is provided in subsection 1.2.2, along with other features they exhibit, revealing more facets of complex network diversity.

In this book, we emphasize networking aspects that are of a decentralized nature and their structure and behavior resembles that of most distributed complex networks encountered in general. Furthermore, the proliferation of computing devices and computers in addition to the development of diverse and social networking applications has led to the emergence of a new and rapidly developing application area, namely that of online social networks. The social dimension has been shown to have significant impact on wired networks, especially the Internet [135], and it is expected to have a similar if not a more vast one on wireless networks, due to the capabilities of modern smartphones and respective provider services. Thus, in order to provide a more complete picture of the methods associated with analyzing and controlling complex communications networks, we also focus on the impact of the social network layer on the actual physical one.

This book takes a more radical perspective, by establishing a top-bottom approach in addition to the traditional bottom-up. In the latter, in complex communications networks, most of the network design techniques took an approach where the lower protocol layer mechanisms affected the design of the higher ones. For instance, the properties and operation of the physical layer have been taken into account for the design of the MAC layer protocol and the MAC protocol has been considered for the design of the routing functions in turn. However, this approach has not yielded fascinating results in the case of wireless distributed networks. In most cases, the employed mechanisms are essentially the ones designed for wired networks, properly adapted in order to

[1]The order of a network denoted in the caption of the figure as well is formally defined in Chapter 2, Section 2.1.1.

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Table 1.1: Scaling of order of various complex networks.

Network	Order of scale
computer networks	billions
Internet	billions
corporate network	thousands
home network	dozens
university campus network	thousands
cellular phone networks	billions
electrical power grids	trillions
sensor networks	hundreds of thousands
roadmap networks	trillions
social networks	billions
food webs	hundreds
brain cell networks	billions
protein interaction networks	hundreds of thousands
affiliation networks	hundreds
citation networks	hundreds
open market networks	decades
bank networks	thousands
GDP[2] flow networks	hundreds
cash flow networks	billions
air-traffic networks	thousands
collaborator networks	decades (hundreds)
logistics networks	thousands–millions

yield the desired operation in wireless. Quality of Service (QoS) and advanced features, such as good scaling, resilience, etc., were not considered due to the fact that requirements for such elements were not realistic in the early days of emergence of distributed wireless networks.

However, as the requirements and demand for such advanced services increase every day and modern applications have become the driving force, rather than the underlying technology, more sophisticated topology modification mechanisms are required. According to the approach of this book, elements of the higher layer, such as the social, are exploited for directly modifying the lowest physical topology, thus closing the design loop in an evolutionary fashion, similar to the one observed in natural cognitive processes [109]. Such an approach will allow more targeted and efficient adaptations of the underlying complex communication network topology, thus increasing the value of an infrastructure without requiring major cost/resource sacrifice.

The following chapters (Chapter 2 and Chapter 3) will focus on the background theory, as well as the classification and analysis of various network

[2]GDP: Gross domestic product.

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modification mechanisms for wireless decentralized networks that exploit social features from the corresponding online social networks. The engineering of complex networks of any type is not predictable and/or controllable because the scientific basis for analyzing, building, and evaluating such designs is still immature. Thus, getting a grip of the fundamental science of networks in terms of structure, dynamics, and evolution is a topic of immense interest and critical value for the benefit and progress of human societies, as covered in this work.

The level of analysis in complex networks spans multiple and diverse perspectives for different types of networks. For instance, in complex communications networks, there are mainly three analysis perspectives, i.e., physical, logical, and social, as explained before and as will be analyzed in more detail in the following chapters. Fully understanding such analysis perspectives will enable building cross-level mechanisms in a cognitive fashion for each network application, in a manner where not only the mechanisms of a layer build on the features of lower-layer mechanisms, but also the lower-layer mechanisms exploit features offered by the higher-layer mechanisms. This book will offer the background and arsenal to achieve such cognitive operation in complex networks, with special emphasis on wireless complex communications networks.

Finally, we refer to a significant aspect of complex network analysis, which refers to the modeling of different network types represented or studied analytically, or their modeling as nodes bearing a specific processing (differential) rule, etc. In the first, a complex network represents the diversity of the various types of networks included and treated cumulatively as network models. In this case, the analysis takes into account that the property is studied across the various network types considered, which exhibit different properties and topologies. Thus, in order to consider such variations, for instance studying routing in ad hoc and cellular networks, a generic 'complex' network type is considered. The term complex on this occasion is indicative of the various and diverse properties exhibited by the different topologies needed to be taken into account in the generic study of a process, i.e., here, routing. In the second case, the term complex refers to the actual nodes of a network, which can also vary in application and scope, and characterizes the complexity of their features. More specifically, complex network nodes may vary in intelligence and processing capabilities. However, if nodes are capable of executing some type of computation, simple or more advanced, then the cumulative behavior could exhibit various degrees of complexity and, thus, complex behavior may be observed or engineered on demand.

The first step towards understanding such emerging and complex behaviors is to understand the fundamentals of network emergence and operations and then deal with the tools required for their proper control. In the following we start with network fundamentals and their network taxonomy, in order to provide a concise overview of networks and their application span.

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1.2.1 Complex Networks Fundamentals

The cornerstone question of complex networks regards the overall reason for the formation and emergence of networked structures, within any type of application framework and diverse operation of the networking structures. This question has become more prominent lately with the increased interest attracted by complex networks. It has been more broadly and thoroughly put across the disciplines involved in the theory of complex networks than in the past.

Interest in network research has exploded during the past ten years (especially the last ten years for communications and the last five for a broader interest in different types of network research). Networks enable the necessities and conveniences of modern life, which can be easily observed in multiple facets of human social life and natural processes. For instance, different types of communications networks enable diverse and pervasive types of communications among people, online social networks have enabled new forms of social contact and new norms of social living, and transportation networks of different types, e.g., international highways, air-corridors, etc., have enabled more efficiency in terms of time and consumed resources in the transportation of people and goods. Especially, engineered networks are a major driver of the increasingly global economy and social evolution, as can be verified with the cases of road networks, air traffic airways, telecommunications networks, and, lately, online social networks.

In any case, scientists involved in various capacities in the study of emerging networks, and especially those with analytical backgrounds, have wondered whether there exists a single and broad reason explaining the formation of networks across all different application perspectives. The importance of such a reason would be significant since it would not only explain why networks develop in various facets of life, but it would also drive the evolution of such networks and indicate the dynamics of their typical behavior.

Substantial consideration has been accumulated on this key question and across disciplines. It has turned out that the answer to this critical question is a simple and profound, yet critical emerging trade-off underlying the existence of all networks and involving the operation of all the entities constituting a network. More formally:

Definition 2 *(Network formation) The main reason for the formation of any network observed in any aspect of nature or human society is the emerging trade-off of gain versus cost of collaboration for the entities constituting the network with their (inter)-relations or the network cumulatively.*

The whole concept of such a trade-off is based on the notion of collaborative operation. In fact, collaboration of network entities appears as the fundamental reason for the formation of a network and the gain (benefit) or cost respectively emerge as consequences, namely measurable outcomes that drive the very reason of existence of a network (i.e., collaboration) to one or

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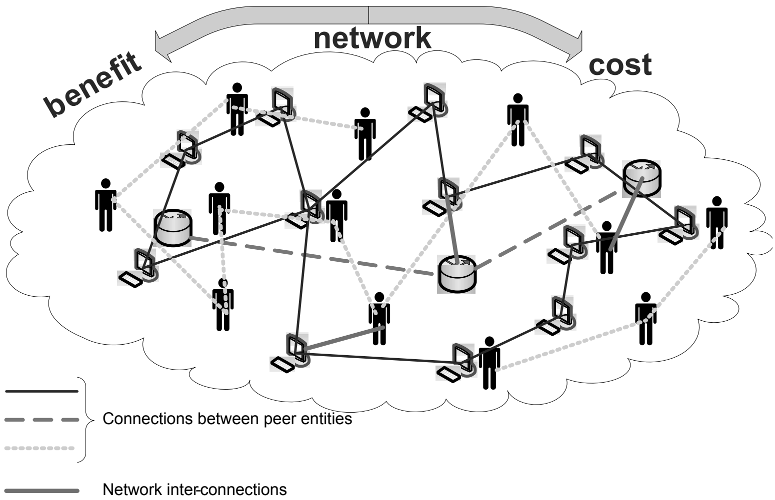

Figure 1.1: Network formation trade-off.

the other direction as shown in Figure 1.1. This notion of collaboration may seem weird, especially for distributed complex networks, where the entities are supposed to act selfishly, aiming only at their own benefit. However, even in this case some sort of collaboration between network entities is implicit (or underlying), so that the whole structure remains concrete. In a different case, should the network nodes be completely reluctant to collaborate in some sense, those nodes would sustain their operation without any need for a network structure. Their objectives would be better met away from the rest of the network, and if all nodes had such potential, there would be no point in forming a network. Thus, some form of collaboration is the very essence of network formation.

Definition 2 does not only mention collaboration as the reason for network formation. In addition, it describes the dynamics that drive network formation. Such mechanics are described by the underlying trade-off between benefit vs. cost of collaboration, which can be observed and quantified with measurable ways in all types of emerging networks and within all application perspectives where they appear. Furthermore, the benefit vs. cost of collaboration trade-off involves both the individual entities of the network, i.e., nodes, players, actors, etc., as well as the network as a whole and can be considered in various levels of the network, i.e., node level, node group level, or the whole network, by using different and diverse quantitative parameters. A network engineer can exploit the benefit vs. cost trade-off to drive the design of various mechanisms of the networks from one direction of the trade-off to the other depending on the desired operational requirements and application demands. For instance, in wireless ad hoc networks, the obtained benefit is the wireless and flexible transmission of data at the cost of energy consumed for the wireless transmission.

Table 1.2: Indicative examples of the benefit vs. cost of collaboration trade-off for various network types.

Network	Benefit of collaboration	Cost of collaboration
Computer networks	information (data) exchange	power/financial
Cellular networks	human communication/ mobility	power/financial
Internet	information exchange	financial
Wireless ad hoc networks	communication/flexibility	energy/interference
Cortex cell networks	message passing	energy
protein interaction networks	information tranfer/energy	food consumption
metabolic networks	energy	biochemical reactions
food webs	survival	effort
social networks	communications	privacy
air-traffic networks	resource management	communication cost
roadmap networks	shortest routes	initial and maintenance cost
affiliation network	context information	privacy
financial networks	information	privacy
GDP flow networks	economy assessment	independence
bank networks	cash flow monitoring	fraud risk

Table 1.2 provides indicative examples of the aforementioned benefit vs. cost of collaboration trade-off for various types of complex networks. The benefit and cost columns provide only some indicative benefit/cost types in each case, and in most cases, several other important benefit vs. cost trade-offs may be identified at various levels of analysis of such networks.

1.2.2 Complex Network Taxonomy and Examples

It has already been explained that complex networks are quite diverse, varying in numerous aspects of their structure, operation, and application framework/scope. For this reason, several classifications emerge, each of which is developed according to different metrics/features, while also serving a different purpose. In Table 1.3 we first provide a list of the parameters that can be used in different cases to segregate complex networks. Each parameter yields a different classification, so that a complex network might belong to different classes based on these parameters. For instance, a biological network may belong to the same class as a communication network according to the type of network, but the two might belong in different classes according

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Table 1.3: Complex network taxonomy classification parameters.

Parameter	Means of verification
Network type	topology/implementation
Scope	operation/benefit
Application framework	environment/purpose
Origin (formation)	observation/simulation
Scientific discipline	mathematical analysis tools
Operation	developing mechanisms
Scale	number of entities/interactions
Performance	properties/features quantities
Reliability	network mechanisms
Security	topology/mechanisms

to the formation criterion. Network type is concerned with the very essence of each network in terms of entities-interactions, where different types exhibit different properties, features, etc. For example, a small-world network is fundamentally different from a random network.[3] The scope and application framework are slightly related; however, the first is concerned mainly with the benefit obtained in the gain vs. cost trade-off, while the second criterion is mainly concerned with the applications where the scope is realized, e.g., in communications networks the application framework spans over information dissemination, Internet services, etc. The origin criterion explicitly concerns the gain vs. cost trade-off and how this develops and leads to the formation of a network, while the scientific discipline cumulatively describes the mathematical tools that can be used to analyze and further control them. The operation criterion regards the developing mechanisms, mainly in algorithmic terms and their function/results, while the scale criterion is concerned with the variability of network behavior, as the size of the network in terms of entities and interactions between them varies. The latter is also closely related to the performance criterion, which can be used to classify networks, according to specifically defined performance indices. Finally, reliability and security are two criteria that have been employed lately for segregating the capabilities of different networks and this is taken into account further in the network design and analysis.

The second column of Table 1.3 denotes the means of verification for each classification parameter provided, namely how the classification can be realized. Specifically, regarding network types, the topology (in a mathematical sense) can be a differentiation factor, while for the scope criterion, the operation and benefit obtained by it (in the benefit vs. cost of collaboration trade-off) can be used for identifying and classifying the various networks.

[3]Both network types will be explicitly defined in the following chapters.

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Table 1.4: Origin (formation) of complex network classification.

Natural	Human-initiated	Artificial
biological	social networks	computers
brain/cortex networks	power-law	mobile devices
evolutionary	online social networks	cellphones
genetic	business	sensor
transcriptional	open-market	delay-tolerant
immuno-suppressive	corporate	mesh
neuron networks	GDP flow	vehicular
ecologic	production	roadmap
protein networks	supply/logistics	air-traffic
regulatory	scientific	power-grid
substance networks	affiliation	artificial neural networks
material networks	family	IT networks
species	language	pipelines/utility networks
virus/disease	malware[4]	circuits
food webs	newsfeeds	transportation

Following the classification criteria, we then proceed with some interesting complex network taxonomies that serve various purposes and are of major interest for the scope of this book. Of course, the classification parameter list provided is non-exhaustive and many more criteria may be devised. Table 1.3 summarizes the most common ones with regard to current studies and concerns related to complex networks and Network Science study.

One of the most useful of these classifications is the one that takes into account the origin of network formation and operation, namely whether the network was formed spontaneously or artificially and whether its operation is dictated by natural or artificial factors as well. According to this parameter, complex networks maybe characterized as *natural*, *human-initiated*, and *artificial*.

Natural networks include those complex networks that emerge in Nature and continue their spontaneous operation/evolution for the duration of their lifetime. Characteristic examples are complex networks emerging in biology, such as protein receptor networks, blood cell networks, cortex neural networks, etc. Additional examples are provided in Table 1.4. The emerging gain vs. cost of collaboration trade-offs among the participating entities can be identified even for such networks that emerged naturally through spontaneous evolution and continue to evolve in most cases. In many cases, it seems that Natural networks form as consequences of serving some gain of collaboration objectives among cells, proteins, etc., and usually once their cost becomes greater, e.g., as cells become old, vessels and receptors age, etc., the networks progressively

[4]Malware is a generic term to denote spreading malicious software cumulatively.

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become dysfunctional and eventually cease their operation, fulfilling their scope.

The second broad category of complex networks includes those that were initiated by humans, but their operation and evolution is not controlled by humans, at least not currently or in the near future. In fact, one of the underlying goals of this book is to set a framework for enabling analysis and control of networks of this category, and this within potentially multiple application frameworks. Characteristic examples of this complex network category are networks emerging in finance, information, and news dissemination networks, rumor spreading networks, malware propagation networks, production and supply chain networks, etc. More extensive examples are provided in Table 1.4. For this category of complex networks, the benefit part of the formation trade-off is evident. Usually such networks are created in order to serve a practical need, or operation of daily human life. However, this comes at an operational cost, which can vary in form and performance. The objective here is to properly control this trade-off in order to increase the gain with the minimum possible cost. However, sometimes it might be required to sacrifice some of the benefit in order to obtain much larger cost savings (and vice versa when the trade-off is balanced towards the cost minimization side).

The third class in this classification is the completely engineered complex networks. Such networks have been conceptualized and created artificially, and most of the time we have control over them, at least up to an acceptable degree. Communications networks are a typical example. They were humanly designed from their inception, then reached full-scale, covering the globe, and nowadays administrators and investors control the way they expand and evolve. Similarly, transportation networks and their subnetworks, such as air-traffic, roadmap, and sealine networks, have been developed and are constantly adapted to fit the needs of humans regarding traveling and product transport (logistics). More examples of such networks are provided in Table 1.4, along with application perspectives of their operation. The gain vs. cost of collaboration of the network entities has the same form as for human initiated/spontaneous evolution complex networks. Such networks have been designed to offer some benefit, e.g., data bits transferred in communications networks, while incurring some operational cost, e.g., energy in wireless networks. Balancing such trade-offs is the main objective of engineers, and usually adapting it to operational requirements or society trends becomes another important objective.

Another important network category, and perhaps the most useful from the perspective of complex network analysis classification, is the one more related to the structural nature of each complex network type and it is mainly based on the mathematical representation of such networks as graphs. By structural nature, we refer to the interactions developed between the entities of a network and the properties/features of the entities and their interactions cumulatively. This mathematical representation will be the explicit topic of the next chapter (Chapter 2) and the specific features of each separate category of network classes according to their structure will be provided in later chapters (Chapter 5 and Chapter 6). Here we only provide the corresponding classification with some characteristic examples of complex networks, and postpone analysis for the following chapters. The list of examples is non-exhaustive and mainly aims at providing an overview of the corresponding network instances, based on which the corresponding network types can be identified in practical cases. Table 1.5 contains the classification of complex networks according to their underlying structure. This could be considered the most important classification of complex network from an engineering and scientific point of view, since it is indicative of the expected properties and behaviors developed or emerging in each type of network. We should note that a scale-free network mentioned in the table is essentially a network whose degree distribution follows a power-law, at least asymptotically. Thus, for the rest of the book, we will employ the term "power-law" to denote networks following exactly a power-law degree distribution and "scale-free" to denote those that follow such degree distribution asymptotically.

In many cases, it suffices to accurately identify the type of a complex network, and then employ standard methodologies developed for the different classes of network types. It should be explicitly noted that a network is always a representation or model of observable reality, but not the reality itself. As a representation model, the network does not always provide the complete information associated with its actual representation. However, it does explain the basic mechanisms and the characteristic functions/features the network has compared to other types of networks. The latter must be done in a manner where no two networks having different operations overlap in terms of modeled behaviors by the corresponding representations. Thus, the representation should bear the properties of uniqueness and accuracy, in order to be able to distinguish between different types of complex networks and at the same time be able to use them properly for the analysis and control of their functions. A third element for each representation is efficiency/convenience. This means that a representation should be manageable in terms of space and complexity requirements for the current technological potentials available. A representation requiring significant amounts of storage memory or one that cannot be processed in the amount of time allowed by the corresponding application framework is unsuitable and essentially of no use. Efficiency in storage and handling convenience in the manipulation and exploitation are essential elements for a network representation as well.

Among the types of complex networks provided in Table 1.5, this book will focus strongly on complex communications networks and especially wireless networks. Wireless distributed devices have nowadays dominated their desktop counterparts and it is expected that soon the wired infrastructure will mainly be restricted to a backbone carrier role, while the wireless will not be just a plain access last-hop interface, but rather an added-value flexible and autonomous network that uses the wired core for overseas and long-distance

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Table 1.5: Topology-based complex network classification.

Network type	Network examples
Regular	Lattices
	Grids
	Crystals
	Chains
	Optical ring networks
	Cellular phones
	Supercomputing infrastructures
	Cloud services
	Sensor
Random	Peer-to-peer
	Gas molecules (in equilibrium)
	Brownian motion
	email virus netoworks
	Grid percolation
	Immunization networks
Mesh	Sensor
	Delay-tolerant networks
	Optical networks
	ZigBee/Bluetooth
	LTE-A (4G)
	WiFi (802.11x networks)
Power-law	Metabolic
	Population of cities
	Word frequencies
	Co-authorship networks
	Affiliation networks
	Neurons
Scale-free	Social networks
	WWW
	Internet (AS[a] routers)
	DNS[b] routers
	Protein interaction networks
	Inter-bank payments
	Airline networks
Multi-hop	Military networks
	TETRA
	Packet radio networks (CSMA/CA)
	Sensor
	Vehicular
	Roadmaps
	LTE-A (4G) networks
	Cognitive Radio networks

[a] AS: autonomous systems.
[b] DNS: Domain Name Service.

connections only [75]. It is envisioned that the bulk of the local traffic will be transferred through wireless channels, and in addition, enhanced and demanding applications will be locally supported by wireless networks in order to decongest the wired core [111].

On the other hand, wireless distributed networks, such as ad hoc, sensor, mesh, vehicular, delay tolerant and WiFi, exhibit several impairments and do not inherently support a seamless transition from a wired-oriented application design philosophy widely followed until today to a wireless-centered data transmission expected in the future. In addition, the underlying technology has not exhibited the respective development of the application layer, e.g., the tremendous proliferation of online social networks. The latter inherently bear some features, such as logarithmic scaling and robustness, that would mostly be desired in artificial networks. For this reason, it is strongly required that wireless distributed infrastructures are modified in a fashion that ensures the realization of the demanding and diverse applications, without significantly impacting their operation and resource management. Network modifications should be as transparent as possible and they should allow the maximum possible flexibility between the original and induced networks, enabling on-demand responses to different operational time scales and requirements. This would also align the progress in content and infrastructure, thus smoothing out the transition from legacy systems, where the main information sharing paradigm is that the user acts solely as information consumer of the offered services and data, to more advanced and efficient architectures, where the end-user has turned into both information consumer and producer [122], given the capabilities offered by the current consumer electronic devices.

In the next section, complex network analysis (CNA) will be put into a broader perspective for Network Science research and the corresponding content, status, and challenges faced by network engineers. It will essentially provide a broader perspective for the methods and approaches presented in this book.

1.3 Network Science

The previous discussion on complex networks represents a cumulative effort to develop models of emerging network structures, irrespective of their potential application framework and any practical use they might have. However, as in all other scientific fields, for complex networks too, it is desired to develop a broader framework, where it will be possible to combine theory with application and create a strong bond between modeling and practice.

Network Science is a term that has been coined lately to denote exactly this broader and more ambitious effort for a proper scientific field devoted solely to the study, analysis, and applications of networks, wherever and whenever they emerge. A simple definition of Network Science is the following:

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Preface

In this book, we start the exploration of evolutionary dynamics for complex networks with a working example that might look familiar to many people, at least partially. The specific example intends to highlight the various aspects of everyday life and work where humans encounter, use, act on and obtain information from their interaction with complex communications networks, as well as numerous other emerging functions. Such an example will drive the following steps of the exploration of this book into a research domain currently shaping and even expanding rapidly. Then we provide a more elaborated overview of the topic, related goals, and features provided by this book. Finally, we provide potential alternative strategies for studying the material provided, depending on whether the book is intended as a research reference, an undergraduate or graduate course reference manual, or simply a reference of broader interest.

Working Example

An executive of a multi-national company hires a taxi from Tokyo Financial Center to go towards the International airport, to catch her return flight to the United States. The driver quickly consults the GPS device of the vehicle for the traffic street map, in order to identify the fastest route to the airport. The executive has requested a speedy lift, which will ensure she boards on time. The route duration estimation is 40min, safely enabling the executive to check her email through her mobile handheld device in the meantime, rather than worry about catching her flight. Both the accuracy of the GPS application and the luxury of a good international roaming plan allow her to focus on her job, while not wasting energy on logistics. The latest email requires her to complete a report, thus, she also opens up her tablet device, connects to the 4G network of the local provider, and via roaming and VPN, she connects safely to the intranet of her corporation, in order to complete the short report online and make it accessible to her supervisor in Philadelphia as soon as possible.

Incidentally, as soon as the taxi reaches the airport, the executive receives an emergency call, informing her that she needs to reschedule her flight and visit the corporate offices in Los Angeles for a couple of days before returning

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to the headquarters in Philadelphia. She heads straight to the airline helpdesk and requests an immediate flight change. The teller checks with the information system of the airline and is able to locate a convenient flight reroute. The executive will now fly from Tokyo to Chicago and instead of boarding the connecting flight towards Philadelphia, she will board a connection towards Los Angeles with only a slight delay of an additional hour. It just occurred to the executive how important the airliner network proves to be in such cases, where scheduling and other data have to be recalled and updated upon such last minute modifications. Next, the executive checks the new flight data, boarding times, duration, distance, mileage account, etc. from her smartphone via the airline application account. She also updates her social network profile status property in all social networks she uses, while waiting to board, in order to let her close friends and colleagues know of her coming plans.

During the flight the executive connects to the airplane's WiFi infrastructure in order to check her social accounts, read the news, and watch something On Demand, such as a movie, or missed episodes of her favorite TV series. Two of her college friends now living in Los Angeles have sent her invitations for dinner, once they were notified by her social network status that she will be in town. The executive checks her schedule and decides to join them as soon as her assignment there is over. At the same time, one of her friend's article posts in the social network has gained numerous "likes" and popularity, and she decides to check the article that coincidentally appeared in her favorite newspaper, before she continues watching the latest episode of her favorite TV series she unavoidably missed due to her original assignment.

Upon her arrival at Los Angeles she feels somewhat exhausted and probably a bit sick. Suspicious from various spreading news stories she heard over the last couple of days in some of the cities she visited through her trip, she quickly consults some of the latest medical blogs for her symptoms, while waiting for her pick-up. She eventually believes she might have got the latest flu from her business trip and heads directly to the nearest available hospital, which she found through her smartphone device and a relevant application. By collecting information from medical blogs and hospital databases, and based on symptom input by the user in conjunction to the selected town, the app is capable of suggesting such a hospital. In the hospital, the physicians that examine her consult the hospital records for recent virus alerts, and eventually they decide to proceed with some further lab tests and physical monitoring.

Eventually, the doctors inform her that she will need to receive medication and the prescribed antibiotics will take some time to spread through her immune system, a cell network going through her body, before she will start feeling better and be safely released. In the meantime, the corresponding agency of the Centers for Disease Control and Prevention in the hospital needs to know her exact travel plan, in order to obtain more accurate estimates of the flu's spreading dynamics. The epidemics control and prevention agency, which is informed from the hospital authorities, is interested in assessing the danger levels for a virus spread in the general population, and

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thus experts of the agency consult with the executive, inquiring about her traveling. Combining such data with other information obtained by talking to similar patients, they will become capable of reconstructing a propagation network for the specific virus and variations throughout the nation, obtaining the respective infection and recovery rates and assessing the importance of the situation. This will enable them to better track the flu propagation network and thus increase the efficacy of their countermeasures when needed.

Meanwhile, the executive is released after a few hours of close observation and an imminent improvement of her physical condition. The latest antibiotics employed by the doctors were created based on feedback similar to that obtained by epidemiologists consulting with the executive in previous cases. The antibiotics reacted in a targeted and rapid fashion in her blood and cell networks, allowing her to recover fast and luckily continue her planned occupation with the minimum possible delay and overhead. She is now capable of continuing her job, without suffering nasty symptoms and feeling assured she will not be endangered in the coming days.

After her assignment, she finally meets with friends from Los Angeles, as planned during her flight, most of which are active in the financial field as well. They decide to start with dinner and at the same time spend some time discussing the latest trends in their jobs and lives, while occasionally checking several facts, photos, and articles online through their mobile devices. By the end of their dinner, they decide to continue their night by having some more fun. They can solve this quickly by using the latest social applications. In a city like Los Angeles and with some aid by their smartphones they decide to quickly book online seats for a theater play they found interesting among those offered in the application, since some available seats were luckily still available. They completed the transaction smoothly and rapidly, securing their spots in the theatre. They also came across a post in an online nightlife guide for a seemingly nice bar in the neighborhood, and decide to visit it right after the play. While in the cab, the executive reflects once more on how easy it has become to have all those options and features through the established networks and how their interconnection enabled them to do so much on such a short notice, whereas in former times, the same arrangements would take at least 1–2 days of prior arrangements.

A couple of days later, after all her activities in Los Angeles are finished and while on her return flight to Philadelphia, the executive is now more relaxed and feels like scheduling her weekend online using her tablet and exploiting the features of business class seating, like Internet access–communication capabilities. It is time to allocate some time for herself. She has received an invitation for a tennis match and she is able to confirm her availability through email and also book a court through the Web service of the tennis club where she is registered to avoid suffering any court unavailability. She was also informed of an upcoming birthday party of one of her close friends. She immediately indicated her attendance and in addition, she was able to chat with some other friends that were online for the proper organization of the party through her

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social network mobile service.

Having set her social activities for the weekend, while in flight she decided to selectively read the latest local news in Philadelphia, where it turned out several things happened while she was out of town. Being registered in customized and automated newsfeeds, she was able to quickly locate the most interesting articles for her taste. She was also able to quickly form her personal opinion on them and post some comments in the relevant discussion forums and blogs. She was even able to follow several immediate responses to her comments by spending the remaining flight time productively on topics she enjoyed discussing.

During a reflective moment, she realized she will not be required to manually update all of her updates and modifications in her schedule and document management systems, as the latest cloud services will do so automatically, allowing her to find everything in order once she turns her devices on back in her place.

As soon as she landed, she was relieved that yet another demanding business trip came to an end. While riding a taxi from the airport towards her apartment, she spent some time reflecting on various moments from her trip and it occurred to her how many times she used modern technology and especially networked devices and services in order to finish her job more easily, communicate with colleagues and friends, and eventually document and boost her work. Once more, she had to appreciate the benefit of a networked lifetime. That eventually made her think a bit more how many other aspects of networked life she was actually using on a daily or less frequent basis and in a subconscious manner. All these have been delicately underlaying her daily routine for quite some time, and those regarding her health, from the moment she was born. She felt a bit happier her everyday life was now easier than what it would have been decades back and felt calm that she was now in a position to get some rest, enjoying what seemed to be a very revitalizing and fascinating weekend before a new week in the job started.

Topics and Features of the Book

The example of the previous section cannot characterize by any means a typical person, even in the more technologically-aware societies of our contemporary world. Even though there exist people that have to cope with similar rigor, most of the professionals and non-professionals have a more plain style of living. However, the example presents cumulative various facets of modern societies with respect to working, socializing, hobbies, entertainment and practically any aspect of human life. It can be suggested that the example combines many of the challenges that numerous people have to face, various other tasks they have to accomplish, or occupations they want to achieve on a daily basis. It illustrates how modern technology has changed human life, and how many different tasks can be possibly achieved nowadays with the use of

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modern devices, services, and infrastructures, even under strict or emergency constraints. Furthermore, the example provides a glimpse into the future demands and requirements that the modern style of living might impose over communications technology and information societies in general.

Above all, the example highlights the important role that various types of networks play in our modern societies. Essentially, it illustrates how modern societies are centered around various types of information and infrastructure networks. These networks span not only technological communications networks, such as those formed by mobile devices, the Internet, airline databases, and mobile applications, but also involve other type of networks as well. For instance, biological networks, such as protein and nerve networks, virus infections, financial networks, such as stock and trade markets, and numerous others. Networks of different types emerge everywhere, and conversely, similar types of networks emerge in rather diverse fields of human activity. For example, small-world networks, which will be analyzed in detail in subsequent chapters of the book, emerge in biology, computer networks, and social networks, at the same or different scales.

Most people would identify a subset of the presented example to match their daily lives to a lesser or greater degree. Through that, one may identify a plethora of naturally emerging networks or developed networks that have been specifically designed to interfere with our daily lives to the extent that this becomes routine. In any case, the emerging networking structures are very important and in addition, they operate most of the time in the background, as it happens with biological, financial, and other critical types of networks. What is more important is that this trend of identifying and exploiting more consciously various types of networks is increasing with a strong tendency to further intensify. As the technological means enable researchers and professionals to perform larger scale studies with greater accuracy, better control of such network structures and mechanisms developing on them can be achieved and eventually exploited for improving the quality of living of the current and future generations.

Among others, the above example illustrates characteristic cases of human interaction and emergence of various and diverse types of networks in our modern lives. Starting with telecommunications, professionals are able to perform their jobs remotely from various places of the world, as if locally present in their offices. Travelers are capable of scheduling and adapting their journeys on the fly and in the most efficient manner by exploiting mobile devices, global services, and integrated infrastructure networks. Airlines are in a position to reschedule their passengers, ensuring the most efficient transportation of persons and products in the most convenient manner. Doctors and epidemiologists are capable of monitoring the spreading of diseases and viruses and eventually may determine the severity of a threatening situation for the population. Also, the understanding of biological and metabolic pathways within the human or animal cell networks enables the development of more efficient and more rapidly acting medicines. Critical or more casual infor-

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mation on financial markets can also be quickly communicated through hybrid social-communication networks, enabling more educated decisions and safer risk asset management, or learning about rumors and critical updates that could optimize decision-making and minimize the undertaken risk. Finally, modern communication and IT infrastructures have enabled the development of various social networks, which in turn have enabled people to experience various events, updates, and news even when far away from their friends, families, or other social groups they belong to. Such social networks have enabled the integration of social circles with activities in a virtual reality that could be properly exploited for a more exciting and valuable daily life of modern societies.

The common denominator and main feature of all the above emerging cases of networks in all aspects considered is the formation/development, operation, control, and eventual exploitation of the emerging networking structures, either natural, human-initiated, or completely artificially engineered. All such networks interfere directly with our lives in various capacities and for various purposes. Several of them appear simple in their operation, while others yield such complicated behaviors that currently we are not even close to understanding them, setting aside any aspirations for obtaining some type of desired control over them. This book will consider exactly this feature of the emerging networks and more specifically it will do so from the perspective of evolutionary dynamics, namely by focusing on the factors and mechanisms affecting the dynamic modification, spontaneous or designed, of these structures, as they evolve in time and sometimes even in space.

The second notable feature in the example of the previous section is the evident diversity of the emerging networks and corresponding processes/mechanisms developing on top of them. The application framework diversity where these networking structures develop is even more diverse in scope, nature, and objectives. However, in most cases even within this diversity, fundamental, common, and generic problems of a mathematical nature emerge among the various disciplines. For instance, the networking problems of virus propagation among host machines in a wireless decentralized communications network is similar in nature and mechanics to the problem of virus propagation in humans, faults in engineering complex production lines, and news in information channels around the globe. This potential provides a great opportunity for tackling critical problems in generic, efficient, and convenient ways that would benefit multiple disciplines cumulatively and magnify the potential progress in various fields. This book will cover the diversity exhibited by the modern study of networks, by presenting and analyzing the available networking structures along with their properties, applications, and special features. Even though the book will not be exhaustive, the most characteristic, important, and useful network types with applications in the most interesting fields are included in the analysis provided.

The main topic of this book is devoted to the objective of first analyzing complex communications networks by exploiting multiple and diverse math-

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ematical methodologies from other disciplines of Network Science and then improving their operation and control approaches over them in a seamless and efficient manner. This is a twofold goal, which will start by introducing the basic analytical tools that can be used for the analysis and study of complex networks in general, independently from specific scientific fields of research. Following this, the focus will shift to exploiting fundamental elements of complex networks in more advanced evolutionary mechanisms, which can be employed for improving artificial networks and more specifically wireless decentralized communications networks, such as ad hoc, sensor, and mesh networks. The whole approach taken is a holistic study of complex communications networks inspired by the inherently hierarchical structuring of more general complex networks themselves (as will be explained in detail in the next chapter) and the goal will be to jointly exploit elements from the multiple perspectives and mechanisms of complex networks in the improvement and advancement of communications networks, in a manner that will enable and inspire similar efforts in other disciplines as well and thus, eventually, contribute to developing a novel and constant-improvement feedback approach among the various disciplines of Network Science and complex networks, as will be presented in the following chapters.

Roadmap and Book Objectives

This book has mainly been developed as a self-contained volume covering both breadth and depth of evolutionary dynamics for wireless communications networks. However, multiple uses may be achieved by following different coverage sequences and selecting different parts of each chapter.

Following the instigated chapter sequence provides a gradual and holistic viewpoint of the corresponding field, starting with coverage of the broader scope of Network Science and complex networks, then proceeding with the development of the necessary background in terms of mathematical content and algorithmic approaches, and finally, progressively applying several of the concepts presented in the background-devoted section into frameworks and mechanisms covering the dynamic and evolutionary behavior/improvement of wireless networks.

In the aforementioned thread of coverage, several parts have been covered in more detail, while others have been briefly touched on, citing other sources that the more interested audience may consider. In case the reader wishes to obtain a holistic perspective of evolutionary dynamics, but at the same time does not have the luxury of time, several more specialized parts have been noted with an asterisk and could be omitted in an initial, more breadth-oriented study.

The book also jointly covers the theory and applications of the presented approaches. The reader may select those theoretical approaches or applications that are of more interest or relevance to his/her interests on an on-

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demand basis and according to the level of detail he/she wishes. References to more extensive sources and manuals or more detailed treatises are provided, when the treatment in the book does not contain significant detail.

This book is also meant to be used in other ways, apart from its basic reference manual use. One of these possible uses is as an undergraduate textbook for more advanced relevant courses, e.g., introductory courses on Network Science, complex networks, or evolutionary network dynamics. Some basic knowledge of computer/communications networks probability theory and differential equations is considered prerequisite in these cases.

Finally, another use, and perhaps a more targeted one, is as a main textbook for an introductory graduate course, covering the fundamentals of complex network analysis and network engineering. In this case, the book can be used to prove theoretical tools and practical examples for eventually exploiting elements of complex network analysis in the design and optimization of communication networks, and thus aid students working in relevant fields. However, the methodologies presented could be of interest for graduate students and researchers of other disciplines, i.e., social sciences, etc., in which case the book can be exploited in a selective manner, where the instructor will be choosing excerpts of interest in a more focused manner.

As such, and since the complete material cannot be covered within a single semester course, both at the undergraduate and graduate levels, we suggest potential chapter layouts that could be utilized for constructing coherent material for relevant courses. The flowchart in Figure 1 depicts such chapter outlines. In the middle, the cover-to-cover chapter flow approach is shown, as the main suggested coverage of the book. On the left and right hand sides of the figure, the flowchart depicts suggestions for deviating from the cover-to-cover flow of the coverage, which can be determined according to the specific objectives of an instructor, for an undergraduate and graduate course respectively (left-hand side for undergraduate and right-hand side for graduate uses).

Finally, we note that the book contains some appendices, which can be used within a course as needed, or simply as references for the independent researcher or student, should a quick reference background be needed, as noted in the text.

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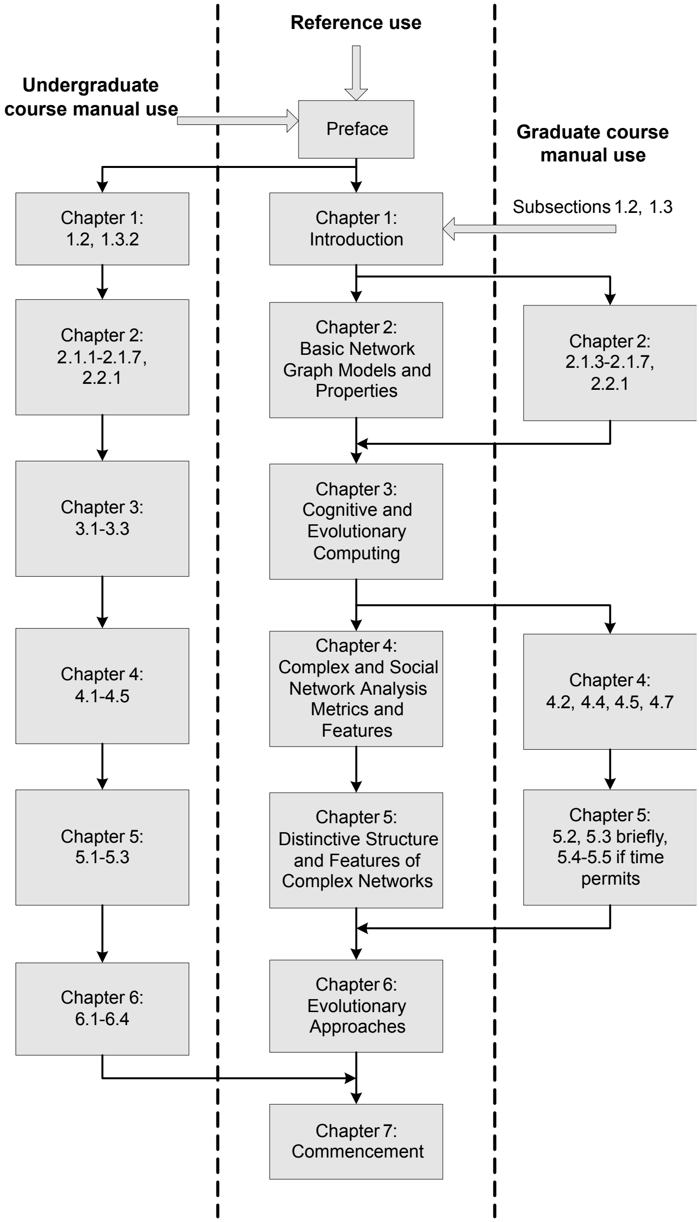

Figure 1: Potential use of the book as a long-term research companion and/or undergraduate or graduate course manual.

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