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复杂网络及其新近研究进展简介*

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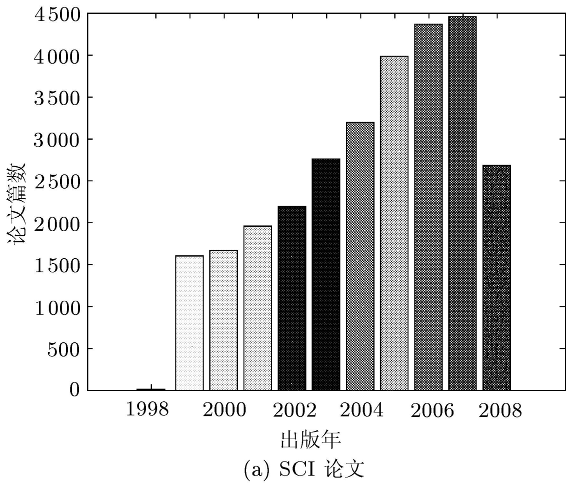
摘 要 简单地介绍了近 10 年来蓬勃发展的复杂网络研究新领域, 特别是其中最具代表性的随机网络、小世界网络和无尺度网络模型及其基本参数和概念, 并简要地回顾了复杂网络理论在生物和大脑神经网络、流行病传播与免疫控制、交通与社会经济、无线通讯、计算机和互联网、传感器网络、语言学与社会科学以及群体活动和编队飞行问题中的分散控制、稳定性特别是一致性问题等方面的应用趋势.

关键词 复杂网络, 规则网络, 随机网络, 小世界网络, 无尺度网络

1 引 言

20 世纪 80 年代以来, 以互联网为代表的计算机和信息工程技术的迅猛发展使人类社会大步迈入了一个 "网络时代". 从互联网到万维网、从电力网到交通网、从生物体中的大脑神经网到新陈代谢网、从科研合作网到各种政治、经济、社会关系网等, 人们事实上已经生活在一个充满着各种各样的复杂网络的世界之中. 这种全球网络化一方面极大地提高了人类的生产效率和生活质素, 如无线手机通话和电子邮件通信以及 GPS 交通导航等, 另一方面也给人类生活和社会活动带来了不少新的麻烦, 如传染病和计算机病毒的快速传播以及大面积停电事故等. 因此, 人类社会的日益网络化要求人类对各种人工和自然的复杂网络的结构、性质和行为有更清楚的认识和驾驭. 长期以来, 通信网络、电力网络、生物网络和社会网络等分别是通信科学、电力科学、生命科学和社会科学互不相交的研究对象, 而今天被称为复杂网络 (complex network) 的理论分支所包揽. 大体上说, 复杂网络要研究的是各种看上去互不相干但其实密切关联的形形色色网络之间的共同属性和处理它们的普适性方法. 从 20 世纪 90 年代开始, 复杂网络的研究逐步形成了一个自我完备的学科, 甚至被称为 "网络的新科学"[1,2]. 复杂网络作为一个新的研究领域, 它的基本理论正渗透到从数理科学到生命科学、工程科学甚至社会科学等众多不同的领域中去. 事实上, 复杂网络的研究已经成为了近 10 年来全世界在不同学科领域 (包括力学、物理、生物、系统控制、通信技术、社会、经济和军事等) 中的科学家们的研究热点 (图 1). 今天, 对复杂网络的定性与定量特征的认识和理解已成为网络时代科学研究中一个共同而又极其重要的挑战性课题.



(a) SCI 论文

图 1 以 "复杂网络" 为关键词的 SCI 论文和 EI 论文发表情况统计

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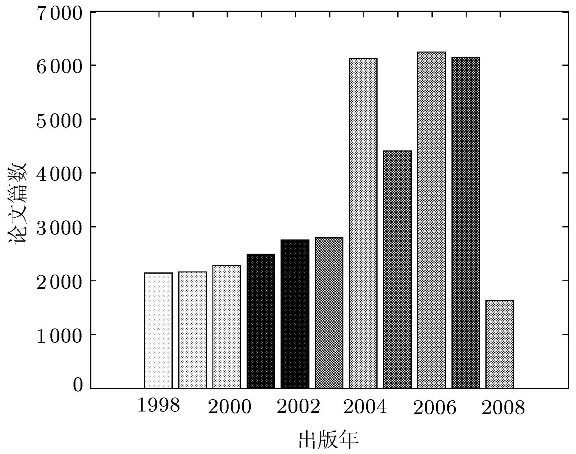

(b) EI 论文

图 1 以 "复杂网络" 为关键词的 SCI 论文和 EI 论文发表情况统计 (续)

2 复杂网络的主要参数和基本模型

从数学的角度来说, 一个网络可以用一幅图来表示. 每一幅图或网络都是由两个基本元素组成的: 节点和边, 其中一个节点可以代表互联网上的一台计算机、万维网上的一个网站、移动通信网中的一部手机、神经网络中的一个细胞、社会网络中的一个人或者一个公司等等, 而一条边可以代表互联网上的一条光纤、万维网上的一种通路、移动通信网中的一次会话、神经网络中的一根经络、社会网络中的一层关系或者一笔交易等等. 一个网络或者一幅图, 由于节点和边之间存在不同的联结方式, 就具有不同的拓扑结构并且可以具有非常不同的特性和行为, 因而需要用不同的数学模型来描述 [3]. 最具代表性的网络模型包括规则网络、随机网络、小世界网络和无尺度网络; 各种网络中最重要的一些性质和参数包括度和度分布、群集系数、距离和平均最短路径长度、介数等 [4,5]. 下面先定义复杂网络的几个主要参数、然后介绍相关的几个基本网络模型.

2.1 主要参数

度 (degree) 和度分布 (degree distribution): 网络上一个节点的度通常定义为这个节点具有的连接边的数目. 例如, 有 5 条连接边的节点的度就是 5. 这样, 把具有相同度的节点的个数分别统计起来, 可以得到一张度的分布图, 就像学生的成绩分布图一样. 不同结构性质的网络具有不同的节点度分布, 例如一般来说规则网络具有 δ 分布、随机网络和小世界网络具有 Poisson 分布、无标度网络具有幂指数分布. 具有相同性质的不同网络会有相同的节点度分布, 但它们节点度分布中的参数值会不尽相同.

群集系数 (clustering coefficient): 群集系数的概念用来刻画所关心的某个节点它的直接邻居节点之间也互相连接的稠密程度, 定义为 0 到 1 之间的一个实数值. 例如, 假定某节点 A 的度为 5, 即它有 5 个邻居节点; 如果这 5 个邻居都互不相连, 则节点 A 的群集系数为 0, 但如果这 5 个邻居全都互相连接, 则节点 A 的群集系数为 1. 整个网络的群集系数定义为它所有节点群集系数的平均值. 显然星形规则网络的群集系数为 0, 而全连接的规则网络的群集系数为 1. 全连接网络和小世界网络都具有比较大的平均群集系数, 随机网络和无标度网络则具有比较小的平均群集系数.

距离 (distance) 和平均最短路径长度 (average shortest path-length): 两个节点之间的距离可以有许多不同的定义, 其中最简单也最常用的就是它们之间最短连边的条数. 例如, 假定节点 A 和节点 B 直接相连, 那么它们的距离是 1; 如果它们连接的最短路径要通过另一个节点 C, 那么它们的距离就是 2. 一个网络的平均最短路径长度则定义为该网络上所有存在的节点距离的平均值. 一般来说, 全连接网络、小世界网络和随机网络都有比较短的平均最短路径长度, 而链形、环形和树形等规则网络都具有比较长的平均最短路径长度.

介数 (betweenness): 介数分节点介数和连边介数, 前者定义为网络中两两相连的节点对之间通过该节点的所有连边的总数量; 后者定义为网络中两两相连节点对之间通过该边的所有连边的总数量. 从概念上来说, 介数可以理解为在网络上通过所关心的节点或者连边的数据流通量. 显然, 在讨论网络数据流通管理控制时, 节点介数比节点度常常更为重要; 不过节点度非常容易计算, 介数就难算得多了. 一个网络的节点 (连边) 平均介数就是网络上所有节点 (连边) 介数的平均值. 一般来说, 稀疏的网络介数低、稠密的网络介数高.

2.2 网络模型

要对不同的复杂网络进行描述和研究, 首先要对它们建立相应的数学模型. 对网络模型作严格分类是相当困难的. 但大致上复杂网络可以划分为三大类型: 首先是规则网络和随机网络; 这

两种极端类型的网络能明确地定义, 其中规则网络包括全连接网络, 环形、链形、星形网络以及格点和分形图等非常规则的确定性网络, 而随机网络则指按照某种明确的统计规律生成的网络, 主要是经典的随机图模型及其派生出来的相关模型. 其他一般性的网络模型只能笼统地归到第 3 类了, 是介于规则和随机网络模型之间的、有一定的规则但也有一定的随机性的所有其他网络; 这是一个很大的类别, 其中包括相当重要的小世界网络和无标度网络、以及加权网络和演化网络等等. 本文以下部分只谈及规则网络、随机网络、小世界网络和无标度网络.

2.2.1 规则网络

规则网络 (regular network) 是最简单、但也是研究历史最长的一类网络, 可以追索到 1736 年欧拉的七桥问题 [3,4], 甚至更早. 除了像全连接网络, 环形、链形、星形网络以及格点和分形图等非常规则的确定性网络之外, 一种常见的规则网络是由多个节点组成的广义环状网络, 其中每个节点只与它最邻近的若干个节点连接. 在规则网络中, 通常节点的度分布为 δ 函数, 节点的群集系数比较高, 平均最短路径长度也比较长.

2.2.2 随机网络

随机图 (random graph) 的数学理论始于 1960 年 Erdos 和 Renyi 的一篇经典论文 [6], 其后被称为 ER 随机图论, 应用于网络则称为随机网络模型, 定义为 [7]: 在由 n 个节点、总共 $C_n^2 = n(n-1)/2$ 条可能存在的边中, 随机地选取 m 条边所形成的网络, 记之为 $G(n,m)$. 由这样的 n 个节点和 m 条边组成的网络共有 $C_{n(n-1)/2}^m$ 种, 全体构成一个概率空间, 每一个网络在其中出现的概率是相等的. 另一种等价的随机网络模型是二项式模型, 定义为 [7]: 给定 n 个节点, 假定任意一对节点之间存在一条边的概率为 p, 记这样形成的网络为 $G_{n,p}$. 整个网络中边的数目是一个随机变量, 其期望值为 $n(n-1)p/2$. 因此得到一个 n 个节点和 m 条边的网络的概率为 $p^m(1-p)^{n(n-1)/2-m}$. 如果令 $m = n(n-1)p/2$, 则两个模型 $G(n,m)$ 和 $G_{n,p}$ 等价.

ER 随机网络的节点度服从 Poisson 分布, 因而比较 “均匀” 即大部分的节点度相差不多, 并且它具有较小的平均最短路径长度和较小的群集系数. ER 随机网络模型在提出后、直到 20 世纪 90 年代末, 在近 40 年时间里逐步发展成了一门博大精深的数学分支, 衍生出不少变种, 也成为了描述各种复杂网络的主要工具.

20 世纪 90 年代以来, 由于现代大型高速计算机数据处理和运算能力的飞速发展, 人们对各种复杂网络进行了大规模的仿真试验, 结果发现现实世界中绝大多数的网络既不是完全规则的、又不是完全随机, 于是提出了一些更符合实际的网络模型, 其中小世界网络和无标度网络模型十分成功地描述了许许多多像互联网、万维网、无线通信网、电网、生物神经网、交通网、社会关系网、科研合作网以及与力学特别是统计力学和量子力学密切相关的形形色色的复杂网络.

2.2.3 小世界网络

小世界网络 (small-world network) 模型于 1998 年由美国 Cornell 大学理论和应用力学系的博士生 Watts 及其导师 Strogatz 提出 [8]. 他们提出的 (WS) 小世界网络模型可以从一个具有 n 个节点的规则环形网络开始, 假定环上每一个节点都与两侧各 K 条边相连, 然后对每条边以概率 p 作随机重新连接, 即断开以后与随机选取的第 3 个节点相连 (但不允许自我连接和重复连接). 因为随机选取的第 3 个节点很可能位于远处 (这时, 新连接的边叫做 “长程边”), 这种长程边的随机连接的结果就大大地减小了整个网络的平均最短路径长度, 而对网络的群集系数影响却不大, 使得生成的新网络具有所谓的 “小世界” 特性, 即同时具有较小的平均最短路径长度和较大的群集系数, 后者明显有别于 ER 随机网络模型. 小世界网络也是比较 “均匀” 的, 即大部分的节点度相差不多, 节点度近似服从 Poisson 分布.

稍后, Newman 和 Watts 对上述的 WS 模型作了少许改动, 提出了另一个相近但较好的 (NW) 小世界网络模型 [9], 其做法是不去断开原来环形初始网络的任何一条边、而只是在随机选取的节点对之间增加一条边 (这时, 新连接的边很可能是长程边). 这一模型比 WS 模型容易分析, 因为它在形成过程中不会出现孤立的节点簇 (子图).

值得提及的两个重要的相关工作是, Dorogovtsev 和 Mendes 对 NW 小世界网络模型作了精确求解 [10], 而 Kleinberg 则在二维格点图的基础上提出了一个一般性的小世界模型, 使得新模型的平均最短路径长度是可调的, 进而得到了一种

非常有效的快速算法 [11].

2.2.4 无标度网络模型

1999 年, 美国 Norte Dame 大学物理系的 Barabasi 教授和他的博士生 Albert 从统计物理的观点出发, 通过追踪万维网的动态演化过程, 发现了许多复杂网络都具有的一种大规模的高度自组织特性, 其中网络的节点度服从幂律分布: k^{-r}, 其中 k 是节点度变量而 r 是一个与标度无关的常数 [12]. 形成这种无标度网络 (scale-free network) 的两个要点是节点增加和择优连接, 特别是后者. Barabasi-Albert (BA) 无标度网络模型在生成过程中, 先从一个全连接的小网络 (最简单情形就是单个节点) 开始, 每一步以某种概率增加一个新的节点, 而新节点要与网络中已经存在的一些节点进行随机连接, 连接的概率和被选节点的度成正比 (称为择优连接). 可以证明, BA 网络的节点度服从 $r=3$ 的幂律分布. 稍后, Albert 和 Barabasi 在 BA 模型中引进了小世界的那种随机重新连接边的机制, 得到了推广的 BA 模型, 允许其节点度服从 $2<r<3$ 的幂律分布 [13]. 后来, 其他研究人员还提出了许多变种的无尺度 BA 类型的模型 [4,5].

这些无尺度 BA 类型的模型的一个显著特点是它们结构的 "不均匀" 性, 即少数节点有很高的度、但大部分的节点的度却很小. 这种无标度网络的平均最短路径长度和群集系数也较小, 但比同规模的随机网络的群集系数要大.

复杂网络的小世界和无标度特性的发现是近年来网络研究的一次重要突破, 后来的许多现实网络的实证研究表明, 物理世界中的网络既不是非常理想的规则网络, 也不是完全随机的网络, 而是介乎于确定性与随机性之间的、具有某些特定规律同时具有某些统计特性的网络, 许多还兼容了小世界和无标度两者的一些基本性质. 10 年来, 复杂网络的研究开展得蓬蓬勃勃, 出版了不少专著 [1,4,5,14~20] 和许多综述性评论性文章 [21~29].

3 复杂网络研究的一些新进展

近 10 年来, 复杂网络已经成为了不同科学领域 (包括力学、物理、生物、系统控制、通信技术、社会、经济和军事等) 中的科学家们的热点研究方向. 随着研究的不断深入, 近二三年来复杂网络在诸多方面都取得了长足的进展, 如在复杂网络建模与拓扑结构 [30~41]、动力学性质 [18,42,43]、网络涌现行为 [1,2,44,45]、复杂网络的鲁棒性与脆弱性 [45~49] 等方面.

在复杂网络群体行为和动力学的研究中, 同步和一致行为由于其重要的现实意义及其普遍性已经有很长时间的研究历史并且越来越受到广泛关注 [50~62]. 不同网络与不同类型的同步问题都受到了注意, 包括特殊耦合结构或特殊节点的网络同步 [63~80]、自适应同步行为 [81,82]、物理学中的相位同步与频率同步 [83~85]、有向网络同步 [86~91]、聚类同步 [92~99]、时滞网络同步或反同步 [100~106]、两个网络之间的同步 [107] 和全局同步 [108~110] 等等. 对于一个给定的复杂网络, 网络结构参数与同步能力有什么关系呢? 这一问题目前已有很多统计结果 [111~117]. 但是, 到目前为止, 尚未发现一个独立的结构参数能完全反映网络同步能力. 复杂网络同步控制, 特别是牵制控制 (pinning control) 也得到了深入研究 [118~125]. 与复杂网络同步问题直接相关的控制论问题, 尤其是群体活动 (swarming) 和编队飞行 (flocking) 问题中的分散控制、稳定性特别是一致性 (consensus) 问题, 近年来都受到了高度的重视 [126~157].

随着复杂网络理论研究的深入发展, 复杂网络应用方面的研究也得到了广泛关注, 特别是与生物体的新陈代谢系统、大脑神经网络相结合得到了大量的研究成果 [158~173], 与生物传染病相结合、在流行病传播与免疫控制方面取得了有意义的进展 [174~190]. 此外, 复杂网络上的博弈 [191~197]、复杂网络在交通网络与社会经济中的应用 [198~208]、通讯网络中的应用 [209~216]、计算机网与互联网中的应用 [217~221]、传感器网络中的应用 [222~235]、语言词汇网络与社会意见传播 [236~245] 等方面都有许多令人鼓舞的成果. 最新近的一篇综述文献 [246] 和一期专刊 [247] 阐述了复杂网络多方面的实际应用.

以上提到的各个方面的理论和应用的研究充分反映了当前各个领域科研人员的共同兴趣以及他们对重要方向和课题的理解和认同, 值得国内同行们关注.

参 考 文 献

1 Barabasi A L. Linked: The New Science of Networks. Massachusetts: Persus Publishing, 2002

2 Watts D J. The 'new' science of networks. *Annual Review of Sociology*, 2004, 30: 243~270

3 王树禾. 图论. 北京: 科学出版社, 2004

4 汪小帆, 李翔, 陈关荣. 复杂网络 —— 理论与应用. 北京: 清华大学出版社, 2006
5 郭雷, 许晓鸣 (主编). 复杂网络. 上海: 科技教育出版社, 2006
6 Erdos P, Renyi A. On the evolution of random graphs. *Publ Math Inst Hungary Acd Sci*, 1960, 5: 17∼60
7 Bollobasi B. Random Graphs. New York: Academic Press, 2001
8 Watts D J, Strogatz S H. Collective dynamics of 'small-world' networks. *Nature*, 1998, 393(6684): 440∼442
9 Newman M E J, Watts D J. Renormalization group analysis of the small-world network model. *Phy Lett A*, 1999, 263: 341∼346
10 Dorogovtsev S N, Mendes J F F. Evolution of networks. *Adv Phys*, 2002, 51: 1079∼1187
11 Kleinberg J. Navigation in a small world. *Nature*, 2000, 406: 845
12 Barabasi A L, Albert R. Emergence of scaling in random networks. *Science*, 1999, 286(5439): 509∼512
13 Albert R, Barabasi A L. Topology of evolving networks: local events and universality. *Phys Rev Lett*, 2000, 85(24): 5234∼5237
14 Wu C W. Synchronization in Coupled Chaotic Circuits and Systems. Singapore: World Scientific, 2002
15 Bornholdt S, Schuster H G, eds. Handbook of Graphs and Networks. Weinheim: Wiley-VCH, 2003
16 Watts D J. Six Degree. New York: Norton, 2003
17 Pastor-Satorras R, Vespignani A. Evolution and Structure of the Internet. UK: Cambridge University Press, 2004
18 Durrett R. Random Graph Dynamics. Boston: Cambridge University Press, 2006
19 Newman M E J, Barabasi A L, Watts D J, eds. The Structure and Dynamics of Networks. New Jersey: Princeton University Press, 2006
20 Wu C W. Synchronization in Complex Networks of Nonlinear Dynamical Systems. Singapore: World Scientific, 2007
21 Strogatz S H. Exploring complex networks. *Nature*, 2001, 410: 268∼276
22 Albert R, Barabasi A L. Statistical mechanics of complex networks. *Reviews of Modern Physics*, 2002, 74: 47∼97
23 Wang X F. Complex networks: topology, dynamics, and synchronization. *Int J Bifur Chaos*, 2002, 5(12): 885∼916
24 Wang X F, Chen G. Complex networks: small world, scale free and beyond. *IEEE Circuits and System Magazine*, 2003, 3(1): 6∼21
25 Newman M E J. The structure and function of complex networks. *SIAM Review*, 2003, 45: 167∼256
26 Boccaletti S, Latora V, Moreno Y, et al. Complex networks: structure and dynamics. *Physics Reports*, 2006, 424: 175∼308
27 Yuan B S, Wang B H. Growing directed networks: organization and dynamics. *New J Physics*, 2007, 9: 282
28 Costa L F, Rodrigues A, Travieso G, et al. Characterization of complex networks: A survey of measurements. *Adv in Phys*, 2007, 56(1): 167∼242
29 Arenas A, Diaz-Guilera A, Kurths J, et al. Synchronization in complex networks. 2008, arXiv: 0805.2976v1
30 Bianconi G, Gulbahce N, Motter A E. Local structure of directed networks. *Phys Rev Lett*, 2008, 100(11): 118701
31 Fang J Q, Li Y, Bi Q. From a harmonious unifying hybrid preferential model towards a large unifying hybrid network model. *Int J Modern Phys B*, 2007, 21(30): 5121∼5142
32 Fang J Q, Bi Q, Li Y, et al. Toward a harmonious unifying hybrid model for any evolving complex networks. *Adv in Complex Syst*, 2007, 10(2): 117∼141
33 Bedogé C, Masucci A P, Rodgers G J. Diophantine networks. 2007 arXiv: 0712.1723v1
34 Chen M, Yu B, Xu P, Chen J. A new deterministic complex network model with hierarchical structure. *Physica A*, 2007, 385: 707∼717
35 Lancaster D. Cluster growth in two growing network models. *J Phys A*: *Math Gen*, 2002, 35: 1179∼1194
36 Clauset A, Moore C, Newman M E J. Hierarchical structure and the prediction of missing links in networks. *Nature*, 2008, 453: 98∼101
37 Fortunatoa S, Castellano C. Community structure in graphs. 2007, arXiv: 0712.2716
38 Li X, Chen G. A local-world evolving network model. *Physica A*, 2003, 328: 274∼286
39 Li Y, Fang J Q, Liu Q, Liang Y. Small world properties generated by a new algorithm under same degree of all nodes. *Comm in Theo Physics*, 2006, 45(5): 950∼954
40 Zhang Z Z, Zhou S G, Fang L J, et al. Maximal planar scale-free Sierpinski networks with small worlds effect and power law strength-degree correlation. *Euro Phys Lett*, 2007, 79: 38007
41 Zhang Z Z, Zhou S G, Wang Z Y, Shen Z. A geometric growth model interpolating between regular and small-world networks. *J Phys A*: *Math Theo*, 2007, 40: 11863∼11876
42 Kirst C, Timme M. Bifurcation from network of unstable attractors to heteroclinic switching. 2007, arXiv: 0709.3432v1
43 Mart A C, Ponce C M, Masoller C. Dynamics of delayed-coupled chaotic logistic maps: influence of network topology, connectivity and delay times. 2007, arXiv: 0712.0325v1
44 Jezewski W. On the emergence of scaling in weighted networks. *Physica A*, 2007, 379: 691∼700
45 Nykter M, Price N D, Larjo A, et al. Critical networks exhibit maximal information diversity in structure-dynamics relationships. *Phys Rev Lett*, 2008, 100: 058702
46 Albert R, Jeong H, Barabasi A L. Attack and error tolerance in complex networks. *Nature,* 2000, 406: 387∼482
47 Callway D S, Newman M E J, Strogatz S H, Watts D J. Network robustness and fragility: percolation on random graphs. *Phys Rev Lett*, 2000, 85(16): 4626∼4628
48 Lestas I C, Vinnicombe G. Scalable robust stability for nonsymmetric heterogeneous networks. *Automatica*, 2007, 43: 714∼723
49 Sun S W, Liu Z X, Chen Z Q, Yuan Z Z. Error and attack tolerance of evolving networks with local preferential attachment. *Physica A*, 2007, 373: 851∼860
50 Pikovsky A, Rossenblum M, Kurths J. Synchronization: A Universal Concept in Nonlinear Sciences. New York: Cambridge University Press, 2001
51 Strogatz S H, Stewart I. Coupled oscillators and biological synchronization. *Scientific American*, 1993, 12: 102∼109
52 Neda Z, Ravasz E, Vicsek T, et al. The sound of many hands clapping. *Nature*, 2000, 403: 849∼850

53 Blekhman I I. Synchronization in Science and Technology. New York: ASME Press, 1988
54 Winfree A T. Biological rhythms and the behavior of populations of coupled oscillators. *J Theo Biol*, 1967, 16: 15～42
55 Kuramoto Y. Chemical Oscillations, Waves and Turbulence. Berlin: Springer-Verlag, 1984
56 Kaneko K. Coupled Map Lattices. Singapore: World Scientific, 1992
57 Chua L O. CNN: A Paradigm for Complexity. Singapore: World Scientific, 1993
58 Wu C W, Chua L O. Synchronization in an array of linearly coupled dynamical systems. *IEEE Trans Circuits Syst-I*, 1995, 42: 430～447
59 Wu C W, Chua L O. Application of graph theory to the synchronization in an array of coupled nonlinear oscillators. *IEEE Trans Circuits Syst-I*, 1995, 42: 494～497
60 Shwin P, Buescu J, Stewart I. Bubbling of attractors and synchronization of chaotic oscillators. *Phys Lett A*, 1994, 193: 126～139
61 Gauthier D J, Bienfang J C. Intermittent loss of synchronization in coupled chaotic oscillators: Toward a new criterion for high-quality synchronization. *Phys Rev Lett*, 1996, 77: 1751～1754
62 Pecora L M, Carroll T L. Master stability functions for synchronized coupled systems. *Phys Rev Lett*, 1998, 80(10): 2109～2112
63 Barahona M, Pecora L M. Synchronization in small-world systems. *Phys Rev Lett*, 2002, 89(5): 054101
64 Belykh I V, Belykh V N, Hasler M. Blinking model and synchronization in small-world networks with a time-varying coupling. *Physica D*, 2004, 195: 188～206
65 Gade P M, Hu C K. Synchronous chaos in coupled map lattices with small-world interactions. *Phys Rev E*, 2000, 62(5): 6409～6413
66 Checco P, Biey M, Kocarev L. Synchronization in random networks with given expected degree sequences. *Chaos Solitons Fractals*, 2008, 35(3): 562～577
67 Chen L, Lu J. Synchronization of complex network with drivingly coupled scheme. *Chinese Phys Lett*, 2007, 24(7): 1853～1856
68 Hong H, Choi M Y, Kim B J. Synchronization on small-world networks. *Phys Rev E*, 2002, 65: 026139
69 Lin W. Adaptive chaos control and synchronization in only locally Lipschitz systems. *Phys Lett A*, 2008, 372(18): 3195～3200
70 Li X. Uniform synchronous criticality of diversely random complex networks. *Physica A*, 2006, 360(2): 629～636
71 Goh K L, Kahng B, Kim D. Universal behavior of load distribution in scale-free networks. *Phys Rev Lett*, 2001, 87: 278701
72 Lü J H, Yu X H, Chen G, Cheng D Z. Characterizing the synchronizability of small-world dynamical networks. *IEEE Trans Circuits Syst-I*, 2004, 51(4): 787～796
73 Kocarev L, Amato P. Synchronization in power-law networks. *Chaos*, 2005, 15: 024101
74 Moreno Y, Pacheco A F. Synchronization of Kuramoto oscillators in scale-free networks. *Europhysics Lett*, 2004, 68: 603～609
75 Wang X F, Chen G. Synchronization in scale-free dynamical networks: robustness and fragility. *IEEE Trans Circuits Syst-I*, 2002, 49(1): 54～62
76 Wang X F, Chen G. Synchronization in small-world dynamical networks. *Int J Bifur Chaos*, 2002, 12(1): 187～192
77 Gong B, Yang L, Yang K. Synchronization on Erdos-Renyi network. *Phys Rev E*, 2005, 72: 037101
78 Fan J, Wang X F. On synchronization in scale-free dynamical networks. *Physica A*, 2005, 349: 443～451
79 Nair S, Leonard N E. Stable synchronization of mechanical system networks. *SIAM J Contr Optim*, 2008, 47(2): 661～683
80 Li C G, Chen G. Phase synchronization in small-world networks of chaotic oscillators. *Physica A*, 2004, 341: 73～79
81 Sorrentino F, Ott E. Adaptive synchronization of dynamics on evolving complex networks. *Phys Rev Lett*, 2008, 100: 114101
82 Bu S L, Zhang Y W, Wang B H. Synchronizing complex networks by an adaptive adjustment mechanism. *Chinese Phys Lett*, 2006, 23(11): 909～912
83 Paissan G H, Zanette D H. Synchronization of phase oscillators with heterogeneous coupling: a solvable case. *Physica D*, 2008, 237(6): 818～828
84 Jalan S, Amritkar R E. Self-organized and driven phase synchronization in coupled maps. *Phys Rev Lett*, 2003, 90(1): 014101
85 Ichinomiya T. Frequency synchronization in random oscillator network. *Phys Rev E*, 2004, 70: 026116
86 Belykh I, Hasler M. When symmetrization guarantees synchronization in directed networks. *Int J Bifur Chaos*, 2007, 17(10): 3387～3395
87 Li Z, Lee J. New eigenvalue based approach to synchronization in asymmetrically coupled networks. *Chaos*, 2007, 17: 043117
88 Wu J, Jiao L. Observer-based synchronization in complex dynamical networks with nonsymmetric coupling. *Physica A*, 2007, 386(1): 469～480
89 Chavez M, Hwang D U, Amann A, et al. Synchronization is enhanced in weighted complex networks. *Phys Rev Lett*, 2005, 94: 218701
90 Chavez M, Hwang D U, Amann A, et al. Synchronizing weighted complex networks. *Chaos*, 2006, 16: 015106
91 Wu C W. Synchronization in networks of nonlinear dynamical systems via a directed graph. *Nonlinearity*, 2005, 18: 1057～1064
92 Belykh V N, Belykh I V, Mosekilde E. Cluster synchronization modes in an ensemble of coupled chaotic oscillators. *Phys Rev E*, 2001, 63: 036216
93 Chen L, Lu J. Cluster synchronization in a complex dynamical network with two nonidentical clusters. *J Syst Sci Complex*, 2008, 21(1): 20～33
94 Huang L, Lai Y, Kwangho P, et al. Synchronization in complex clustered networks. *Front Phys China*, 2007, 2(4): 446～459
95 Qin W X, Chen G. Coupling schemes for cluster synchronization in coupled Josephson equations. *Physica D*, 2004, 197: 375～391
96 Wu X, Wang B H, Zhou T, et al. Synchronizability of highly clustered scale-free networks. *Chinese Phys Lett*, 2006, 23: 1046～1049
97 McGraw P N, Menzinger M. Clustering and synchronization of oscillator networks. *Phys Rev E*, 2005, 72: 015101

98 Ma Z J, Liu Z R, Zhang G. A new method to realize cluster synchronization in connected chaotic networks. *Chaos*, 2006, 16(2): 023103
99 Sorrentino F, Ott E. Network synchronization of groups. *Phys Rev E*, 2007, 76: 056114
100 Wang Q Y, Chen G, Lu Q S, Hao F. Novel criteria of synchronization stability in complex networks with coupling delays. *Physica A*, 2007, 378(2): 527∼536
101 Wang L, Dai H, Sun Y. Synchronization criteria for a generalized complex delayed dynamical network model. *Physica A*, 2007, 383(2): 703∼713
102 Wang L, Dai H, Dong H, et al. Adaptive synchronization of weighted complex dynamical networks with coupling time-varying delays. *Phys Lett A*, 2008, 372(20): 3632∼3639
103 Wu W, Chen T. Desynchronization of pulse-coupled oscillators with delayed excitatory coupling. *Nonlinearity*, 2007, 20(3): 789∼808
104 Wu J, Jiao L. Synchronization in dynamic networks with nonsymmetrical time-delay coupling based on linear feedback controllers. *Physica A*, 2008, 387(8-9): 2111∼2119
105 Zhang Q, Lu J, Lu J, Tse C K. Adaptive feedback synchronization of a general complex dynamical network with delayed nodes. *IEEE Trans Circuits Syst-II*, 2008, 55(2): 183∼187
106 Li C G, Chen G. Synchronization in general complex dynamical networks with coupling delays. *Physica A*, 2004, 343: 236∼278
107 Li C, Sun W, Kurths J. Synchronization between two coupled complex networks. *Phys Rev E*, 2007, 76: 046204
108 Li Z, Chen G. Global synchronization and asymptotic stability of complex dynamical networks. *IEEE Trans Circuits Syst-II*, 2006, 53(1): 28∼33
109 Li Z, Jiao L, Lee J. Robust adaptive global synchronization of complex dynamical networks by adjusting time-varying coupling strength. *Physica A*, 2008, 387(5-6): 1369∼1380
110 Li Z, Chen G. Robust adaptive synchronization of uncertain complex networks. *Phys Lett A*, 2004, 324: 166∼178
111 Belykh I V, Lange E, Hasler M. Synchronization of bursting neurons: what matters in the network topology. *Phys Rev Lett*, 2005, 94: 188101
112 Bernardo M D, Garofalo F, Sorrentino F. Effects of degree correlation on the synchronization of networks of oscillators. *Int J Bifur Chaos*, 2007, 17(10): 3499∼3506
113 Donetti L, Hurtado P I, Munoz M A. Entangled networks, synchronization, and optimal network topology. *Phys Rev Lett*, 2005, 95: 188701
114 Gomez-Gardenes J, Moreno Y, Arenas A. Paths to synchronization on complex networks. *Phys Rev Lett*, 2007, 98: 034101
115 Hong H, Kim B J, Choi M Y, Park H. Factors that predict better synchronizability on complex networks. *Phys Rev E*, 2004, 69: 067105
116 Nishikawa T, Motter A E, Lai Y C. Hoppensteadt F C. Heterogeneity in oscillator networks: are smaller worlds easier to synchronize? *Phys Rev Lett*, 2003, 91(1): 014101
117 Zhao M, Zhou T, Wang B H, et al. Relations between average distance, heterogeneity and network synchronizability. *Physica A*, 2006, 371(2): 773∼780
118 Chen T P, Liu X W, Lu W L. Pinning complex networks by a single controller. *IEEE Trans Circuits Syst-I*, 2007, 54(6): 1∼11
119 Liu X, Chen T P. Synchronization analysis for nonlinearly-coupled complex networks with an asymmetrical coupling matrix. *Physica A*, 2008, 387: 4429∼4439
120 Li X, Wang X F, Chen G. Pinning a complex dynamical network to its equilibrium. *IEEE Trans Circuits Syst-I*, 2004, 51(10): 2074∼2085
121 Liu Z X, Chen Z Q, Yuan Z Z. Pinning control of weighted general complex dynamical networks with time delay. *Physica A*, 2007, 375: 345∼354
122 Wang X F, Chen G. Pinning control of scale-free dynamical networks. *Physica A*, 2002, 310: 521∼531
123 Xiang L Y, Liu Z X, Chen Z Q, et al. Pinning control of complex dynamical networks with general topology. *Physica A*, 2007, 379: 298∼306
124 Wang L, Dai H P, Dong H, et al. Adaptive synchronization of weighted complex dynamical networks through pinning. *Euro Phys J B*, 2008, 61: 335∼342
125 Li R, Duan Z S, Chen G. Cost and effects of pinning control for network synchronization. 2007, arXiv: 0710.2716v1
126 Vicsek T. A question of scale. *Nature*, 2001, 411: 421∼421
127 Okubo A. Dynamical aspects of animal grouping: swarms, schools, flocks and herds. *Adv Biophysics*, 1986, 22: 1∼94
128 Parrish K. Complexity, pattern, and evolutionary trade-offs in animal aggregation. *Science*, 1999, 284(4): 99∼101
129 Tanner H G, Jadbabaie A, Pappas G J. Stable flocking of mobile agents, Part I: fixed topology; Part II: dynamic topology. *IEEE Conf on Decision and Control*, 2003, 2010∼2015; 2016∼2021
130 Su H S, Wang X F, Lin Z L. Flocking of multi-agents with a virtual leader, Part I: with minority of informed agents; Part II: with a virtual leader of varying velocity. *IEEE Conf on Decision and Control*, 2007, 1429∼1434, 2937∼2942
131 Arcak M. Passivity as a design tool for group coordination. *IEEE Trans Auto Contr*, 2007, 52(8): 1380∼1390
132 Shi H, Wang L, Chu T G. Virtual leader approach to coordinated control of multiple mobile agents with asymmetric interactions. *Physica D*, 2006, 213: 51∼65
133 Hong Y, Cao L, Cheng D, Hu J. Lyapunov-based approach to multi-agent systems with switching jointly-connected interconnection. *IEEE Trans Auto Contr*, 2007, 52(5): 943∼948
134 Liu Z X, Guo L. Synchronization of Vicsek model with large population. *Chinese Control Conference*, 2007, 673∼677
135 Li T, Zhang J F. Sampled-data based average consensus control for networks of continuous-time integrator agents with measurement noises. In: Chinese Control Conference. 2007-07-26∼31, Zhang Jiajie, China. IEEE Catalog Number: CFP0840A, 2007. 716∼720
136 Mogilner A, Edelstein-Keshet L. Spatio-temporal order in populations of self-aligning objects: formation of oriented patches. *Physica D*, 1996, 89: 346∼367
137 Mogilner A, Edelstein-Keshet L. A non-local model for a swarm. *J Math Biology*, 1999, 38: 534∼570
138 Toner J, Tu Y. Flocks, herds, and schools: A quantitative theory of flocking. *Phys Rev E*, 1998, 58(4): 4828∼4858
139 Toner J, Tu Y. Hydrodynamics and phases of flocks. *Annals of Physics*, 2005, 318: 170∼244

140 Couzin I D, Krause J, Franks N R, et al. Effective leadership and decision-making in animal groups on the move. *Nature*, 2005, 433(3): 513∼516

141 Couzin I D, Krause J, James J, et al. Collective memory and spatial sorting in animal groups. *J Theo Biology*, 2002, 218(1): 1∼11

142 Portegys T E. Goal-seeking behavior in a connectionist model. *Artific Intell Review*, 2001, 16: 225∼253

143 Bauso D, Giarre L, Pesenti R. Non-linear protocols for optimal distributed consensus in networks of dynamic agents. *Syst Contr Lett*, 2006, 55: 918∼928

144 Cortes J. Distributed algorithms for reaching consensus on general functions. *Automatica*, 2008, 44: 726∼737

145 Jadbabaie A, Lin J, Morse A S. Coordination of groups of mobile autonomous agents using nearest neighbor rules. *IEEE Trans Auto Contr*, 2003, 48(6): 988∼1001

146 Moreau L. Stability of multiagent systems with time-dependent communication links. *IEEE Trans Auto Contr*, 2005, 50(2): 169∼182

147 Fax J A, Murray R M. Information flow and cooperative control of vehicle formations. *IEEE Trans Auto Contr*, 2004, 49(9): 1465∼1476

148 Olfati-Saber R. Flocking for multi-agent dynamic systems: algorithms and theory. *IEEE Trans Auto Contr*, 2006, 51(3): 401∼420

149 Olfati-Saber R, Murray R M. Consensus problems in networks of agents with switching topology and time delays. *IEEE Trans Auto Contr*, 2004, 49(9): 1520∼1533

150 Olfati-Saber R, Fax J A, Murray R M. Consensus and cooperation in networked multi-agent systems. *Proceedings of the IEEE*, 2007, 97(1): 215∼233

151 Porfiri M, Stilwell D J. Consensus seeking over random weighted directed graphs. *IEEE Trans Auto Contr*, 2007, 52(9): 1767∼1773

152 Ren W, Beard R W. Consensus seeking in multiagent systems under dynamically changing interaction topologies. *IEEE Trans Auto Contr*, 2005, 50(5): 655∼661

153 Ren W. Multi-vehicle consensus with a time-varying reference state. *Syst Contr Lett*, 2007, 56: 474∼483

154 Ren W, Beard R W, Atkins E M. Information consensus in multivehicle cooperative control. *IEEE Control Systems Magazine*, 2007, 27(2): 71∼82

155 Wu C W. Synchronization and convergence of linear dynamics in random directed networks. *IEEE Trans Auto Contr*, 2006, 51(7): 1207∼1210

156 Xiao F, Wang L. State consensus for multi-agent systems with switching topologies and time-varying delays. *Int J Control*, 2006, 79(10): 1277∼1284

157 Barabasi A L. The architecture of complexity. *IEEE Control Systems Magazine*, 2007, 27(4): 33∼42

158 Liu Z R, Luo J G. From lag synchronization to pattern formation in one-dimensional open flow models. *Chaos Solitons Fractals*, 2006, 30 (5): 1198∼1205

159 Bassett D S, Bullmore E. Small-world brain networks. *Neuroscientist*, 2006, 12: 512∼523

160 Couzin L. Collective minds. *Nature*, 2007, 445: 715

161 Dhamala M, Jirsa V K, Ding M. Enhancement of neural synchrony by time delay. *Phys Rev Lett*, 2004, 92(7): 074104

162 Eguiluz V M, Dante R C, Guillermo A C, et al. Scale-free brain functional networks. *Phys Rev Lett*, 2005, 94: 018102

163 Gong Y B, Xu B, Xu Q, et al. Ordering spatiotemporal chaos in complex thermosensitive neuron networks. *Phys Rev E*, 2006, 73: 046137

164 Hasegawa H. Synchronization in small-world networks of spiking neurons: Diffusive versus sigmoid couplings. *Phys Rev E*, 2005, 72: 056139

165 Ray C, Ruffini G, Marco-Pallares J, et al. Complex networks in brain electrical activity. *A Letters Journal Exploring the Frontiers of Physics*, 2007, 79: 38004

166 Motter A E, Gulbahce N, Almaas E, Barabasi A L. Predicting synthetic rescues in metabolic networks. *Molecular Systems Biology*, 2008, 4(168): 1744∼4292

167 Linow M M, Weckwerth W, Hütt M T. Consistency analysis of metabolic correlation networks. *BMC Systems Biology*, 2007, 1(44): 17520509

168 Rossoni E, Chen Y H, Ding M Z, et al. Stability of synchronous oscillations in a system of Hodgkin-Huxley neurons with delayed diffusive and pulsed coupling. *Phys Rev E*, 2005, 71: 061904

169 Wang Q Y, Lu Q S, Chen G, Guo D H. Chaos synchronization of coupled neurons with gap junction. *Phys Lett A*, 2006, 356: 17∼25

170 Wang Q Y, Lu Q S. Phase synchronization in small world chaotic neural networks. *Chinese Phys Lett*, 2005, 21: 1329∼1332

171 Wang Q Y, Lu Q S, Chen G. Subthreshold stimulus-aided temporal order and synchronization in a square lattice noisy neuronal network. *Europhysics Lett*, 2007, 77: 10004

172 Wang Q Y, Duan Z S, Feng Z S, et al. Synchronization transition in gap-junction-coupled leech neurons. *Physica A,* 387, 2008, 4404∼4410

173 Wang Q Y, Duan Z S, Huang L, et al. Pattern formation and firing synchronization in networks of map neurons. *New J Physics*, 2007, 8(393): 1∼11

174 Boguna M, Pastor-Satorras R. Epidemic spreading in correlated complex networks. *Phys Rev E*, 2002, 66(4): 047104∼047107

175 Boguna M, Pastorras R, Vespignani V. Absence of epidemic threshold in scale-free networks with degree correlations. *Phys Rev Lett*, 2003, 90(2): 028701∼028703

176 Cohen R, Havlin S, Avraham D. Efficient immunization strategies for computer networks and populations. *Phys Rev Lett*, 2003, 91(24): 247901∼247904

177 Liljeros F, Edling C R, Stanley H E, et al. Sexual contacts and epidemic thresholds. *Nature*, 2003, 423(6940): 605∼606

178 Moreno Y, Pastor-Satorras R, Vespignani A. Epidemic outbreaks in complex heterogeneous networks. *Euro Phys J B*, 2002, 26(4): 521∼529

179 Newman M E J. Spread of epidemic disease on networks. *Phys Rev E*, 2002, 66(1): 016128∼016139

180 Pastor-Satorras R, Vespignani A. Epidemic dynamics and endemic states in complex networks. *Phys Rev E*, 2001, 63(6): 066117∼066124

181 Pastor-Satorras R, Vespignani A. Epidemic dynamics infinite size scale-free networks. *Phys Rev E*, 2002, 65(3): 035108∼035111

182 Pastor-Satorras R, Vespignani A. Immunization of complex networks. *Phys Rev E*, 2002, 65(3): 036104∼036111

183 Wang J Z, Liu Z R, Xu J H. Epidemic spreading on uncorrelated heterogenous networks with non-uniform transmission. *Physica A*, 2007, 382: 715∼721
184 Yang R, Wang B H, Ren J, et al. Epidemic spreading on heterogeneous networks with identical infectivity. *Phys Lett A*, 2007, 364: 189∼193
185 Small M, Walker D M, Tse C K. Scale-free distribution of avian influenza outbreaks. *Phys Rev Lett*, 2007, 99: 188702
186 Massad E, Ma S, Chen M, et al. Scale-free network of a dengue epidemic. *Applied Math Comput*, 2008, 195: 376∼381
187 Huang L, Lai Y C, Chen G. Understanding and preserving the cascading breakdown in complex clustered networks. *Phys Rev E*, 2008, 78: 036116
188 Guo W P, Li X, Wang X F. Epidemics and immunization on Euclidean distance preferred small-world networks. *Physica A*, 2007, 380: 684∼690
189 Shi H J, Duan Z S, Chen G. An SIS model with infective medium on complex networks. *Physica A*, 2008, 387: 2133∼2144
190 Volchenkov D, Volchenkova L, Blanchard P H. Epidemic spreading in a variety of scale free networks. *Phys Rev E*, 2002, 66(4): 046137∼046146
191 Gao K, Wang W X, Wang B H. Self-questioning games and ping-pong effect in the BA network. *Physica A*, 2007, 380: 528∼538
192 Rong Z H, Li X, Wang X F. Roles of mixing patterns in cooperation on a scale-free networked game. *Phys Rev E*, 2007, 76: 027101
193 Wang W X, Ren J, Chen G, Wang B H. Memory-based snowdrift game on networks. *Phys Rev E*, 2006, 74: 056113
194 Wang W X, Lu J, Chen G, Hui P M. Phase transition and hysteresis loop in structured games with global updating. *Phys Rev E*, 2008, 77: 046109
195 王龙, 伏峰, 陈小杰等. 复杂网络上的演化博弈. 智能系统学报, 2007, 2(2): 1∼10
196 王龙, 伏峰, 陈小杰等. 演化博弈与自组织合作. 系统科学与数学, 2007, 27(3): 330∼343
197 赵晟莹, 郭强, 王文旭等. 复杂网络上博弈行为的研究进展. 电子测量技术, 2007, 30(4): 93∼96
198 Gong H, Liu H, Wang B. An asymmetric full velocity difference car-following model. *Physica A*, 2008, 387(11): 2595∼2602
199 Cai S M, Yan G, Zhou T, et al. Scaling behavior of an artificial traffic model on scale-free networks. *Phys Lett A*, 2007, 366: 14∼19
200 Ranta E, Fowler M S, Kaitala V. Population synchrony in small-world networks. *Proc R Soc B*, 2007, 1546: 1∼8
201 Ortega J L, Aguillo I, Cothey V, Scharnhorst A. Maps of the academic web in the European higher education area: an exploration of visual web indicators. *Scientometrics*, 2008, 74(2): 295∼308
202 Palla G, Barabasi A L, Vicsek T. Quantifying social group evolution. *Nature*, 2007, 446: 664∼667
203 Wang L, Dai H P, Sun Y X. Random pseudofractal networks with competition. *Physica A*, 2007, 383: 763∼772
204 Zhou T, Jiang L L, Su R Q, Zhang Y C. Effect of initial configuration on network-based recommendation. *A Letters Journal Exploring the frontiers of Physics*, 2008, 81: 58004
205 Zhou T, Ren J, Medo M, Zhang Y. Bipartite network projection and personal recommendation. *Phys Rev Lett*, 2007, 76: 046115
206 Tatem A J, Hay S I. Climatic similarity and biological exchange in the worldwide airline transportation network. *Proc Royal Soc*, 2007, 274: 1489∼1496
207 Zhu C P, Zhou T, Yang H, et al. The process of coevolutionary competitive exclusion: speciation, multifractality and power-laws in correlations. *New Journal of Physics*, 2008, 10: 023006
208 Li P, Wang B H. Extracting hidden fluctuation patterns of Hang Seng stock index from network topologies. *Physica A*, 2007, 378: 519∼526
209 Cao L, Li X. Mixed evolutionary strategies imply coexisting opinions on networks. *Phys Rev E*, 2008, 77: 016108
210 Maxemchuk N F, Ouveysi I, Zukerman M. A quantitative measure for telecommunications networks topology design. *IEEE/ACM Trans on Networking*, 2005, 13(4): 731∼742
211 Tam W M, Lau F C, Tse C K, et al. Effect of clustering in a complex user network on the telephone traffic. *Physica A*, 2006, 371: 745∼753
212 Xia C, Shi Y, Li X, Gao W. P2P worm detection based on application identification. *Front Comput Sci China*, 2007, 1(1): 114∼122
213 Xia Y, Hill D J. Attack vulnerability of complex communication networks. *IEEE Trans Circuits Syst-II*, 2008, 55(1): 65∼69
214 Xia Y, Tse C K, Lau F C, et al. Scale-free user-network approach to telephone network traffic analysis. *Phys Rev Lett*, 2005, 72: 026116
215 Xia Y, Tse C K, Lau F C, et al. Analysis of telephone network traffic based on a complex user network. *Physica A*, 2006, 368: 583∼594
216 Xiao S, Xiao G, Cheng T H. Tolerance of intentional attacks in complex communication networks. *IEEE Communications Magazine*, 2008, 46(1): 146∼152
217 Masucci A P, Rodgers G J. The network of commuters in London. 2007, arXiv: 0712.1960v1
218 Shorten R, King C, Wirth F, Leith D. Modelling TCP congestion control dynamics in drop-tail environments. *Automatica*, 2007, 43: 441∼449
219 Smith R D. Data traffic dynamics and congestion on a single link. 2008, arXiv: 0802.3554
220 Xia C, Shi Y, Li X, Gao W. P2P worm detection based on application identification. *Front Comput Sci China*, 2007, 1(1): 114∼122
221 何克清, 刘婧, 李兵. 软件网络. 北京: 科学出版社, 2008
222 Akyildiz I F, Su W, Sanakarasubramaniam Y, et al. Wireless sensor networks: a survey. *Computer Networks*, 2002, 38(4): 393∼422
223 Dimakis A G, Sarwate A D, Wainwright M J. Geographic gossip: efficient averaging for sensor networks. *IEEE Trans Signal Processing*, 2008, 56(3): 1205∼1216
224 Gupta V, Chung T H, Hassibi B, Murray R M. On a stochastic sensor selection algorithm with applications in sensor scheduling and sensor coverage. *Automatica*, 2006, 42(1): 251∼260
225 Heidelberger R. Sensors and synchronicity. *Nature*, 2007, 450: 623625
226 李晓维, 徐勇军, 任丰原. 无线传感器网络技术. 北京: 北京理工大学出版社, 2007

227 Li Q, Rus D. Grobal clock synchronization in sensor networks. *IEEE Trans Computers*, 2006, 55(2): 214~226
228 Milner S, Desai A. Autonomous reconfiguration in free-Space optical sensor networks. *IEEE J Selected Area in Comm*, 2005, 23(8): 1556~1563
229 Milner S, Desai A. Self-organizing broadband hybrid wireless networks. *J Opt Networking*, 2005, 4(7): 446~459
230 Milner S, Lorca J, Anibha A, Vishkin U. A bootstrapping model for directional wireless networks. *IEEE Comm Lett*, 2006, 10(12): 840~842
231 Puccinelli D, Haenggi M. Wireless sensor networks: Applications and challenges of ubiquitous sensing. *IEEE Circuits and System Magazine*, 2005, 5(3): 19~29
232 Tsai H, Chu C, Chen T. Mobile object tracking in wireless sensor networks. *Computer Communications*, 2007, 30: 1811~1825
233 Su W L, Akyildiz I F. Time-diffusion synchronization protocal for wireless sensor networks. *IEEE/ACM Trans Networking*, 2005, 13(2): 384~397
234 赵志峰, 郑少仁. Ad Hoc 网络体系结构研究. 电信科学, 2001, 17(1): 14~17
235 唐秋玲, 杨柳青, 覃团发, 张淑仪. 无线传感器网络中 PPM 节能调制方案. 中国科学 E 辑, 2007, 37(12): 1583~1596
236 Yang H X, Wang W X, Wang B H. Asymmetric negotiation in structured language games. *Phys Rev E*, 2008, 77: 027103
237 Gong T, Wang W S Y. Computational modeling on language emergence: a coevolution model of lexicon, syntax and social structure. *Language and Linguistics*, 2005, 6(1): 1~42
238 Kalampokis A K, Kosmidis K, Argyrakis P. Evolution of vocabulary on scale-free and random networks. *Physica A*, 2007, 397: 665~671
239 Dorogovtsev S N, Mendes J F F. Language as an evolving word web. *The Royal Society*, 2001, 1824: 2606~2606
240 Motter A E, Moura A P S, Lai Y C, Dasgupta P. Topology of the conceptual network of language. *Phys Rev E*, 2002, 65: 065102
241 Cancho R F I, Solé R V. The small-world of human language. *The Royal Society*, 2001, 268: 2261~2265
242 Zhou S, Hu G, Zhang Z, Guan J. An empirical study of Chinese language networks. *Physica A*, 2008, 387: 3039~3047
243 Garlaschelli D, Loffredo M I. Effects of network topology on wealth distributions. 2008, arXiv: 0711.4710v2
244 Guo Q, Liu J G, Wang B H, et al. Opinion spreading with mobility on scale-free networks. *Chinese Phys Lett*, 2008, 25(2): 773~775
245 Lorenz J. Continuous opinion dynamics under bounded confidence: a survey. 2008, arXiv: 0707.1762v2
246 da Fontoura Costa L, Oliveira Jr O N, Travieso R, et al. Analyzing and modelling real-world phenomena: a survey of applications. 2007, arXiv: 0711.3199v1
247 Barrat Q, Boccaletti S, Caldarelli G, et al. eds. Special Issue on "Complex networks: from biology to information technology". *J Phys A*: *Math Theo*, 2008, 41: 220301

INTRODUCTION TO COMPLEX NETWORKS AND THEIR RECENT ADVANCES*

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Abstract This article introduces the new notion of complex networks, especially the representative models of random-graph networks, small-world networks and scale-free networks as well as related basic concepts and modeling parameters. It also briefly summarizes their applications to biological systems and neural networks, epidemic spreading and immunization over networks, transportation systems, social and economic networks, wireless communication and sensor networks. And finally it reviews the problems of distributed control, stability and consensus analysis in their applications to swarming, flocking and synchronization.

Keywords complex network, random-graph network, small-world network, scale-free network

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