Research on Control and Management Methods for Complex Wireless Networks (Postprint)

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Date: 2017-03-10T00:00:00+00:00

Abstract

It is still based on the stop-and-wait model. For large-scale systems, the stop-and-wait model substantially impacts program parallel efficiency. This paper proposes a non-stop-and-wait algorithm-level fault tolerance strategy—the hot replacement strategy. When node failures occur during program execution, rather than stopping and waiting to recover data on the failed node, a redundant node replaces the failed node, enabling computation to continue. The final correct result can be derived through a linear transformation. To validate the effectiveness of the proposed scheme, we implemented fault-tolerant High Performance Linpack (HPL) by integrating the fault tolerance capabilities of MPICH and evaluated the scheme' s performance. Experimental results demonstrate that even at small scales, our scheme' s performance significantly outperforms algorithmic failure recovery techniques.

Full Text

Preamble

Vol. 9 No. 2 Information Technology Letter Vol.9 No.2
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Abstract

Modern network development has increasingly exhibited nonlinear "dynamical" characteristics of diversity, inter-fusion, and collaborative evolution. This paper analyzes future wireless network control and management research methods from the perspective of fractal dynamical features of network "fusion" growth. The research focuses on the main thread of future wireless network fusion and its physical manifestation development, explores the scientific foundational theories of wireless network control and management, and finally introduces the R&D

deployment carried out by the Wireless Communication Technology Research Center of the Institute of Computing Technology according to wireless network development and industrial demands.

Keywords: complex wireless networks, control and management, dynamics

1 Introduction

Since the 1980s when information technology entered a high-speed development channel, more than 30 years have passed, yet there is still no sign of slowdown. Due to advances in materials science, computer science, high-spectrum-efficiency signal processing technologies, and network-based information application technologies, this development trend has actually further accelerated. Particularly after 2000, information technology applications based on communication networks have permeated every aspect of social life. With the socialization of information networks, the development and application of communication networks have become deeply intertwined with people' s social lives [1]. On platforms such as computers, mobile phones, and intelligent terminals, establishing a virtual world through various communication connections to conduct shopping, social networking, diary writing, property management, and other activities has become a lifestyle habit for a large portion of the population. Moreover, the IP-all-IP nature of next-generation network technology "Long Term Evolution (LTE)" makes personalized connections anytime and anywhere increasingly ubiquitous. This renders the "Amazon butterfly effect" a potential risk that exists everywhere and at all times in the network world—any event occurring in the network, if not effectively controlled, could cause enormous damage to physical society. How to effectively control networks, especially how to develop, control, and manage networks well in the era of ubiquitous wireless networks, has become a tremendous challenge facing current wireless communication network development.

This paper analyzes future wireless network control and management research methods by examining the changing demands of wireless networks from the perspective of network "fusion" growth and the dynamical characteristics of traffic flows, and finally introduces the R&D deployment carried out by the Wireless Communication Technology Research Center of the Institute of Computing Technology, Chinese Academy of Sciences, according to wireless network development and industrial demands.

The emergence of Apple' s iPad and iPhone series products as core intelligent terminals in 2010 heralded the official arrival of the broadband mobile era characterized by multi-network and multi-service convergence. Chinese and European/American operators who had been lamenting that 3G (third-generation mobile communication systems) deployment lacked "killer applications" were surprised to discover that their built broadband was not actually "broad" — routine applications from smartphone users alone had rapidly and ruthlessly consumed 3G bandwidth, not to mention multimedia applications! Further-more, home femtocells will directly open the originally closed cellular wireless communication network to users, and through fusion applications with IP technology, make the entire network increasingly transparent. This transparent fusion itself will enable each user not only to freely use services provided by the network but also to instantly create and provide services on the network, becoming a virtual service operation provider based on the new generation of open networks. Current wireless mobile phone user penetration is already quite high. Although the bandwidth requirements of current intelligent terminals have already overwhelmed service providers, the development of wireless sensor networks and the Internet of Things is still in its infancy and will form tens of billions of virtual users. Operators are fueling this trend, striving to replace traditional production and lifestyle patterns with communication-based production and lifestyle patterns within a broader scope, penetrating and partially substituting other traditional industries with the communication industry to maximize communication industry profits. The currently nearly saturated 3G network obviously cannot meet these demands, prompting operators to accelerate the development of 4G (fourth-generation mobile communication systems) that can provide greater bandwidth. Such wireless networks will have several characteristics:

- The underlying technology LTE-Advanced introduces a flattened IP network architecture. This transparent architecture, combined with multi-hop relaying and small home base stations, gives the new generation of wireless communication networks fractal growth characteristics.
- Multi-hop relaying and small home base station technologies will lead to fault cascading effects in wireless networks, making existing control and management methods inadequate.
- Not only does the network structure have fractal characteristics, but its traffic flows will also have fractal characteristics.

The aforementioned complex fractal phenomena in wireless networks have actually long appeared in the Internet and have attracted relevant research attention. Currently proposed scientific research models for complex networks mainly include the random topology model (Erdös and Rényi Model, ER model) [2], the "small-world" model (WS model) proposed by Watts and Strogatz [3], and the scale-free model (BA model) proposed by Barabasi and Albert [4]. The BA model proposes two important network evolution mechanisms: growth and preferential attachment. By fitting these two properties, complex networks can be constructed through continuous node growth. Currently, the growth characteristics of wireless networks primarily accessed through home micro-cellular networks and wireless local area networks (WLAN) possess features of these models. This implies that wireless network growth also conforms to clustering, satisfying certain power laws and fractal dimensions. Deriving the corresponding parameters of these models may enable precise management of wireless network resource management and service control. Figure 1 [Figure 1: see original paper] shows the global Internet routing topology in 1999, where the ER model has an average distance of 4 0 .= , following a power law distribution: ( )P k k

− , 2 2 , with clustering coefficient c= 0.3.

If described using the WS model, its average distance is 14 L = , and the degree distribution function is: 1( )P k 2 ( ) k − k − 2 1). 2 72). According to this model' s calculations, when over 99.5% of websites have connection counts below 100, there are four ten-thousandths of websites with more than 1000 connections, and three hundred-thousandths of websites exceeding 3,000 mainstream resources as mainstream resources can largely satisfy people' s daily needs. Figure 1 illustrates the indegree distribution of a BA network with outdegree of 3, with network scale of 6000.

We can observe that the topological growth structure of wireless network systems resembles the bronchial tree of animal lungs, which to some extent is also similar to urban sewer pipe networks. Research on wireless network control and management can largely draw lessons from biological control methods of natural fractal-like structures with similar characteristics. Figure 2 [Figure 2: see original paper] shows the structure of a lung bronchial network tree [6]. In Figure 2, when the branching number is determined, optimal values for fluid transport can be obtained for different length ratios and branching levels. Similarly, if we can derive the fractal dimension of wireless network growth distribution and its traffic flow dynamical equations, we can obtain theoretical guidance for wireless network construction and resource control management. In this regard, besides the network topology structure itself, people have also been attempting to find concise formulas like the Erlang formula [2] previously applied in telephone networks to describe the relationship between traffic and network performance, in order to better implement network traffic control. As we all know, the Erlang formula was derived based on independent and identically distributed Poisson processes. After IP introduction into wireless mobile networks, the popularization of smartphone applications makes user traffic self-similar, making Poisson processes unsuitable for its analysis and modeling. Therefore, new traffic equations need to be studied according to the new characteristics of wireless network traffic—that is, to find out the traffic transport properties under self-similar traffic and fractal wireless networks as a theoretical basis for controlling and managing wireless networks. Moreover, what distinguishes wireless communication networks from other natural systems is that the core participants of networks are humans. Networks have become inseparable from human society, and the social complexity of humans is fully brought into networks. The bounded rationality and personal preferences brought by individual self-awareness and group consciousness, along with the historicity and decision-making intelligence when participating in networks, have caused wireless network systems to evolve into complex giant systems. From network topology structure to network service flows, complete diversification and fractality have emerged. These multifractal characteristics lead to the complexity of network growth and service behavior. Although wireless network architecture design has been continuously improved and network control and management have been strengthened due to computer technology applications, people' s understanding of wireless network growth behavior and user service behavior remains very limited, and corresponding control and management methods lack support from scientific foundational theories. Under such circumstances, studying network behavior dynamics of wireless network dynamic evolution laws according to the self-similar characteristics of wireless network growth behavior and user service flows has become a new and extremely challenging task. It is crucial for us to grasp the basic characteristics of future wireless network growth behavior, discover the internal laws of network user behavior, and will provide scientific theoretical support for scientific management, rational utilization, and effective control of wireless networks.

3 Fractal Dynamical Characteristics Analysis Methods for Wireless Network Development

Network fractal dynamics is the science that studies the dynamic evolution laws of networks. Different types of networks in nature exhibit both similar dynamic behaviors and dynamic evolution behaviors with their own network characteristics during their evolution processes. In recent years, research on network evolution fractal dynamics and network behavior dynamics has increasingly attracted attention, with research achievements often being fundamental and original. Therefore, it is considered basic scientific research on networks. The purpose of network dynamics research is to understand the laws of network evolution and behavior, and to conduct system structure design, algorithm design, etc., according to these laws to guide healthy network development. Additionally, network dynamics research can also verify network design principles, system structures, and algorithm performance from the side.

Therefore, network dynamics research is considered the foundation of network research. The research methods for network dynamics are briefly introduced below.

3.1 Network Evolution Fractal Dynamics

In recent years, some international scientists have used statistical physics methods to study complex communication network systems with fractal characteristics. Stochastic geometry has made considerable progress based on this type of research. Its purpose is to obtain random topological characteristics of network development through statistical analysis, and then obtain general network evolution laws. So far, important 阶段性 conclusions obtained from research on communication network fractal characteristics are that communication networks have small-world characteristics and scale-free characteristics. Table 1 compares the main statistical characteristic quantities of several networks, clearly showing the similarities and differences between various network models and actual networks. Based on the discovery of network small-world characteristics and scale-free characteristics, academia has set off an upsurge in complex network modeling research. The ultimate purpose of studying network topology structure laws is to understand the evolution mechanisms of various networks and the influence of topological characteristics on other evolution dynamics on networks. In the past, the abstract method for studying network dynamics was to construct random graphs. Once realizing that previous random graphs could not truly describe networks, the dynamical equations obtained on random graphs might no longer be applicable. Latest research mostly focuses on re-examining previously obtained laws.

3.2 Network Information Flow Dynamics

The self-similarity of network information flow is an important discovery in Internet-related research. Leland et al. [7] first studied the distribution characteristics of information packets in networks in the early 1990s, and pointed out in their 1994 research paper that the arrival time of information packets transmitted in Ethernet local area networks has a certain degree of self-similarity on time scales, and has long-range correlation or burstiness in time. This challenged the traditional widespread use of Poisson models to represent network transmission. Subsequent studies showed that this self-similarity or long-range correlation characteristic exists to varying degrees in different types of networks and at different network layers. A common feature of these research results is that the studied network service flows are basically generated by computer applications. This reveals the characteristics of network service flows with computing technology platforms as network end nodes, and indirectly implies that wireless network information flows generated by smartphones and mobile computing technology will have both the original independent distribution mode service flow characteristics and self-similarity, requiring new research on their information flow dynamics description. Researchers have also discovered that complexity phenomena such as phase transitions and power laws widely exist in computer networks. For instance, research on network critical phenomena focuses on analyzing the conversion characteristics and conditions between network congestion and non-congestion states. An important conclusion is that the network state at the critical point is the state where network work efficiency is highest. Some scholars have studied phase transition phenomena in network models with different topological structures. T. Ohira et al. [8] built network models on two-dimensional grid-like topological structures, studied the influence of network parameters and routing strategies on phase transition curves, and pointed out that as long as routing strategies are precisely selected and their parameters adjusted, the phase transition process of the network reaching the congestion phase can be maximally delayed, thereby obtaining the best network performance. H. Fuks et al. [9] further provided formal strict definitions of network models and studied the impact of adding connections between nodes (equivalent to adding communication lines in networks) on network phase transition behavior. The results showed that adding connection lines does not always improve network performance, and the results also strongly depend on routing selection strategies in the network. The above research results have important reference value for the next step in wireless network information flow dynamics research.

In addition, communication network service data flow control and management have considerable similarities with current intelligent traffic flow control and management. Some control and management methods applied in intelligent traffic can be used in communication network resource allocation and service control management. In a 2001 review article published in *Physics Reports*, it was pointed out that self-organized criticality and phase transition complexity phenomena in cellular automata used to describe traffic flow control could be applied to computer communication networks [10]. Current conclusions on self-organized criticality phenomena in computer networks are still limited. Researchers have divided self-organized behaviors appearing in computer networks into two levels: node level and data packet level, and studied them separately through simple one-dimensional cellular automata models, obtaining that computer communication network system behavior exhibits self-organized criticality phenomena. The basis of data packet level research is that network nodes play a regulatory role in data packet flows, and conversely, data packet flows also affect node behavior. At the data packet level, the main focus is on the interaction between data packets, i.e., the overall behavior at the data packet level. Originally uncorrelated data packet flows may exhibit long-range correlation characteristics after being modulated by nodes.

3.3 Network Propagation and Percolation Dynamics

As mentioned earlier, the rapid development of wireless communication networks makes the "Amazon butterfly effect" potentially a reality in networks. In fact, current events caused by mobile phone viruses, computer viruses, and illegal information flows on networks are essentially "Amazon butterfly" events. How to describe and control such events has always been the focus of communication network operations. Pastor-Satorras et al. [11] studied the spread of computer viruses on the Internet and found certain similarities with the spread of biological infectious diseases. The difference is that the infection rate of biological viruses must exceed a certain threshold to truly become epidemic; otherwise, the virus will quickly disappear, while the spread of viruses on the Internet does not necessarily have such a threshold. However, the control ideas for biological viruses should be applicable to communication network control. The latest research methods on network propagation and percolation study virus propagation characteristics and related dynamical behaviors on specific network topology models. Existing research shows that there is no threshold on scale-free networks, so once a virus infects somewhere on the Internet, it will quickly spread across the network. Therefore, previous virus propagation models built on random networks all need to be re-verified under new network topology structures to establish dynamical equations that conform to actual network propagation characteristics, and then establish information propagation dynamical equations that conform to network characteristics to design protection strategies and enhance network security.

3.4 Network Cascading Dynamics

In network control and management, isolation and recovery of faulty nodes is an important content. As wireless communication networks become increasingly flattened and base stations move closer to the user side, the cascading catastrophe that may be triggered by a single access base station failure is also increasing. In real life, "catastrophic" cascading effects can be seen everywhere, such as traffic congestion on transportation networks, sudden interruption of communication networks, large-scale power outages caused by power network failures, etc. By studying the mechanisms and related influencing factors of these catastrophes, we can guide the optimal design of wireless network topology and system structures to maximally avoid such catastrophes.

Describing cascading reactions on networks and establishing corresponding control models is the main direction of current network cascading dynamics research. The research method of Bianconi and Marsili [12] is: imagine a large number of information packets propagating on the computer Internet. Due to fluctuations in information volume, the information volume at a certain node may reach or exceed the node' s throughput capacity. At this time, if information packets still need to pass through this node, the router will change the routing of the information packets to bypass the congested node. However, this detour may also cause congestion at other nodes downstream of the router, and this congestion will in turn require more information packets to detour, potentially causing more node congestion. The earliest established micro-disturbance and related cascading reaction model is the BTW model [13]. This model can simulate the realization of self-organized criticality (SOC), in which micro-disturbances to the system can cause cascading reactions of various scales. Arcangelis and Herrmann [14] studied cascading problems on small-world networks (AH model). Goh et al. [15] studied cascading problems on scale-free networks, obtained the relationship between cascading reaction scale distribution functions and network node degree power-law distribution exponents (GLKK model), and can study through simulation of network cascading dynamics laws whether network information transmission will be interrupted when network nodes suffer corresponding attacks and how to overcome this phenomenon through certain network operations.

The purpose of the aforementioned research work is to seek scientific theoretical guidance for future wireless network resource allocation and service control management. As mentioned earlier, with the fusion of computing technology and communication, networks have become part of human society. Such socialized networks have two basic characteristics: 1) nodes are people (agents) and groups (multi-agents) using or controlling them; 2) connections are reflections of various social relations, having locality and hierarchy. It is precisely these two characteristics that make network evolution possess human characteristics. We study its dynamical behavior, identify the basic parameters of its dynamical equations, such as: clustering, degree correlation, cooperative similarity betweenness, transitivity, hierarchy, and clustering coefficient, etc., thereby scientifically understanding network development laws and providing guidance for future network construction.

4 R&D Deployment of Wireless Center at Institute of Computing Technology

According to information technology development and national strategic development requirements for the information industry, the Wireless Center, combining its years of research accumulation in the wireless mobile communication field, has established the following research objectives: to achieve low-cost, low-energy-consumption broadband intelligent wireless green communication systems through research on multi-antenna, cooperative transmission, relaying, self-organizing networks, spectrum sharing, advanced physical layer transmission, cross-layer optimization, and other technologies. Specifically, the goals are: to reduce system power consumption to 1% of current system power consumption through research on new mobile communication network architectures and transmission technologies; to form a new direction leading international disciplinary research and development by studying and developing new mobile network architectures conforming to "network behavior dynamics"; and to ensure communication dominance in future military operations for our army through research on broadband wireless triple-communication technologies.

The above overall objectives include the formulation and implementation of one plan, support from two projects, and research layout in three directions.

- **One Plan** refers to the Wireless "Longan Network" Plan, whose implications include:
  - Low-cost, low-power equipment (Low Cost & Power)
  - Convergence of multiple wireless platforms (Convergence)
  - Intelligent wireless resource and service control management (Intelligence)
  - Proactive self-configuration (Active Auto configuration)
  - Access self-adaptation (Access Self-Adaption)
  - New hybrid heterogeneous wireless network (New Hybrid Wireless Network)

  The formulation of the Longan Plan not only refines the overall objectives of broadband intelligent wireless green communication but also closely integrates the direction of communication technology development and evolution with the actual situation of frontier research at the Wireless Center. Through the implementation of this plan, a large number of independently innovative core scientific and technological achievements will be produced within the next 20 years, providing core technical support for the development of China' s communication industry.

- **Two Projects** refer to the "Green Wireless Communication System Research Project" and the "Broadband Triple-Communication Research Project." These are two frontier research projects. The goal of "Key Technology Research on Green Broadband Wireless Communication Systems" is to achieve overall optimization of network structure and reduce system power consumption through research on new mobile communication network architectures and transmission technologies. "Broadband Triple-Communication Network Technology Research" mainly focuses on the strategic objectives of achieving broadband "communication-while-moving," "communication-under-jamming," and "communication-under-interference,"studying new military communication technologies and equipment with strong survivability, rapid mobility, and collaborative interoperability capabilities, conducting integrated joint design according to multiple requirements to comprehensively improve the electronic defense combat capabilities of tactical broadband wireless communication systems and ensure communication dominance in future military operations.
- **Three Directions** refer to the layout of frontier research that can be divided into the following three directions:
  - **Network Architecture Research Direction:** To meet the requirements of self-configuration, self-healing, and self-adaptation in green communication networks and broadband triple-communication networks, overall optimization of network structure is needed. This direction mainly studies new network system architectures from the perspective of network structural dynamics, focusing on the design of top-level protocol systems.
  - **Wireless Resource Management Research Direction:** Research on wireless resource management systems and mechanisms in hybrid environments, self-organizing wireless resource allocation architectures, joint resource allocation strategies for narrowband and broadband services, and collaborative allocation schemes to improve communication quality.
  - **Carrier Transmission Technology Research Direction:** Research on advanced broadband wireless transmission technologies under high-speed mobility with low energy consumption, low interference, and high spectrum efficiency, multi-carrier cooperative diversity transmission, virtual multi-antenna technologies, etc.

References

[1] Zhang Yucheng, *Proposal Report on Conducting Network Dynamics Research*

Using Systems Science Methodology, Internal Report of Institute of Computing Technology, Chinese Academy of Sciences, 2006
Bollobás, B. (2001). *Random Graphs* (2nd ed.). Cambridge University Press. ISBN 0521797225
[3] D.J. Watts and S.H. Strogatz. Nature 393 (1998), p. 440. Full Text via CrossRef | View Record in Scopus | Cited By in Scopus (6779)
[4] Albert-László Barabási & Réka Albert (October 1999). "Emergence of scaling in random networks" . *Science* 286: 509–512. doi:10.1126/science.286.5439.509.
[5] Wang Binghong, *Theoretical Basis of Dual-Structure World Wide Web*, Report of University of Science and Technology of China, 2005
[6] Kitaoka H. Takaki R. Suki B. A three-dimensional model of the human airway tree. *J Appl Physiol* 1999; 87: 2207-2217
[7] W. Leland, M. Taqqu, and D. Wilson, "On the self-similar nature of ethernet traffic (extended version)" , *IEEE/ACM Trans. Networking*, vol. 2, pp. 1-15, 1994.
T. Ohira and R. Sawatari. Phys. Rev. E 58 (1998), p. 193. APS full text | Full Text via CrossRef | View Record in Scopus | Cited By in Scopus (125).
Fuks, H., Lawniczak, AT: Performance of data networks with random links. *Mathematics and Computers in Simulation* 51 (1999) 101-117
[10] Chapman, S. C. and N. W. Watkins, Avalanching and Self-Organised Criticality, a paradigm for geomagnetic activity? *Space Sci. Rev.* 95, 293-307 (2001).
[11] R. Pastor-Satorras, A. Vázquez, and A. Vespignani. Dynamical and correlation properties of the internet. *Physical Review Letters*, 87 (25): 258701 (4), 2001
[12] G. Bianconi, M. Marsili, Phys. Rev. E 70 (2004) 035105.
[13] Bak, P., Tang, C. and Wiesenfeld, K. (1987). "Self-organized criticality: an explanation of 1 / f noise" . *Physical Review Letters* 59: 381–384
[14] L. DE ARCANGELIS, H.J. HERRMANN, Self-organized criticality on small world networks, *Physica A*, 308, 545-549 (2002), cond-mat/0110231;
[15] K. -I. Goh, D. -S. Lee, B. Kahng and D. Kim, Phys. Rev. Lett. 91, 148701(2003).

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Note: Figure translations are in progress. See original paper for figures.