Title	複雑ネットワークにおける連結ロバスト性の構造的要因に関する研究
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Abstract

Modern infrastructures such as communication networks, transportation systems, and energy supply networks, as well as social and biological systems, can be modeled as complex networks with highly uneven connectivities. A fundamental issue in these systems is the robustness of connectivity, namely, how well global connectivity is preserved when nodes are removed by failures, natural disasters, or malicious attacks. While previous studies have mainly focused on statistical properties such as degree distribution and average degree, the structural and geometric factors underlying robustness of connectivity have not been fully investigated.

This dissertation aims to clarify the structural factors that govern the robustness of connectivity in complex networks. Two kinds of networks which are wildly exist in real-world systems are investigated: scale-free networks, which have highly uneven connectivities, such as WWW, and spatial networks, which embedded in the surface of Earth such as road and communication systems constrained by geography. The robustness of connectivity is evaluated using two measures: a robustness index defined as the area under the curve of the largest connected component during node removal, and a critical fraction of removed nodes at which network fragmentation becomes most pronounced. Several attack strategies, including recalculated degree attacks, recalculated betweenness attacks, and belief propagation attacks that approximate the worst loop destruction, are applied.

For scale-free networks, the power-law exponent is continuously varied within a realistic range from $\gamma \sim 2.1$ (WWW) to $\gamma \sim 4.0$ (western power-grid in U.S.), showing that an increase in the exponent narrows the degree distributions, enlarges holes in networks represented by longer average length of the shortest loops, and leads to a consistent improvement with upper bound in robustness of connectivity. These results demonstrate that the robustness and the average length of the shortest loops is strongly affected by the variance of the degree distributions.

For spatial networks, networks are constructed using population data from major Japanese urban regions based on relative neighborhood graph and Gabriel graphs. Three node placements are considered: population-based (Pop.), in which nodes are preferentially located in densely populated areas to meet concentrated access demand; inverse population-based (Inv.), in which nodes are placed in sparsely populated areas for lower cost of construction; and uniform (Uni), in which nodes are distributed randomly to represent an intermediate spatial configuration.

Overall, the robustness of connectivity is primarily determined by the variance of the degree distribution and the length of the shortest loops. In scale-free networks, as the power-law exponent increases and the degree distribution becomes narrower, larger holes emerge within the network, leading to an improvement of the robustness. In spatial networks, local modulars formed by spatial concentration of nodes and short links show a strong influence on the robustness of connectivity. When nodes are unevenly placed according to population, strong local modules are formed, and the loss of bridging links causes the network to fragment rapidly. As a result, the robustness decreases markedly with increasing modularity. The findings of this study provide an important theoretical foundation for the robustness-oriented design of real-world infrastructure networks and complex systems.

Keywords: Robustness of connectivity, Complex networks, Scale-free networks, Spatial networks, Shortest loops, Modularity, Infrastructure networks.