Basic Theory of Network Science—the Network, Spatial Characteristics, and Spatial Information

Hiroshi Saito

Abstract

NTT Network Technology Laboratories is researching a new theory to support networks that focuses on spatial information handled by networks. This article discusses an evaluation of geometric probability based on integral geometry and the design and control of new network characteristics.

Keywords: spatial characteristics, spatial information, geometric probability

1. A brilliant theory is timeless

Traffic theory, which is said to originate in a paper written by A. K. Erlang, the renowned Danish telephone engineer, has been subsequently expanded by many theorists in this field and in the field of queuing theory in applied mathematics. It has been a theoretical pillar supporting the operations of information and communication networks for about 100 years and has become essential not only in the design of telephone networks but in the design of computer systems as well. At NTT, research in the field of traffic theory has also led to some brilliant achievements such as Takagi's theorems*, which provide a theoretical basis for determining an optimal architecture for switch channels.

Today, however, there are fewer areas in which traffic theory can be applied. One reason for this is that the unit of facility design has become larger. Another reason is the wide use of best-effort policies; that is, there is no longer a need for detailed design. The third reason is that resources themselves have become cheaper. It has been shown in NTT's Interconnection Accounting Reports and elsewhere that the book-value ratio of traffic-dependent network facilities (facilities that either increase or decrease in number according to traffic volume) has been decreasing greatly. This is making traffic design as well as traffic control and quality control within the network less meaningful and is diminishing the fruits of traffic theory.

2. Space-related theory

The introduction of theories that support the network is the responsibility of the network operator through research and development efforts. In light of the present situation, there is a need for theoretical development along a new direction. We have decided, in particular, to target a theory that deals with spatial information against the background of academic demands (expansion of existing theory, which is based mainly on probability theory and theory of stochastic processes along the time axis, to a theory that incorporates spatial phenomena) and social trends (enhancement of physical/spatial information-gathering capabilities in conjunction with the proliferation of mobile devices and sensors). Actually, in the field of networks, space-related theories already exist, for example, radio propagation theory in mobile communications. The theory targeted by our current research, however, covers the entire network or all information related to the space handled by the network. As such, we expect this research to be the first

* Takagi's theorems: A series of theorems presented around 1970 dealing with link connections and switch-channel connections, including results related to optimal connections.

of its kind in the world.

3. Integral geometry and geometric probability

Probability related to the positional relationships of geometric figures is called *geometric probability*, and the theory that derives this probability is called *integral geometry*. Here, defining the probability related to the spatial relationship of two objects in terms of geometric probability can give rise to a variety of discussions. For example, if we let one object represent the network and the other a disaster area, we can talk about the probability that the network will pass through that disaster area. Of course, it would be convenient if the position of the disaster area could be predicted, but even if it cannot, this probability can still be obtained provided that information can be given on the occurrence of a disaster area of a certain size in a specific region.

This situation is similar to our experience in traffic theory; although we cannot predict the arrival of individual calls or packets, we can calculate the call-loss rate or buffer-overflow rate in traffic theory. Next, if we let one of two objects represent a target of detection and the other object represent detectors such as sensors, this theory can give rise to discussions on the handling of spatial information collected by the network. These may include ideas such as "How would the arrangement of sensors affect the detection probability?" or "If we collect a lot of detection results, to what extent can we learn something about the target object such as its shape?"

4. A new world

For example, the above probability that the network will pass through a disaster area can provide knowledge on a new method for configuring networks. Integral geometry, moreover, enables concrete and quantitative discussions to be held on the network. These may include the geographical shape of a communication-path network that would minimize or reduce the probability of passing through a disaster area, or the geographical and spatial arrangement of servers that would minimize the probability that servers providing services to a certain area would be cut off due to a disaster. A network achieved by design and control methodologies based on the above theory is called a *Disaster-free Network* [1–3].

A Disaster-free Network is just one application example of this theory. It should also be possible to discuss a relationship between the network and spatial phenomena unrelated to natural disasters so that network measures other than those for anti-disaster readiness can be improved.

5. Future developments

Similar to the way in which traffic theory enables network traffic design and control, the new theory introduced here will make it possible to design and control network characteristics that up to now have not been targeted in design and control efforts. As a result, we can expect the development of a safe and secure network and the provision of new network services.

References

[1] H. Saito, "Concept and Implementation of Disaster-free Network," Keynote speech, DRCN 2015 (11th International Conference on Design of Reliable Communication Networks), Kansas City, USA, Mar. 2015.

[2] H. Saito, "Toward the Realization of Disaster-free Networks," NTT Technical Review, Vol. 13, No. 6, 2015.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201506ra1.html

[3] H. Saito, "Improving Disaster Resistance Performance through Network Design Methodology—Toward the Realization of Disaster-free Network—," J. IEICE, Vol. 98. No. 9, 2015.

Hiroshi Saito

Executive Research Engineer, NTT Network Technology Laboratories.

He graduated from the University of Tokyo with a B.E. in mathematical engineering in 1981, an M.E. in control engineering in 1983, and a Dr.Eng. in teletraffic engineering in 1992. He joined NTT in 1983. His research interests include traffic technologies of communications systems, network architecture, and ubiquitous systems. He has served as an editor and guest editor of technical journals including Performance Evaluation, IEEE Journal of Selected Areas in Communications, and IEICE Trans. on Communications, and as the organizing or program committee chairman of several international conferences. He was the Director of Journal and Transactions of IEICE and is currently an editorial board member of Computer Networks. Dr. Saito is a fellow of IEEE (Institute of Electrical and Electronics Engineers), IEICE (Institute of Electronics, Information and Communication Engineers), and ORSJ (Operations Research Society of Japan), and a member of IFIP (International Federation for Information Processing) Working Group 7.3. More information can be found at http://www9.plala.or.jp/hslab.