Modelling Peer-to-Peer Data Networks under Complex System Theory

Cyrus Shahabi and Farnoush Banaei-Kashani

Computer Science Department,
University of Southern California,
Los Angeles, California 90089
{shahabi,banaeika}@usc.edu

A Peer-to-peer Data Network (PDN) is an open and evolving society of peer nodes that assemble into a network to pool and share their data (or more generally, their resources represented by data) for mutual benefit. By an interesting analogy to a democratic human society, when nodes join the PDN society, while they agree to follow a restricted set of common rules in interaction with their peers (i.e., the social rules governing the PDN society), they preserve their autonomy as individuals. For example, as part of their social obligations all PDN nodes (or at least those who are good PDN citizens) create and maintain connection with a set of neighbor nodes and participate in cooperative query processing (e.g., forwarding search queries for data discovery). Aside from the social rules, the PDN leaves the behavior of the individual nodes unregulated and flexible, to be managed by their users based on their individual preferences and/or to allow for natural uncertainties and constraints. For instance, nodes may join and leave the PDN society as they decide (by user decision or due to unwanted node/link failure), they control their own resources, and they select their neighbors according to their own administrative policy or physical constraints (e.g., connecting to the nodes that are both accessible and physically close as neighbors). In this sense, individual nodes are self-governed, autonomous, and independent. There is a trade-off between the extent of the social rules and the autonomy of the individual PDN nodes; the more extensive and interfering the social rules, the autonomy of the nodes is more restricted.

Modelling Peer-to-Peer Data Networks PDNs are distributed query processing systems with an open architecture. The first step toward realizing these systems is to select an appropriate approach to model such systems. As a direct consequence of the computing model described above, a PDN is 1) a self-organizing system, i.e., there is no central entity to organize the PDN and any kind of structural and functional organization emerges from the distributed interaction among PDN nodes; 2) a dynamic system, i.e., the node-set, data-set, and link-set of the PDN are dynamic and in continuous renewal; and 3) a large-scale system, because as an open and beneficial society it tends to attract numerous nodes that intermittently join the society. The combination of these three characteristics makes PDN a "complex system", i.e., a system that is hard to represent/describe information theoretically (considering the large amount of information required to represent the state of the system), and hard to analyze computation theoretically (considering the complexity of computing the state transition of the system). An appropriate modelling approach for such complex PDNs must 1) be compatible with the PDN computing model as a democratic society, and 2) provide a framework with a set of conceptual, experimental, and analytical tools to contemplate, measure, and analyze PDNs; a framework which is neither oversimplified nor overcomplicated to remain both accurate and applicable to such complex systems. We propose the "complex system theory" as the modelling framework for PDNs.

State-of-the-Art Currently, distributed computing is the framework adopted to model PDNs. With this modelling approach, in line with the traditional system-engineering routine, the system designer implicitly assumes almost full control over the system components and resources. This assumption allows reducing the complexity of the system by imposing fabricated restrictions, and consequently, enables designing efficient mechanisms and architectures. Such an assumption may be valid with typical engineered systems that are managed by a unique authority that governs the entire system. However, it is incompatible with the democratic PDN computing model, where autonomy of the nodes is an essential requirement. Hence, with this modelling approach the resulting solutions are unrealistic and inapplicable for the real PDN applications. Such theoretical solutions that enforce the controlling assumption give rise to dictatorial PDN societies, which are unattractive for prospective citizens, and intolerant and/or fragile to disobedience of their members that want to maintain their autonomy.

The main representative of such solutions is a family of lookup systems, the Distributed Hash Tables (DHTs) [9, 13, 10], which are designed for efficient search in PDNs. DHTs regulate both the data placement and the network topology of the PDN. With the regulated data placement, it is as if the entire data-set of the PDN is owned by a single authority that collects the data from the nodes (the actual owners) and re-distributes the data among them (as a set of slave data storage units/nodes) according to a certain data placement policy to achieve efficient access. Enforcing the data placement violates the autonomy of the PDN nodes in controlling their own data, and for example, is inapplicable to the PDN applications where nodes must maintain their own and only their own data because of security concerns. Moreover, such an unnatural data distribution is an instance of over-engineered design and raises significant practical issues. For example, the communication overhead of transferring the data (or pointers to the data) from the actual owner of the data to where the data is placed can be overwhelming. This important cost factor, which is due whenever the node joins the PDN or its data is updated, is often overlooked in the analysis of the efficiency of the DHTs.

Similarly, with the regulated network topology, among all possible choices of neighborhood, each node is required to connect to a particular pre-defined set of nodes as neighbors. Enforcing the neighborhood of a node violates the autonomy of the node in selecting its neighbors according to its own administrative policy or physical constraints. For example, it is quite possible that none of the designated neighbors for a node are physically accessible to the node when it joins the PDN; hence, leaving the node isolated. Considering such problems with DHTs, it is not surprising that despite significant efforts of the research community in enhancing and promoting DHTs as the only academic solution for efficient search in PDNs, DHTs are not adopted as practical solutions for any real PDN applications such as file-sharing systems. Instead, these systems have unstructured network topology and prefer to use naive search mechanisms such as flooding, which is not efficient but compatible with the PDN computing model, and hence, practical.

A New Modelling Framework: Complex System Theory The complex system theory is a unifying meta-theory for collective study of the "complex" systems. Various fields of study, such as sociology, physics, biology, chemistry, etc., were established to study different types of initially simple systems and gradually matured to analyze and describe instances of incrementally more complex systems. The complex system theory is an interdisciplinary field of study which is recently founded based on the observation that analytical and experimental concepts, tools, techniques, and models developed to study an instance of complex system in one field can be adopted, often almost unchanged, to study other complex systems in other fields of study [5]. This meta-theory provides a common modelling framework consisting of a rich set of tools adopted from various fields to study all complex systems under one umbrella.

In this framework, complex systems are modelled as large-scale networks of functionally similar (or peer) nodes, where the links represent some kind of system-specific node-to-node interaction. For example, a social network is a network of people who communicate in a society, a biological network (at the cellular scale) is a network of cells which exchange mass and energy in a biological organ, and a molecular network is a network of molecules that interact by exchanging kinetic and potential energy. Most of the complex systems studied under the complex system theory are natural systems, where nodes are autonomous while they also follow certain natural principles/laws (e.g., the second law of Newton governs kinetic interactions among molecules in a molecular network). Moreover, most of the natural complex systems are also self-organizing, dynamic, and large-scale. Considering the similarity between these features and those of PDNs, we argue that PDNs should also be promoted from the domain of traditional distributed computing systems to the realm of natural complex systems. Consequently, PDNs will be studied alongside their peer systems under the complex system theory, within a modelling framework which is both compatible with PDN's open/autonomous computing model and rich to capture PDN's complexity. With a rich set of tools specially designed to analyze complex systems, the complex system theory is a promising modelling framework for PDNs.

Previously, this modelling approach is successfully applied to the Internet. For example, Ohira et al. [8] used self-organized criticality (i.e., a self-similarity model from the complex system theory [11]) to explain the self-similar scaling behavior of the Internet traffic flows, and Albert et al. [1] employed concepts from statistical mechanics (which was originally developed by physicists to study the collective behavior of the molecular networks, such as temperature and pressure of a mass of gas) to understand the reasons for the power-law connectivity in the Internet topology. However, to the best of our knowledge, modelling PDNs under the complex system theory is novel.

Research Agenda We categorize PDNs as instances of complex systems and apply the complex system theory as a modelling framework to study PDNs. Our general research agenda is to extend application of the complex system theory to PDNs by:

1. Adopting models and techniques from a number of impressively similar complex systems (e.g., social networks) to design and analyze PDNs; and
2. Exporting the findings from the study of PDNs (which are "engineered" complex systems, hence, more controllable) to other complex system studies.

We study usefulness of this modelling framework by pursuing two case studies, both focused on the problem of efficient search in PDNs. Observing the similarity between PDNs and social networks, we adopt two models from the study of social networks to develop efficient search mechanisms for two types of PDNs. Search is a generic primitive for query processing in PDNs: a mechanism that locates the required data in response to one or more types of queries is a search mechanism. Developing efficient search mechanisms for the self-organizing, dynamic, and large-scale PDNs is a challenging task. We recognize two different types of PDNs that require significantly different search approaches: unindexable PDNs and indexable PDNs.

Traditionally, index structures are used for efficient search in large-scale distributed object repositories such as distributed databases. By indexing, the repository is organized/structured into a distributed data structure that allows real-time search with minimum cost and short response time. With unindexable PDNs, the extreme dynamism of the PDN node-set, data-set and link-set renders any attempt to self-organize the network to an index-like structure (for efficient query processing) impossible and/or inefficient. Without indexing, efficient search is only possible by efficient scanning of the network nodes. For unindexable PDNs, we introduce the STEPS (Search with Tunable Epidemic Sampling) search mechanism [3] that enables efficient processing of partial selection queries (i.e., selection queries that can be satisfied by a partial result-set rather than the entire result-set). STEPS is inspired by the SIR (Susceptible-Infected-Removed) epidemic disease propagation model for social networks [6]. We also employ the percolation theory [12], a common analytical tool in the complex system theory, to formalize and analyze STEPS.

On the other hand, with the indexable PDNs, the dynamism of the PDN is such that the benefit of indexing the PDN still exceeds the overhead of maintaining/updating the index. For indexable PDNs, we propose a self-organizing mechanism that structures the PDN to SWAM (Small-World Access Method) [4], a search-efficient structure that enables efficient processing of various similarity queries (namely, exact-match, range, and kNN queries). SWAM is a distributed index structure that organizes the PDN nodes in order to index the data content of the nodes while it avoids changing the natural placement of the data. For the design of SWAM as well as its search dynamics, we were inspired by small-world models [15, 2, 7, 14]. Small-worlds are models proposed to explain efficient communication in social networks. These two case studies strongly confirm applicability and appropriateness of the complex system theory as a modelling framework for PDNs.

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