Research Statement for Xiaowei Yang

I am fascinated by the design, implementation, evaluation, and understanding of complex systems (especially networked and distributed systems) that have selfish participants with competing interests. My goal is to eventually develop rigorous and scientific methods that lead to better design and deeper understanding. I'm most interested in two fundamental challenges found in such systems. First, the large number of interacting participants in a complex system often leads to undesirable emergent behaviors. Numerous incidents in the Internet, such as the TCP congestion collapse in the late 80s, and the recent BGP slow convergence problem, all show that individually well-engineered systems may generate perplexing behaviors when networked together. The challenge is how to design networked complex systems with overall predictable behaviors. Second, because different participants in the system often have competing interests, system designers cannot assume that the participants will be cooperative. The challenge is how to design a system that operates well with selfish participants.

In my work on system design, I focus on a design methodology that first recognizes the interests of system participants and then designs system components to take the competing interests into account. Different assumptions about the interests of system participants may lead to quite different system designs. My dissertation provides a concrete example.

My doctoral thesis presents the design and evaluation of a new Internet routing architecture. My work involves both technical and economic issues. The Internet was designed in an earlier time as an academic experiment. With its commercialization, there emerged two groups of Internet participants: the service providers that sell service to make a profit and users (both clients and servers) that want to run applications at a reasonable cost. The interactions between users and providers, and among providers themselves, are unavoidably shaped by economic forces. As a basic economic principle, user choice creates competition, which disciplines the market and drives technology innovation. However, the current Internet architecture gives users little control over the domain-level routes their packets take. As a consequence, users cannot choose their wide area providers separately from their local providers. In the future, users are likely to face only one or two choices for local providers, i.e., cable or DSL. This lack of choice will reduce the competitive pressures on wide area providers, and subsequently, stifle technology innovation.

My dissertation is the first proposal that thoroughly works out all essential components of an Internet routing architecture that supports user choice. To enable this architecture, four problems need to be addressed: how to discover and select routes, how to represent routes, how to detect and handle route failures, and how to compensate providers.

Today, although IP has a source routing option, there is no system support for users to discover routes. Thus, users seldom use source routing. I designed my new architecture to support scalable route discovery by leveraging three system components: a provider-rooted hierarchical addressing scheme, a Topology Information Propagation Protocol, and a distributed Name-To-Route Resolution Service. The Topology Information Propagation Protocol propagates address allocation information to users as well as inter-domain topology information based on policy configurations. It runs in a link-state like fashion and has the property of fast convergence. The Name-To-Route Resolution Service tells a user the addresses, and optionally the topology information, of another user with whom he wants to communicate. Combining this information and the information learned from the Topology Information Propagation Protocol, a user is able to choose an initial route to communicate with another user without knowing the entire inter-domain topology.

The provider-rooted hierarchical addressing scheme enables efficient route representation in a packet header. An address uniquely identifies a domain-level route segment rather than just an endpoint location. The most common type of domain-level route, consisting of a source route segment and a destination route segment, can then be represented by just a source and a destination address. To facilitate deployment, I designed the packet header format to be compatible with IPv6.

In the new architecture, users detect route failures using a combination of proactive failure notification and reactive failure discovery. The provider compensation model is still contract-based so that no per packet based accounting or micro-payment schemes are necessary.

My work provides a solid technical foundation for economists and policy makers to shape the landscape of the future ISP market. I have performed extensive packet-level simulations as well as analytical modeling to validate the scalability, robustness, and correctness of my design, using the most recent results from topology measurement and domain relationship inference.

Another area I am deeply interested in is system evaluation and the fundamental understanding of system behaviors. Systematic evaluation and thorough understanding provide insight and guidance for future design. I often combine high-fidelity and large scale simulations with analytical models for system evaluation and understanding. Detailed simulations with system models derived from real world measurements provide insight on system behaviors and are good at revealing subtle design flaws. Every piece of my work includes such simulations.

Building an analytical model is also an important step towards a complete understanding. Analytical models provide high-level descriptions of system behaviors under a variety of operating conditions. One is forced to identify the essential parameters of the system and ignore the trivial ones when building an analytical model. With such a model, one can quickly grasp the average behaviors of a system under a wide spectrum of parameters, and identify the most sensitive system parameters. It would take months of simulations and data collection to gain such insights for large-scale systems. For my M.S. thesis, I developed an analytical model that captures the long term throughput of each flow and the queue size at each router for window-based flow control networks. As part of my dissertation, I developed an analytical model to study the cost of reactive routing under various packet loss rates in collaboration with Arthur Berger. The model is able to describe the system behavior with low probability events when the simulation method becomes insufficient to provide insight in such situations.

System evaluation should build upon real world measurement results. Those results provide reality checks on the underlying assumptions we make about a system. Sometimes conclusions drawn from popular theoretical models may differ significantly from those drawn from models derived from real world measurements. With Dimitri Krioukov and Kevin Fall, I evaluated the performance of one of the best known scalable routing schemes, the Thorup-Zwick scheme. The performance metric is the routing stretch, which is the ratio between the length of a path a packet actually takes and the length of the shortest path. Using both simulations and analysis, we found that the Thorup-Zwick scheme works well on real Internet topology. It has an average stretch of about 1.1, which is much lower than the theoretical upper bound of 3, and is significantly lower than the results obtained on a common random network model, which assumes node degree has a uniform random distribution.

Human factors are also an important aspect in system design and evaluation simply because systems are used by humans. In my early research, I studied the effects of bottleneck link speed on user perceived web browsing performance. My study shows that when the bottleneck speed exceeds 1Mbps, the round trip times are the dominant factor in user perceived delays. Further increasing link speed has negligible effect on user perceived performance. Therefore, the two broadband residential services, DSL and cable modem, are basically equivalent from this perspective.

Future Directions

Looking forward, I will continue my work on complex systems that have selfish participants with competing interests. The Internet is an exemplar of complex systems with a highly diverse pool of participants, and for this reason, it will continue to be my focus area. I am also interested in other types of networks such as wireless ad hoc networks, sensor networks, overlay networks, and peer-to-peer networks. I will describe a few specific projects I plan to work on.

Dynamics of Selfish Routing: Continuing my interest in Internet routing, I'd like to study the dynamics of selfish routing. With the deployment of my routing architecture, or the increasing use of overlay networks, users would have more control over routing. Each user will pick a favorite route according to their preferences, and their choices might interfere with each other. Recent work on this subject has focused on the system properties in the equilibrium state. Little has been done in analyzing the dynamic interactions among selfish users, and between user choices and the traffic engineering efforts of network operators. I believe this understanding is the first step towards designing control mechanisms that maintain high utilization and stability of the network while allowing user choice.

Packet-level Authentication: In a distributed and heterogeneous environment, before granting a service, a service provider usually wants to verify whether the service requester is a legitimate user. For application-layer service providers, service authentication is a well-studied problem and can use any end-to-end authentication mechanism. However, for network-layer service providers, the service provided is packet forwarding. I call the problem of authenticating the legitimacy of a packet at any point (as opposed to the end point) in the network before forwarding it the “packet-level authentication” problem. I’d like to investigate how to solve this problem with reasonable computational and signaling costs. I believe the solution to this problem will enable new Internet business models and a wide range of new services. For example, a wide area provider, or an overlay provider will be able to sell various services directly to end customers.

Benchmark Simulation Configurations: It is important to use realistic parameter settings in order to perform high-fidelity simulations. Another project I plan to work on is the design of a simulation configuration framework that generates benchmark simulation configurations from real-time measurement results. The commonly used configuration generators such as GT-ITM, Inet, and BRITE build analytical models from measurement results and generate topologies using the analytical models. The analytical models do not provide all necessary simulation parameters such as link delay, bandwidth, buffer size, link failure patterns, and traffic patterns. Recent measurement results are able to answer some of these questions. I would like to design a framework that samples real-time measurement results to create “benchmark” simulation configurations. The configurations will be updated periodically by measurement results. I believe this work will complement and enrich the existing tool set for protocol design, testing, and comparison.

Incentive Design for Overlay Networks and Peer-to-Peer Networks: I would also like to expand my interests into other types of networks, such as wireless ad hoc networks, overlay networks, and peer-to-peer networks. Currently, participants in these networks voluntarily provide service for each other. I’d like to investigate system architectures that can attract more selfish users by providing economic incentives.