SYNERGY OF PEER-TO-PEER SYSTEMS AND MOBILE AD-HOC NETWORKS

BOOTSTRAPPING AND ROUTING

WEI DING

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PREFACE

From the turn of the new millennium, the decentralization movement has gained more and more attention. Popular examples, which are given not only from pure technical viewpoint, but also from the user viewpoint, include eBay, Expedia, YouTube, Skype, iPhone, Bluetooth, BitTorrent, Gnutella, various commercial sensor networks motes, SETI@home, etc. The core of the decentralization movement is the idea of giving more autonomy, more control, and more respect to ordinary users of a computing system, or a network, or a product. With fast growing user body of more fancy cell phones and other mobile devices, the technical trend has been blend into a world-wide cultural fashion.

Contrary to the client/server model, the decentralized model tries much harder to meet the need of ordinary network users. It gives users much more control and freedom, not only in content of communication, but also in manipulation of system/network. The model encourages active participation in drastically wider areas. Many researchers believe it could replace the client/server model in next few decades.

Independent of specific lower layer technologies, Peer-to-Peer (P2P) systems are decentralized systems with self organized overlays. They are highly adaptive to dynamic changes, especially those in lower layers. The decentralized nature of this adaptiveness makes the central controller unnecessary. Previously, major objective of P2P systems is to discover and share distributed resources, especially user generated content and community based services. Many other applications have been envisaged, tested, and implemented, including web caching, VoIP (e.g. Skype), decentralized storage, decentralized databases, naming services, and cooperative application.

Mobile Ad-hoc Networks (MANETs) is another leading technology in the decentralization movement. P2P systems and MANETs share similar foundations. Both break away from infrastructure-base and client/server model. Both are adaptive, self-organized, and self-repaired. Both use multi-hop and multicast transmission.

In terms of real world applications, however, P2P systems and MANETs are divergent. P2P systems currently enjoy more than 60% global Internet traffic, while MANETs have found only few commercial applications after more than a decade intensive research. If we take away sensor networks and Bluetooth from MANETs, as many people did in recent literature, almost nothing has been made with commercial fame.

Remarkable research initiatives in the synergy of P2P systems and MANETs, which results in synergized P2P systems over MANETs, have been sparked by this interesting phenomenon. Primary objective is to export P2P principles to MANETs to improve efficiency and scalability as well as establishing practical applications. So far, following applications have been tested

- Content/resource lookup
- Content/resource discovery
- Data dissemination/replica
- Distributed storage system
- Wireless beeping
- Instant messaging
- Indexing
- Emergency data sharing
- Subscriber/distributor system

In this area, much attention was paid to routing. Many other issues have been ignored and desperately long for answers. These issues include the feasibility of the synergy in terms of overhead, unstructured vs. structured P2P systems, address configuration, and most importantly, bootstrapping. These problems have remained indispensable for any attempt of exploring the synergized P2P systems over MANETs.

This book will discuss all these issues with focus on bootstrapping and routing of the synergized P2P systems over MANETs. In this book the author tries to integrate rigorous analysis with intuitions and empirical results. Many recent publications and projects are referred and well knit into a clear theme.

To the best of the author's knowledge so far, there is no previous monologue devoted to the bootstrapping of the synergized P2P systems over MANETs.

The book is intended to be a handbook for researchers and industrial professionals in the area of synergized P2P systems over MANETs. It could also be used as a secondary textbook at graduate level.

CONTENTS

Chapter 1

INTRODUCTION

1.1. BACKGROUND

The topic of this book is about bootstrapping and routing of peer-to-peer (P2P) systems over mobile ad-hoc networks (MANETs). The objective of this book is to give a big picture on current research in these areas, which aims at building effective and efficient structured P2P systems over MANETs. To fully understand the context, the following concepts need to be clarified.

1.1.1. P2P Systems

In handling large decentralized computing systems, the client/server model has become increasingly awkward and cumbersome in terms of scalability. As the system grows larger, it becomes harder and harder to guarantee the success and quality of service of simple tasks like timely response, load balancing, and fault-tolerance within the framework of the client/server model. On the other hand, the decentralized paradigms, in which processing power and other resources are distributed among all nodes, seem to meet the challenge of scalability well. [PBV2005] P2P systems are one of most promising candidates among these paradigms.

P2P systems, or P2P networks in some publications, are a new trend in distributed computing. Similar to other technologies in decentralized computing family, the deviation from the client/server model is the first characteristic of P2P systems. Their second important feature is their capability in self-organization when setting up connection and self-healing when some parts of the system break down.

There are two kinds of P2P systems: unstructured and structured. Structured P2P systems use fixed topologies like ring or grid for routing. As the name implies, unstructured P2P systems lack the mechanism to maintain and utilize such topologies. Unstructured P2P systems were developed earlier and more mature in typical P2P applications like file sharing. Structured P2P systems came to the world later but have been theoretically more sophisticated. Most structured P2P systems rely upon an overlay network at a certain higher layer (e.g. application layer), which uses above mentioned topologies in routing at the layer. Structured P2P systems are also called structured P2P overlay networks.

1.1.2. Distributed Hash Table

Structured P2P overlay networks have become a convenient template for various distributed applications. The fundamental abstraction shared by all these structured overlays, on which all kinds of applications are based, is key-based routing. Keys are mapped to nodes. Routing a given key is equivalent to finding the host node responsible for the key. The overlay topology is defined by neighborhood relations specified in local routing tables on all nodes. Both key allocation and key-based routing are via Distributed Hash Table (DHT).

A DHT distributes data over a structured P2P system with aid of a fixed topology. Basic storage unit and data structure are (key, value) pairs. Node ID is homogeneous to a key. Hence a (key, value) pair could be mapped to a node by hashing the key. Each node is responsible for some section of the key space. The power of a DHT lie in its efficiency to quickly find any given (key, value) pair. The efficiency comes from carefully designed topology structure, node data structure and routing strategies seamlessly integrated into the topology. Basic DHT operations are

- Store(key; value): node ID ← (key; value)
- Locate(key): node ID ← Locate(key)
- Retrieve(key): value ← Retrieve(key)

1.1.3. Mobile Ad-Hoc

In English, the word "ad hoc" is defined as "improvised and often impromptu" [Heritage2000], which in networking context implies dynamic, temporary, autonomous, and no fixed infrastructure. Mobile ad hoc networks are distributed communication and computing systems that are consisted of multiple wireless mobile nodes (to use P2P efficiently, it should be in a large scale, which usually has hundreds or more nodes). These nodes switch on or off, move, and make decisions dynamically and independently, and form arbitrary and transitory (so called "ad-hoc") networks by node discovery and self-organization. Nodes in the formed ad hoc network cooperate to provide variety of network functionalities. The network is maintained by self-healing among these nodes inside the network. No pre-existing communication infrastructure is needed. A physical central controller is absolutely a taboo in MANETs, though a logical central controller is possible in virtual structures like hierarchies, for example, a cluster head. [CCL2003], [RR2002]

1.2. SYNERGIZED P2P SYSTEMS OVER MANETS

1.2.1. Bootstrapping

Comparing to other areas like routing, MAC, and security, bootstrapping has received less attention since very beginning in both MANETs and P2P communities. A common circumvention is using idealistic assumptions such as bootstrapping is realized by node joining. These assumptions often do not hold in reality and make implementation very difficult, if not impossible.

In some literature, synonyms like automatic configuration and self-organization are used with same semantics as bootstrapping. Bootstrapping is the automatic self-organizing procedure to initialize the network and all nodes inside the network, such that the structured P2P system can smoothly start its normal operations. It involves three tasks:

1. node address automatic configuration (assignment)
2. setting up the specific network topology
3. building node data structures, which are DHTs here

Since node address configuration is performed below the Network layer in ISO Open Systems Interconnection (OSI) model, addressing is optional for bootstrapping. In most cases, task 3 is contained in task 2.

Specific topological structure is essential for structured P2P systems, most controls and data transmission are based upon this structure. After assigning node IDs at the overlay layer, the structure should be built before a structured P2P system can work normally. For example, Chord must build a ring. In the area of Internet-based P2P systems, significant effort has been made to construct initial topology for bootstrapping. Successful protocols like T-Man [JB2005], T-Chord, and Ring Network has been proposed and tested.

On the other hand, in area of P2P systems over MANETs, no success has been made in spontaneous topology construction in a distributed self-organized manner. Most related recent publication is a paper entitled "Bootstrapping Chord in Ad Hoc Networks - Not Going Anywhere for a While" by Cramer and Fuhfmann [CF2006], which gives a rather gloomy prediction. After careful examining, we found that neither ground nor reasoning is tenable in their arguments. Our analysis is discussed in Section 6.4.2.

We propose a complete configuration free self stabilizing protocol Ring Ad-hoc Network (RAN), which we believe is the first successful attempt in the filed of bootstrapping structure P2P systems over MANETs.

RAN has integrated merits from T-Chord, and Ring Network and adapt very well to MANETs. RAN uses only neighbors and local information to build a ring topology in node ID space. Upon this ring, entire Chord protocol could run immediately with optimal configuration at full speed, without any stabilization. RAN includes automatic non-IP address configuration into bootstrapping. Dynamic address configuration is usually deliberately ignored in previous approaches by assuming that an ideal IP address configuration has been a priori established from the very beginning.

1.2.2. Routing

Routing has been a number one topic in entire distributed networking area for a very long time. Many other functions have been inserted, seamlessly or in a far-fetched manner, into routing. For new comers, sometimes it seems everything is a routing problem and can be solved by routing protocol. Most typical examples are bootstrapping, security, and energy efficiency. The author believes that the man-made integration unnecessarily complicated, sometimes hided, the real situation and the research on these situations.

Bootstrapping is the example of how routing could hide a heterogeneous problem so long and so effectively. Most protocols, in both MANETs and P2P systems (or P2P networks, as denoted in literature), unconsciously treat bootstrapping as an essential part of routing. As a result, most of them simply solve the bootstrapping problem with the techniques for node joining, very similar to the solution for repairing a broken link. In this book, the difference between bootstrapping and routing and different solutions for the bootstrapping problem in synergized P2P systems over MANETs, are discussed in chapters 4, 5, 6, and 7.

Most remaining part of the book discusses the routing of the synergized P2P systems over MANETs. In the synergized circumstance, all routing designs have to address the pivotal problem of scalability, which means the unacceptable cost increase when the size of the system (or network) increases into higher magnitude.

Chapter 8 discusses the first successful routing protocol for the synergized systems, namely Dynamic P2P Source Routing (DPSR), which was proposed by Hu's research group at Purdue University. [HDP2003] Chapter 9 discusses Ekta, another more advanced routing protocol from the Hu group. [PDH2004] Chapter 10 introduces Virtual Ring Routing Protocol. [CCNOR2006] To solve the scalability problem, all these three approaches discarded strict layering practiced by most prior works. Instead, all three protocol adopted cross-layer design and pushed the P2P DHT down from higher layers like application layer to lower layers like routing layer and data link layer.

In the last two chapters, a hierarchical design is introduced to deal with the scalability problem from another angle. This is a basic strategy in networking, which has been used in ARPANET, Internet, and web, among many others. Chapter 11 describes PeerNet, which deviate from prevailing IP addressing to solve the scalability problem. [EFK2003] PeerNet adopted a clear separation of node ID from its IP address. The changing address of a node reflects its location in the network. The node's ID is permanent. PeerNet proposed fully distributed algorithms map these two addressing schemes to each other.

Chapter 12 explicates the detailed routing scheme of the Safari protocol and its Masai implementation developed at Rice University. [DKPPSDJR2008] Safari is a probabilistic, self-organizing, and decentralized protocol in which nodes are organized in an adaptive, proximity-based hierarchy. Its major advantage lies in its scalability. Safari shows the scalability in route discovery and maintenance for considerably large MANETs.

Chapter 2

PEER-TO-PEER SYSTEMS

2.1. P2P MODEL

P2P overlay systems provide fast resource advertisement, resource discovery, resource retrieval, and other services without a central controller. The concept of peer-to-peer systems first appeared in the mid 1990s. As file sharing platforms, especially to distribute MP3 music files over Internet, peer-to-peer systems turned into a hot research topic in the late 1990s. A traditional P2P system is built upon IP networks, i.e. internetworks built upon TCP/IP architecture. Examples of IP networks include the Internet, IP based LANs and WANs, other networks that adopt at least IP layer in TCP/IP as their network layer in ISO/OSI model. Traditional P2P systems use IP networks as the underlying communication carrier. An IP capable host can reach anyone and anything attached to the Internet by an IP address. Same things will happen to other IP networks like members of IEEE 802 family. With the help of P2P overlay, IP layer could tell a host how and where to find a given content or another participant host. The basic task of P2P overlay systems is to connect to other peers and find out interesting content.

These P2P systems are distributed and self-organized. By P2P jargons, a host is called peer, because all hosts have same status, share same responsibility, and the relationship among them is characterized by equality. Unused bandwidth, storage, CPU cycles at the edge of the network are utilized for the common good of a system. Peers enjoy great freedom and privacy. Consumers are also producers, so aggregate resources grow exponentially with utilization. There is no single point of failure in a P2P system.

The emergence of P2P overlay model was a counteraction against long time tradition of client/server model in computing and communication. In the client/server model, powerful, reliable servers provide data and services; clients request data and services from servers. The client/server model has proved to be so successful by its famous offspring like World Wide Web, database systems, and FTP. However, it has following inherent defects:

- need of central controller
- single point of failure
- unused resources at the system edge
- poor scalability
- dictatorship in which clients feel like slaves

P2P systems address above defects of client/server model very well. At large P2P model aims at sharing and exchanging resources and services between peers. These resources and services include information (file or data structure), CPU cycles, storage (memory, cache, and disk), I/O devices, even human presence, etc. P2P model takes advantage of existing computing capacity, storage, and network connectivity, so end users can unite and leverage their collective power to carry out huge task or achieve mutual benefits.

In a P2P system, all nodes are clients, servers, and routers (relay node) at same time. All nodes provide and consume resources and services. No centralized data source or controller endangers the system as the single point of failure. Nodes collaborate directly with each other. Any node can initiate a connection. All nodes are totally free; they may enter and leave the network arbitrarily. It is "the ultimate form of democracy on the Internet" as well as "the ultimate threat to copy-right protection on the Internet." [Kaashoek2003]

P2P systems have following advantages: [Muthusamy2003]

- Efficient use of resources
  - Unused resources like bandwidth, storage, CPU cycles at the edge of the network become available to any user
- Scalability
  - Consumers of resource also produce resource. If remarkable consumers get into the system, aggregate resources will grow with utilization.
  - Self-scaling
- Reliability

  - No single point of failure
  - Geographic distribution
  - Replicas
  - Built-in fault tolerance
- Easy administration
  - Nodes self organizing
  - No need to deploy servers
  - Load balancing

Besides file sharing, P2P model has been used in collaborative Internet (e.g. ICQ, shared whiteboard), distributed computing (e.g. JXTA), audio and video media streaming (e.g. Pichat, Peercasting), multiplayer network games (e.g. Doom), VoIP (e.g. Skype), grid computing (e.g. UC Berkley Seti@home Project), and many other scenarios. However, P2P systems for file sharing remain to be the oldest and most sophisticated P2P application. In a typical file sharing network, a user makes files (music, video, etc.) on her computer available to others. Then another user connects to the network, searches for the files, finds the first user's computer, and downloads files directly from first user's computer.

2.2. Classification

The common classification criterion for P2P systems is routing topology. By this criterion, P2P systems fall into two categories: unstructured P2P systems and structured P2P systems. [Muthusamy2003]

An unstructured P2P network is formed when links in the P2p overlay are established arbitrarily. Therefore, an unstructured P2P system does not have a fixed topology for routing. Such networks can be easily constructed as a new peer that wants to join the network can copy existing links of another node and then form its own links over time. In an unstructured P2P network, if a peer wants to find a desired piece of data in the network, the query has to be flooded through the network to find one or more peers that are holding the data. Well-known P2P systems like Napster, Gnutella, and KaZaA are unstructured.

The primary disadvantage with such networks is that the queries may not always be resolved. Popular content is likely to be available at several peers and any peer searching for it is likely to succeed. If a peer is looking for rare data shared by only few peers, that search may easily fail. Flooding causes a