A Decentralized Content-based Aggregation Service for Pervasive Environments

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Outline

- Motivation, requirements, challenges
- Meteor: Content-based interaction/messaging middleware
- Content-based decentralized aggregation service
- Deployment and evaluation
- Related work
- Conclusion
Motivation

- Ubiquity of devices with embedded computing and communications capabilities
- Emergence of pervasive Grid environments and applications
  - Realize information-driven, context-aware, computationally intensive end-to-end distributed applications
- System, application, information uncertainty!
- Programming abstractions and middleware services
  - Scalable, self-managing, adaptive
  - Based on content
  - Asynchronous and decoupled (opportunistic) interactions
  - Efficient and flexible information access, aggregation, assimilation
Data Aggregation and Assimilation in Pervasive Grid Environments

- Large volumes of heterogeneous and continuous data streams
  - Centralized, batch-processing solutions not feasible
- Dynamic system behavior
  - Availability, quality of data
- Dynamic application requirements
Project Meteor: Middleware Stack

- A self-organizing tiered overlay network
  - Bottom tier is a structured overlay, e.g., Chord, CAN, etc.
- Content-based routing engine (Squid)
  - Flexible content-based routing and querying with guarantees and bounded costs
  - Decentralized information discovery
- Associative Rendezvous Messaging
  - Symmetric post programming primitive
  - Content-based decoupled interaction with programmable reactive behavior
  - *Decentralized content-based in-network aggregation service*
Associative Rendezvous (AR)

- Content-based decoupled interactions:
  - All interactions are based on content, rather than names or addresses
  - The participants (e.g. senders and receivers) communicate through an intermediary, the rendezvous point
  - The communication is asynchronous. The participants can be decoupled both in space and time.

- Programmable reactive behaviors:
  - The reactive behaviors at the rendezvous points are encapsulated within messages => flexibility, expressivity, and multiple interaction semantics
The Semantics of Associative Rendezvous Interactions

- **Messages:**
  - (header, action, data)
  - Symmetric post primitive: does not differentiating between interest/data

- **Associative selection**
  - match between interest and data profiles

- **Reactive behavior**
  - Execute action field upon matching

Profile = list of (attribute, value) pairs:
Example:

\(<(\text{sensor\_type, temperature}), (\text{latitude, 10}), (\text{longitude, 20})>\)
Content-based Aggregation Services

- Extends the AR programming abstraction to enable content-based aggregation services
  - AR post(<L, speed, 3600>, retrieve(AVERAGE, 300))
  - Region L: (35-60, 40-80)
  - find the average speed in the stretch of road specified by region L every 5 minutes for the next 1 hour

- Compute the traffic bottleneck along Route 95 from East Brunswick to NYC in the next one hour

- Estimate the time needed to enter NYC

- 1. Anyone exceed speed limit
- 2. Where is the maximum speed on road
- 3. Minimum speed on road and where
Self-organizing Overlay (Chord)

- A self-organizing P2P ring overlay
- Nodes and data have unique identifiers (keys), from a circular key space (0 to $2^m$)
- Each node maintains a routing table, called “finger table”
- A key is stored at the first node whose identifier is greater or equal with the key
- The request is routed to the neighbor node closer to the destination
- Routes in $O(\log n)$ hops

**Finger** = the successor of (this node id + $2^{i-1}$) mod $2^m$, $0 \leq i \leq m$

Routing from node 1 to node 6
SquidTON: Reliability and Fault Tolerance

- Pervasive Grid systems are dynamic, with nodes joining, leaving and failing relatively often
  - => data loss and temporarily inconsistent overlay structure
  - => the system cannot offer guarantees
- Build redundancy into the overlay network
- Replicate the data

**SquidTON = Squid Two-tier Overlay Network**
- Consecutive nodes form unstructured groups, and at the same time are connected by a global structured overlay (e.g. Chord)
- Data is replicated in the group
Content-based Routing (Squid)

- Route based on semantic headers
  - Use a dimension-reducing mappings to map from multidimensional information space => 1-dimensional index space
    - can route based on keywords, partial keywords, wildcards and ranges
  - Builds on an underlying DHT lookup mechanism
- Offers guarantees: all destinations matched by the content will be identified with bounded costs (messages, intermediate nodes, etc.)
Squid – Definitions

Keyword tuple (used to specify the destination)

- List of \( d \) keywords, wildcards and/or ranges
- Example:
  - (temperature, celsius), (temp*, *), (*, 10, 20-25)

- Simple keyword tuple
  - Contains only complete keywords

- Complex keyword tuple
  - Contains wildcards and/or ranges
Content Indexing: Hilbert SFC

- $f: \mathbb{N}^d \rightarrow \mathbb{N}$, recursive generation

- Properties:
  - Digital causality
  - Locality preserving
  - Clustering

Cluster: group of cells connected by a segment of the curve
Content Indexing and Routing

**Content profile 1:**
(2,1)

Generate the clusters associated with the content profile

**Content profile 2:**
(4-7,0-3)

**Content profile 3:**
(*, 4)

Rout to the nodes that store the clusters

Send the results to the requesting node

Matching messages

Matching messages
Squid: Routing Optimization

- More than one cluster are typically stored at a node
- Not all clusters that are generated for a query exist in the network => optimize!
- SFC generation recursive => clusters generation is recursive => the process of cluster generation can be viewed as a prefix tree (trie)
- Optimization: embed the tree into the overlay, and prune nodes during the construction phase
Decentralized In-network Aggregation

- **Post AR messages** with *aggregation* behaviors in the system
  - Content indexing: from n-dimension to 1-dimension using Hilbert SFC
  - Content-based routing: prefix trie construction
  - Decentralized in-network aggregation
    - Use aggregation tries for back-propagating and aggregating matching data items

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**Indexing using SFC**

- **Post** \(<p_1, p_2, \ldots, p_N>, \text{action (aggrBehavior)})\)
- **Area in the N-dimensional semantic space**
- **Segments in the 1-dimensional index space**

**Trie-based In-network Aggregation**

- **Matched data items**
- **Trie-based Content Routing**

**Back-propagation of matched data**

**Trie construction**
Trie Construction

- Recursive resolution of message profile to construct prefix trie
Trie-based Content Routing

- Embed the tree into overlay network
- Node 100001 is responsible for storing the subtree routed at 011*
Trie-based In-Network Aggregation (I)

- AR message was issued at node 111000
- First recursion level results in clusters with prefix 0
- At node 000000, further level recursion, the cluster 011 and 0010 are identified and padded with 0, for example;
- Node receive the sub-queries generate next level recursion, …
Trie-based In-Network aggregation (II)

- Caching to improve latencies
- Managing system dynamics
  - Joins, Leaves, Fails
- Load balancing
- Building geographical awareness into the overlay
Miscellaneous Issues and Optimizations

- Varied Link Latencies
- Caching to reduce routing latencies
- Load balancing
- Addressing churn
  - Join, leave
- Failures
  - Leaf peers, intermediate peers, source peer
- Geographical locality (to an extent)
Meteor: Implementation Overview

- Current implementation builds on JXTA
- Chord, Squid and AR Messaging layer are implemented as event-driven JXTA services
- Deployments
  - Local area network
    - 64 1.6 GHz Pentium IV nodes with 100 Mbps Ethernet interconnection network
  - Orbit sensor network testbed
    - 400 802.11 radio nodes with 802.11 wireless connections
  - PlanetLab wide-area testbed
Experimental Evaluation

- Aggregation services:
  - Complex queries issued from each of the three deployment environments
    - Post(34-444, temp*, retrieve(count))
  - Effectiveness of in-network aggregation
    - Aggregate range queries
    - Number of messages processed in the network
  - Robustness in case of single peer failures

- Note that the performance of Squid and AR have been separately evaluated
Scalability of the Aggregation Services

Aggregate query:
post(<(100-300, 75-125), temperature>, retrieve(avg, 300))
Effectiveness of In-Network Aggregation

- Simulation results
  - 500 nodes
- AR aggregate message:
  - Post(<100-230, 35-120>, retrieve(avg))
- Fig (a) number of messages with/without in-network aggregation
- Fig (b) actual number of messages per peer
Robustness of Aggregation Service

- Assume single node failure
  - An intermediate node fails at about 205 time ticks
  - On-going aggregation operations are lost at this node
- About 100 ms required to correct the aggregation trie in a LAN environment
Related works

- Aggregation in P2P environments
  - Astrolabe, Cone, PHT
- Aggregation in sensor networks
  - Cougar, TAG
- Meteor
  - Content-based aggregation abstraction
    - Asynchronous and decoupled
  - No persistent state maintained in the network
  - Trie reused across aggregations
  - Guarantees
Summary

- Content-based, decoupled interactions and aggregations are essential for pervasive Grid applications
- Meteor provides unified programming abstractions for content-based decoupled interactions and decentralized in-network aggregation
  - Recurrent and spatially constrained queries
  - Scalable and efficient trie-based design and implementation
- Deployments on LAN, Orbit and PlanetLab
  - Scalability, performance, robustness