Pushing dynamic and ubiquitous event-based interaction in the Internet of services: a middleware for event clouds

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Outline

1. Introduction
2. Distributed RDF storage
3. Distributed RDF pub/sub
4. Distributed RDF load balancing
5. Implementation
6. Conclusion
Outline

1. Introduction
   - Motivation
   - Context
   - Problem definition

2. Distributed RDF storage

3. Distributed RDF pub/sub

4. Distributed RDF load balancing

5. Implementation

6. Conclusion
Motivation

- Exponential growing of information produced
  - Internet of Things
    - Internet scale collection of connected data sources

- Data mining
  - Prerequisite
    - Integrate data from heterogeneous sources
  - Discover interesting patterns
    - Filter information of interest and correlate them with others

- Semantic Web
  - Provides a full technology stack (RDF, SPARQL, RDFS, OWL, etc.) for managing structured data
  - Mainly in a synchronous and centralized environment
Context: PLAY and SocEDA projects

EventCloud Middleware

Send data synchronously or asynchronously
Context: PLAY and SocEDA projects

EventCloud Middleware

Platform users

Subscribe to detect interesting patterns and react consequently
Context: PLAY and SocEDA projects

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CEP
Complex Event Processing engine (Etalis/Esper)

EventCloud Middleware

EP-SPARQL
EP-SPARQL
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Send data synchronously or asynchronously

Event sources
Scalable storage and retrieval of RDF-based data
EventCloud Middleware
Asynchronous notification
Synchronous SPARQL
Asynchronous SPARQL
Publish
Publish
Publish

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Event sources
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Problem definition

1. How can we efficiently store and retrieve Semantic Web data in a distributed environment?
2. How can we pragmatically filter and disseminate Semantic Web events to users with individual preferences?

- Challenges
  - Data indexing/retrieval
  - Near real-time filtering
  - Load balancing
  - Scalability

Middleware devoted to storing, retrieving synchronously but also disseminating selectively and asynchronously RDF data
Outline

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2. Distributed RDF storage
   - Background
   - P2P Infrastructure for RDF
   - Evaluation

3. Distributed RDF pub/sub

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Peer-to-Peer (P2P) networks

- **Unstructured P2P networks**
  - links between peers are chosen randomly
  - bad performance for search (flooding)

- **Structured P2P networks**
  - various topologies (ring, hypertorus, tree)
  - communication overhead for *join/leave*
  - more efficient for lookup

Chord

CAN

P-grid
Peer-to-Peer (P2P) networks

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RDF/SPARQL

- Resource Description Framework (RDF)
  - Model information based on tuples (3-tuple or 4-tuple)
  - Quadruples depicted as \( q = (g, s, p, o) \mid g, s, p, o \in RDFTerm \)

- SPARQL (SPARQL Protocol and Query Language)
  - Declarative query language for RDF data
  - Highly expressive query language
    - Several query types (SELECT, DESCRIBE, CONSTRUCT, ASK)
    - Multiple graph patterns (Basic, Union, Constraints)
    - Many solution modifiers (DISTINCT, LIMIT, OFFSET)
Elementary query types

- **Atomic queries** are quadruple patterns where the graph, the subject, the predicate and/or the object may be a variable
  - 
    - $(g, s, p, o)$
    - $(g, s, ns:creator, W3C)$

- **Conjunctive queries** are expressed as a list of quadruple patterns (sub-queries).
  - 
    - $(g_1, s, p_1, o_1) \land (g_1, s, p_2, o_2)$

- **Range queries** involve queries for single or multiple variables whose values fall into a range defined by the query
  - 
    - $(g, s, p, o)$ FILTER $v_1 \leq o < v_2$
Related works

**P2P**
- RDFPeers
- RDFCube
- LIAROU et al.

**NoSQL**
- CumulusRDF
- H₂RDF
- AllegroGraph
- BigData

- Limited SPARQL support
- Monolithic software architecture
- Hashing for indexing and storing RDF data
Related works

### P2P
- RDFPeers
- RDFCube
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- CumulusRDF
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#### Limited SPARQL support

#### Monolithic software architecture

#### Hashing for indexing and storing RDF data

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1. Filali, “Improving resource discovery in P2P systems”.
2. Bongiovanni, “Design, formalization and implementation of overlay networks; application to RDF data storage.”
Hashing vs Lexicographic based indexing

- **Hash based indexing**
  - Uniform hash functions
    - Destroy data locality
  - Locality preserving hash functions
    - Keep relative distance between input values and output values but cause load imbalances

- **Lexicographic order based indexing**
  - Preserves data locality
    - Native support for range queries
  - Distribution on peers depends of data values

Lexicographic based indexing exhibits similar properties to hash based indexing using locality preserving hash functions without the extra complexity of hashing
Our P2P infrastructure

- Built atop Content Addressable Network (CAN)
  - Resources are distributed in a 4-dimensional space $\mathbb{D}$
    - $\mathbb{D}$ is divided into zones
    - Each zone is managed by a peer
    - Each zone may contain multiple resources
    - A resource is a quadruple $q = (g, s, p, o)$ indexed as a point in $\mathbb{D}$
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No hashing but lexicographic order
Routing algorithms

- **Unicast routing**
  - Used to route a message to one specific peer in the CAN space
    - Based on a key that depicts a point to reach
  - Scheme based on greedy forwarding per dimension
    - Does not use euclidean distance since radix 1114112 is used

- **Multicast routing**
  - Used to route messages to a subset of peers on the CAN overlay
    - Based on optimal broadcast proposed by Francesco Bongiovanni\(^3\)

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\(^3\) Bongiovanni and Henrio, “A Mechanized Model for CAN Protocols”. 
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Unicast routing is used to index a quadruple

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Multicast routing is the substrat for retrieving information

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RDF data indexing

Data: Quadruple $q$
begin
    if $q \notin$ peer’s zone then
        Forward the request to the closest neighbor
    else
        Store $q$;
        Send back response;
    end
end

No hashing but lexicographic order
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RDF data retrieval

SPARQL Query $Q$

```sparql
SELECT ?g ?user WHERE {
  GRAPH ?g {
    ?user foaf:name "John Doe".
    ?user foaf:age ?age
  }
  FILTER (?age \geq 18 \&\& ?age \leq 25)
}
```

SPARQL Decomposer
RDF data retrieval

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SELECT ?g ?user WHERE {
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**SPARQL Decomposer**

- \( q_1 \) \( ?user \) \( \text{foaf:name} \) "John Doe"
- \( q_2 \) \( ?user \) \( \text{foaf:age} \) ?age
  - FILTER \( ?age \geq 18 \&\& ?age \leq 25 \)

**Implementation**

- RDF data retrieval
  - SELECT ?g ?user WHERE {
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**Conclusion**

- Distributed RDF storage
- Distributed RDF pub/sub
- Distributed RDF load balancing

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Query Manager

SPARQL Colander

$P_1$

$P_2$

$P_3$

$P_4$

$P_5$
RDF data retrieval

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P₁

P₂

P₃

P₄

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```

Graph $Q_1$

```
?user foaf:name "John Doe"
```

Graph $Q_2$

```
?user foaf:age ?age
FILTER ?age ≥ 18 && ?age ≤ 25
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**SPARQL Query Q**

```
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  FILTER (?age \(\geq\) 18 \&\& \(\leq\) 25)
}
```

**Diagram**

- **SPARQL Query Q** (green box) generates two subqueries:
  - `q1`: `?user foaf:name "John Doe"` (blue arrow)
  - `q2`: `?user foaf:age ?ageFILTER ?age \(\geq\) 18 \&\& ?age \(\leq\) 25` (blue arrow)

- **SPARQL Colander** (green box) processes the subqueries:
  - `q1` (blue arrow) sent to `P1`
  - `q2` (blue arrow) sent to `P2`

- **Query Manager** (green box) coordinates the retrieval process:
  - `q1` (blue arrow) sent to `P1`
  - `q2` (blue arrow) sent to `P2` and `P4`

- **Node P1** (green box) receives `q1` and processes it.

- **Node P2** (green box) receives `q2` and processes it.

- **Node P3** (green box) receives `q1` from `P2`.

- **Node P4** (green box) receives `q2` from `P2`.

- **Node P5** (green box) is connected to `P4` and `P3`.
RDF data retrieval

SPARQL Query $Q$

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  }
  FILTER (?age ⩾ 18 && ?age ⩽ 25)
}
```

Diagram:
- **SPARQL Query** $Q$
- **SPARQL Decomposer**
- **Query Manager**
- **SPARQL Colander**
- **Processes** $P_1$, $P_2$, $P_3$, $P_4$, $P_5$
RDF data retrieval

SPARQL Query $Q$

```
SELECT ?g ?user WHERE {
  GRAPH ?g {
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```
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SPARQL Colander

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P1

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RDF data retrieval

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SPARQL Decomposer

SPARQL Colander

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Experimental setup

- Up to 300 peers with 75 machines on the Grid’5000 testbed
  - Xeon L5420@2.5GHz
  - 16 GB RAM
  - 7200 RPM HDD

- Dataset
  - BSBM Berlin SPARQL benchmark
    - Built around an e-commerce usecase

- Queries
  - Q1 Conjunctive query with same subject
  - Q2 Atomic query with fixed predicate and object
  - Q3 Atomic query with fixed predicate and free subject and object
  - Q4 Conjunctive query with two variables in each subquery
Experiments

Performance results strongly depend on the type of queries
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   - Evaluation

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Context

- Event Driven Architecture
  - Publish/Subscribe
    - asynchronous communication style
    - Subscribers
    - Publishers
    - Event notification service
  - Entities are decoupled in space, time and synchronization

- Publish/subscribe layer for RDF data
  - Reuses some technologies from the Semantic Web stack
  - Filters and disseminates RDF events to interested parties
  - Stores published events for future reuse
Context

- **Event Driven Architecture**
  - Publish/Subscribe *asynchronous* communication style
    - Subscribers
    - Publishers
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  - Entities are decoupled in *space, time* and *synchronization*

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Related works: pub/sub systems

Do not focus on the specific characteristics of RDF

Attribute/value pairs vs Tuples

Constraints defined at startup (event size, type, domain)

4 Tibco, “TIB/Rendezvous White Paper”.
5 Fitzpatrick, Slatkin, and Atkins, PubSubHubbub protocol.
6 Carzaniga, Rosenblum, and Wolf, “Design and evaluation of a wide-area event notification service”.
7 Pietzuch and Bacon, “Hermes: A distributed event-based middleware architecture”.
8 Li, Ye, Kim, Chen, and Lei, “A scalable and elastic publish/subscribe service”.

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21/45
Related works: RDF pub/sub systems (1)

- **RDFPeers**\(^9\)
  - Built atop MAAN
  - Rendezvous nodes are created for publications and subscriptions
  - Each publication is indexed three times
  - Not possible to subscribe for all information
  - Some join constraints are not supported
  - Popular RDF terms are ignored (e.g., rdf:type)

- **Ranger et al.**\(^10\)
  - Information sharing platform using multicast trees
  - The peers participating to the propagation are responsible for removing duplicate results within the limit of their buffer

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\(^9\) Cai, Frank, Yan, and MacGregor, “A subscribable peer-to-peer RDF repository for distributed metadata management”.

\(^10\) Ranger and Cloutier, “Scalable peer-to-peer RDF query algorithm”.
Related works: RDF pub/sub systems (2)

- **CSBV**\(^{11}\)
  - Distributed Hash Table (DHT) agnostic
  - Each publication is indexed seven times

- **Shvartzshnaider et al.**\(^{12}\)
  - Support arbitrary tuples
  - Combine AI and P2P research by applying Rete algorithms
  - Ad-hoc scripting language for subscribing
  - No explanation about how duplicates are avoided when in-memory buffers overflow
  - No experiment is provided

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\(^{11}\) Liarou, Idreos, and Koubarakis, “Continuous RDF query processing over DHTs”.

\(^{12}\) Shvartzshnaider, Ott, and Levy, “Publish/subscribe on top of DHT using RETE algorithm”. 
Proposed data and subscription model

• Data Model
  ▶ RDF quadruple \( q = (g, s, p, o) \mid g, s, p, o \in RDFTerm \)
  ▶ Compound Event
    - \( CE = (q_1, \ldots, q_i, \ldots, q_n) \mid q_i = (g_i, s_i, p_i, o_i) \)
    - Ability to put more things in an event

• Subscription Model
  ▶ Filter language based on a subset of SPARQL

  1. \( SELECT \ ?g \ ?name \ WHERE \ { \)
  2. \( GRAPH \ ?g \ { \)
  3. \( \ ?user \ :foaf:name \ "John\ Doe" . \)
  4. \( \ ?user \ :foaf:age \ ?age \)
  5. \( } \ FILTER \ (?age >= 18 \ \&\& \ ?age <= 25) \)
  6. \( } \)

  ▶ Two sub-subscriptions (SSs): one on line 3 and one on line 4–5
  ▶ Subscription matched by a subset of quadruples from a CE
Indexing subscriptions and events

• Indexing a subscription

\[ S = SS_1 \land SS_2 \]

• Indexing a compound event

\[ CE = \begin{cases} q_1 \\ q_2 \\ q_3 \end{cases} \]
Indexing subscriptions and events

- Indexing a subscription

- Indexing a compound event

\[
S = SS_1 \land SS_2
\]

\[
SS_1 = (\exists x, p)
\]

\[
SS_2 = (r, \exists y)
\]

\[
CE = \begin{cases} q_1 \\ q_2 \\ q_3 \end{cases}
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Indexing subscriptions and events

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\[
S = SS_1 \land SS_2
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\[SS_1 = (?x, p)\]

\[SS_2 = (r, ?y)\]

• Indexing a compound event

\[CE = \{ q_1, q_2, q_3 \} \]

\[(a,z) \rightarrow (z,a)\]
Indexing subscriptions and events

• Indexing a subscription

\[ S = SS_1 \land SS_2 \]

\[ SS_1 = (\exists x, p) \]

\[ SS_2 = (r, ?y) \]

\[ m \]

\[ t \]

\[ (a,a) \]

\[ (z,a) \]

\[ (a,z) \]

\[ (z,z) \]

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Indexing subscriptions and events

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Perform matching
Publish/Subscribe Algorithms

1. Chained Semantic Matching Algorithm (CSMA)
   - Inspired from the original idea of CSBV\(^{13}\)
   - Events published in parallel
   - Subscriptions matched sequentially (chain)
   - Subscribers may require a final filtering operation to prevent duplicates

2. One-step Semantic Matching Algorithm (OSMA)
   - Subscriptions matched in one step
   - Improves matching time (i.e. delivery time perceived by subscribers)
   - Avoids duplicate notifications that may be received per CE on subscribers with CSMA

\(^{13}\) Liarou, Idreos, and Koubarakis, “Continuous RDF query processing over DHTs”.
Chained Semantic Matching Algorithm (CSMA)

\[ S = (\pi x, p) \land (r, \pi y) \]

\[ \begin{align*}
q_1 &= (h / \mathbb{p}) \\
q_2 &= (x / \mathbb{q}) \\
q_3 &= (r / \mathbb{d})
\end{align*} \]

\[ q_2 \text{ does not satisfy } SS_1 \]

\[ q_3 \text{ matches no subscription} \]

\[ q_1 \text{ matches } SS_1 \]

\[ S' = \{r / \mathbb{y}\} \]

\[ q_2 \text{ is not satisfying } SS_1 \]

\[ q_3 \text{ is satisfying } SS_2 \]

\[ \text{Trigger notification to user} \]
Chained Semantic Matching Algorithm (CSMA)

\[ S = (\exists x, p) \land (r, ?y) \]

\[ SS_1 = (\exists x, p) \quad SS_2 = (r, ?y) \]

\[ \begin{align*}
q_1 &= (h, p) \\
q_2 &= (x, q) \\
q_3 &= (r, d)
\end{align*} \]

\[ q_2 q_1 q_3 \]

\[ m \quad t \]

\[ (a, z) \quad (z, z) \]

\[ (a, a) \quad (z, a) \]

\[ m \quad t \]

\[ q_1 \quad q_2 \quad q_3 \]

\[ = CE \]
Chained Semantic Matching Algorithm (CSMA)

\[ S = (\exists x, p) \land (r, ?y) \]

Indexing \( S \) according to \( SS_1 \)

\[ SS_1 = (\exists x, p) \quad SS_2 = (r, ?y) \]

\[ \begin{align*}
q_1 & = (h/p) \\
q_2 & = (x/q) \\
q_3 & = (r/d) \\
\{ q_2, q_3 \} & = CE 
\end{align*} \]
Chained Semantic Matching Algorithm (CSMA)

Indexing $S$ according to $SS_1$

$S = (\forall x, p) \land (r, ?y)$

$SS_1 = (\forall x, p)$  $SS_2 = (r, ?y)$

$q_1 = (z, z)$
$q_2 = (z, a)$
$q_3 = (a, z)$

$q_2$ does not satisfy $SS_1$
$q_3$ matches no subscription
$q_1$ matches $SS_1$

Rewriting $S$ into $S'$

$S' = (r, ?y)$

Checking subscriptions satisfaction
$q_2$ is not satisfying $SS_1$
$q_3$ is satisfying $SS_2$

Trigger notification to user
Chained Semantic Matching Algorithm (CSMA)

\[ S = (?x, p) \land (r, ?y) \]

\[ SS_1 = (?x, p) \quad SS_2 = (r, ?y) \]

Indexing \( S \) according to \( SS_1 \)

\[ q_1, q_2, q_3 \quad \{ \quad = CE \]
Chained Semantic Matching Algorithm (CSMA)

\[ S = (?x, p) \land (r, ?y) \]

\[ SS_1 = (?x, p) \quad SS_2 = (r, ?y) \]

\[ q_1 \]
\[ q_2 \]
\[ q_3 \] \[ = CE \]

Indexing \( S \) according to \( SS_1 \)

\[ q_1 = (h, p) \]
\[ q_2 = (x, q) \]
\[ q_3 = (r, d) \]

Performing matching between subscriptions and events

\( q_2 \) does not satisfy \( SS_1 \)

\( q_3 \) matches no subscription

\( q_1 \) matches \( SS_1 \)

Rewriting \( S \) into \( S' \)

\[ S' = (r, ?y) \]

Checking subscriptions satisfaction

\( q_2 \) is not satisfying \( SS_1 \)

\( q_3 \) is satisfying \( SS_2 \)

Trigger notification to user
Chained Semantic Matching Algorithm (CSMA)

Indexing $CE$

$q_1 = (h, p)$
$q_2 = (x, q)$
$q_3 = (r, d)$

$S = (?x, p) \land (r, ?y)$

$SS_1 = (?x, p)$ $SS_2 = (r, ?y)$

Performing matching between subscriptions and events $q_2$ does not satisfy $SS_1$ $q_3$ matches no subscription $q_1$ matches $SS_1$
Chained Semantic Matching Algorithm (CSMA)

Indexing $CE$

$q_1 = (h, p)$
$q_2 = (x, q)$
$q_3 = (r, d)$

$S = (?x, p) \land (r, ?y)$

$SS_1 = (?x, p)$  $SS_2 = (r, ?y)$

Performing matching between subscriptions and events
$q_2$ does not satisfy $SS_1$
$q_3$ matches no subscription
$q_1$ matches $SS_1$

Rewriting $S$ into $S'$

$S' = (r, ?y)$

Checking subscriptions satisfaction
$q_2$ is not satisfying $SS_1$
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Trigger notification to user
Chained Semantic Matching Algorithm (CSMA)

Indexing $CE$

$q_1 = (h, p)$
$q_2 = (x, q)$
$q_3 = (r, d)$

$S = (?x, p) \land (r, ?y)$

$SS_1 = (?x, p)$  $SS_2 = (r, ?y)$
Chained Semantic Matching Algorithm (CSMA)

\[ S = (x, p) \wedge (r, y) \]

\[ SS_1 = (x, p) \quad SS_2 = (r, y) \]

\[ q_1 = (h, p) \]
\[ q_2 = (x, q) \]
\[ q_3 = (r, d) \]

Performing matching between subscriptions and events:
- \( q_2 \) does not satisfy \( SS_1 \)
- \( q_3 \) matches no subscription
- \( q_1 \) matches \( SS_1 \)

Rewriting \( S \) into \( S' \):
\[ S' = (r, y) \]

Checking subscriptions satisfaction:
- \( q_2 \) is not satisfying \( SS_1 \)
- \( q_3 \) is satisfying \( SS_2 \)

Trigger notification to user.
Chained Semantic Matching Algorithm (CSMA)

Performing matching between subscriptions and events

- $q_2$ does not satisfy $SS_1$
- $q_3$ matches no subscription
- $q_1$ matches $SS_1$

Indexing $S$ according to $SS_1$

$SS_1 = (?x, p)$  
$SS_2 = (r, ?y)$

Rewriting $S$ into $S'$

$S' = (r, ?y)$

Checking subscriptions satisfaction

- $q_2$ is not satisfying $SS_1$
- $q_3$ is satisfying $SS_2$

Trigger notification to user
Chained Semantic Matching Algorithm (CSMA)

$S = (?x, p) \land (r, ?y)$

$SS_1 = (?x, p)$  $SS_2 = (r, ?y)$

$S' = (r, ?y)$

Rewriting $S$ into $S'$. $S'$

Checking subscriptions satisfaction $q_2$ is not satisfying $SS_1$ $q_3$ is satisfying $SS_2$

Trigger notification to user
Chained Semantic Matching Algorithm (CSMA)

Rewriting $S$ into $S'$

$S'=(r, ?y)$

$q_1 \{ q_1, q_2, q_3 \} = CE$
Chained Semantic Matching Algorithm (CSMA)

\[ S = (x, p) \land (r, y) \]

\[ SS_1 = (x, p) \quad SS_2 = (r, y) \]

Rewriting \( S \) into \( S' \)

\[ S' = (r, y) \]

\[ q_1 \]
\[ q_2 \]
\[ q_3 \]

\[ \{ q_1, q_2, q_3 \} = CE \]
Chained Semantic Matching Algorithm (CSMA)

Checking subscriptions satisfaction

- \( q_2 \) is not satisfying \( SS_1 \)
- \( q_3 \) is satisfying \( SS_2 \)

Indexing \( S \) according to \( SS_1 \)

- \( q_1 \) matches \( SS_1 \)
- \( q_2 \) does not satisfy \( SS_1 \)
- \( q_3 \) matches no subscription

Rewriting \( S \) into \( S' \)

\[ S' = (r, y) \]

Performing matching between subscriptions and events

\[ q_1 \]
\[ q_2 \]
\[ q_3 \]

Checking subscriptions satisfaction

- \( q_2 \) is not satisfying \( SS_1 \)
- \( q_3 \) is satisfying \( SS_2 \)

Trigger notification to user
Chained Semantic Matching Algorithm (CSMA)

\[ S = (?x, p) \land (r, ?y) \]

\[ SS_1 = (?x, p) \quad SS_2 = (r, ?y) \]

Indexing

\[ S \text{ according to } SS_1 \]

\[ q_1 = (h / comma.math p) \]

\[ q_2 = (x / comma.math q) \]

\[ q_3 = (r / comma.math d) \]

Performing matching between subscriptions and events

\[ q_2 \text{ does not satisfy } SS_1 \]

\[ q_3 \text{ matches no subscription} \]

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Rewriting \( S \) into \( S' \)

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\[ q_2 \text{ is not satisfying } SS_1 \]

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Trigger notification to user

\[ \{ q_1, q_2, q_3 \} = CE \]
One-step Semantic Matching Algorithm (OSMA)

\[ S = (?x, p) \land (r, ?y) \]

\[ \begin{align*}
q_1 & = h/p \\
q_2 & = x/q \\
q_3 & = r/d \\
\{ q_1, q_2, q_3 \} & = CE
\end{align*} \]
One-step Semantic Matching Algorithm (OSMA)

\[ S = (?x, p) \land (r, ?y) \]

\[ SS_1 = (?x, p) \quad SS_2 = (r, ?y) \]

\[
\begin{align*}
q_1 &= (h, p) \\
q_2 &= (x, q) \\
q_3 &= (r, d)
\end{align*}
\]

\[
\begin{align*}
SS_1 &\Rightarrow CE_q_1 \\
SS_2 &\Rightarrow CE_q_2 \\
q_3 &\Rightarrow CE_q_3
\end{align*}
\]

Indexing \[ S \text{ according to } SS_1 \]

Indexing \[ CE_q_1 = (h, p) \]

\[ q_2 = (x, q) \]

\[ q_3 = (r, d) \]

Performing matching between subscriptions and events \[ q_3 \text{ and the } CE \] sent along with the quadruple.

The subscriber is notified by the peer responsible for the first of the matching quadruples contained by the \[ CE \].
One-step Semantic Matching Algorithm (OSMA)

\[ S = (\forall x, p) \land (r, \forall y) \]

\[ SS_1 = (\forall x, p) \quad SS_2 = (r, \forall y) \]

Indexing \( S \) according to \( S_1 \)

\[ q_1 \quad q_2 \quad q_3 \]

\[ \{ q_1, q_2, q_3 \} = CE \]
One-step Semantic Matching Algorithm (OSMA)

Indexing $S$ according to $S_1$

$S = (?x, p) \land (r, ?y)$

$SS_1 = (?x, p)$  $SS_2 = (r, ?y)$

$q_1 = (h, p)$  $q_2 = (x, q)$  $q_3 = (r, d)$

$\{ q_1, q_2, q_3 \} = CE$
One-step Semantic Matching Algorithm (OSMA)

\[ S = (?x, p) \land (r, ?y) \]

\[ SS_1 = (?, x, p) \quad SS_2 = (r, ?y) \]

Indexing \( S \) according to \( S_1 \)

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q_1 & = (h, p) \\
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Performing matching between subscriptions and events \( q_3 \) and the CE sent along with the quadruple matches no subscription

CE Peers indexing \( q_1 \) and \( q_2 \) are each satisfying \( S \)

The subscriber is notified by the peer responsible for the first of the matching quadruples contained by the CE

\[ \{ q_1, q_2, q_3 \} = CE \]
One-step Semantic Matching Algorithm (OSMA)

\[ S = (?x, p) \wedge (r, ?y) \]

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One-step Semantic Matching Algorithm (OSMA)

Indexing $CE$

$q_1 = (h, p)$
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$q_3 = (r, d)$

$S = (?, p) \land (r, ?y)$
$SS_1 = (?, p)$  $SS_2 = (r, ?y)$
One-step Semantic Matching Algorithm (OSMA)

Indexing $CE$

$q_1 = (h, p)$
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Performing matching between subscriptions and events $q_3$ and the $CE$ sent along with the quadruple matches no subscription $CE$ Peers indexing $q_1$ and $q_2$ are each satisfying $S$ 

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One-step Semantic Matching Algorithm (OSMA)

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One-step Semantic Matching Algorithm (OSMA)

Performing matching between subscriptions and events

$$S = (?x, p) \land (r, ?y)$$

$$SS_1 = (?x, p) \quad SS_2 = (r, ?y)$$

Indexing according to $$S$$

$$SS_1 = (?x, p) \quad SS_2 = (r, ?y)$$

$$q_1 = (h, p) \quad q_2 = (x, q) \quad q_3 = (r, d)$$

$$q_1 \quad CE \quad q_2 \quad CE \quad q_3 \quad CE$$

The subscriber is notified by the peer responsible for the first of the matching quadruples contained by the CE.

Performing matching between subscriptions and events

$$CE$$

$$q_1 \quad CE \quad q_2$$

$$q_3$$

$$CE$$

$$z, a$$

$$z, z$$

$$m$$

$$t$$

$$S = (?)x, p \land (r, ?y)$$
One-step Semantic Matching Algorithm (OSMA)

\[
S = (\exists x, p) \land (r, ?y) \\
SS_1 = (\exists x, p) \quad SS_2 = (r, ?y)
\]

\[
q_3 \text{ and the } CE \text{ sent along with the quadruple matches no subscription}
\]

\[
\begin{align*}
q_1 & = CE \\
q_2 & = CE \\
q_3 & = CE \\
q_1, q_2, q_3 & = CE
\end{align*}
\]
One-step Semantic Matching Algorithm (OSMA)

Peers indexing $q_1$ and $q_2$ are each satisfying $S$

$S = (?x, p) \land (r, ?y)$

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One-step Semantic Matching Algorithm (OSMA)

The subscriber is notified by the peer responsible for the first of the matching quadruples contained by the \( CE \).
## CSMA vs OSMA

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<tr>
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<th>Duplicates</th>
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**Table:** Comparison of the two publish/subscribe algorithms.
## CSMA vs OSMA

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Table: Comparison of the two publish/subscribe algorithms.

Experiments are required to confirm the promising behavior of OSMA.
Experimental setup

- Up to 25 nodes from the French Grid’5000 testbed
  - Xeon E5520@2,26GHz
  - 32 GB RAM
  - 7200 RPM HDD
- Each result is the average execution time for 6 runs
- Workload made of synthetic events
  - Each CE embeds 5 quadruples
  - Size per CE is about 670 Bytes
- Subscriptions are path queries
  - Each subscription embeds 5 SSs
  - \((?g, ?s1, p1, ?o1) \land (?g, ?o1, p2, ?o2) \land \ldots \land (?g, ?o_{k-1}, p_k, ?o_k)\)
Experiments

(a) Impact of overlay size

OSMA outperforms CSMA by a factor of 5.43 because it does not require to rewrite subscriptions.

(b) Impact of subscriptions

CSMA throughput remains almost stable because rewritten subscriptions involves more peers.

Trade-off between CSMA and OSMA
Outline

1. Introduction
2. Distributed RDF storage
3. Distributed RDF pub/sub
4. Distributed RDF load balancing
   - Background
   - Load balancing solution
   - Evaluation
5. Implementation
6. Conclusion
Background

- RDF data are highly skewed
  - Some RDF terms occur more often than others (e.g. `rdf:type`)
    - According to Kotoulas\(^\text{14}\) the most popular term appear around 10–20% of all others

\(^\text{14}\) Kotoulas, Oren, and Van Harmelen, “Mind the data skew: distributed inferencing by speeddating in elastic regions".
Background

- RDF data are highly skewed
  - Some RDF terms occur more often than others (e.g. `rdf:type`)
    - According to Kotoulas\textsuperscript{14} the most popular term appear around 10–20% of all others

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{chart.pdf}
\caption{Perfect distribution on peers}
\end{figure}

\textsuperscript{14} Kotoulas, Oren, and Van Harmelen, “Mind the data skew: distributed inferencing by speeddating in elastic regions".
## Related works

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Load balancing decision during join/leave

Usually one resource considered

Solutions that often differ by minor but subtle changes
Related works

Static

- Bayers et al.
- Battré et al.
- RCAN
- Meghdoot

Dynamic

- Godfrey et al.
- Bienkowsky et al.
- Vu et al.
- Mercury

Load balancing decision during join/leave

Usually one resource considered

Solutions that often differ by minor but subtle changes

Our goal is to propose a dynamic solution that is flexible enough to balance RDF data on peers but also other resources
Proposed solution

1. Detecting load imbalances
Proposed solution

1. Detecting load imbalances
   ▶ Measuring load
Proposed solution

1. Detecting load imbalances
   ▶ Measuring load
     - Define resources/criteria to consider

RDF Data
Query load
Subscription load
Proposed solution

1. Detecting load imbalances
   - Measuring load
     - Define resources/criteria to consider
   - Deciding about imbalance
Proposed solution

1. Detecting load imbalances
   ▶ Measuring load
     - Define resources/criteria to consider
   ▶ Deciding about imbalance
     - Define imbalance states

   Data:
   - C
   - M
   - E
   - K

   Result:
   - LoadState
   
   ```
   for i ∈ M do
     // i, load measurement index
     // m, load measurement value
     if m ≥ E[i] × K1[i] then
       return LoadState(Overloaded[C[i]])
     else if m < E[i] × K2[i] then
       return LoadState(Underloaded[C[i]])
     return LoadState(Normal)
   ```

   • Absolute strategy
     - Define threshold based on local information (e.g. Hard disk drive space capacity)
   • Relative strategy
     - Aggregate information from other peers to estimate network load and use it as threshold
 Proposed solution

1. Detecting load imbalances
   ▶ Measuring load
     - Define resources/criteria to consider
   ▶ Deciding about imbalance
     - Define imbalance states
     - Propose load state estimation algorithm

```
Data:  C, M, E, K_1, K_2
Result:  LoadState

for i, m ∈ M do
  // i, load measurement index
  // m, load measurement value
  if m ≥ E[i] × K_1[i] then
    return LoadState(Overloaded, C[i])
  if m < E[i] × K_2[i] then
    return LoadState(Underloaded, C[i])
  return LoadState(Normal)
```
Proposed solution

1. Detecting load imbalances
   ▶ Measuring load
     - Define resources/criteria to consider
   ▶ Deciding about imbalance
     - Define imbalance states
     - Propose load state estimation algorithm
     - Define how threshold is estimated

- **Absolute strategy**
  ▶ Define threshold based on local information
    (e.g. Hard disk drive space capacity)

- **Relative strategy**
  ▶ Aggregate information from other peers to estimate network load and use it as threshold
Proposed solution

1. Detecting load imbalances
   - Measuring load
     - Define resources/criteria to consider
   - Deciding about imbalance
     - Define imbalance states
     - Propose load state estimation algorithm
     - Define how threshold is estimated

2. Balancing the load
Proposed solution

1. Detecting load imbalances
   ▶ Measuring load
     - Define resources/criteria to consider
   ▶ Deciding about imbalance
     - Define imbalance states
     - Propose load state estimation algorithm
     - Define how threshold is estimated

2. Balancing the load
   ▶ Selecting imbalance receiver
Proposed solution

1 Detecting load imbalances
   ▶ Measuring load
      - Define resources/criteria to consider
   ▶ Deciding about imbalance
      - Define imbalance states
      - Propose load state estimation algorithm
      - Define how threshold is estimated

2 Balancing the load
   ▶ Selecting imbalance receiver
      - Use neighbor(s), allocate new peer or leverage information exchanged for estimating threshold values
Proposed solution

1. Detecting load imbalances
   ▶ Measuring load
      - Define resources/criteria to consider
   ▶ Deciding about imbalance
      - Define imbalance states
      - Propose load state estimation algorithm
      - Define how threshold is estimated

2. Balancing the load
   ▶ Selecting imbalance receiver
      - Use neighbor(s), allocate new peer or leverage information exchanged for estimating threshold values
   ▶ Executing load balancing (per criteria)
Proposed solution

1. Detecting load imbalances
   - Measuring load
     - Define resources/criteria to consider
   - Deciding about imbalance
     - Define imbalance states
     - Propose load state estimation algorithm
     - Define how threshold is estimated

2. Balancing the load
   - Selecting imbalance receiver
     - Use neighbor(s), allocate new peer or leverage information exchanged for estimating threshold values
   - Executing load balancing (per criteria)
     - Taking advantage of join/leave operations through virtual peers
Executing scale-out load balancing for RDF data

- Partition zones based on centroid not middle
- Record statistical information about distribution
  - Using background threads to reduce overhead

(a) Cutting based on middle
(b) Cutting based on centroid
Executing scale-out load balancing for RDF data

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Executing scale-out load balancing for RDF data

- Partition zones based on centroid not middle
- Record statistical information about distribution
  - Using background threads to reduce overhead

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- Workload is real data extracted from a Twitter data flow
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  - Size is about $10^5$ quadruples
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- Virtual peers with peers allocation only (scale-out)
  - Using 32 peers

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<th>Dynamic load balancing</th>
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<tr>
<td>Middle</td>
<td>Absolute</td>
</tr>
<tr>
<td>559.4%</td>
<td>119.75%</td>
</tr>
<tr>
<td>Centroid</td>
<td>Relative</td>
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<tr>
<td>69.5%</td>
<td>96.57%</td>
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Table: Load balancing strategies comparison using relative stddev.
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Outline

1. Introduction
2. Distributed RDF storage
3. Distributed RDF pub/sub
4. Distributed RDF load balancing
5. Implementation
   Middleware design
   Performance tuning
6. Conclusion
Middleware design (EventCloud)

Figure: Stack of main software blocks designed and/or used.
Implementation-level performance and tuning aspects

- **Serialization** *(section 6.2.2)*
  - Prevent message payload marshalling/unmarshalling at each routing step

- **Local storage** *(section 6.2.3)*
  - Proposed delayer mechanism to perform bulk processing
  - Investigated parameters to improve throughput

- **Multi-active objects** *(section 6.2.1)*
  - Hard and soft limit definition
    - Required due to datastructures contention and I/O accesses
  - Support for scheduling requests according to priorities
    - Purpose is to avoid starvation
Outline

1. Introduction
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Conclusion

• Contribution
  ▶ Middleware devoted to storing, retrieving synchronously but also disseminating selectively and asynchronously RDF data
    - Synchronous RDF data indexing and retrieval
    - Asynchronous RDF data indexing and retrieval
    - RDF data load-balancing
    - Modular architecture with reusable abstractions
Perspectives

• Increasing reliability and availability
  ▶ Safe recovery in case of peers failure
    - Replication (e.g. checkpointing or state machines)

• Optimizing query and subscriptions evaluation
  ▶ Improving query plan execution
  ▶ Subscriptions summarization

• Reasoning over RDF data
Thank you for your attention

😊
Publications


Backup slides
Hash based indexing using indexes

\[ p_1 = (s_1, p_1) \]

\[ p_2 = (s_1, p_2) \]

\[ (?s, p_1) \]
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Hash based indexing using indexes

\[ p_1 = (s_1, p_1) \]
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\[ (s_1, p_1) \rightarrow (h(s_1 + p_1), h(s_1 + p_1)) \]
\[ p_1 = (s_1, p_1) \rightarrow (h(s_1), h(s_1)) \]
\[ (h(p_1), h(p_1)) \]
\[ (h(s_1 + p_1), h(s_1 + p_1)) \]

\[ p_2 = (s_1, p_2) \rightarrow (h(s_1), h(s_1)) \]
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\[ (h(p_2), h(p_2)) \]
\[ (h(s_1 + p_2), h(s_1 + p_2)) \]
**CAP theorem**

- Any practical database can only provide 2 of the 3 desirable properties: *Consistency*, *Availability*, and *Partitionability*.

The choice of a storage backend is a tradeoff guided by the requirements of a particular use case.
SPARQL queries support

- Distributed RDF storage (synchronous)
  - External point of view
    - Full SPARQL 1.0 support
  - Internal point of view
    - Only atomic queries and range queries (FILTERs with XPath tests operators)

- Distributed RDF pub/sub (asynchronous)
  - Limitations
    - Uses the SELECT query form
    - Contains at most one group GRAPH pattern with a graph variable
    - Returns the graph variable declared in the GRAPH pattern
  - Allowance
    - Multiple triple patterns may be used inside the graph pattern defined in the subscription
    - One or more FILTER clauses are also allowed to restrict solutions
    - Standard logical operators but also filter functions like REGEX, STRSTARTS, etc. are permitted
R1 Events and subscriptions are assumed to be submitted to the event notification service by means of proxies

R2 Clocks are assumed synchronized between machines inside the P2P network only

R3 Causal ordering between publish and subscribe requests handled asynchronously from a same proxy must be enforced

R4 Quadruples must *eventually* be stored on peers

R5 Events that must be notified are notified
**Pub/sub layer requirements (2)**

**R6** Data indexation does not rely on hashing on in order to avoid multiple indexations of the same publications

**R7** Subscribers must have the possibility to receive notifications as:

- a signal
- a collection of bindings (values matching the variables contained by their subscription)
- the full event that has matched their interests

**R8** No *false positives* nor *duplicates*
Unicast routing complexity

Figure: Unicast routing complexity comparison (made by Lokman RAHMANI)
Evaluation concurrent insertions

Evolution of the time for concurrent insertions with 300 peers cooperating.
CSMA – Indexing a subscription

1. Extract the first atomic\textsuperscript{15} or range\textsuperscript{16} query (SS)
2. Forward the subscription \(S\) on peers managing \(SS'\) conditions
3. Each peer receiving \(S\)
   3.1 Stores \(S\)
   3.2 Finds quadruples matching \(SS\)
   3.3 Rewrites \(S\) and index derived subscription or notifies subscriber

\[
\text{SELECT } ?g \ ?\text{name WHERE } \{ \text{GRAPH } ?g \{ ?\text{user foaf:name } ?\text{name } .
\text{?user foaf:age } ?\text{age } \} \text{ FILTER (} ?\text{age } \geq 18 \& \& ?\text{age } \leq 25 \} \}
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\(q_1=\text{(ex:event74,ex:toto,foaf:name,"Toto")}\)

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\[\text{Rewriting}\]

\[
?g \ ?\text{user foaf:name } ?\text{name} \rightarrow \text{ex:event74 } ?\text{user foaf:age } ?\text{age FILTER } ?\text{age } >= 18 \& \& ?\text{age } <= 25
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\begin{verbatim}
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```
```

\(q_2=(\text{ex:event74, ex:toto, foaf:age, } "24" \text{ } \text{xsd:integer})\)

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Subscription fully satisfied

\(^{15}\text{ Quadruple where any RDF term may be a variable}\)

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CSMA

Indexing a publication

1. Publish each \( q \) from a CE independently

2. Each peer receiving \( q \)
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   2.2 Finds SSs satisfied by \( q \)
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Notification reception

- Each subscriber receiving a notification \( n \)
  - Starts a full event reconstruction process
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**Notification reception**

- Each subscriber receiving a notification $n$
  - Starts a full event reconstruction process
OSMA

Indexing a subscription

- Same as CSMA

Indexing a publication

1. Send the whole CE on peers using each $q$ as routing key
2. Each peer receiving the Compound Event by using $q$ as key
   2.1 Stores $q$ but not the full CE
   2.2 Finds subscriptions (not SS(s)) satisfied by the CE in one step
   2.3 Notifies the subscriber about the CE (under one condition)
      - No reconstruction required
      - No duplicate notifications
Avoiding duplicates with OSMA

- A peer notifies a match if and only if it is responsible for the first of the matching quadruples contained by the CE

\[
\text{CE} = \langle ?x/r \rangle
\]

\[
\begin{align*}
(a,a) &\rightarrow q_1 \\
(a,z) &\rightarrow q_2, q_3 \\
(z,z) &
\end{align*}
\]

\[
S = (?x, r)
\]
Avoiding duplicates with OSMA

- A peer notifies a match if and only if it is responsible for the first of the matching quadruples contained by the $CE$

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Avoiding duplicates with OSMA

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CE = \{ (a,a), (a,z), (z,z) \}
\]

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Avoiding duplicates with OSMA

- A peer notifies a match if and only if it is responsible for the first of the matching quadruples contained by the CE.
Impact of the number of publications

CSMA throughput decreases quickly with the number of publications due to required reconstructions.
Scalability with one accept-all subscription

In contrary to CSMA, OSMA does not generate any duplicate. Consequently, OSMA performs much better than CSMA whose the throughput stagnates.
**Time to store publications on peers**

![Graph showing time to store publications on peers]

**OSMA requires more bandwidth than CSMA since the full CE is sent along with each quadruple.**
Background

- **Load balancing goals**
  - achieve maximum resources utilization
  - avoid overload
  - maximize throughput/minimize response time
  - prevent crashing

- **Load balancing strategies**
  - **Data replication**
    - Improve data access by balancing queries load but not data itself
  - **Data relocation through indirections**
    - Mechanisms are expensive to maintain up to date pointers
  - **Multiple hash functions for indexing data**
    - Increase lookup complexity
  - **Virtual peers (peers relocation or allocation)**
    - Maintenance overhead
Background

• RDF data are highly skewed
  ▶ Some RDF terms occur more often than others (e.g. rdf:type)
    - According to Kotoulas\textsuperscript{17} the most popular term appear around 10–20% of all others
  ▶ Many RDF term prefixes (namespaces) are the same
  ▶ RDF terms belong to groups of characters, where members of each group surround a particular and common character, thus shaping RDF terms clusters.

• Skewness affects data distribution on peers (hot-spots)
  ▶ Prevents system scalability

\textsuperscript{17} Kotoulas, Oren, and Van Harmelen, “Mind the data skew: distributed inferencing by speeddating in elastic regions”.
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- RDF data are highly skewed
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  - Prevents system scalability

\textit{Achieve maximum resources utilization to maximize throughput}

\textit{Hashing is not the solution when the issue is the popularity}

\textsuperscript{17}Kotoulas, Oren, and Van Harmelen, "Mind the data skew: distributed inferencing by speeddating in elastic regions".
Background

- **Static load balancing**
  - System load is assumed stable (no continuous insertions or deletions)
  - Load balancing decision taken during the join of a peer

- **Dynamic load balancing**
  - Decisions and adaptations at runtime
  - Support for endless data insertions
Proposed solution

Balancing load

• Selecting imbalance receiver (*setting parameter* $E$)
  ▶ Absolute strategy
    - Purely local decision based on parameters defined at startup
  ▶ Relative strategy
    - Make use of a gossip protocol to estimate network load

• Virtual peers
  ▶ Peers allocation and/or relocation
  ▶ Reuse existing join and leave operations
  ▶ Good compromise between overhead, implementation complexity and achievable results
Experiments

![Graph showing static load balancing using middle vs centroid partitioning.](image)

**Figure:** Static load balancing using middle vs centroid partitioning.
High-level view of the EventCloud architecture

Tracker2 ➔ Tracker1 ➔ Tracker3

4-dimensional Content Addressable Network

PutGet Proxy ➔ Publish Proxy ➔ Subscribe Proxy
Internal proxies architecture

PutGet Proxy
- PutGet API
  - Query Plan Generator
  - Query Decomposer
  - Query Plan Executor
  - Message Dispatcher

Subscribe Proxy
- Subscribe API
  - Query Decomposer
  - Message Dispatcher
  - Notification Receiver

Publish Proxy
- Publish API
  - Message Dispatcher
Internal peer architecture

Peer $i$

4D CAN Overlay

P2P Substrate

- Delayer
- Publish/Subscribe Matcher

Local Storage

- Subscriptions Datastore
- Events Datastore
- Colander Datastore

Load Balancing Manager
Priorities effect on reconstructions with CSMA

![Graph showing the effect of priorities on reconstruction time with CSMA. The x-axis represents elapsed time, and the y-axis represents reconstruction time (in ms). The graph compares reconstruction time without priorities to with priorities. The y-axis is on a log scale.]