A Self-Organizing P2P System with Multi-Dimensional Structure

Presentation and Analysis of Self-CAN

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Structured P2P Systems

Benefits of Structured P2P Systems

- Modern P2P systems adopt **structured overlay**: rings, multi-dimensional grids, trees
- Resource keys are assigned to peers using **hash functions**
  - *a resource discovery operation is transformed into a peer lookup operation, which can be performed in logarithmic time*
- Structured P2P overlays and **Distributed Hash Tables** are also adopted in **Grid and Cloud Computing**. One major example: *Amazon Dynamo*

But there are also drawbacks…

- **Lack of self-organizing properties**. Structured systems are rigid.
  - *Difficulties to adapt to rapid changes, for example to node churning*
- Management of **complex and range queries**. Due to the use of hash functions, the keys of similar resources are spread over distant peers
- **Load balancing** is far from optimal. The peers that are assigned the most popular keys may be significantly more loaded than others.

Self-* Properties in Structured P2P Systems

- **How can self-organizing properties be obtained?**
  - We use **mobile agents**, which travel the overlay and order resource keys
  - Agent operations are inspired by the behaviour of **ant colonies**
- **What are the benefits vs. classical structured systems?**

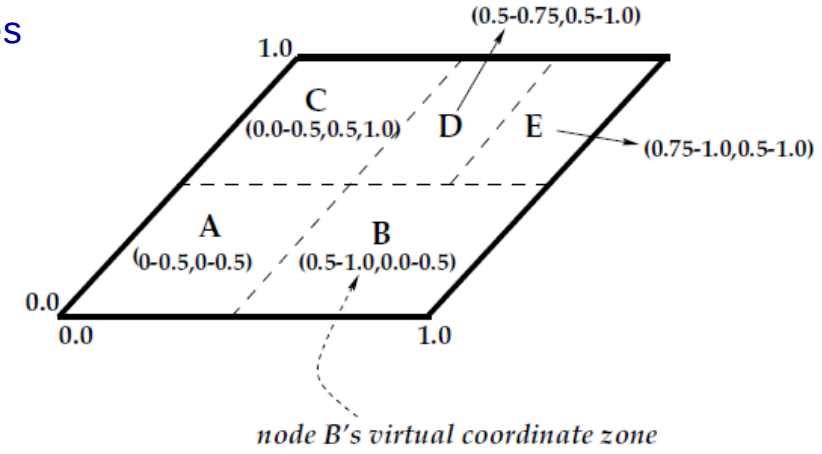
  Essentially three:
  - peer indexes and resource keys are **decoupled**, which opens the possibility to give a semantic meaning to keys, and helps the execution of class/range queries
  - **better load balancing**
  - **dynamic properties** are improved (e.g., management of joining and departing nodes)
- **What are the specific features of Self-CAN?**
  - Self-CAN exploits the **multi-dimensional overlay** of CAN, but adds self-* properties
  - Multi-dimensional values of resource keys can match **resource attributes**: e.g., the attributes of a host can express CPU power, RAM memory and type of operating system
  - Efficient execution of **multi-dimensional range queries**, essential in Grids and Clouds

Quick resume of CAN (1/2)

- In CAN each **resource** is assigned a **point** in a **D**-dimensional space.
- Each **peer** is assigned a **region** in the same space, and is required to manage the resource keys comprised in that region.
- Each peer is connected to **2D** neighbors, 2 for each dimension

Example of a 2-dimensional CAN overlay with 5 nodes

(from the CAN paper)

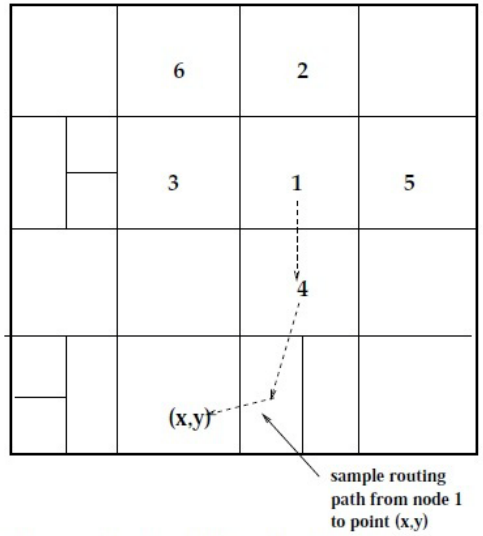


Quick resume of CAN (2/2)

- The search path follows connections among adjacent peers. If a D-dimensional space is partitioned among N_p peers, the average path length is $(1/4) \cdot D \cdot N_p^{1/D}$
- If the value of *D is logarithmic* with respect to the number of peers N_p, other important indexes are logarithmic. For example, if $D \sim (\log_2 N_p)/2$:
  - *the average length of the search path is* $(\log_2 N_p)/2$
  - *the number of a peer's neighbors is* $\log_2 N_p$

Example of a routing path in a 2-dimensional CAN overlay

(from the original CAN paper)



Key concepts of Self-CAN

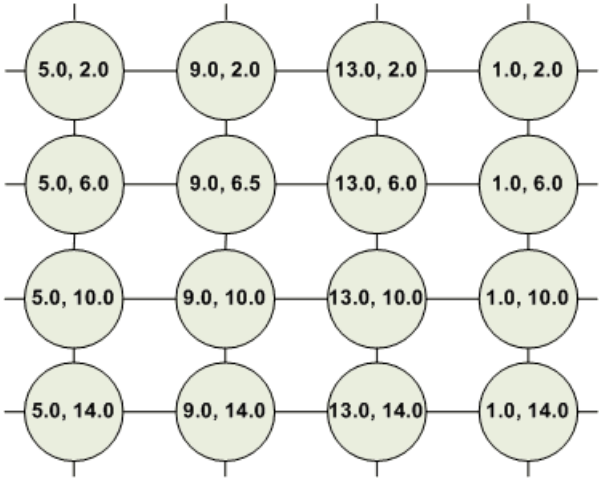
- Self-CAN exploits the CAN overlay, but **decouples** resource keys and peer indexes.
  - *key values may be associated with resource attributes*
- The resource keys **self-organize** along the D-dimensional space while preserving the **sorting of key values along each dimension**
  - *queries can reach a target key without knowing in advance the identity of the responsible peer*
  - *efficient management of **range and class queries***
- Key sorting is obtained through **pick** and **drop** operations of ant-inspired mobile agents.
- Keys are moved using **peer centroids** as a reference.

Peer centroids

- The centroid of a peer is the **D-dimensional vector** of key values that minimizes the distance from itself and the values of the keys stored in the local region.
- Example: **D=2**, and for each dimension keys assume values in the range {**0**..**15**}. Resources are so categorized in **256** classes.
- The keys stored in the local region are: (**1**,**15**), (**3**,**14**), (**5**,**0**), (**3**,**1**).
- The centroid is **C=(3,15.5)**, because for each dimension the centroid value minimizes the "circular" distance between itself and the keys
- The objective of mobile agents is to pick and drop keys by comparing them to centroids. Some examples:
  - *the key* (**1**,**15**) *should be moved towards a predecessor peer along the first dimension*
  - *the key* (**3**,**1**) *should be moved towards a successor peer along the second dimension*
  - *an agent arriving at this peer with the key* (**3**,**15**) *should drop it in the current peer*

Sorting of keys and peer centroids

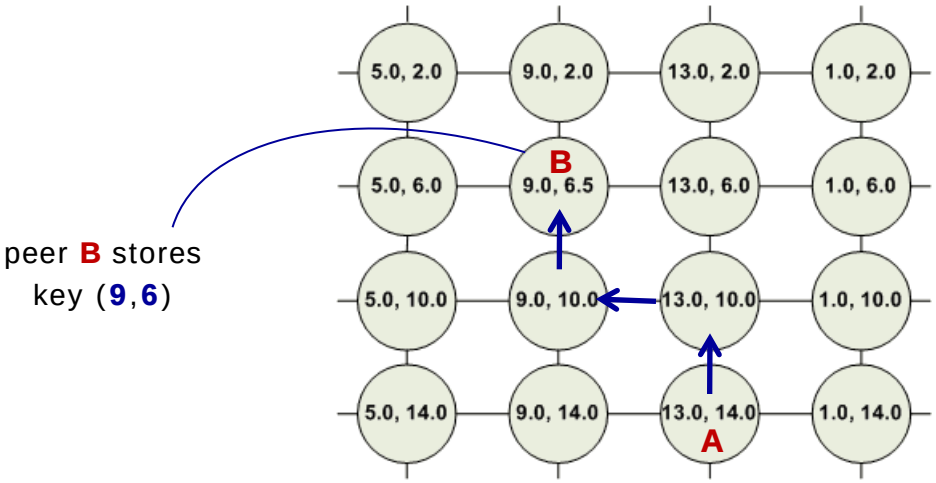
- Pick and drop operations **gradually sort keys** and **peer centroids** over the D-dimensional structure.
- Once the ordering is achieved, it is easily maintained even when the environment changes, for example when peers connect/depart, or keys are added/modified



A 2-DIMENSIONAL SELF-CAN NETWORK WITH 16 PEERS.
PEER CENTROIDS ARE SORTED ALONG BOTH DIMENSIONS.

Discovery procedure

- Every key is stored in a peer whose **centroid is very similar to the key**
- It is possible to search a key by following the **gradient of peer centroids** along the D dimensions.



THE PEER **A** STARTS A RESOURCE PROCEDURE TO FIND KEY (**9**,**6**).

THE SEARCH MESSAGE FOLLOWS THE CENTROID GRADIENT AND ARRIVES AT PEER **B**, WHICH MOST PROBABLY STORES THE DESIRED KEY, BECAUSE THE CENTROID IS VERY SIMILAR

Operations of Self-CAN agents

- Each agent performs a few simple operations, cyclically:
  1) while it is not carrying any key, the agent **hops** from a peer to an adjacent one, chosen randomly;
  2) at any new peer, it decides whether or not to **pick** a key out of the peer;
  3) after taking a key, the agent **jumps** to a new adjacent peer, moviong towards a region in which peer centroids are more similar to the key
  4) at the new peer, the agent decides whether or not to **drop** the carried key.
- Pick and drop operations are executed on the basis of **Bernoulli trials** whose probability depends on the **similarity** between the key and the local centroid

Similarity and Pick Operation

- To decide whether or not to pick a key, the agent evaluates the **similarity f(k,c)** between the key **k** and the local centroid **c**:

$$f(k,c) = 1 - \frac{1}{D}\sum_{i=1}^{D}\frac{\Delta_i}{L_i/2}$$

Δi = *distance between* ***k*** *and* ***c*** *over the i-th dimension*

Li/2 = *is the maximum distance over dimension i*

- The value of **f(k,c)** ranges between **0** (minimum similarity) and **1** (maximum similarity)

- The decision to perform the pick operation is the result of a **Bernoulli trial**.
  The **pick probability** for the trial is inversely proportional to the similarity **f(k,c)**

$$P_{pick}(k) = \frac{\alpha_p}{\alpha_p + f(k,c)}$$

α_p = *parameter with value between 0 and 1*

Jump and Drop

- While carrying a key **k**, the agent selects the dimension along which the distance between **k** and the centroid **c** is the largest
  - if **k > c** along this dimension, the agent jumps to the **successor** peer
  - if **k < c** the agent jumps to the **predecessor** peer
- At any new peer, the agent tries to drop the key. The drop operation is the result of another Bernoulli trial
- The drop probability is directly proportional to the to **f(k,c)**, the similarity between the key and the new centroid

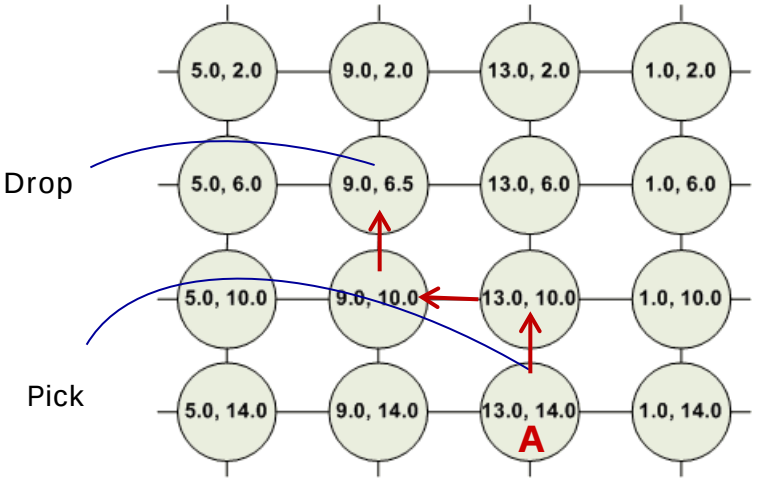
$$P_{drop}(k) = \frac{f(k,c)}{\alpha_d + f(k,c)}$$

α_d = *parameter with value between 0 and 1*

- Pick and drop operations rapidly sort the keys over the multi-dimensional space!

Example of pick and drop operations

- An agent at peer **A**, with centroid **(13.0, 14.0)**, evaluates the key **(9,6)**
- The similarity function is low, therefore the key is likely to be **picked**
- The key is brought towards the peer **B** having centroid **(9.0, 6.5)**
- The similarity is high, so the key is likely to be **dropped** here!



$$P_{drop}(k) = \frac{f(k,c)}{\alpha_d + f(k,c)} \quad = 0.85$$

$$P_{pick}(k) = \frac{\alpha_p}{\alpha_p + f(k,c)} \quad = 0.64$$

Performance Evaluation

- Simulation experiments have been performed to check:

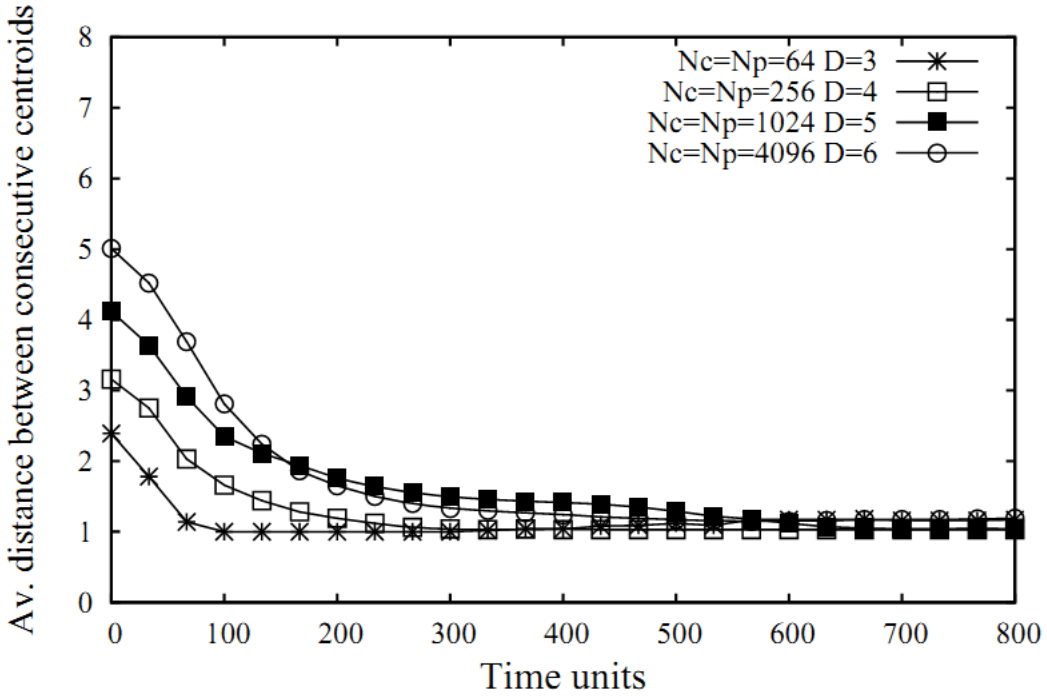
  1) the **sorting** of centroids and keys
  2) the key **clustering**: are the keys stored in the same peer similar to each other? How much are they distant from local centroids?
  3) the performance of **discovery** operations (both punctual and range queries)
  4) the **load balance**

- Scenario:

  - Number of peers **Np**: 256 to 4096
  - Number of resource classes **Nc**: 256 to 4096
  - Number of dimensions **D**: 2 to 6
  - $\mathbf{P_{gen}} = 1$: each peer generates one agent
  - Each peer publishes 15 resources on average
  - Peer connection time: 5 hours on average
  - The **time unit** is defined as the average time between two successive movements of an agent (in the experiments, time unit=5 s)

Average centroid distance

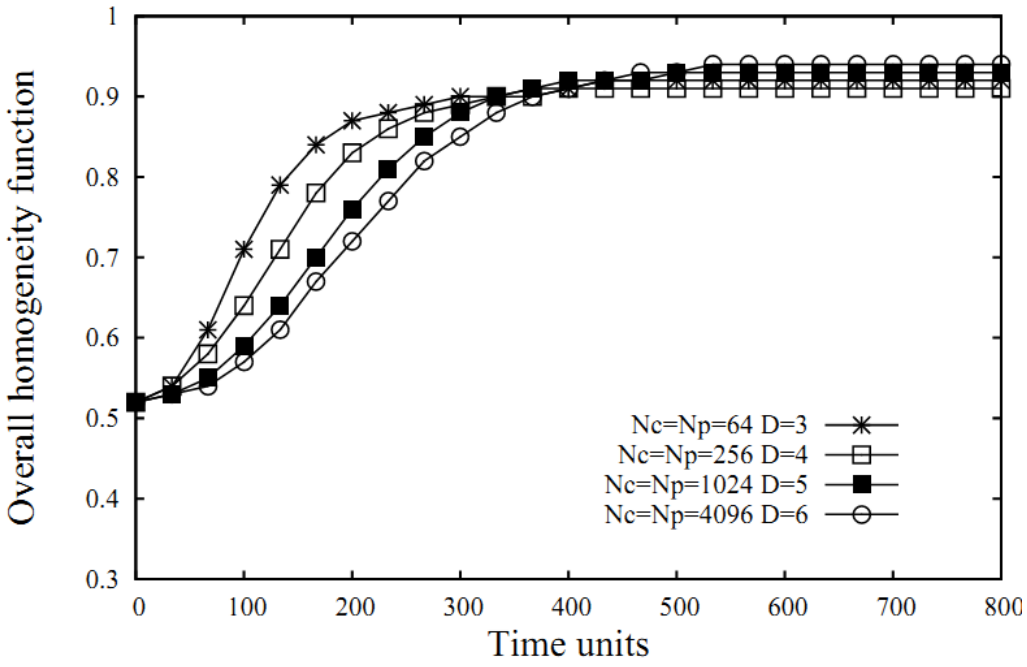
- Curves are obtained for different network sizes (**Np**) and number of classes (**Nc**)
- If keys and centroids are correctly sorted, the average centroid distance tends to $\sqrt[D]{Nc} / \sqrt[D]{Np} = 1$



- It is observed that:
  - the centroid distance always converges to **1**
  - the **time to convergence** increases with the network size, but is always reasonable
  - In a steady condition, sorting is **rapidly recovered** after any environmental change

Homogeneity of keys

- The homogeneity function of a peer can assume values between 0 and 1, and higher values correspond to high degrees of **clustering** in the peer.

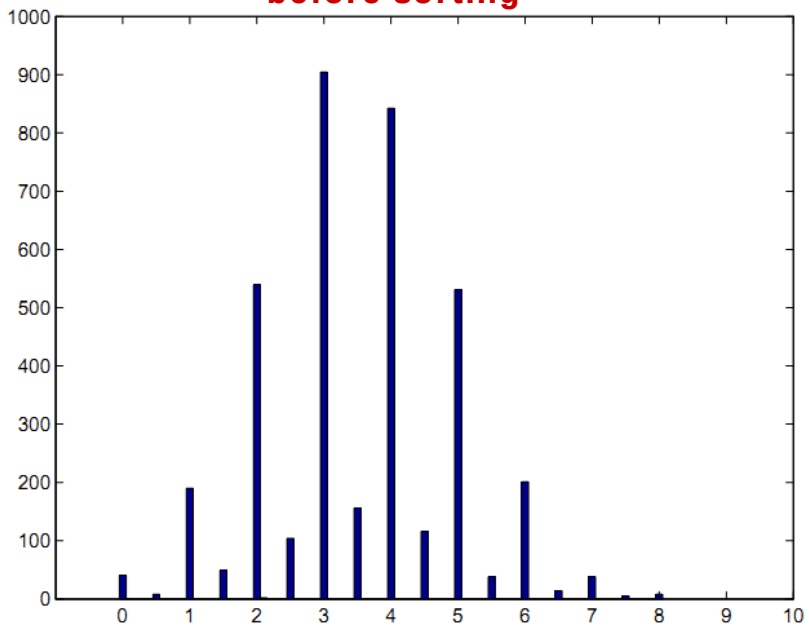


- After a rapid increase in the transient phase, the index stabilizes to values higher than **0.90**.
- The index is hardly affected by the network size, which confirms the **scalability** of Self-CAN.

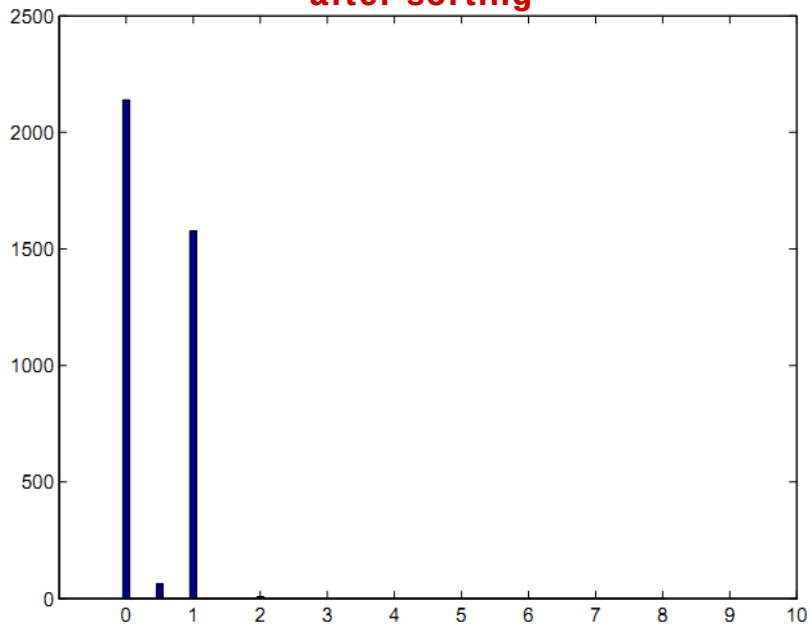
Distance between keys and local centroids

- Distribution of the distance between keys and local centroids. Np=256, Nc=256

before sorting



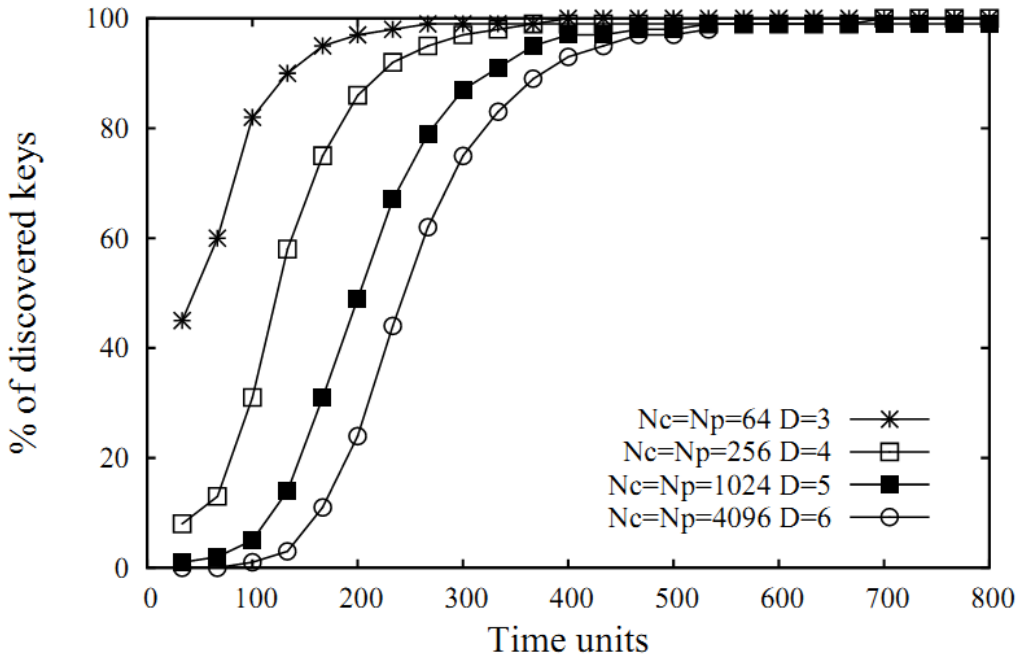
after sorting



- Before sorting the distribution of the distance is wide and centered on the value of **4**
- After sorting the distance is between **0** and **1**
- Consequence: A key can be discovered by directing queries towards the peer having a centroid value similar to the key

Average number of discovered results

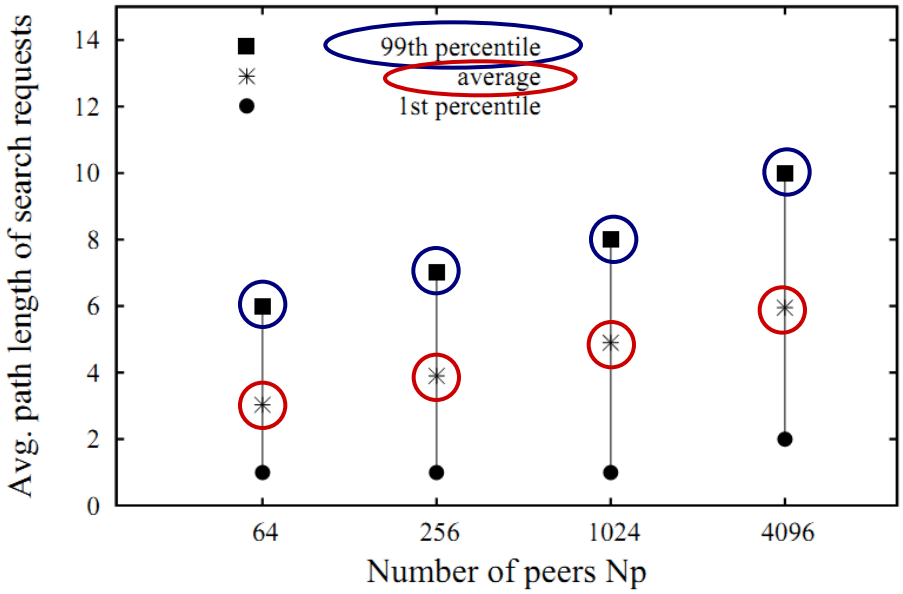
- A query can find several resources having a specified target key (**class query**)
- The figure shows the percentage of discovered keys with respect to the total number, while the network is being reordered



- When keys are sorted, a class query can find practically **all the target keys**!

Path length of search messages

- **Average** length of the query path, and **1st** and **99th** percentiles

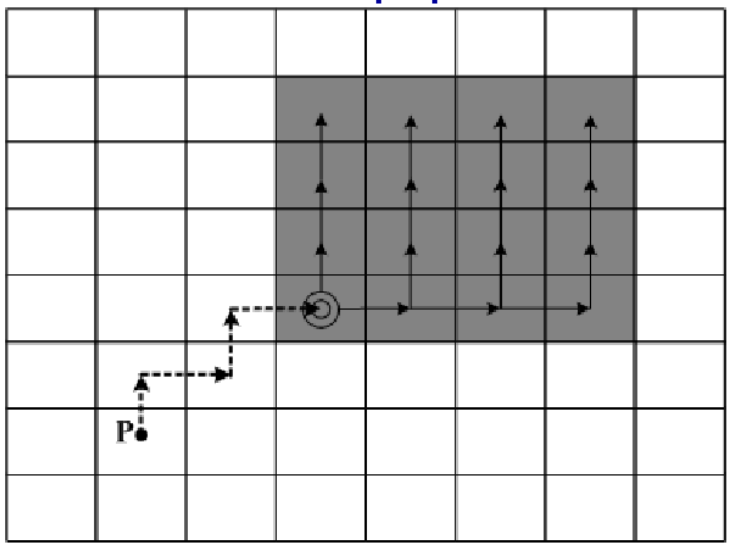


- The **average path length** is about **log(Np)/2**: the mean feature of CAN, log search, is kept by Self-CAN
- the **99th percentile** is about **log(Np)**, so the discovery time is logarithmic also in the most unfortunate cases!

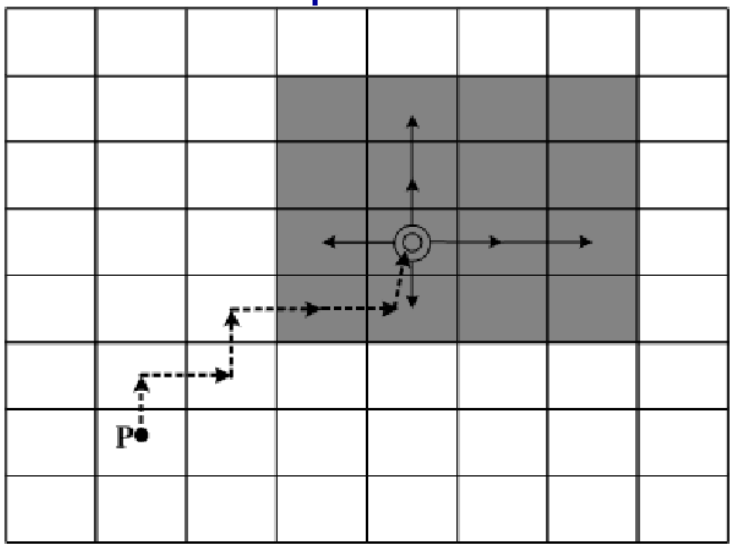
Range Queries

- Two approaches to serve range queries: **sweep up** and **explosion**
  - The **sweep up** approach aims to reach every peer that may contains target keys included in the intervals of the range query.
  - The **explosion** approach aims to reach the core of the region, and then rapidly collect a sufficient number of target keys

sweep up



explosion



Load Balancing

- In this experiment the central peers store a larger number of **popular keys**
- Notation **N**/**M** means: **N** keys, **M** of which belong to the most popular classes

before sorting

20/0	20/0	20/0	20/0	20/0	20/0	20/0	20/0
20/0	20/0	20/0	20/0	20/0	20/0	20/0	20/0
20/0	20/0	20/0	20/0	20/0	20/0	20/0	20/0
20/0	20/0	20/0	**50/50**	**50/50**	20/0	20/0	20/0
20/0	20/0	20/0	**50/50**	**50/50**	20/0	20/0	20/0
20/0	20/0	20/0	20/0	20/0	20/0	20/0	20/0
20/0	20/0	20/0	20/0	20/0	20/0	20/0	20/0
20/0	20/0	20/0	20/0	20/0	20/0	20/0	20/0

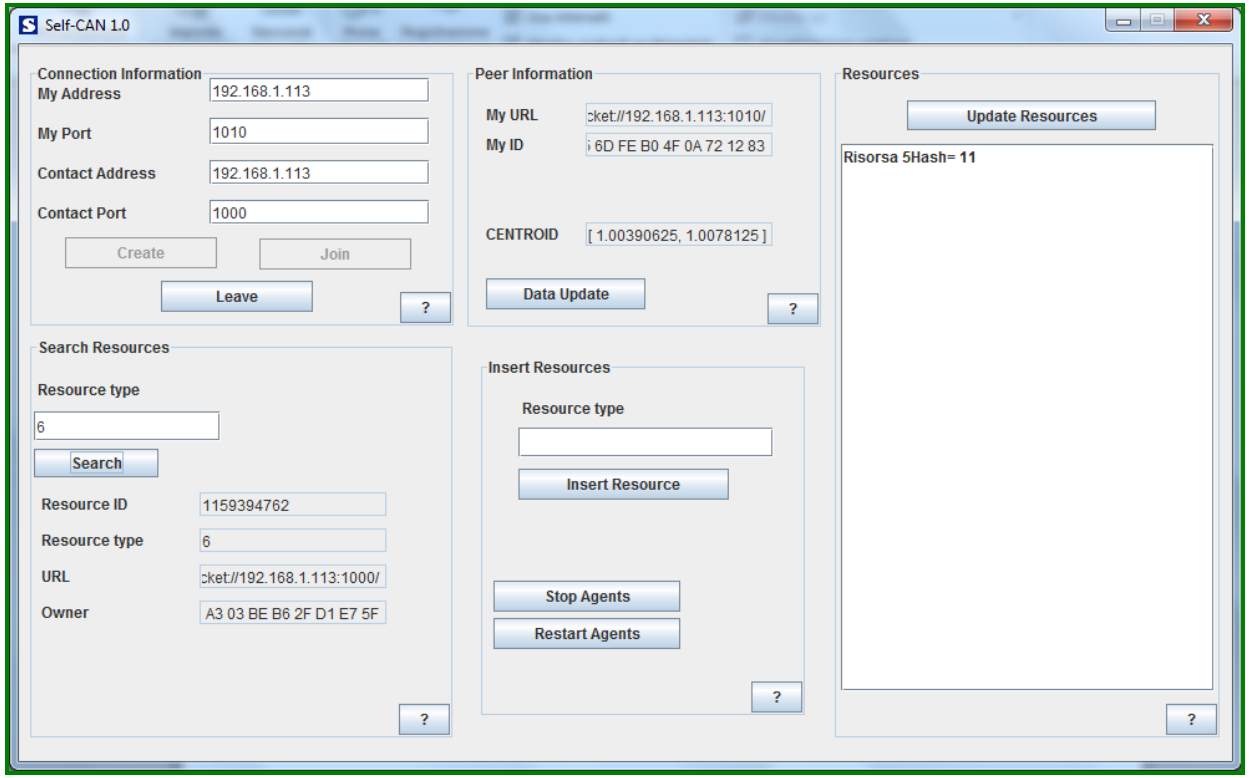
after sorting

18/0	18/0	19/0	18/0	20/0	17/0	22/0	21/0
20/0	19/0	20/0	22/0	19/0	20/0	18/0	18/0
19/0	19/0	23/0	**24/10**	**23/11**	21/0	20/0	23/0
25/0	21/0	**26/13**	**27/27**	**28/28**	**26/8**	25/0	22/0
25/0	21/0	**26/7**	**27/27**	**28/28**	**28/8**	23/0	23/0
21/0	24/0	19/0	**26/16**	**25/17**	20/0	20/0	19/0
18/0	23/0	19/0	24/0	24/0	18/0	23/0	22/0
20/0	19/0	24/0	25/0	24/0	21/0	21/0	17/0

- Agent operation distribute keys to peers in a **fair fashion**
- **Popular keys** are distributed over a larger number of peers

Self-CAN prototype

- The prototype of Self-CAN is available at **http://self-can.icar.cnr.it**
- The prototype has a GUI that allows the user to create or join a network, publish resources, search resources by name or by key
- The Java code is available



Thank you for your attention!