Dynamic Storage Load Balancing with Analogy to Thermal Diffusion for P2P File Sharing

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Outline

- Background and Motivation
- Storage Load Balancing Inspired by Thermal Diffusion
  - Concept
  - Analysis
- Simulation
- Summary

Peer-to-Peer (P2P) File Sharing Network

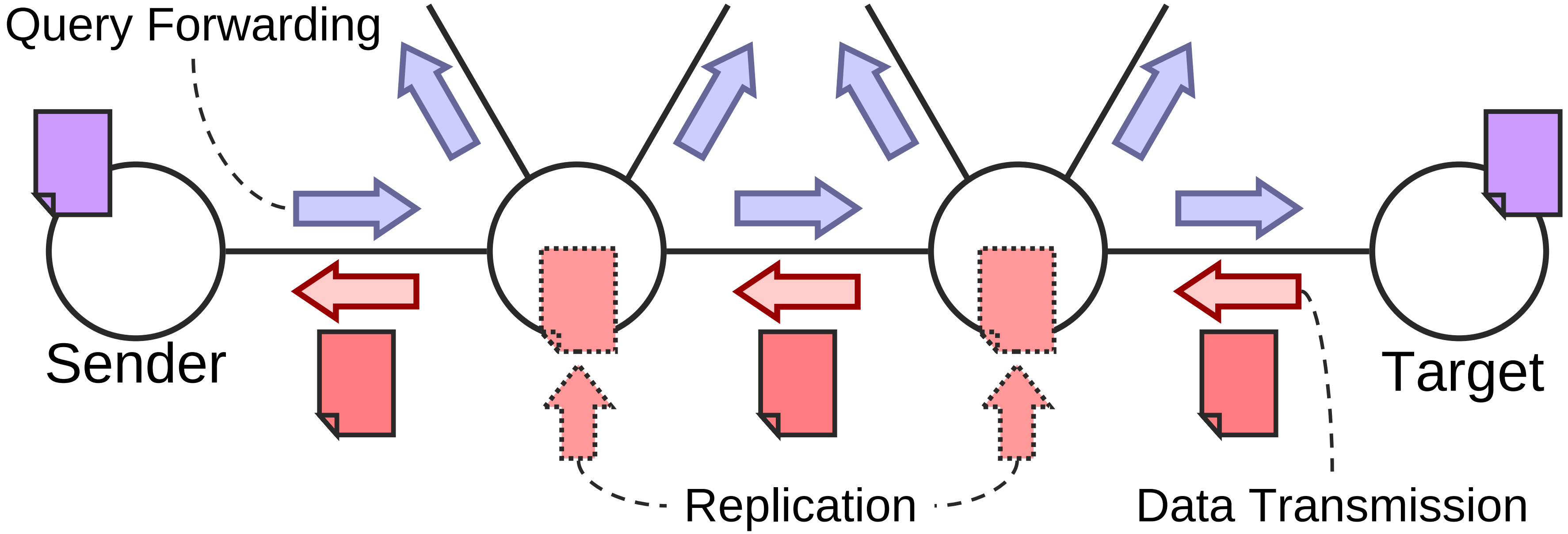
- Peer-to-Peer (P2P) file sharing network
  - Features
    - Each host (peer) acts as both server and client.
    - Each peer communicates directly with the other peers.
  - Classification
    - Structured P2P network
      - File locations are managed
      - File search is reliable
    - Unstructured P2P network
      - File locations are not managed
      - File search is not reliable

File replication

- Allocating replicas of original data on multiple peers -

Path Replication (PR)

- Allocate replicas to all peers on the search path



Path Replication (PR)

- Storage load would be biased to high degree node
  - Random walk-based query forwarding method
    - The probability with which a random walker (query) stays at a peer is proportional to its degree.
    - More files are replicated in high degree peers than in low degree peers.
- The P2P network might be unreliable and unstable.
- It is desirable for storage load balancing.

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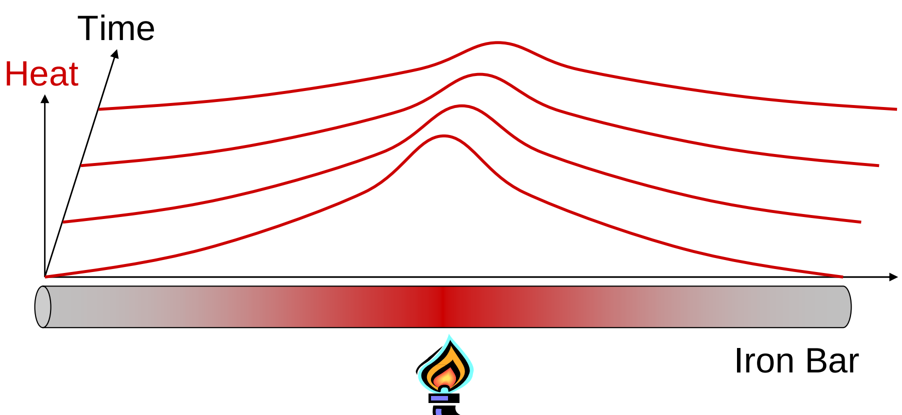
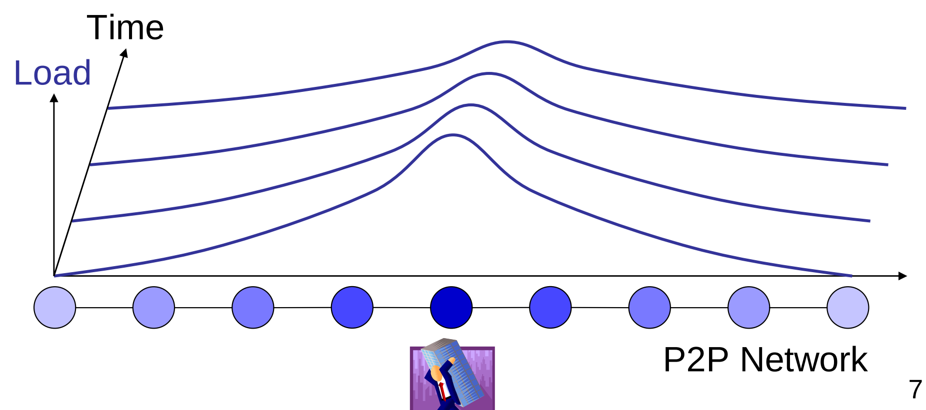
Analogy between Heat Diffusion and Storage Load Balancing

Process	Heat Diffusion	Storage Load Balancing
Field	Iron bar	P2P network
Component	Molecule of Iron	Peer
Substance	Heat	Storage load

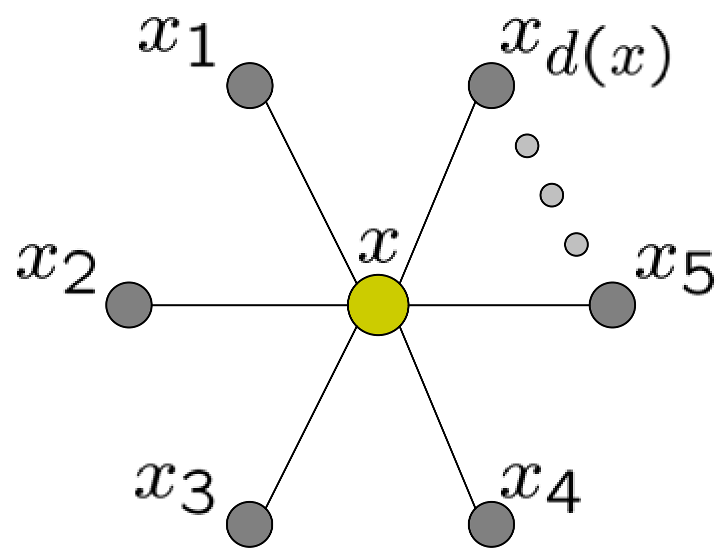
- Storage load balancing (Heat diffusion) is achieved by the cancellation of local imbalance of load in peers (molecules of Iron) in the P2P network (iron bar) via dynamic, autonomous, and distributed manner.





Measure for Local Imbalance of Storage Load

- $L(x,t)$: Storage utilization ratio of the peer x at time t ($0 \leq L(x,t) \leq 1$)
- $d(x)$: Nodal degree of peer x
- x_i : Peer adjacent to the peer x ($i = 1, \ldots, d(x)$)



$$\mathbf{D} \cdot L(x,t) = \frac{\sum_{i=1}^{d(x)} L(x_i,t)}{d(x)} - L(x,t)$$

$$(-1 \leq \mathbf{D} \cdot L(x,t) \leq 1)$$

Fundamental Strategy for Achieving Storage Load Balancing

- Create a replica in peer x on the search path with probability (replication ratio) $P(x,t)$.
- When the storage utilization ratio of peer x is lower/higher than its neighboring peers (i.e., the value of $\mathbf{D} \cdot L(x,t)$ is large/small), the replication ratio $P(x,t)$ becomes higher/lower.

$$\mathbf{D} \cdot L(x,t) = \frac{\sum_{i=1}^{d(x)} L(x_i,t)}{d(x)} - L(x,t)$$

$$(-1 \leq \mathbf{D} \cdot L(x,t) \leq 1)$$

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Another Aspect of Operator D

$$\mathbf{D} \cdot L(x,t)$$

$$= \frac{1}{d(x)} \sum_{i=1}^{d(x)} L(x_i,t) - L(x,t)$$

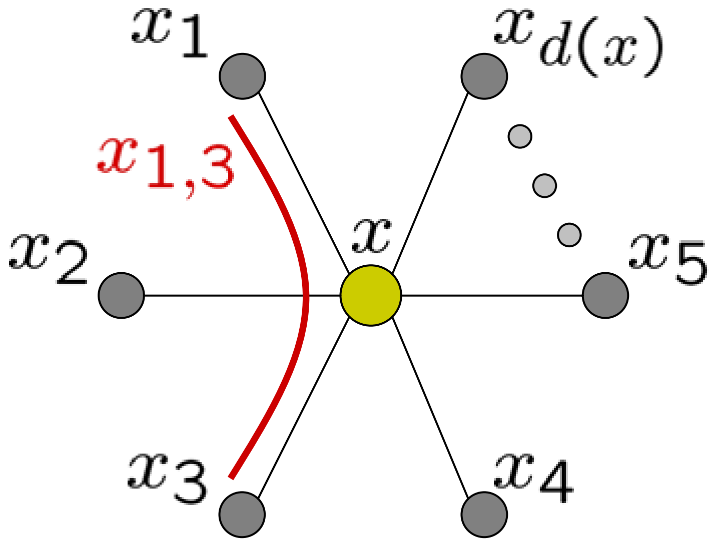
$$= \frac{1}{d(x)} \sum_{i=1}^{d(x)} (L(x_i,t) - L(x,t))$$

$$= \frac{1}{d(x)(d(x)-1)} \sum_{i<j} (L(x_i,t) + L(x_j,t) - 2L(x,t))$$

Another Aspect of Operator D

$$\mathrm{D}\cdot L(x,t) = \frac{1}{d(x)(d(x)-1)}\sum_{i<j}(L(x_i,t)+L(x_j,t)-2L(x,t))$$

- Regard a row of x_i , x, and x_j (x_i-x-x_j) with respect to all of the combination of i and j as an axis.
- Sum of second order derivatives on x_i-x-x_j ($x_{i,j}$).



Operator **D** can be regarded as (discrete version of) d(x)(d(x)-1)-th order Laplacian.

$$\sum_{i<j}\frac{\partial^2}{\partial x_{i,j}^2} = \left\{\frac{\partial^2}{\partial x_{1,2}^2}+\frac{\partial^2}{\partial x_{1,3}^2}+\ldots+\frac{\partial^2}{\partial x_{1,d(x)}^2}\right\} + \left\{\frac{\partial^2}{\partial x_{2,3}^2}+\frac{\partial^2}{\partial x_{2,4}^2}+\ldots+\frac{\partial^2}{\partial x_{2,d(x)}^2}\right\} + \ldots + \left\{\frac{\partial^2}{\partial x_{d(x)-1,d(x)}^2}\right\}$$

Another Aspect of Fundamental Strategy

- When the storage utilization ratio of peer x is averagely more convex/concave than its neighboring peers (i.e., the value of $\mathbf{D} \cdot L(x,t)$ is large/small), the replication ratio $P(x,t)$ becomes higher/lower.

$$\mathbf{D} \cdot L(x,t) = \frac{1}{d(x)(d(x)-1)} \sum_{i<j} (L(x_i,t) + L(x_j,t) - 2L(x,t))$$

Transition of Storage Utilization Ratio

- Storage utilization ratio at time $t + \Delta t$

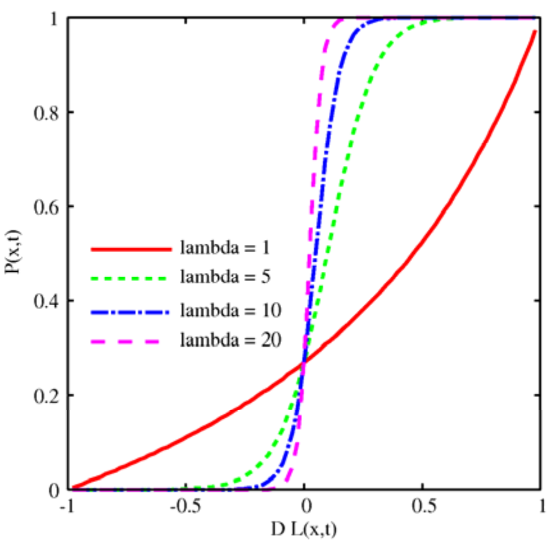
$$\mathbb{E}[L(x, t + \Delta t) | L(x, t), R(f), I(x, t), S(x)]$$
$$= L(x, t) + P(x, t) \frac{R(f) I(x, t) \Delta t}{S(x)}$$

  - R(f): Size of file f.
  - S(x): Storage capacity of peer x.
  - I(x,t): If a file request is received by peer x at time t, I(x,t) = 1, and 0 otherwise.
  - This equation holds for any P(x,t).
    - Dynamics of file replication can be controlled by the design of P(x,t).

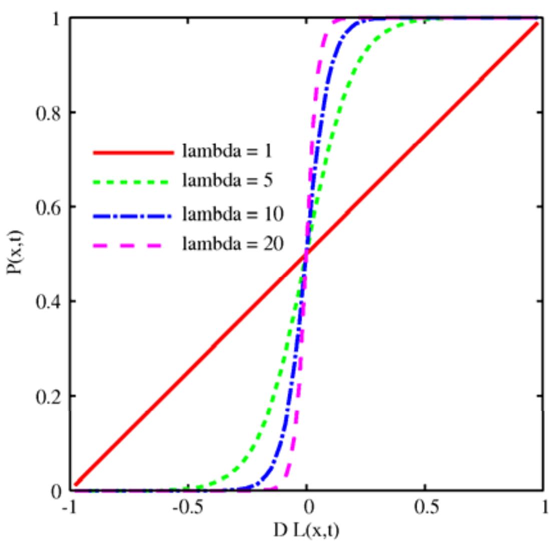
Design of P(x,t)

- Proposed Method

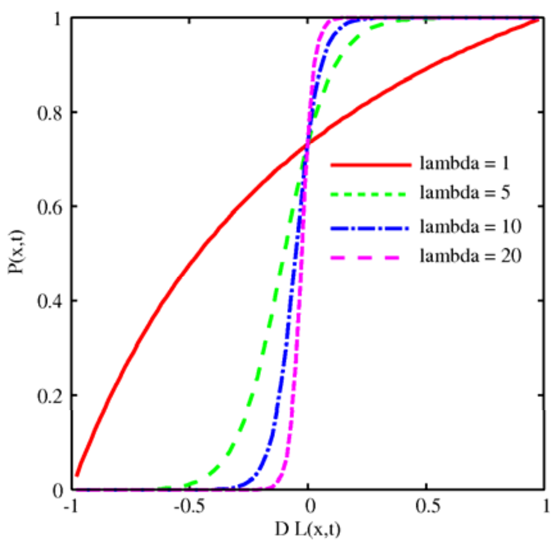
$$P(x,t) = \frac{1}{2} + \frac{1}{2}\tanh(\mu + \lambda \tanh^{-1}(\mathbf{D} \cdot L(x,t)))$$



$\mu = -0.5$



$\mu = 0$



$\mu = 0.5$

Analytical Analogy with Thermal Diffusion Equation

- Proposed Method

Proportional to second order derivative (Laplacian)

Heat source

$$\frac{\mathbb{E}[L(x,t+\Delta t)|L(x,t),R(f),I(x,t)]-L(x,t)}{\Delta t} \approx \frac{R(f)I(x,t)(1+\mu)}{2S(x)} + \frac{\lambda R(f)I(x,t)}{2S(x)}\mathbf{D}\cdot L(x,t)$$

Search performance

Storage load balancing performance

- Thermal diffusion equation (without heat source)

$$\frac{\partial T(x,t)}{\partial t} = K\frac{\partial^2}{\partial x^2}T(x,t) = K\nabla^2 T(x,t)$$

  - T(x,t): Temparature of x at time t.

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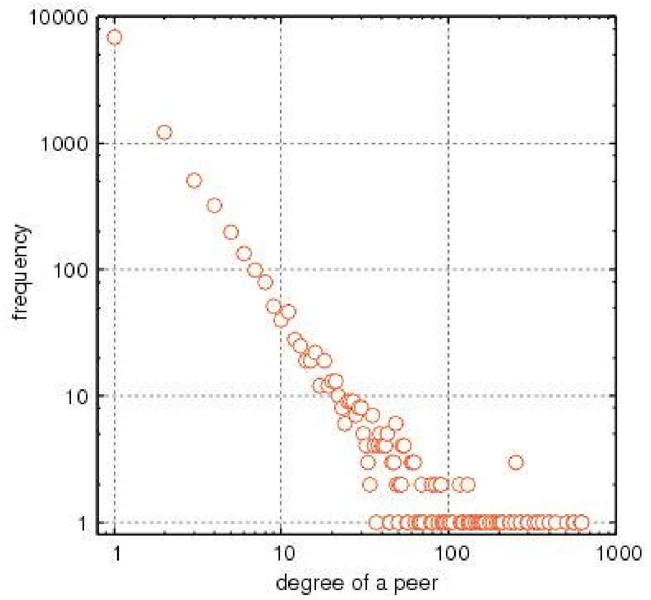
Simulation Model

- Degree distribution: Power-law
  - Total number of peers: 10,000
  - Total number of links: 20,000
- Storage capacity (S(x)): 40
- File size (R(f)): 1
- Total number of file types: 100
- Total number of file search: 50,000
- Selection of requested file: Random
- Selection of file requesting peer: Random
- Query forwarding: 16-walker random walk
  - Each walker with a query randomly walks around peers.



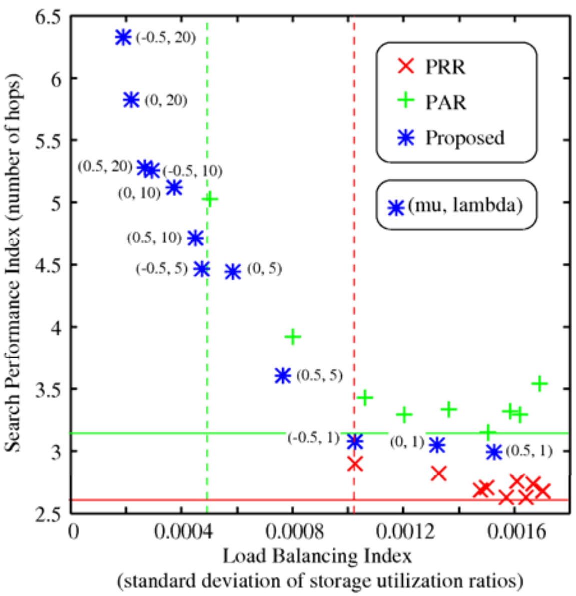
Evaluation Criteria

- Storage load balancing performance
  - The standard deviation of the average storage utilization ratio of peers with same degree at the moment at which the average storage utilization ratio of every peers exceeds 0.025, 0.05, and 0.1.
    - Smaller value means better load balancing performance.
- Search performance
  - The number of hops needed to find requested files at the moment at which the average storage utilization ratio of every peers exceeds 0.025, 0.05, and 0.1.
    - Smaller value means better search performance.

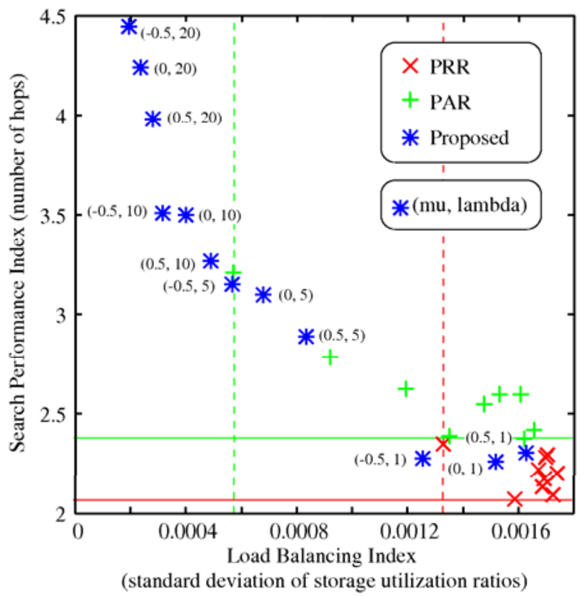
Comparative File Replication Methods

- Path Random Replication (PRR)
  - Allocate a replica to a peer on the search path with constant probability (replication ratio) which is not dependent on the storage utilization ratio of the peer.
- Path Adaptive Replication (PAR)
  - Allocate a replica to a peer on the search path with variable probability (replication ratio) which is dependent only on the storage utilization ratio of the peer.

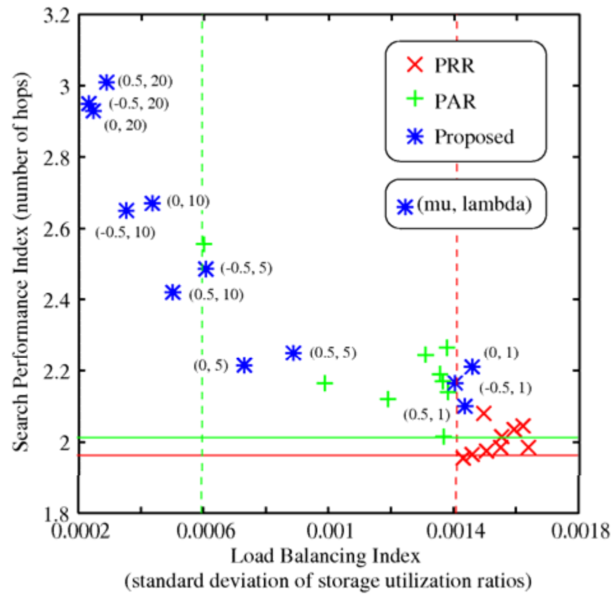
Results: Roles of Parameters



Average storage utilization ratio: 0.025



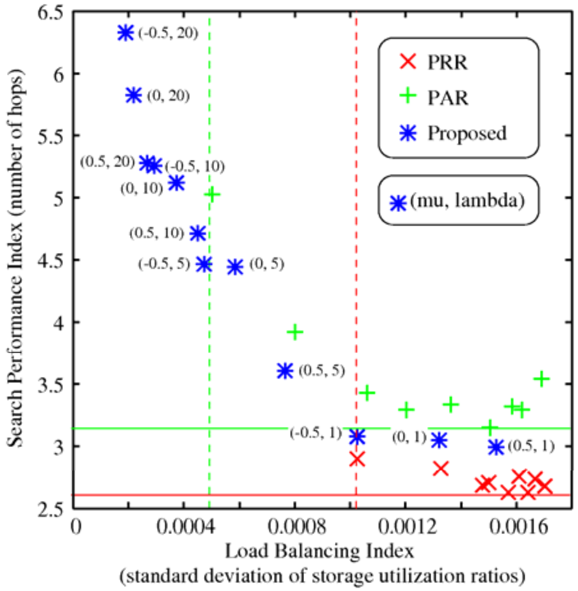
Average storage utilization ratio: 0.05



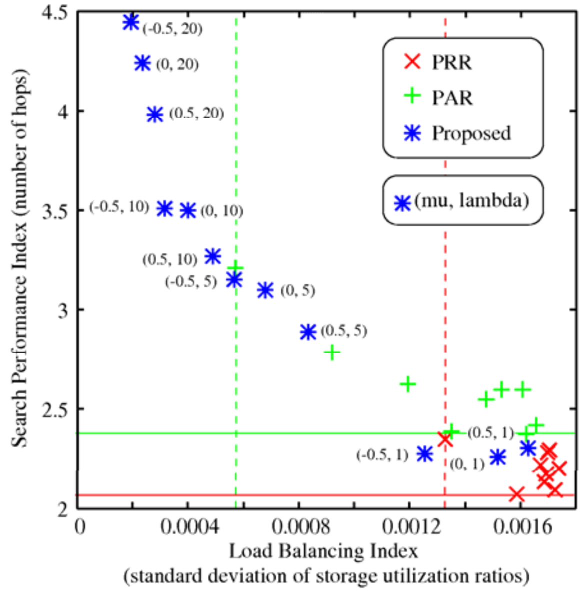
Average storage utilization ratio: 0.1

- With the value of μ fixed, the bigger the value of λ, the better the storage load balancing performance.
- With the value of λ fixed, the bigger the value of μ, the better the search performance.

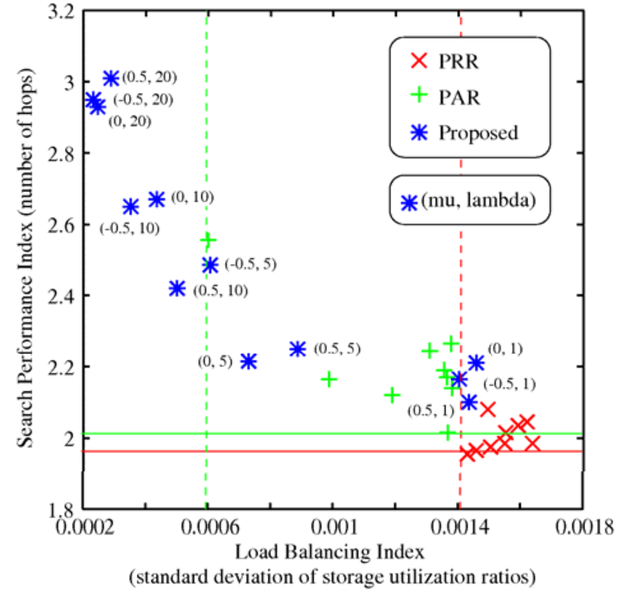
Results: Abilities of Proposed Method



Average storage utilization ratio: 0.025



Average storage utilization ratio: 0.05



Average storage utilization ratio: 0.1

- Better storage load balancing ability that PRR and PAR cannot give with any values of their parameters.
- Better trade-off points exploring ability that PRR and PAR cannot give with any values of their parameters.

Summary

- Proposal:
  - A file replication method with analogy to thermal diffusion for storage load balancing in unstructured P2P file sharing networks.
- Theoretical Analysis:
  - Statistical analogy with a thermal diffusion equation.
- Simulation Results:
  - Better ability not only in balancing storage load among peers but also widely exploring the performance trade-off.