Optimal Crawling Strategies for Web Search Engines

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joint work with

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Introduction

- Web search engines employ multiple crawlers
  - To maintain local copies of web pages
  - To build data structures such as inverted indexes
- But web pages are updated frequently
  - 23% of web pages change daily
  - 40% of commercial web pages change daily
  - Half-life for a web page is 10 days
- So crawlers must revisit web pages frequently to maintain *freshness*
  - Question: How should one do this optimally?

Two part Scheme

- Component 1: Solve the “Crawling frequency” problem
  - Find optimal number of times to crawl each page
  - Find optimal times to crawl each page
- Component 2: Solve the “Crawler Scheduling” problem
  - Create optimal achievable crawler schedule based on idealized crawler times

Contributions

- Crawling frequency problem
  - More appropriate optimization metric
    - Based on level of *embarrassment*, not just on staleness
  - Unified framework (Stationary Marked Point Processes) to handle wide variety of web page update distribution types
    - Poisson, Pareto, Weibull
    - Quasi-deterministic
  - State-of-art algorithms for finding optimal number of crawls
    - General and practical: Real-life constraints
    - Extraordinary computationally efficient: Problems are *huge*
  - Algorithms for finding ideal crawl times

Contributions

- Scheduling problem
  - Exact transportation problem solution
  - Real-life constraints

- Analysis of update patterns from several IBM-hosted web sites
  - Grand Slam Tennis
    - Australian, French, US Opens; Wimbledon
  - Golf
    - Master’s, Ryder’s Cup
  - Olympic Games
    - Nagano, 1998; Sydney 2000
  - Awards
    - Tonys, Grammys

- Summary: Interupdate time distributions span wide range of behaviors

Related Work

- Cho & Garcia-Molina (2000)
  - Compare “uniform” and “proportional” allocation rules
  - Solved crawling frequency problem for Poisson updates

- Coffman, Liu, & Weber (2000) consider Poisson updates, and also include *access* times.
  - crawls to a page should be as “evenly spaced” as possible (to maximize average freshness)

- Talim, Liu, Nain, & Coffman (1999): optimize *number* of crawlers. (Indexing capacity v/s starvation of the indexing engine.)

Key Notation

Variable	Description
N	Number of web pages to be crawled
T	Web crawler scheduling interval length
R	Number of crawls allowed in interval $[0, T]$
C	Number of crawlers
S_k	Number of crawls by crawler k in time T

Table 1: Notation summary

Crawling Frequency Problem: Preliminaries

- Suppose we crawl web page i x_i times during scheduling interval T...
  - ...at times $0 \leq t_{i,1} < t_{i,2} < \ldots < t_{i,x_i} \leq T$
  - ...with $x_i \leq R$.
- Compute probability $p_i(t_{i,1}, \ldots, t_{i,x_i}, t)$ that search engine will have stale copy of web page i at time $t \in [0, T]$:
- Compute *time-average* staleness probability measure

$$a_i(t_{i,1}, \ldots, t_{i,x_i}) = \frac{1}{T} \int_0^T p_i(t_{i,1}, \ldots, t_{i,x_i}, t) dt. \tag{1}$$

- Set *staleness*

$$\mathcal{A}_i(x_i) = a_i(t^*_{i,1}, \ldots, t^*_{i,x_i}). \quad (2)$$

- Set
  - w_i to be *embarassment* weights
  - m_i to be minimum number of acceptable crawls for web page i
  - M_i to be Maximum number of acceptable crawls for web page i

Crawling Frequency Problem:

Minimize

$$\sum_{i=1}^{N} w_i \mathcal{A}_i(x_i) \qquad (3)$$

subject to the constraints

$$\sum_{i=1}^{N} x_i = R$$
$$x_i \in \{m_i, \ldots, M_i\}.$$

- Solution to *discrete, separable resource allocation problem (RAP)*:
  - $O(NR^2)$
- But $\mathcal{A}_i$ is *convex*
  - So much faster algorithms exist

Crawling Frequency Problem: Loose Ends

- Computing the weights w_i of the *embarassment level* metric for each web page i

- Computing the functional forms of p_i, a_i and $\mathcal{A}_i$ for each web page i, based on the update pattern distribution

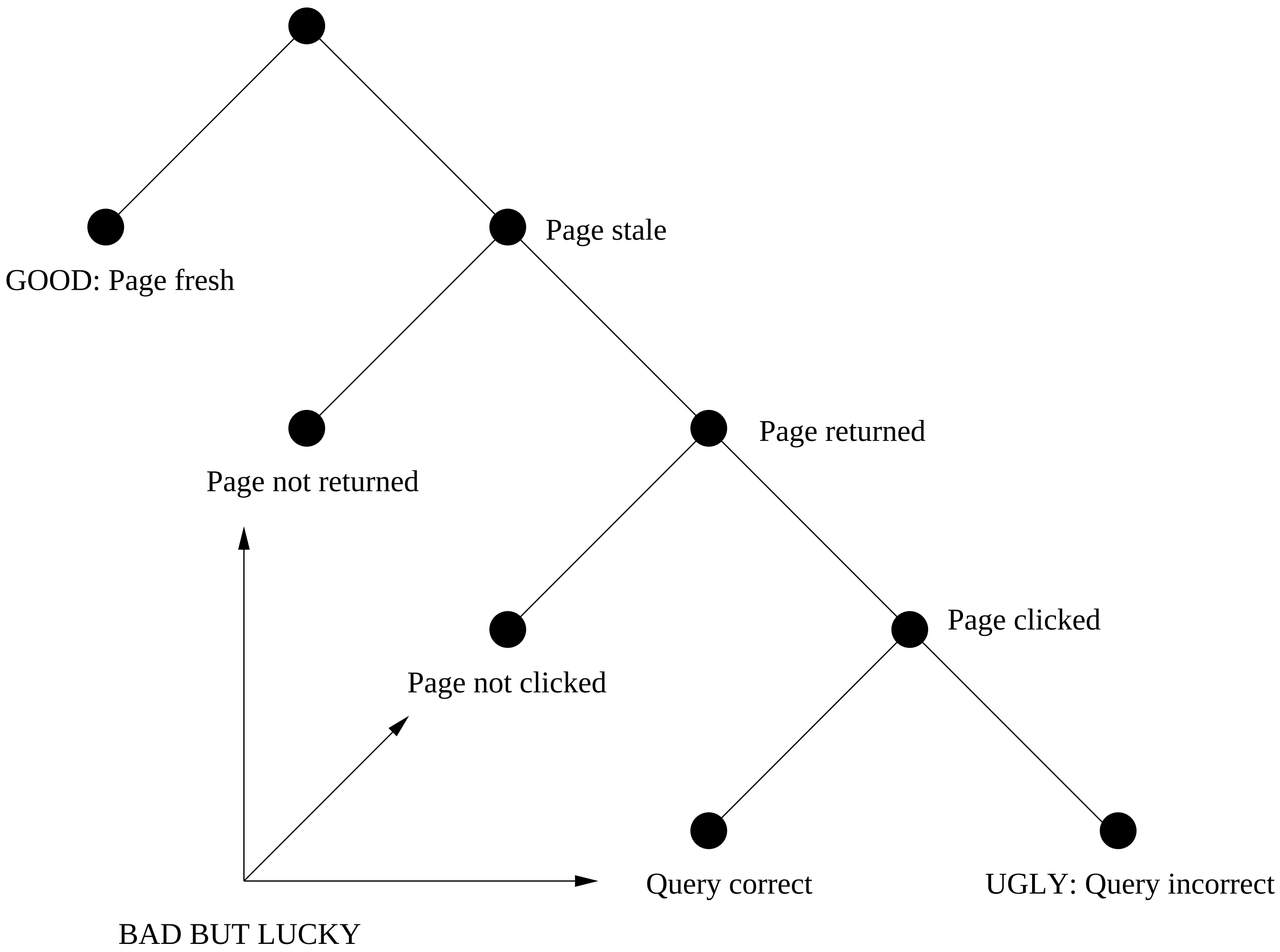
- Solving the resulting discrete, convex, separable resource allocation problem

Embarrassment Metric

- *Good*: Search engine has fresh copy of web page

- *Bad*: Stale...
  - ...but *lucky*
    - ∗ ♣ Web page not returned to client as result of query
    - ∗ ♣♣ Returned to client, but not clicked on by client
    - ∗ ♣♣♣ Returned to client, clicked on but correct with respect to query
  - ...and *unlucky*
    - ∗ Returned to client, clicked on...
      - · ♢♠♡ ...and incorrect with respect to query
      - · ♢♠♡ ...or gone
      - · Up to 14% of search engine links are typically broken

Computing the Weights w_i



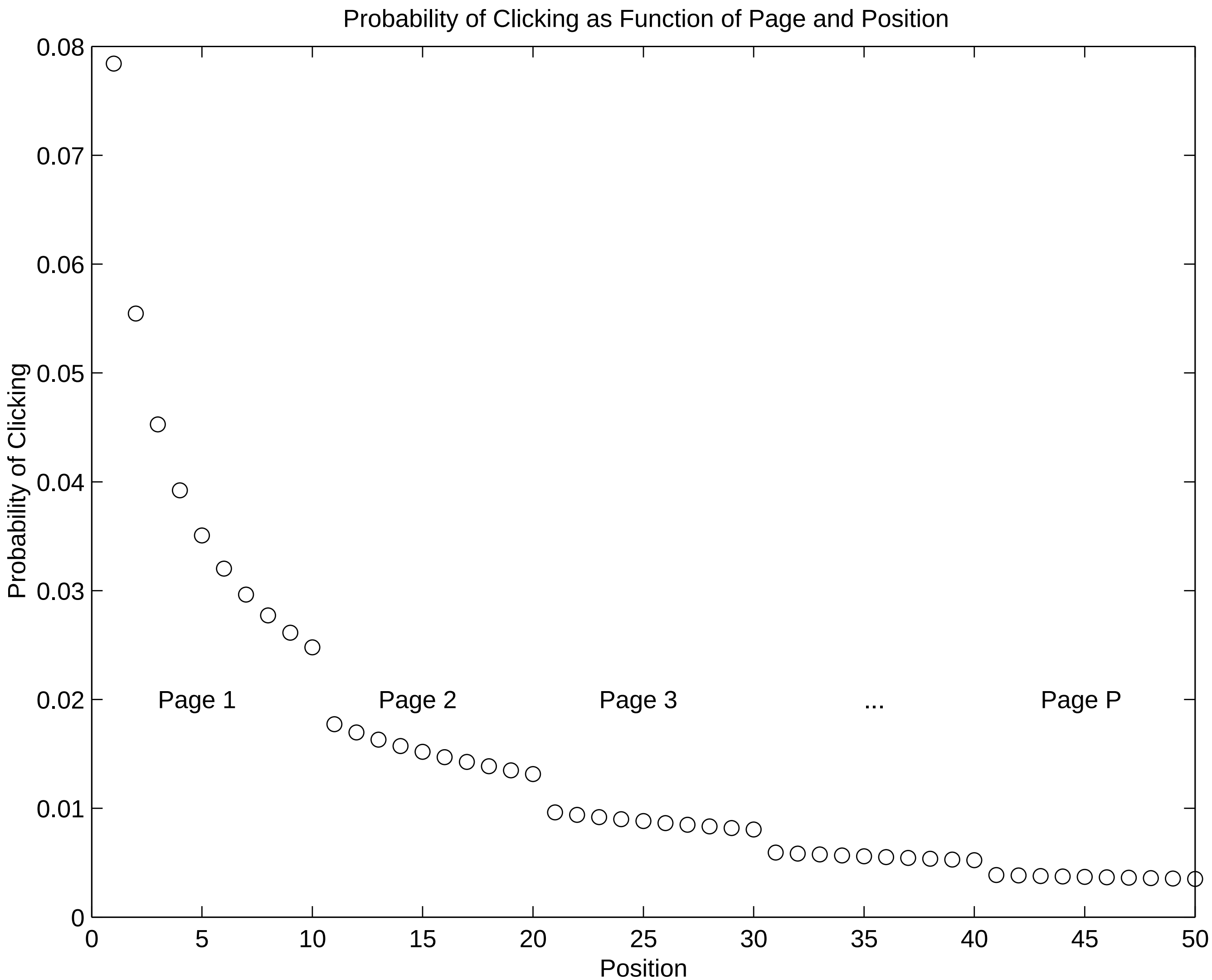
- Let $b_{i,j,k}$ denote the probability that the search engine will return page i in position j of query result page k

- Let $c_{j,k}$ denote the frequency that a client will click on a returned page in position j of query result page k

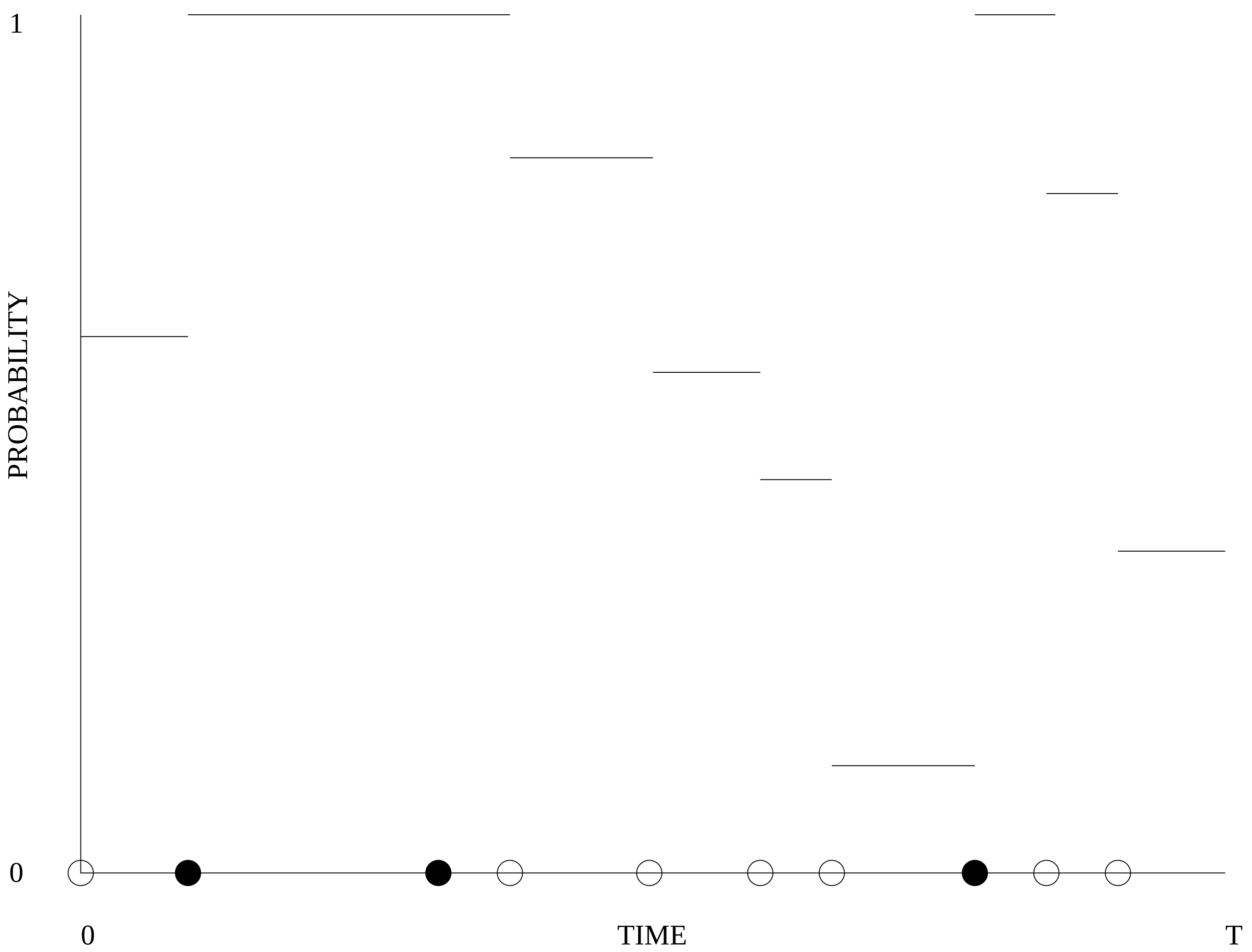
- Let d_i denote the probability that a query to a stale version of page i yields an incorrect response

- Then $w_i = d_i \sum_j \sum_k c_{j,k} b_{i,j,k}$

Probability of Clicking As Function of Position/Page



Probability Function for Quasi-Deterministic Web Pages



Computing the Functions $\bar{p}_i$, $\bar{a}_i$ and $\mathcal{A}_i$: Quasi-Deterministic Case

- P_i possible update times, $0 \leq s_{i,1} < s_{i,2} < \ldots < s_{i,P_i} \leq T$
- Update $s_{i,j}$ occurs with probability $q_{i,j}$
- $u_{i,j} \; = \; s_{i,j+1} - s_{i,j}$
- Can assume $x_i \leq P_i + 1$
- Define binary decision variables

$$y_{i,j} = \begin{cases} 1 & \text{if a crawl occurs at time } s_{i,j} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

- Define

$$J_{1,t} = max\{j|0 \leq j \leq x_i,\ s_{i,j} \leq t\}, \quad (5)$$

which is index of latest potential update time before t; and

$$J_{2,t} = max(0, \{j|0 \leq j \leq x_i,\ y_{i,j} = 1,\ s_{i,j} \leq t\}), \quad (6)$$

which is index of latest potential update time before t that will be crawled

- Then, the *freshness* probability function is:

$$\bar{p}(y_{i,0}, \ldots, y_{i,P_i}, t) = \prod_{j=J_{2,t}+1}^{J_{1,t}} (1 - q_{i,j}) \quad (7)$$

- The *average staleness* is

$$\bar{a}(y_{i,0}, \ldots, y_{i,P_i}) = \sum_{j=0}^{P} u_{i,j}(1 - \prod_{k=J_{i,j}+1}^{j} (1 - q_{i,j})) \tag{8}$$

To compute $\mathcal{A}_i$, minimize

$$\bar{a}(y_{i,0}, \ldots, y_{i,P_i}) \tag{9}$$

Subject to the constraints

$$y_{i,j} \in \{0, 1\} \tag{10}$$

And

$$\sum_{j=0}^{P} y_{i,j} = x_i \tag{11}$$

Quasi-Deterministic Case

- A simple dynamic program solves the problem optimally.

- *Greedy* algorithm does *exceptionally* well; is at least within e/(e-1) of optimal, possibly better. (Series of papers by Fisher, Nemhauser, Wolsey, Cornuejols and Conforti on maximizing submodular functions)

  – Greedy's $\mathcal{A}_i$ is also convex!

Computing the Functions p_i, a_i and $\mathcal{A}_i$: Poisson Case

- Probability of update occurring within t units of time: $1 - e^{-\lambda_i t}$
- Suppose we crawl x_i times at times $t_{i,1}, \ldots t_{i,x_i}$
- Define $\hat{t} = max\{t_{i,j} | 0 \leq j \leq x_i,\ t_{i,j} \leq t\}$
- Then $p_i(t_{i,1}, \ldots, t_{i,x_i}, t) = 1 - e^{-\lambda_i (t - \hat{t})}$
- And $a_i(t_{i,1}, \ldots, t_{i,x_i}) = 1 + \frac{1}{\lambda_i T} \sum_{j=0}^{x_i} \left(e^{-\lambda_i (t_{j+1} - t_j)} - 1\right)$
- So let $u_{i,j} = t_{i,j+1} - t_{i,j}$

Poisson Case

To find $\mathcal{A}_i$ minimize

$$1 + \frac{1}{\lambda_i T} \sum_{j=0}^{x_i} (e^{-\lambda_i u_{i,j}} - 1) \tag{12}$$

subject to the constraints

$$0 \leq u_{i,j} \leq T, \tag{13}$$

and

$$\sum_{j=0}^{x_i} u_{i,j} = T. \tag{14}$$

- A continuous, convex, separable resource allocation problem: solution is trivial.

- So $u^*_{i,j} = T/(x_i + 1)$

A Unified Framework

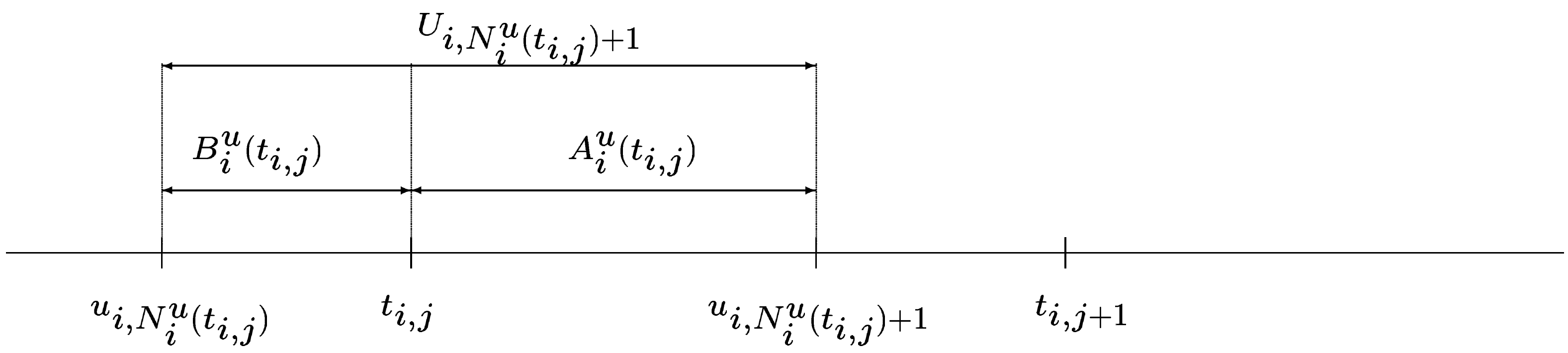


Figure 1: Example of a Marked Point Process

A Unified Framework

- From standard renewal-theoretic arguments, the time-average staleness can be computed as:

$$a_i(t_{i,1},\ldots,t_{i,x_i}) \quad = \quad \frac{1}{T}\sum_{j=0}^{x_i}\int_{t_{i,j}}^{t_{i,j+1}}\left(1 \,-\, \lambda_i\int_0^{\infty}\overline{G}_i(t-t_{i,j}+v)\,dv\right)dt.$$

Here $\overline{G}_i(\cdot)$ is the complementary c.d.f. of the inter-update time distribution.

NOTE: Summands are *separable*, *identical*! So optimal crawl times are evenly spaced.

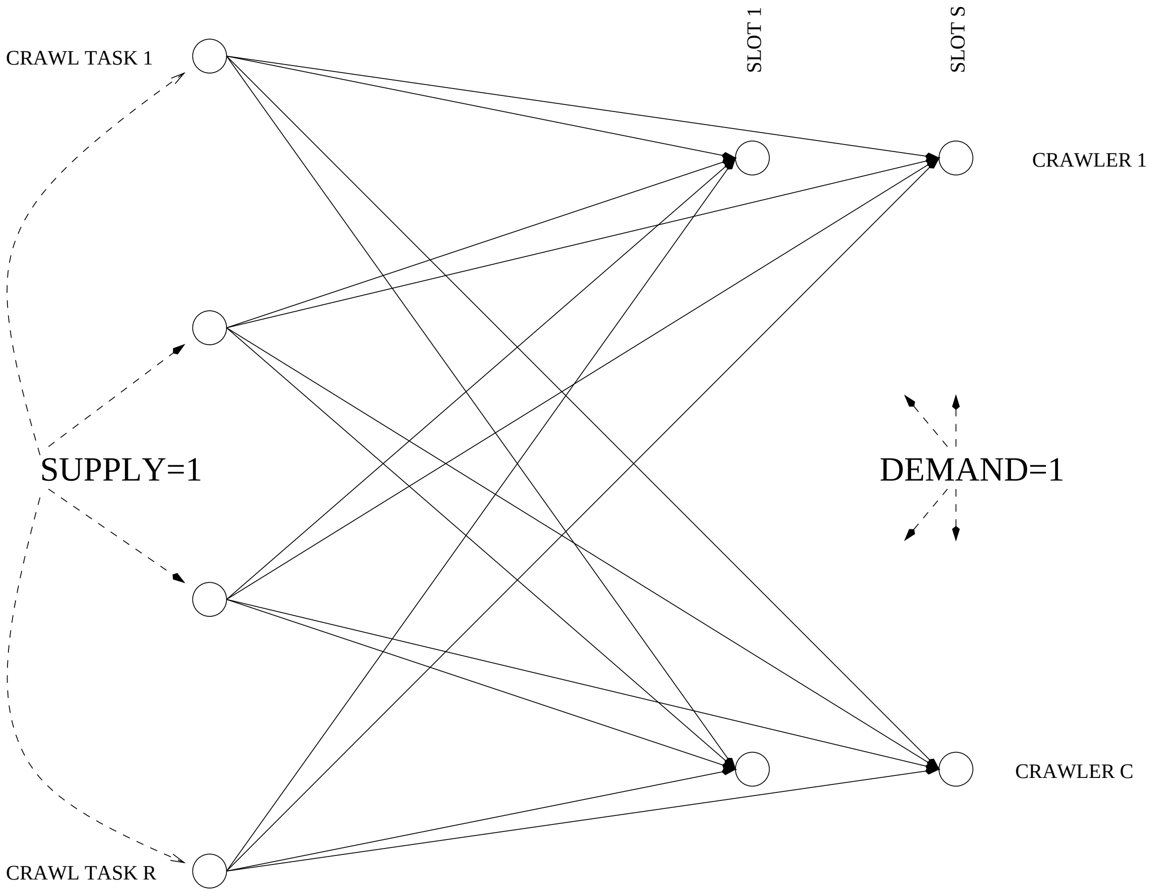
Solving the Discrete, Separable, Convex RAP

- Fox greedy algorithm
  - $O(N + R \log N)$
- Galil and Megiddo algorithm
  - $O(N(\log R)^2)$
- Frederickson and Johnson algorithm
  - $O(\max\{N, N \log(R/N)\})$
- Continuous relaxation / bracket and bisection algorithm also possible

Crawler Scheduling Problem

- C crawlers
  - Crawler k can handle S_k crawls in time T
- Time slots $T_{k,l}$
- Cost functions
  - For stochastic web pages $S(t) = |t - t^*_{i,j}|$
  - For quasi-deterministic web pages $S(t) = \begin{cases} \infty & \text{if } t < t^*_{i,j} \\ t - t_{i,j} & \text{otherwise} \end{cases}$
- Solvable as *transportation* problem

Transportation Problem Network



Transportation Problem Formulation

$$\text{Minimize } \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{M} R_i(T_{jk}) f_{ijk} \qquad (15)$$

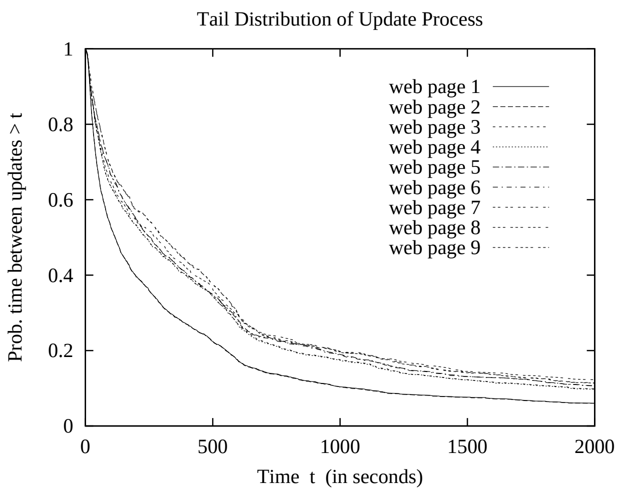
such that

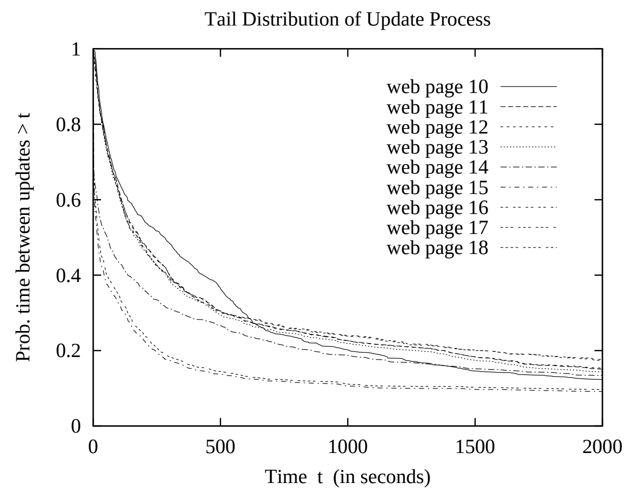
$$\sum_{i=1}^{M} f_{ijk} = 1 \; \forall \; 1 \leq j \leq N \text{ and } 1 \leq k \leq M \qquad (16)$$

and

$$\sum_{j=1}^{N}\sum_{k=1}^{M} f_{ijk} = 1 \; \forall \; 1 \leq i \leq M \qquad (17)$$

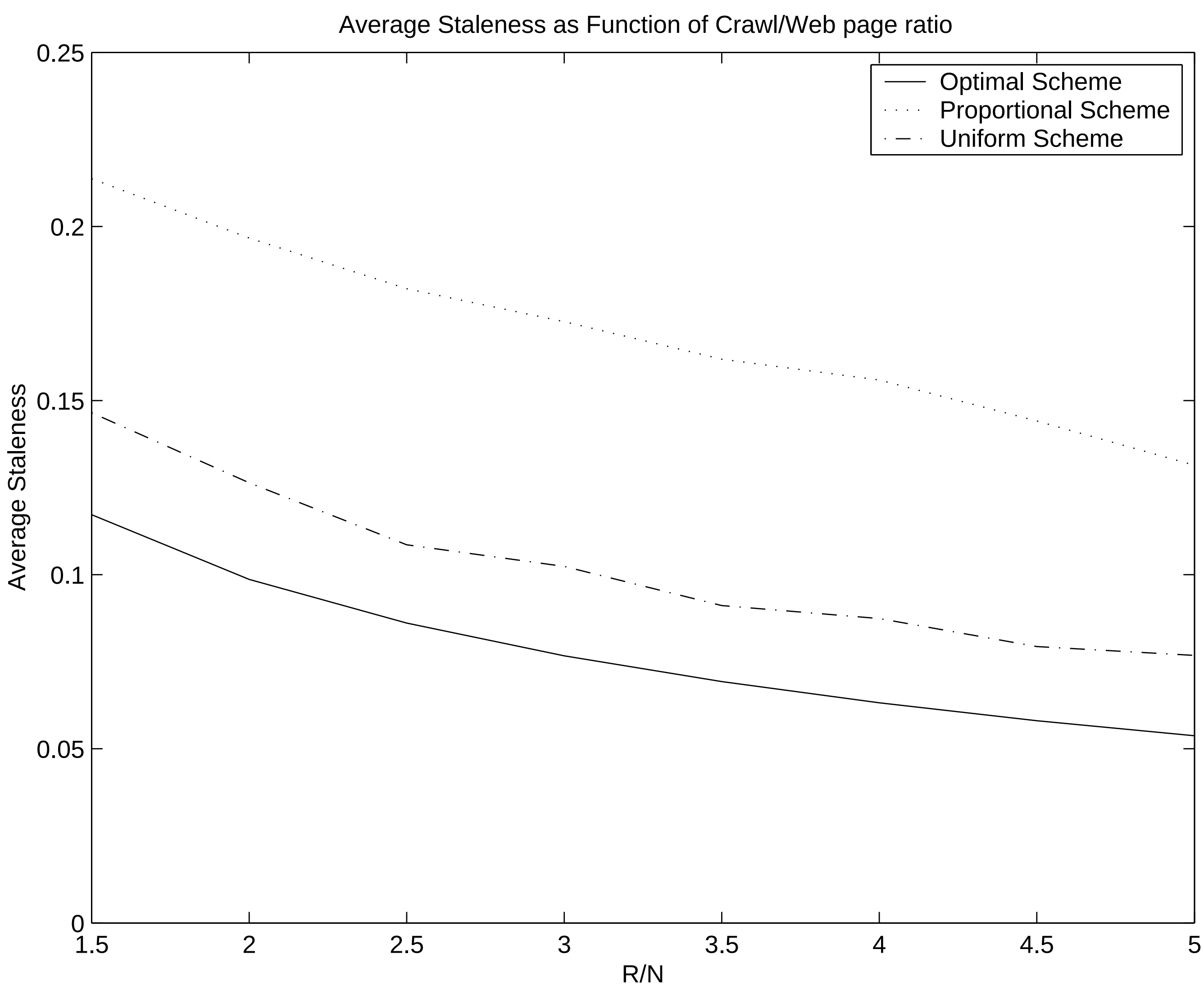
Tail Distributions of Update Processes



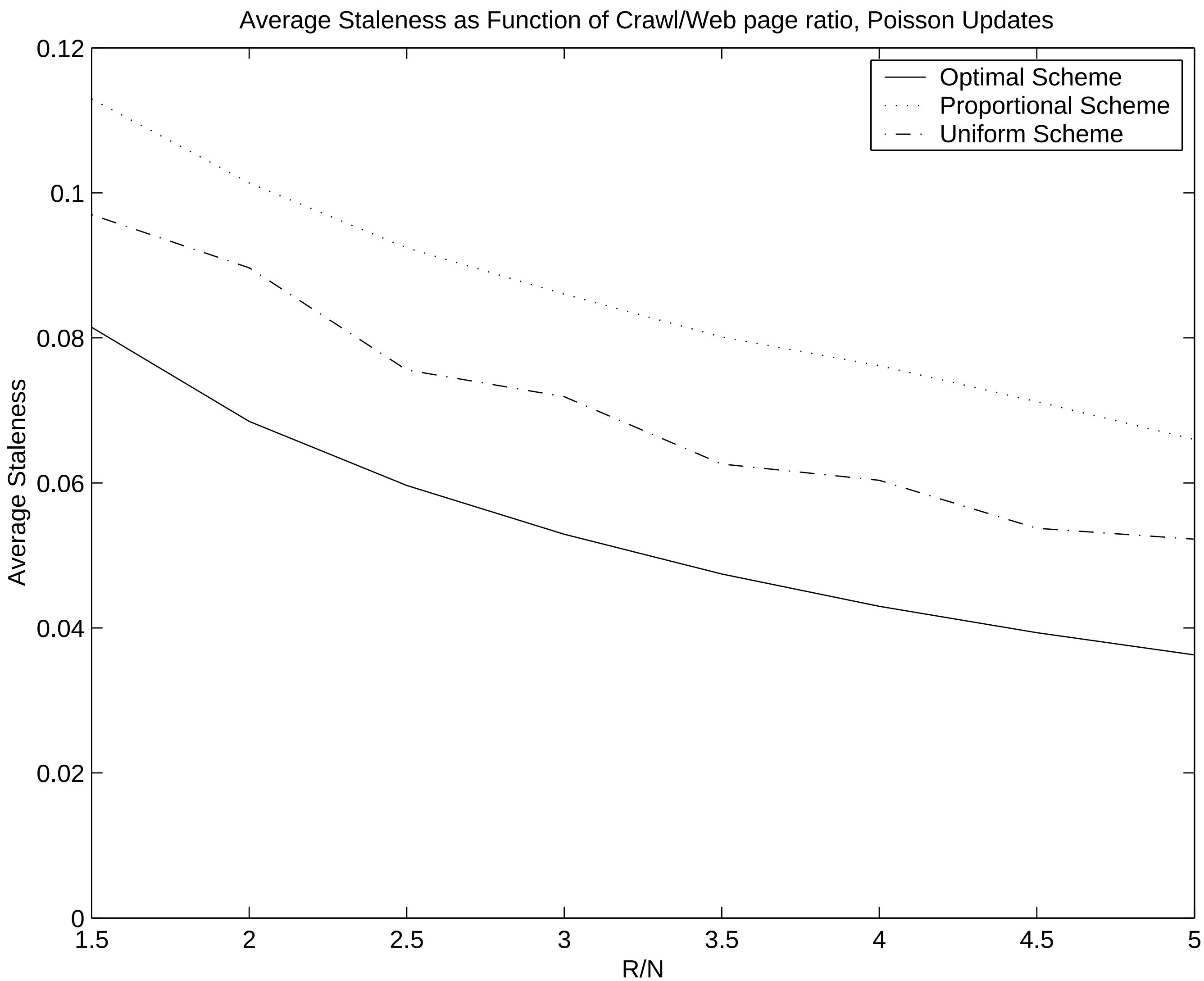


- Real web logs
- Can vary across many distribution types
  - Not typically Poisson
  - Often Weibull
  - Sometimes Pareto
  - Quasi-deterministic examples also exist

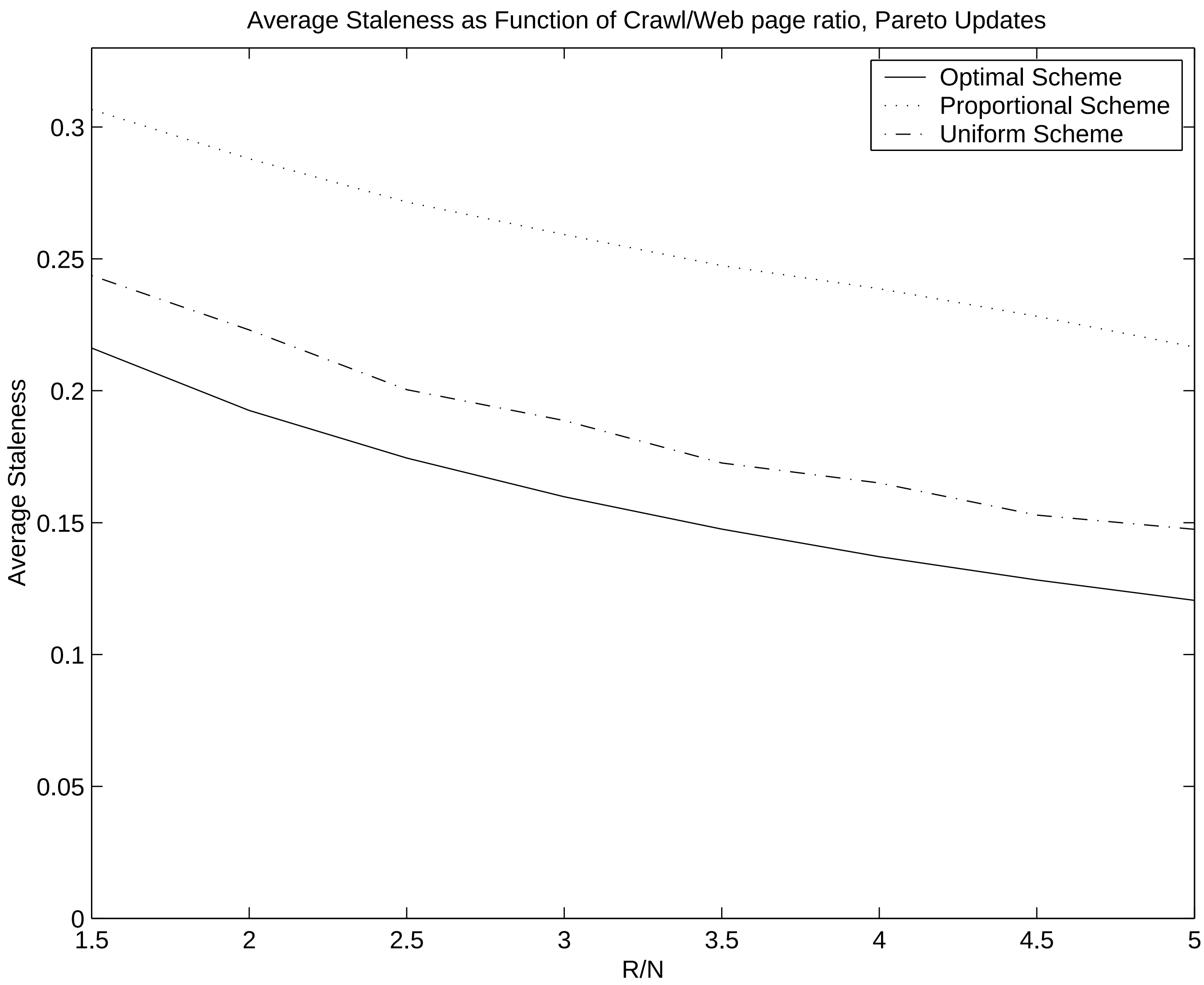
Average Staleness Metric Examples: Mixed



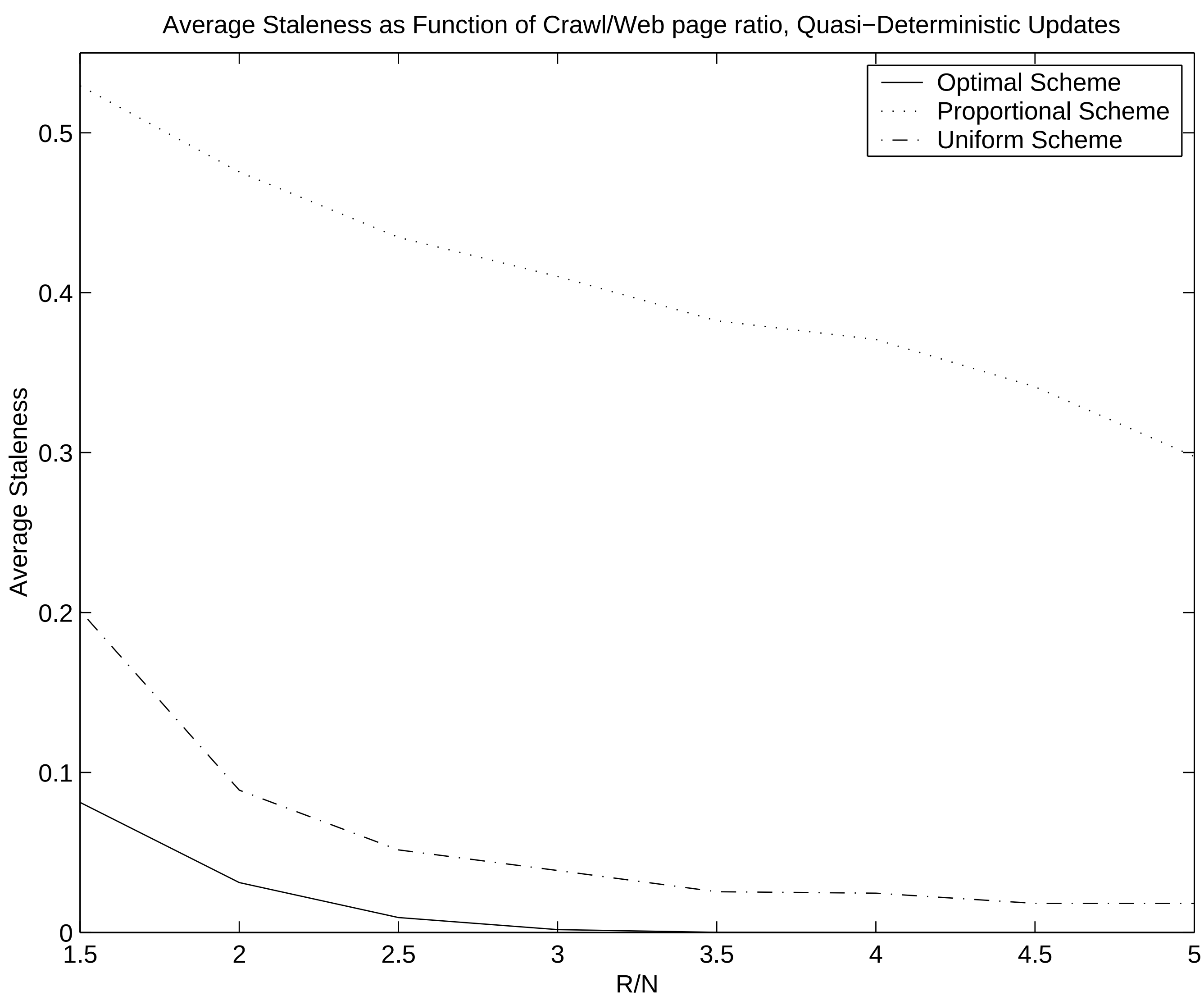
Average Staleness Metric Examples: Poisson



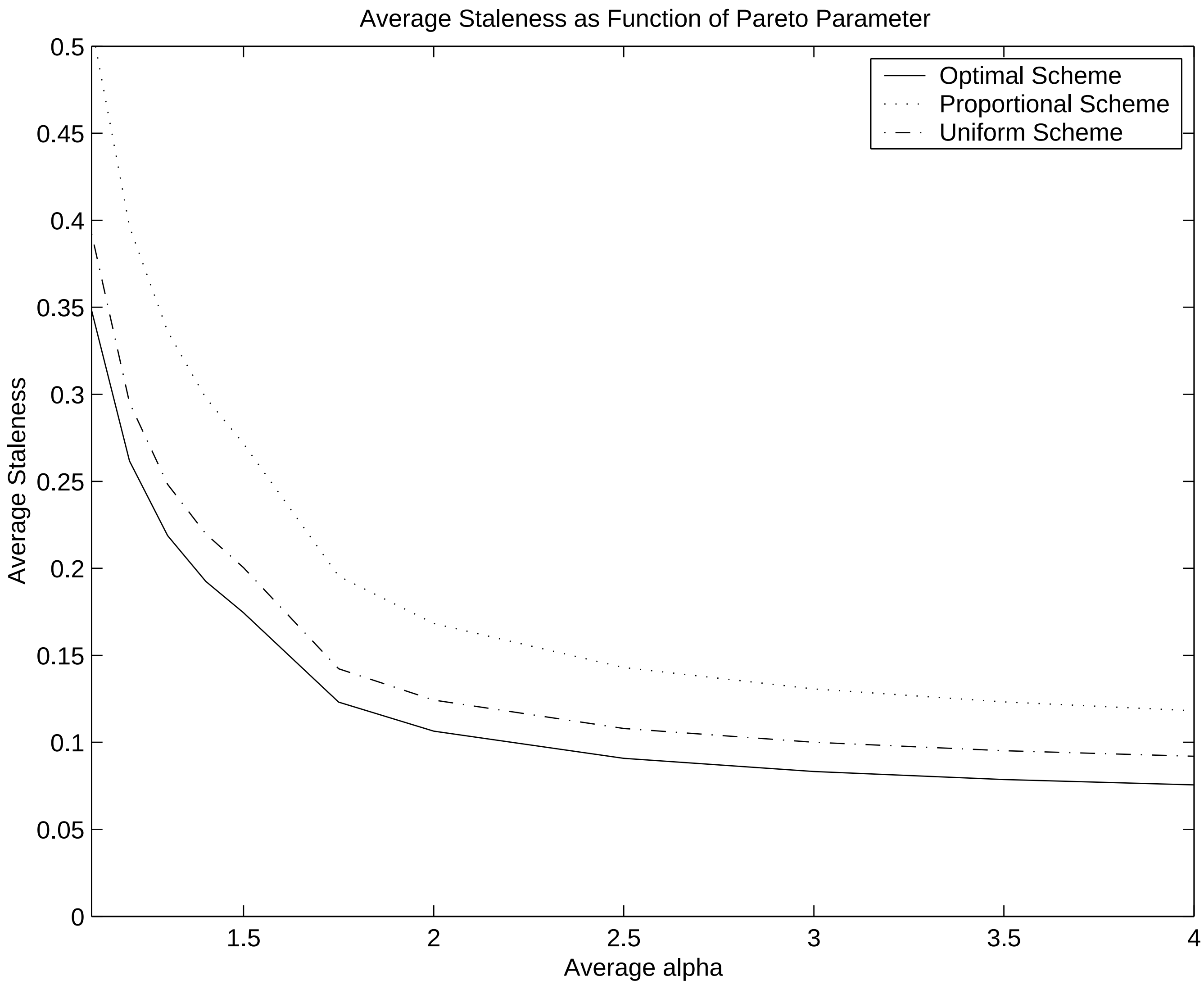
Average Staleness Metric Examples: Pareto



Average Staleness Metric Examples: Quasi-Deterministic



Pareto Example



Scheduling Problem Example

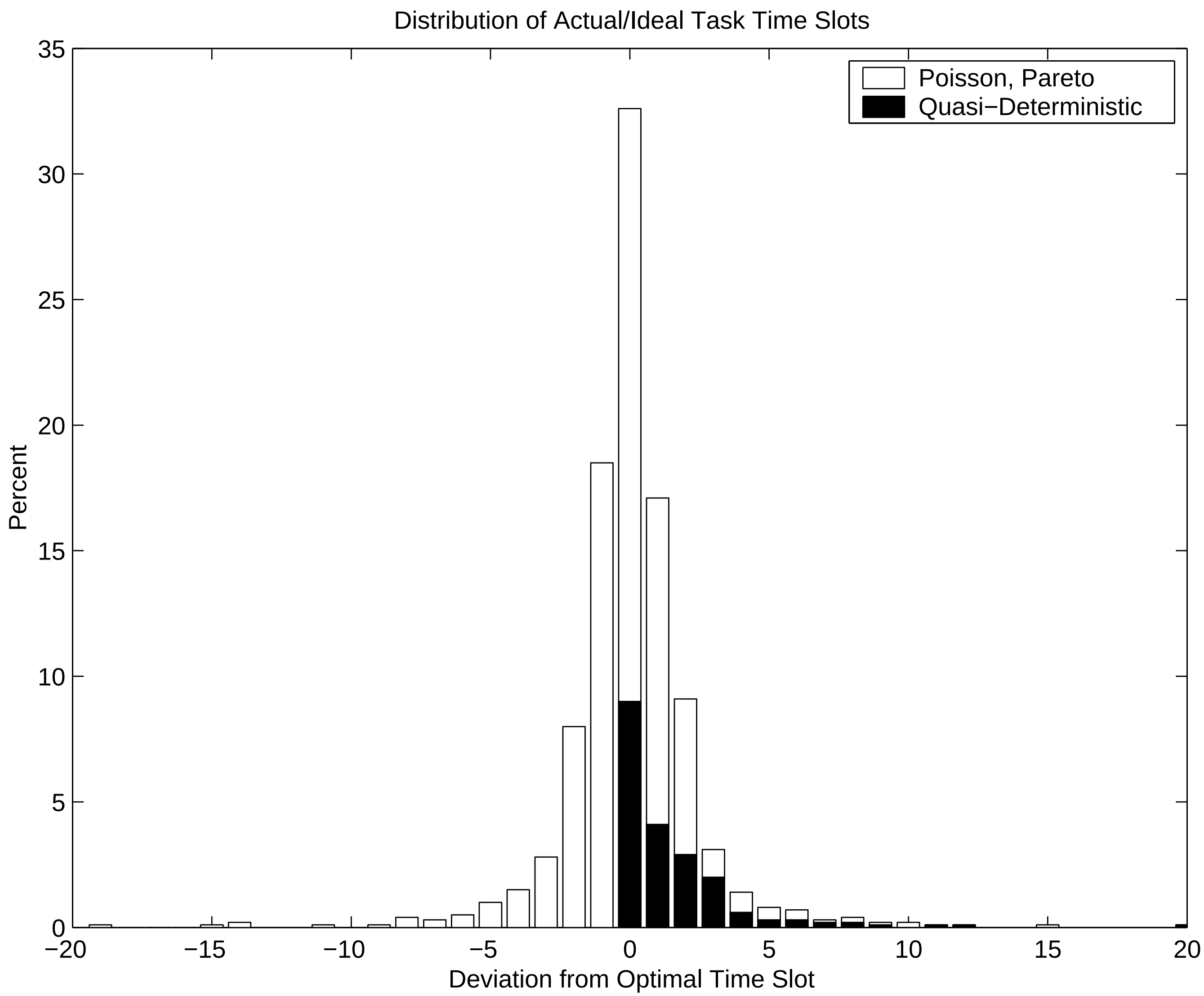


Figure 2: Transportation Problem Solution

Conclusions

- New formulation and solution for important search engine crawler optimization problem
  - Crawling frequency problem
    - Embarassment metric
    - General update distributions
    - Extraordinarily fast RAP solution
  - Crawler scheduling problem
    - Transportation problem formulation
- Study of real web log data
  - Shows many distribution patterns