A Simulation Study of the Stochastic Compensation Effect for Packet Reordering in Multipath Data Streaming

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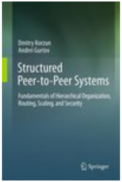
Multipath Data Streaming

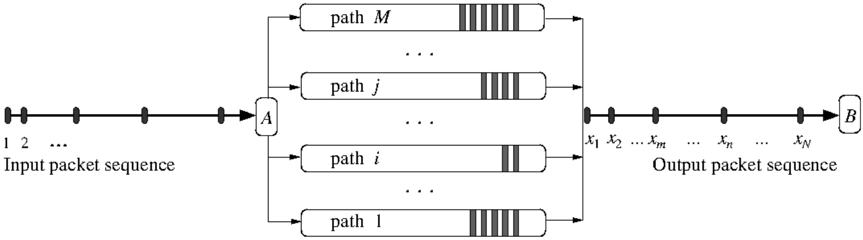
- A source schedules packets $1, 2, \ldots, N$ to split the stream among the different paths $1, 2, \ldots, M$, proportionally to their rates
- The rates are estimated based on such observable path characteristics as delay or bottleneck bandwidth
- Application domains:
  - Data transfer in the Internet: multi-homed hosts and TCP sessions
  - Wireless communication: multipath traffic in overlay networks
  - Load balancing: splitting a single flow across multiple network paths
  - Peer-to-Peer systems: many neighbors to forward a packet
- D. Korzun and A. Gurtov.
  Structured Peer-to-Peer Systems:
  Fundamentals of Hierarchical Organization,
  Routing, Scaling, and Security.
  Springer, 2013



Packet Reordering: Motivation

- Multipath data streaming $A \to B$
- Source A applies rate-proportional scheduling, either
  - deterministic (e.g., round-robin),
  - or randomized (e.g., Bernoulli scheme)
- Since network path characteristics are random there may be a large number of out-of-order packets at the destination
- Degradation of the application performance, especially when distant packets are reordered
- Destination B has to keep a large resequencing buffer for sorting incoming packets
- Randomized strategy at A may lead to improvements:
  - Variability of system state parameters are partially compensated by randomizing input parameters
  - The stochastic compensation effect

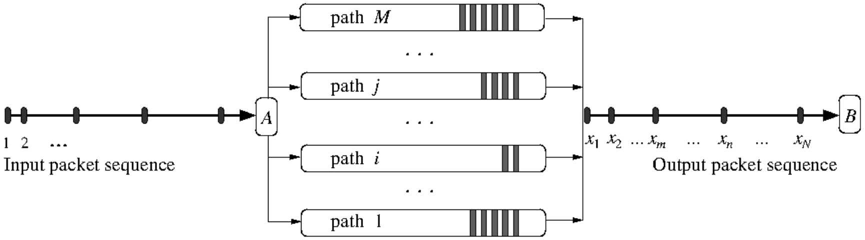
Packet Reordering: Problem Statement (1/2)



- Discrete uniform time $n = 1, 2, \dots, N$ to serve N-packet stream:
  - At time instance n the next packet is forwarded (asynchronous departure process)
  - Each packet n is instantaneously dispatched to a path i using a scheduler at A

- Source A always has data to send and the forwarding cost is negligible for all paths $i = 1, 2, \dots, M$

Packet Reordering: Problem Statement (2/2)



- Let $S_n^{(i)} > 0$ be the end-to-end delay of packet n in path i
- Destination B reassembles the sequence of packets
  - The nth position in the output sequence is occupied by the packet of input sequence number x_n

Assumptions

- No network loss, $S_n^{(i)} < \infty$
  $\rightsquigarrow$ the output is a permutation of the input sequence
- No bandwidth bottlenecks
  $\rightsquigarrow$ an arbitrary number of packets can be sent sequentially to path i without affecting the delay
- $\{S_n^{(i)}\}$ is i.i.d with generic element $S^{(i)}$
  and the mean delay $\tau_i = \mathsf{E}[S^{(i)}]$, $0 < \tau_i < \infty$,

$$p_i = \frac{\mu_i}{\mu_i + \cdots + \mu_M}, \quad i = 1, \ldots, M. \tag{1}$$

- No complete knowledge of path states (e.g., on-the-fly packets)
  - A can estimate μ_i
  - The case of parallel non-observable queues in queuing systems
- All M paths are order-preserving:
  for any two packets following the same path if $x_n < x_m$ then $n < m$ (i.e., FCFS discipline)

Metrics of Packet Reordering (1/2)

- Let $1 \leq n < m \leq N$ be packet positions in the output sequence
- Set $r_{nm} = m - n$ if $x_n > x_m$ and $r_{nm} = 0$ otherwise
- The reorder distance probability: an arbitrary output packet n is reordered on distance k with probability

$$d_k = \mathrm{P}[r_{n,n+k} > 0]. \tag{2}$$

- Let $r_n = n - x_n$ be displacement of packet n from its original position. The displacement probability distribution:

$$f_k = \mathrm{P}[r_n = k], \quad -N < k < N, \tag{3}$$

i.e., f_k shows the frequency of packets of displacement k

Metrics of Packet Reordering (2/2)

- For each given n, consider the last reordered packet m. Then the maximum reorder distance is on average

$$\rho_{\max}(N) = \frac{1}{N}\sum_{n=1}^{N} \max_{n<m} r_{nm}.$$

Estimation of resequencing buffer size needed at the destination

- Reorder entropy: the total disorder of a packet sequence,

$$\rho_{\mathrm{ent}}(N) = -\sum_{f_k>0} f_k \ln f_k.$$

- Concentrated (low $\rho_{\max}$) or dispersed (high $\rho_{\max}$) displacement
  - If no reordering ($f_0 = 1$), then the minimum $\rho_{\mathrm{ent}} = 0$ is achieved
  - The maximum $\rho_{\mathrm{ent}} = \ln(2N + 1)$ is for uniformly displaced packets

Scheduling Strategies: Deterministic vs. Randomized

- WRR scheduler operates in loop $i = 1, 2, \ldots, M$
  - Each iteration assigns a batch of subsequent packets to path i
  - The number of packets in a batch for path i is fixed to Cp_i, where C is a constant common for all paths
  - Lengthy packet batches are constructed for fast paths when there are slow paths
- BN scheduler forwards any packet n to path i with probability p_i
  - Packet batches of variable length appear
  - If $p_i = p = 1/M$ for any path i then batches are assigned in accordance with the geometric distribution
  - Batch of l successive packets $n, n+1, \ldots, n+l-1$ has the probability $(1-p)p^l$

Simulation Model: Path Delay Distributions

- *Exponential:* PDF $f_i(x) = \lambda_i e^{-\lambda_i x}$ has mean $\tau_i = 1/\lambda_i$ and variance $\sigma_i^2 = 1/\lambda_i^2$
- *Power-law:* PDF $f_i(x) = \frac{\alpha_i - 1}{s_i^{\min}} \left(\frac{x}{s_i^{\min}} \right)^{-\alpha_i}$ has the minimal value $s_i^{\min}$
  - If $\alpha_i \leq 2$ the mean is infinite, otherwise $\tau_i = \frac{\alpha_i - 1}{\alpha_i - 2} s_i^{\min}$
  - If $\alpha_i \leq 3$ the variance is infinite, otherwise $\sigma_i^2 = \frac{\alpha_i - 1}{\alpha_i - 3} (s_i^{\min})^2$
  - equivalent to Pareto distribution (by substitution $\alpha_{\mathrm{prt}} = \alpha - 1$)
  - continuous counterpart of the Zipf-like distribution

Simulation Model: Experiments of Group I

The number of paths is varied as $M = 2, 3, \ldots, 15$

- *Identical:* Every path has the same delay probability distribution parameters: $\forall i\ S^{(i)} = S$
- *Similar:* The delay probability distribution parameters are varied such that $\forall i\ S^{(i)} \approx S$
- *Slow & fast:* Given M paths are classified as slow and fast. If i is slow and j is fast then $\tau_i \gg \tau_j$. The share of slow paths is $0 < q_{\text{slow}} < 1$

Pattern	Exponential		Power-law			
	$\lambda \sim U[a,b]$	$\tau_{\text{avg}} = \sigma_{\text{avg}}$	$\alpha_{\text{prt}} \sim U[a,b]$	$s_{\min}$	τ_{avg}	σ_{avg}
Identical	0.3	3.3	2.3	10	17.7	21.3
Similar	$0.3, 0.4$	2.9	$2, 3$	$10, 20$	25	22.4
Slow	$0.1, 0.12$	9	$2, 2.3$	$10, 30$	37.4	65.8
Fast	$0.3, 0.4$	2.9	$3.3, 3.4$	$1, 5$	4.3	2

Simulation Model: Experiments of Group II

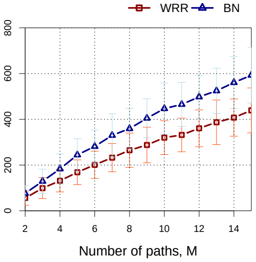
The number of paths is fixed to $M = 2$

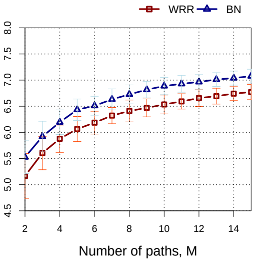
- Fixed path: delay distribution parameters are fixed
- Varied path: parameters are varied reducing the mean delay

	Exponential		Power-law, $s^{\min} \sim U[2,3]$		
	$\lambda \sim U[a,b]$	$\tau_{\text{avg}} = \sigma_{\text{avg}}$	$\alpha_{\text{prt}} \sim U[a,b]$	τ_{avg}	σ_{avg}
Fixed path	$1.00, 2.00$	0.67	$2.5, 2.7$	4.06	3.25
Varied path	$0.01, 0.02$	66.67	$1.5, 1.8$	6.35	∞
	$0.03, 0.05$	25.00	$2.0, 2.3$	4.67	8.23
	$0.10, 0.20$	6.67	$2.5, 2.8$	4.02	3.06
	$0.30, 0.50$	2.50	$3.0, 3.3$	3.66	1.92
	$1.00, 2.00$	0.67	$3.5, 3.8$	3.44	1.41
	$2.50, 3.00$	0.36	$4.0, 4.3$	3.29	1.10
	$3.00, 3.50$	0.31	$4.5, 4.8$	3.18	0.91
	$3.50, 4.00$	0.27	$5.0, 5.3$	3.10	0.77

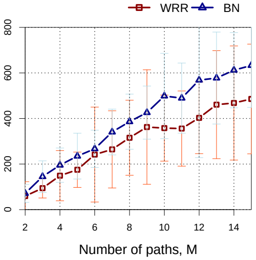
Identical paths in streaming $N = 10^4$ packets

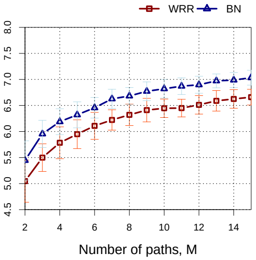
- Exponential delay





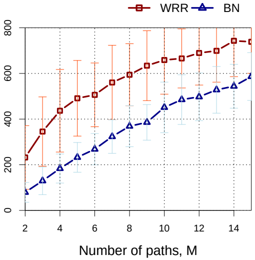
- Power-law delay

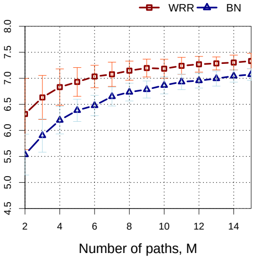




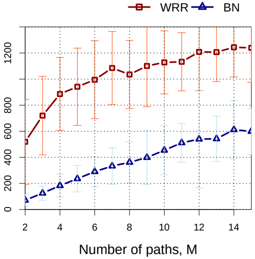
Similar paths for $N = 10^4$

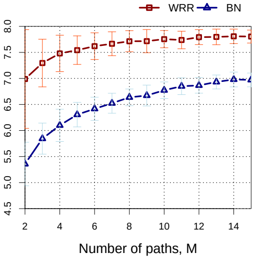
- Exponential delay





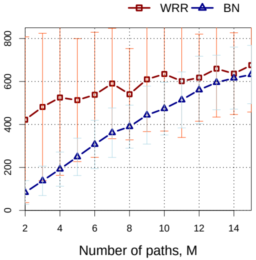
- Power-law delay

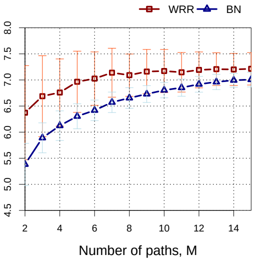




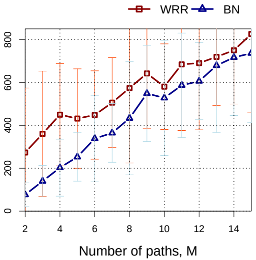
Slow & fast paths for $N = 10^4$ and $q_{\text{slow}} = 75\%$

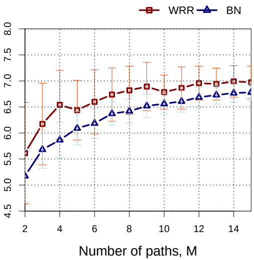
- Exponential delay





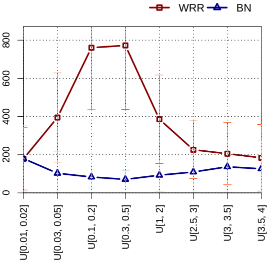
- Power-law delay

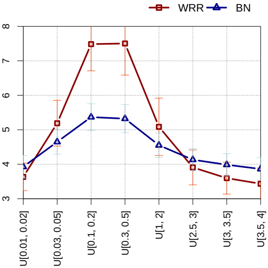




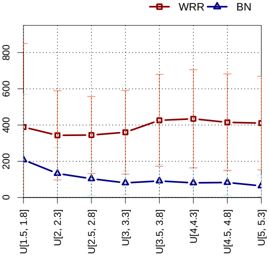
One path is fixed and the other is varied

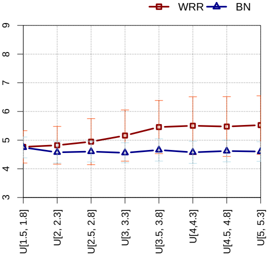
- Varied exponential delay





- Varied power-law delay





Conclusion

- We compared weighted round-robin scheduler (deterministic) and Bernoulli scheduler (randomized) using simulation experiments
- Our hypothesis: randomness of transmission delay can be compensated with randomizing the packet scheduling
- Our results show that the randomization reduces packet reordering, and the stochastic compensation effect has a place for certain multipath configurations
- We expect that utilization of this effect in networking applications can essentially improve the application performance when the path diversity of underlying networks is high

Thank you

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