Reduced Load Approximations for Large-Scale Optical WDM Networks Offering Multiclass Services

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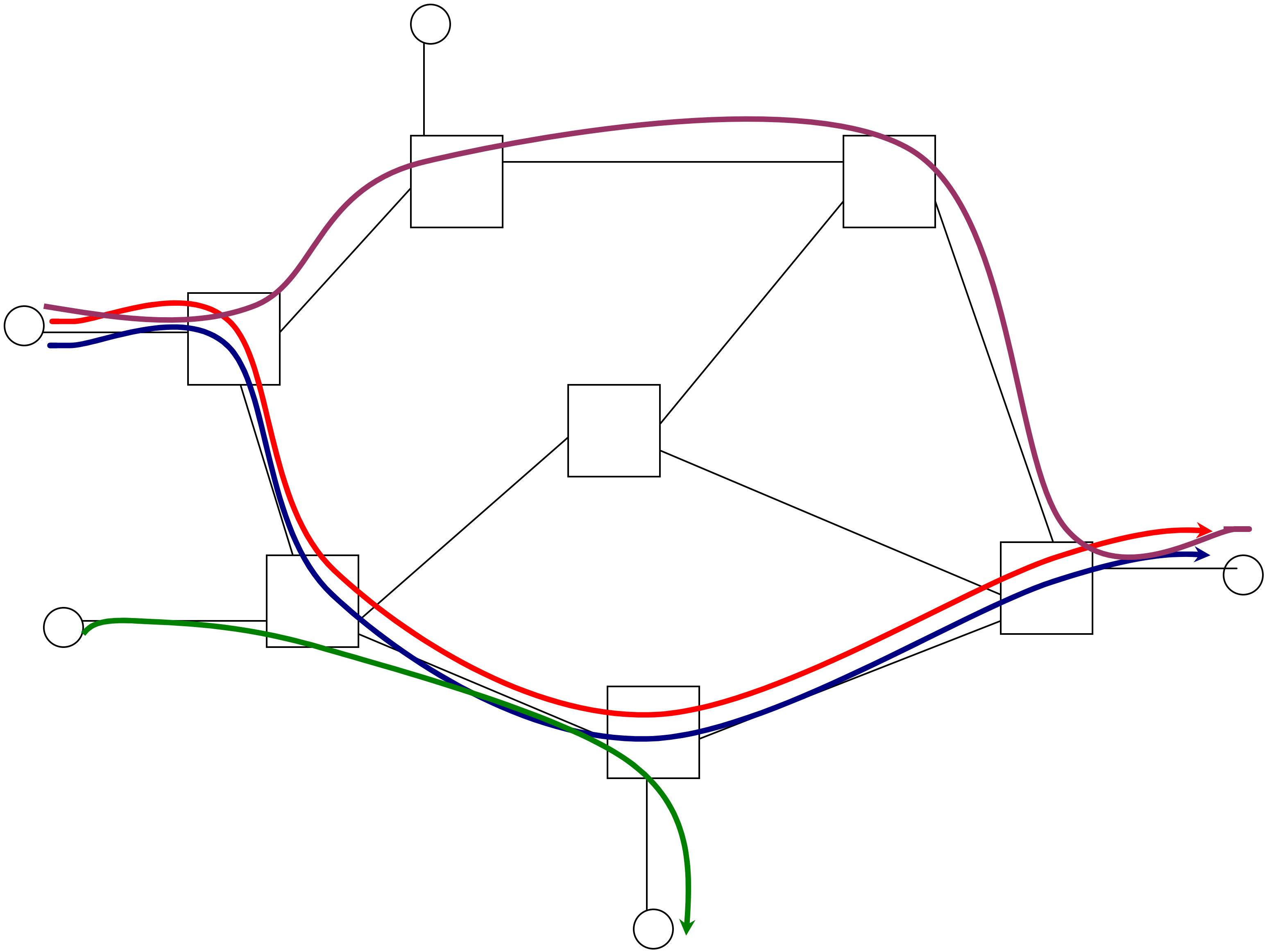


We assume *wavelength continuity constraint* on lightpaths.

Analytical Model of Traffic and Service

- Multiclass services belong to set S.
- OD node pairs predetermined in the network (set O).
- Call arrivals of class s *in* S on OD pair o *in* O are Poisson with rate a_o^s. Holding time (service connection period) is exponentially distributed with mean $1/\mu^s$, and each call requires b^s number of wavelengths.
- Each service class s (*in* S) call is characterized by a unique couple of $(b^s, 1/\mu^s)$ of number of wavelengths and average holding period requirements.

Routing and Wavelength Assignment

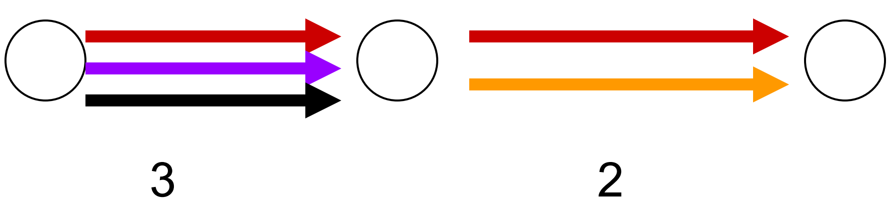
- Class-specific route set,
  $R^s(o) \equiv \{\ r^s(o,1),\ r^s(o,2),\ \ldots,\ r^s(o,n^s{}_o)\ \}$ on each OD pair o.
  - Each route set has multiple link-disjoint routes: one designated primary route and alternate routes.
- Following static and dynamic wavelength routing policies considered in our analysis
  - Fixed Routing (FR),
  - Least Loaded Routing (LLR), and
  - Fixed Alternate Routing (FAR).
- Wavelength assignment policy is assumed random.

Performance

- Our performance measure is per class, per OD pair approximate blocking probabilities given by L_o^s, s in S, o in O.
- Markovian system
  - State space explosion
  - For each link j in J, the link state is 2^C, where C is the number of wavelengths.

Approximation Approach

- Approximation Assumptions (variant from Birman [1] for multiclass services)
  - We consider random variable X_j representing the number of idle wavelengths on link j .
  - We assume that X_j's for different j's are statistically independent.
  - When there are m_j number of idle wavelengths on link j, the time until next call of class s in S is exponentially distributed with parameter $\alpha_j^s(m_j)$, the setup rate of class s on link j.
- Define $q_j(m_j) = P[X_j = m_j]$, $m_j=0,\ldots,C$ as idle wavelength distribution on link j.



Approximation Approach

Relate X_j's for links to the number of wavelengths available in a path, combinatorics suggested by Birman, 96.

$$p_n\left(m_{j_1},\ldots,m_{j_{h(r)}}\right)$$
$$\equiv P\left[X_r = n \middle| X_{j_1} = m_{j_1}, X_{j_2} = m_{j_2}, \cdots, X_{j_{h(r)}} = m_{j_{h(r)}}\right]$$

Probability distribution of the number of wavelengths available in route *r* can be derived from distribution

$$q_j(m_j) \equiv P\left[X_j = m_j\right]$$

Thus, the blocking probability at route *r*.

Approximation Approach: Interdependency

- State dependent per class setup rate $\alpha_j^s(.)$ is dependent on the blocking probability at route r that contains link j, thus on the idle wavelength distribution $q_k(.)$ for links k belonging to a route that contains link j.
- $q_k(\ )$ also depend on $\alpha(\ )$.

Example of dependency of $\alpha_j^s(.)$ on state occupancy distribution $q_k(.)$

- For e.g., in Fixed Routing case,

$$\alpha_j^s(m_j) = \begin{cases} 0, & 0 \le m_j < b^s \\ \sum_{r=r^s(o,1)\forall o: j\in r} a_o^s \Pr\left(X_r \ge b^s \mid X_j = m_j\right), & b^s \le m_j \le C \end{cases}$$

where $P\left(X_r \ge b^s \mid X_j = m_j\right) = \sum_{m_{j2}=b^s}^{C} q_{j_2}\left(m_{j_2}\right)\left(1 - \sum_{n=0}^{b^s-1} p_n\left(m_{j_2}, m_j\right)\right)$

for route $r = \{j_1 = j, j_2\}$ (two links),

Example of dependency of $\alpha_j^s(.)$ on state occupancy distribution $q_k(.)$

For Least Loaded Routing (LLR) case,

$$\alpha_j^s\left(m_j\right)=\begin{cases} 0, & 0 \le m_j < b^s \\ \displaystyle\sum_{r=r^s(o,1)\forall o: j\in r} a_o^s \Pr\left(X_r \ge b^s \mid X_j = m_j\right), & b^s \le m_j \le t^s \\ \displaystyle\sum_{r=r^s(o,1)\forall o: j\in r} a_o^s \Pr\left(X_r \ge b^s \mid X_j = m_j\right) + \sum_{r=r^s(o,i),i\ne 1,\forall o: j\in r} a_o^s\, L_{r^s(o,1)}^s \Pr\left(alt = r, X_r > t^s \mid X_j = m_j\right) & t^s < m_j \le C \end{cases}$$

Dealing with interdependency: Fixed-Point Iteration

- Sketch of the fixed-point approximation algorithm (need to specialize for particular routing policy)
  1. Initialization Step: Set initial $\alpha_j^s(.)$, set $L_o^s = 0$ *for all o, s.*
  2. Evaluate idle wavelength distribution $q_j(.)$ on all links *j in J.* (Will use Knapsack approximation)
  3. Compute $\alpha_j^s(.)$ using step 2, for all *j, s.*
  4. Compute L_o^s using step 2, for all *o,s;* go to Step 2.
  5. Convergence test for L_o^s. If success, then exit; else goto step 2.

Knapsack Approximation

- We use knapsack approximation (Kaufman [4], Roberts [9]) for solving idle wavelength distribution on links *j in J* under multiclass traffic

$$\text{Define} \quad \gamma_j^s(i) = \alpha_j^s(C-i), i \in \Lambda$$

$$\overline{q}_j(i) = q_j(C-i), i \in \Lambda$$

$$m_j \overline{q}_j(i) = \sum_{s \in S} \frac{1}{\mu^s} b^s \gamma_j^s(i-b^s) \overline{q}_j(i-b^s), i \in \Lambda - \{0\}$$

$$\sum_{m_j=0}^{C} \overline{q}_j(i) = 1$$

  - We propose a recursive procedure for knapsack approximation.

- Now, $q_j(.)$ is dependent on state dependent setup rates for all classes *s in S* whose traffic arrives on link *j*.

Per Class, per OD pair Approximate Blocking Probabilities L_o^s

- Given idle wavelength distribution on links on route/routes between an OD pair, we can compute per class, per OD pair approximate blocking probabilities L_o^s for FR, LLR and FAR.
- State dependent setup rates $\alpha_j^s(.)$ depend on L_o^s, which in turn depends on $q_j(.)$.
- We see the dependency on each other of $\alpha_j^s(.)$ and $q_k(.)$ where *j, k in J.*

Evaluating Per Class, per OD pair Approximate Blocking Probabilities L_o^s

- Given idle wavelength distribution on links on route/routes between an OD pair, we can compute per class, per OD pair approximate blocking probabilities L_o^s for FR, LLR and FAR.
- Approximate Blocking Probability for FR case with a route $r = \{j_1, j_2, \ldots, j_{h(r)}\}$

$$L_o^s = 1 - \prod_{j \in r}\left(1 - q_j^s\right) + \sum_{m_{j_1}=b^s}^{C} \cdots \sum_{m_{j_{h(r)}}=b^s}^{C} q_{j_1}\left(m_{j_1}\right) \ldots q_{j_{h(r)}}\left(m_{j_{h(r)}}\right) \sum_{n=0}^{b^s-1} p_n\left(m_{j_1}, \ldots, m_{j_{h(r)}}\right)$$

$$q_j^s = \sum_{m_j=0}^{b^s-1} q_j\left(m_j\right)$$

- Details for approximate blocking probabilities for LLR/FAR: takes some work.

Example: Evaluating L_o^s for FR policy, 2 link case

$$L_o^s = \Pr[X_r < b^s]$$

$$= 1 - \sum_{m_j = b^s}^{C} \Pr[X_r \geq b^s \mid X_j = m_j].\Pr[X_j = m_j]$$

$$= 1 - \sum_{m_{j_2} = b^s}^{C} \sum_{m_j = b^s}^{C} q_j(m_j).q_{j_2}(m_{j_2}).\left(1 - \sum_{n=0}^{b^s - 1} p_n\left(m_j, m_{j_2}\right)\right)$$

$$= 1 - \left(1 - \sum_{m_j = 0}^{b^s - 1} q_j(m_j)\right).\left(1 - \sum_{m_{j_2} = 0}^{b^s - 1} q_{j_2}(m_{j_2})\right) + \sum_{m_{j_2} = b^s}^{C} \sum_{m_j = b^s}^{C} q_j(m_j).q_{j_2}(m_{j_2}).\sum_{n=0}^{b^s - 1} p_n\left(m_j, m_{j_2}\right)$$

$$= 1 - \prod_{j \in r}\left(1 - q_j^s\right) + \sum_{m_{j_2} = b^s}^{C} \sum_{m_j = b^s}^{C} q_j(m_j).q_{j_2}(m_{j_2}).\sum_{n=0}^{b^s - 1} p_n\left(m_j, m_{j_2}\right), \quad (\text{since} \quad r = \{j_1 = j, j_2\})$$

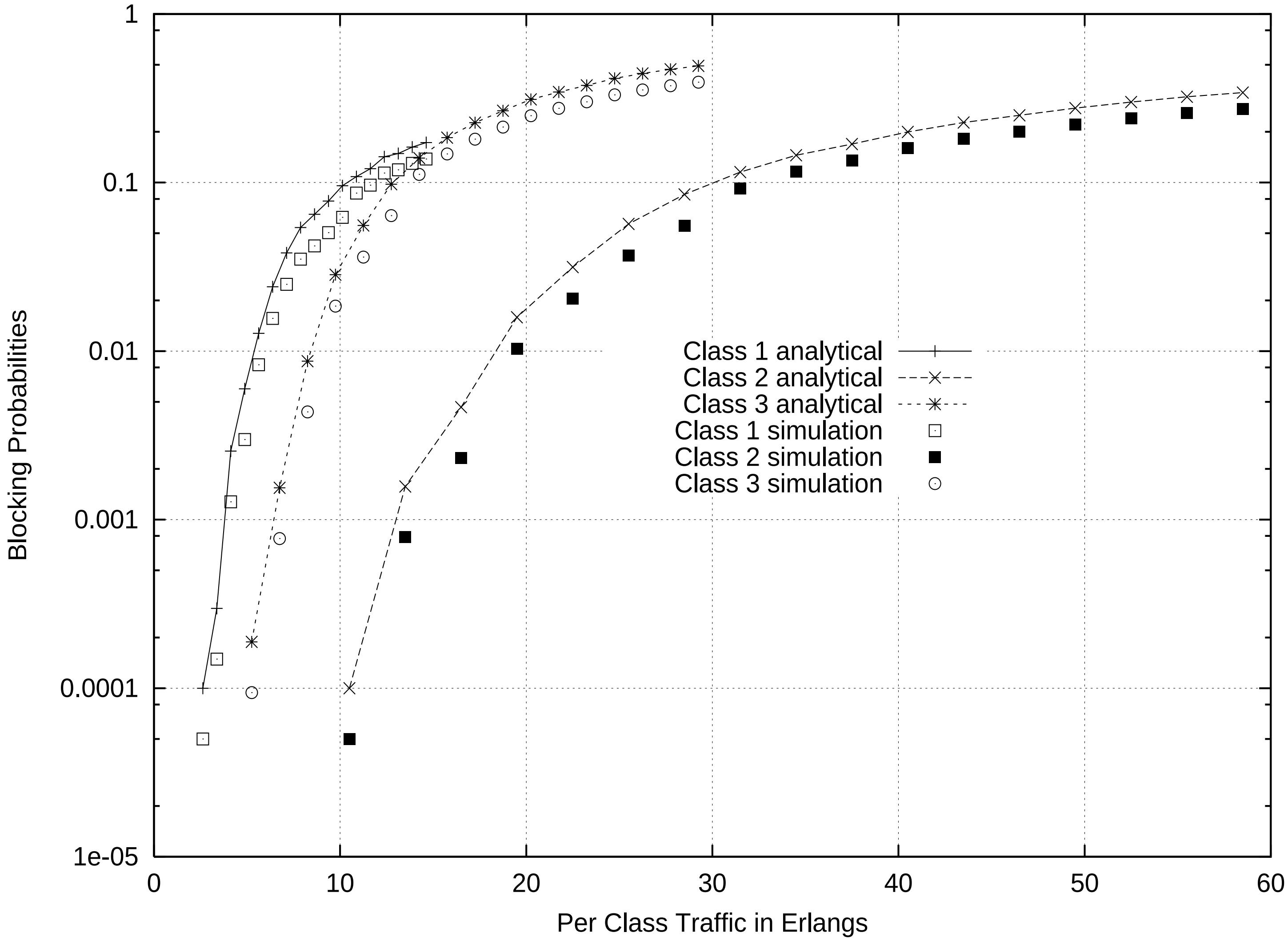
Experimental Results

- Simulations run to compare with computed fixed-point approximation blocking probabilities.
- Simulations based on discrete-event simulation model. Simulation results are given as 95% confidence intervals estimated by method of batch means. The number of batches is 20.
- Different network topologies used: fully connected 6-node network, ring network, large mesh topology (NSFNet)
- Three service classes in the network with $(b^s, 1/\mu^s)$ given by *(1, 1/4), (2,1), (3, 1/2).*
- Simulation results closely match the analytical results for different traffic regimes: low, medium and high; thus validating our proposed analytical model.

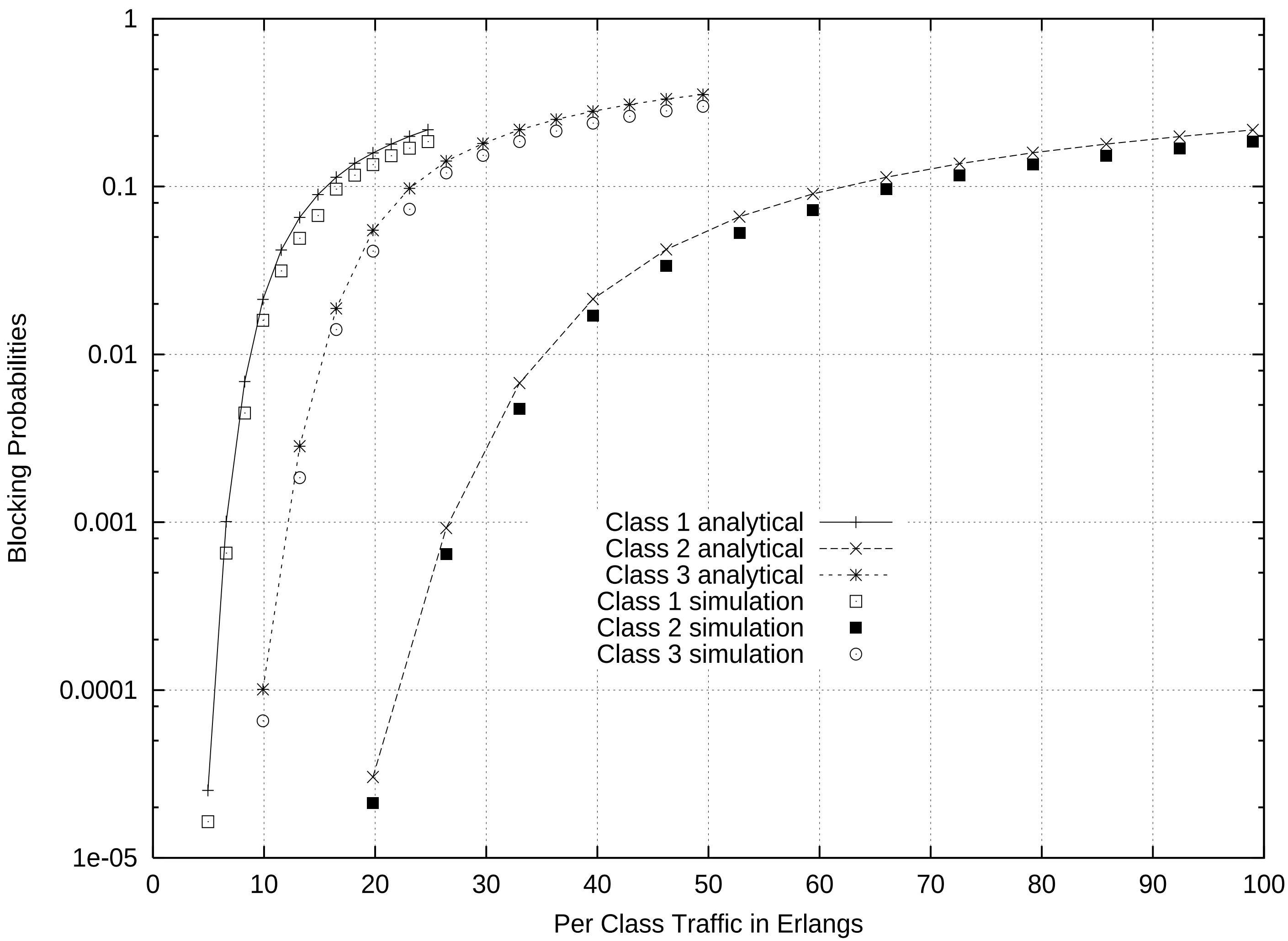
Experimental Results on 6-node fully connected network, FR policy

Network	Topology 1 with Fixe Routing,		Moderate Traffic	(arrival rate 1.2 per unit time)		J=7, C=18
OD Pair	Class s=1		Class s=2		Class s=3	
Route	Loss (simulation)	Approx. loss	Loss (simulation)	Approx. loss	Loss (simulation)	Approx. loss
{0}	(0.000945,0.001515)	0.001226	(0.00276,0.00374)	0.003391	(0.006022,0.007398)	0.007038
{0,1}	(0.003873,0.006727)	0.005901	(0.0147,0.0199)	0.01832	(0.03065,0.04335)	0.04036
{6}	(0.0004755,0.0008445)	0.0008134	(0.001804,0.002756)	0.002265	(0.004203,0.004697)	0.004769
{5,4}	(0.0009081,0.001472)	0.001249	(0.003029,0.004491)	0.003459	(0.006276,0.007704)	0.007187
{5}	(0.0005256,0.0009344)	0.0005217	(0.001725,0.002775)	0.00146	(0.003566,0.004774)	0.003115
{2,3,6}	(0.002621,0.02138)	0.01802	(0.03419,0.07781)	0.05663	(0.0651,0.1149)	0.1194
{1,2}	(0.005278,0.008922)	0.005975	(0.01547,0.01813)	0.01856	(0.03268,0.04292)	0.04087
{1,2,3}	(0.01219,0.02181)	0.021	(0.05967,0.08833)	0.06478	(0.1001,0.1539)	0.134
{0,5}	(0.002292,0.006708)	0.003809	(0.01025,0.01655)	0.01208	(0.02511,0.03289)	0.02746
{2}	(0.001095,0.001405)	0.001247	(0.002757,0.003543)	0.003454	(0.006537,0.007943)	0.007179
{2,3}	(0.004047,0.007753)	0.005989	(0.01711,0.02289)	0.01859	(0.03255,0.04365)	0.04092
{0,1,2}	(0.008077,0.02192)	0.0155	(0.03234,0.06166)	0.04951	(0.07848,0.1175)	0.1062
{3}	(0.001054,0.001586)	0.001256	(0.002954,0.004006)	0.003476	(0.007021,0.008659)	0.007217
{3,4}	(0.002273,0.005127)	0.004767	(0.01212,0.01888)	0.01499	(0.03044,0.03916)	0.0336
{4}	(0.000318,0.000562)	0.0005014	(0.001171,0.001669)	0.001403	(0.002532,0.003668)	0.002995

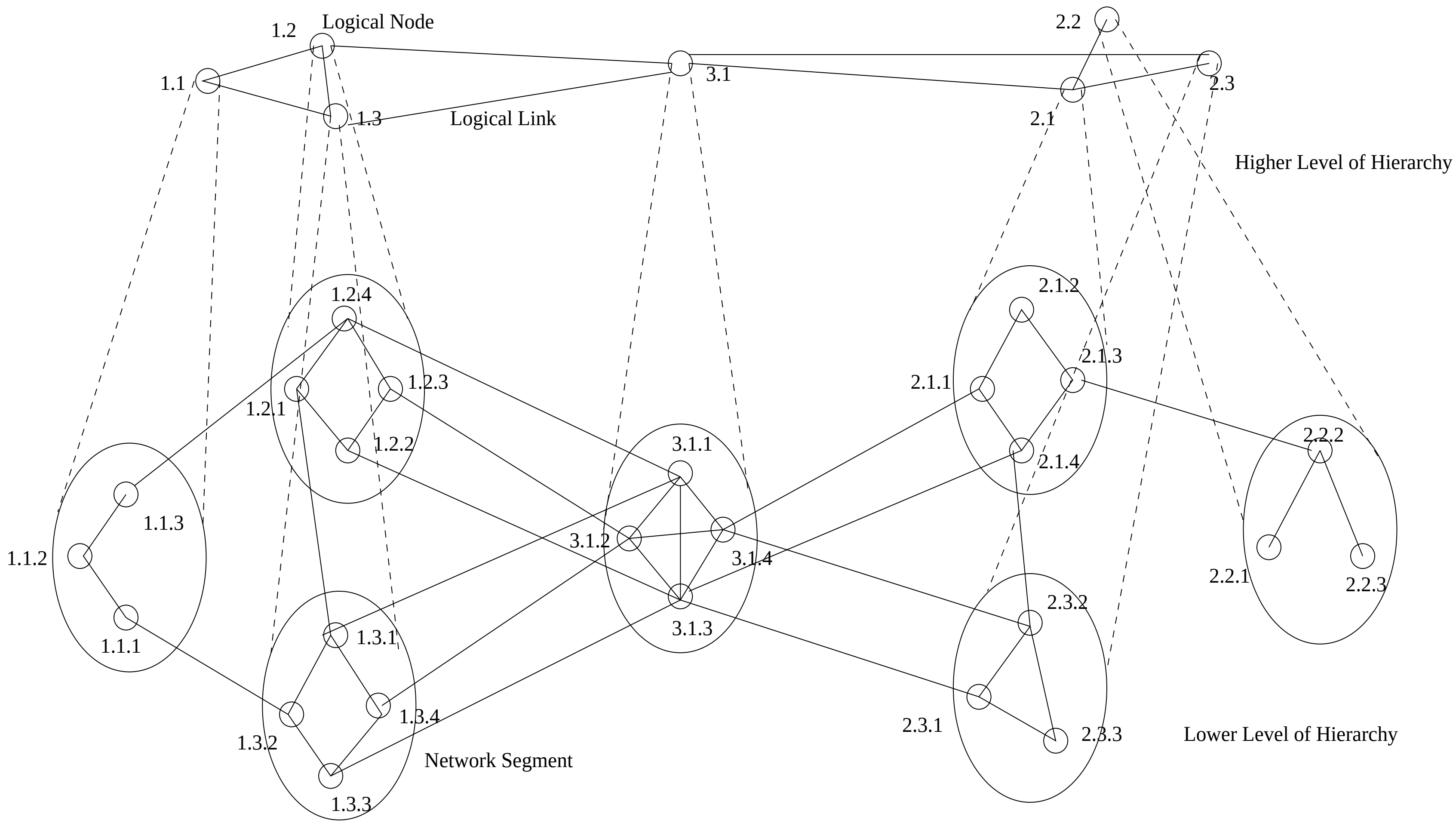
Experimental Results on 6-node fully connected network, LLR policy



Experimental Results on NLR Network*, FR policy



Model of Large-Scale Optical Network Topology: Two-Level Hierarchical Network Topology



Our Approach – Analytical Model

- Multiclass services belonging to set *S*.
- OD node pairs have been predetermined on the large-scale optical network (set *O*) and incoming traffic for an OD pair arrives at the origin node.
- Call arrivals of class *s in S* on OD pair *o in O* are Poisson with rate λ_o^s. Holding time (service connection period) is exponentially distributed with mean $1/\mu^s$, and requires b^s number of wavelengths.
- Each service class *s* (*in S)* call is characterized by a unique couple of $(b^s, 1/\mu^s)$ of number of wavelengths and average holding period requirements.
- *Our performance measure is end-to-end per class, per OD pair approximate blocking probabilities given by* L_o^s*, s in S, o in O.*

Our Approach – Analytical Model

- We model the large-scale optical network as a two-level hierarchical multiclass loss network (next slide).
- We define *Intergroup Routing* which is conceptually very similar to interdomain routing
  - Efficient and scalable routing mechanism on such large-scale optical networks.
- An Intergroup route is a sequence of logical nodes connected by logical links.
  - Each of these logical nodes/links is called a *route element*.
- Between an origin-destination (OD) node pair, we assume a *fixed* intergroup route.
- However, we assume that the constituent network segments (logical nodes) have the flexibility to implement their own routing policies from: FR, LLR and FAR. Wavelength assignment policy is assumed random.
- We assume wavelength continuity constraint *within* each network segment; however we assume “gateway” crossconnects have full wavelength conversion capability.

Reduced Load Approximation Assumptions

- Route Element Blocking Independence
  - Blocking on different route elements in an intergroup route are independent.
- Poisson Thinning
  - Per class incoming traffic arrivals on any route element is Poisson, and is thinned due to blocking encountered on the other route elements of the fixed intergroup route between any OD pair (exogenous traffic on any OD pair assumed Poisson).

End-to-End Per Class, per OD pair Approximate Blocking Probabilities

- Multiclass End-To-End Approximate Blocking Probabilities L_o^s is given by ($L_{g,o}^s$: route element blocking probability)

$$L_o^s = 1 - \prod_{g \in H^s(o)} \left(1 - L_{g,o}^s\right)$$

- where $H^s(o)$: set of route elements on each intergroup route, for each o, s.
- (Due to reduced load approximation assumption.)
- We need to derive the constituent route elements (logical nodes and logical links) blocking probabilities.

Approximate Blocking Probabilities for Logical Nodes

- Logical nodes (i.e. network segments at lower level of hierarchy) may have their own different topologies, routing policies (FR, LLR or FAR).
- We leverage off earlier results developed for approximate blocking probabilities for multiclass services (we need to set the state-dependent per class call setup rate on each link as the thinned Poisson rate from the exogenous Poisson arrival rate λ_o^s on OD pair *o in O, s in S*).

$$a_{\hat{o}}^{s} = \sum_{o:o\in S_g,\hat{o}=l(o)} \lambda_o^s \prod_{k\in H^s(o)-\{g\}} \left(1 - L_{g,o}^{s}\right)$$

- Here *g* represents the logical node.

Approximate Blocking Probabilities for Logical Links

- Assuming route for OD pair *o in O* passes through optical link *j* belonging to logical link *g*, then the approximate blocking probabilities per class is given by

$$L^s_{g.o} = \sum_{m_j=0}^{b^s-1} q_j\left(m_j\right)$$

- Use *knapsack* approximation to evaluate the above from the state-dependent per class call setup rates.

$$\alpha^s_j\left(m_j\right) = \begin{cases} 0, & 0 \le m_j < b^s \\ \displaystyle\sum_{\substack{o:g\in H^s(o), \\ o \text{ uses link } j, \\ j \text{ in } g}} \lambda^s_o \prod_{k\in H^s(o)-\{g\}} \left(1 - L^s_{k.o}\right) & b^s \le m_j \le C_g \end{cases}$$

Computational Approach for Evaluating Approximate Blocking Probabilities

- As before, we resort to using fixed-point iterations to numerically evaluate L_o^s.
- The key idea is that, at each every iteration the fixed-point algorithm computes end-to-end per class approximate blocking probabilities on a intergroup route, in two steps.
  - First, it determines the blocking probabilities on the constituent route segment (logical nodes and logical links).
  - Using that, it determine overall end-to-end blocking probabilities.
- The reduced load approximations are central to the fixed-point computations.

Sketch of the Reduced Load Approximation, Fixed-Point Algorithm for Approximate Blocking Probabilities (per class, per OD pair)

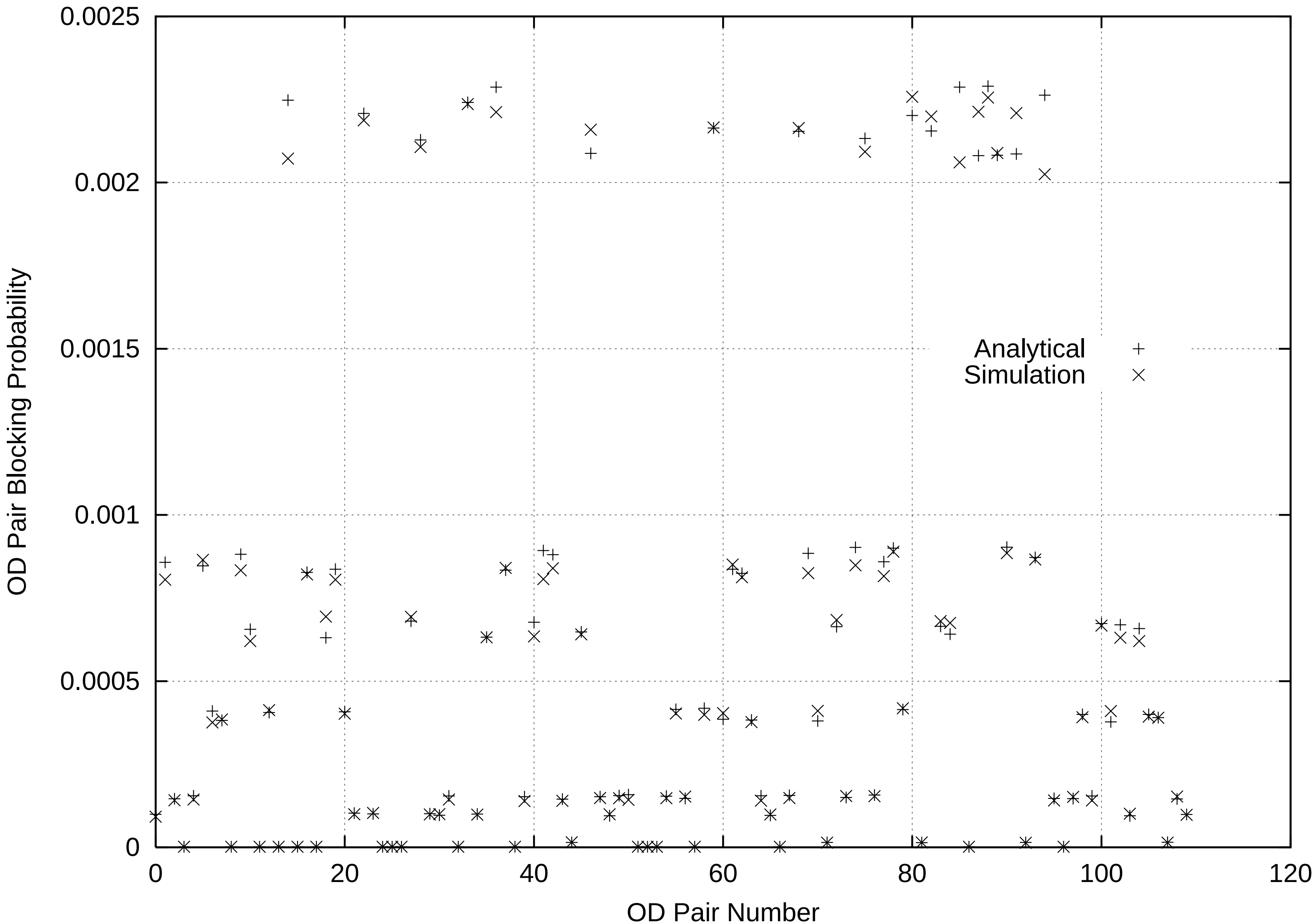
1. *Initialization Step*: Set initial $\alpha_j^s(.)$ for all links j in logical nodes/links, set $L_o^s = 0$ *for all o, s*.
2. *Knapsack approximation* to evaluate idle wavelength distribution $q_j(.)$ on all links j in logical nodes/links.
3. For all OD pairs *o in O*, compute route element (logical nodes/logical links) blocking probabilities. (For logical nodes and logical links, use knapsack approximation for idle wavelength distribution on optical links and the approximate blocking probability expressions previously developed for FR/LLR/FAR in Chapter 3.)
4. Compute end-to-end approximate blocking probabilities L_o^s using step 3, *for all o, s.*
5. Convergence test for L_o^s. If success, then exit.
6. Compute $\alpha_j^s(.)$. Goto step 2.

Experimental Results: Comparison of simulation results with analytical results FR/FAR/LLR on different network segments, moderate to high traffic loading per class

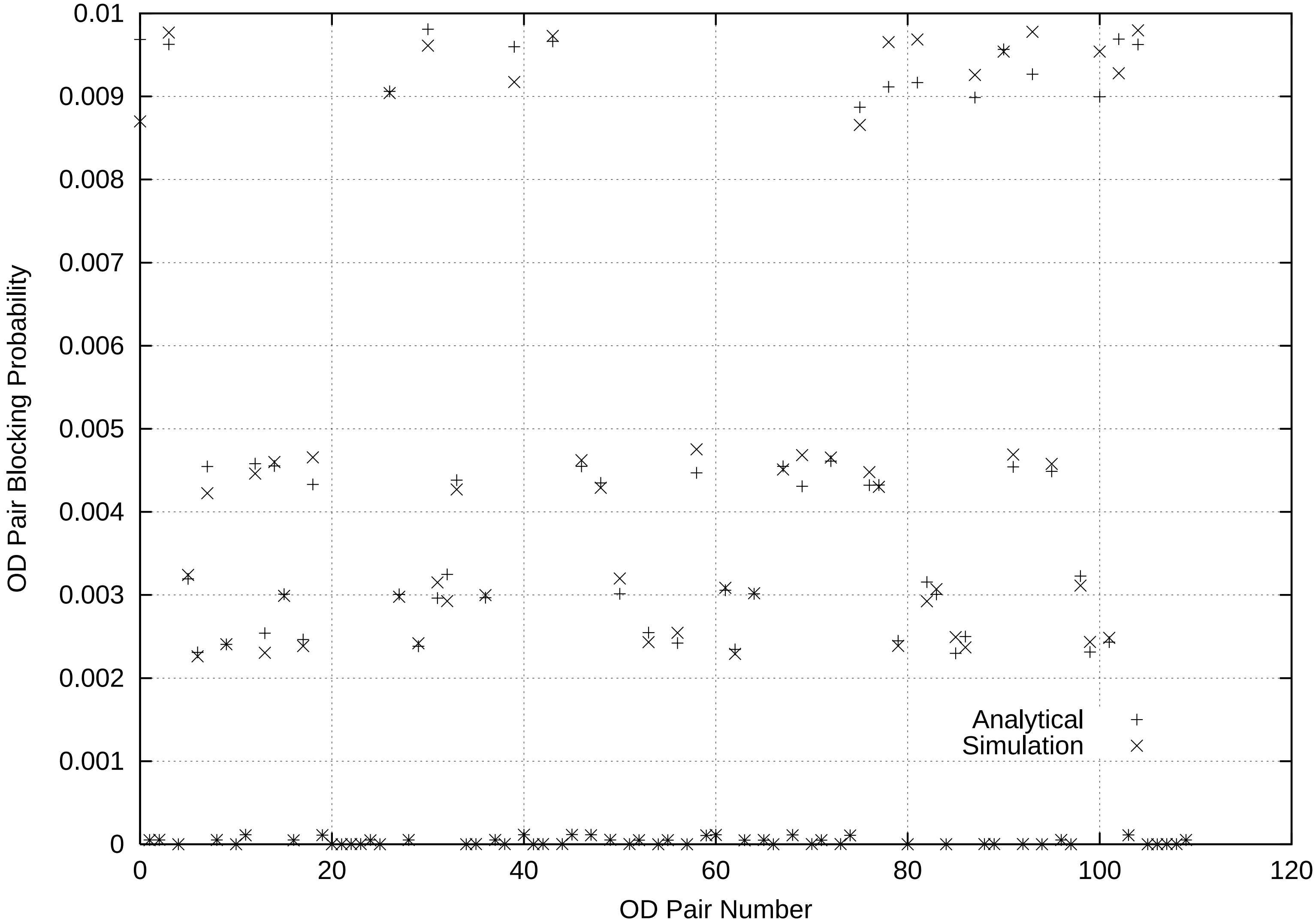
Comparing Analytical/Simulation results of OD Pair Blocking Probabilities for select OD pairs,						
for scenario (b), per class moderate traffic arrival rate = 0.12 per OD pair						
	Class s=1		Class s=2		Class s=3	
OD Pair o	Loss (simulations)	Approx. Loss	Loss (simulations)	Approx. Loss	Loss (simulations)	Approx. Loss
(1.1.2,2.2.3)	(0.004422,0.009484)	0.01314	(0.01037,0.02269)	0.01856	(0.01921,0.03835)	0.03781
(1.3.2,2.1.4)	(0.00396,0.01001)	0.007703	(0.01086,0.02157)	0.02434	(0.01885,0.04243)	0.03174
(1.2.3,2.1.1)	(5.999e-06,1.882e-05)	1.68E-05	(8.077e-06,1.9e-05)	6.59E-06	(2.533e-06,4.188e-05)	2.88E-05
(1.3.2,2.2.1)	(0.0001076,0.0002288)	0.0001887	(0.0006754,0.0009949)	0.0008615	(0.00134,0.001796)	0.001739
(1.2.1,2.2.2)	(0.009764,0.01692)	0.01465	(0.02247,0.04242)	0.03415	(0.04674,0.07335)	0.06017
(1.3.4,2.3.1)	(7.894e-06,1.879e-05)	6.31E-06	(2.872e-05,7.573e-05)	1.60E-05	(6.795e-06,7.753e-05)	4.59E-05
(1.2.2,2.3.2)	(6.588e-05,0.0003028)	0.0001292	(5.05e-05,0.0007721)	0.0003862	(0.0005817,0.001977)	0.002481
(1.1.3,2.1.3)	(0.02462,0.03005)	0.03116	(0.06789,0.07839)	0.0712	(0.1037,0.1171)	0.111

Comparing Analytical/Simulation results of OD Pair Blocking Probabilities for select OD pairs,						
for scenario (b), per class heavy traffic arrival rate = 0.15 per OD pair						
	Class s=1		Class s=2		Class s=3	
OD Pair o	Loss (simulations)	Approx. Loss	Loss (simulations)	Approx. Loss	Loss (simulations)	Approx. Loss
(1.1.2,2.2.3)	(0.01198,0.02148)	0.01655	(0.0248,0.0436)	0.03852	(0.04428,0.07294)	0.06685
(1.3.2,2.1.4)	(0.01025,0.02166)	0.01661	(0.02846,0.04918)	0.0394	(0.0493,0.07023)	0.06541
(1.2.3,2.1.1)	(6.469e-06,7.098e-05)	3.91E-05	(3.686e-05,0.0002058)	0.000128	(0.0001495,0.0003125)	0.0002648
(1.3.2,2.2.1)	(0.000652,0.0009662)	0.0008671	(0.00211,0.002806)	0.002386	(0.004214,0.005068)	0.004821
(1.2.1,2.2.2)	(0.02631,0.03719)	0.03578	(0.05819,0.09069)	0.07851	(0.1014,0.1471)	0.1277
(1.3.4,2.3.1)	(2.045e-06,4.282e-05)	2.54E-05	(6.211e-05,0.0001509)	0.0001107	(6.173e-05,0.0002552)	0.0001703
(1.2.2,2.3.2)	(3.728e-05,0.0009977)	0.0005215	(0.001013,0.002856)	0.001977	(0.002466,0.003544)	0.003322
(1.1.3,2.1.3)	(0.05297,0.05483)	0.05695	(0.1275,0.1212)	0.1333	(0.1822,0.1852)	0.1991

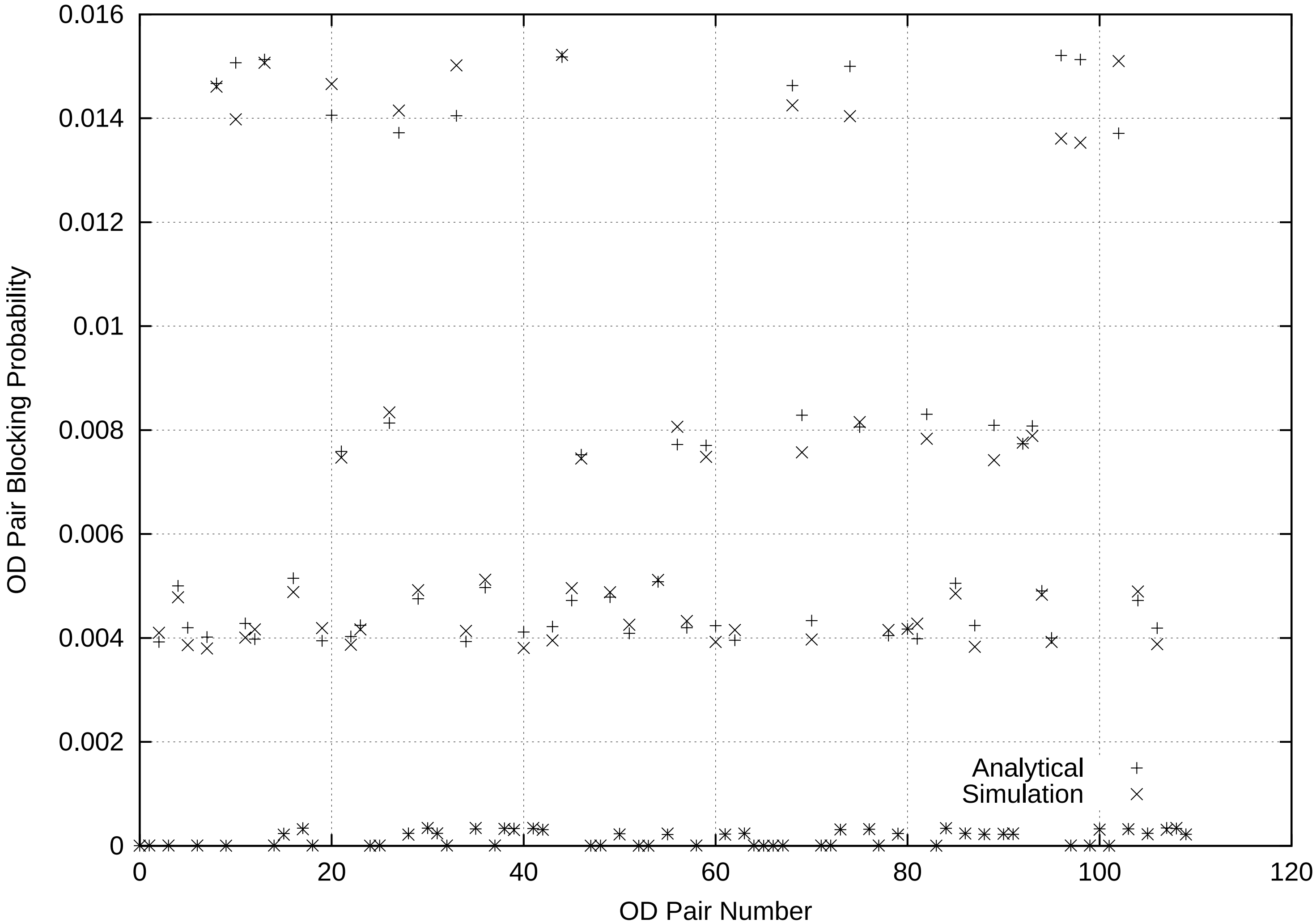
Blocking Probability for Class 1 with routing scenario (a), moderate arrival rate 0.12 per unit time, per OD pair



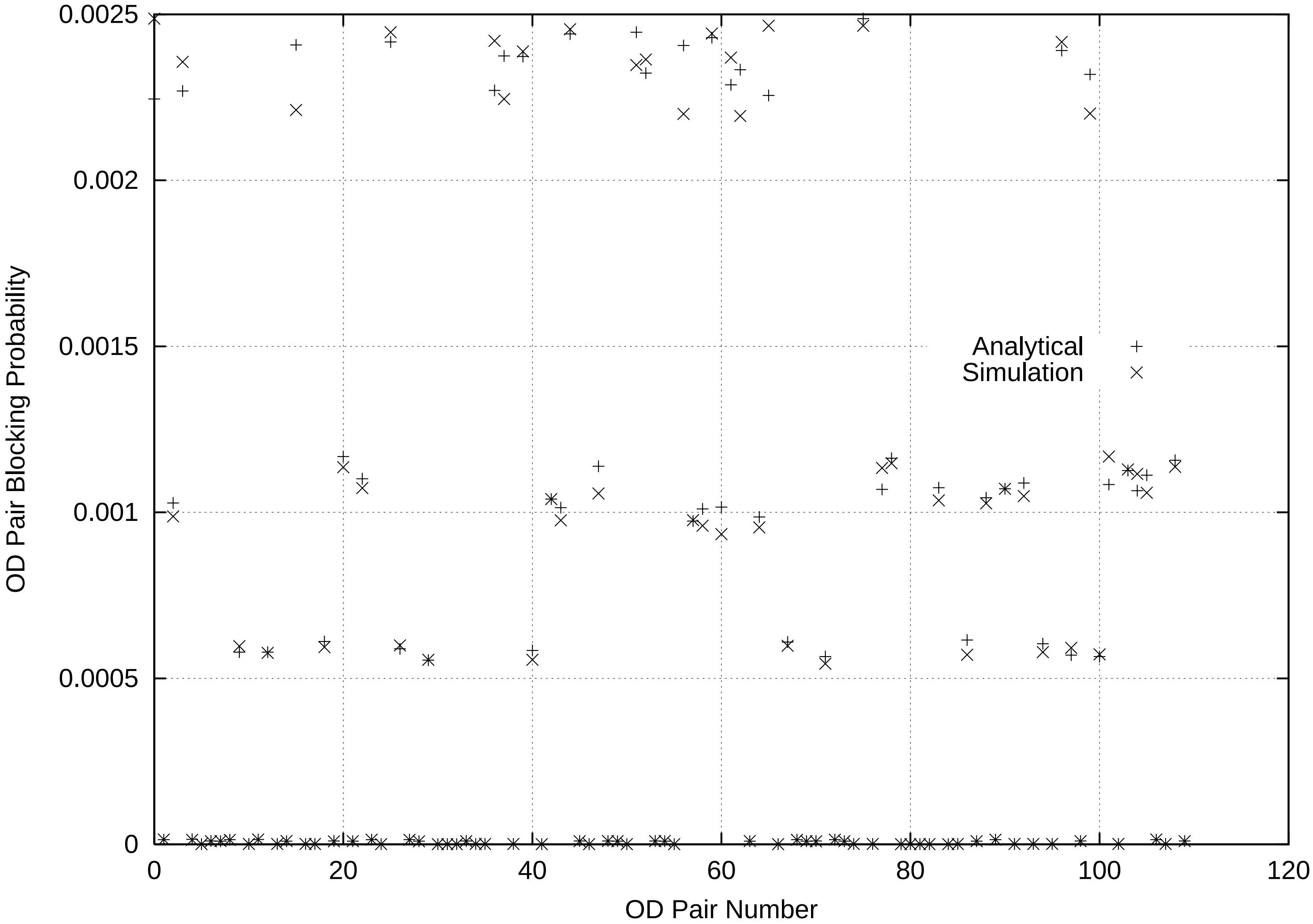
Blocking Probability for Class 2 with routing scenario (a), moderate arrival rate 0.12 per unit time, per OD pair



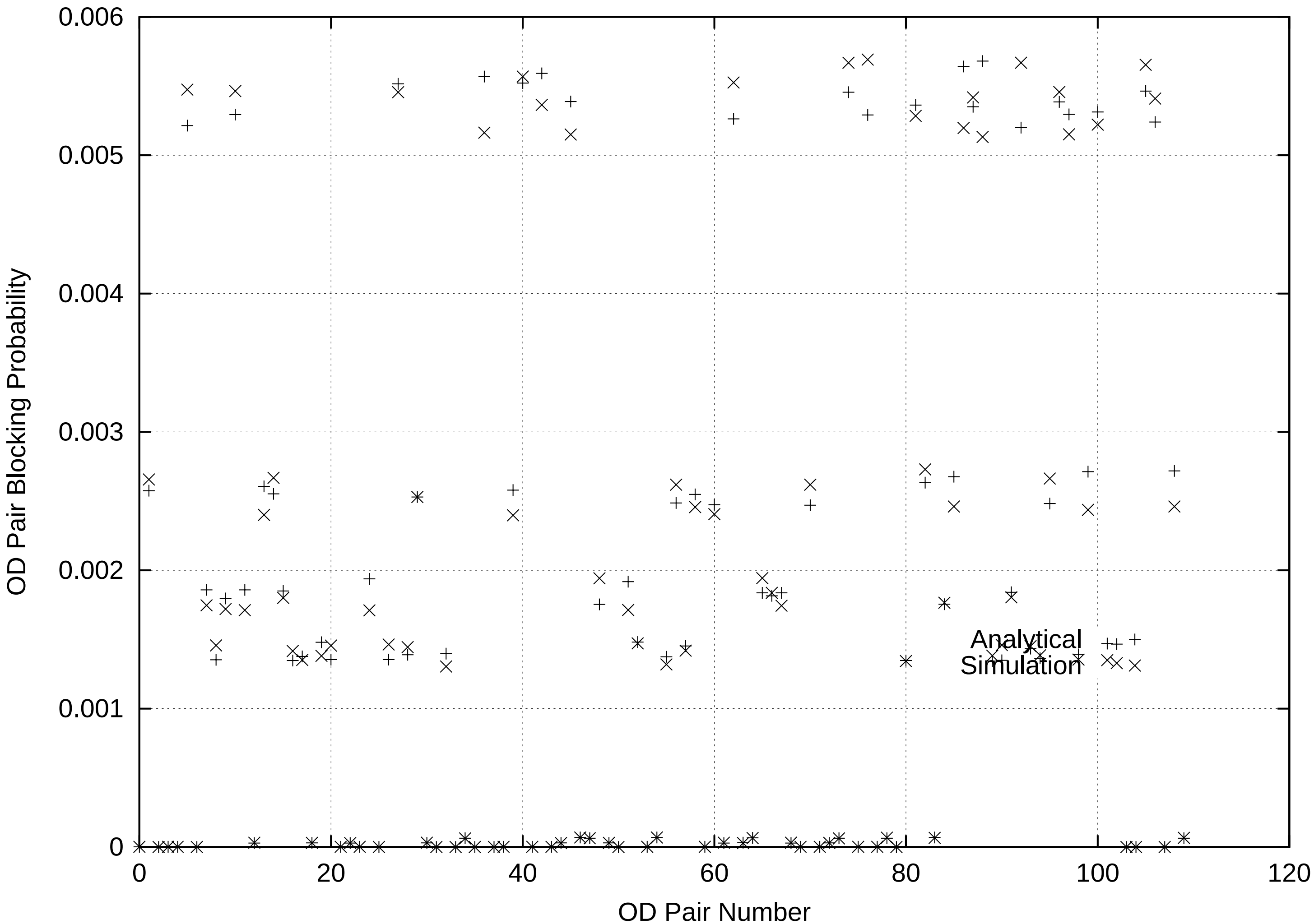
Blocking Probability for Class 3 with routing scenario (a), moderate arrival rate 0.12 per unit time, per OD pair



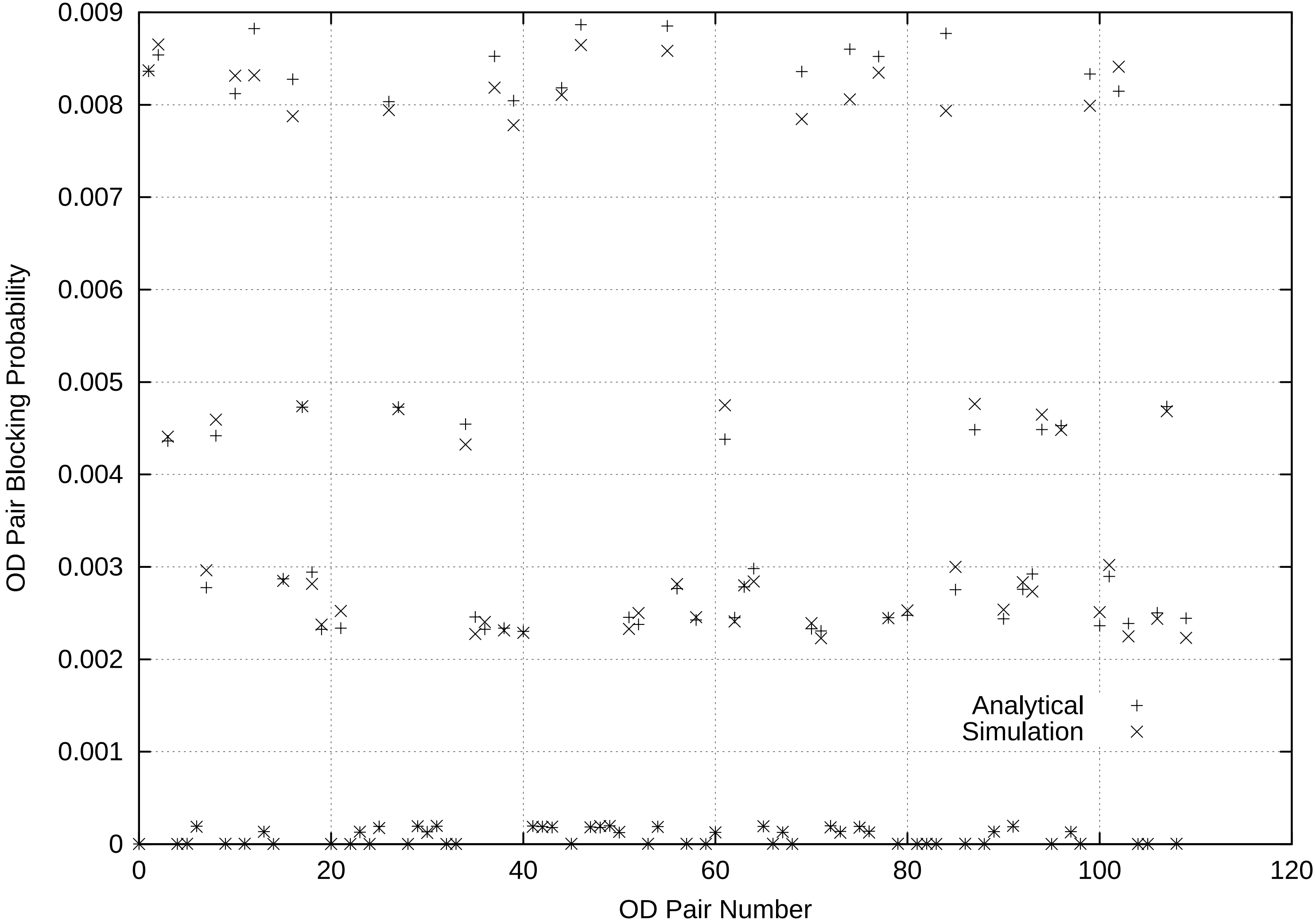
Blocking Probability for Class 1 with routing scenario (b), moderate arrival rate 0.12 per unit time, per OD pair



Blocking Probability for Class 2 with routing scenario (b), moderate arrival rate 0.12 per unit time, per OD pair



Blocking Probability for Class 3 with routing scenario (b), moderate arrival rate 0.12 per unit time, per OD pair



Approximate Blocking Probabilities for Multiclass Services in Wavelength Routed Optical Networks- **Our Contributions**

- We compute approximate blocking probabilities for *multiclass services* on optical WDM network. We develop fixed-point approximation algorithms for different static and dynamic routing policies: Fixed Routing (FR), Least Loaded Routing (LLR) and Fixed Alternate Routing (FAR).
- Our results generalize previous results for "single-class services" (Birman [1], etc.)
- Network topology assumed arbitrary, unlike previous works.
- Class-specific route sets in our work.
- We use *knapsack* approximation for idle wavelength distribution in links. We also give a recursive procedure for that. This approximation never before used in optical WDM networks (with wavelength continuity constraints).
- For FR case, we bring out an interesting observation that the per class approximate blocking probability can be expressed as sum of two terms: one independent of wavelength continuity constraint and the other solely dependent on the constraint.

Reduced Load Approximations for Large-Scale Optical WDM Networks offering Multiclass Services – **Our Contributions**

- We propose a performance analysis for *multiclass* services in large-scale optical WDM networks with multiple optical WDM networks interconnected with each other.
- Large-scale optical network infrastructure architecture with optical WDM networks in metro/regional and core backbone networks is a recent emergence (Zhu, Jukan, Ammar).
- To our knowledge, no analytical methodology exists for performance evaluation for large-scale optical networks, even for single class services.
- We present a reduced load approximation scheme for performance analysis; we develop fixed-point approximation algorithm for computing *per class end-to-end approximate blocking probabilities*.

Our Contributions (Cont'd)

- We assume that different network segments (optical WDM networks) in the large-scale network may fall under different administrative domains, and have
  - Different network topologies
  - Different resource capabilities - link capacities (in wavelengths)
  - Have the flexibility to implement their own wavelength routing policies; we consider that they implement one of the following static and dynamic routing policies: Fixed Routing (FR), Least Loaded Routing (LLR), and Fixed Alternate Routing (FAR).
  - Wavelength continuity constraint *within* network segment routes (however we assume gateway crossconnects have full wavelength conversion capabilities).
- (Our analysis caters to these above requirements.)

Conclusions

- We have considered important resource allocation and performance analysis for *multiclass* services in all-optical WDM networks.

Key Reference List

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2. S.P. Chung, A. Kashper, and K.W. Ross, Reduced Load Approximations for Multirate Loss Networks, *IEEE Trans. Comm.*, Aug. 1993.
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8. D. Mitra, J.A. Morrison, and K.G. Ramakrishnan, ATM Network Design and Optimization: A Multirate Loss Network Framework, *IEEE/ACM Trans. Networking*, Aug. 1996.
9. J.W. Roberts, A Service System with Heterogeneous User Requirements, *Performance of Data Comm. Systems and Their Applications*, North Holland, 1981.
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12. M. Wright, Interior Point Methods for Constrained Optimization, *Acta Numerica*, 1992.
13. Y. Zhu, A. Jukan, and M. Ammar, Multi-segment Wavelength Routing in Large-Scale Optical Networks, *Proc. IEEE ICC,* 2003.

Comments on Computational Approach

- It is difficult to analytically prove whether
  - The fixed-point approximation algorithms for different routing policies converge to a solution
  - If so, whether the solution is unique.
- In fact, this is not proven for even the simpler case of single class problem (Birman [1]). This remains a topic for future research.
- However, in our computational experience, the algorithms converged to a solution for all the network topologies considered (next slide).

Some New Observations

- Through Observations 3.3.1 – 3.3.3, we bring out novel observations for FR case.

- *Observation 3.3.1:* Specialized for full-wavelength conversion case.
- *Observation 3.3.2:* We bring out the observation that L_o^s can be decomposed into two terms: one independent of wavelength continuity constraint and the other dependent solely on the wavelength continuity constraint.
- *Observation 3.3.3:* Specialized for single class case (reduces to expression in Birman [1]).

Backgrounds

“Multirate loss network with fixed routing”

- Ross TCOM Aug93
  - Circuit switch
  - Multicalss: each class defined by call arrival rate, average holding time, number of circuits (rates) requested per call, and a route. (One fixed route per class)
  - Kelly 86, product-form among “classes”

Reduced load approximation

- Assuming that blocking occurs independently from link to link and
- That the offered load to a link is reduced by blocking on other links (reduced load).
- Leads to nonlinear fixed-point eqn.

Reduced load approximations for multiclass (multirate)

- Kelly's approximation: Accurate for single-rate loss network, inaccurate for multi-rate.
- Knapsack approximation: compute blocking prob. of each class at each link.
- Pascal Approximation

Multirate loss network with state-dependent routing

- Ross, ToN feb 93
- Extension of Kelly, Math. Oper. Res. 90 (single-rate, reduced load approx. for state-dependent routing) to multi-rate.

Motivation

- In our work, we make new contributions to the areas of resource allocation and performance analysis of *multiclass* services in optical WDM networks. To our best knowledge, ours is the first contribution in these areas.
- Background for our work -
  - Impressive recent advances in optical networking - emerging network control solutions would increasingly automate and alleviate the process of service provisioning in networks.
  - Allows the network operators to efficiently build-in new service types into the networks; service differentiation allows operators to cater to requirements of different types of clients; paves way for enhancing operational revenues/profitability.
  - Different types of services can be envisioned in optical WDM networks which differ in resource requirements (number of wavelengths) and subscription periods.
  - In such a setting, the need for efficient resource allocation methods and performance evaluation techniques are imperative; *our work focuses on these aspects*
- We also consider some important resource allocation problems in communication networks.

Key Reference List

1. A. Birman, Computing Approximate Blocking Probabilities for a Class of All-Optical Networks, *IEEE JSAC*, Jun 1996.
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