Resource Provisioning in Optical Networks

Invited Talk @IIT Indore, India

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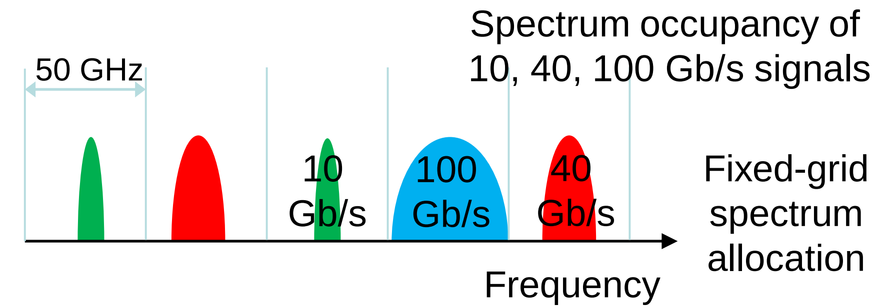
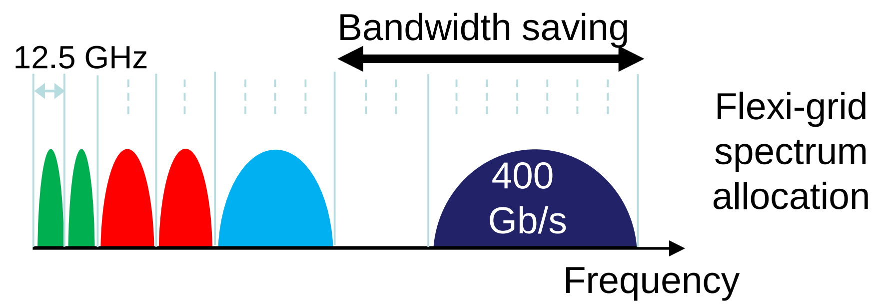
DLR

A Brief Overview of Optical Network Evolution

- Internet traffic growth, Big-data, Cloud computing and research networks driving deployment of Terabit/s
- Wavelength-division multiplexing
  - Used in backbone network (Gbit/s)
  - Tbit/s spectrum too broad to fit
  - 50/100 GHz fixed grid
  - Bandwidth wastage



- Elastic optical network (EON)
  - Finer and flexi-grid (6.25/12.5 GHz)
  - BVT (OFDM-based), switches
  - Better spectrum utilization
  - Superchannel support (Tbit/s)
  - Distance-adaptive modulation



Finer grid: frequency slot or slice

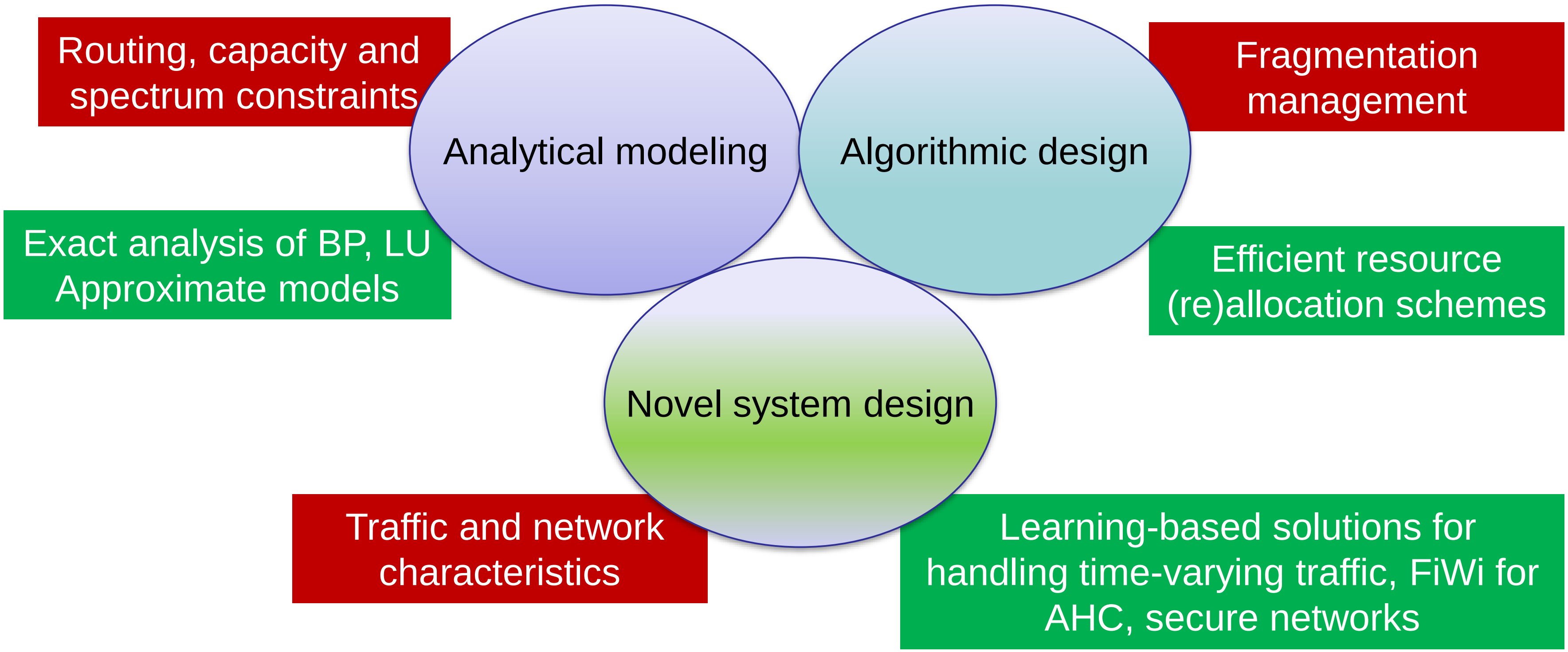
Elastic Optical Networking is Promising

- P. Winzer, “Optical Networking Beyond WDM,” *IEEE Photonics Journal,* vol. 4, no. 2, pp. 647–651, 2012.
- O. Gerstel, M. Jinno, A. Lord, and S. B. Yoo, “Elastic optical networking: A new dawn for the optical layer?" Communications Magazine, IEEE, vol. 50, no. 2, pp. s12{s20, 2012.

Resource Provisioning is a key Challenge in EONs

Resources: fibers, spectrum, transponders, etc. ➡ Lightpath (optical channel) establishment

Challenges: latency, impairments, routing, spectrum allocation, faults, security, etc.

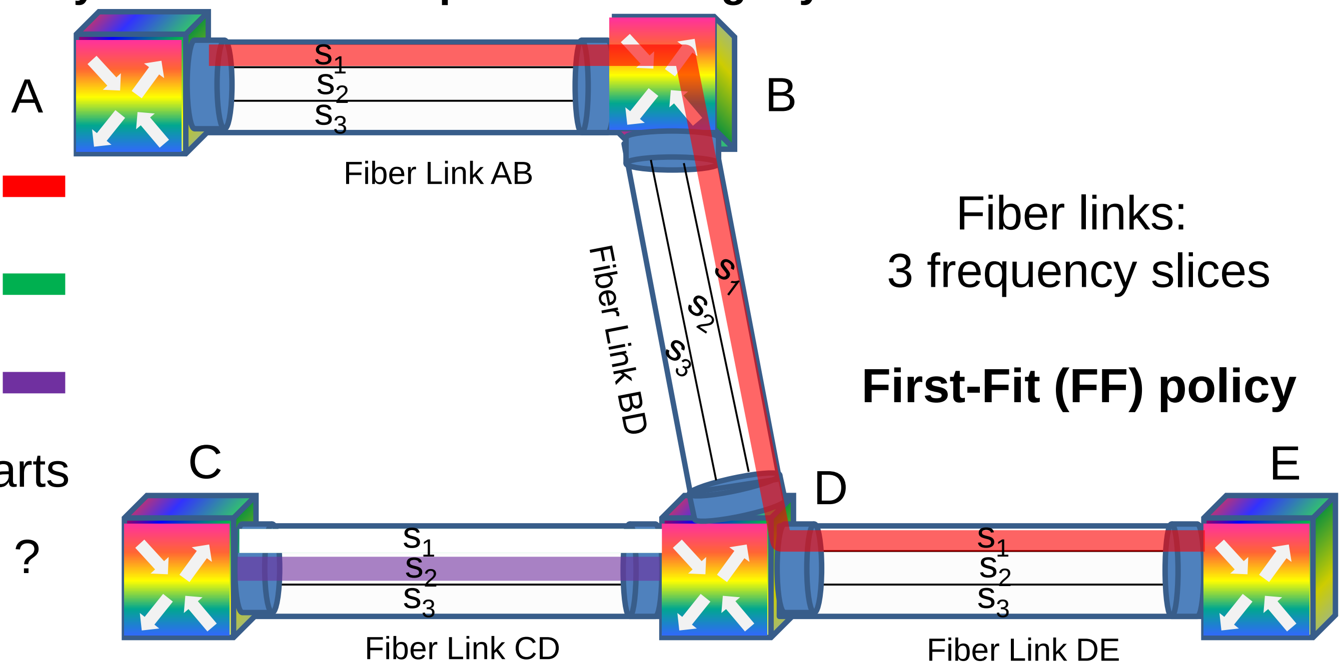


Challenges with Routing & Spectrum Allocation in EONs

- Routing and Spectrum Allocation (RSA) for lightpath establishment
  - **Routing:** Fixed, Fixed-alternate, Dynamic
  - **Spectrum allocation:** Random-Fit (RF), First-Fit (FF), Fragmentation-aware
  - **Spectrum continuity constraint** and **Spectrum contiguity constraint**

Time

- Request$_1$ A-E: 1 slice
- Request$_1$ C-D: 1 slice
- Request$_2$ C-D: 1 slice
- Connection$_1$ C-D: departs
- Request$_1$ C-E: 2 slices ?



Fiber links:
3 frequency slices

First-Fit (FF) policy

Spectrum fragmentation → Connection blocking probability ⬆ Resource utilization ⬇

RSA Modeling in Elastic Optical Networks (Stochastic)

1990 | 2012

Pre-WDM (Telephony) | WDM | EON | Time

Erlang model, 1920's $(M/M/c/c \ \& \ M/M/c)$

Kelly's reduced load model,1991

[Birman'1996; Sridharan and Sivarajan' 2004; Kuppuswamy and Lee'2009; etc.]

[Christodoulopoulos et al'; Yu et al; Peng et al' 2013; Beyranvand et al'2014; Singh and Jukan'2019, etc.]

- Exact models: accurate and useful for small networks

  *H. Beyranvand et al, IEEE TOC 2014 => a so-called (inaccurate) exact network Markov model

  **S. K. Singh and A. Jukan, INFOCOM 2019 => Exact network Markov model

- Approximate Models: less accurate, but scalable
  - Erlang-based models: Connection setup rate on a link j is $\alpha_k^j(\mathrm{x}) = \sum_{o:j\epsilon r(o)} \lambda_k^o$
  - Reduced load independence model $\alpha_k^j(\mathrm{x}) = \sum_{o:j\epsilon r(o)} \lambda_k^o \times \underbrace{\Pr[Z_{r(o)} \geq d_k | X_j = x_j]}_{\text{Reduced load contribution}}$
  - Reduced load correlation model: open problem

original external offered rate thinned by capability of demand acceptance

* H. Beyranvand et al, "An analytical framework for the performance evaluation of in EONs," IEEE Trans. on Comm., 2014.
** S. K. Singh, and A. Jukan, "Computing Blocking Probabilities in EONs with Spectrum Defragmentation," **INFOCOM**, 2019.

RSA Modeling in EONs: Our Approach

- Existing stochastic RSA models ignore key issues*
- Our work: Exact Network Markov model for small scale EONs, and Reduced Load Approximation models for large scale EONs
- Assumptions and limitations
  - Poisson arrival (λ_k^o) & exponential departure (μ_k)
  - Fixed-alternate routing; Spectrum allocation: Random-Fit (RF) or First-Fit (FF)
  - A class-k connection request is blocked if there are insufficient ($\leq d_k$) contiguous and continuous free slices on its routes.
- Notations and parameters

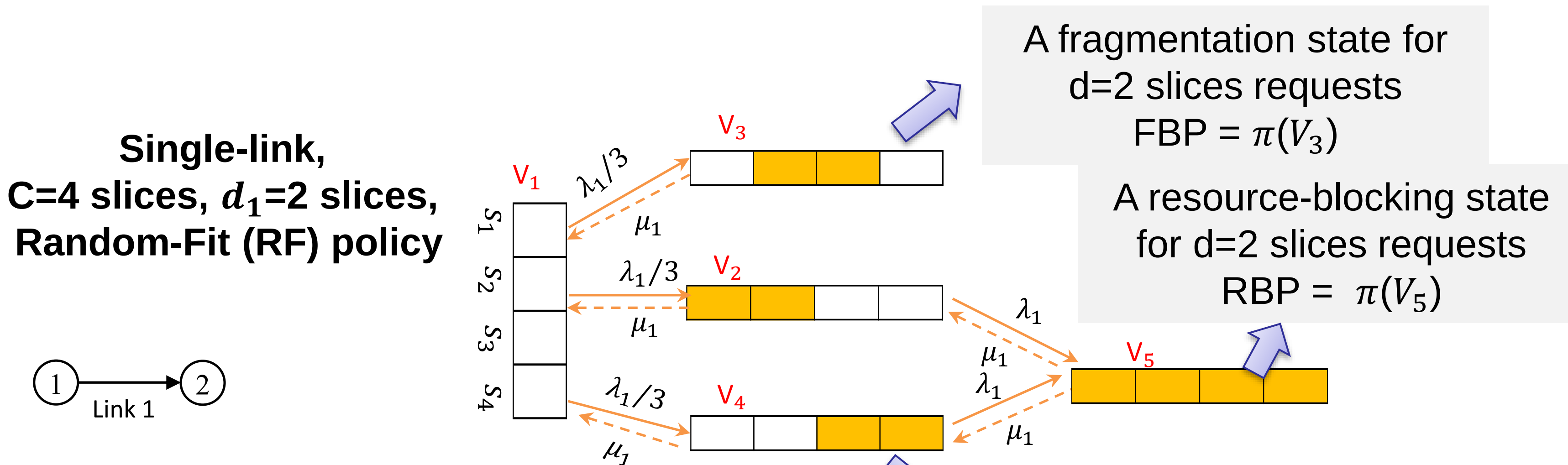
C	Capacity of each fiber link (in slices)
K	Number of bandwidth classes, k=1,2,…, K
d_k	Bandwidth demand of class-k connection (in slices)
$r(o)$	Routes between an origin-destination (OD) node-pair $o = \{1,2,\dots,\|O\|\}$
λ_k^o	Class-k connection request arrival rate on OD pair o
μ_k	Class-k connection departure rate

* 1.H. Beyranvand, M. Maier, and J. Salehi, “An analytical framework for…,” IEEE Trans. on Comm., vol. 62, no. 5, 2014.
2. L. Peng, C.-H. Youn, and C. Qiao, “Theoretical analyses of lightpath blocking performance in co-ofdm optical networks with/without spectrum conversion," IEEE Communications Letters, vol. 17, no. 4, pp. 789-792, 2013.

Exact Network Markov Model

- Exact Network Markov Model (Complexity: Non-polynomial)
  - Define network states: $V_i \equiv (S^1, S^2, \dots, S^{|J|})$, where a link state $S^j \equiv \left(s_1^j, s_2^j, \dots, s_C^j\right)$

    s_i^j = free/busy slice
  - Find transition rates, obtain stationary network state probabilities
  - Compute blocking probability



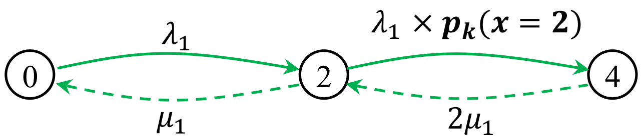
First-Fit (FF) generally generates lower # of fragmentation states

V_1, V_2, V_4 are non-blocking states for d=2 slices requests

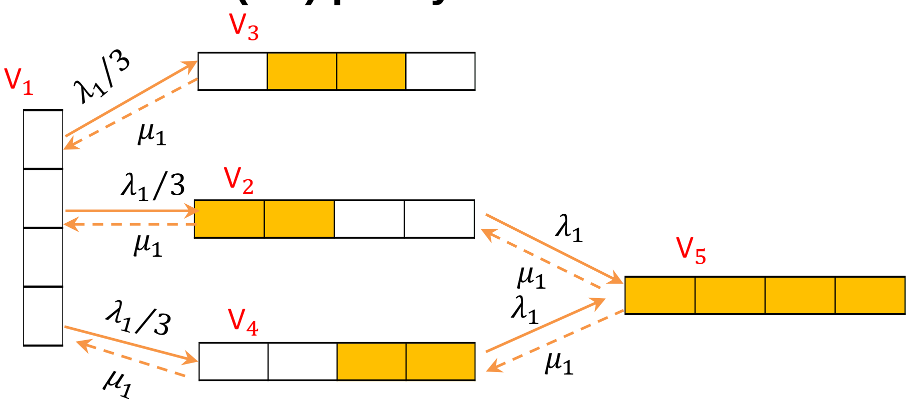
Approximate Network Models: Our Approach

- A Link state (X_j) is represented by # of occupied slices (x_j)
- Compute connection setup rates and departure rates for each link j
- Apply fixed-point iteration algorithm to compute state probabilities & BP

Approximation model



Single-link,
C=4 slices, d_1=2 slices,
Random-Fit (RF) policy



Exact model

Probability of Acceptance:

$$p_k(x) = \Pr[Z_{r(o)} \geq d_k | X_j = x_j]$$

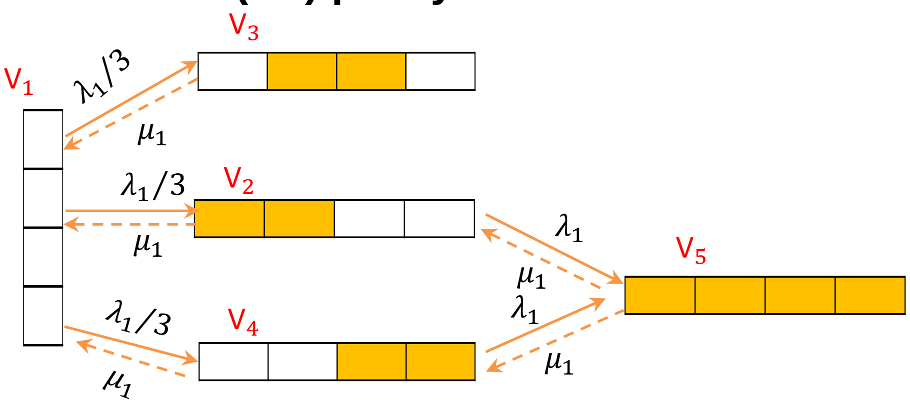
Approximate Probability of Acceptance Computation

- Ours
  1. Equiprobable Exact States (EES)
  2. Spectrum Occupancy Correlation (SOC)
  3. Uniform approximation

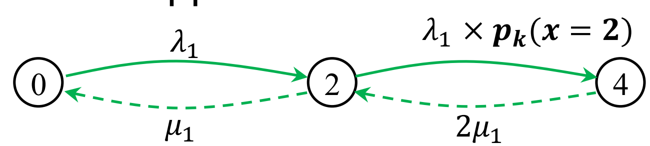
- Others*
  1. Kaufman-based
  2. Binomial approach

Simpler, not Reduced load model

Single-link,
C=4 slices, d_1=2 slices,
Random-Fit (RF) policy



Approximation model



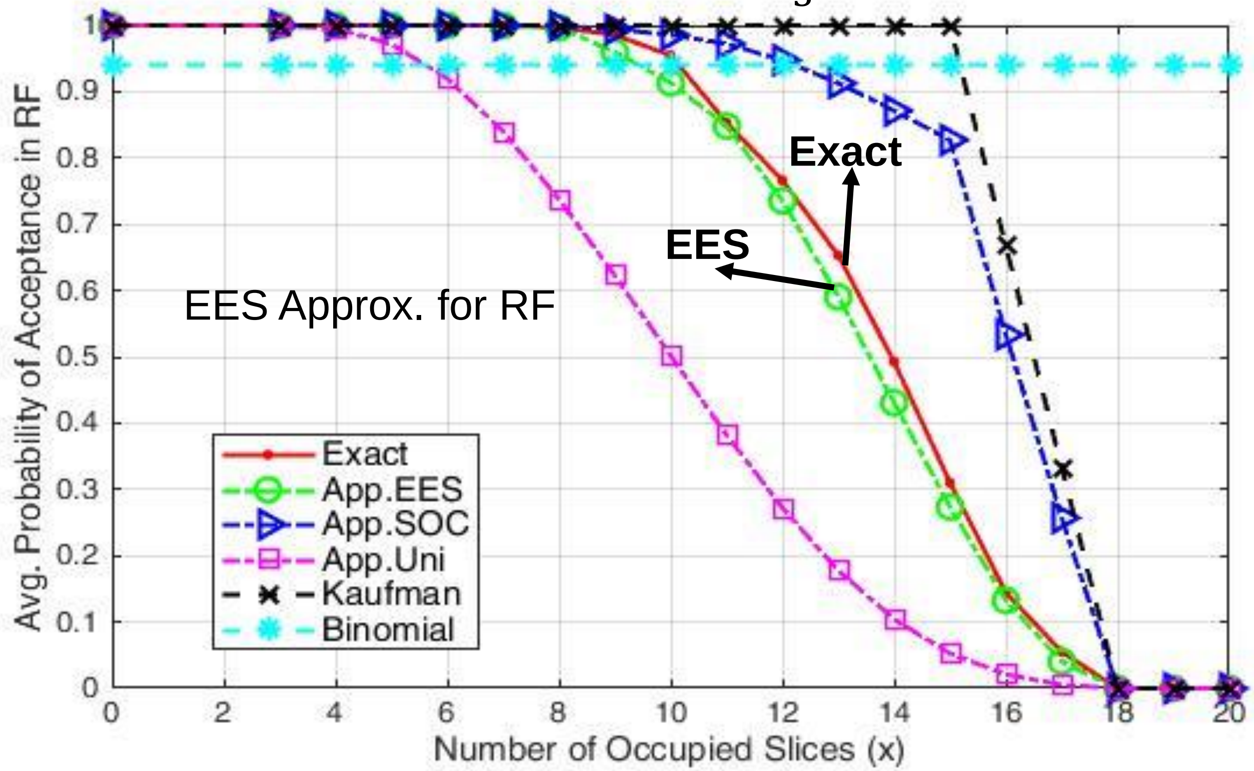
Approximation methods	Prob. of Accept. $p_k(x=2)$
EES	2/3
SOC	Load-dependent
Uniform	3/6
Kaufman	1
Binomial	Load-dependent

Ignores valid spectrum patterns

*[1] H. Beyranvand et al, “An analytical framework for the performance evaluation in EONs,” IEEE Trans. on Comm., 2014.
[2] L. Peng et al, “Theoretical analyses of lightpath blocking performance …in EONs," IEEE Comm. Lett, 2013.

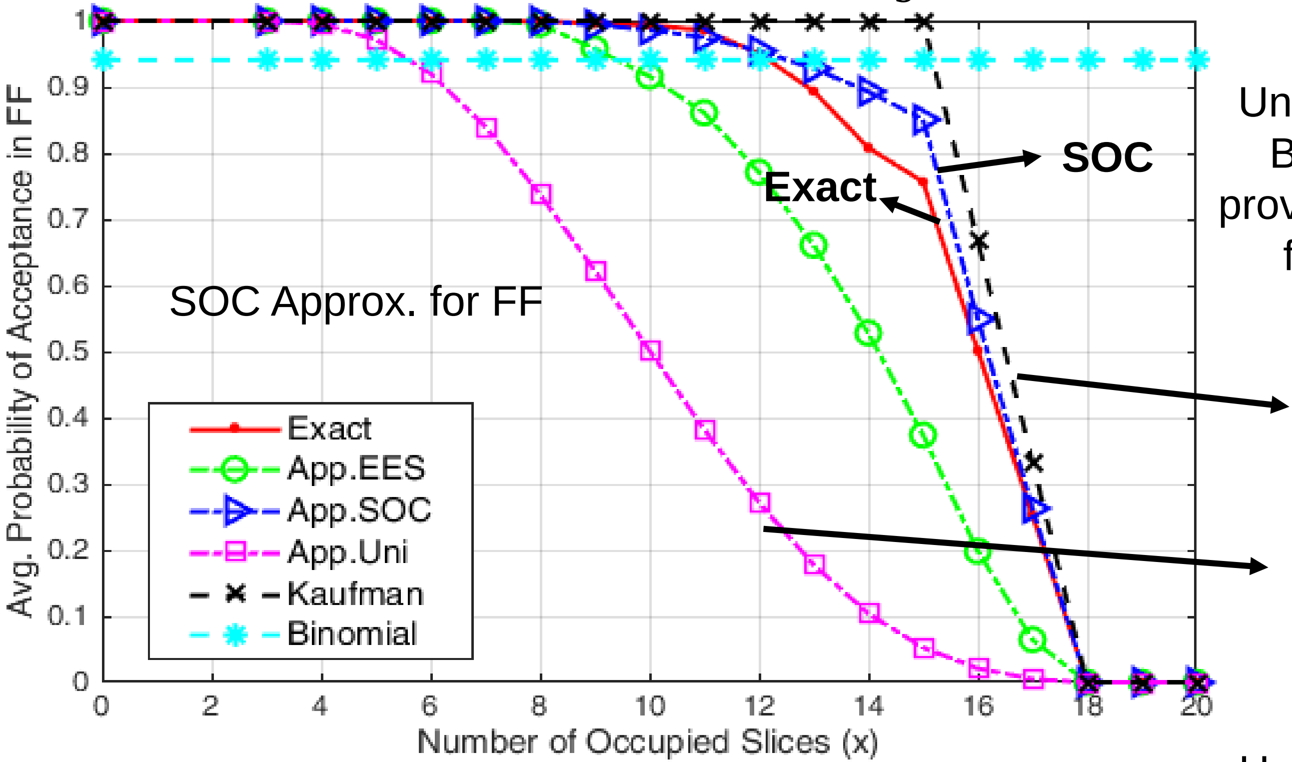
Comparison of Various Approximations under RF

- Link capacity C = 20 slices; Demands (d_k)= {3,4,5} slices, offered load=1.2 Erlang;
- Avg. probability of acceptance $p(x) = \frac{1}{3}\sum_{k=1}^{3} p_k(x)$



Comparison of Various Approximations under FF

- Link capacity C = 20 slices; Demands (d_k)= {3,4,5} slices, offered load=1.2 Erlang;
- Avg. probability of acceptance PoA $\mathrm{p}(x) = \frac{1}{3}\sum_{k=1}^{3} p_k(x)$



Uniform, Kaufman, Binomial do not provide different PoA for RF and FF

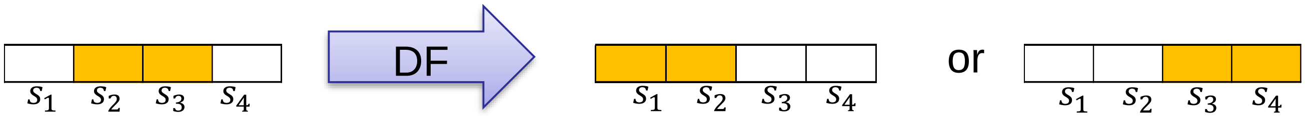
Kaufman Overestimates

Uniform Underestimates

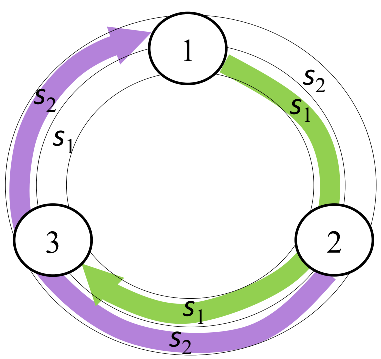
Binomial Under/overestimates

Spectrum Fragmentation is Inevitable in EONs

- Spectrum defragmentation is a solution
- **Defragmentation (DF)**: A resource reallocation scheme to reconfigure connections in EONs to consolidate a large block of free slices



- Assumptions*: reactive trigger, exponential reconfiguration time
- **Exact DF model**: include DF states, network transits to least-fragmentation state(s) after reconfiguration and accepts of waiting connection(s)
- Some fragmented states cannot be defragmented in ring/mesh networks



Approx. Probability of Acceptance under DF:

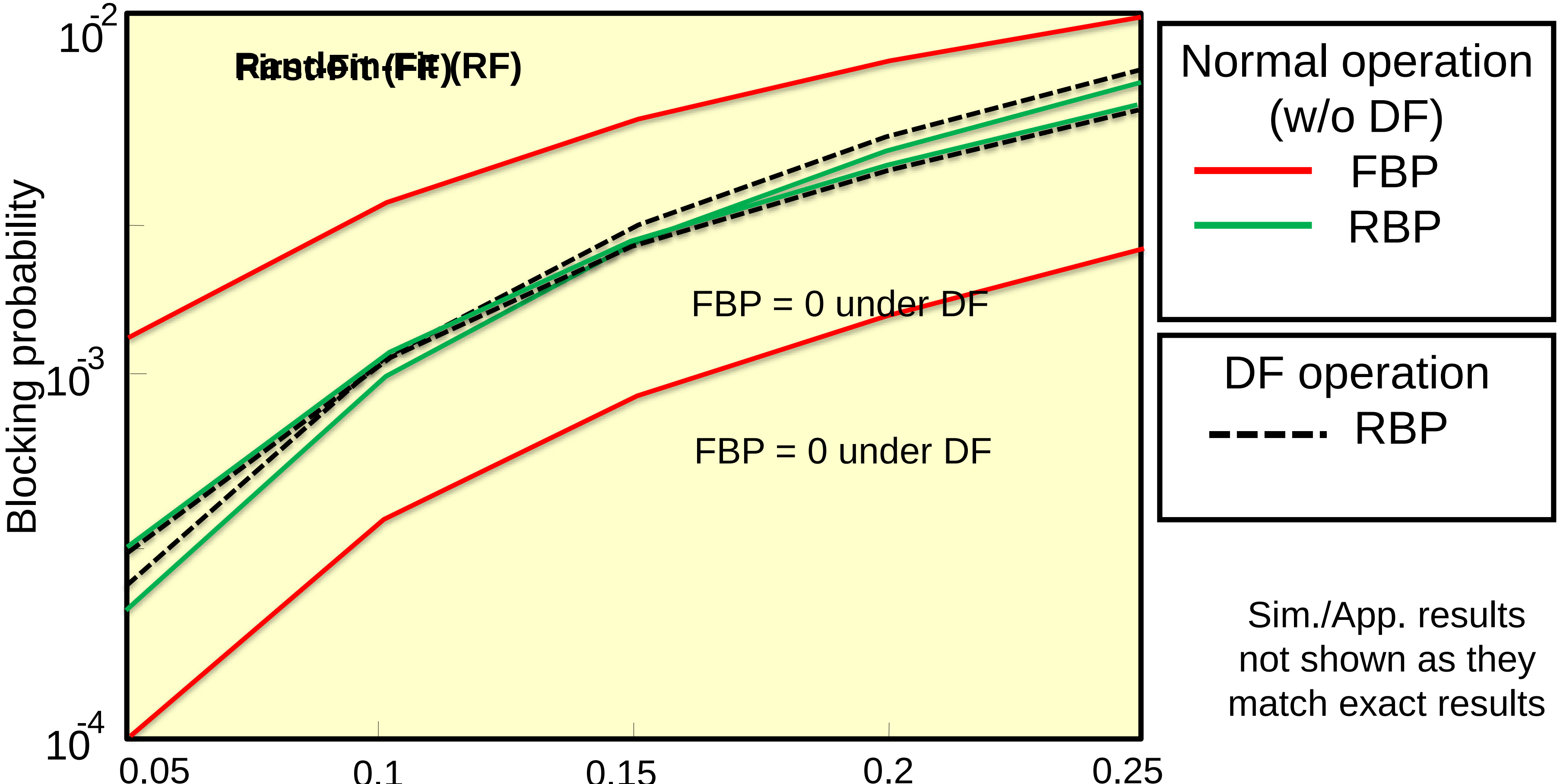
$$p_{k,DF}^{App.EES}(\boldsymbol{x_r}) = \prod_{i=1}^{h} \frac{|\mathbb{NB}(x_{j_i},k)|}{|\Omega_S(x_{j_i})|} + \prod_{j_i \in r:\mathbb{FI}(x_{j_i},k)\neq 0} \frac{|\mathbb{FI}(x_{j_i},k)|}{|\Omega_S(x_{j_i})|}$$

.*S. K. Singh, and A. Jukan, “Computing Blocking Probabilities in EONs with Spectrum Defragmentation," **INFOCOM**, 2019.

Impact of DF in Networks with Bus Topology

2-link network (Exact results)

Link capacity C=10 slices, demands (d) = (3,4) slices, μ_k=1, mean reconfig time=0.001



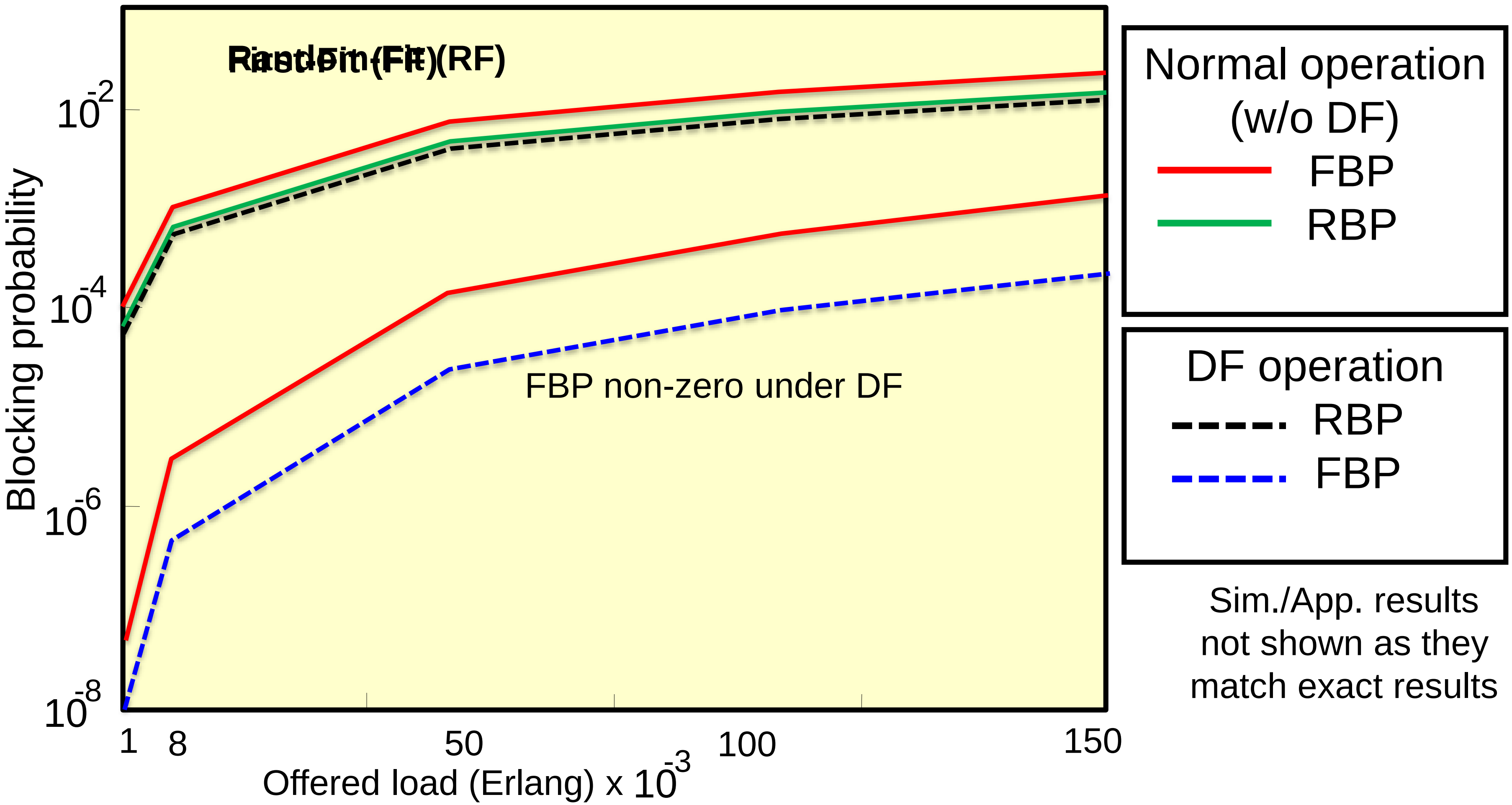
Offered load (Erlang) = $\sum_k \sum_{o:} \lambda_k^o \times 1/\mu_k$

Sim./App. results not shown as they match exact results

Impact of DF in Networks in Ring/Mesh Topology

3-node ring network (Exact results)

Link capacity C=7 slices, demands (d) = (3,4) slices, μ_k=1, mean reconfig time=0.001

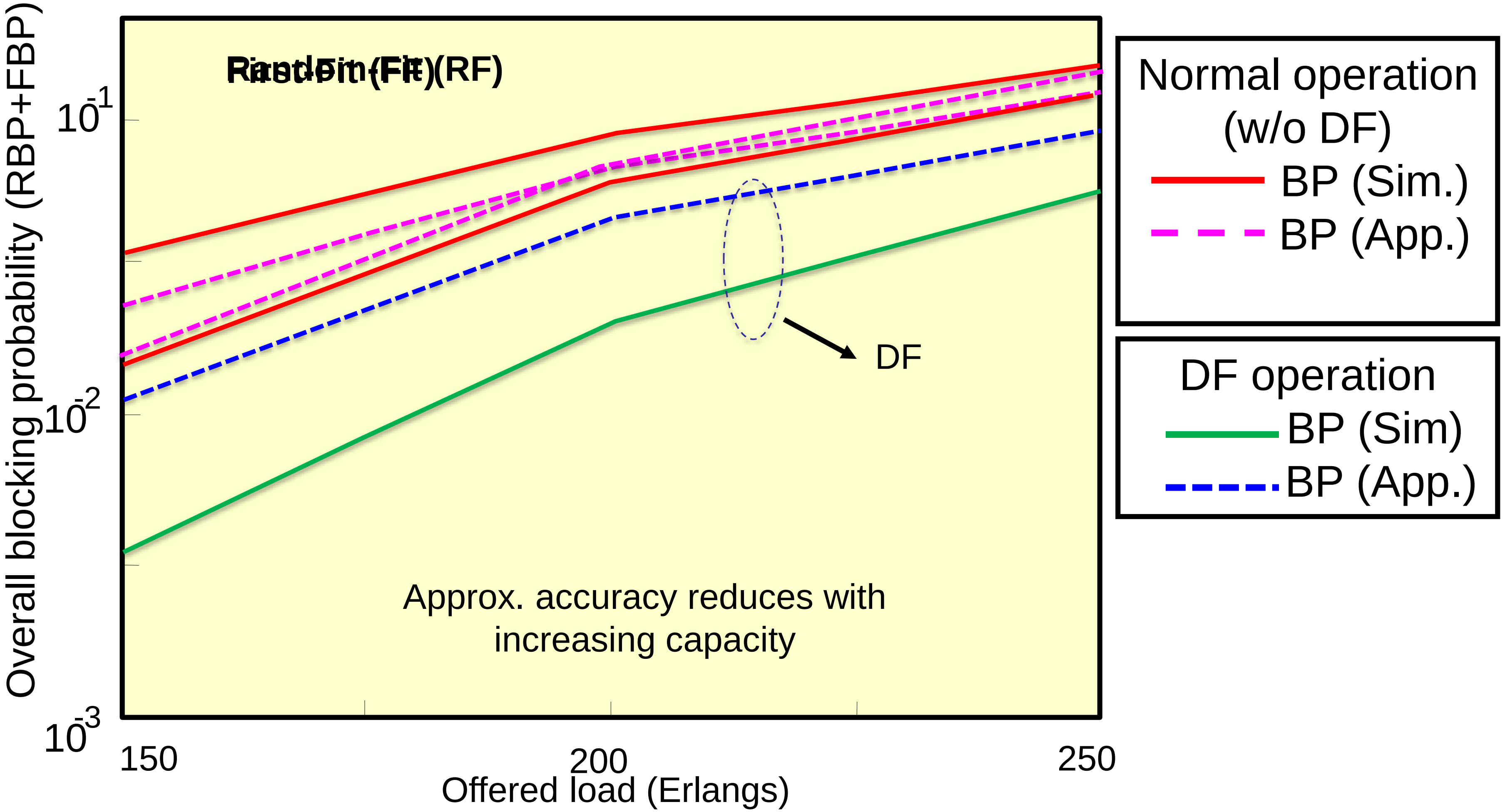


Sim./App. results not shown as they match exact results

Defragmentation Impact in a Large Scale Network

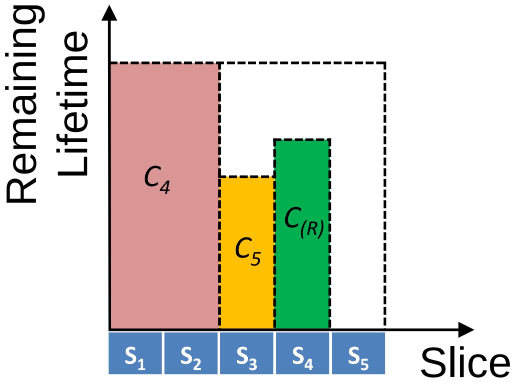
14-node NSF network with 182 OD pairs (Simulation and Approx.)

Link capacity C=100 slices, demands (d) = (3,4,6) slices, μ_k=1, mean reconfig time=0



Algorithmic Design of Efficient Resource Allocation

- Fragmentation a multidimensional problem
  - spectral, time and spatial
- Holding-Time-Aware Resource Allocation (HTA-RA) scheme*
  - Use residual lifetime of connections



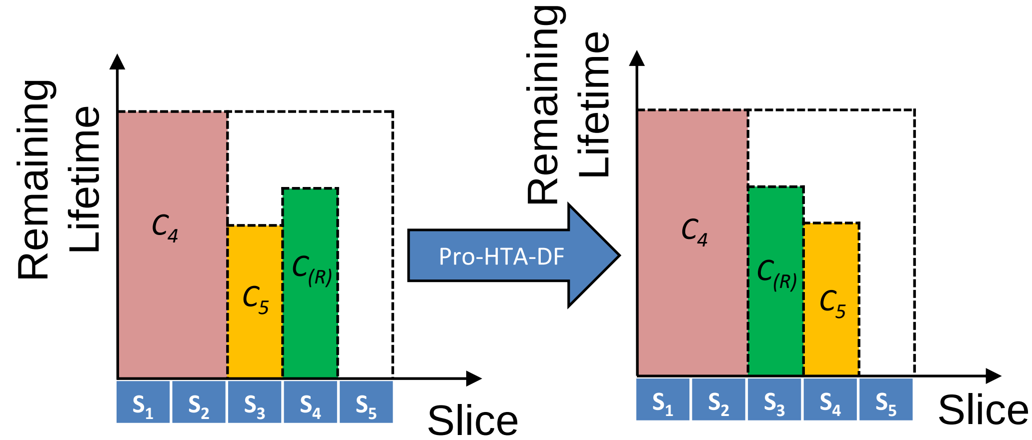
- In dynamic environment, Holding-Time-Aware Defragmentation (HTA-DF) is essential

*S. K. Singh and A. Jukan, "Efficient Spectrum Defragmentation with Holding Time Awareness in EONs," IEEE/OSA Journal of Optical Communications and Networking, vol. 9, no. 3, pp. B78-B89, 2017.

Algorithmic Design of Efficient Defragmentation

- Proactive approach

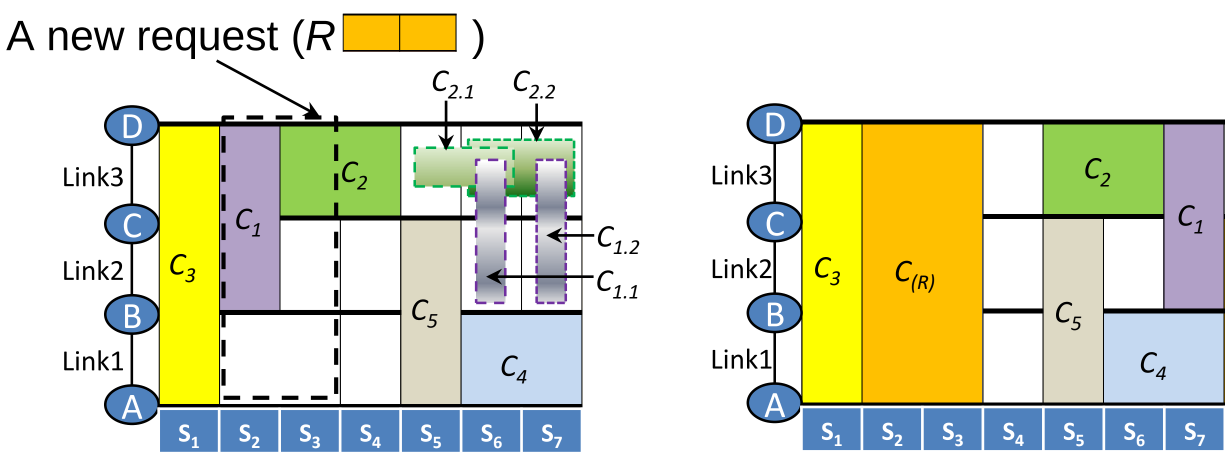
  (Pro-HTA-DF)



(a) Before DF (b) After DF

- Reactive approach

  (Re-HTA-DF)

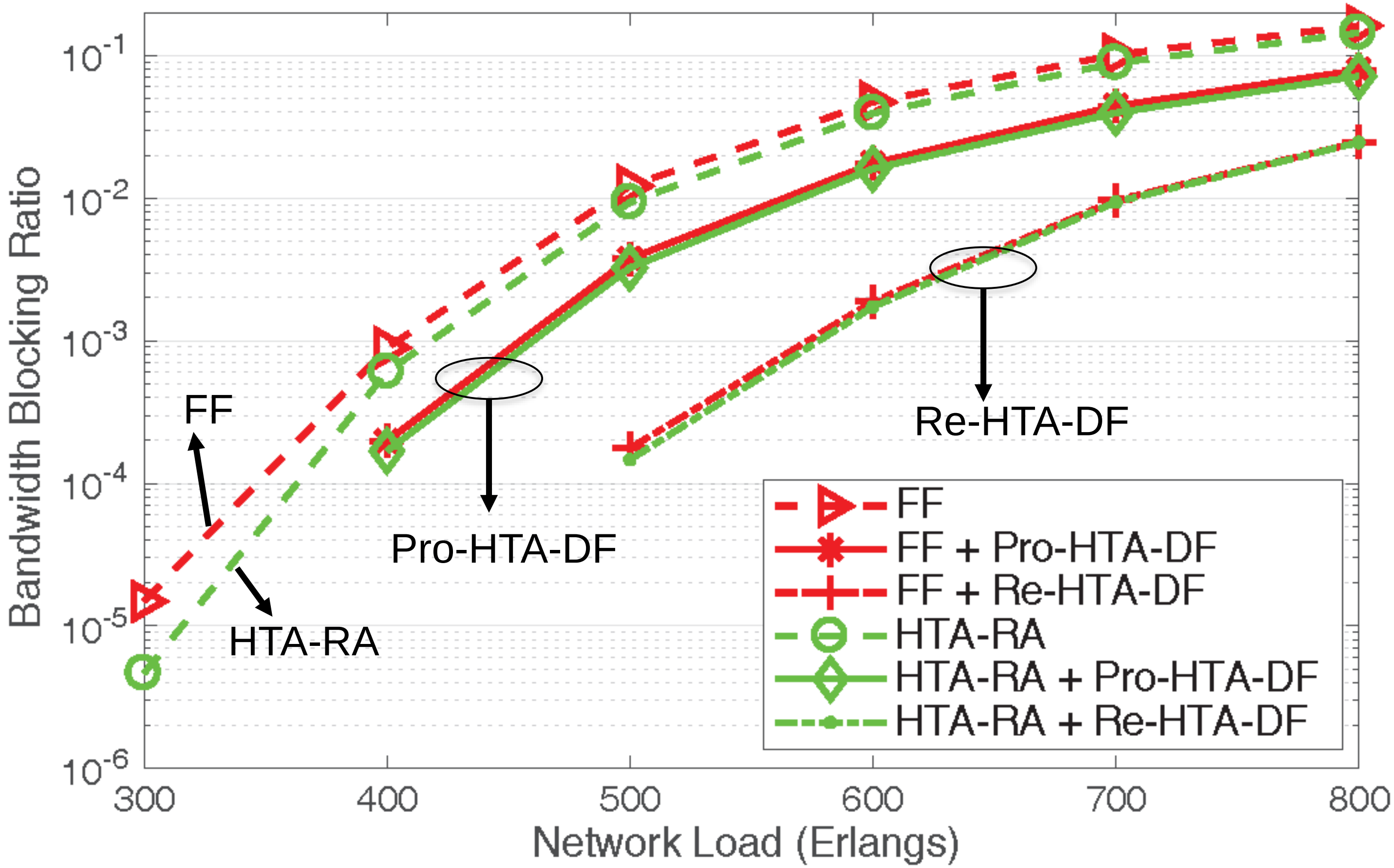


*S. K. Singh and A. Jukan, “Efficient Spectrum Defragmentation with Holding Time Awareness in EONs," IEEE/OSA Journal of Optical Communications and Networking, vol. 9, no. 3, pp. B78-B89, 2017.

Resource Allocation with Proactive/Reactive DF?

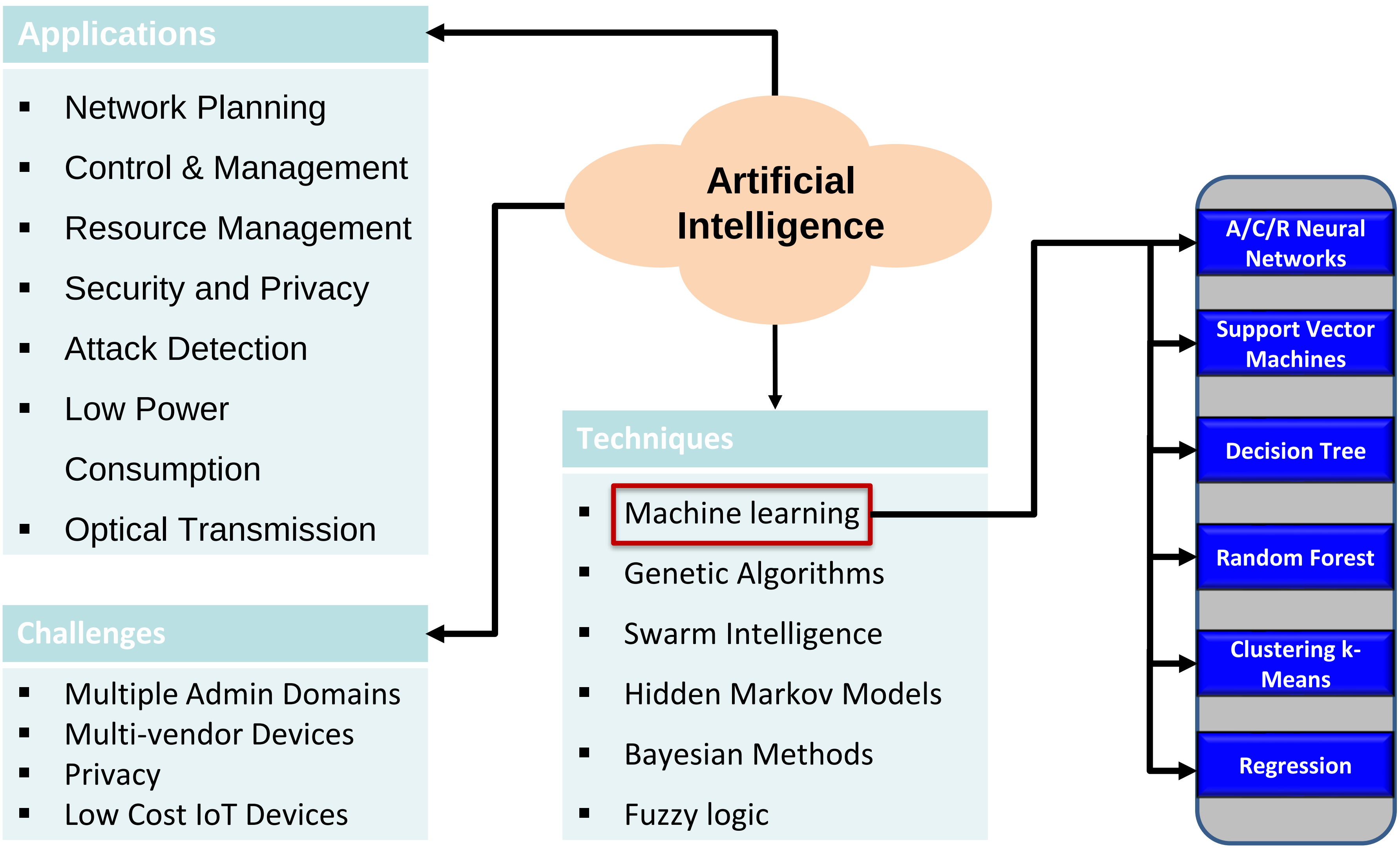
- **14-node NSF network with 21 bidirectional links**

Link capacity C=200 slices, demands (d) = (10,40,100) Gbit/s, DP-QPSK



*S. K. Singh and A. Jukan, “Efficient Spectrum Defragmentation with Holding Time Awareness in EONs," IEEE/OSA Journal of Optical Communications and Networking, vol. 9, no. 3, pp. B78-B89, 2017.

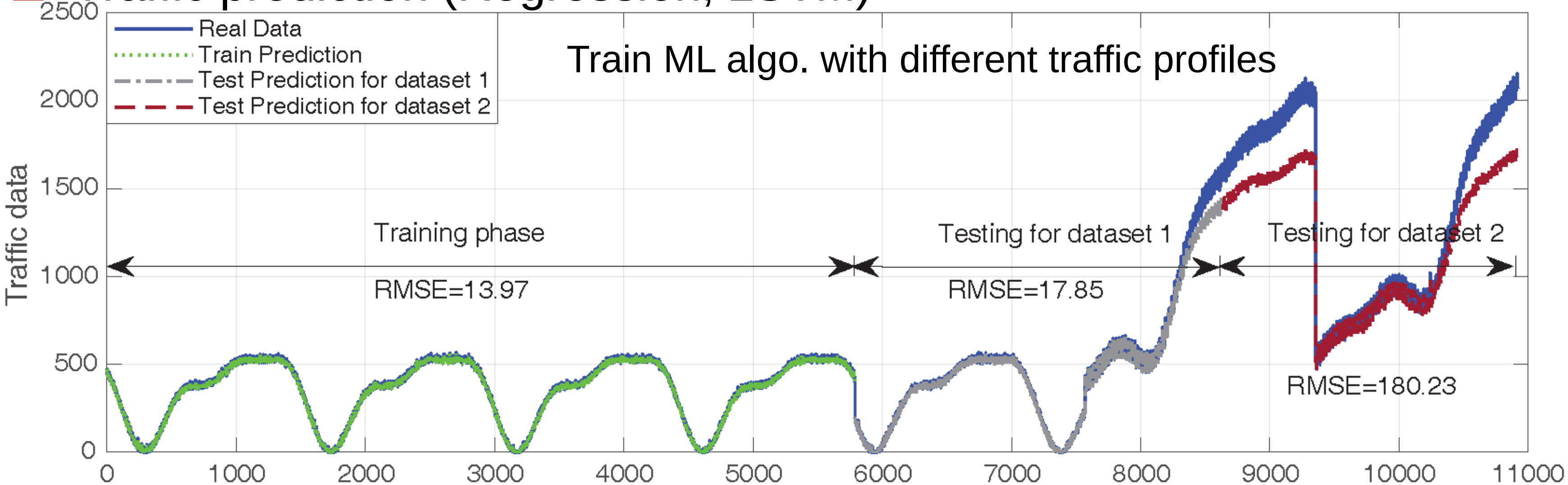
Resource Management & Novel System Design with AI*



*J. Mata, I. de Miguel, R. J Duran, and N. Merayo, S. K Singh, A. Jukan, and M. Chamania, “Articial intelligence (AI) methods in optical networks: A comprehensive survey,” Optical Switching and Networking, vol. 28, pp.43-57, 2018

Handling Time-Varying Traffic in ODCN with ML

- DC traffic are diverse, bursty (ON/OFF), service time heavy-tailed distr.
- ML-assisted efficient resource (re)allocation algorithms*
  - Route a new request along a lightpath whose residual life is comparable to the request's estimated mean service time.
- Traffic prediction (Regression, LSTM)

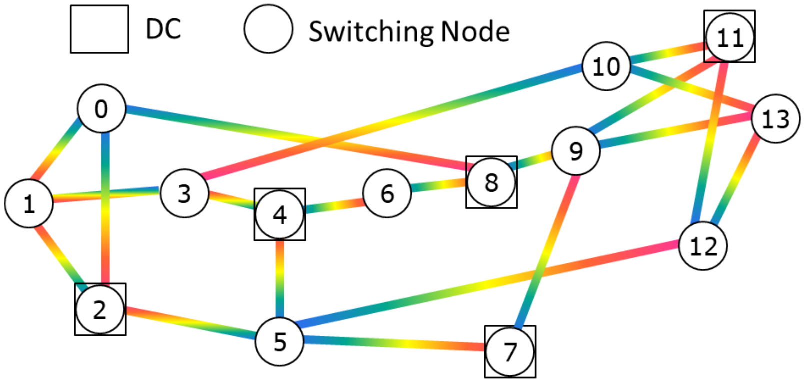


Time-varying traffic $$m(t) = \alpha + \sum_{k=1}^{n} \beta_k \times \sin(\omega_k t + \phi_k)$$

* S. K. Singh and A. Jukan, "Machine Learning-based Prediction for Resource (Re)allo-cation in Optical Data Center Networks," IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 10, issue 10, pp. D12-D28, 2018.

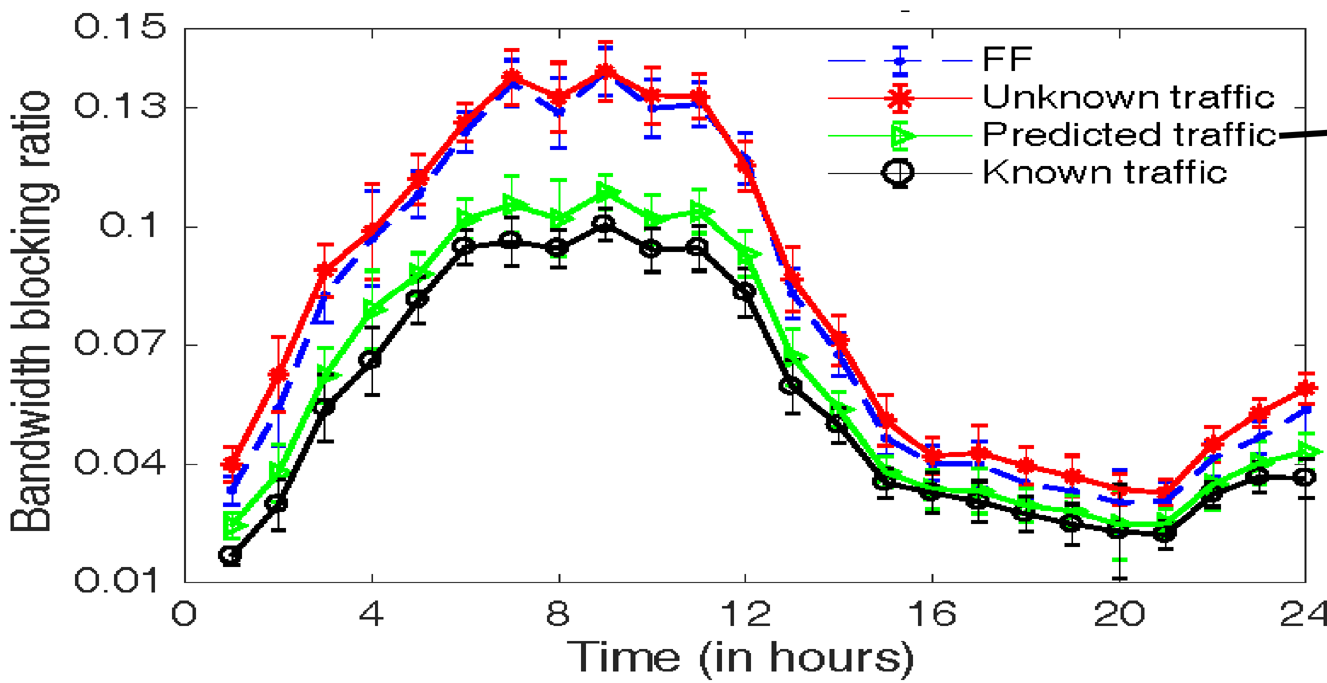
Performance of ML-Assisted Resource Allocation

Traffic Assumptions:
Demand: {10, 40, 100} Gbit/s
Time-varying **exponential** arrival rates: λ_κ
Time-varying **Lognormal** holding (service) times: μ_κ



Inter-ODCN (NSFNET)

Fiber link with 3 cores
Core capacity C=200 slices

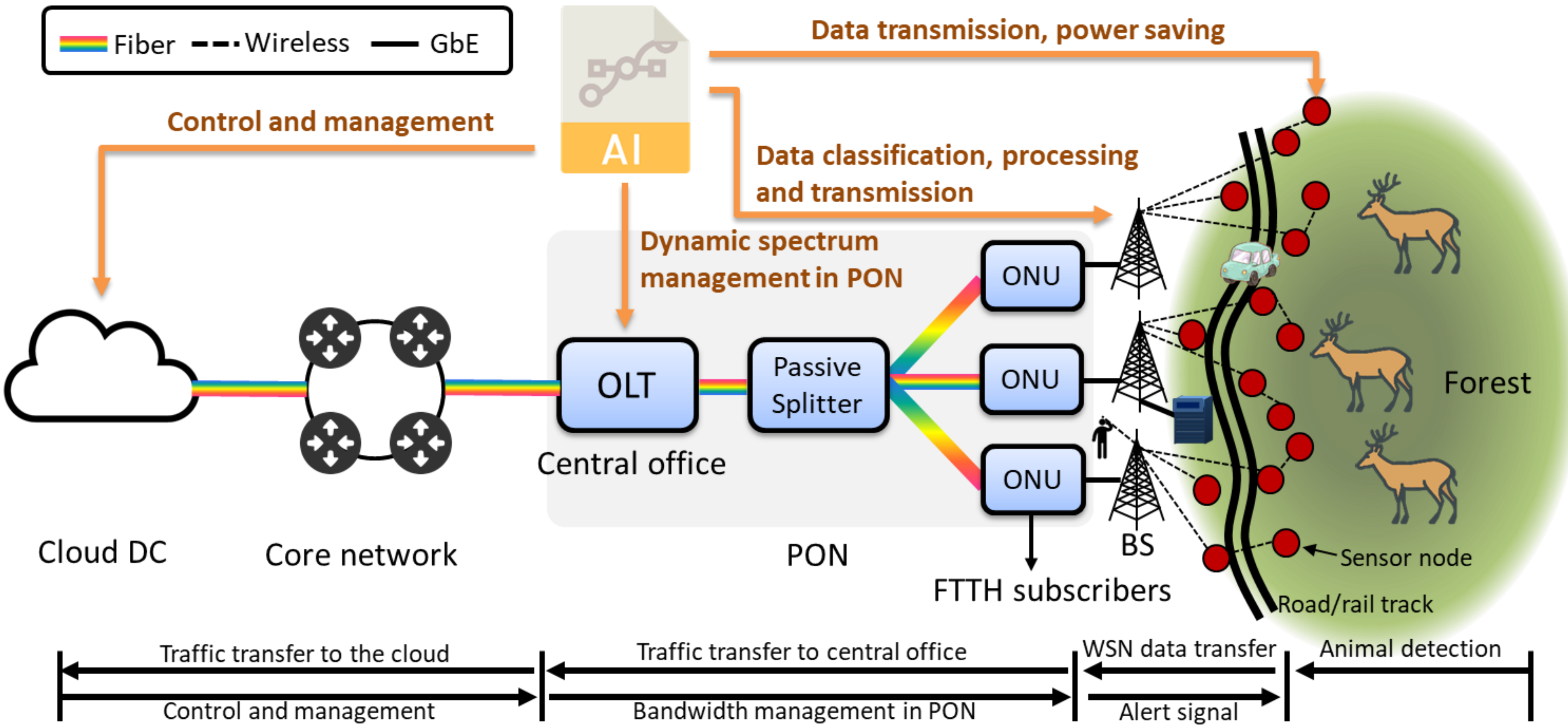


ML-assisted RA scheme

* S. K. Singh and A. Jukan, “Machine Learning-based Prediction for Resource (Re)allo-cation in Optical Data Center Networks," IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 10, issue 10, pp. D12-D28, 2018.

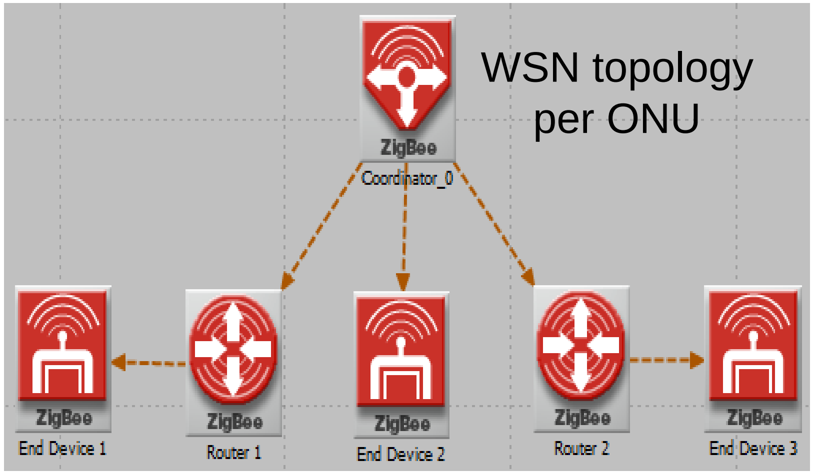
ML-Assisted Early Warning System*

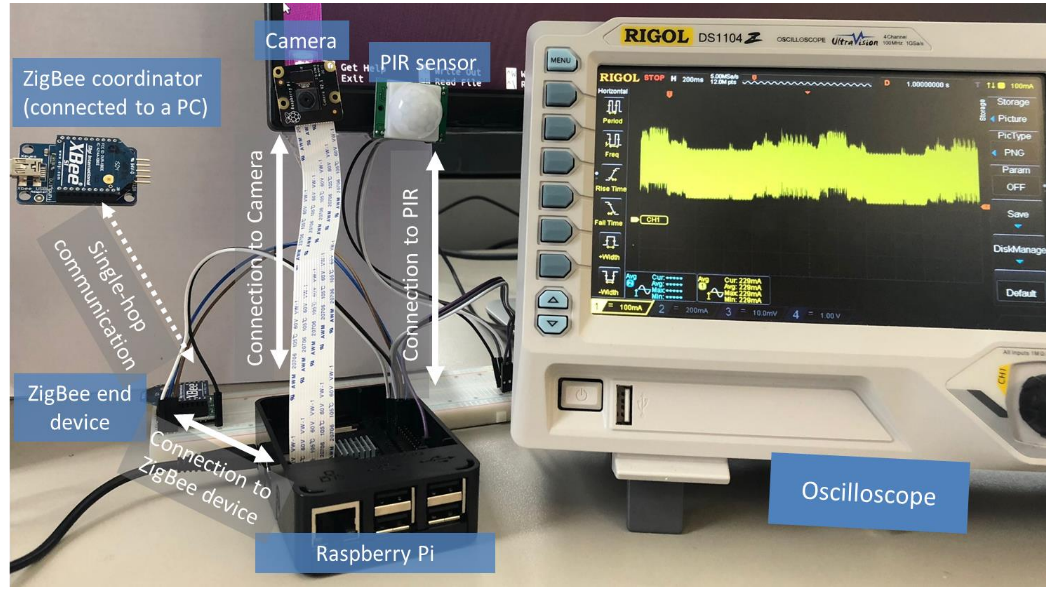
- Every year there are hundreds of thousands of Animal-vehicle collision worldwide



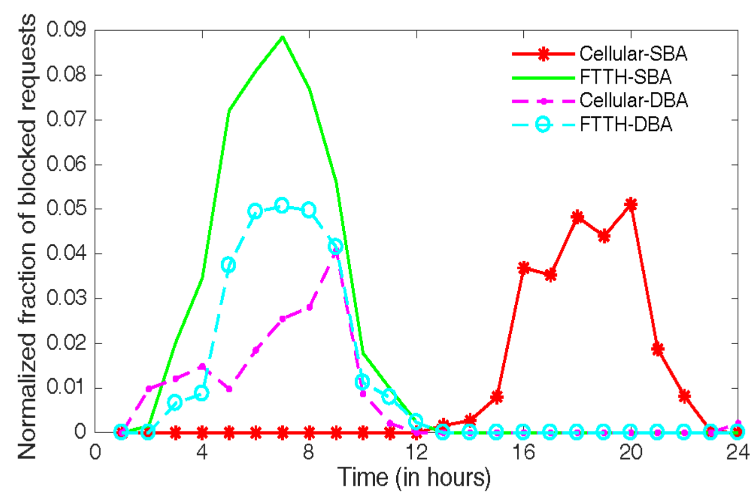
* S. K. Singh, F. Carpio, and A. Jukan, "Improving Animal-Human Cohabitation with Machine Learning in Fiber-Wireless Networks," *MDPI Journal of Sensor and Actuator Networks*, vol. 7, no. 3, 2018.

Simulation and Experimental Setup and Results

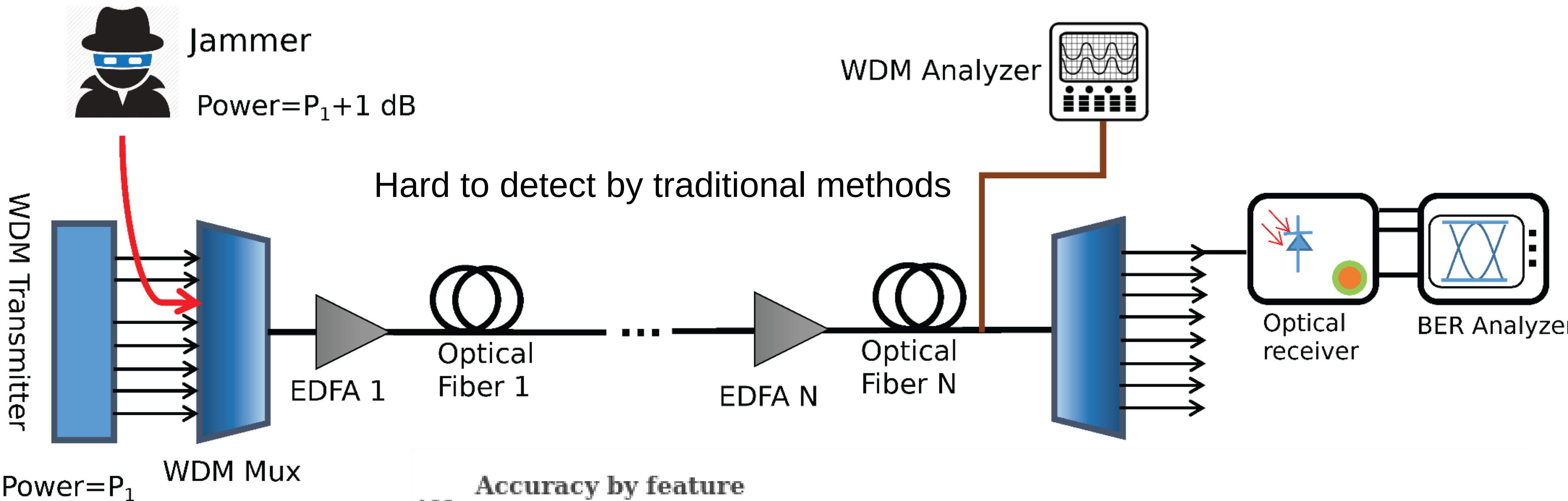




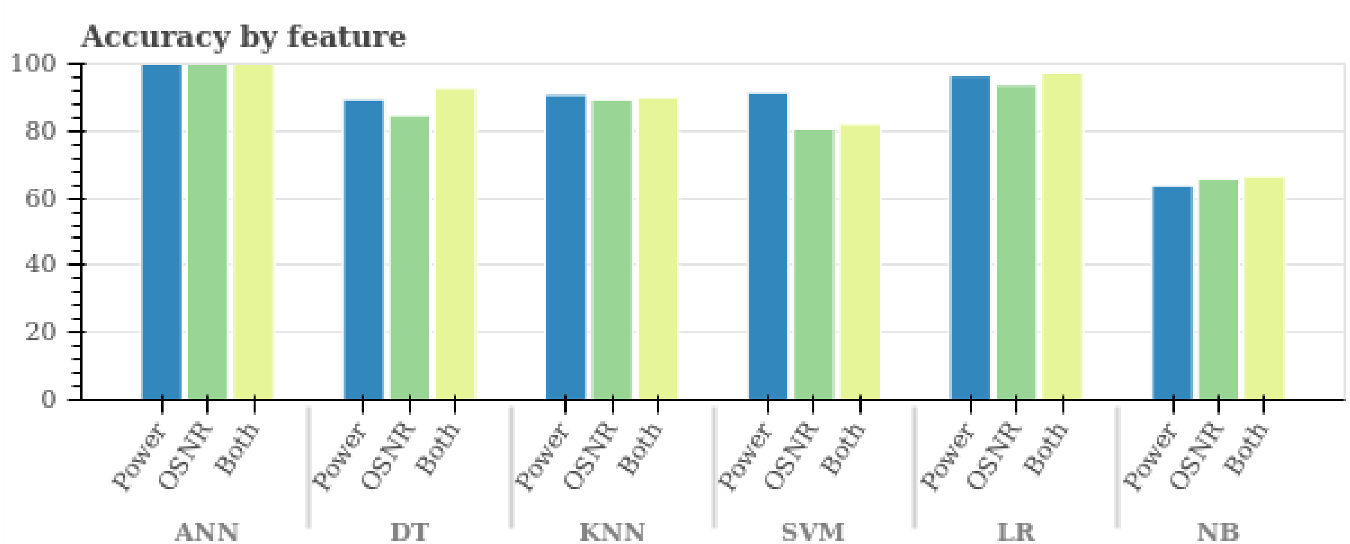
- Processing @edge=> reduces alert notification time, and energy
- Dynamic bandwidth management in PON for time-varying traffic classes (Cellular, FTTH, others) by traffic prediction



ML-Assisted Power Jamming Attack Detection and Prevention



500 data samples
50-50% (Un)jammed



* M. Bensalem, S. K. Singh, and A. Jukan, "Machine Learning Techniques to Detecting and Preventing Jamming Attacks in Optical Networks," under submission in IEEE Globecom 2019.

Conclusions

- Elastic optical networking is promising
  - Support for heterogeneous demands
  - Able to provision beyond 100 Gbit/s channel

- Requirements and challenges
  - Flexible bandwidth-variable transponders, and switches
  - Resource provisioning is complex
  - Spectrum fragmentation is inevitable, defragmentation is required

- Thesis Contribution
  - Analytical modeling of routing and spectrum allocation schemes with/without DF
  - Efficient algorithms for resource provisioning (Holding-Time-Aware-based)
  - ML-assisted intelligent resource provisioning and novel system design

References

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2. K. Kuppuswamy and D. C. Lee, “An analytic approach to efficiently computing call blocking probabilities for multiclass wdm networks,” IEEE/ACM Transactions on Networking (TON), vol. 17, no. 2, pp. 658–670, 2009.
3. H. Beyranvand, M. Maier, and J. Salehi, “An analytical framework for the performance evaluation of node-and network-wise operation scenarios in elastic optical networks,” IEEE Trans. on Commun., vol. 62, no. 5, pp. 1621–1633, 2014.
4. L. Peng, C.-H. Youn, and C. Qiao, \Theoretical analyses of lightpath blocking performance in co-ofdm optical networks with/without spectrum conversion," IEEE Communications Letters, vol. 17, no. 4, pp. 789-792, 2013.
5. <u>S. K. Singh</u> and A. Jukan, “Computing Blocking Probabilities in Elastic Optical Networks with Spectrum Defragmentation," in proc. of IEEE Conference on Computer communications (**INFOCOM**), Paris, April 2019.
6. <u>S. K. Singh</u> and A. Jukan, “Machine Learning-based Prediction for Resource (Re)allo-cation in Optical Data Center Networks," IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 10, issue 10, pp. D12-D28, 2018.
7. <u>S. K. Singh</u> and A. Jukan, “Efficient Spectrum Defragmentation with Holding Time Awareness in EONs," IEEE/OSA JOCN, vol. 9, no. 3, pp. B78-B89, 2017.
8. <u>S. K. Singh</u>, F. Carpio, and A. Jukan, “Improving Animal-Human Cohabitation with Machine Learning in Fiber-Wireless Networks," *MDPI Journal of Sensor and Actuator Networks*, vol. 7, no. 3, 2018.
9. M. Bensalem, <u>S. K. Singh</u>, and A. Jukan, Machine Learning Techniques to Detecting and Preventing Jamming Attacks in Optical Networks," under submission in IEEE Globecom, 2019.

Questions?

Thanks

Approximation Models: Our Approach

- Reduced load approximation; statistical independence link assumption
- For each link j, find connection setup rate per class per state

$$\alpha_k^j(x_j) = \sum_{m=1}^{\kappa_o} \sum_{o:j\in r(o,m)} \lambda_k^{o,m} Pr(Z_{r(o,m)} \geqslant d_k | X_j = x_j; \bar{x}_j)$$

$$Pr(Z_r \geqslant d_k | X_j = x_j; \bar{x}_j) = \sum_{x_{j_2}=0}^{C-d_k} \cdots \sum_{x_{j_h}=0}^{C-d_k} \pi_{j_2}(x_{j_2}) \cdots \pi_{j_h}(x_{j_h}) \times p_k(\mathbf{x}_r; \bar{\mathbf{x}}_r)$$

Probability of Acceptance $p_k(\boldsymbol{x_r}; \overline{\boldsymbol{x}}_{\boldsymbol{r}}) \equiv \Pr[Zr \geq dk \,|X_{j_1} = x_{j_1}, X_{j_2} = x_{j_2}, \ldots, X_{j_h} = x_{j_h}; \overline{\boldsymbol{x}}_{\boldsymbol{r}}]$

- For each link j, find connection departure rates per class
- Apply fixed-point iteration algorithm to compute fragmentation blocking probability (FBP) and resource blocking probability (RBP)

$BP_k^o =$

Poisson assumption: Under this assumption, calls arrive at a link as a Poisson process and the corresponding arrival rate is the original external offered rate thinned by blocking on other links, thus known as the reduced load.

*S. K. Singh and A. Jukan, “Computing Exact and Approximate Blocking Probabilities in Elastic Optical Networks," under submission in IEEE Transaction on Networking 2018. Available on arXiv: https://arxiv.org/pdf/1706.07747.pdf.

Approximation Models: Existing Approaches

- Link state (X) is represented by # of occupied slices (x); $\pi(x) \equiv \Pr[X = x]$

H. Beyranvand, M. Maier, and J. Salehi, "An analytical framework for the performance evaluation of node-and network-wise operation scenarios in elastic optical networks," IEEE Transaction on Communications, vol. 62, no. 5, pp. 1621–1633, 2014.

- **Kaufman's Approach** (Ignoring fragmentation and RSA constraints)

$$p_k(x) = \begin{cases} 1, & 0 \le x \le C - d_k \\ 0, & \text{otherwise} \end{cases}$$

$$x * \pi(x) = \sum_{k=1}^{K} d_k \left(\frac{\lambda_k}{\mu_k}\right) \pi(x - d_k)$$

$$\sum_{x=0}^{C} \pi(x) = 1$$

$$Link\ BP_k^{Kaufman} = \sum_{x=C-d_k+1}^{C} \pi(x)$$

$$\text{OD Route } BP = 1 - (1 - BP_{link})^h$$

- **Binomial Approach** based on [*]

$$p = 1 - \frac{1}{C} \sum_{i=0}^{C} x\pi(x)$$

p: probability that a slice is free on a link;

$$f(C, d_k) = \sum_{i=1}^{d_k} \left(f(C - i, dk)(1 - p)p^{i-1}\right) + p^{d_k}$$

Replace p with p^h for h-hop route

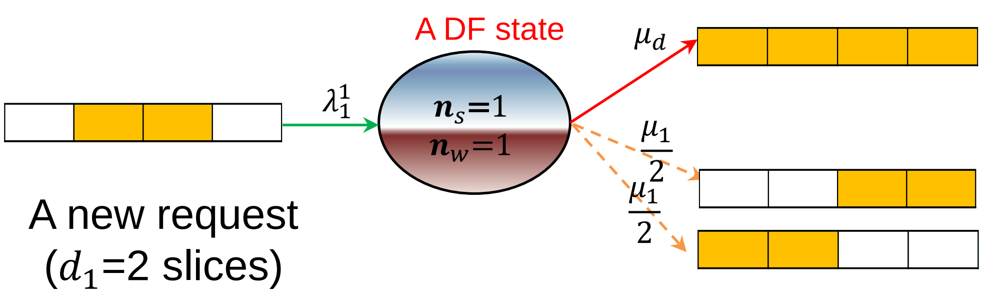
$$Link/Route\ BP_k^{Binomial} = 1 - f(C, d_k)$$

* L. Peng, C.-H. Youn, and C. Qiao, "Theoretical analyses of lightpath blocking performance in co-ofdm optical networks with/without spectrum conversion," IEEE Communications Letters, vol. 17, no. 4, pp. 789-792, 2013.

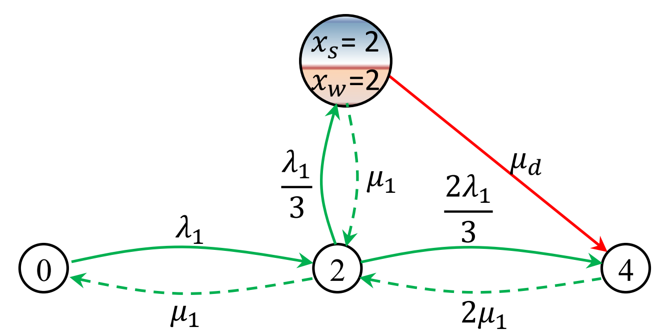
Exact and Approx. Models of Reactive Defragmentation*

- Assumptions:
  - Put on hold (delayed) to triggering request, and serve it after DF
  - Reconfiguration time ~ $\exp(1/\mu_d)$
  - DF also completes when a serving connection departs (since $1/\mu_k >> 1/\mu_d$)

- Example: Single-link, C=4 slices, d=2 slices, RF policy



Exact model

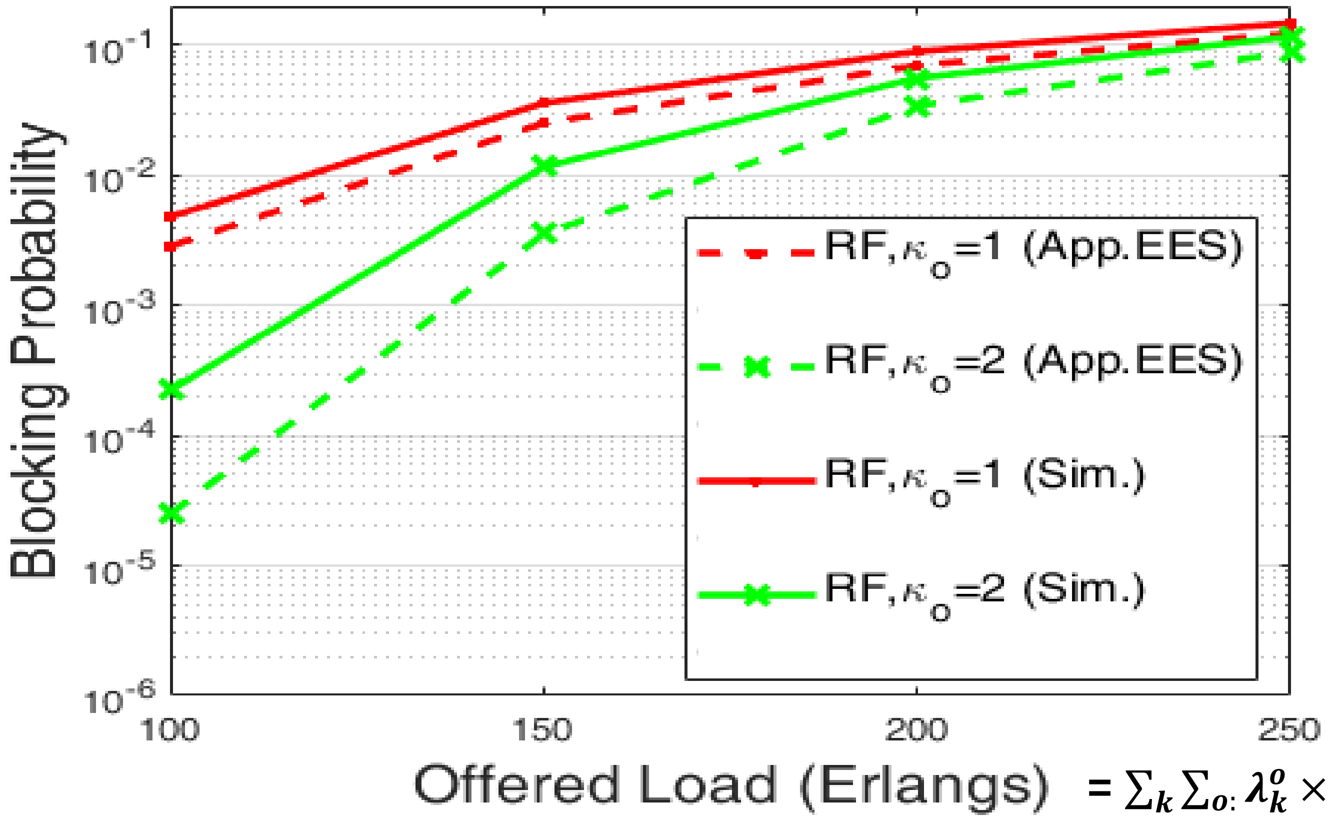


Approximation model (small scale)

Accuracy Analysis under RF policy

- **14-node NSF network with 182 OD pairs, RF policy**

  Link capacity C=100 slices, demands (d) = (3,4,6) slices,
  Mean service time ($1/\mu_k$) = 1 unit

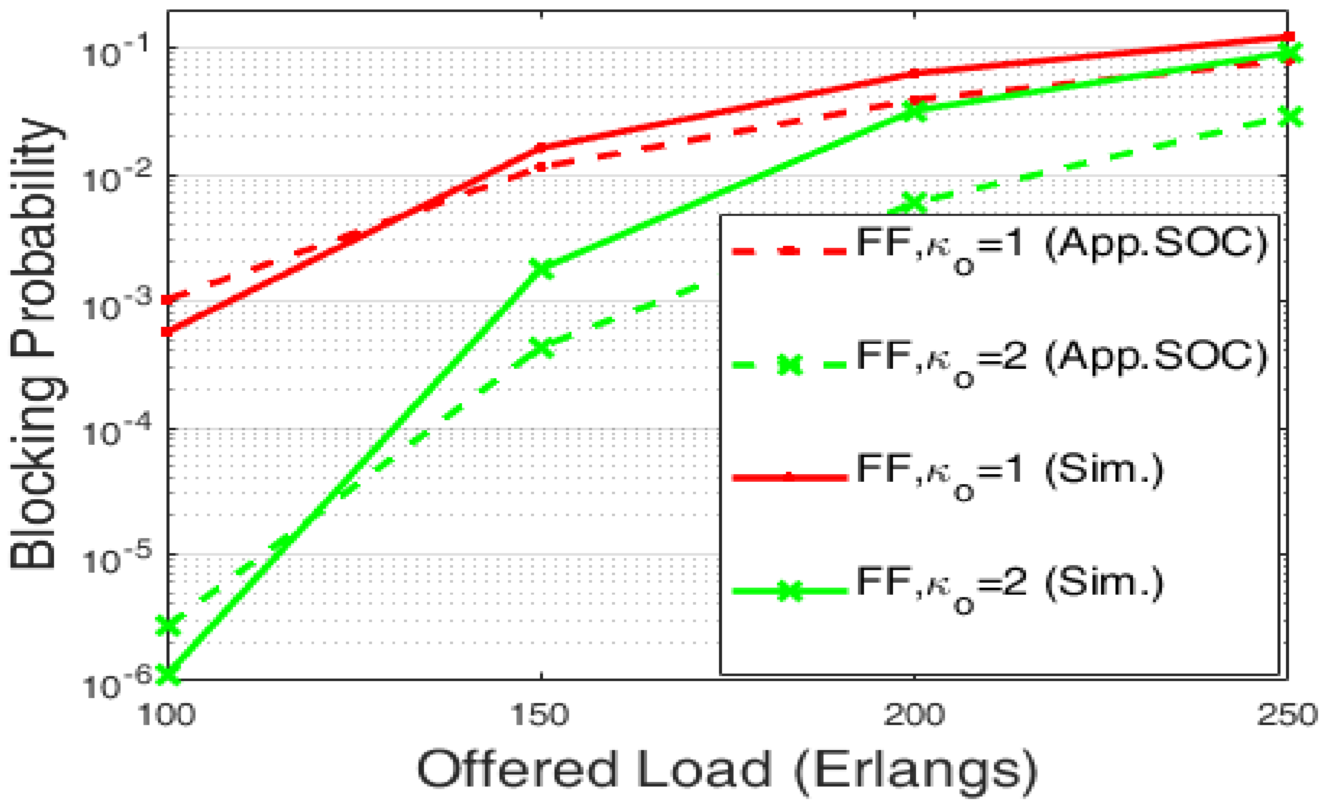


$= \sum_k \sum_{o:} \lambda_k^o \times 1/\mu_k$

Accuracy Analysis under FF policy

- **14-node NSF network with 182 OD pairs, FF policy**

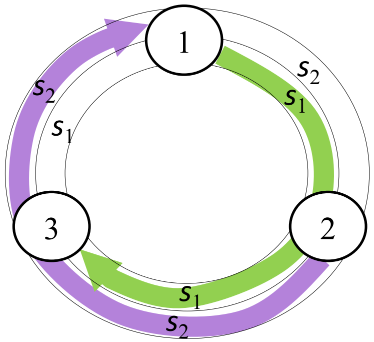
  Link capacity C=100 slices, demands (d) = (3,4,6) slices,
  Mean service time ($1/\mu_k$) = 1 unit



Exact and Approx. Defragmentation Modeling

- The First Exact Defragmentation (DF) Network (Markov) Model
  - Include DF states: # of serving and waiting connections (o,k)
  - Assumptions: DF ~ $\exp(\mu_d)$ and DF also completes when a serving connection departs (since $1/\mu_k$>> $1/\mu_d$)

- Approximation Model:
  - All fragmented states can't be defragmented

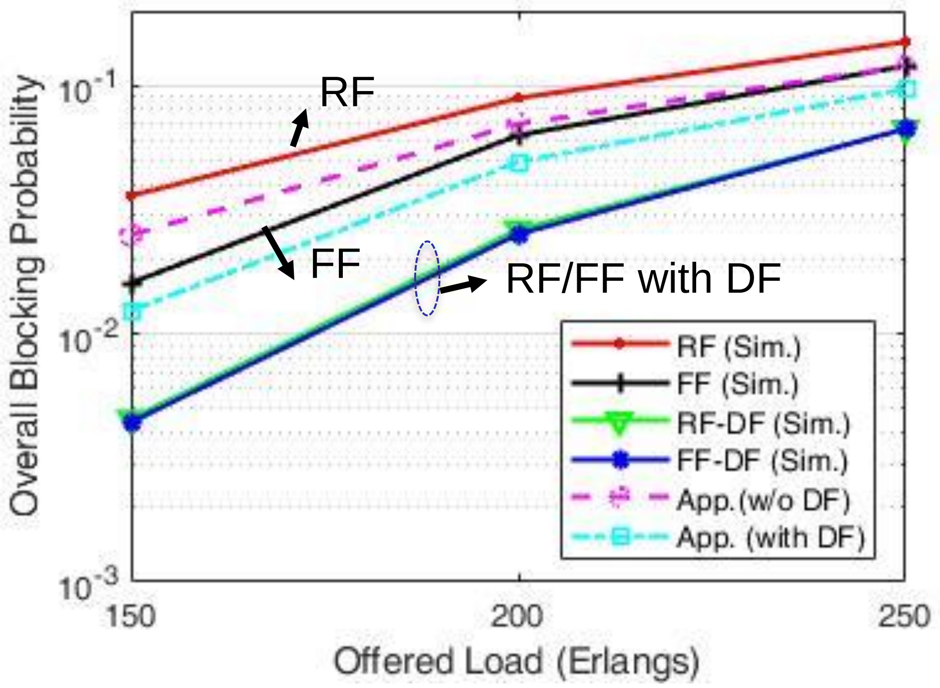


$$p_{k,DF}^{App.}(\mathrm{x}_r;\bar{\mathrm{x}}_r)=\prod_{j_i\in r}p_k^{App.}(x_{j_i};\bar{x}_{j_i})+\prod_{j_i\in r:|FB(x_{j_i},k)|\neq 0}g_k^{App.}(x_{j_i};\bar{x}_{j_i})$$

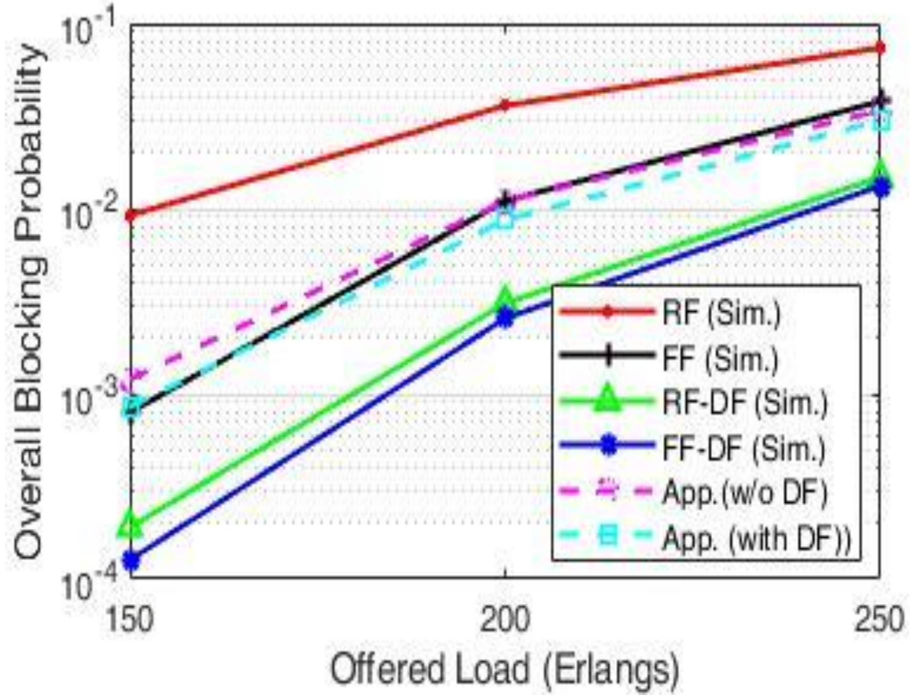
Defragmentation Impact in a Large Scale Network

- 14-node NSF network with 182 OD pairs (Simulation and Approx.)

C=100 slices, d=(3,4,6), reconfig. time=0



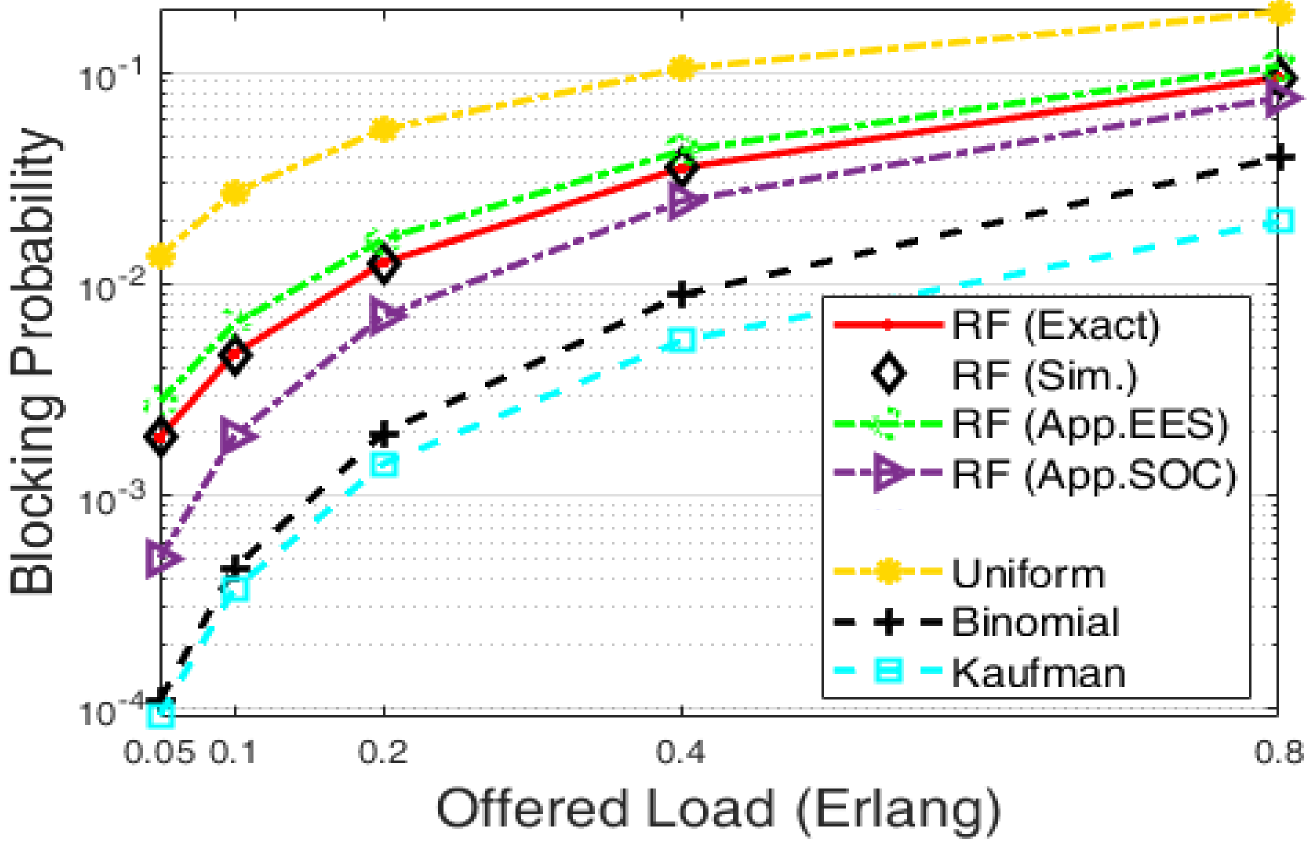
C=200 slices, d=(4,6,10), reconfig. time=0



Accuracy of Exact and App. Approaches under RF policy

- A 2-Hop network with 3 OD pair routes (RF policy)

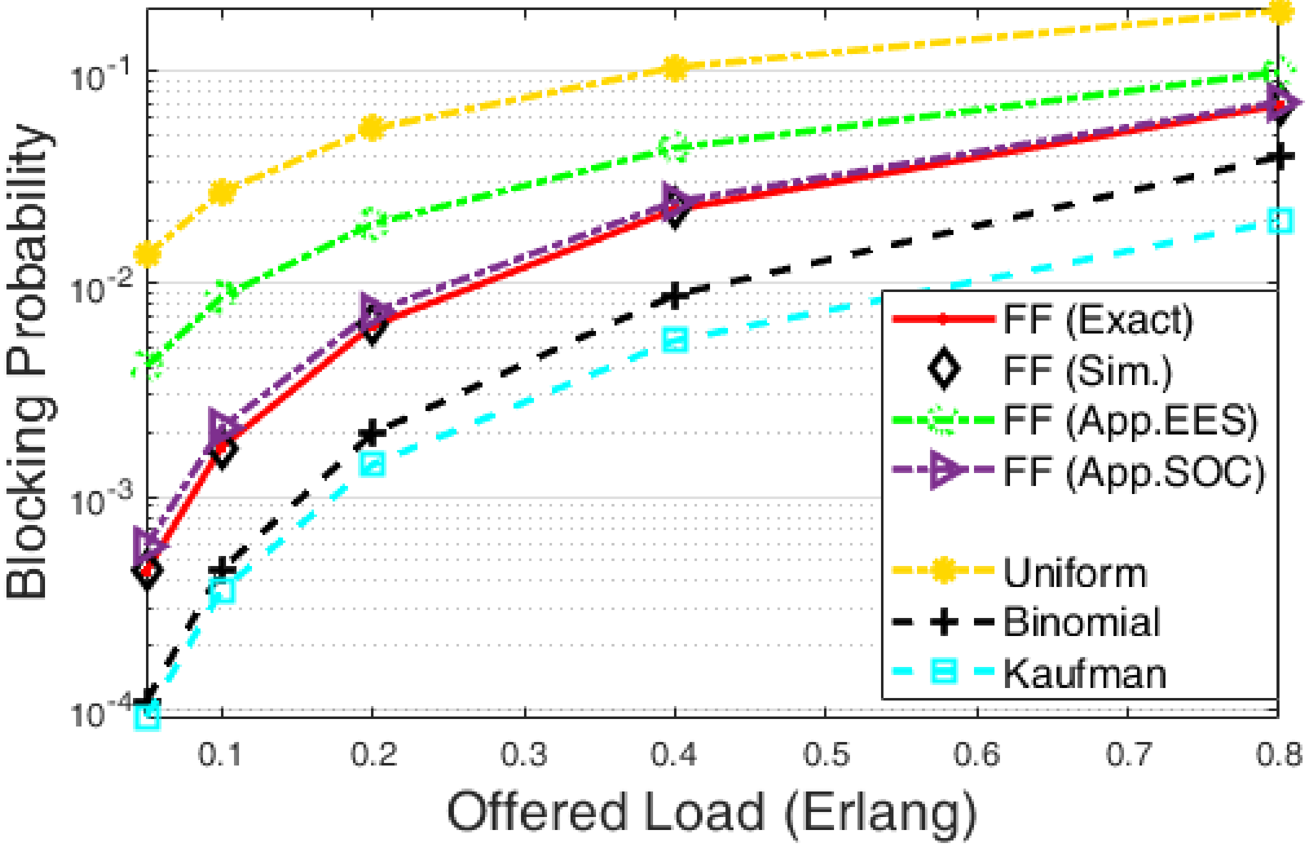
Link capacity C=10 slices, demands (d) = (3,4) slices



Accuracy of Exact and App. Approaches under FF policy

- A 2-Hop network with 3 OD pair routes (RF policy)

Link capacity C=10 slices, demands (d) = (3,4) slices



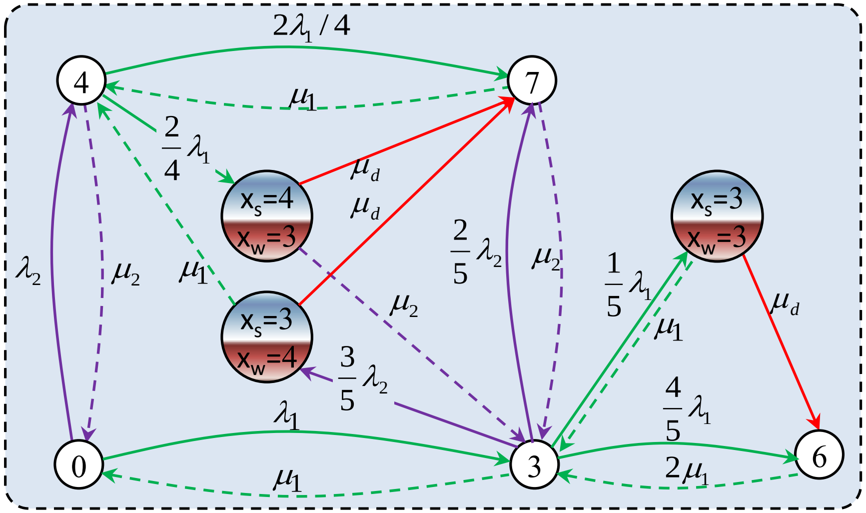
Defragmentation Modeling: Approximation Approach

- DF Reduced state (Approximation) link model

$$g_k^{App.EES}(x) = \frac{|\mathbb{FI}(x,k)|}{|\Omega_S(x)|}$$

$$g_k^{App.SOC}(x;\bar{x}) = \frac{|\mathbb{FI}(x,k)|}{|\Omega_S(x)|} \times \left(1 - exp\left(-\frac{\bar{x}}{C} \times |log(\frac{x}{\bar{x}})|\right)\right)$$

$$p_{k,DF}^{App.}(\mathbf{x}_r;\bar{\mathbf{x}}_r) = \prod_{j_i \in r} p_k^{App.}(x_{j_i};\bar{x}_{j_i}) + \prod_{j_i \in r:|FB(x_{j_i},k)|\neq 0} g_k^{App.}(x_{j_i};\bar{x}_{j_i})$$

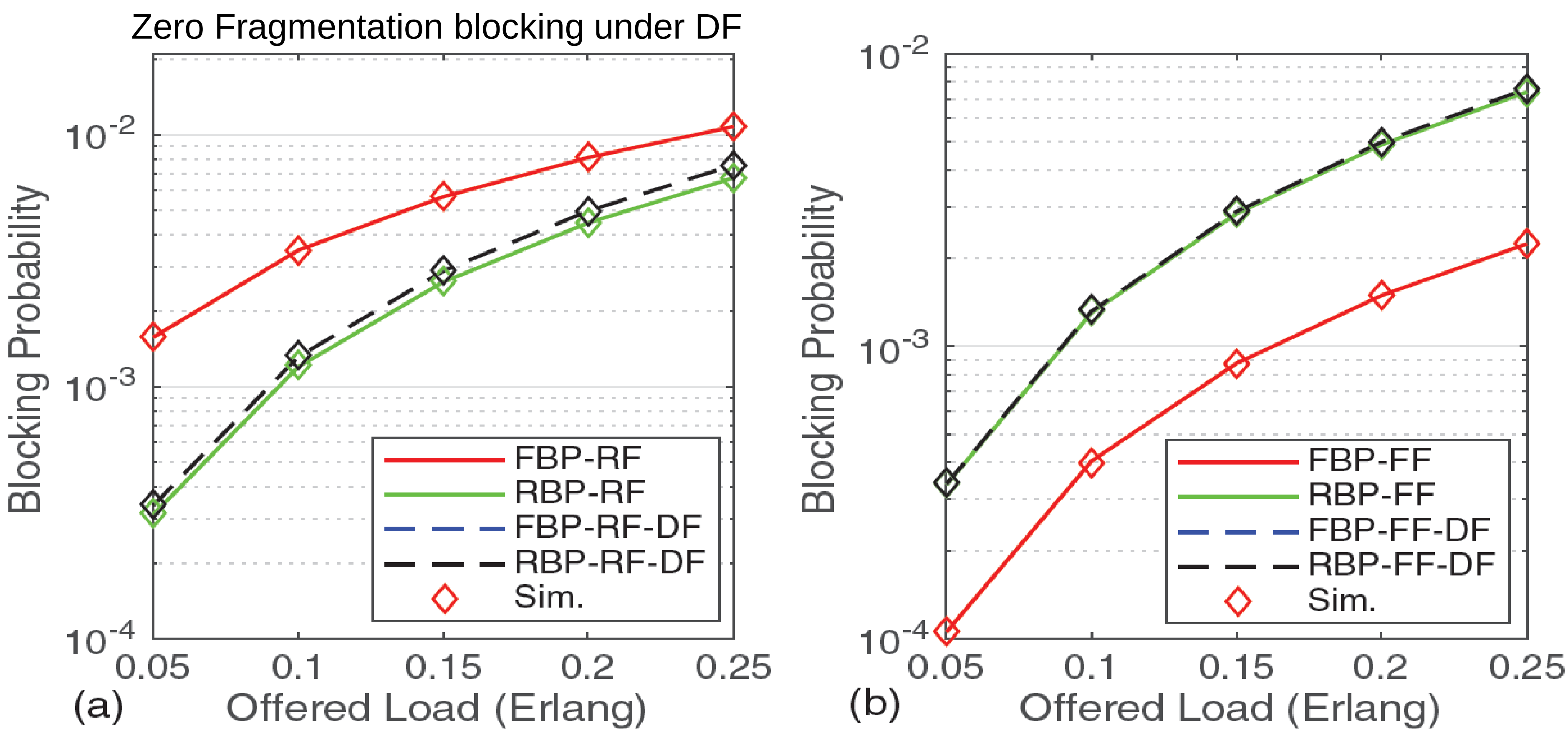


S. K. Singh, A. Jukan, "Computing Blocking Probabilities in Elastic Optical Networks with Spectrum Defragmentation," **INFOCOM**, 2019.

Impact of DF in Networks with Bus Topology

- **2-link network with 3 OD pairs (Exact and Simulation results)**

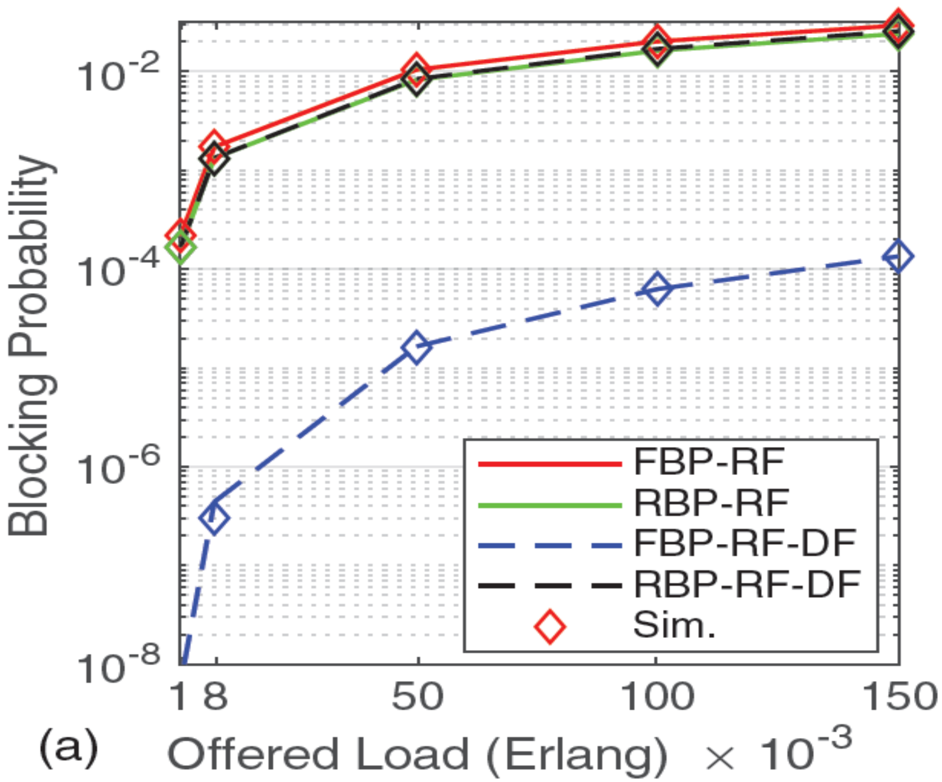
Link capacity C=10 slices, demands (d) = (3,4) slices



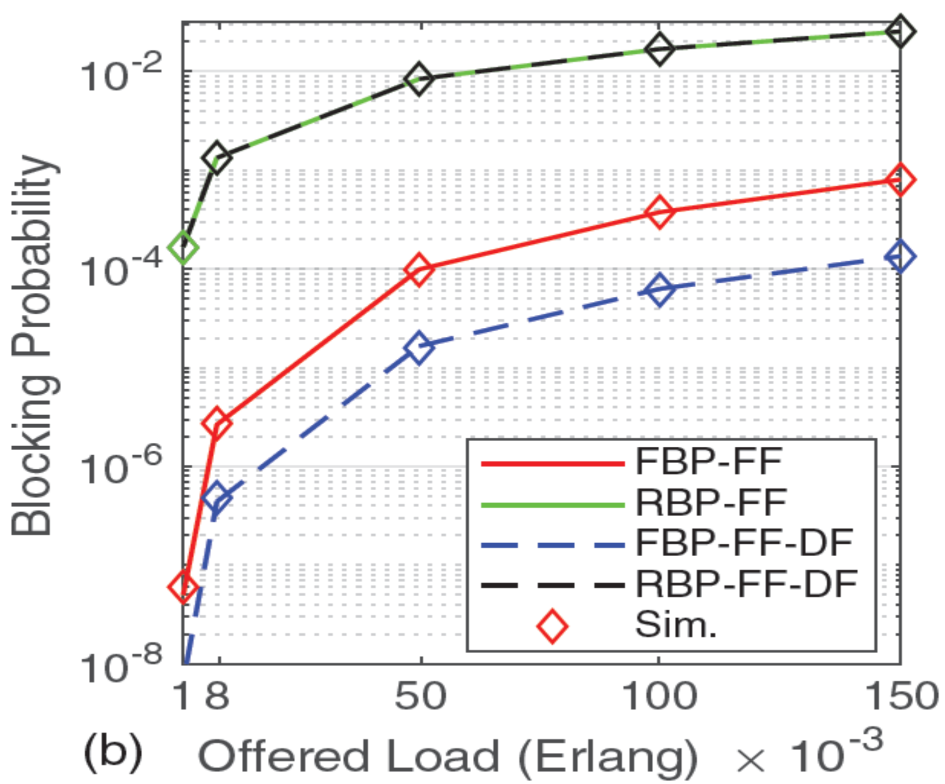
Impact of Defragmentation in Ring/Mesh Networks

- **3-node ring network with 6 OD pairs (Exact and Simulation results)**

Link capacity C=7 slices, demands (d) = (3,4) slices



(a)



(b)