The ACTION Project: Applications Coordinate with Transport, IP and Optical Networks

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WTON 2015
PI Cover Areas

Application

Design

Experiment

MV

Data-Center
+ Network

Model
+ Optimized Method

NY

Energy efficient

Optical Transport

EO

AF

Platform
Outline

• Part I:
  – Background
  – Objectives and work program organization

• Part II:
  – Analytical modeling effort at UT Dallas
Background

• Four enabling technologies
  1. Elastic Optical Networks (Flex Grid) [a]
     • WSS, Bandwidth Variable Transceivers (BVT), Energy Efficient Ethernet (EEE)
  2. Sub-wavelength circuits (OTN, DSON)
  3. Dynamic circuit/virtual circuit (VC) technologies
     • MPLS, VLAN, Ctrl. plane solutions (RSVP-TE, PCEP)
  4. Software Defined Network (SDN)/OpenFlow

• Measurements show that
  – Internet links are underutilized [b]
  – Networks are not operated in an energy-efficient manner [c]

Good reasons for operating today’s Internet links at low utilization (25-35%)
≡ Challenges of high-utilization operation of a network

1. Failure handling: Additional network load placed on links
3. Avoid packet losses: TCP throughput sensitive to losses
4. Allow sufficient headroom for poor planning (imperfect traffic forecasts) or poor routing (imbalanced load)
Objectives

• Develop an Applications Coordinating with Transport, IP, and Optical Networks (ACTION) architecture
  – by integrating four enabling technologies
  – by operating links at higher utilization while meeting the four challenges of high-utilization operation

• Why operate at high utilization: the network will need fewer powered-on links, and hence the network will consume smaller levels of energy (power) to move the same number of information bits (bits/sec)
  – analogy: flying a half-empty large airplane!
**ACTION Project Overview**

**Track 3:** Introduce 4 new technologies into datacenter networks

**Track 4:** Introduce 4 new technologies into campus networks

**Core provider networks**

- *Parallel links*
- *FlexWDM DSON*
- *FlexGrid/OTN/DSON*
- *IP/MPLS/VLAN*
- *OF*

**ACTION SDN controller**

**Tracks 1 and 2:** Introduce 4 new technologies into core (also metro) networks

**Metro/access provider networks**

**Access link**

**Campus networks**

**Datacenters**

**Hosts**

**ACTION Management System**

**Track 0:** ACTION PCE algorithms and design
Work Program Organization

• **Track 0: ACTION SDN controller**
  – Controls both OpenFlow Ethernet switches/IP routers PLUS optical cross-connects

• **Four application tracks (applications for dynamic circuit services)**
  – Routers are circuit endpoints (aggregate traffic: ACTION Management System)
    • **Track 1: Virtual Topology Management**
      Leverage long-timescale variations (such as night/day traffic patterns) to power off or reduce link rates for energy savings while planning for failures
    • **Track 2: Link Self-Sizing**
      Analyze short-timescale variations by observing IP-network link-level traffic (via SNMP MIB reads) and then ask ACTION SDN controller to adjust rate of elastic optical paths (used to realize IP-layer links) whenever possible for energy savings
  – Computers are circuit/VC “endpoints” (individual flows: application triggers from endpoints)
    • **Track 3: Hybrid Data-Center Networks**
      EON + applications (Hadoop scheduling)
    • **Track 4: Campus Networks**
      Router access links adjustment
Track 0: ACTION SDN Controller

• New path computation algorithms
  – Take into account Quality of Transmission (QOT) metrics
  – Consider energy consumption
  – Account for failures
  – Handle traffic fluctuations
  – Intra-domain path selection
  – Inter-domain path selection (East-West API)
  – Multi-layer path selection
    • e.g., by coordinating with per-layer SDN controllers

• Architecture, design and prototyping
  – Reduction of circuit setup delay

Domain definition: a network owned and operated by one organization
ACTION SDN Controller

Core, metro, campus, datacenter networks

Quality of Transmission (QoT)
- OSNR and BER
- Traffic Independent PLIs
- Traffic Dependent PLIs

Circuit setup delay factors
- Control plane
- Optical devices (OA, WSS)
- Tx/Rx re-synchronization

Power consumption factors
- Router I/O BVT
- FFT for DSC multiplexing
- Optical amplifiers

1GE increments

ACTION SDN controller

Parallel links

Router or switch

OXC

FlexWDM DSON

OA

WSS
Track 4

• Objective:
  – Bring 4 new technologies to campus networks

• Applications:
  – Network administrator requests temporary augmentation of access link capacity for special events on campus (e.g., football game)
  – Host-application triggers dynamic circuits (e.g., moving human genome sequence rough or processed data)
Current Campus

Metro/access provider network

Fixed Ethernet rate, e.g. 1GE, 10GE

Access link

Hosts

IP/Eth/VLAN

Campus networks

Metro/access provider network

ACTION Track 4

Metro/access provider network

ACTION SDN controller

Port(s) that is (are) shared dynamically

FlexWDM DSON

Hosts

Access links

Port that is dynamically powered on and off

Genome app.

Football game

Save energy

Improve utilization

Access link

ACTION SDN controller

Hosts

Access links

IP/Eth/VLAN

Campus networks

IP/Eth/VLAN

Campus networks
Work Plan (Track 4)

• Prototype campus applications and test with VLAN switches on test-beds (e.g., Keio test-bed)
  – Test assumptions
  – Collect measurements

• Define and implement simulation modules based on experimental data (e.g., CPqD test-bed)
  – PLI models for EON and DSON
  – Circuit setup delay models for optical components, physical control plane and signaling
  – Energy consumption models

• Obtain real traffic traces from campuses

• Run simulations and/or create analytical models of campus network to estimate energy savings
Analytical Modeling Effort

“Spectrum Contiguity Fragmentation Analysis in a Two-Service Elastic Optical Link”

Shuyi Yan and Joobum Kim
Contents

• Introduction
• Proposed spectrum fragmentation analytical models
  – Simple approximation model
  – Accurate model
• Numerical results
  – Single fiber study
  – Network-wide study (from simulation)
• Conclusion
Introduction

• Elastic Optical Network (EON)
  – Provide elastic optical bandwidth to support various data rates by allocating spectrum resources proportionally to the amount of traffic carried by demands
  – Higher spectrum utilization (compared to the traditional WDM)
  – Contiguity fragmentation of spectrum slices is a potential roadblock

• Definition of contiguity fragmentation:
  – The occurrence of small and non-contiguous spectrum slices that cannot be used to accommodate large connection requests
Objective of Study

• Investigate the nature of contiguity fragmentation theoretically in EON
• Propose two analytical models for an optical fiber link hosting two types of service
  – Simple approximation model
  – Accurate model
System Assumptions

- \( N = \) number of spectrum slices
- Fully Sharing spectrum resources (no shared band)
- Two groups of requests in a single link
- The size of group 1 (2) request is \( m \) (\( n \)), respectively
- \( m = 1, \; n = n \times m \)
- Traffic load \( \rho = \frac{\lambda_1}{\mu_1} = \frac{\lambda_2}{\mu_2} \)
- Random Fit scheme
- Semi-flexible grid [1]
Simple Approximation Model
Approximation MC Model

- 2-dimensional MC state transition diagram

- Markov Chain (MC) is represented by a super-state \((i, j)\), where \(i\) is the number of group 1 requests and \(j\) is the number of group 2 requests currently reserved in the link

- Blocking probability due to fragmentation \((P_{(i,j)})\) experienced by group 2 requests
Approximation Model

- $P_{(i,j)}$ = blocking probability due to fragmentation
  - Example: $N=4, \ m=1, \ n=2, \ i=2, \ and \ j=0$, then $P_{(2,0)} = ?$
    - $P_{(2,0)}$ = The number of blocked permutations / The number of all possible permutations
    - Total number of permutations to assign two group 1 requests = 6
    - Total number of blocked permutations = 4

\[ P_{(2,0)} = \frac{4}{6} \]

: Allocated (Not available)
: Available

Group 2 request cannot be assigned in this case, Because of semi-flexible grid policy
Approximation Model

• Blocking Probability due to fragmentation \((P_{(i,j)})\)
  
  – The total # of slices : \(N\), Superchannel size : \(n\), The # of superchannels: \(\frac{N}{n}\)
  
  – When \(i + j < \frac{N}{n}\), \(P_{(i,j)} = 0 \Rightarrow\) There is at least one empty superchannel
  
  – When \(i + j \geq \frac{N}{n}\), \(P_{(i,j)} \neq 0\)
    
    • Allocate \(j\) group 2 requests into \(\frac{N}{n}\) superchannels, the # of superchannels available for allocating \(i\) group requests : \(\bar{j} = \frac{N}{n} - j\)
    
    • As long as \(i\) requests occupy all the \(\bar{j}\) superchannels, next coming group 2 requests are blocked

• General formula \(P_{(i,j)}\)
  
  – \(K\) : The number of superchannels that are used to reserve \(i\) group 1 requests
    
    • \(K_{\text{min}} = \left[ \frac{i}{n} \right], K_{\text{max}} = \min \left( i, \frac{N}{n} - j \right)\)
    
    • \(\text{num}(i, K, \bar{j})\) : The number of ways allocating \(i\) requests into \(K\) superchannels

  \[
  P_{(i,j)} = \frac{\text{The number of ways allocating } i \text{ group 1 requests in } K_{\text{max}} \text{ superchannels}}{\text{The number of ways allocating } i \text{ group 1 requests in } N-jn \text{ slices}} = \frac{\text{num}(i, K_{\text{max}}, \bar{j})}{\binom{N-jn}{i}}
  \]
Approximation Model

- The expression for \( \text{num}(i, K_{\text{max}}, j) \) is obtained by extrapolation

1) \( \text{num}(i, K, j) = \text{num}(i, K_{\text{min}}, j) = \text{num}(i, \lfloor \frac{L}{n} \rfloor, j) \)

\[
\text{num} \left( i, \lfloor \frac{L}{n} \rfloor, j \right) = \binom{\frac{N}{n} - j}{\lfloor \frac{L}{n} \rfloor} \binom{\lfloor \frac{L}{n} \rfloor \cdot n}{i}
\]
# of combinations that one can use to choose \( \lfloor \frac{L}{n} \rfloor \) superchannels out of available \( \frac{N}{n} - j \) superchannels

# of combinations that one can to assign \( i \) requests to \( \lfloor \frac{L}{n} \rfloor \cdot n \) slices

2) \( \text{num}(i, K, j) = \text{num}(i, \lfloor \frac{L}{n} \rfloor + 1, j) \)

\[
\text{num} \left( i, \lfloor \frac{L}{n} \rfloor + 1, j \right) = \binom{\frac{N}{n} - j}{\lfloor \frac{L}{n} \rfloor + 1} \binom{(\lfloor \frac{L}{n} \rfloor + 1) \cdot n}{i} - \binom{\lfloor \frac{L}{n} \rfloor + 1}{\lfloor \frac{L}{n} \rfloor} \binom{\lfloor \frac{L}{n} \rfloor \cdot n}{i}
\]

- \( \text{num} \left( i, \lfloor \frac{L}{n} \rfloor + 1, j \right) \)

# of combinations that one can use to choose \( \lfloor \frac{L}{n} \rfloor + 1 \) superchannels out of available \( \frac{N}{n} - j \) superchannels

# of combinations that one can to assign \( i \) requests to \( (\lfloor \frac{L}{n} \rfloor + 1) \cdot n \) slices

- Assign \( i \) requests to \( \lfloor \frac{L}{n} \rfloor \cdot n \) slices

- # of cases that \( i \) requests are assigned to \( \lfloor \frac{L}{n} \rfloor \) superchannels out of \( \lfloor \frac{L}{n} \rfloor + 1 \) superchannels
Approximation Model

3) \( \text{num}(i, K, j) = \text{num}(i, \lceil \frac{i}{n} \rceil + 2, j) \)

\[
\cdot \text{num} \left( i, \lceil \frac{i}{n} \rceil + 2, j \right) = \left( \frac{n - j}{n} \right) \left( \frac{\lceil \frac{i}{n} \rceil + 2}{i} \right) \left( \frac{\lceil \frac{i}{n} \rceil + 1}{i} \right) - \left( \frac{\lceil \frac{i}{n} \rceil + 2}{2} \right) \left( \lceil \frac{j}{n} \rceil \cdot n \right)
\]

- # of combinations that one can use to choose \( \lceil \frac{i}{n} \rceil + 2 \) superchannels out of available \( \frac{n}{n} - j \) superchannels

- # of combinations that one can to assign \( i \) requests to \( \lceil \frac{i}{n} \rceil + 2 \cdot n \) slices

- # of cases that \( i \) requests are assigned to \( \lceil \frac{i}{n} \rceil + 1 \) superchannels out of \( \lceil \frac{i}{n} \rceil + 2 \) superchannels

- Assign \( i \) requests to \( \lceil \frac{i}{n} \rceil + 1 \cdot n \) slices

- # of cases that \( i \) requests are assigned to \( \frac{i}{n} \) superchannels out of \( \lceil \frac{i}{n} \rceil + 2 \) superchannels

- Assign \( i \) requests to \( \frac{i}{n} \cdot n \) slices
Approximation Model

4) Generally,

\[
\text{num}(i, K, j) = \begin{cases} 
\left( \frac{N}{n} - j \right) \binom{K \cdot n}{i} 
& \text{if } K = K_{\text{min}} \\
\left( \frac{N}{K} - j \right) \binom{K \cdot n}{i} - \sum_{w=1}^{K-K_{\text{min}}} (-1)^{w+1} \binom{K}{w} \binom{(K-w) \cdot n}{i} 
& \text{if } K \leq K_{\text{max}}
\end{cases}
\]

5) When \( K = K_{\text{max}} \)

\[
\text{num}(i, K_{\text{max}}, j) = \left( \frac{N}{K_{\text{max}}} - j \right) \binom{K_{\text{max}} \cdot n}{i} - \sum_{w=1}^{K_{\text{max}}-K_{\text{min}}} (-1)^{w+1} \binom{K_{\text{max}}}{w} \binom{(K_{\text{max}}-w) \cdot n}{i}
\]

Therefore

\[
\therefore \quad P(i, j) = \frac{\text{num}(i, K_{\text{max}}, j)}{\binom{N-j \cdot n}{i}}
\]

where, \( \binom{N-j \cdot n}{i} \): The \# of ways \( i \) group 1 requests are assigned to \( N - j \cdot n \)
Approximation Model

- Example: $N = 16$, $m = 1$, $n = 4$, $i = 8$, $j = 0$, $P_{(8,0)} = ?$
  
  - $K_{\text{min}} = \left\lceil \frac{i}{n} \right\rceil = 2$, $K_{\text{max}} = \min \left( i, \frac{N}{n} - j \right) = 4$
  - When 8 requests occupy 4 superchannels, group 2 requests are blocked

1) $K = K_{\text{min}} = 2$
   - $\text{num}(8,2,4) = \binom{4}{2} \left( \frac{2 \cdot 4}{8} \right)$

2) $K = 3$
   - $\text{num}(8,3,4) = \binom{4}{3} \left[ \left( \frac{3 \cdot 4}{8} \right) - \left( \frac{3}{1} \right) \left( \frac{2 \cdot 4}{8} \right) \right]$

3) $K = K_{\text{max}} = 4$
   - $\text{num}(8,4,4) = \binom{4}{4} \left\{ \left( \frac{4 \cdot 4}{8} \right) - \left[ \binom{4}{1} \left( \frac{3 \cdot 4}{8} \right) - \binom{4}{2} \left( \frac{2 \cdot 4}{8} \right) \right] \right\}$

\[ P_{(8,0)} = \frac{\text{num}(8,4,4)}{16 - 0 \times 4} \]
Numerical Results

• Event-driven simulation platform
  – Semi-flexible spectrum allocation with random-fit assignment policy
  – Cases: A single fiber case and network-wide

• Simulation assumptions
  – Two types of service
  – Service requests are generated by Poisson arrival process
  – Service time is described by an exponential distribution random variable
  – The spectrum of a fiber is divided to form $N = 80$
  – Even offered traffic load ($\rho = \lambda_1/\mu_1 = \lambda_2/\mu_2$)

• Performance metrics
  – $BP_1 =$ probability group 1 request is blocked
  – $BP_2 =$ probability group 2 request is blocked
  – $BP = (\lambda_1 BP_1 + \lambda_2 BP_2) / (\lambda_1 + \lambda_2)$
Numerical Results

- $N = 80$
- $m = 1$, $n = 2$
- A single fiber link

Uneven (unfair) blocking across the two services $BP_1 \neq BP_2$
Numerical Results

- $N = 80$
- $m = 1$, $n = 4$
- A single fiber link

Blocking unfairness is exacerbated across the two services $BP1 \neq BP2$
Numerical Results

- $N = 80$
- $m = 1$, $n = 8$
- A single fiber link
- Traffic load

$BP_1$ is non-monotonic!
Accurate Model
Accurate MC Model

• A continuous time MC in a single fiber link
  – A state is represented by a super-state \((i, j, e)\)
    • \(i\) : The number of group 1 requests \((0 \leq i \leq N)\)
    • \(j\) : The number of group 2 requests \((0 \leq j \leq N/n)\)
    • \(e\) : The number of available superchannels \((0 \leq e \leq N)\)
  – The MC states are subject to
    • \(i \geq 0, j \geq 0, e \geq 0\) and \(i + j \times n + e \times n \leq N\)
  – Example : \(N=8, m=1\) and \(n=2\)

1,1,2

\[\begin{array}{c}
\bullet \\
\bullet \\
\end{array}\]

\[\begin{array}{c}
\text{\# of group 2 requests (}j\text{) = 1} \\
\text{\# of available superchannels (}e\text{) = 2} \\
\text{\# of group 1 requests (}i\text{) = 1}
\end{array}\]
Accurate MC Model
Accurate MC Model

- Example: $N=8$, $m=1$ and $n=2$

\[\begin{align*}
0,0,4 &
\end{align*}\]

- Group 1 request

\[\begin{align*}
0,1,3 &
\end{align*}\]

- Group 2 request

\[\begin{align*}
1,0,3 &
\end{align*}\]

- \(\lambda_1\)

\[\begin{align*}
2,0,3 &
\end{align*}\]

- \(\mu_1\)

\[\begin{align*}
2,0,2 &
\end{align*}\]

- \(\frac{1}{7}\lambda_1\)

\[\begin{align*}
2,0,3 &
\end{align*}\]

- \(2\mu_1\)

\[\begin{align*}
1,1,2 &
\end{align*}\]

- \(\lambda_2\)

\[\begin{align*}
2,1,2 &
\end{align*}\]

- \(\mu_2\)

\[\begin{align*}
2,1,1 &
\end{align*}\]

- \(6\lambda_1\)

\[\begin{align*}
1,0,3 &
\end{align*}\]

- \(\lambda_1\)

\[\begin{align*}
1,1,2 &
\end{align*}\]

- \(\lambda_2\)
Accurate MC Model

• Example: $N=8$, $m=1$ and $n=2$
Accurate MC Model

• State transition diagram

• Arrival of group 2 request: Transition \((i, j, e) \rightarrow (i, j + 1, e - 1), e > 0\)
  – The transition rate: \(\lambda_2\)

• Departure of group 2 request: Transition \((i, j, e) \rightarrow (i, j - 1, e + 1)\)
  – The transition rate: \(j\mu_2\)
Accurate MC Model

• Arrival of group 1 request
  – Transition \((i, j, e) \rightarrow (i + 1, j, e - 1)\): the request is assigned one slice of one of available superchannels
  – Transition \((i, j, e) \rightarrow (i + 1, j, e)\): the request is assigned one slice of one of the superchannels, which are already partially used by group 1 request(s)
  – The transition rate

\[
\lambda_1(i, j, e, e_{\text{next}}) = \begin{cases} 
\frac{e \cdot n}{s_{\text{unused}} + e \cdot n} \lambda_1 & (i, j, e) \rightarrow (i + 1, j, e - 1) \\
\frac{S_{\text{unused}}}{s_{\text{unused}} + e \cdot n} \lambda_1 & (i, j, e) \rightarrow (i + 1, j, e) 
\end{cases}
\]

The number of superchannels that are not used by group 2 requests
\((\bar{j} = N/n - j)\)
  – The number of superchannels either partially or completely used by \(i\) group 1 requests \((K = \bar{j} - e)\)
  – The number of unused slices in \(K\) superchannels \((s_{\text{unused}} = K \cdot n - i)\)
Accurate MC Model

- Departure of group 1 request
  - If $i = K$, transition $(i, j, e) \to (i - 1, j, e + 1)$: a departure will *always* free one superchannel
    - The transition rate: $i\mu_1$
  - If $i \geq (K - 1) \cdot n + 2$, transition $(i, j, e) \to (i - 1, j, e)$: a departure will *never* free a superchannel
    - The transition rate: $i\mu_1$
  - If $K < i < (K - 1) \cdot n + 2$, transition $(i, j, e) \to (i - 1, j, e + 1)$ or $(i - 1, j, e)$: a departure *may or may not* free a superchannel
    - The transition rate
      \[
      \mu_1(i, j, e, e_{\text{next}}) = \begin{cases} 
      \frac{\text{emp}(i, K, \bar{j})}{\text{num}(i, K, j)} \mu_1 & (i, j, e) \to (i - 1, j, e + 1) \\
      \left(i - \frac{\text{emp}(i, K, \bar{j})}{\text{num}(i, K, j)}\right) \mu_1 & (i, j, e) \to (i - 1, j, e) 
      \end{cases}
      \]
      
      - $\text{emp}(i, K, \bar{j}) = \binom{\bar{j}}{1} \binom{n}{1} \cdot \text{num}(i - 1, K - 1, \bar{j} - 1)$
      - $\text{num}(i, K, \bar{j}) = \binom{\bar{j}}{K} \cdot \sum_{w=0}^{K - K_{\text{min}}} (-1)^w \binom{K}{w} \binom{K - w}{i} \cdot n$
      - $K_{\text{min}} = \lceil i/n \rceil$
Numerical Results

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- \( m = 1, \ n = 2 \)
- A single fiber link

Uneven (unfair) blocking across the two services: \( BP_1 \neq BP_2 \)
Numerical Results

- $N = 80$
- $m = 1, n = 4$
- A single fiber link
Numerical Results

- $N = 80$
- $m = 1, n = 8$
- A single fiber link
- Traffic load in linear scale
Numerical Results

- $N = 80$
- $m = 1$, $n = 8$
- A single fiber link
- Traffic load in log scale
Numerical Results

- \( N = 80 \)
- \( m = 1, \ n = 16 \)
- A single fiber link
- Traffic load in linear scale

Accurate Model
Numerical Results

- $N = 80$
- $m = 1, \ n = 16$
- A single fiber link
- Traffic load in log scale

Both models are accurate at relatively low offered load
Model Complexity
Complexity = Number of States in MC

- $N = 80, m = 1$

- Approximation model
  \[ S(N, n) = \frac{1}{2} (N + 2) \left( \frac{N}{n} + 1 \right) \]
  \[ \rightarrow O(N^2/n) \]

- Accurate model
  \[ S(N, n) = \sum_{t=1}^{N+1} \frac{t}{2} (2 + (t - 1)(n - 1)) \]
  \[ \rightarrow O(N^3/n^2) \]
Numerical Results (Network-Wide)

• Simulation assumptions (network-wide study)
  – NSF topology with 14 nodes and 21 links
  – Each link has two unidirectional fibers (one per direction)
  – 5 shortest paths are computed using hop-count as metric
  – Used RSA algorithms
    • Semi-flexible algorithm (Semiflex) [1]
    • $K$ Shortest Path with First-Fit policy (KSP_FF) [2]

Numerical Results

• Network case
  – NSF topology, $N=80$, $m=1$, $n=8$
Numerical Results (Network)

- Network case
  - NSF topology, \( N=80, m=1, n=16 \)
Summary

• Proposed analytical models capture the contiguity fragmentation phenomenon in a two-service elastic fiber link
  – The low-complexity approximation model offers good approximation of the blocking probabilities, but underestimates $BP_1$
  – The accurate model well captures the blocking probabilities of the two service types in a single fiber
  – A non-monotonic (oscillating) blocking pattern for $BP_1$ is revealed
• Oscillating blocking patterns are also experienced in network-wide blocking probabilities as shown through simulation
• Solutions for mitigating unfair blocking probabilities across services while retaining overall low blocking probability are being sought
Thank you!

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Complexity = Number of States in MC

- \( N = 400, \ m = 1 \)

- Approximation model
  \[
  S(N, n) = \frac{1}{2} (N + 2) \left( \frac{N}{n} + 1 \right)
  \rightarrow O\left(\frac{N^2}{n}\right)
  
  - Accurate model
  \[
  S(N, n) = \sum_{t=1}^{\frac{N+1}{n}} \frac{t}{2} \left(2 + (t - 1)(n - 1)\right)
  \rightarrow O\left(\frac{N^3}{n^2}\right)
  
  ![Graph showing the total number of states vs. the total number of slices (N)]