PhD Dissertation Defense

Service Profile-Aware Control Plane: A Multi-Instance Fixed Point Approximation within A Multi-Granularity VPN Loss Networks Perspective

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Outline

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Problem Statement

- **The architectures and functional operation of existing control plane components do not consider the service profile layer parameters**
- **This lack of harmony between the service profile layer, control plane layer, and network infrastructure layer exist in current IETF and ITU control plane models**
- **This lack of harmony leads to inefficient utilization of network resources**
- **Therefore, the problem is to develop a new Service Profile-Aware (SPA) control plane model that provides this harmony and then demonstrate its superiority over existing control plane models**
- **SPA control plane components were architected to utilize both the service profile layer parameters and network infrastructure detailed resource representation parameters**

Introduction: Problem Motivation/Significance

- **This research proposes a new SPA control plane model**
  - Detailed description of its architectural and functional operation
  - Analytically shows its superiority over existing IETF and ITU control plane models
- **The performance of the IETF/ ITU/SPA control plane models were analyzed in a common framework from the following perspectives:**
  - Transport network granularity realization
  - Operational level
  - Component-level interaction between the transport layer, control plane layer, and the service profile layer

Introduction: Research Approach

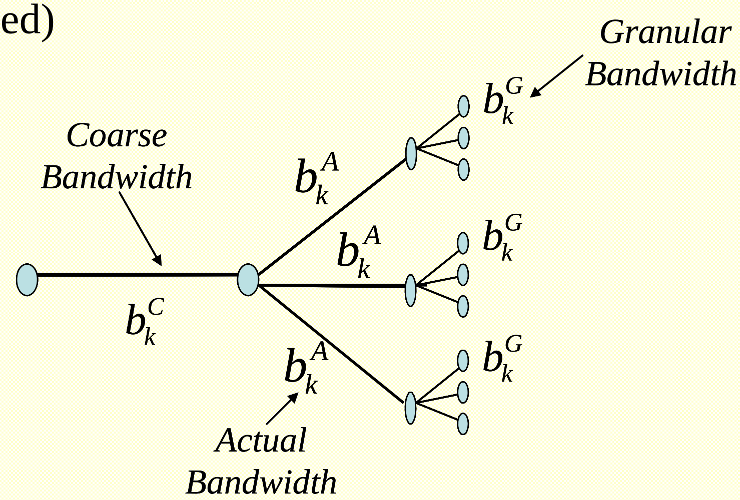
- **This research**
  - Defined the architectures of the multiple configured VPN service proposed models
  - Defined the architectures and functional operation of the control plane components for the three control plane models
  - Developed the mathematical models for the traffic management schemes of the three control plane models
    - Used Fixed Point Approximation (FPA) analytical model to compute the performance metrics for the traffic management schemes of the three control plane models
- **The superiority of the SPA control plane over IETF/ITU models was analytically demonstrated**

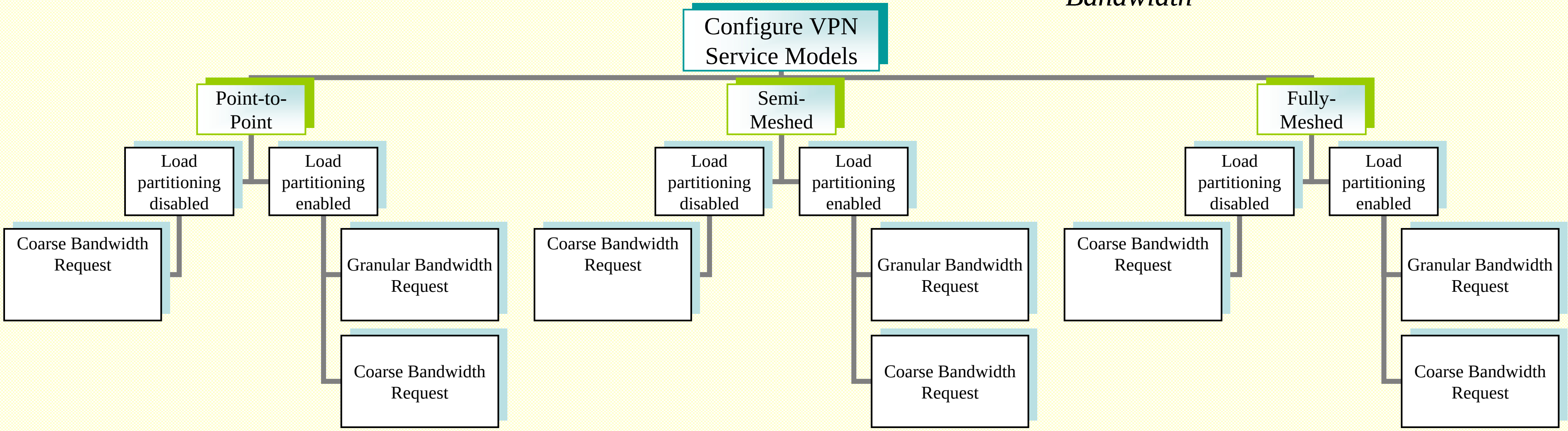
Contributions

- **Developed detailed architectures for the service configuration models from the following three perspectives:**
  - Service flow connectivity
  - Load partitioning flexibility
  - Service demand granularity
- **Developed architectures for the three control plane models (IETF, ITU, SPA) from the following three perspectives:**
  - Transport network granularity realization
  - Component-level
  - Operational-level
- **Developed mathematical formulation for each traffic management scheme of the three control plane models using Fixed Point Approximation (FPA)**
- **Demonstrated the superiority of the SPA over IETF and ITU control plane models using the following performance metrics:**
  - Service request blocking probability
  - Permissible "non-blocked" load
  - Transport resources utilization performance metrics
- **This work provides a significant shift in network design and traffic management for future wired and wireless networks**
  - More efficient utilization of network resources due to SPA enforcement of harmony between the service profile layer, control plane layer, and network infrastructure layer

Configured VPN Service Models

- **Nine possible service models were considered based on the configured service profile parameters:**
  - Service flow connectivity (Point-Point, Semi-Meshed, Fully-Meshed)
  - Arrival load partitioning flexibility (Dedicated, Shared)
  - Service demand granularity (Granular, Coarse)





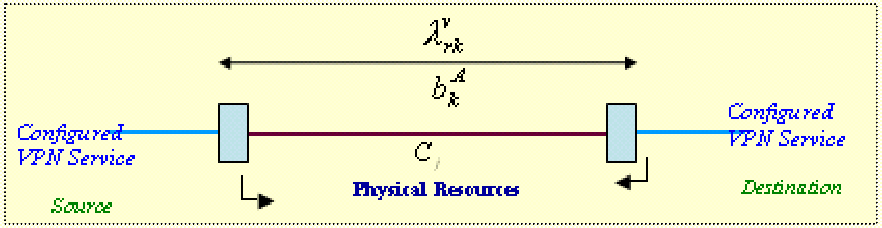
Configure VPN Service Models

- Point-to-Point
  - Load partitioning disabled
    - Coarse Bandwidth Request
  - Load partitioning enabled
    - Granular Bandwidth Request
    - Coarse Bandwidth Request
- Semi-Meshed
  - Load partitioning disabled
    - Coarse Bandwidth Request
  - Load partitioning enabled
    - Granular Bandwidth Request
    - Coarse Bandwidth Request
- Fully-Meshed
  - Load partitioning disabled
    - Coarse Bandwidth Request
  - Load partitioning enabled
    - Granular Bandwidth Request
    - Coarse Bandwidth Request

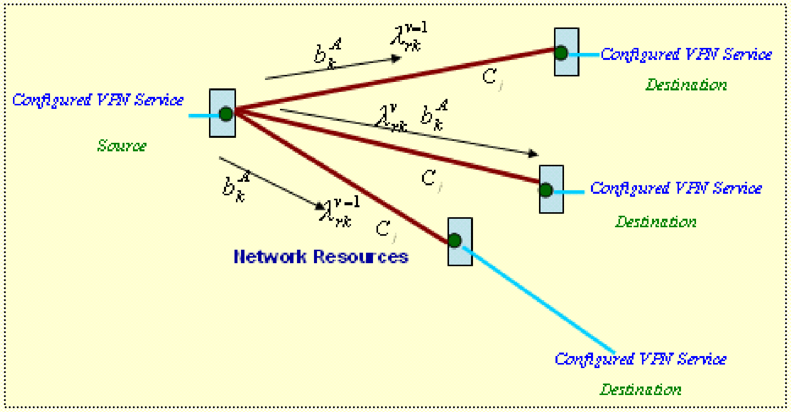
Configured VPN Service Models “Cont.”

Definitions and Notations

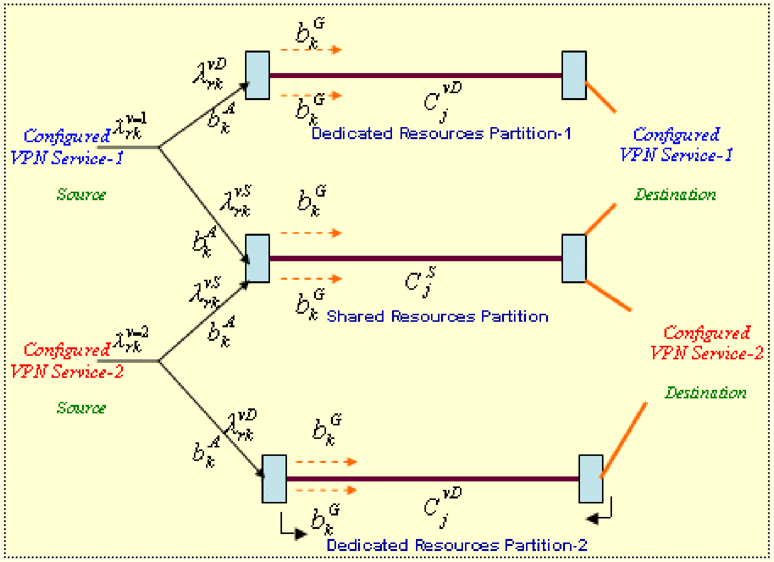
1. C_j : The physical capacity or bandwidth of link *j*,
2. Dedicated Resource C_j^{vD} : The dedicated capacity on link *j* for configured service *v*.
3. Shared Resources C_j^{S} : The shared capacity on link *j*.
4. VPN Resources C_j^{v} : The VPN capacity on link *j*. $C_j^{v} = C_j^{vD} + C_j^{S}$
5. λ_{rk}^{v} : The arrival rate of class *k* calls between node pair *r* for configured service *v*.
6. λ_{rk}^{vD} : The dedicated arrival rate.
7. λ_{rk}^{vS} : The shared arrival rate.
8. b_k^{C} : The coarse bandwidth requirement of class *k* calls
9. b_k^{G} : The granular, sub-rate, bandwidth requirement of b_k^{C}, in units of bandwidth, circuits
10. b_k^{A} : The actual bandwidth requirement of class k



Point-to-Point Dedicated Actual (PDA) Service Configuration



Fully-Meshed Dedicated Actual (FDA) Service Configuration



Point-to-Point Shared Actual (PSA) and Point-to-Point Shared Granular (PSG) Service Configurations

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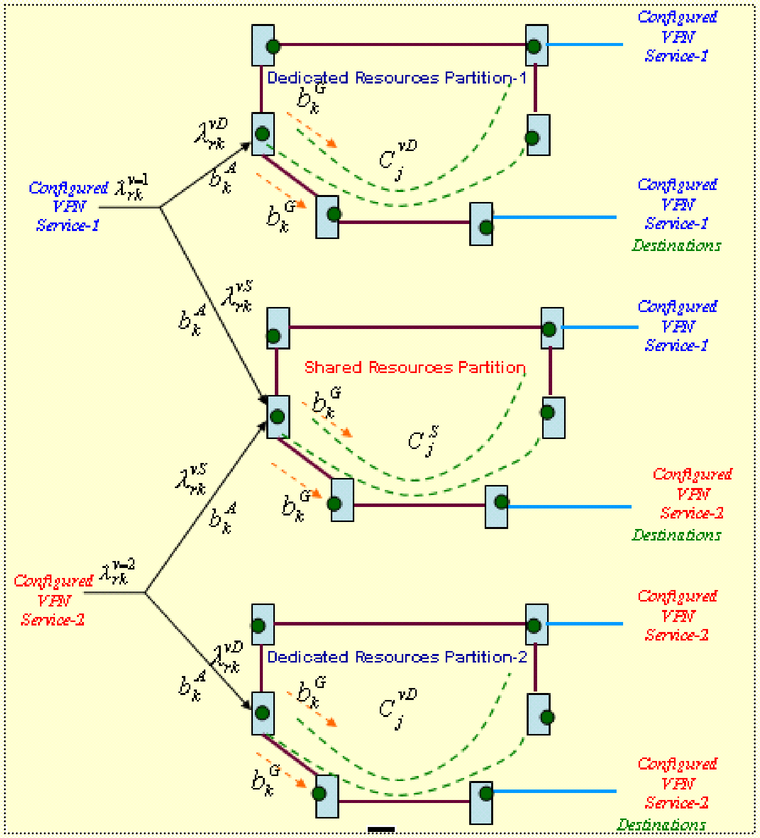
Configured VPN Service Models "Cont."



Fully-Meshed Shared Actual (FSA) and Fully-Meshed Shared Granular (FSG) Service Configurations

Definitions and Notations

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4. VPN Resources C_j^v : The VPN capacity on link *j*. $C_j^v = C_j^{vD} + C_j^S$
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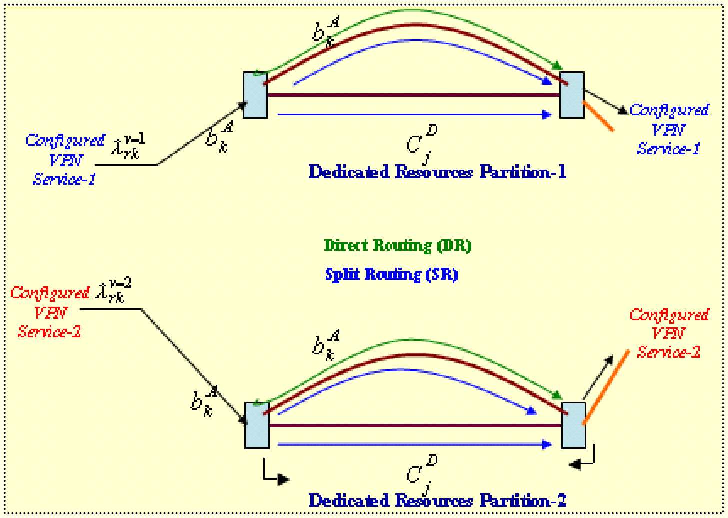
10. b_k^A : The actual bandwidth requirement of class k

- **Analysis focused on Fully-Meshed Shared Granular (FSG) service model**
  - (point-to-point, semi-meshed) are subset of Fully-Meshed
  - Dedicated arrival rate will not benefit from SPA Load Partitioning Function (LPF)
  - Coarse service demands will not benefit from SPA Inverse Multiplexing Function (IMF)

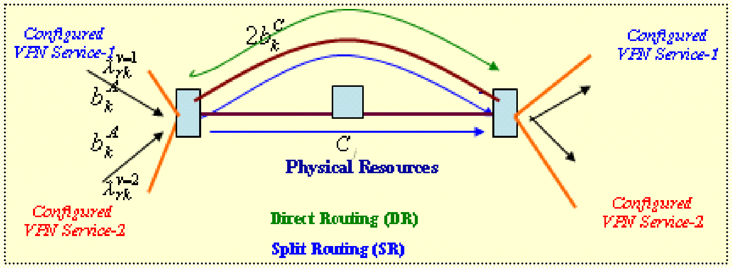
Control Plane Models- Traffic Management Schemes

- **Compared the three control plane models based on the following control plane traffic management capabilities:**
  - Routing update triggers (static vs. state-dependent)
  - Routing granularity level (coarse vs. granular)
  - Load Partitioning Function (LPF): Static Sharing (SS) vs. Network Engineering (NE)
  - Inverse Multiplexing Function (IMF): enabled vs. disabled
- **Routing granularity: Routing tables construction based transport granularity level**
- **Load Partitioning Function (LPF):**
  - Partition the service arrival load into two partitions; dedicated load and shared load
  - Has two options; Static Sharing (SS) and Network Engineering (NE)
    - Static Sharing (SS): Statically partition configured service arrival load into two partitions
      - Based on dedicated/shared resources to the VPN resources capacity ratio
    - Network Engineering (NE): Dynamically partition arrival load between dedicated/shared resources
      - Based on dedicated resources blocking probability
- **Inverse Multiplexing Function (IMF):**
  - Multiplexing/inverse multiplexing of incoming traffic
  - Multiplexing: Sending multiple signals or streams of information on a carrier at the same time
  - Inverse Multiplexing (IM): Dividing a data stream into multiple concurrent streams
    - Transmitted at the same time across separate channels
    - Reconstructed at the other end back into the original data stream

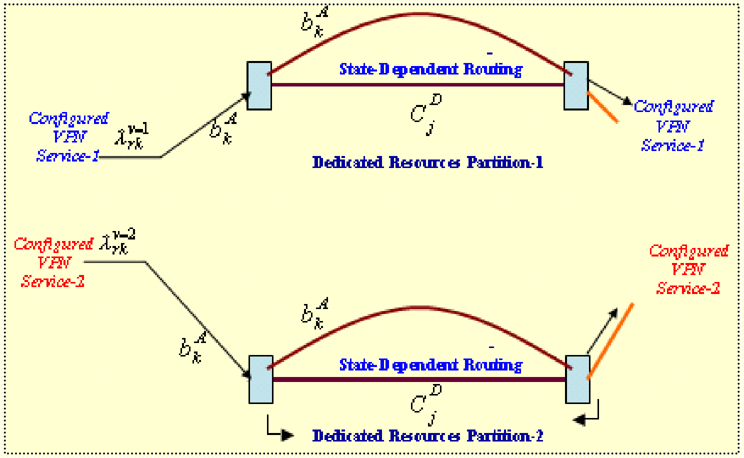
Control Plane Models- Traffic Management Schemes “Cont.”



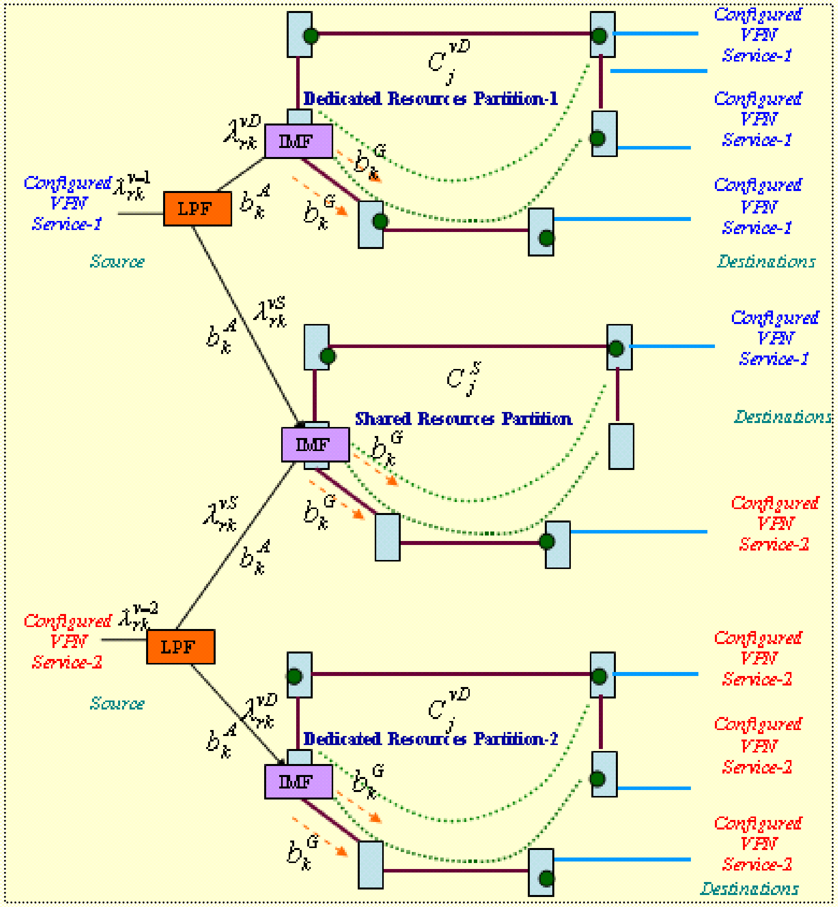
ITU Control Plane Model



IETF Control Plane Model

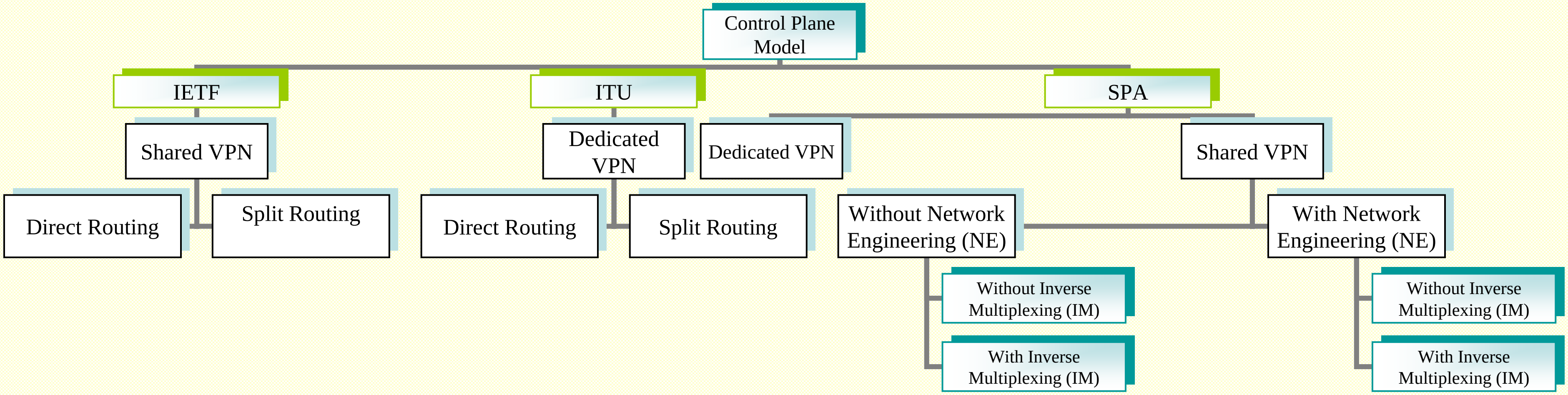


SPA-Dedicated Control Plane Model



SPA-Shared Control Plane Model

Control Plane Models- Traffic Management Schemes "Cont."



Control Plane Model	Routing Component	LPF	IMF
IETF-DR	Static- Direct	Disabled	Disabled
IETF-SR	Static- Split	Disabled	Disabled
ITU-DR	Static- Direct	Disabled	Disabled
ITU-SR	Static- Split	Disabled	Disabled
SPA-Dedicated	State-Dependent	Disabled	Disabled
SPA-Shared W/O (NE,IM)	State-Dependent	Enabled (SS)	Disabled
SPA- Shared (W/ NE, W/O IM)	State-Dependent	Enabled (NE)	Disabled
SPA- Shared (W/O NE, W/ IM)	State-Dependent	Enabled (SS)	Enabled
SPA- Shared W/ (NE,IM)	State-Dependent	Enabled (NE)	Enabled

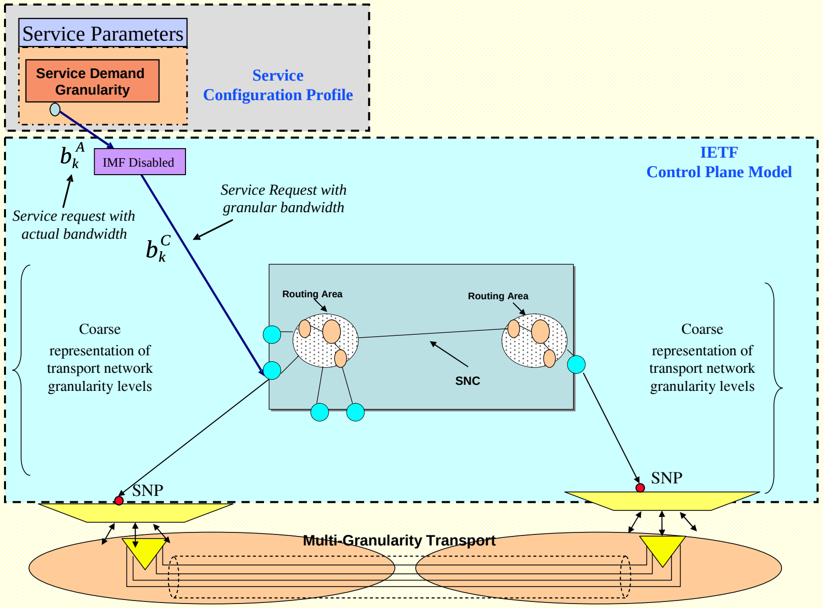
Control Plane Models- Transport Network Realization "Vertical View: Multi-Granularity"

Key Takeaway: ***From a transport resources granularity perspective:***

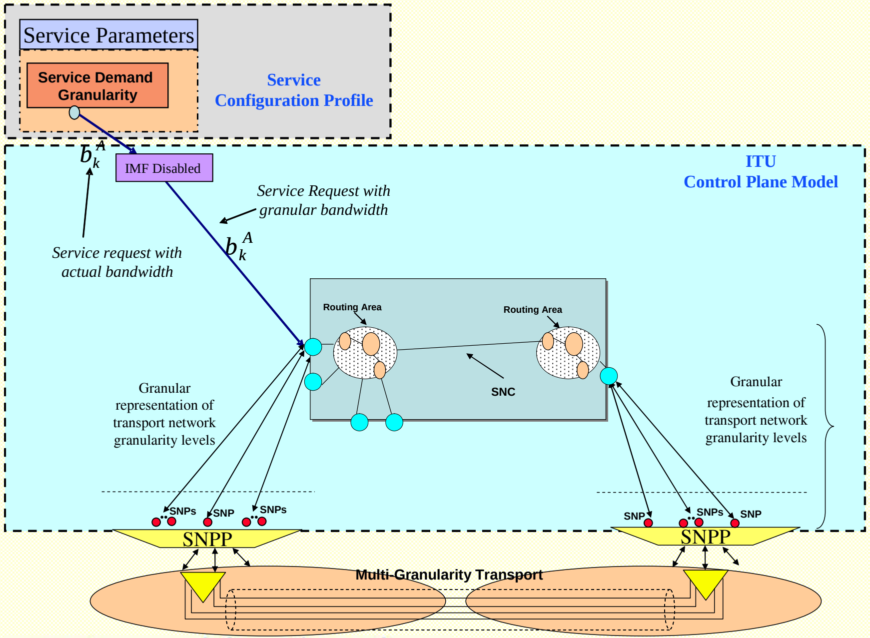
1. **IETF control plane model has coarse resource representation**
2. **ITU/SPA control plane models have granular resource representation**

From a demand granularity perspective:

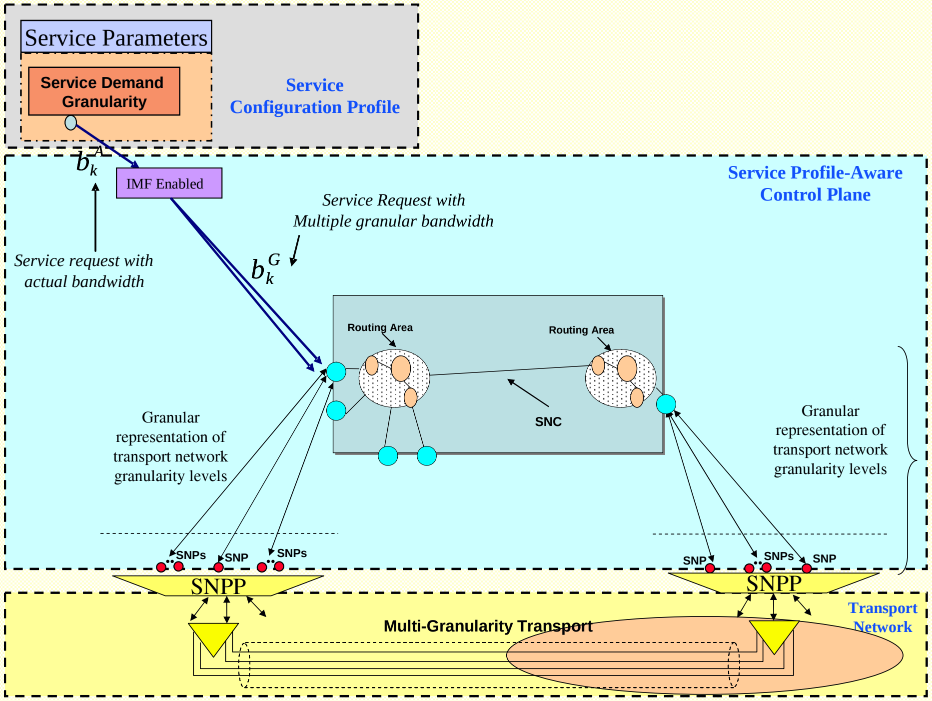
1. **IETF control plane model has coarse demand representation**
2. **ITU control plane model has actual demand representation**
3. **SPA control plane model have granular demand representation**



Service Parameters
Service Demand Granularity
Service Configuration Profile
IETF Control Plane Model
b_k^A
IMF Disabled
Service request with actual bandwidth
Service Request with granular bandwidth
b_k^C
Routing Area
Routing Area
SNC
Coarse representation of transport network granularity levels
Coarse representation of transport network granularity levels
SNP
SNP
Multi-Granularity Transport



Service Parameters
Service Demand Granularity
Service Configuration Profile
ITU Control Plane Model
b_k^A
IMF Disabled
Service request with actual bandwidth
Service Request with granular bandwidth
b_k^A
Routing Area
Routing Area
SNC
Granular representation of transport network granularity levels
Granular representation of transport network granularity levels
SNPs
SNP
SNPs
SNP
SNPs
SNP
SNPP
SNPP
Multi-Granularity Transport



Service Parameters
Service Demand Granularity
Service Configuration Profile
Service Profile-Aware Control Plane
b_k^A
IMF Enabled
Service request with actual bandwidth
Service Request with Multiple granular bandwidth
b_k^G
Routing Area
Routing Area
SNC
Granular representation of transport network granularity levels
Granular representation of transport network granularity levels
SNPs
SNP
SNPs
SNP
SNPs
SNP
SNPP
SNPP
Multi-Granularity Transport
Transport Network

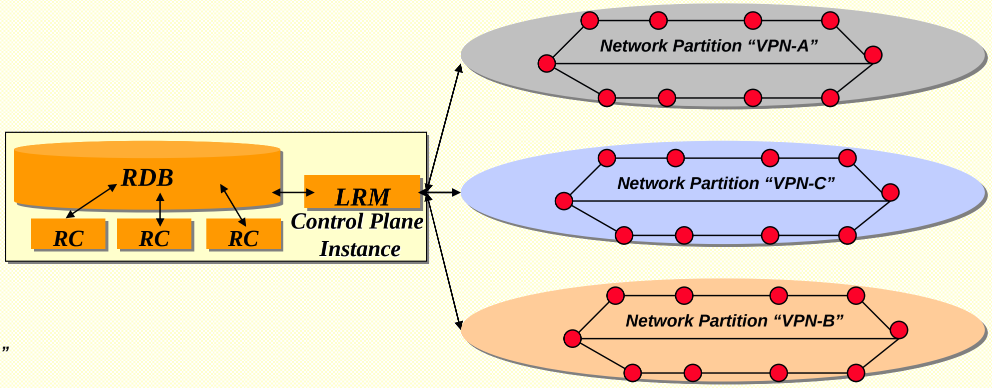
Control Plane Models- Transport Network Realization “Vertical View: Network Partitions”

Key Takeaway: ***From a transport resources perspective:***

1. **IETF control plane model implements Complete Sharing (CS) concept**
2. **ITU control plane model implements Complete Partitioning (CP) concept**
3. **SPA control plane model implements both CP and Virtual Partitioning (VP) concepts**

IETF Control Plane Model

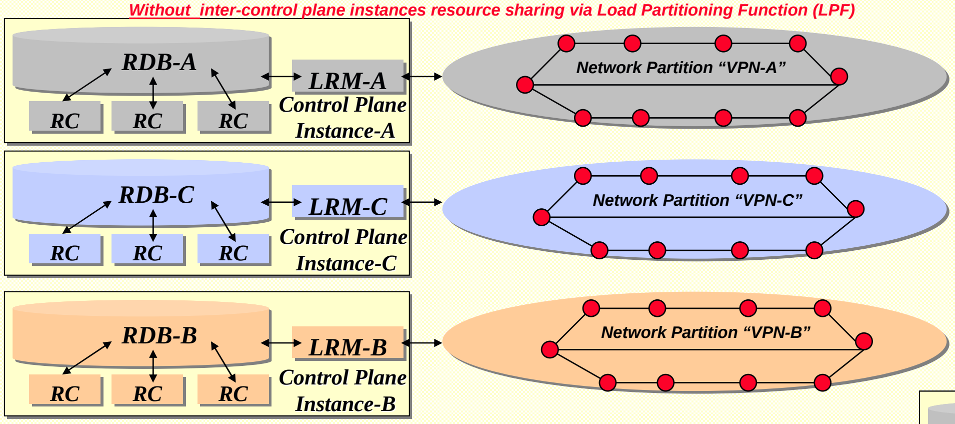
One Control Plane Instance with one RDB for the Three Transport Network Partitions “VPNs”



ITU/SPA-Dedicated Control Plane Models

Three Control Plane Instance with Three RDB partitions for the Three Transport Network Partitions “VPNs”

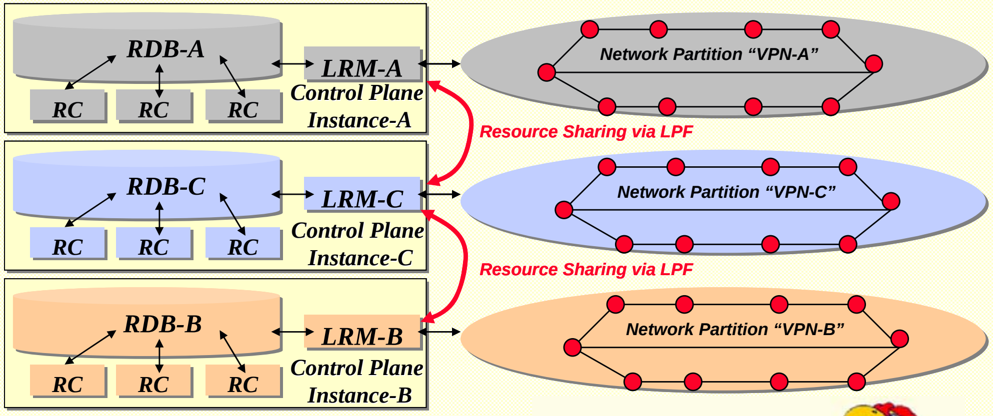
Without inter-control plane instances resource sharing via Load Partitioning Function (LPF)



SPA-Shared Control Plane Model

Three Control Plane Instance with Three RDB partitions for the Three Transport Network Partitions “VPNs”

With inter-control plane instances resource sharing via Load Partitioning Function (LPF)



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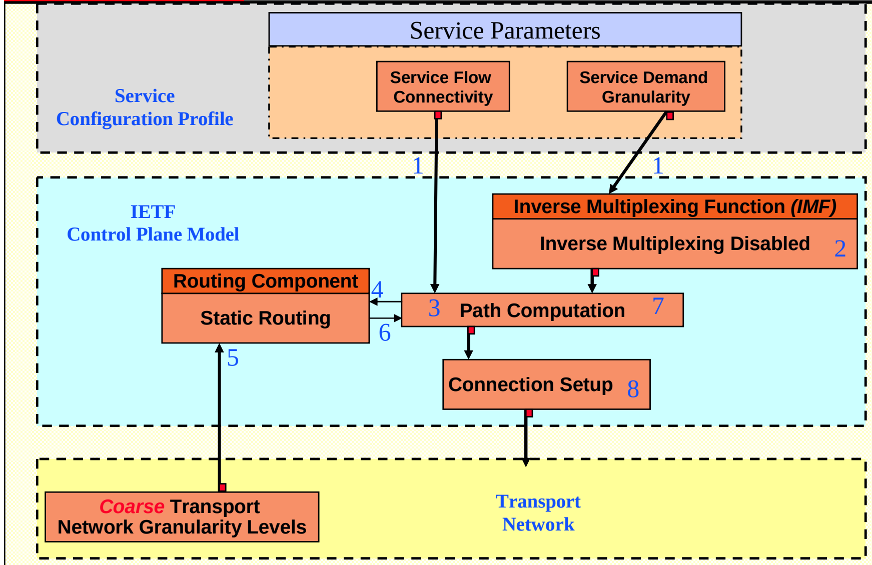
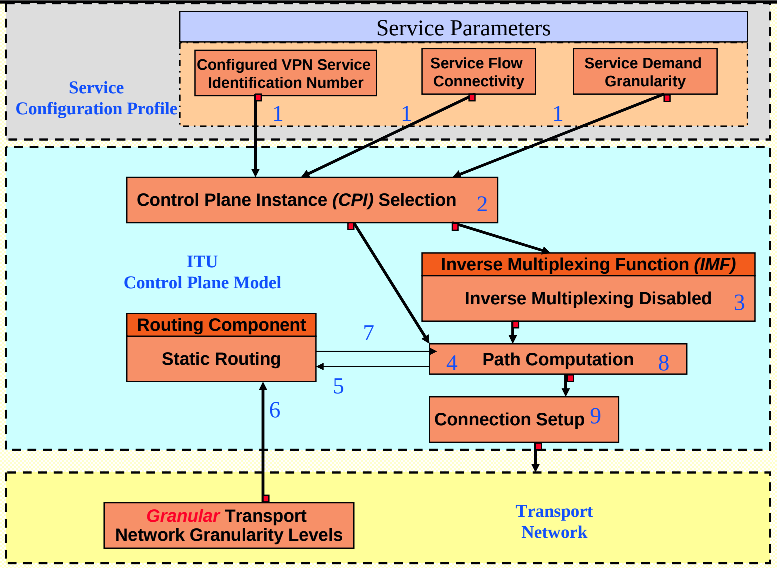
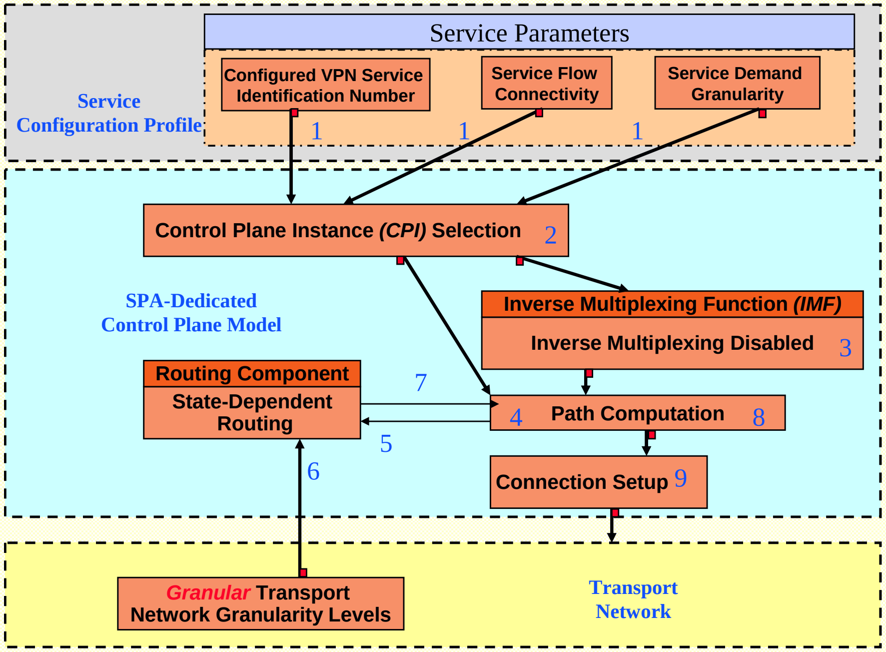
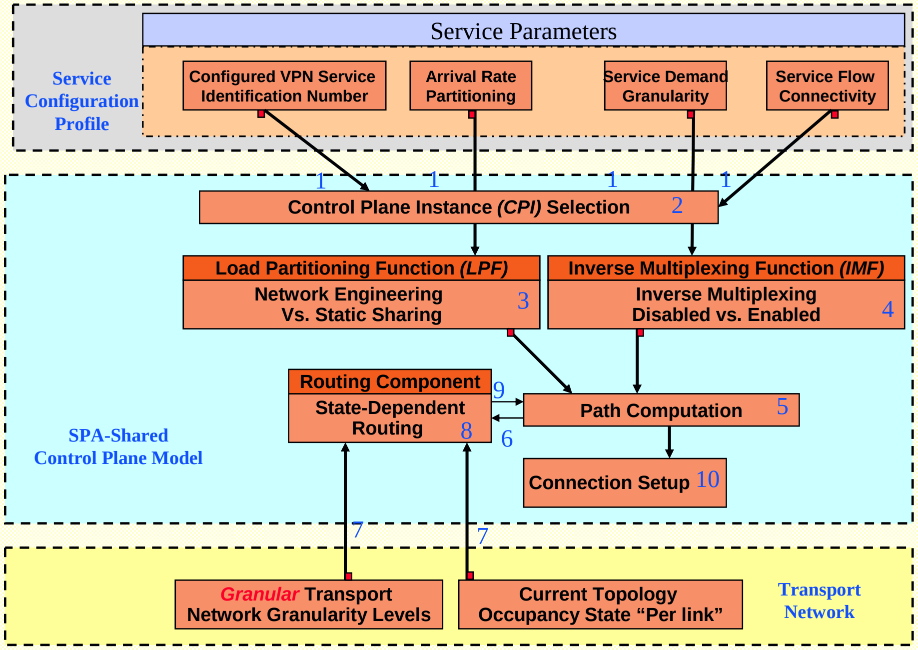
Control Plane Models- Component-Level Interaction



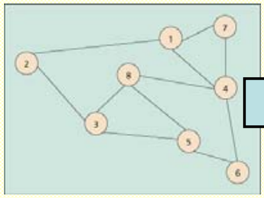






Analysis Methodology- Fixed Point Approximation (FPA) Steps

Topology Parameters



$$N = [1,2,........, N]$$

$$J = [1,2,.........., J]$$

$$R = \#of\_node\_pairs\_in\_topology$$

$$M_r = [M_1, M_{2,} ...., M_r]$$

$$r_m = [r_1, r_2, ..., r_m]$$

$$C_j = [C_1, C_2, ..., C_j]$$

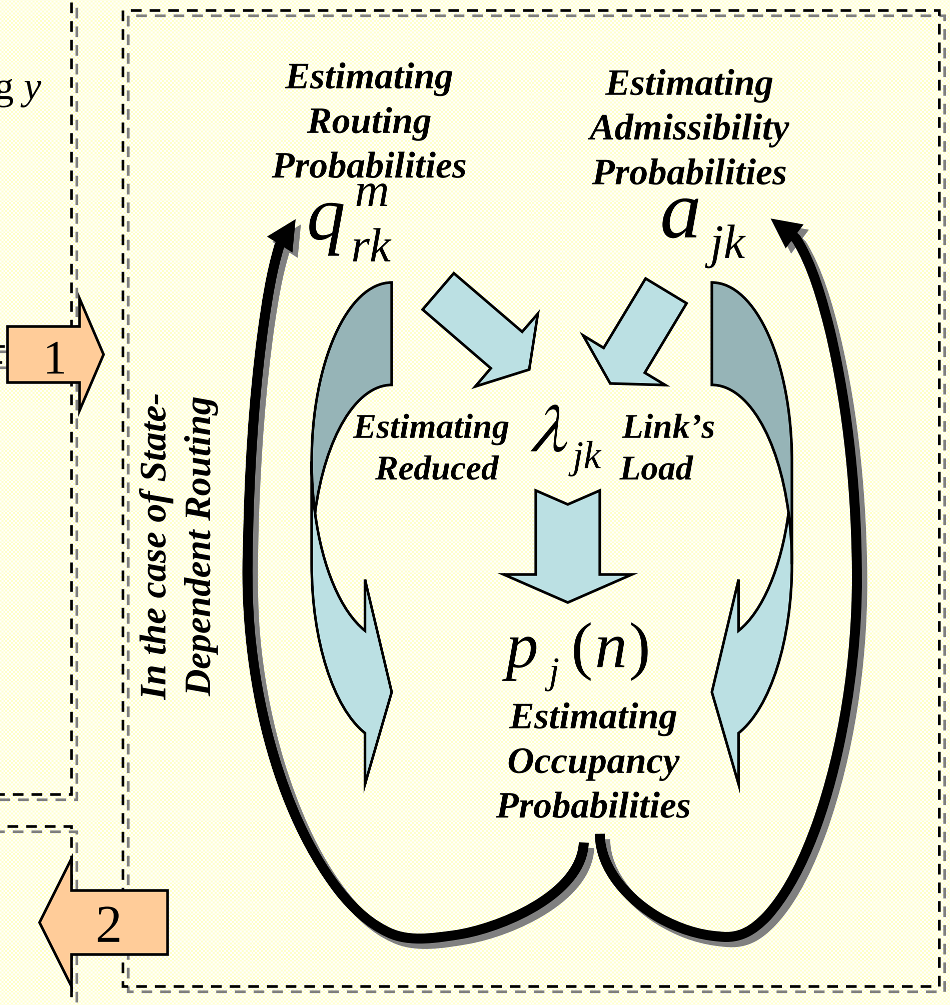
Service Arrivals

$$K = [k_1, k_2, ..., K]$$

$$b_k = [b_1, b_2, ..., b_K]$$

$$\lambda_{jk}^{rm} = [\lambda_{j1}^{rm}, \lambda_{j2}^{rm}, ...\lambda_{jk}^{rm}]$$

$$\mu_k = [\mu_1, \mu_2, ..., \mu_K]$$



In the case of State-Dependent Routing

Estimating Routing Probabilities q_{rk}^{m}

Estimating Admissibility Probabilities a_{jk}

Estimating Reduced λ_{jk} ***Link's Load***

$p_j(n)$ ***Estimating Occupancy Probabilities***

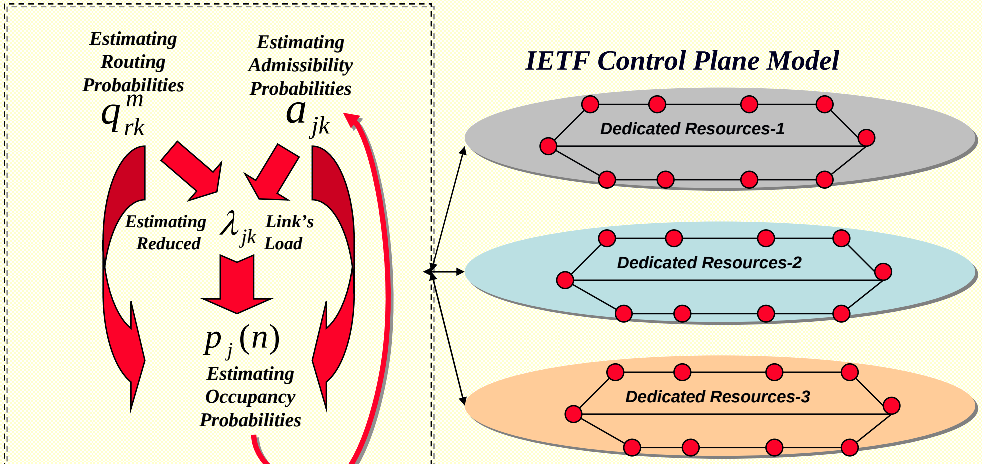
$$B_{rk} = 1 - \sum_m q_{rk}^m \prod_{j \in r_m} a_{jk}$$

Compute Per-Route Blocking Probability

Analysis Methodology- Assumptions

- **Link independence assumption**
  - *Blocking occurs independently from link to link*, determined by their respective arrival rates
  - This assumption becomes more reasonable as traffic gets heavier
- **Poisson calls arrivals**
  - The total offered load to an individual link is also a Poisson process with rate thinned by blocking on other links
- **All links are assumed to be undirected**
- **Stationary inputs**
  - Certain random quantities of interest have well-defined averages including:
    - Number of on-going calls on a link of each class
    - Average service request holding time
    - Reduced load on a link
  - With these averages we can further assume that there is a stationary probability of choosing a particular route under the state-dependent routing scheme
- **Minimal route overlapping for analyzed topologies**
  - FPA accuracy increases compared to DES

Analysis Methodology- FPA for the Three Control Plane Models



Estimating Routing Probabilities q^{m}_{rk}

Estimating Admissibility Probabilities a_{jk}

Estimating Reduced λ_{jk} Link's Load

$p_j(n)$ Estimating Occupancy Probabilities

IETF Control Plane Model

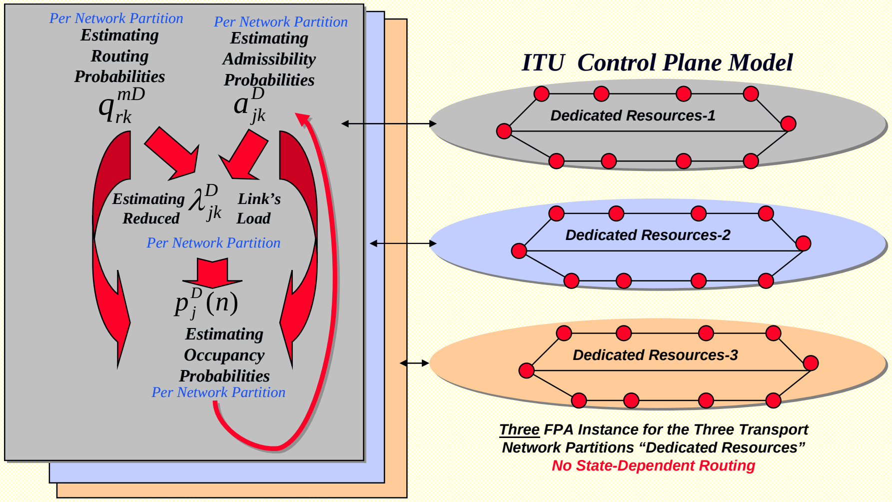
Dedicated Resources-1

Dedicated Resources-2

Dedicated Resources-3

One FPA Instance for the Three Transport Network Partitions "Dedicated Resources"

No State-Dependent Routing



Per Network Partition Estimating Routing Probabilities q^{mD}_{rk}

Per Network Partition Estimating Admissibility Probabilities a^{D}_{jk}

Estimating Reduced λ^{D}_{jk} Link's Load

Per Network Partition

$p^{D}_{j}(n)$ Estimating Occupancy Probabilities

Per Network Partition

ITU Control Plane Model

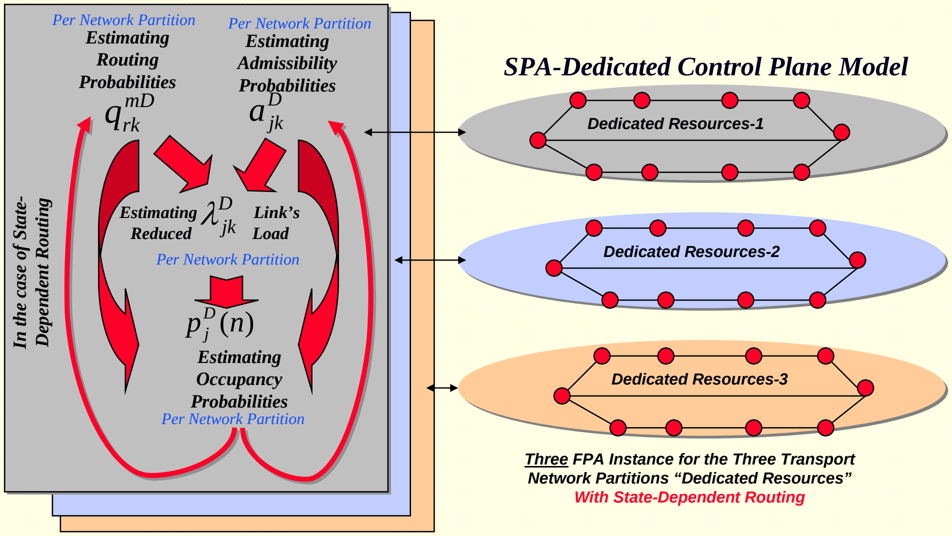
Dedicated Resources-1

Dedicated Resources-2

Dedicated Resources-3

Three FPA Instance for the Three Transport Network Partitions "Dedicated Resources"

No State-Dependent Routing



Per Network Partition Estimating Routing Probabilities q^{mD}_{rk}

Per Network Partition Estimating Admissibility Probabilities a^{D}_{jk}

Estimating Reduced λ^{D}_{jk} Link's Load

Per Network Partition

$p^{D}_{j}(n)$ Estimating Occupancy Probabilities

Per Network Partition

In the case of State-Dependent Routing

SPA-Dedicated Control Plane Model

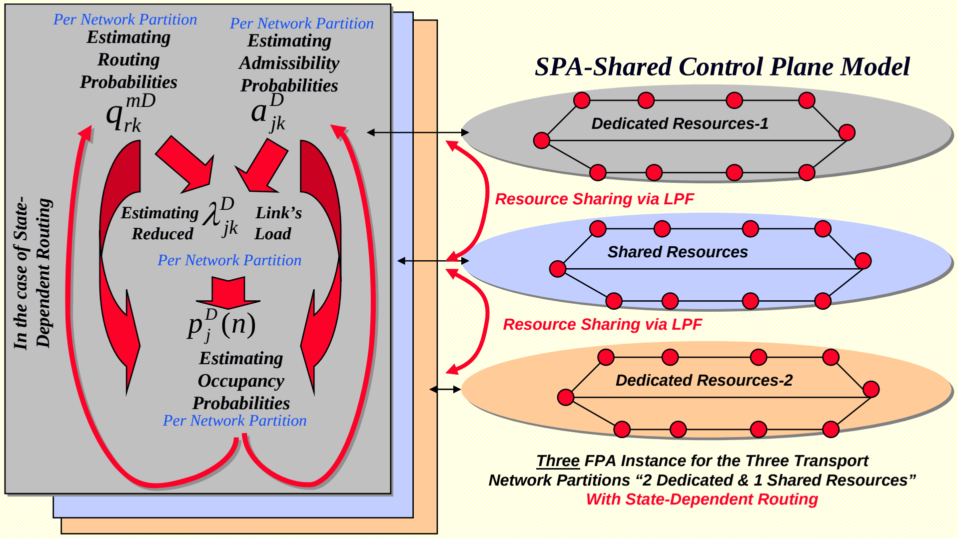
Dedicated Resources-1

Dedicated Resources-2

Dedicated Resources-3

Three FPA Instance for the Three Transport Network Partitions "Dedicated Resources"

With State-Dependent Routing



Per Network Partition Estimating Routing Probabilities q^{mD}_{rk}

Per Network Partition Estimating Admissibility Probabilities a^{D}_{jk}

Estimating Reduced λ^{D}_{jk} Link's Load

Per Network Partition

$p^{D}_{j}(n)$ Estimating Occupancy Probabilities

Per Network Partition

In the case of State-Dependent Routing

SPA-Shared Control Plane Model

Dedicated Resources-1

Resource Sharing via LPF

Shared Resources

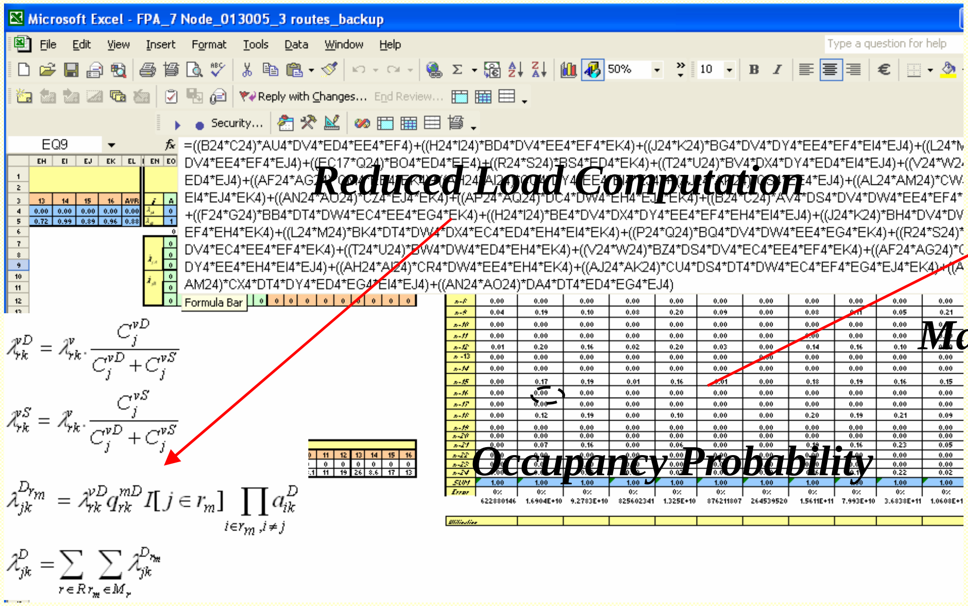
Resource Sharing via LPF

Dedicated Resources-2

Three FPA Instance for the Three Transport Network Partitions "2 Dedicated & 1 Shared Resources"

With State-Dependent Routing

Analysis Methodology- FPA Modeling Environment



Microsoft Excel - FPA_7 Node_013005_3 routes_backup

EQ9 fx =((B24*C24)*AU4*DV4*ED4*EE4*EF4)+((H24*I24)*BD4*DV4*EE4*EF4*EK4)+((J24*K24)*BG4*DV4*DY4*EE4*EF4*EI4*EJ4)+((L24*M DV4*EE4*EF4*EJ4)+((EC17*Q24)*BO4*ED4*EE4)+((R24*S24)*BS4*ED4*EK4)+((T24*U24)*BV4*DX4*DY4*ED4*EI4*EJ4)+((V24*W24 ED4*EJ4)+((AF24*AG [illegible] 4*EJ4)+((AL24*AM24)*CW EI4*EJ4*EK4)+((AN24*AO24)*CZ4*EJ4*EK4)+((AP24*AQ24)*DC4*DW4*EH4*EJ4*EK4)+((B24*C24)*AV4*DS4*DV4*DW4*EE4*EF4* +((F24*G24)*BB4*DT4*DW4*EC4*EE4*EG4*EK4)+((H24*I24)*BE4*DV4*DX4*DY4*EE4*EF4*EH4*EI4*EJ4)+((J24*K24)*BH4*DV4*DV EF4*EH4*EK4)+((L24*M24)*BK4*DT4*DW4*DX4*EC4*ED4*EH4*EI4*EK4)+((P24*Q24)*BQ4*DV4*DW4*EE4*EG4*EK4)+((R24*S24)* DV4*EC4*EE4*EF4*EK4)+((T24*U24)*BW4*DW4*ED4*EH4*EK4)+((V24*W24)*BZ4*DS4*DV4*EC4*EE4*EF4*EK4)+((AF24*AG24)*C DY4*EE4*EH4*EI4*EJ4)+((AH24*AI24)*CR4*DW4*EE4*EH4*EK4)+((AJ24*AK24)*CU4*DS4*DT4*DW4*EC4*EF4*EG4*EJ4*EK4)+((A AM24)*CX4*DT4*DY4*ED4*EG4*EI4*EJ4)+((AN24*AO24)*DA4*DT4*ED4*EG4*EJ4)

Formula Bar

Reduced Load Computation

Occupancy Probability

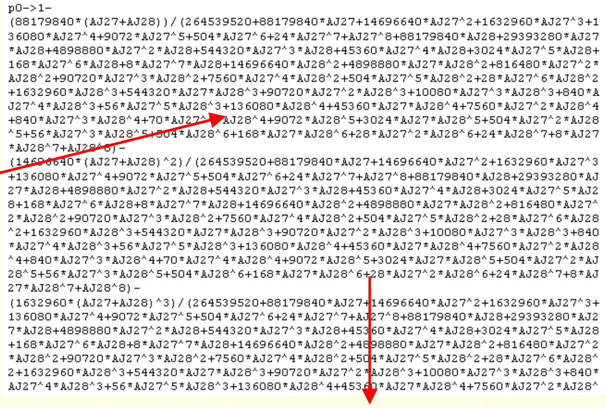
$$\lambda_{rk}^{vD} = \lambda_{rk}^{v} \cdot \frac{C_j^{vD}}{C_j^{vD} + C_j^{vS}}$$

$$\lambda_{rk}^{vS} = \lambda_{rk}^{v} \cdot \frac{C_j^{vS}}{C_j^{vD} + C_j^{vS}}$$

$$\lambda_{jk}^{D_{r_m}} = \lambda_{rk}^{vD} q_{rk}^{mD} I[j \in r_m] \prod_{i \in r_m, i \neq j} a_{ik}^{D}$$

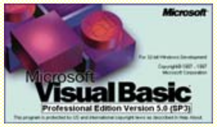
$$\lambda_{jk}^{D} = \sum_{r \in R} \sum_{r_m \in M_r} \lambda_{jk}^{D_{r_m}}$$

Occupancy Probability Computation

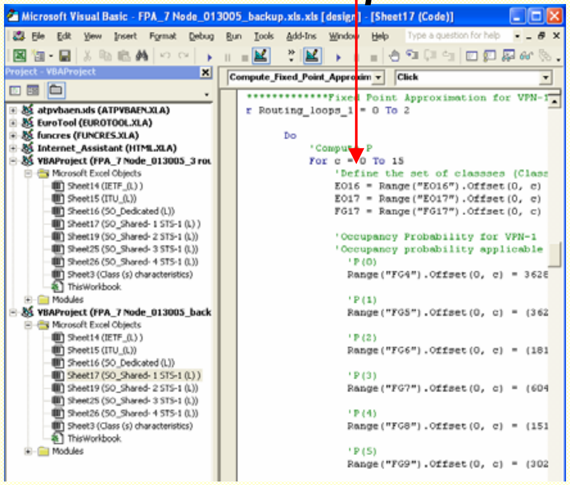


```
p0->1-
(88179840*(AJ27+AJ28))/(264539520+88179840*AJ27+14696640*AJ27^2+1632960*AJ27^3+1
36080*AJ27^4+9072*AJ27^5+504*AJ27^6+24*AJ27^7+AJ27^8+88179840*AJ28+29393280*AJ27
*AJ28+4898880*AJ27^2*AJ28+544320*AJ27^3*AJ28+45360*AJ27^4*AJ28+3024*AJ27^5*AJ28+
168*AJ27^6*AJ28+8*AJ27^7*AJ28+14696640*AJ28^2+4898880*AJ27*AJ28^2+816480*AJ27^2*
AJ28^2+90720*AJ27^3*AJ28^2+7560*AJ27^4*AJ28^2+504*AJ27^5*AJ28^2+28*AJ27^6*AJ28^2
+1632960*AJ28^3+544320*AJ27*AJ28^3+90720*AJ27^2*AJ28^3+10080*AJ27^3*AJ28^3+840*A
J27^4*AJ28^3+56*AJ27^5*AJ28^3+136080*AJ28^4+45360*AJ27*AJ28^4+7560*AJ27^2*AJ28^4
+840*AJ27^3*AJ28^4+70*AJ27^4*AJ28^4+9072*AJ28^5+3024*AJ27*AJ28^5+504*AJ27^2*AJ28
^5+56*AJ27^3*AJ28^5+504*AJ28^6+168*AJ27*AJ28^6+28*AJ27^2*AJ28^6+24*AJ28^7+8*AJ27
*AJ28^7+AJ28^8)-
(14696640*(AJ27+AJ28)^2)/(264539520+88179840*AJ27+14696640*AJ27^2+1632960*AJ27^3
+136080*AJ27^4+9072*AJ27^5+504*AJ27^6+24*AJ27^7+AJ27^8+88179840*AJ28+29393280*AJ
27*AJ28+4898880*AJ27^2*AJ28+544320*AJ27^3*AJ28+45360*AJ27^4*AJ28+3024*AJ27^5*AJ2
8+168*AJ27^6*AJ28+8*AJ27^7*AJ28+14696640*AJ28^2+4898880*AJ27*AJ28^2+816480*AJ27^
2*AJ28^2+90720*AJ27^3*AJ28^2+7560*AJ27^4*AJ28^2+504*AJ27^5*AJ28^2+28*AJ27^6*AJ28
^2+1632960*AJ28^3+544320*AJ27*AJ28^3+90720*AJ27^2*AJ28^3+10080*AJ27^3*AJ28^3+840
*AJ27^4*AJ28^3+56*AJ27^5*AJ28^3+136080*AJ28^4+45360*AJ27*AJ28^4+7560*AJ27^2*AJ28
^4+840*AJ27^3*AJ28^4+70*AJ27^4*AJ28^4+9072*AJ28^5+3024*AJ27*AJ28^5+504*AJ27^2*AJ
28^5+56*AJ27^3*AJ28^5+504*AJ28^6+168*AJ27*AJ28^6+28*AJ27^2*AJ28^6+24*AJ28^7+8*AJ
27*AJ28^7+AJ28^8)-
(1632960*(AJ27+AJ28)^3)/(264539520+88179840*AJ27+14696640*AJ27^2+1632960*AJ27^3+
136080*AJ27^4+9072*AJ27^5+504*AJ27^6+24*AJ27^7+AJ27^8+88179840*AJ28+29393280*AJ2
7*AJ28+4898880*AJ27^2*AJ28+544320*AJ27^3*AJ28+45360*AJ27^4*AJ28+3024*AJ27^5*AJ28
+168*AJ27^6*AJ28+8*AJ27^7*AJ28+14696640*AJ28^2+4898880*AJ27*AJ28^2+816480*AJ27^2
*AJ28^2+90720*AJ27^3*AJ28^2+7560*AJ27^4*AJ28^2+504*AJ27^5*AJ28^2+28*AJ27^6*AJ28^
2+1632960*AJ28^3+544320*AJ27*AJ28^3+90720*AJ27^2*AJ28^3+10080*AJ27^3*AJ28^3+840*
AJ27^4*AJ28^3+56*AJ27^5*AJ28^3+136080*AJ28^4+45360*AJ27*AJ28^4+7560*AJ27^2*AJ28^
```

Mathematica^{TM} Code



Visual Basic^{TM} for FPA



Microsoft Visual Basic - FPA_7 Node_013005_backup.xls.xls [design] - [Sheet17 (Code)]

```
*************Fixed Point Approximation for VPN-1
r Routing_loops_1 = 0 To 2

        Do
            'Compute P
            For c = 0 To 15
                'Define the set of classes (Class
                EO16 = Range("EO16").Offset(0, c)
                EO17 = Range("EO17").Offset(0, c)
                FG17 = Range("FG17").Offset(0, c)

                'Occupancy Probability for VPN-1
                'Occupancy probability applicable
                  'P(0)
                  Range("FG4").Offset(0, c) = 3628

                  'P(1)
                  Range("FG5").Offset(0, c) = (362

                  'P(2)
                  Range("FG6").Offset(0, c) = (181

                  'P(3)
                  Range("FG7").Offset(0, c) = (604

                  'P(4)
                  Range("FG8").Offset(0, c) = (151

                  'P(5)
                  Range("FG9").Offset(0, c) = (302
```

$$\mathbf{Pr}[A_n^D(r_m)] = \prod_{j \in (r_m)} \sum_{k=0}^{C_j^D - n} P_j^D(k)$$

$$|\mathbf{Pr}[A_{n+1}^D(r_m)] = \prod_{j \in (r_m)} \sum_{k=0}^{C_j^D - n+1} P_j^D(k)$$

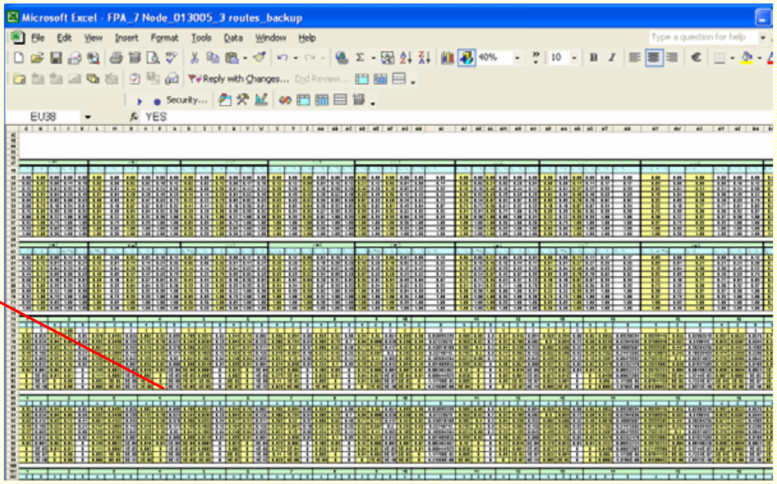
$$\mathbf{Pr}[A_n^D(r_k - r_m)] = \prod_{j \in (r_k - r_m)} \sum_{k=0}^{C_j^D - n} P_j^D(k)$$

$$\Pr[\overline{A}_n^D(r_k - r_m)] = 1 - \prod_{j \in (r_k - r_m)} \sum_{k=0}^{C_j^D - n} P_j^D(k)$$

$$\mathbf{Pr}[A_{n+1}^D(r_k - r_m)] = \prod_{j \in (r_k - r_m)} \sum_{k=0}^{C_j^D - n+1} P_j^D(k)$$

$$\Pr[\overline{A}_{n+1}^D(r_k - r_m)] = 1 - \prod_{j \in (r_k - r_m)} \sum_{k=0}^{C_j^D - n+1} P_j^D(k)$$

$$\mathbf{Pr}[\widetilde{A}_n^D(r_m)] = \mathbf{Pr}[A_n^D(r_m)] - \mathbf{Pr}[A_{n+1}^D(r_m)]$$



Microsoft Excel - FPA_7 Node_013005_3 routes_backup

EU38 fx YES

Mathematical Formulation Highlights “Details available in Appendix-A”

- **Base FPA method was modified based on the unique attributes of each traffic management scheme of the three control plane models**
- **Mathematical formulation steps included:**
  - CAC for multi-rate demands
    - Modified based on each control plane representation of demand granularity
  - Estimating link’s reduced load
    - Modified based on each control plane input load handling capability
  - Estimating link’s admissibility probability
    - Modified based on each control plane representation of transport resources granularity
  - Estimating routing probability
    - Modified based on each control plane routing static vs. state-dependent mechanism
  - Estimating network blocking probability
    - Modified based on the each control plane representation of network partitions
  - Estimating network permissible load
    - Modified based on the each control plane representation of network partitions
  - Estimating network utilization
    - Modified based on the each control plane representation of network partitions

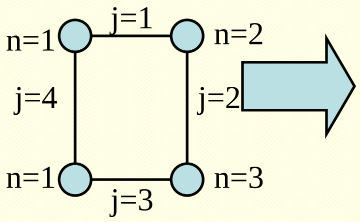
Scenarios & Performance Evaluation- Control Plane Parameters & Performance Metrics

	Routing Probability		Routing Granularity		Control Plane Instance (CPI) Selection	Load Partitioning Function (LPF) enabled		Inverse Multiplexing Function (IMF) enabled	
Component Configuration	Static	State-Dependent	Coarse	Granular		w/o NE	w/ NE	w/o IM	w/ IM
IETF	✓		✓						
ITU	✓			✓	✓				
SPA-Dedicated		✓		✓	✓				
SPA-w/o(NE,IM)		✓		✓	✓	✓		✓	
SPA-w/NE,w/oIM		✓		✓	✓		✓	✓	
SPA-w/oNE,w/IM		✓		✓	✓	✓			✓
SPA-w/(NE,IM)		✓		✓	✓		✓		✓

Performance Metric	*Blocking probability*				*Permissible load*				*Utilization*			
Network Partition Level	D	S	V	L	D	S	V	L	D	S	V	L
IETF				✓				✓				✓
ITU	✓			✓	✓			✓	✓			✓
SPA-Dedicated	✓			✓	✓			✓	✓			✓
SPA-Shared	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Scenarios & Performance Evaluation- FPA modeling parameters

Topology Parameters



$N = [n=1, n=2, n=3, n=4]$

$J = [j=1, j=2, j=3, j=4]$

$R = 6$

$M_r = [M_1 = 2, M_2 = 2, M_3 = 2, M_4 = 2, M_5 = 2, M_6 = 2]$

$r_m = [r_1 = \{1,2\}, r_2 = \{1,3\}, r_3 = \{1,4\}, r_4 = \{2,3\}, r_5 = \{2,4\}, r_6 = \{3,4\}]$

$C_j = [C_1 = 24, C_2 = 24, C_3 = 24, C_4 = 24, C_5 = 24, C_6 = 24]$

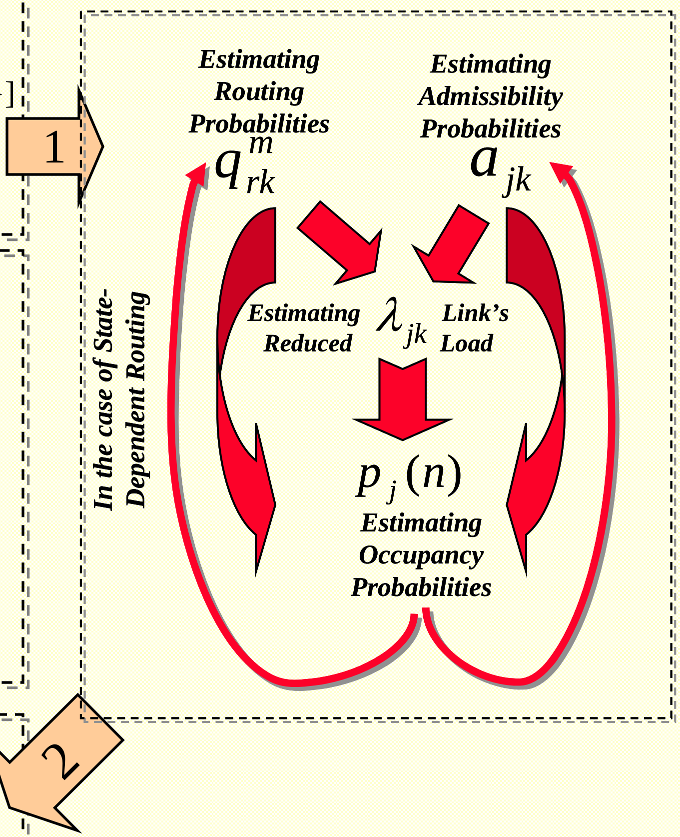
Service Arrivals

$K = [K = 2]$

$b_k = [2STS - 1]$

$\lambda_{jk}^{r_m} = [\lambda_{jk}^{r_m} = 10 -> 30 Erlang]$

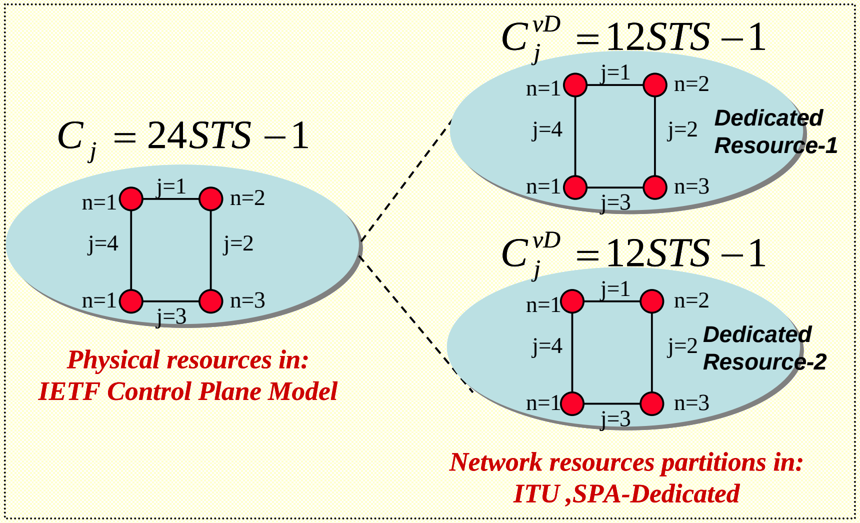
$\mu_k = [\mu_1 = 1]$



$$B_{rk} = 1 - \sum_{m} q_{rk}^{m} \prod_{j \in r_m} a_{jk}$$

Compute Per-Route Blocking Probability

Scenarios & Performance Evaluation- Network Topologies Analyzed



$C_j = 24STS - 1$

$C_j^{vD} = 12STS - 1$

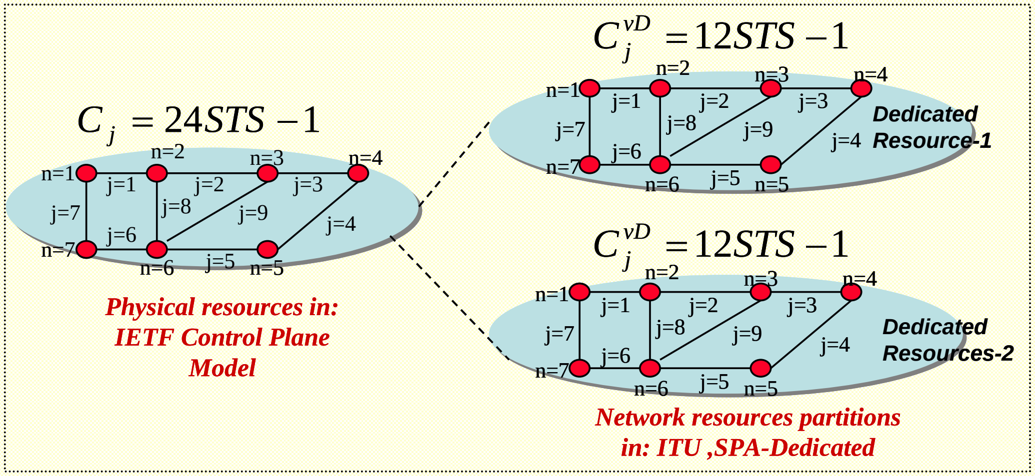
Dedicated Resource-1

$C_j^{vD} = 12STS - 1$

Dedicated Resource-2

Physical resources in: IETF Control Plane Model

Network resources partitions in: ITU ,SPA-Dedicated



$C_j = 24STS - 1$

$C_j^{vD} = 12STS - 1$

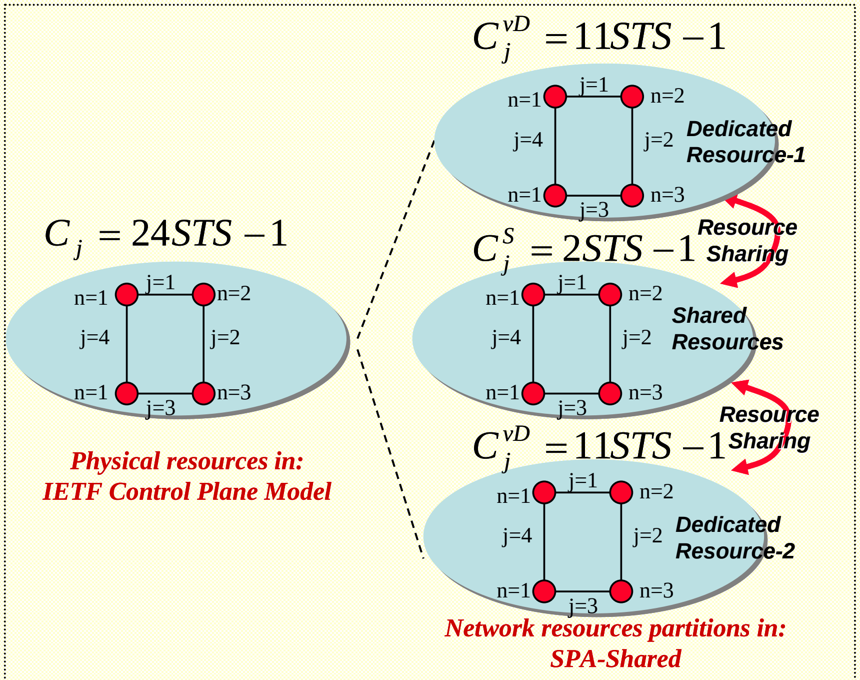
Dedicated Resource-1

$C_j^{vD} = 12STS - 1$

Dedicated Resources-2

Physical resources in: IETF Control Plane Model

Network resources partitions in: ITU ,SPA-Dedicated



$C_j = 24STS - 1$

$C_j^{vD} = 11STS - 1$

Dedicated Resource-1

Resource Sharing

$C_j^{S} = 2STS - 1$

Shared Resources

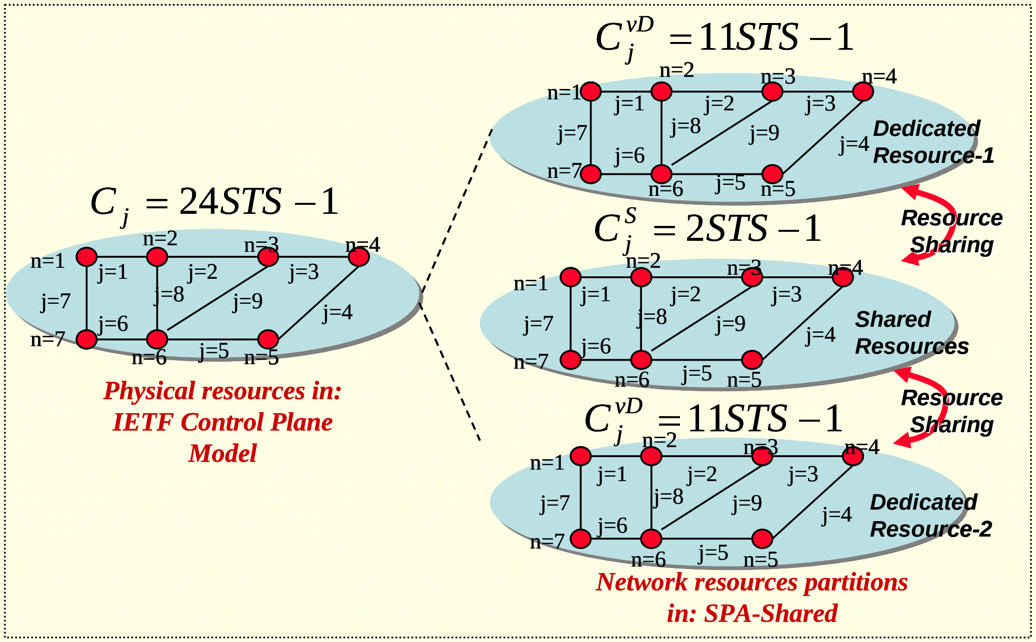
Resource Sharing

$C_j^{vD} = 11STS - 1$

Dedicated Resource-2

Physical resources in: IETF Control Plane Model

Network resources partitions in: SPA-Shared



$C_j = 24STS - 1$

$C_j^{vD} = 11STS - 1$

Dedicated Resource-1

Resource Sharing

$C_j^{S} = 2STS - 1$

Shared Resources

Resource Sharing

$C_j^{vD} = 11STS - 1$

Dedicated Resource-2

Physical resources in: IETF Control Plane Model

Network resources partitions in: SPA-Shared

Mathematical Models Validation- Credibility of Modeling Results

- **Accuracy of mathematical models assumptions**
  - Higher input loads were used to improve the accuracy of results
    - The base method validated that for blocking probabilities under higher input loads, FPA algorithm average percentage error compared to DES is below 5%
  - Minimal route overlapping was considered for the 4-node and 7-node topologies analyzed
    - The base method validated that under minimal routing overlapping for fully connected and random topologies, FPA algorithm accuracy compared to DES increases
- **Accuracy of occupancy probability computation**
  - When the output of the of the occupancy probabilities equations was used in the FPA algorithm, validating that the summation of occupancy probabilities of link *j* for all the states is equal to 1 was carried after each FPA convergence, the percentage of error was 0%
- **Accuracy of routing probability computation**
  - After each FPA convergence, the routing probability constraint, summation of the routing probability for all the routes between a source-destination pair has to equal 1, was validated
  - Percentage error was in the range below 3% for the 7-node topology and 0% for the 4-node topology
- **Accuracy of LPF and IMF traffic management operations**
  - *LPF sanity check:* made sure that the summation of the load applied to the dedicated network resources partitions and the shared network resources partition is equal to the total input load
  - *IMF sanity check:* made sure that the input load before an inverse multiplexing operation is equal to the input load after the inverse multiplexing operation

Mathematical Models Validation- Performance Results Consistent Trends

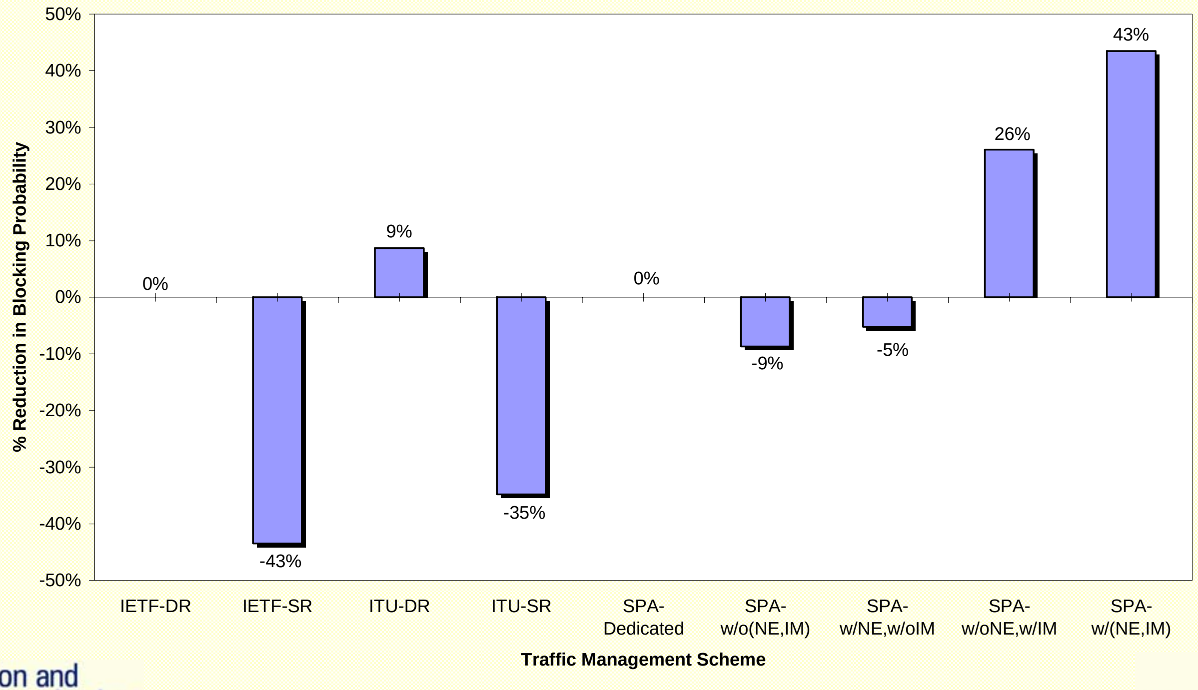
"7-node topology with both 2 & 3 alternate routing"

- **Blocking Probability:**
  - SPA-Dedicated traffic management scheme does not provide any reduction in blocking probability compared to the IETF-DR traffic management scheme
    - But provides higher reduction in blocking probability compared to IETF-SR and ITU-SR traffic management schemes
  - The SPA two traffic management schemes with enabled inverse multiplexing lead to the highest reduction in blocking probability, compared to the rest of the traffic management schemes
- **Permissible Load:**
  - The SPA two traffic management schemes with enabled inverse multiplexing lead to the highest increase in permissible load compared to the rest of the traffic management schemes
  - The SPA-Shared control plane model with disabled inverse multiplexing leads to a reduction in permissible load compared to the IETF-DR traffic management scheme
- **Utilization:**
  - SPA-Shared with enabled inverse multiplexing leads to a lower reduction in utilization compared to the IETF-DR traffic management scheme
  - SPA-Shared with disabled inverse multiplexing leads to higher reduction in utilization compared to IETF-DR traffic management scheme

Performance Analysis Results Highlights- Blocking Probability "Summary View"

- **All SPA traffic management schemes provide a higher reduction in blocking probability compared to the IETF-SR and ITU-SR control plane models**
  - Reduction is 0-131% and 39-122% respectively; depending on the SPA traffic management scheme, and SPA number of alternate routes
- **When IMF is disabled, IETF-DR traffic management scheme produces less blocking probability than SPA control plane model**
- **When IMF is enabled, SPA control plane model leads to the highest reduction in blocking probability compared to IETF-DR**
  - Reduction of 22-48% depending on the number of alternate routes

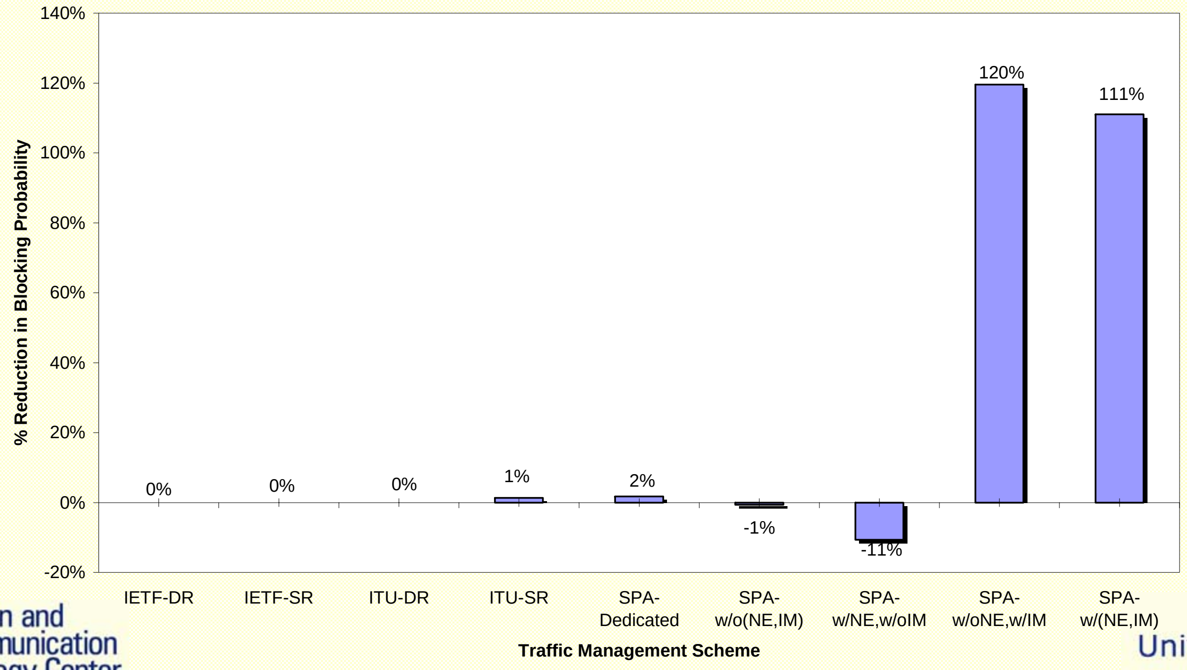
Network-Wide Reduction in Blocking Probability (Physical Resources Level)-
IETF-DR as reference control plnae model
7-Node Topology (3- Alternate Routing)



Performance Analysis Results Highlights- Permissible Load "Summary View"

- **All SPA traffic management schemes, except when IMF is disabled, provide a higher increase in permissible load compared to the IETF-SR and ITU-(DR,SR) control plane models**
  - Increase is 120-134% and 110-120% respectively; depending on the SPA traffic management scheme, SPA number of alternate routes, and the IETF/ITU static routing configuration
- **Highest increase in permissible load occurs for SPA-"w/oNE,w/IM" traffic management scheme**
  - Increase is 120-134% compared to IETF-DR control plane model; depending on the number of alternate routes
- **While enabling IM, performing load partitioning statically or dynamically does not provide a significant impact on the percentage gain in permissible load**
- **While disabling IM and regardless of static or dynamic load partitioning for SPA-Shared control plane model, the SPA control plane model provides less permissible load than IETF-DR control plane model**

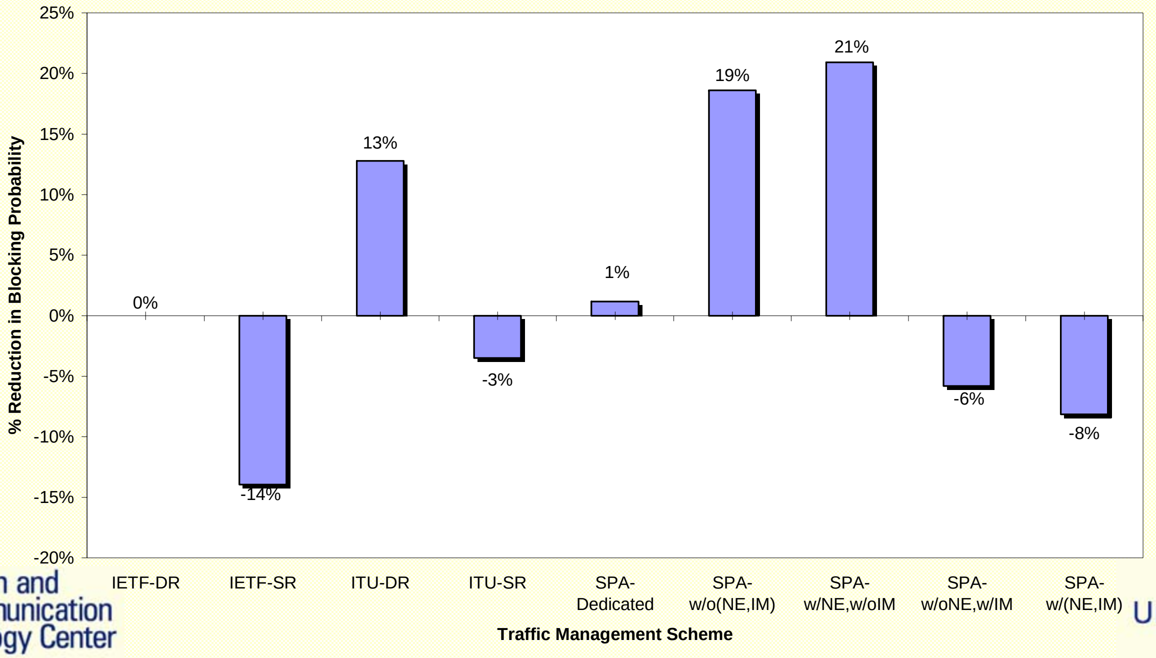
Network-Wide Increase in Permissible Load (Physical Resources Level)-
IETF-DR as reference control plnae model
7-Node Topology (3- Alternate Routing)



Performance Analysis Results Highlights- Utilization “Summary View”

- **All SPA traffic management schemes, except when IMF is enabled, provide a higher reduction in utilization compared to the ITU-(DR,SR) control plane models**
  - Reduction is 8-28% depending on the SPA traffic management scheme, number of SPA alternate routes, and the ITU static routing configuration
- **SPA control plane model provide a reduction in utilization only when IMF is disabled**
  - Reduction is 19-23% depending on the SPA traffic management scheme and number of alternate routes
- **The lowest reduction in utilization occur for “w/(NE,IM)” and “w/oNE,w/IM” SPA traffic management schemes when IMF is configured to enabled Inverse Multiplexing (with IM) and regardless of LPF configuration as static or dynamic partitioning**
  - Increase of 2-8% in utilization over the IETF-DR control plane model depending on the number of alternate routes

Network-Wide Reduction in Utilization (Physical Resources Level)-
IETF-DR as reference control plnae model
7-Node Topology (3- Alternate Routing)



Justification for Generalizing Performance Analysis Results for SPA

- **State-dependent routing distributes the input load across all the identified routes between a source-destination pair based on the traffic occupancy rather than static routing as in IETF/ITU control plane models**
  - This leads to: Blocking probability reduction, permissible load slight increase, and utilization reduction
- **LPF utilizes both the dedicated resources partition and the shared resources partition for the configured VPN service**
  - Thus, the configured VPN service will have more resources than IETF and ITU control plane models
  - This leads to: Blocking probability reduction and utilization reduction
- **IMF splits incoming service request flows between a source-destination pair with an actual bandwidth requirement into multiple flows each with granular bandwidth requirement**
  - Each granular flow is routed independently across the available routes
  - This leads to: Blocking probability reduction, permissible load increase, and utilization increase

Conclusions

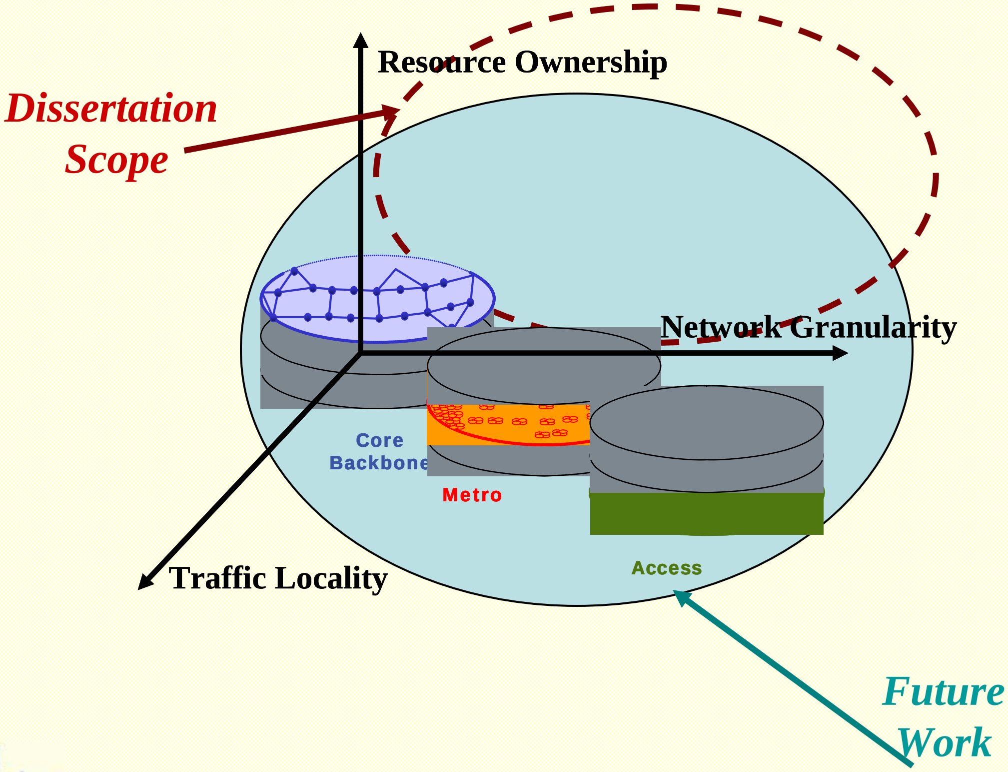
- **All SPA traffic management schemes provide a higher reduction in blocking probability compared to the IETF-SR and ITU-SR control plane models**
  - Reduction is 0-131% and 39-122% respectively
- **When IMF is enabled, SPA control plane model leads to the highest reduction in blocking probability compared to IETF-DR**
- **All SPA traffic management schemes, except when IMF is disabled, provide a higher increase in permissible load compared to the IETF and ITU control plane models**
  - Increase is 120-134% and 110-120% respectively
- **SPA-Shared with enabled load sharing and disabled inverse multiplexing provide a higher reduction in utilization compared to all IETF and ITU traffic management schemes**
  - Reduction is 8-35%
- **The performance analysis results carried on the 7-node topologies for both two and three alternate routes:**
  - Validated the hypotheses of this work
  - Indicated a common trend of the superiority of the SPA control plane model over the IETF and ITU control plane models
- **Thus, the performance analysis concluded with SPA superiority over existing IETF/ITU control plane models**
  - SPA provides a significant shift in network design and traffic management for future wired and wireless networks
  - More efficient utilization of network resources due to SPA enforcement of harmony between the service profile layer, control plane layer, and network infrastructure layer

Recommendations

- **To achieve *maximum* blocking probability reduction over IETF and ITU control plane models, SPA components need to be configured as follows:**
  - State-dependent routing: Enabled
  - Inverse Multiplexing Function (IMF): Enabled
  - Load Partitioning Function (LPF): configured as Network Engineering (NE)
- **To achieve *maximum* permissible load increase over IETF and ITU control plane models, SPA components need to be configured as follows:**
  - State-dependent routing: Enabled
  - Inverse Multiplexing Function (IMF): Enabled
  - Load Partitioning Function (LPF): configured as Static Sharing (SS) or Network Engineering (NE)
- **To achieve *maximum* reduction in utilization over IETF and ITU control plane models, SPA components need to be configured as follows:**
  - State-dependent routing: Enabled
  - Inverse Multiplexing Function (IMF): Disabled
  - Load Partitioning Function (LPF): configured as Static Sharing (SS)

Next Steps/Future Work- Multi-Domain Analysis

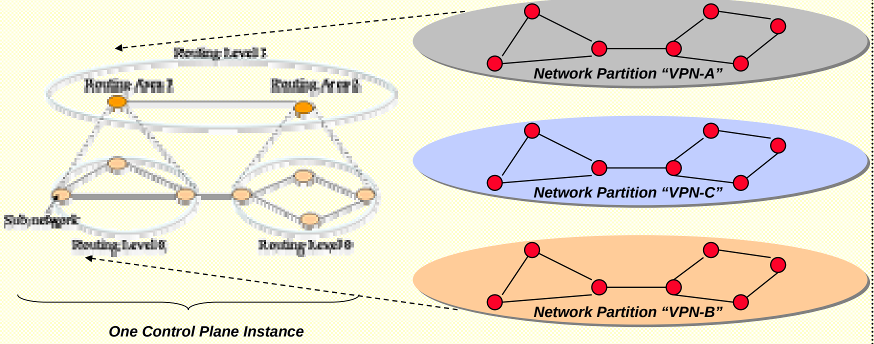
- **Develop methods to predict the performance of the three control plane models for larger topologies**
- **Hierarchal routing architecture is needed**
  - To overcome the current limitations of the routing probability approximation
  - Current FPA mechanism lacks accuracy under large network topologies with *flat* routing architecture



Next Steps/Future Work- Multi-Domain Analysis “Hierarchal Routing”

IETF Control Plane Model

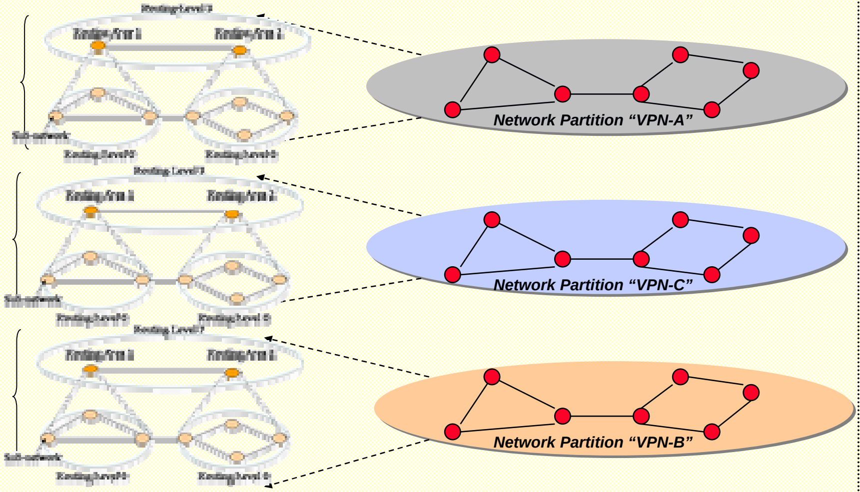
__One__ Control Plane Instance with __one__ **Hierarchal Routing Instance** *for the Three Transport Network Partitions*



ITU/SPA-Dedicated Control Plane Models

__Three__ Control Plane Instance with __Three__ **Hierarchal Routing Instances** *for the Three Transport Network Partitions*

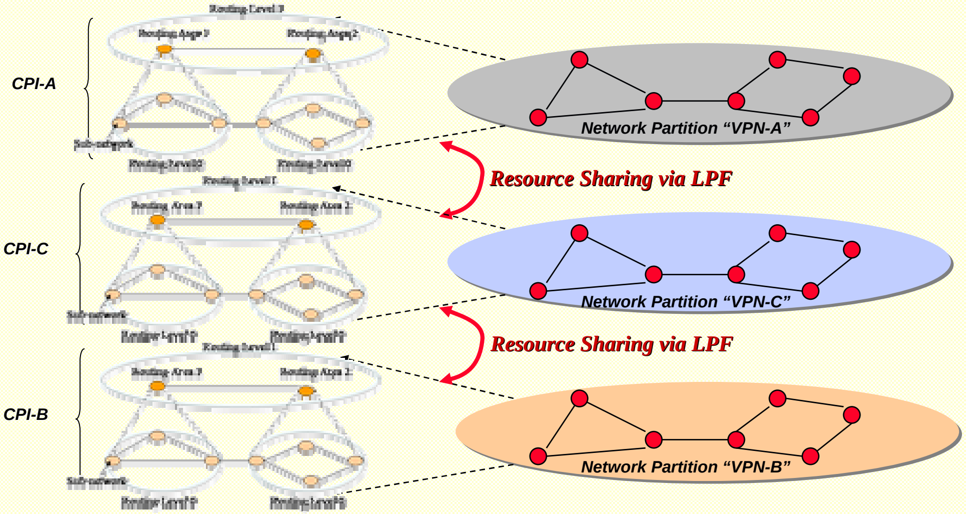
__No__ inter-control plane instances resource sharing via Load Partitioning Function (LPF)



SPA-Shared Control Plane Model

__Three__ Control Plane Instance with __Three__ **Hierarchal Routing Instances** *for the Three Transport Network Partitions*

__With__ inter-control plane instances resource sharing via Load Partitioning Function (LPF)



Discussion & Questions!

PhD Candidate: Wesam Alanqar

Advisor: Prof. Victor Frost

April 25, 2005

Appendix-A: Mathematical Formulation- Step-1: CAC for Multi-Rate Demands

- **IETF control plane model**
  - Routing component advertises the traffic occupancy of the *coarse* granularity levels
  - Service request with actual bandwidth requirements (b_k^A) will consume (b_k^C) resources from (C_j)
  - A call with bandwidth requirement (b_k^A) will be accepted if the following condition apply:

$$b_k^A \le C_j - \sum_{k \in K} b_k^C n_j^k$$

- **ITU & SPA-Dedicated control plane models**
  - Routing component advertises the traffic occupancy of the *fine* granularity levels
  - Service request with actual bandwidth requirements (b_k^A) will consume (b_k^A) resources from (C_j)
  - A call with bandwidth requirement (b_k^A) will be accepted if the following condition apply:

$$b_k^A \le C_j^D - \sum_{k \in K} b_k^A n_{jk}^D$$

- **SPA-Shared control plane model**
  - *Differs* from both the ITU and SPA-Dedicated control plane models
    - Can enable IMF and further divide the service request demand (b_k^A)into sub-rates or granular demands (b_k^G)
  - A call with bandwidth requirement (b_k^A) will be accepted if the following condition apply:

Dedicated Resources: $$b_k^G \le C_j^{vD} - \sum_{k \in K} b_k^G n_{jk}^{vD}$$

Shared Resources: $$b_k^G \le C_j^{vS} - \sum_{k \in K} b_k^G n_{jk}^{vS}$$

Appendix-A: Mathematical Formulation- Step-2: Estimating Link's Reduced Load

▶ IETF control plane model

$$\lambda_{jk}^{r_m} = \lambda_{rk}^{v} q_{rk}^{m} I[\, j \in r_m \,] \prod_{i \in r_m, i \neq j} a_{ik} \dashrightarrow \lambda_{jk} = \sum_{r \in R} \sum_{r_m \in M_r} \lambda_{jk}^{r_m}$$

Link *j* reduced load
based on class *k*

▶ITU & SPA-Dedicated control plane models

$$\lambda_{jk}^{D_{rm}} = \lambda_{rk}^{D} q_{rk}^{mD} I[\, j \in r_m \,] \prod_{i \in r_m, i \neq j} a_{ik}^{D} \dashrightarrow \lambda_{jk}^{D} = \sum_{r \in R} \sum_{r_m \in M_r} \lambda_{jk}^{D_{r_m}}$$

Dedicated resources partition *D* reduced
load on Link *j* based on class *k*

▶SPA-Shared control plane model (Without NE)

$$\lambda_{rk}^{vD} = \lambda_{rk}^{v} \cdot \frac{C_j^{vD}}{C_j^{vD} + C_j^{vS}} \dashrightarrow \lambda_{jk}^{D_{r_m}} = \lambda_{rk}^{vD} q_{rk}^{mD} I[\, j \in r_m \,] \prod_{i \in r_m, i \neq j} a_{ik}^{D} \dashrightarrow \lambda_{jk}^{D} = \sum_{r \in R} \sum_{r_m \in M_r} \lambda_{jk}^{D_{r_m}}$$

$$\lambda_{rk}^{vS} = \lambda_{rk}^{v} \cdot \frac{C_j^{vS}}{C_j^{vD} + C_j^{vS}} \dashrightarrow \tilde{\lambda}_{rk}^{S} = \Big(\sum_{\forall v} \lambda_{rk}^{vS}\Big) \dashrightarrow \lambda_{jk}^{S_{r_m}} = \tilde{\lambda}_{rk}^{S} q_{rk}^{Sm} I[\, j \in r_m \,] \prod_{i \in r_m, i \neq j} a_{ik}^{S} \dashrightarrow \lambda_{jk}^{S} = \sum_{r \in R} \sum_{r_m \in M_r} \lambda_{jk}^{S_{r_m}}$$

▶SPA-Shared control plane model (With NE)

$$\text{Round-1} \begin{cases} {}^{NE}\lambda_{jk}^{D_{r_m}} = \lambda_{rk}^{v} q_{rk}^{mD} I[\, j \in r_m \,] \prod_{i \in r_m, i \neq j} a_{ik}^{D} \dashrightarrow {}^{NE}\lambda_{jk}^{D} = \sum_{r \in R} \sum_{r_m \in M_r} {}^{NE}\lambda_{jk}^{D_{r_m}} \dashrightarrow {}^{NE}\lambda_{rk}^{vS} = \lambda_{rk}^{v} . B_{rk}^{vD} \dashrightarrow B_{rk}^{vD} = 1 - \sum_{m} q_{rk}^{mD} \prod_{j \in r_m} a_{jk}^{vD} \\ {}^{NE}\tilde{\lambda}_{rk}^{S} = \Big(\sum_{\forall v} \lambda_{rk}^{vS}\Big) \dashrightarrow {}^{NE}\lambda_{jk}^{S_{r_m}} = {}^{NE}\tilde{\lambda}_{rk}^{S} q_{rk}^{Sm} I[\, j \in r_m \,] \prod_{i \in r_m, i \neq j} a_{ik}^{S} \dashrightarrow {}^{NE}\lambda_{jk}^{S} = \sum_{r \in R} \sum_{r_m \in M_r} {}^{NE}\lambda_{jk}^{S_{r_m}} \end{cases}$$

$$\text{Round-2} \begin{cases} {}^{NE}\lambda_{rk}^{vD} = \lambda_{rk}^{v} .(1 - B_{rk}^{D}) \dashrightarrow {}^{NE}\lambda_{jk}^{D_{r_m}} = {}^{NE}\lambda_{rk}^{v} q_{rk}^{Dm} I[\, j \in r_m \,] \prod_{i \in r_m, i \neq j} a_{ik}^{D} \dashrightarrow \textit{Round-1 “Dedicated Resources Only”} \end{cases}$$

Dedicated resources partition *D* reduced
load on Link *j* based on class *k*

Appendix-A: Mathematical Formulation- Step-3: Estimating Link's Admissibility Probability

▶ IETF control plane model

$$np_j(n) = \sum_K b_k^C \frac{\lambda_{jk}}{\mu_k} p_j(n - b_k^C) \dashrightarrow a_{jk} = \sum_{n=0}^{C_j - b_k^C} p_j(n)$$

Link *j* admissibility probability based on class *k*

▶ITU & SPA-Dedicated control plane models

$$np_j^D(n) = \sum_{S^v} b_k^A \frac{\lambda_{jk}^D}{\mu_k} p_j^D(n - b_k^A) \dashrightarrow a_{jk}^D = \sum_{n=0}^{C_j^D - b_k^A} p_j^D(n) \dashrightarrow a_{jk} = \frac{\sum_{\forall C_j^D} a_{jk}^D * C_j^D}{C_j}$$

Link *j* admissibility probability based on class *k*

▶SPA-Shared control plane model "without (NE,IM)"

$$np_j^{vD}(n) = \sum_K b_k^A \frac{\lambda_{jk}^{vD}}{\mu_k} p_j^{vD}(n - b_k^A) \dashrightarrow a_{jk}^{vD} = \sum_{n=0}^{C_j^{vD} - b_k^A} p_j^{vD}(n)$$

Dedicated resources *D* of VPN *v* admissibility probability on link *j* for class *k*

$$np_j^S(n) = \sum_K b_k^A \frac{\lambda_{jk}^S}{\mu_k} p_j^S(n - b_k^A) \dashrightarrow a_{jk}^S = \sum_{n=0}^{C_j^S - b_k^A} p_j^S(n)$$

Shared resources *S* admissibility probability on link *j* for class *k*

$$a_{jk}^v = \frac{a_{jk}^{vD}.C_j^{vD} + a_{jk}^S.C_j^S}{C_j^{vD} + C_j^S} \dashrightarrow a_{jk} = \frac{(\sum_{\forall D} a_{jk}^{vD}.C_j^{vD}) + a_{jk}^S.C_j^S}{C_j}$$

Link *j* admissibility probability based on class *k*

▶SPA-Shared control plane model "with/NE, without/IM"

$$np_j^{vD}(n) = \sum_K b_k^A \frac{{}^{NE}\lambda_{jk}^D}{\mu_k} p_j^{vD}(n - b_k^A) \dashrightarrow a_{jk}^{vD} = \sum_{n=0}^{C_j^{vD} - b_k^A} p_j^{vD}(n)$$

$$np_j^S(n) = \sum_K b_k^A \frac{{}^{NE}\lambda_{jk}^S}{\mu_k} p_j^S(n - b_k^A) \dashrightarrow a_{jk}^S = \sum_{n=0}^{C_j^S - b_k^A} p_j^S(n)$$

$$a_{jk}^v = \frac{a_{jk}^{vD}.C_j^D + a_{jk}^S.C_j^S}{C_j^{vD} + C_j^S} \dashrightarrow a_{jk} = \frac{(\sum_{\forall D} a_{jk}^D.C_j^D) + a_{jk}^S.C_j^S}{C_j}$$

Appendix-A: Mathematical Formulation- Step-3: Estimating Link's Admissibility Probability "Cont."

▶SPA-Shared control plane model "without/NE, with/IM"

$$np_j^{vD}(n)=\sum_K b_k^G \frac{i\lambda_{jk}^D}{\mu_k} p_j^{vD}(n-b_k^G) \dashrightarrow a_{jk}^{vD}=\sum_{n=0}^{C_j^{vD}-b_k^G} p_j^{vD}(n)$$

Dedicated resources partition *D* of VPN *v* admissibility probability on link *j* for class *k*

$$np_j^{S}(n)=\sum_K b_k^G \frac{i\lambda_{jk}^S}{\mu_k} p_j^{S}(n-b_k^G) \dashrightarrow a_{jk}^{S}=\sum_{n=0}^{C_j^{S}-b_k^G} p_j^{S}(n)$$

Shared resources partition *S* admissibility probability on link *j* for class *k*

$$a_{jk}^{v}=\frac{a_{jk}^{vD}.C_j^D+a_{jk}^S.C_j^S}{C_j^{vD}+C_j^S} \dashrightarrow a_{jk}=\frac{(\sum_{\forall D} a_{jk}^D.C_j^D)+a_{jk}^S.C_j^S}{C_j}$$

Link *j* admissibility probability based on class *k*

▶SPA-Shared control plane model "with/(NE,IM)"

$$np_j^{vD}(n)=\sum_K b_k^G \frac{{}^{NE}\lambda_{jk}^D i}{\mu_k} p_j^{vD}(n-b_k^G) \dashrightarrow a_{jk}^{vD}=\sum_{n=0}^{C_j^{vD}-b_k^G} p_j^{vD}(n)$$

$$np_j^{S}(n)=\sum_K b_k^G \frac{{}^{NE}\lambda_{jk}^S i}{\mu_k} p_j^{S}(n-b_k^G) \dashrightarrow a_{jk}^{S}=\sum_{n=0}^{C_j^{S}-b_k^G} p_j^{S}(n)$$

$$a_{jk}^{v}=\frac{a_{jk}^{vD}.C_j^D+a_{jk}^S.C_j^S}{C_j^{vD}+C_j^S} \dashrightarrow a_{jk}=\frac{(\sum_{\forall D} a_{jk}^D.C_j^D)+a_{jk}^S.C_j^S}{C_j}$$

Appendix-A: Mathematical Formulation- Step-4: Estimating Routing Probability

- **SPA-Dedicated control plane model**
    - Estimating routing probability is carried independently for each dedicated resources partition

$$\Pr[A_n^D(r_m)] = \prod_{j\in(r_m)} \sum_{k=0}^{C_j^D-n} P_j^D(k) \dashrightarrow \Pr[A_n^D(r_k - r_m)] = \prod_{j\in(r_k - r_m)} \sum_{k=0}^{C_j^D-n} P_j^D(k) \dashrightarrow \Pr[\overline{A}_n^D(r_k - r_m)] = 1 - \prod_{j\in(r_k - r_m)} \sum_{k=0}^{C_j^D-n} P_j^D(k)$$

$$\Pr[A_{n+1}^D(r_m)] = \prod_{j\in(r_m)} \sum_{k=0}^{C_j^D-n+1} P_j^D(k) \dashrightarrow \Pr[A_{n+1}^D(r_k - r_m)] = \prod_{j\in(r_k - r_m)} \sum_{k=0}^{C_j^D-n+1} P_j^D(k) \dashrightarrow \Pr[\overline{A}_{n+1}^D(r_k - r_m)] = 1 - \prod_{j\in(r_k - r_m)} \sum_{k=0}^{C_j^D-n+1} P_j^D(k)$$

$$\dashrightarrow \Pr[\widetilde{A}_n^D(r_m)] = \Pr[A_n^D(r_m)] - \Pr[A_{n+1}^D(r_m)]$$

$$q_{rk}^{mD} = \sum_{n=0}^{C_{\min}(r_m)} \prod_{k=1}^{k=m-1} \Pr[\overline{A}_n^D(r_k - r_m)].\prod_{k=m+1}^{k=M_r} \Pr[\overline{A}_{n+1}^D(r_k - r_m)].\Pr[\widetilde{A}_n^D(r_m)]$$

Dedicated resources partition *D* of VPN *v* routing probability on pair *r* for class *k*

- **SPA-Shared control plane model**
    - Estimating routing probability is carried independently for both dedicated and shared resources partitions
        - Similar set of equations like SPA-dedicated but with different notations

Appendix-A: Mathematical Formulation- Step-5: Estimating Network Blocking Probability

IETF control plane model

$$B_{rk} = 1 - \sum_{m} q_{rk}^{m} \prod_{j \in r_m} a_{jk} \dashrightarrow B_k = \underset{r \in R}{AVR}[B_{rk}]$$

Network-wide blocking probability for class *k*

ITU & SPA-Dedicated control plane models

$$B_{rk}^{D} = 1 - \sum_{m} q_{rk}^{Dm} \prod_{j \in r_m} a_{jk}^{D} \dashrightarrow B_k^{D} = \underset{r \in R}{AVR}[B_{rk}^{D}] \dashrightarrow B_{rk} = \frac{\sum_{\forall C_j^D} B_{rk}^{D} * C_j^{D}}{C_j} \dashrightarrow B_k = \underset{r \in R}{AVR}[B_{rk}]$$

SPA-Shared control plane models

$$B_{rk}^{D} = 1 - \sum_{m} q_{rk}^{mD} \prod_{j \in r_m} a_{jk}^{D} \dashrightarrow B_k^{D} = \underset{r \in R}{AVR}[B_{rk}^{D}]$$

Dedicated resources partition *D* network-wide blocking probability for class *k*

$$B_{rk}^{S} = 1 - \sum_{m} q_{rk}^{mS} \prod_{j \in r_m} a_{jk}^{S} \dashrightarrow B_k^{S} = \underset{r \in R}{AVR}[B_{rk}^{S}]$$

Shared resources partition *S* network-wide blocking probability for class *k*

$$B_{rk}^{v} = \frac{B_{rk}^{D} * C_j^{D} + B_{rk}^{S} * C_j^{S}}{C_j^{D} + C_j^{S}} \dashrightarrow B_k^{v} = \underset{r \in R}{AVR}[B_{rk}^{v}]$$

VPN resources partition *v* network-wide blocking probability for class *k*

$$B_{rk} = \frac{(\sum_{\forall C_j^D} B_{rk}^{D} * C_j^{D}) + B_{rk}^{S} * C_j^{S}}{C_j} \dashrightarrow B_k = \underset{r \in R}{AVR}[B_{rk}]$$

Network-wide blocking probability for class *k*

Appendix-A: Mathematical Formulation- Step-6: Estimating Network Permissible Load

- **IETF control plane model**

$$\hat{\lambda}_{rk} = \sum_{m=1}^{M_r} q_{rk}^{m} \underset{j \in r_m}{MIN}(\lambda_{jk}) \dashrightarrow \hat{\lambda}_{k} = \underset{r \in R}{Avr}[\hat{\lambda}_{rk}]$$

Network-wide permissible “non-blocked” load for class *k*

- **ITU & SPA-Dedicated control plane models**

$$\hat{\lambda}_{rk}^{D} = \sum_{m=1}^{M_r} q_{rk}^{mD} \underset{j \in r_m}{MIN}(\lambda_{jk}^{D}) \dashrightarrow \hat{\lambda}_{rk} = \frac{(\sum_{\forall v} \hat{\lambda}_{rk}^{D} * C_j^{D})}{C_j}$$

- **SPA-Shared control plane models**

$$\hat{\lambda}_{rk}^{D} = \sum_{m=1}^{M_r} q_{rk}^{mD} \underset{j \in r_m}{MIN}(\lambda_{jk}^{D}) \dashrightarrow \hat{\lambda}_{k}^{D} = \underset{r \in R}{Avr}[\hat{\lambda}_{rk}^{D}] \dashrightarrow \hat{\lambda}_{rk} = \frac{(\sum_{\forall v} \hat{\lambda}_{rk}^{D} * C_j^{D})}{C_j}$$

Dedicated resources partition *D* network-wide permissible “non-blocked” load for class *k*

$$\hat{\lambda}_{rk}^{S} = \sum_{m=1}^{M_r} q_{rk}^{mS} \underset{j \in r_m}{MIN}(\lambda_{jk}^{S}) \dashrightarrow \hat{\lambda}_{k}^{S} = \underset{r \in R}{Avr}[\hat{\lambda}_{rk}^{S}]$$

Shared resources partition *s* network-wide permissible “non-blocked” load for class *k*

$$\hat{\lambda}_{rk}^{v} = \frac{\hat{\lambda}_{rk}^{D} * C_j^{D} + \hat{\lambda}_{rk}^{S} * C_j^{S}}{C_j^{D} + C_j^{S}}$$

VPN resources partition *v* network-wide permissible “non-blocked” load for class *k*

$$\hat{\lambda}_{rk} = \frac{(\sum_{\forall D} \hat{\lambda}_{rk}^{D} * C_j^{D}) + \hat{\lambda}_{rk}^{S} * C_j^{S}}{C_j}$$

Appendix-A: Mathematical Formulation- Step-7: Estimating Network Utilization

- **IETF control plane model**

$$U_j = \sum_{n=1}^{C_j} p_j(n) \dashrightarrow U = \underset{j\in J}{Avr}[U_j]$$

Network-wide utilization

- **ITU & SPA-Dedicated control plane models**

$$U_j^D = \sum_{n=1}^{C_j^D} p_j^D(n) \dashrightarrow U_j = \frac{(\sum_{\forall v} U_j^D * C_j^D)}{C_j} \dashrightarrow U^D = \underset{j\in J}{Avr}[U_j^D]$$

Network-wide utilization of dedicated network resources partition *D*

- **SPA-Shared control plane models**

$$U_j^D = \sum_{n=1}^{C_j^D} p_j^D(n)$$

$$U_j^S = \sum_{n=1}^{C_j^S} p_j^S(n)$$

Network-wide utilization of shared network resources partition *S* for link *j*

$$U_j^v = \frac{U_j^D * C_j^D + U_j^S * C_j^S}{C_j^D + C_j^S}$$

Network-wide utilization of VPN network resources partition *v* for link *j*

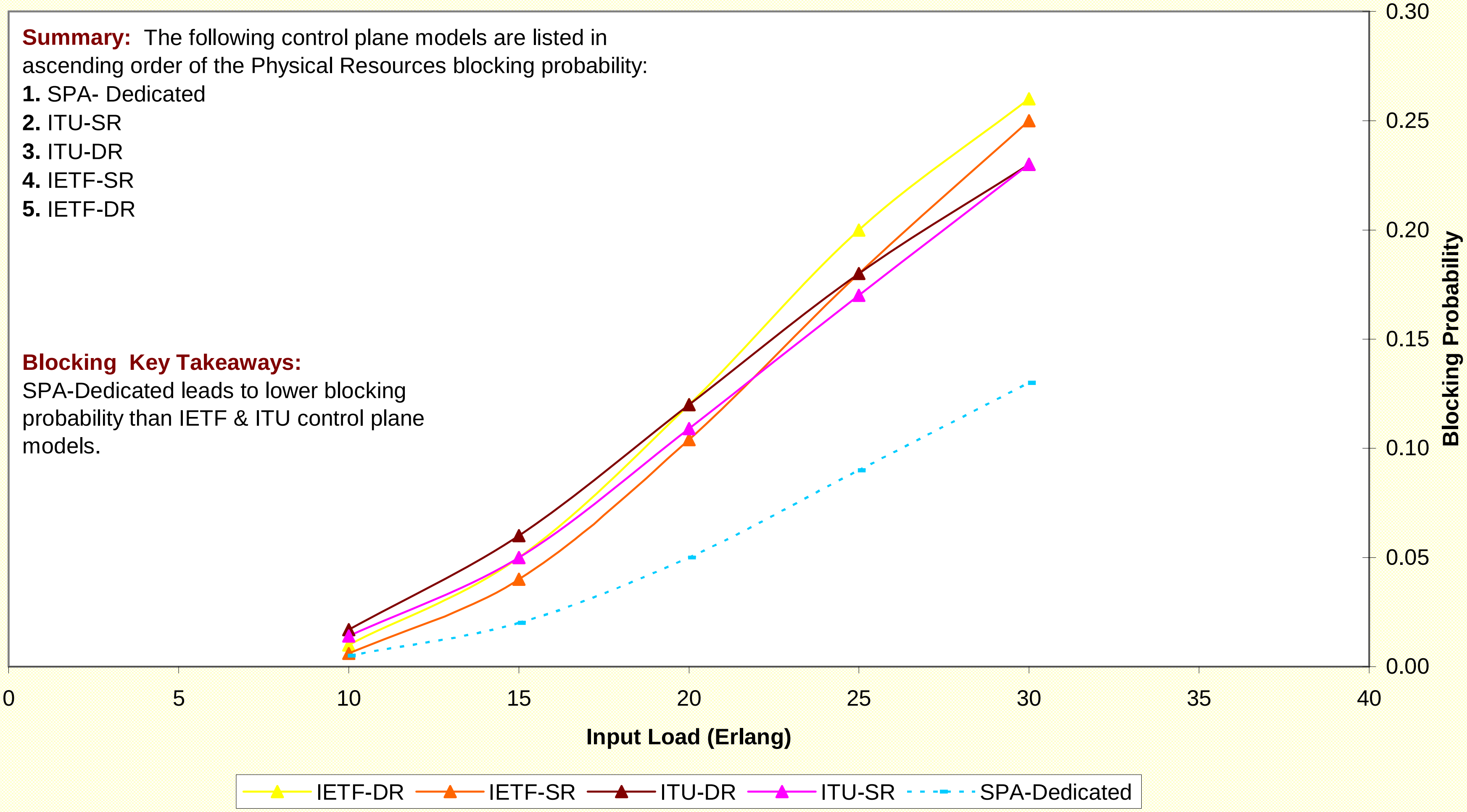
$$U_j = \frac{(\sum_{\forall v} U_j^D * C_j^D) + U_j^S * C_j^S}{C_j}$$

Link *j* utilization based on the utilization of dedicated and shared network resource partitions

$$U = \underset{j\in J}{Avr}[U_j]$$

Appendix-B: 4 Node Topology Detailed Results "Blocking probability"

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physcial Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-Dedicated



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

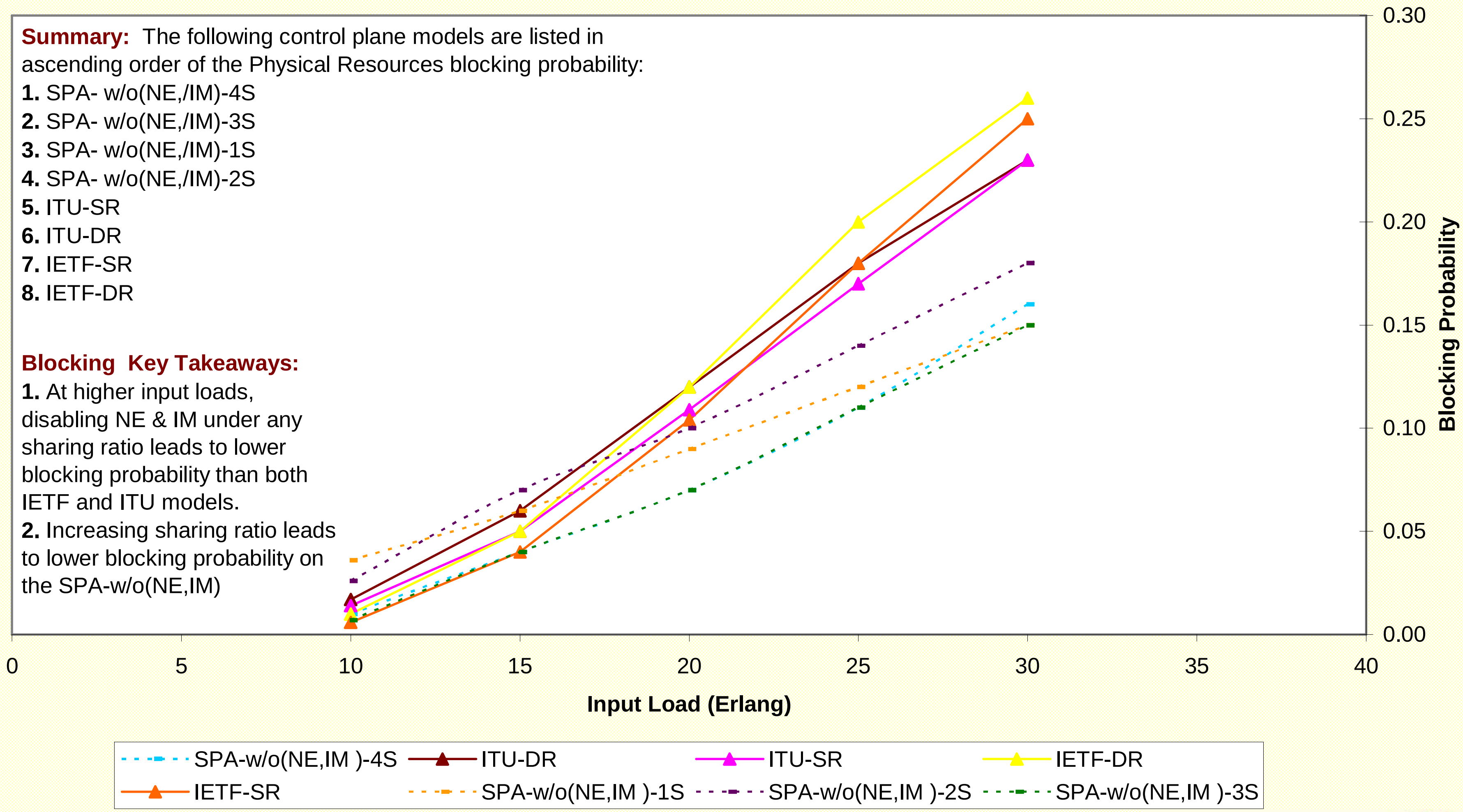
1. SPA- Dedicated
2. ITU-SR
3. ITU-DR
4. IETF-SR
5. IETF-DR

Blocking Key Takeaways:

SPA-Dedicated leads to lower blocking probability than IETF & ITU control plane models.

Appendix-B: 4 Node Topology Detailed Results "Blocking probability"

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/o(NE,IM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. SPA- w/o(NE,/IM)-4S
2. SPA- w/o(NE,/IM)-3S
3. SPA- w/o(NE,/IM)-1S
4. SPA- w/o(NE,/IM)-2S
5. ITU-SR
6. ITU-DR
7. IETF-SR
8. IETF-DR

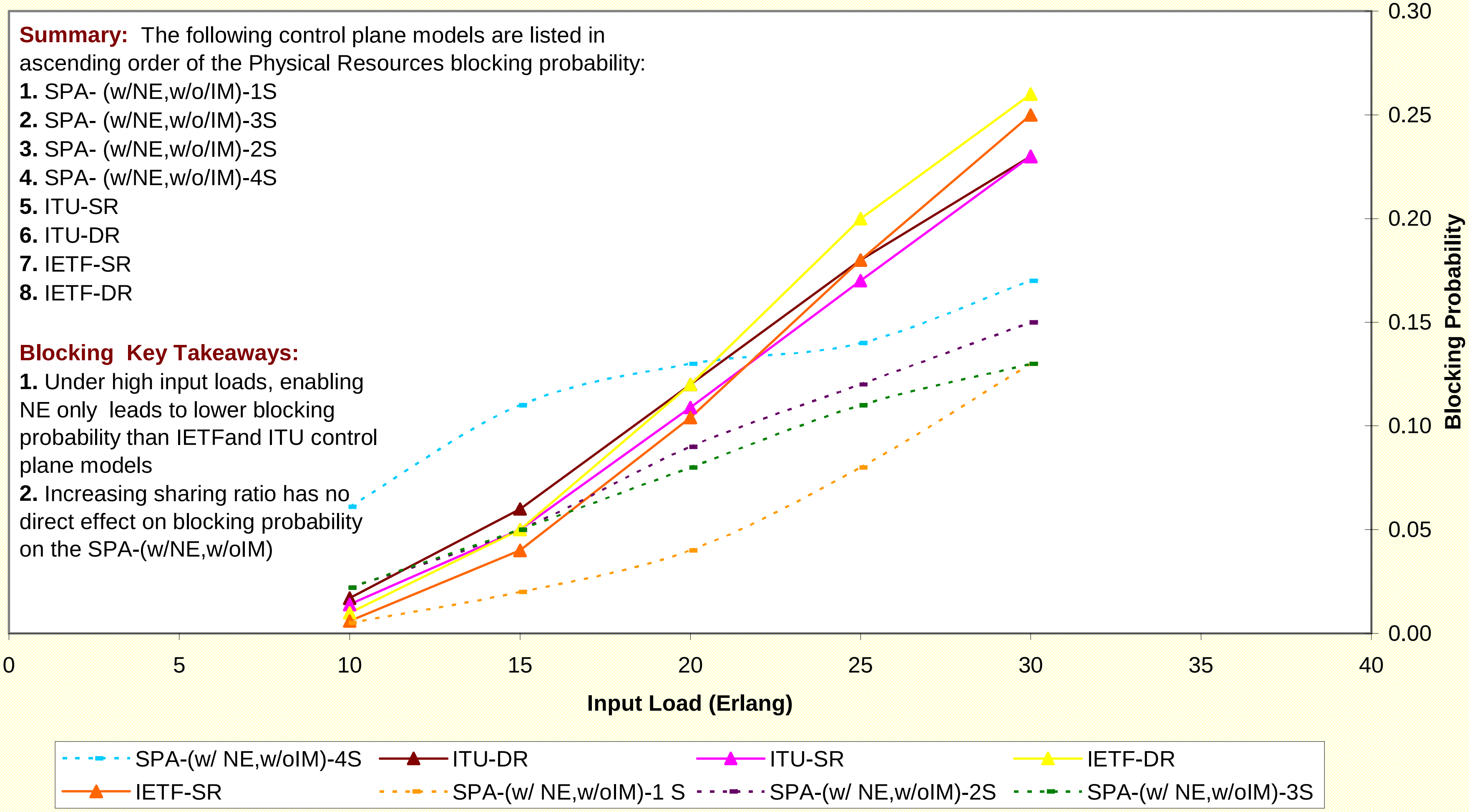
Blocking Key Takeaways:

1. At higher input loads, disabling NE & IM under any sharing ratio leads to lower blocking probability than both IETF and ITU models.

2. Increasing sharing ratio leads to lower blocking probability on the SPA-w/o(NE,IM)

Appendix-B: 4 Node Topology Detailed Results “Blocking probability”

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/NE,w/oIM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. SPA- (w/NE,w/o/IM)-1S
2. SPA- (w/NE,w/o/IM)-3S
3. SPA- (w/NE,w/o/IM)-2S
4. SPA- (w/NE,w/o/IM)-4S
5. ITU-SR
6. ITU-DR
7. IETF-SR
8. IETF-DR

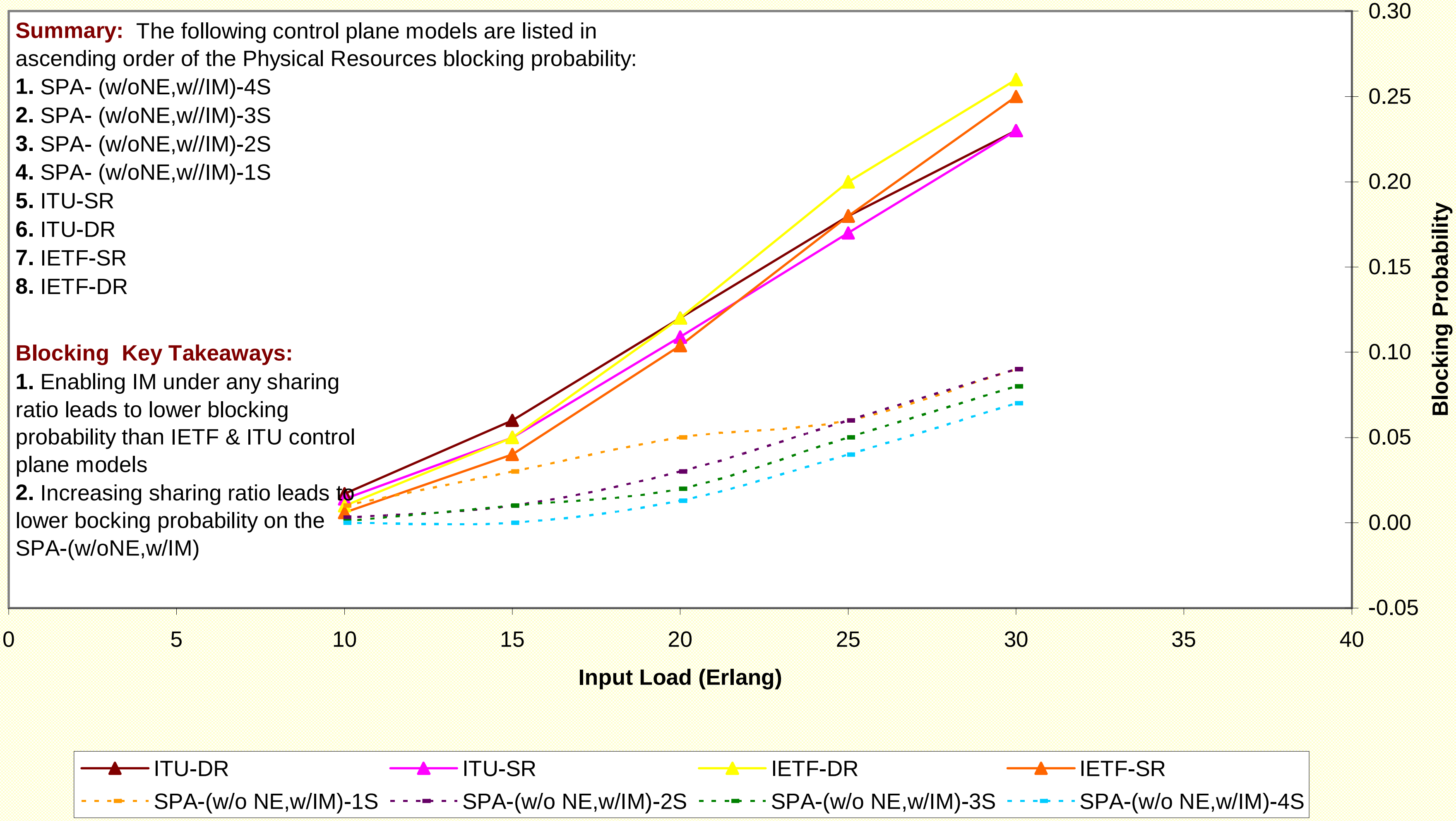
Blocking Key Takeaways:

1. Under high input loads, enabling NE only leads to lower blocking probability than IETFand ITU control plane models

2. Increasing sharing ratio has no direct effect on blocking probability on the SPA-(w/NE,w/oIM)

Appendix-B: 4 Node Topology Detailed Results "Blocking probability"

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/oNE,w/IM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. SPA- (w/oNE,w//IM)-4S
2. SPA- (w/oNE,w//IM)-3S
3. SPA- (w/oNE,w//IM)-2S
4. SPA- (w/oNE,w//IM)-1S
5. ITU-SR
6. ITU-DR
7. IETF-SR
8. IETF-DR

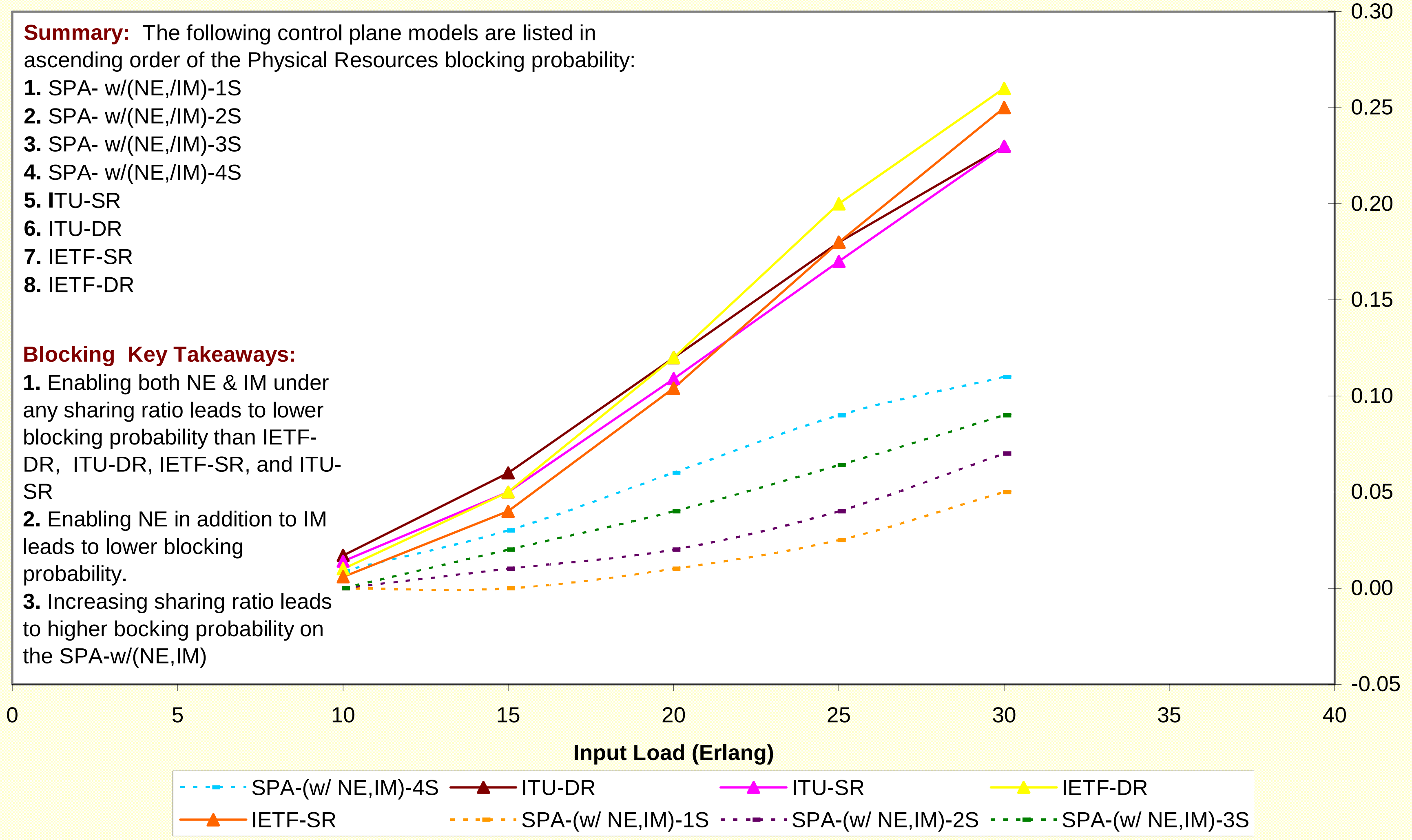
Blocking Key Takeaways:

1. Enabling IM under any sharing ratio leads to lower blocking probability than IETF & ITU control plane models

2. Increasing sharing ratio leads to lower bocking probability on the SPA-(w/oNE,w/IM)

Appendix-B: 4 Node Topology Detailed Results “Blocking probability”

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/(NE,IM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. SPA- w/(NE,/IM)-1S
2. SPA- w/(NE,/IM)-2S
3. SPA- w/(NE,/IM)-3S
4. SPA- w/(NE,/IM)-4S
5. ITU-SR
6. ITU-DR
7. IETF-SR
8. IETF-DR

Blocking Key Takeaways:

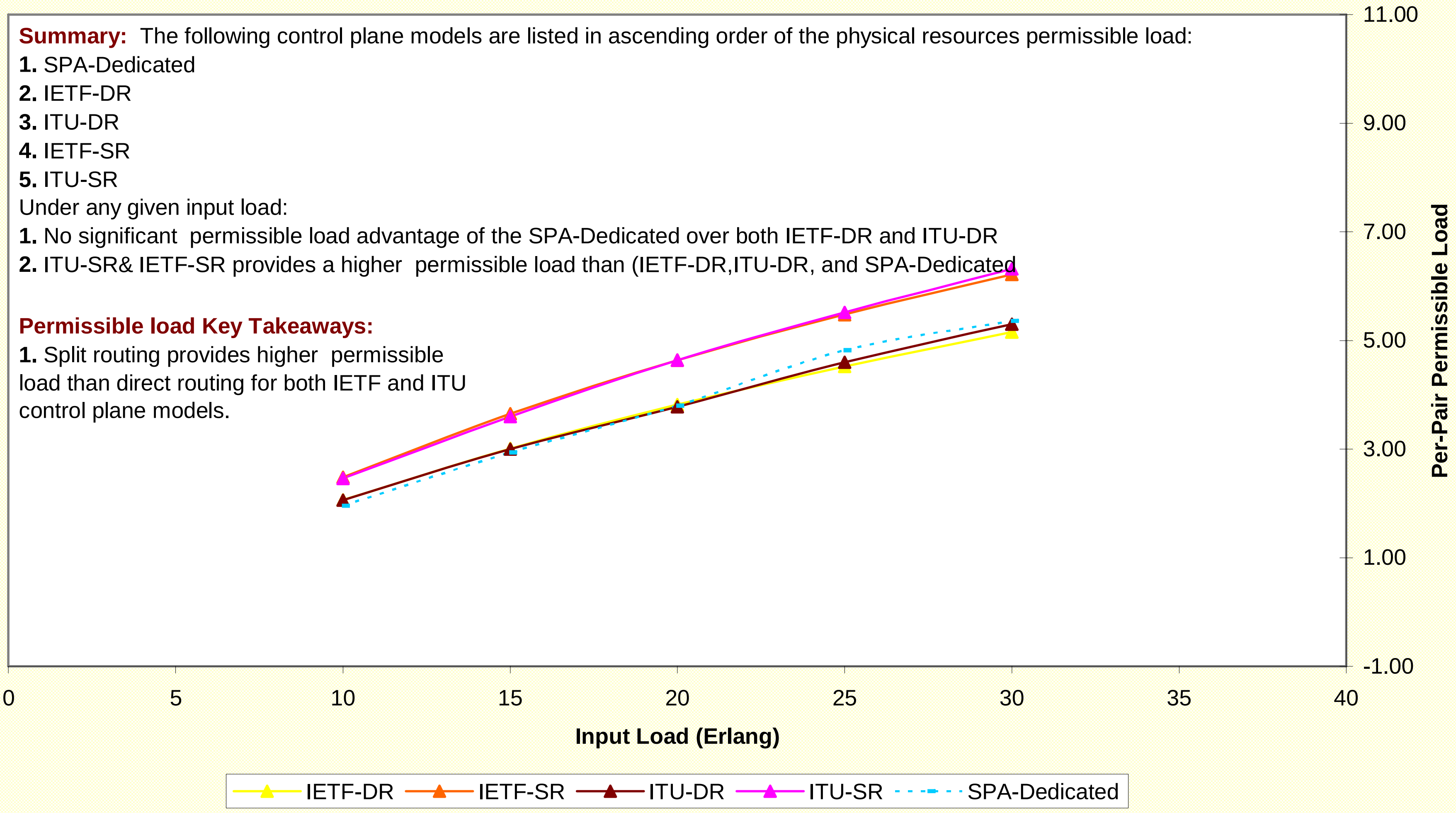
1. Enabling both NE & IM under any sharing ratio leads to lower blocking probability than IETF-DR, ITU-DR, IETF-SR, and ITU-SR

2. Enabling NE in addition to IM leads to lower blocking probability.

3. Increasing sharing ratio leads to higher bocking probability on the SPA-w/(NE,IM)

Appendix-B: 4 Node Topology Detailed Results “Permissible Load”

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-Dedicated



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

1. SPA-Dedicated
2. IETF-DR
3. ITU-DR
4. IETF-SR
5. ITU-SR

Under any given input load:

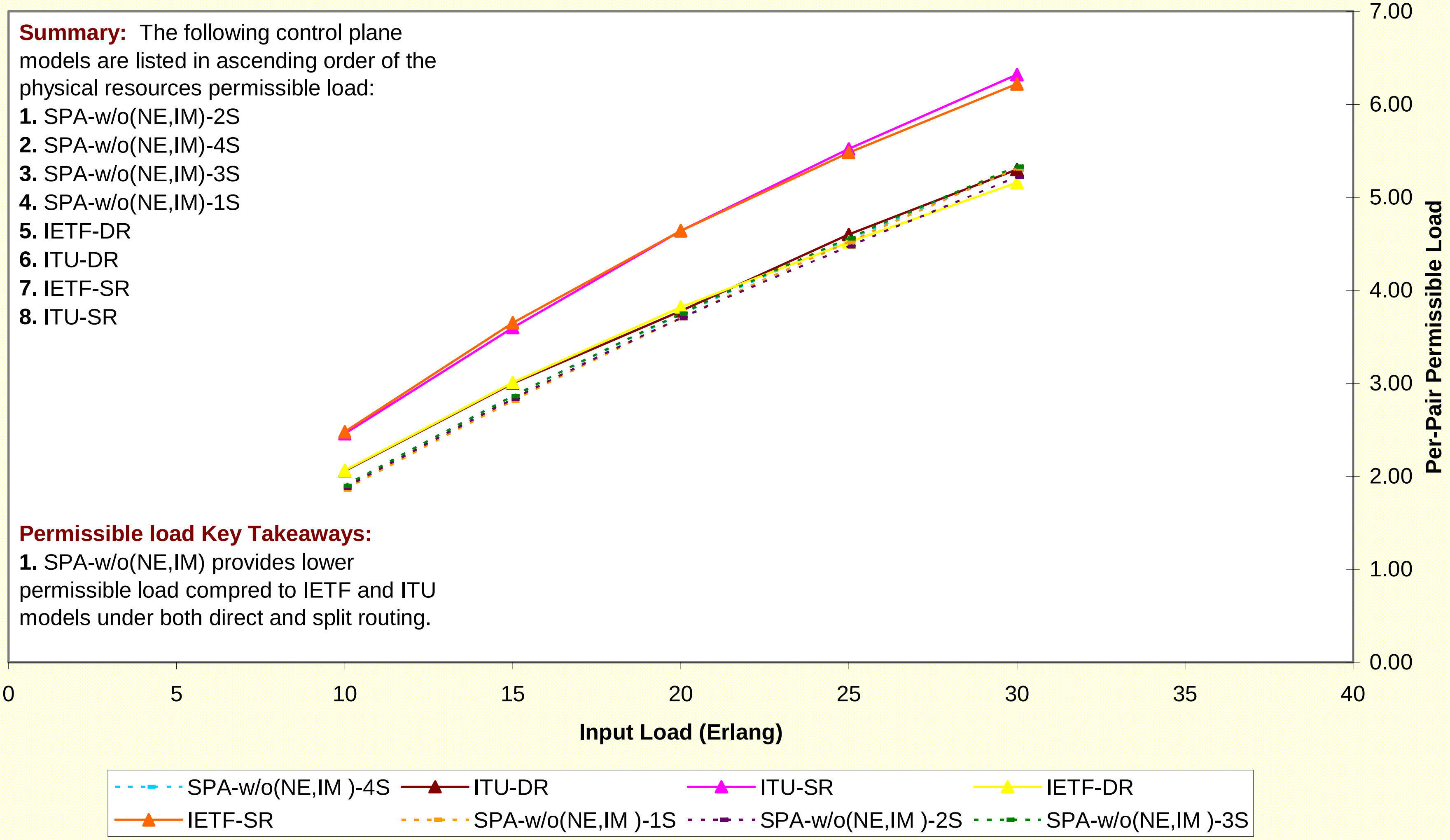
1. No significant permissible load advantage of the SPA-Dedicated over both IETF-DR and ITU-DR
2. ITU-SR& IETF-SR provides a higher permissible load than (IETF-DR,ITU-DR, and SPA-Dedicated

Permissible load Key Takeaways:

1. Split routing provides higher permissible load than direct routing for both IETF and ITU control plane models.

Appendix-B: 4 Node Topology Detailed Results “Permissible Load”

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/o(NE,IM)



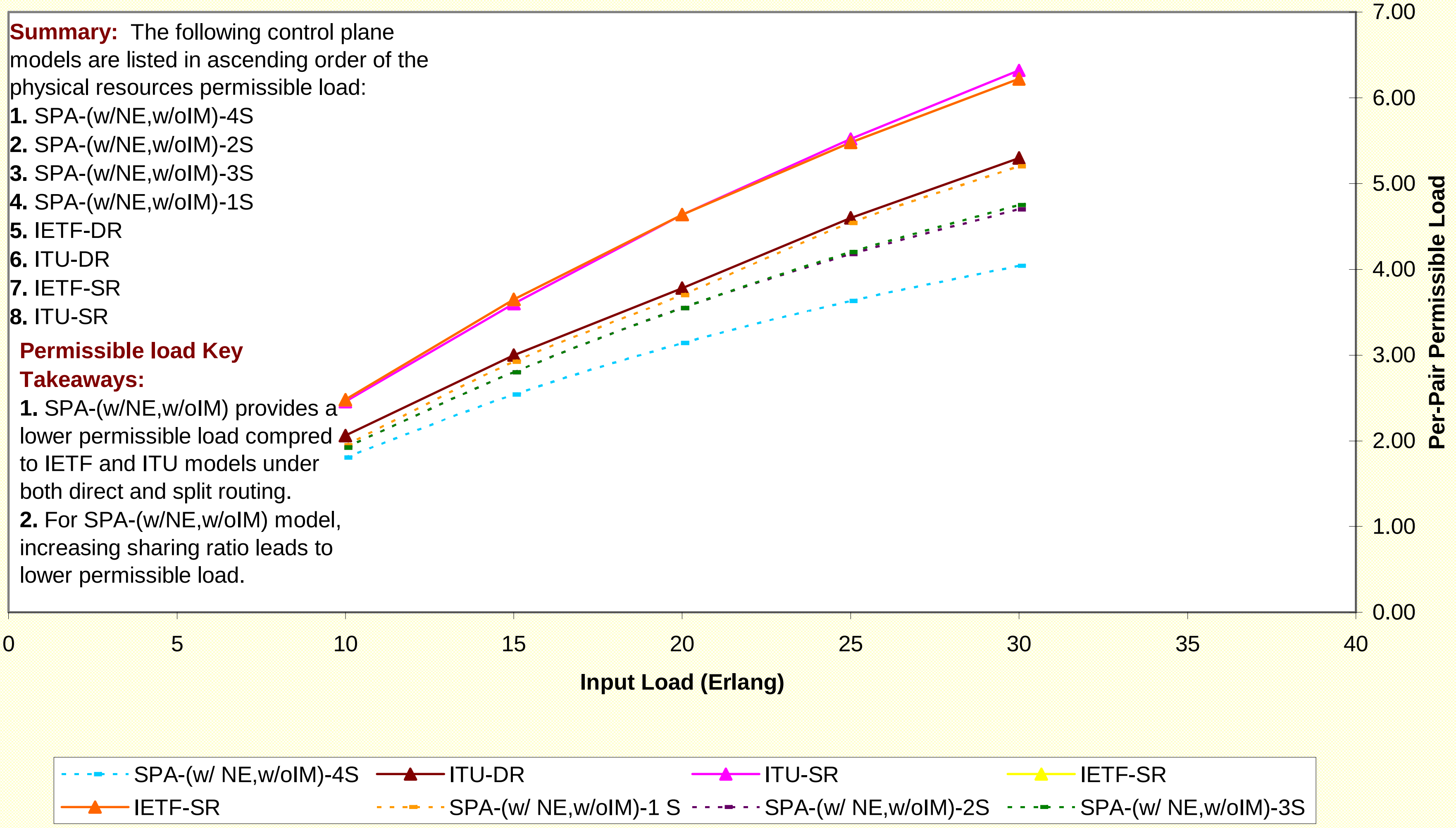
Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

1. SPA-w/o(NE,IM)-2S
2. SPA-w/o(NE,IM)-4S
3. SPA-w/o(NE,IM)-3S
4. SPA-w/o(NE,IM)-1S
5. IETF-DR
6. ITU-DR
7. IETF-SR
8. ITU-SR

Permissible load Key Takeaways:

1. SPA-w/o(NE,IM) provides lower permissible load compred to IETF and ITU models under both direct and split routing.

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/NE,w/oIM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

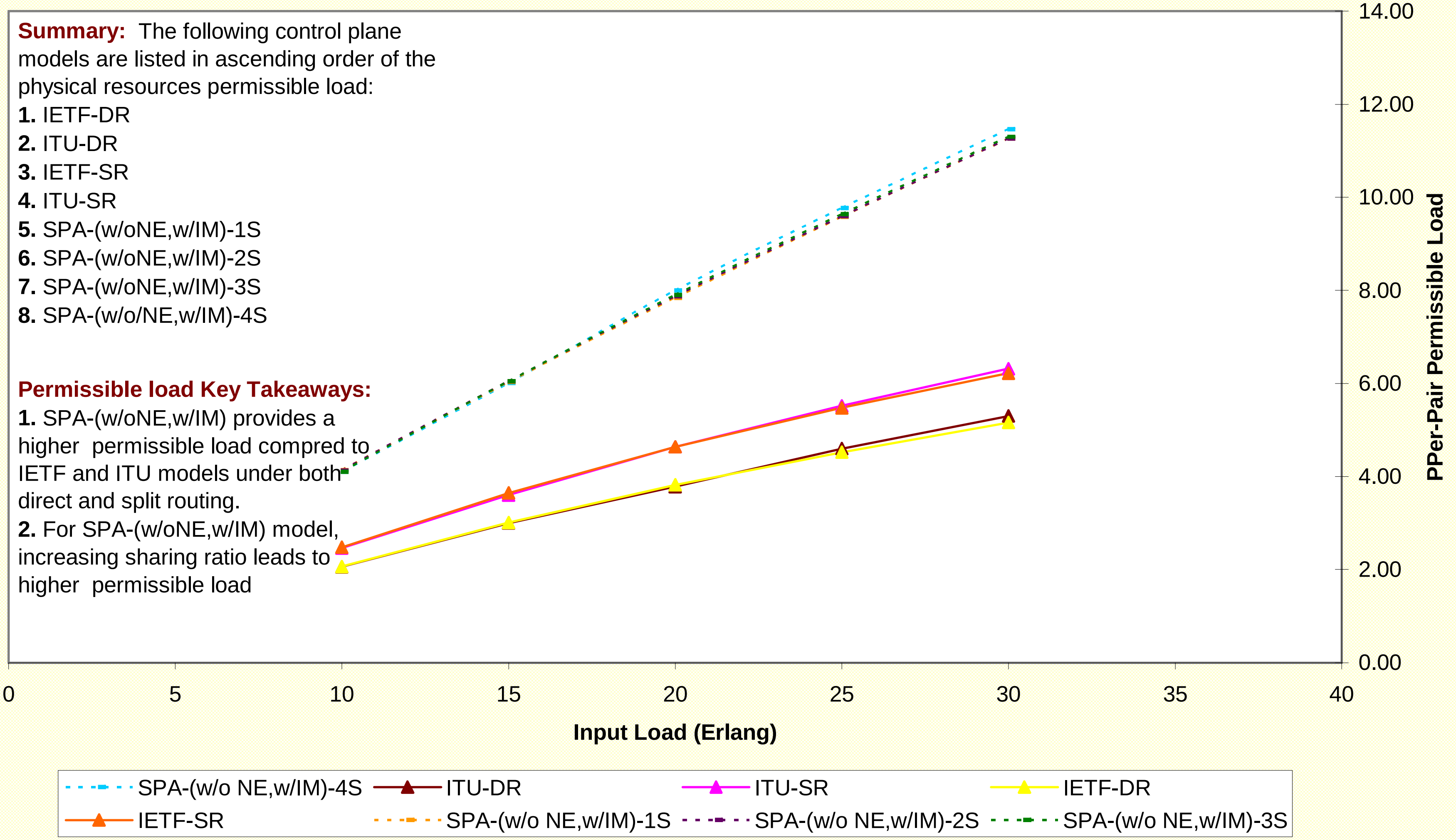
1. SPA-(w/NE,w/oIM)-4S
2. SPA-(w/NE,w/oIM)-2S
3. SPA-(w/NE,w/oIM)-3S
4. SPA-(w/NE,w/oIM)-1S
5. IETF-DR
6. ITU-DR
7. IETF-SR
8. ITU-SR

Permissible load Key Takeaways:

1. SPA-(w/NE,w/oIM) provides a lower permissible load compred to IETF and ITU models under both direct and split routing.
2. For SPA-(w/NE,w/oIM) model, increasing sharing ratio leads to lower permissible load.

Appendix-B: 4 Node Topology Detailed Results “Permissible Load”

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/oNE,w/IM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

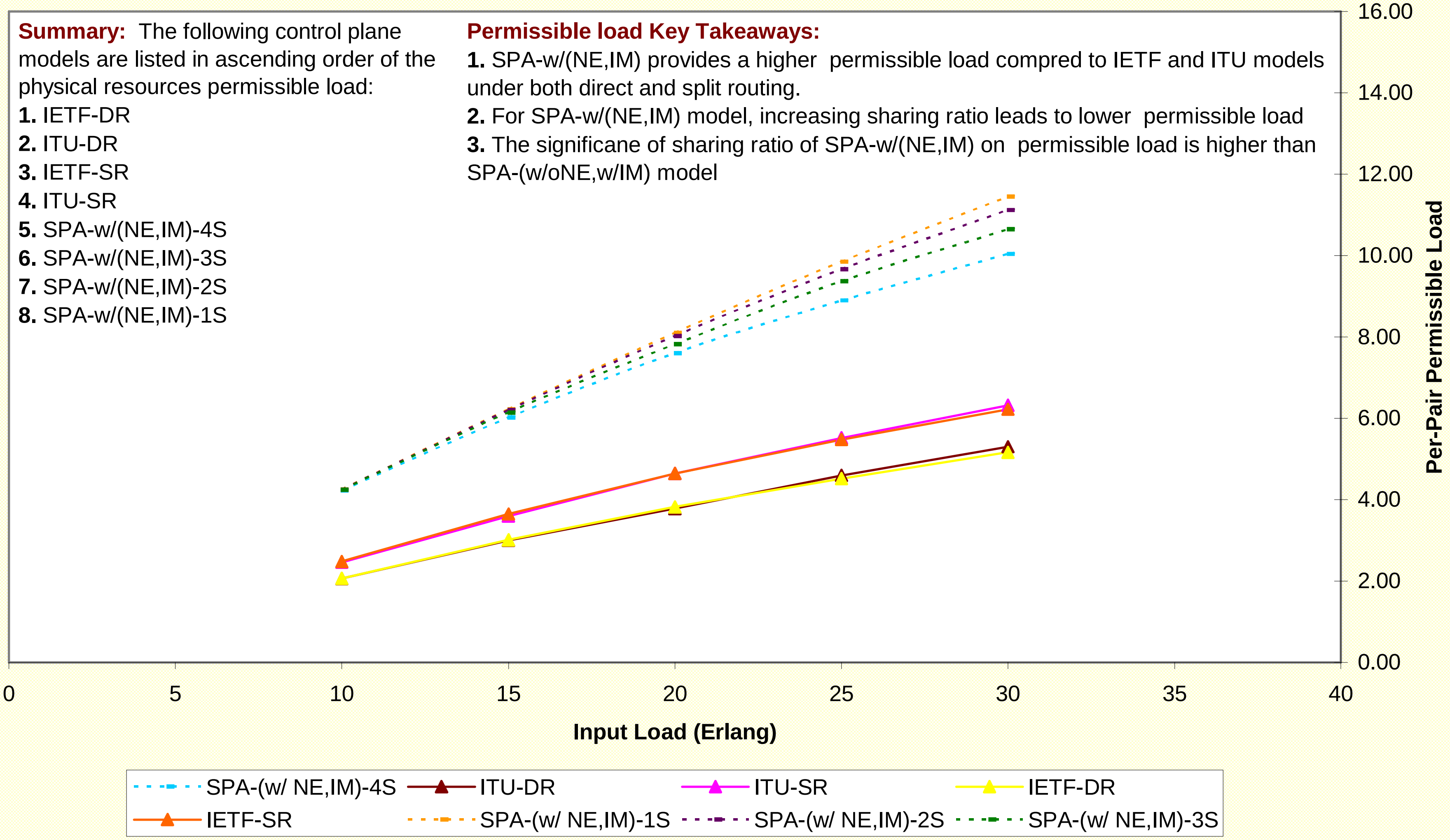
1. IETF-DR
2. ITU-DR
3. IETF-SR
4. ITU-SR
5. SPA-(w/oNE,w/IM)-1S
6. SPA-(w/oNE,w/IM)-2S
7. SPA-(w/oNE,w/IM)-3S
8. SPA-(w/o/NE,w/IM)-4S

Permissible load Key Takeaways:

1. SPA-(w/oNE,w/IM) provides a higher permissible load compred to IETF and ITU models under both direct and split routing.
2. For SPA-(w/oNE,w/IM) model, increasing sharing ratio leads to higher permissible load

Appendix-B: 4 Node Topology Detailed Results "Permissible Load"

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/(NE,IM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

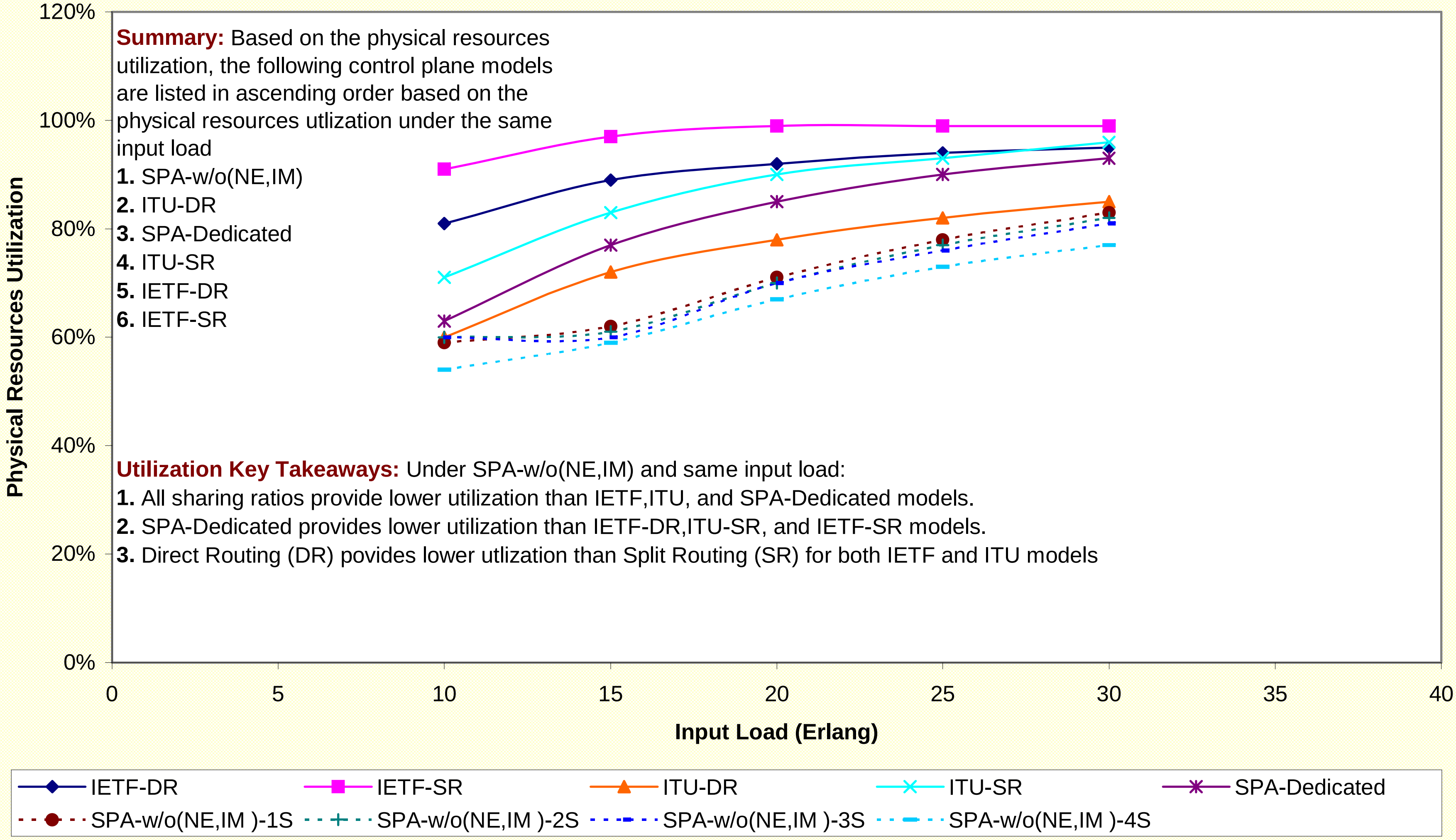
1. IETF-DR
2. ITU-DR
3. IETF-SR
4. ITU-SR
5. SPA-w/(NE,IM)-4S
6. SPA-w/(NE,IM)-3S
7. SPA-w/(NE,IM)-2S
8. SPA-w/(NE,IM)-1S

Permissible load Key Takeaways:

1. SPA-w/(NE,IM) provides a higher permissible load compred to IETF and ITU models under both direct and split routing.
2. For SPA-w/(NE,IM) model, increasing sharing ratio leads to lower permissible load
3. The significane of sharing ratio of SPA-w/(NE,IM) on permissible load is higher than SPA-(w/oNE,w/IM) model

Appendix-B: 4 Node Topology Detailed Results “Utilization”

4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/o(NE,IM)



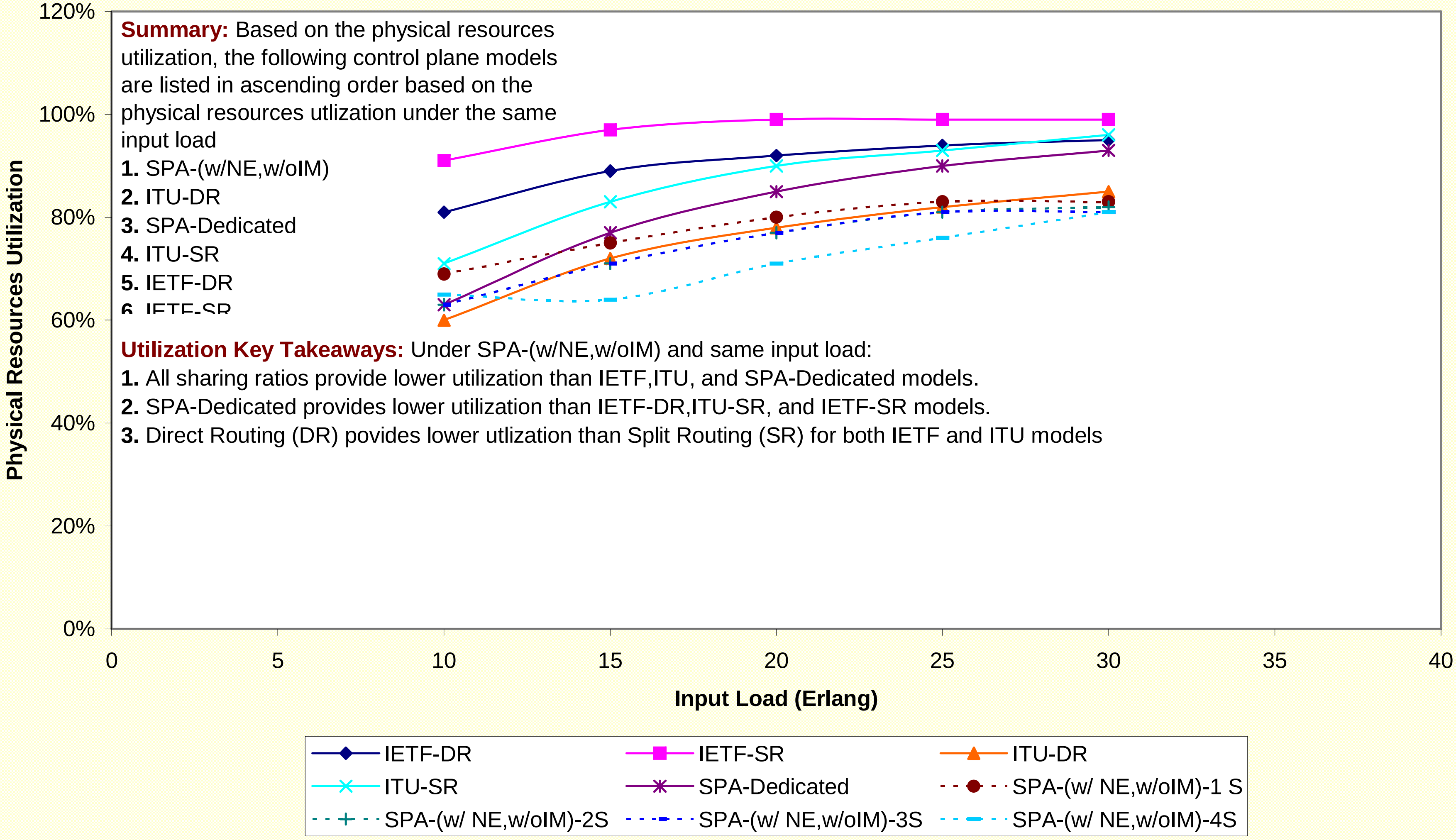
Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

1. SPA-w/o(NE,IM)
2. ITU-DR
3. SPA-Dedicated
4. ITU-SR
5. IETF-DR
6. IETF-SR

Utilization Key Takeaways: Under SPA-w/o(NE,IM) and same input load:

1. All sharing ratios provide lower utilization than IETF,ITU, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-B: 4 Node Topology Detailed Results "Utilization"



4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/NE,w/oIM

Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

1. SPA-(w/NE,w/oIM)
2. ITU-DR
3. SPA-Dedicated
4. ITU-SR
5. IETF-DR
6. IETF-SR

Utilization Key Takeaways: Under SPA-(w/NE,w/oIM) and same input load:

1. All sharing ratios provide lower utilization than IETF,ITU, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

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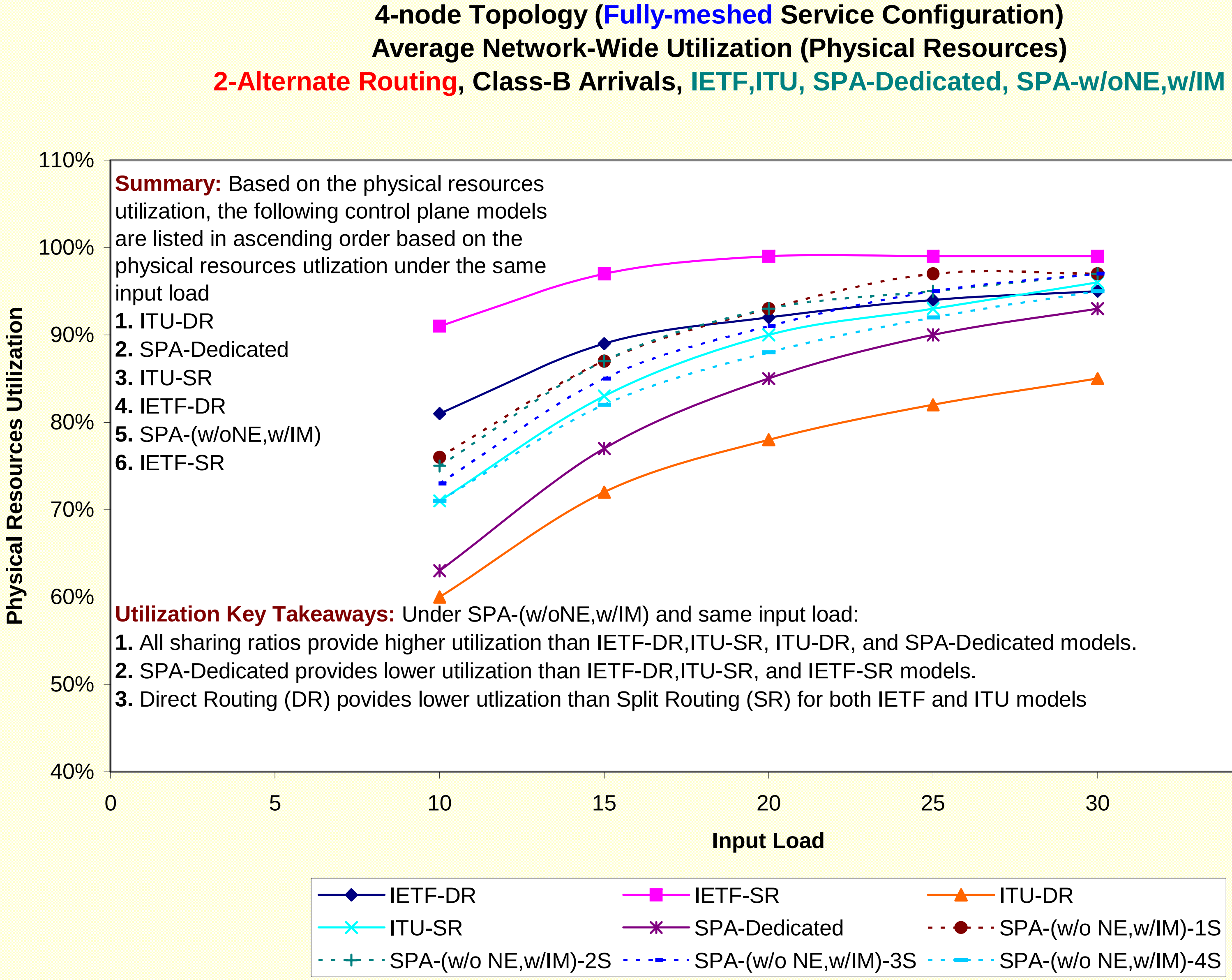
Appendix-B: 4 Node Topology Detailed Results “Utilization”



4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/oNE,w/IM

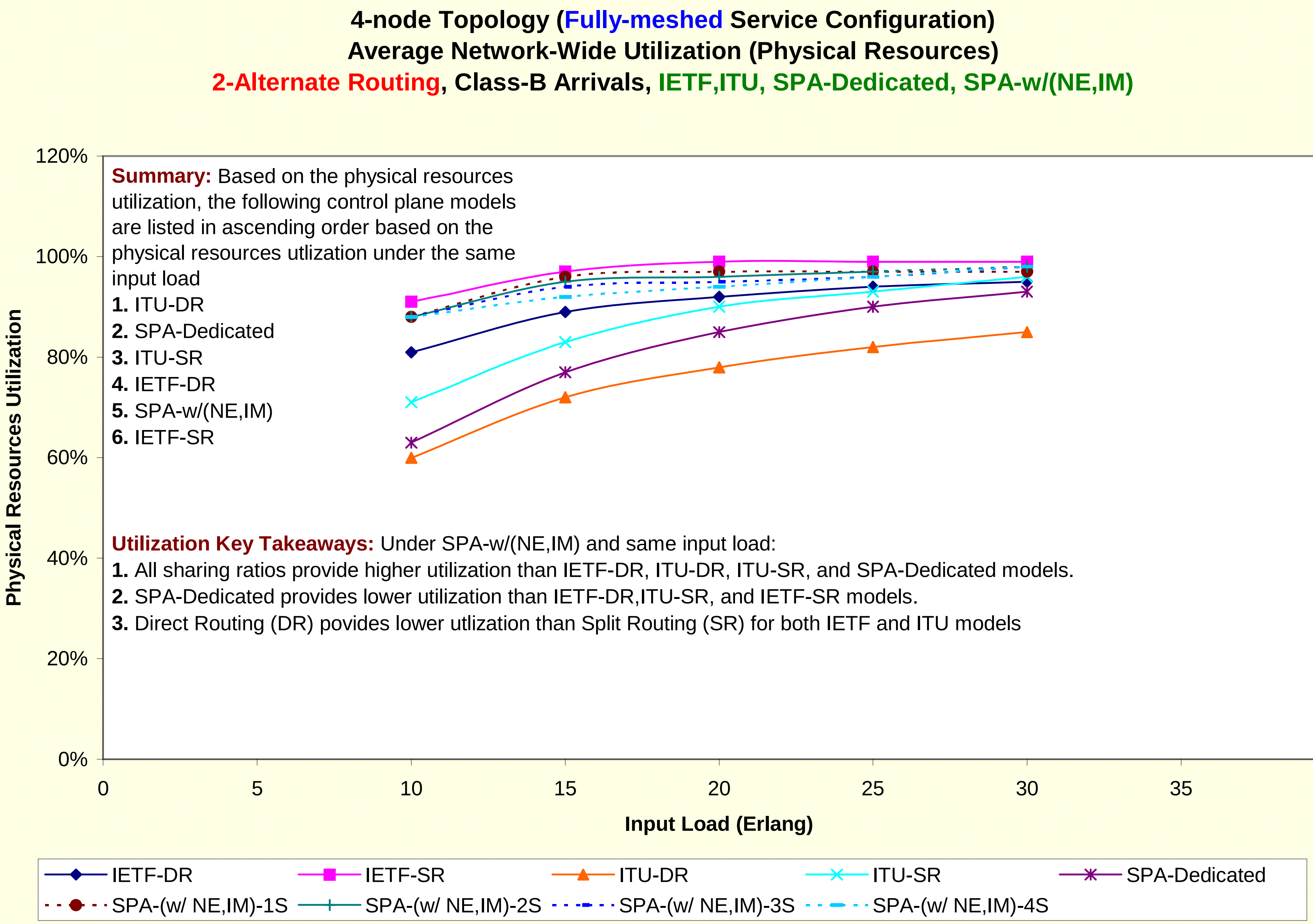
Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

1. ITU-DR
2. SPA-Dedicated
3. ITU-SR
4. IETF-DR
5. SPA-(w/oNE,w/IM)
6. IETF-SR

Utilization Key Takeaways: Under SPA-(w/oNE,w/IM) and same input load:

1. All sharing ratios provide higher utilization than IETF-DR,ITU-SR, ITU-DR, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-B: 4 Node Topology Detailed Results "Utilization"



4-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/(NE,IM)

Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

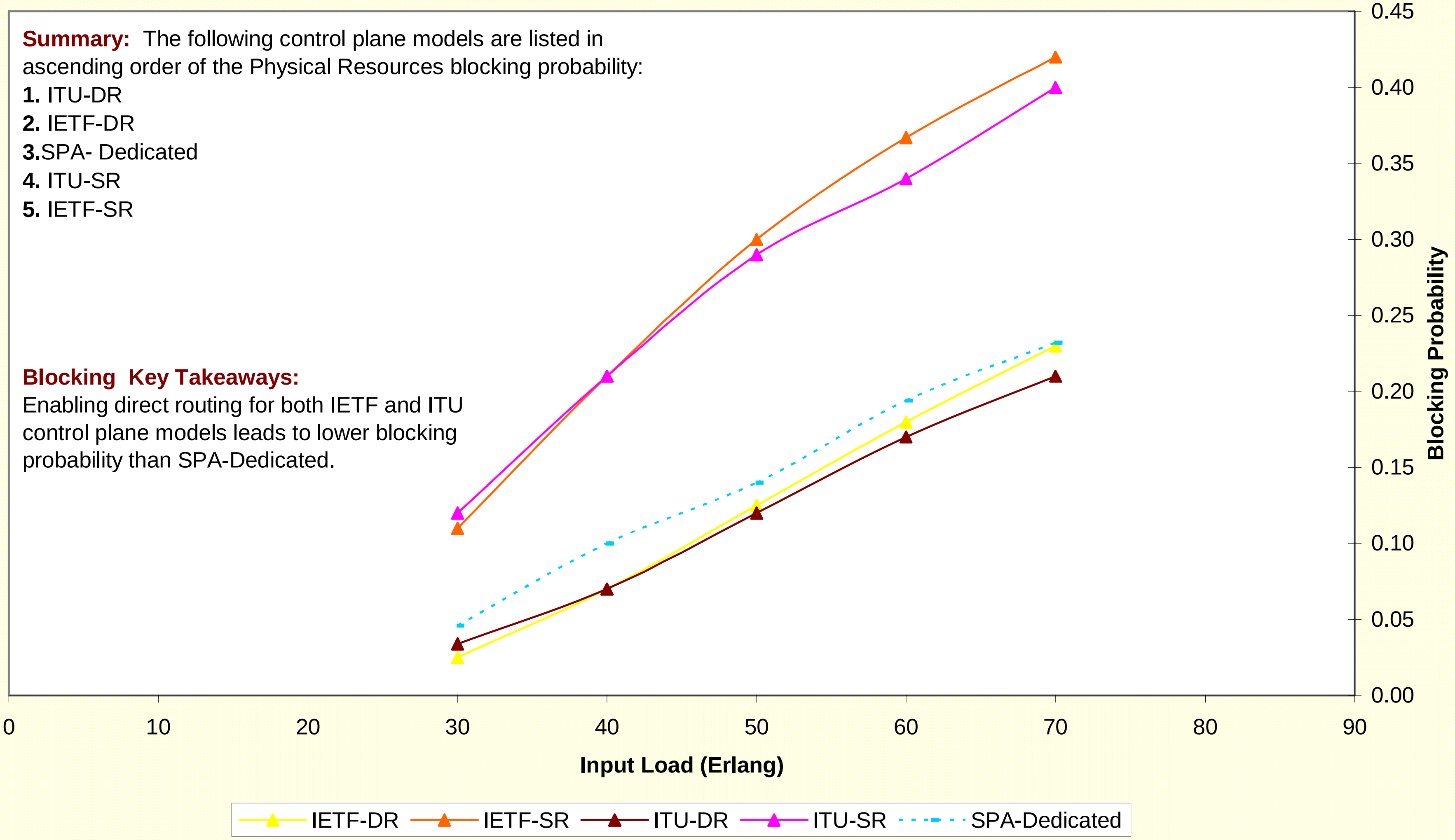
1. ITU-DR
2. SPA-Dedicated
3. ITU-SR
4. IETF-DR
5. SPA-w/(NE,IM)
6. IETF-SR

Utilization Key Takeaways: Under SPA-w/(NE,IM) and same input load:

1. All sharing ratios provide higher utilization than IETF-DR, ITU-DR, ITU-SR, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-C: 7 Node (2 routes) Topology Detailed Results “Blocking probability”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physcial Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-Dedicated



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. ITU-DR
2. IETF-DR
3.SPA- Dedicated
4. ITU-SR
5. IETF-SR

Blocking Key Takeaways:
Enabling direct routing for both IETF and ITU control plane models leads to lower blocking probability than SPA-Dedicated.

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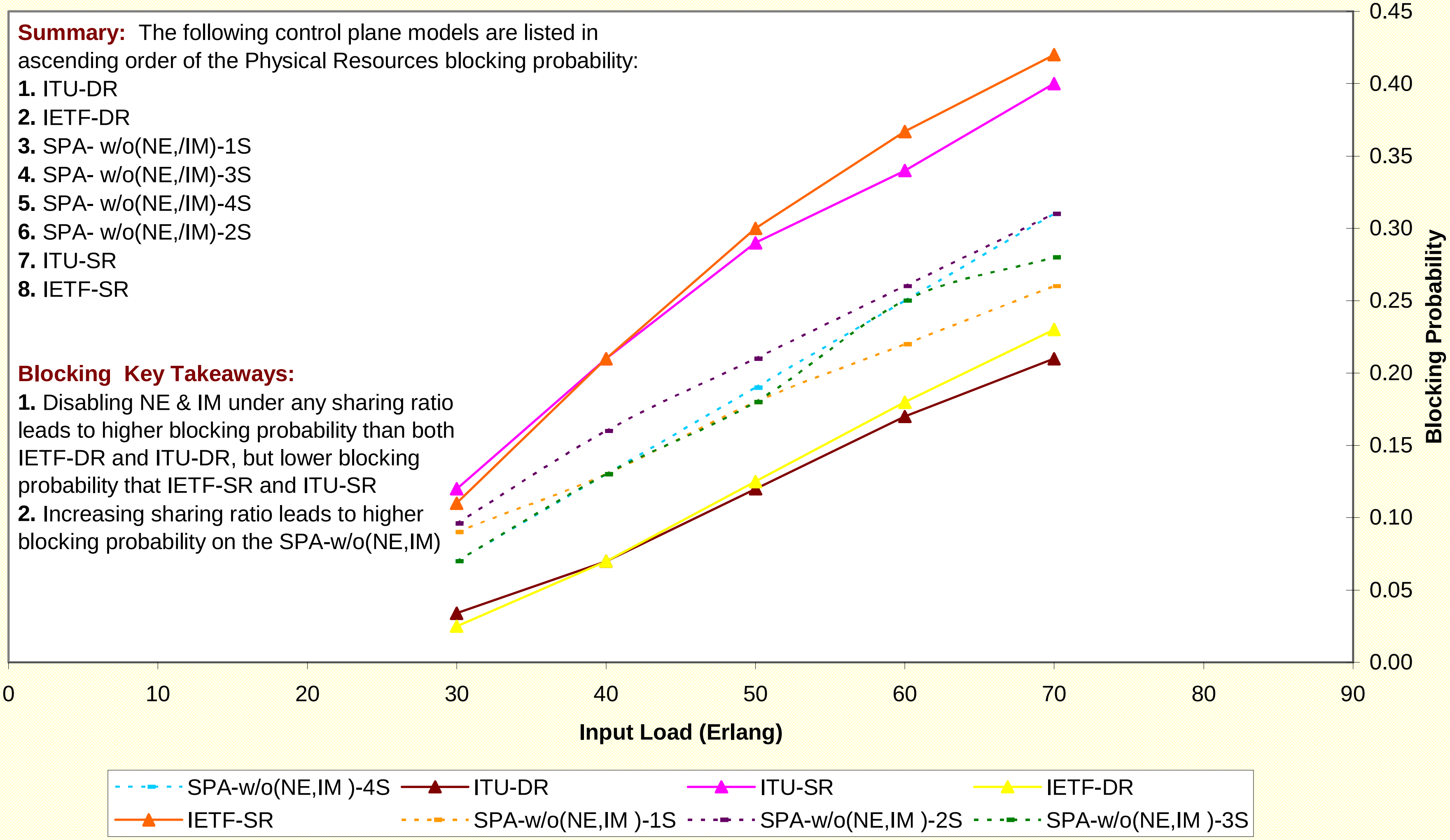
Appendix-C: 7 Node (2 routes) Topology Detailed Results “Blocking probability”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/o(NE,IM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. ITU-DR
2. IETF-DR
3. SPA- w/o(NE,/IM)-1S
4. SPA- w/o(NE,/IM)-3S
5. SPA- w/o(NE,/IM)-4S
6. SPA- w/o(NE,/IM)-2S
7. ITU-SR
8. IETF-SR

Blocking Key Takeaways:

1. Disabling NE & IM under any sharing ratio leads to higher blocking probability than both IETF-DR and ITU-DR, but lower blocking probability that IETF-SR and ITU-SR

2. Increasing sharing ratio leads to higher blocking probability on the SPA-w/o(NE,IM)

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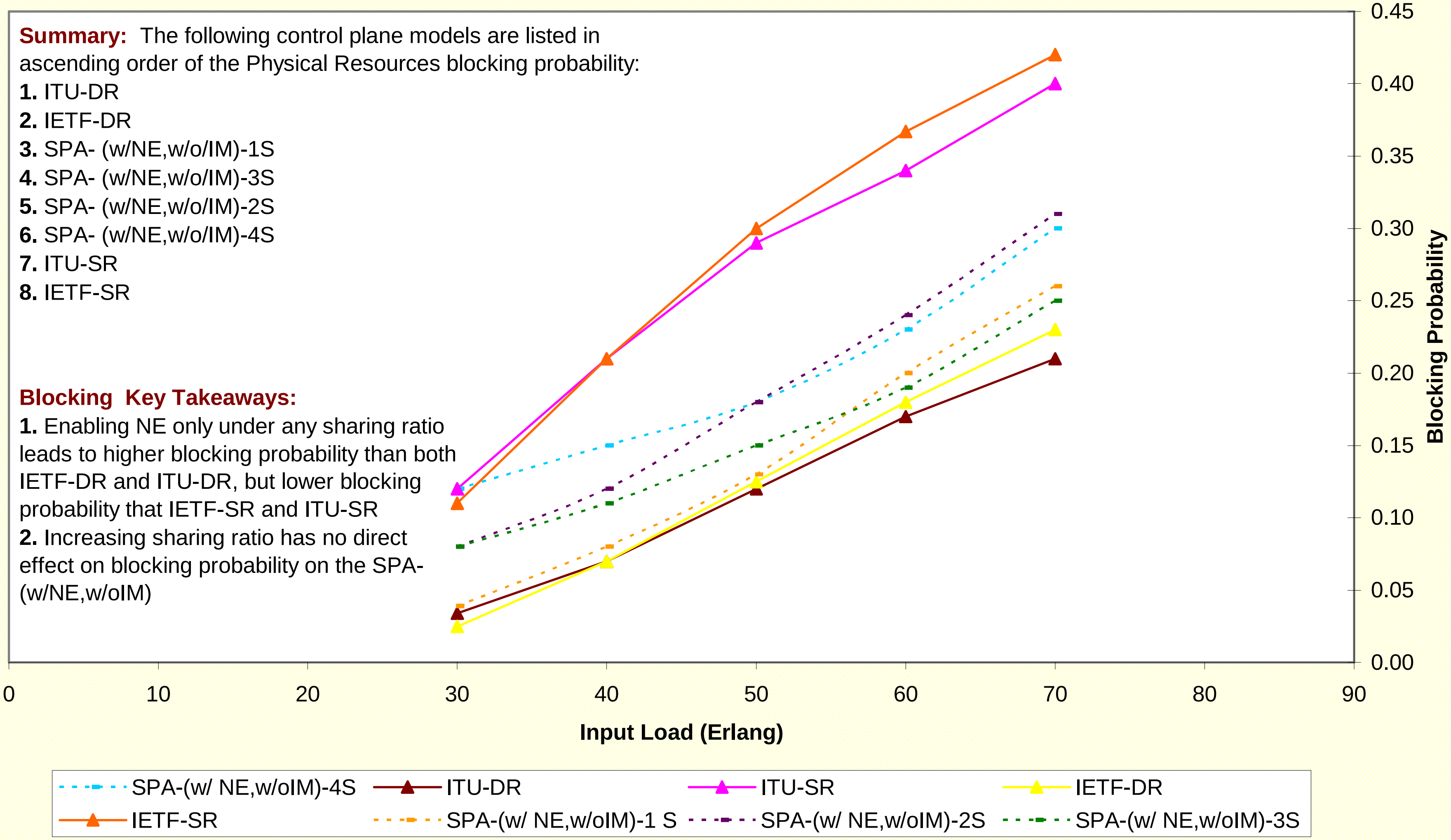
Appendix-C: 7 Node (2 routes) Topology Detailed Results "Blocking probability"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/NE,w/oIM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. ITU-DR
2. IETF-DR
3. SPA- (w/NE,w/o/IM)-1S
4. SPA- (w/NE,w/o/IM)-3S
5. SPA- (w/NE,w/o/IM)-2S
6. SPA- (w/NE,w/o/IM)-4S
7. ITU-SR
8. IETF-SR

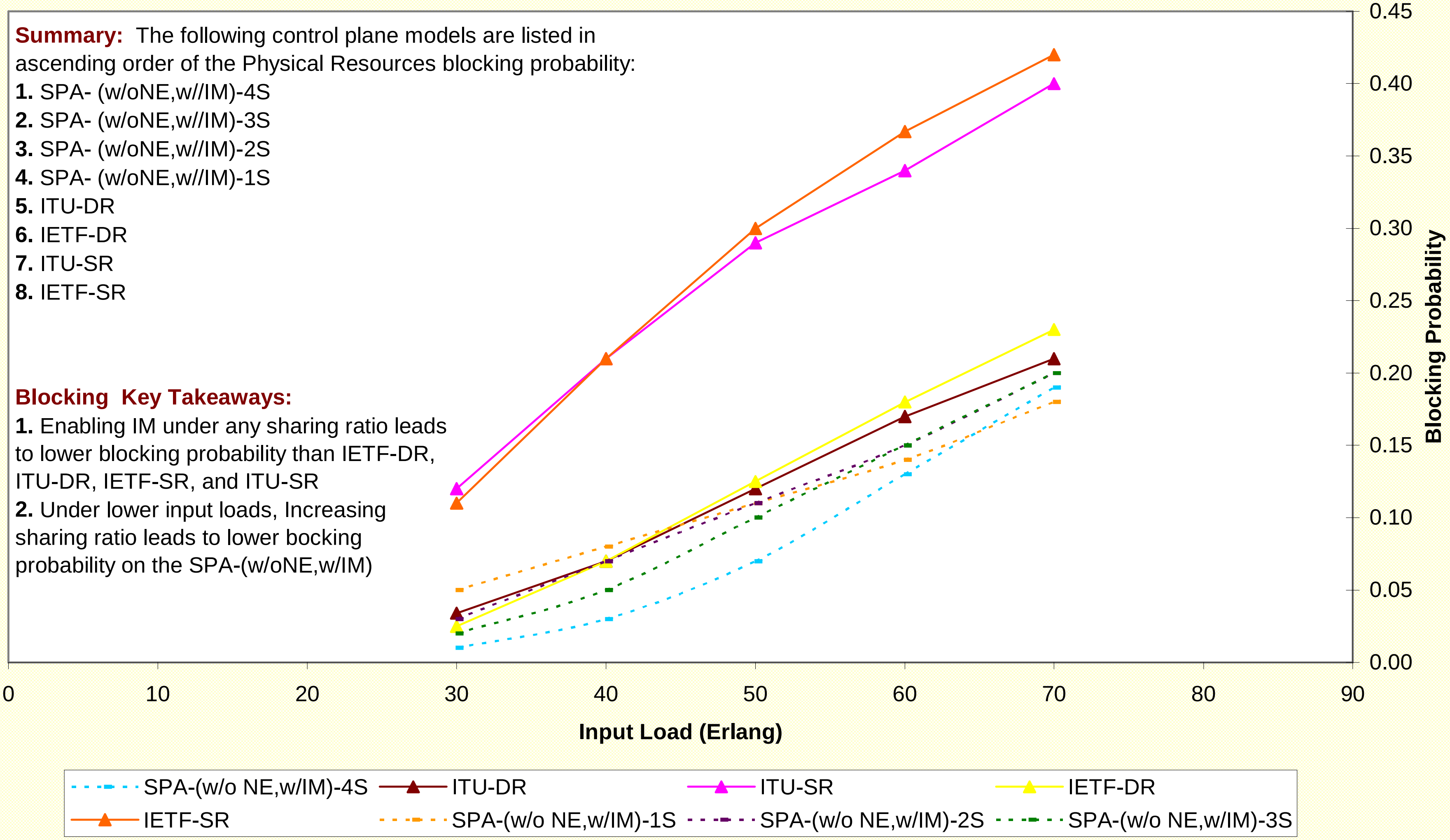
Blocking Key Takeaways:

1. Enabling NE only under any sharing ratio leads to higher blocking probability than both IETF-DR and ITU-DR, but lower blocking probability that IETF-SR and ITU-SR

2. Increasing sharing ratio has no direct effect on blocking probability on the SPA-(w/NE,w/oIM)

Appendix-C: 7 Node (2 routes) Topology Detailed Results “Blocking probability”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/oNE,w/IM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. SPA- (w/oNE,w//IM)-4S
2. SPA- (w/oNE,w//IM)-3S
3. SPA- (w/oNE,w//IM)-2S
4. SPA- (w/oNE,w//IM)-1S
5. ITU-DR
6. IETF-DR
7. ITU-SR
8. IETF-SR

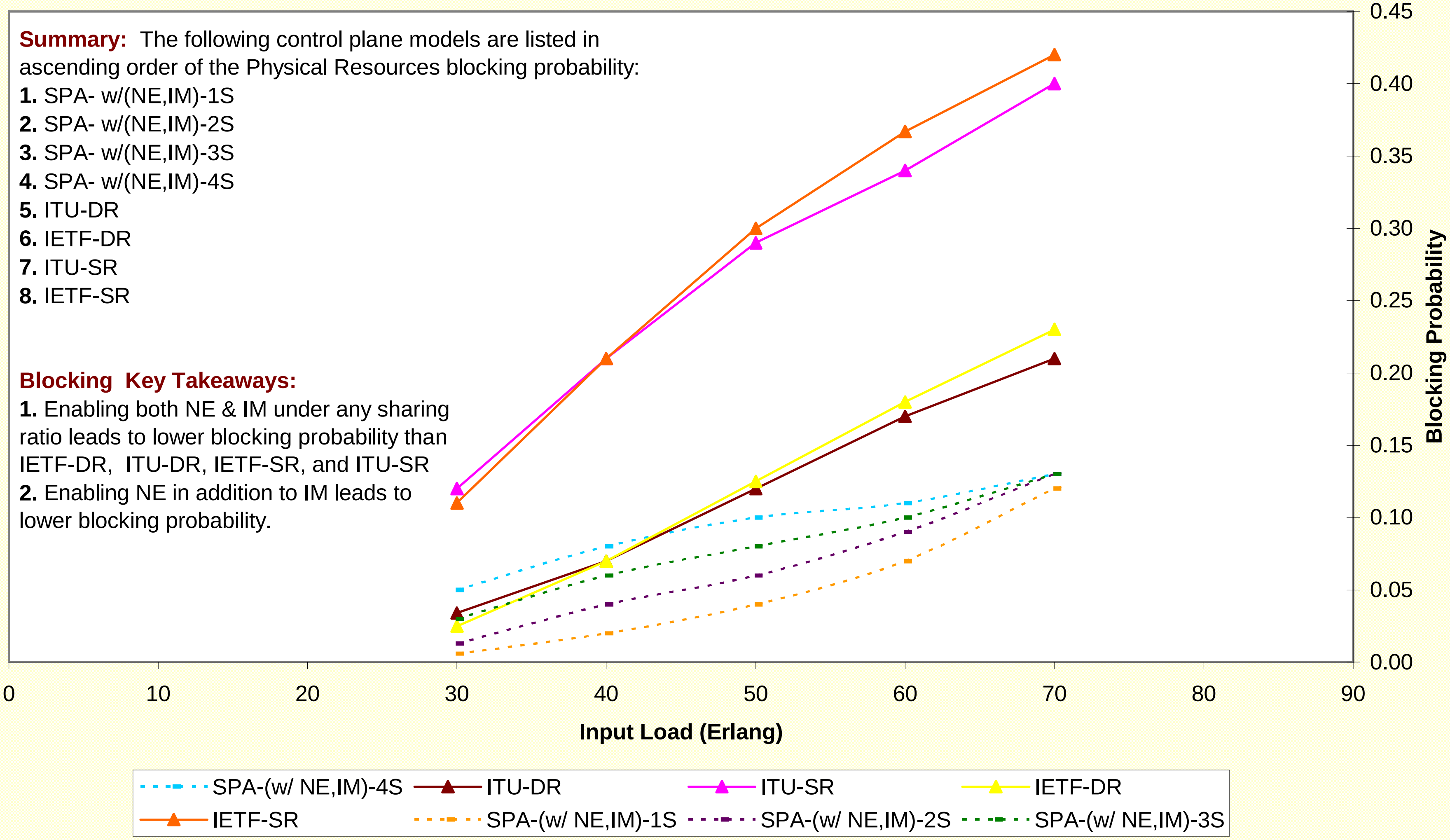
Blocking Key Takeaways:

1. Enabling IM under any sharing ratio leads to lower blocking probability than IETF-DR, ITU-DR, IETF-SR, and ITU-SR

2. Under lower input loads, Increasing sharing ratio leads to lower bocking probability on the SPA-(w/oNE,w/IM)

Appendix-C: 7 Node (2 routes) Topology Detailed Results “Blocking probability”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/(NE,IM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

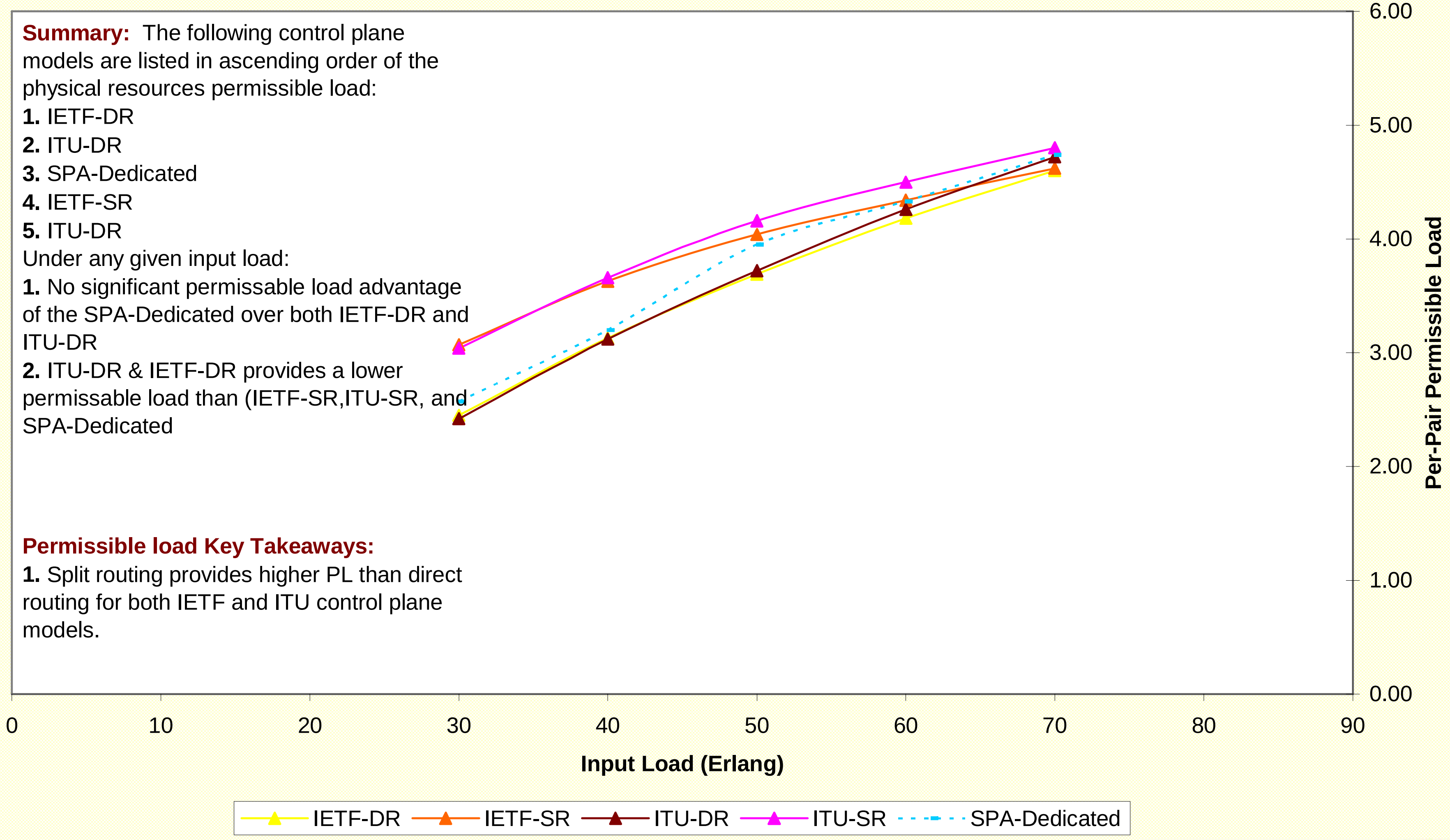
1. SPA- w/(NE,IM)-1S
2. SPA- w/(NE,IM)-2S
3. SPA- w/(NE,IM)-3S
4. SPA- w/(NE,IM)-4S
5. ITU-DR
6. IETF-DR
7. ITU-SR
8. IETF-SR

Blocking Key Takeaways:

1. Enabling both NE & IM under any sharing ratio leads to lower blocking probability than IETF-DR, ITU-DR, IETF-SR, and ITU-SR
2. Enabling NE in addition to IM leads to lower blocking probability.

Appendix-C: 7 Node (2 routes) Topology Detailed Results “Permissible Load”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physcial Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-Dedicated



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

1. IETF-DR
2. ITU-DR
3. SPA-Dedicated
4. IETF-SR
5. ITU-DR

Under any given input load:

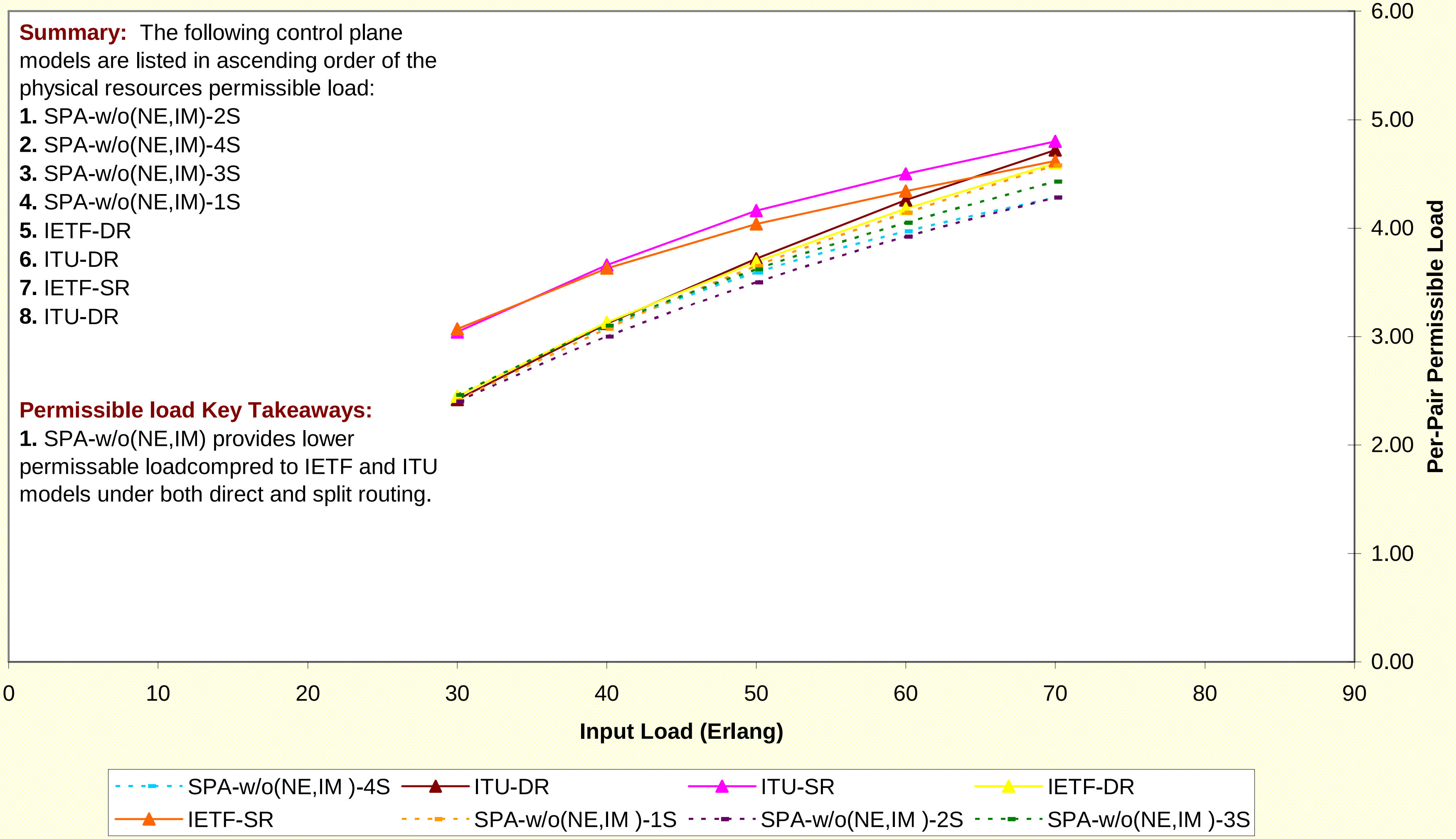
1. No significant permissable load advantage of the SPA-Dedicated over both IETF-DR and ITU-DR
2. ITU-DR & IETF-DR provides a lower permissable load than (IETF-SR,ITU-SR, and SPA-Dedicated

Permissible load Key Takeaways:

1. Split routing provides higher PL than direct routing for both IETF and ITU control plane models.

Appendix-C: 7 Node (2 routes) Topology Detailed Results "Permissible Load"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/o(NE,IM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

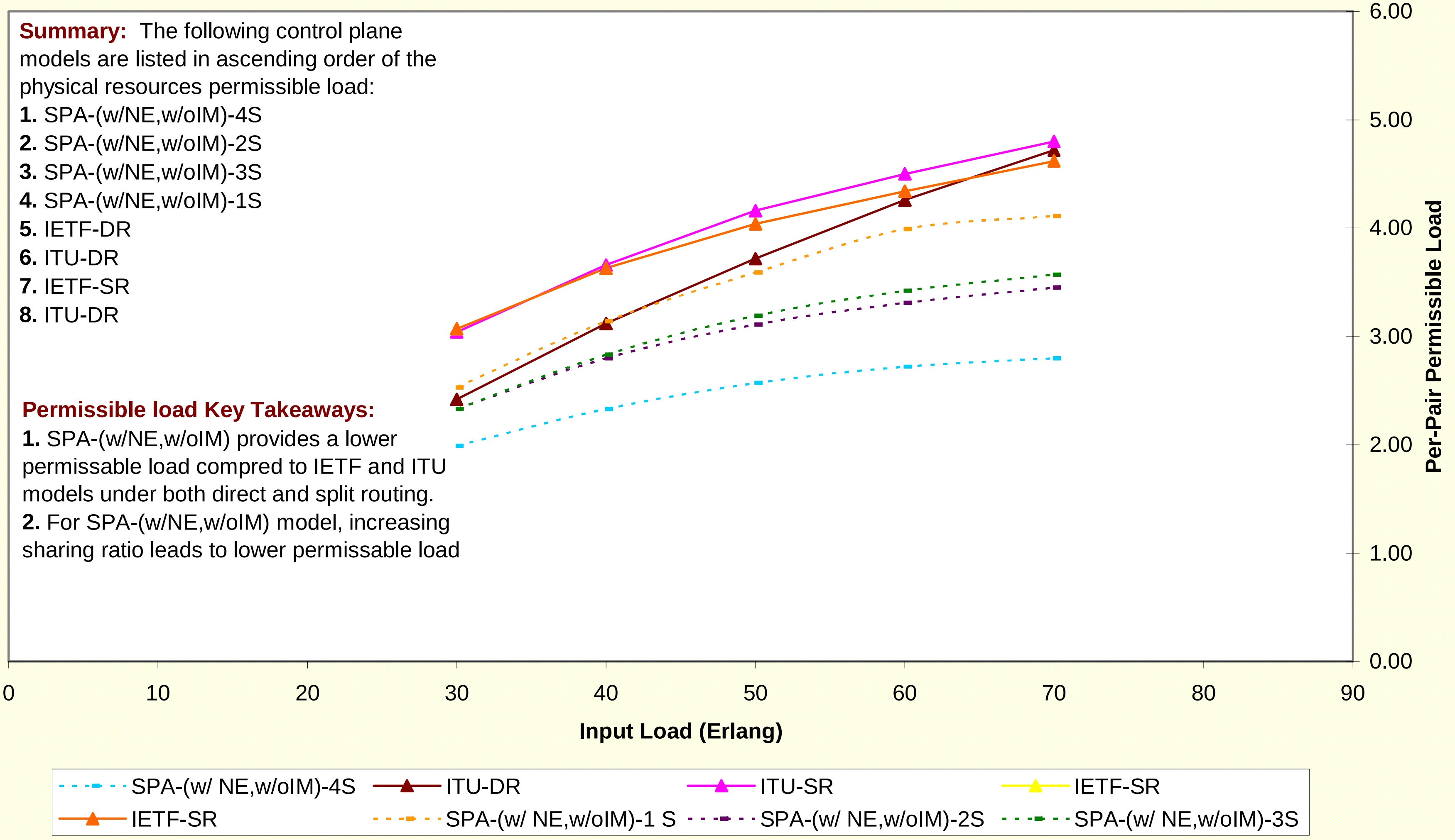
1. SPA-w/o(NE,IM)-2S
2. SPA-w/o(NE,IM)-4S
3. SPA-w/o(NE,IM)-3S
4. SPA-w/o(NE,IM)-1S
5. IETF-DR
6. ITU-DR
7. IETF-SR
8. ITU-DR

Permissible load Key Takeaways:

1. SPA-w/o(NE,IM) provides lower permissable loadcompred to IETF and ITU models under both direct and split routing.

Appendix-C: 7 Node (2 routes) Topology Detailed Results "Permissible Load"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/NE,w/oIM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

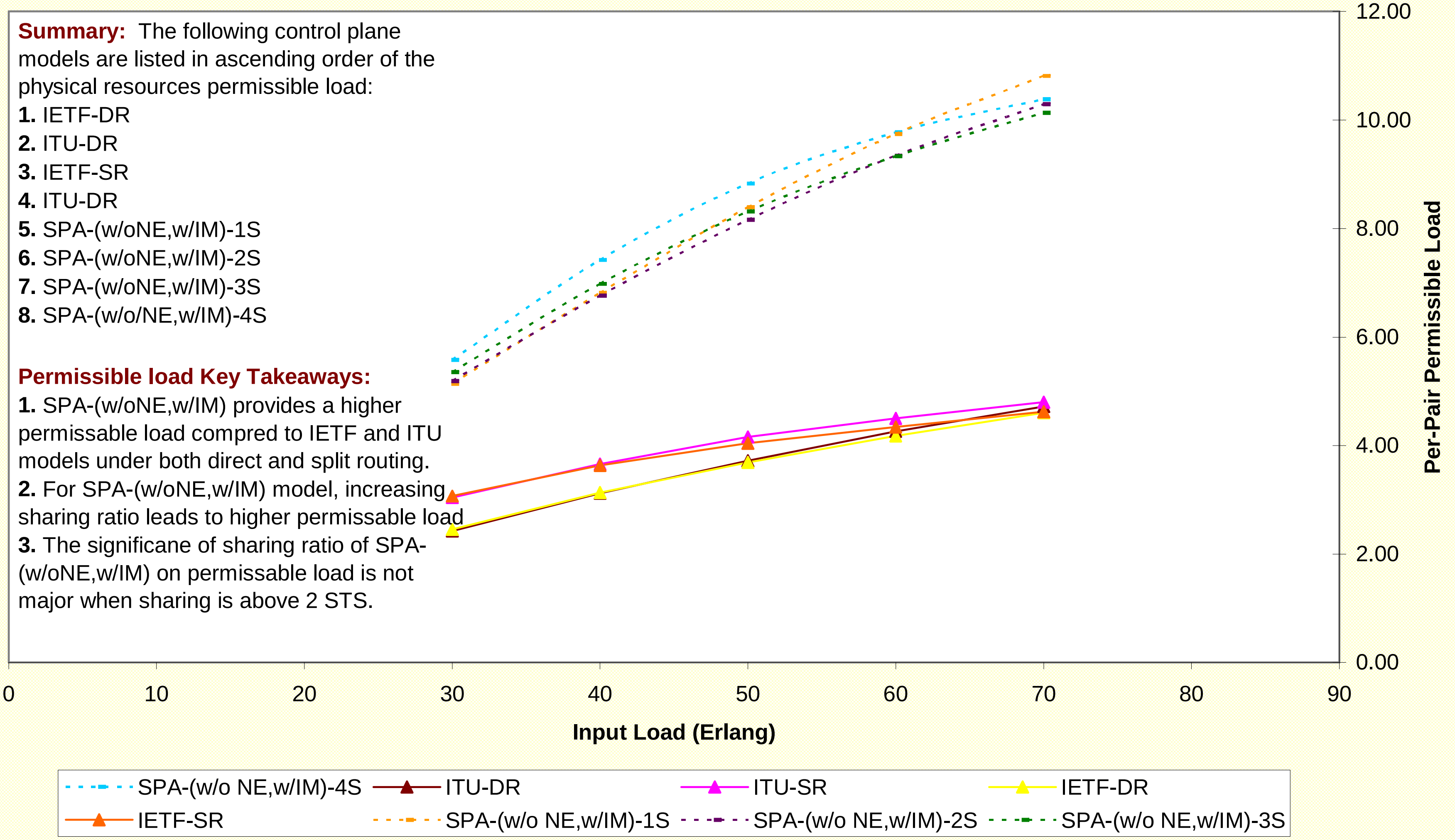
1. SPA-(w/NE,w/oIM)-4S
2. SPA-(w/NE,w/oIM)-2S
3. SPA-(w/NE,w/oIM)-3S
4. SPA-(w/NE,w/oIM)-1S
5. IETF-DR
6. ITU-DR
7. IETF-SR
8. ITU-DR

Permissible load Key Takeaways:

1. SPA-(w/NE,w/oIM) provides a lower permissable load compred to IETF and ITU models under both direct and split routing.
2. For SPA-(w/NE,w/oIM) model, increasing sharing ratio leads to lower permissable load

Appendix-C: 7 Node (2 routes) Topology Detailed Results “Permissible Load”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/oNE,w/IM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

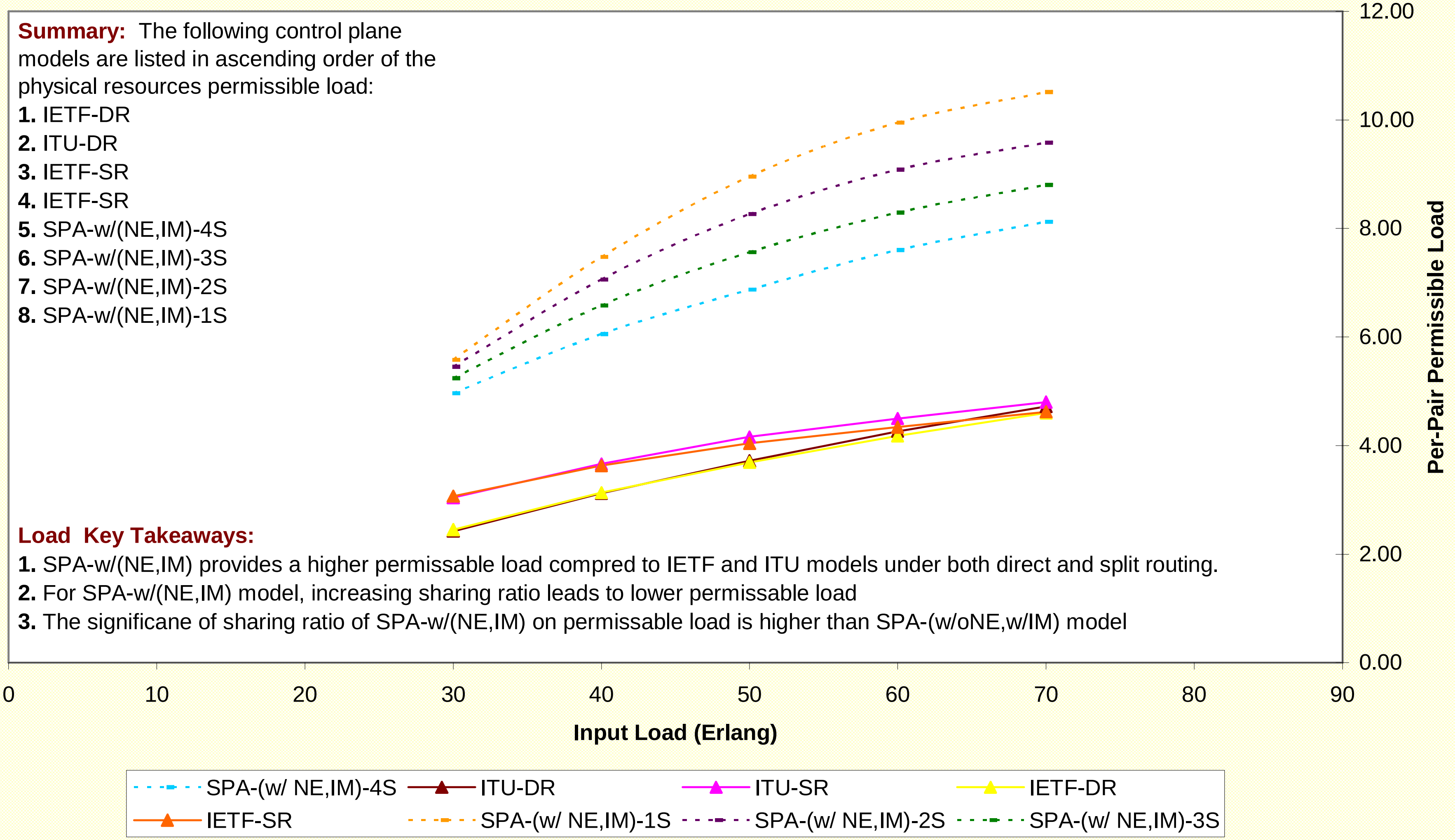
1. IETF-DR
2. ITU-DR
3. IETF-SR
4. ITU-DR
5. SPA-(w/oNE,w/IM)-1S
6. SPA-(w/oNE,w/IM)-2S
7. SPA-(w/oNE,w/IM)-3S
8. SPA-(w/o/NE,w/IM)-4S

Permissible load Key Takeaways:

1. SPA-(w/oNE,w/IM) provides a higher permissable load compred to IETF and ITU models under both direct and split routing.
2. For SPA-(w/oNE,w/IM) model, increasing sharing ratio leads to higher permissable load
3. The significane of sharing ratio of SPA-(w/oNE,w/IM) on permissable load is not major when sharing is above 2 STS.

Appendix-C: 7 Node (2 routes) Topology Detailed Results “Permissible Load”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/(NE,IM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

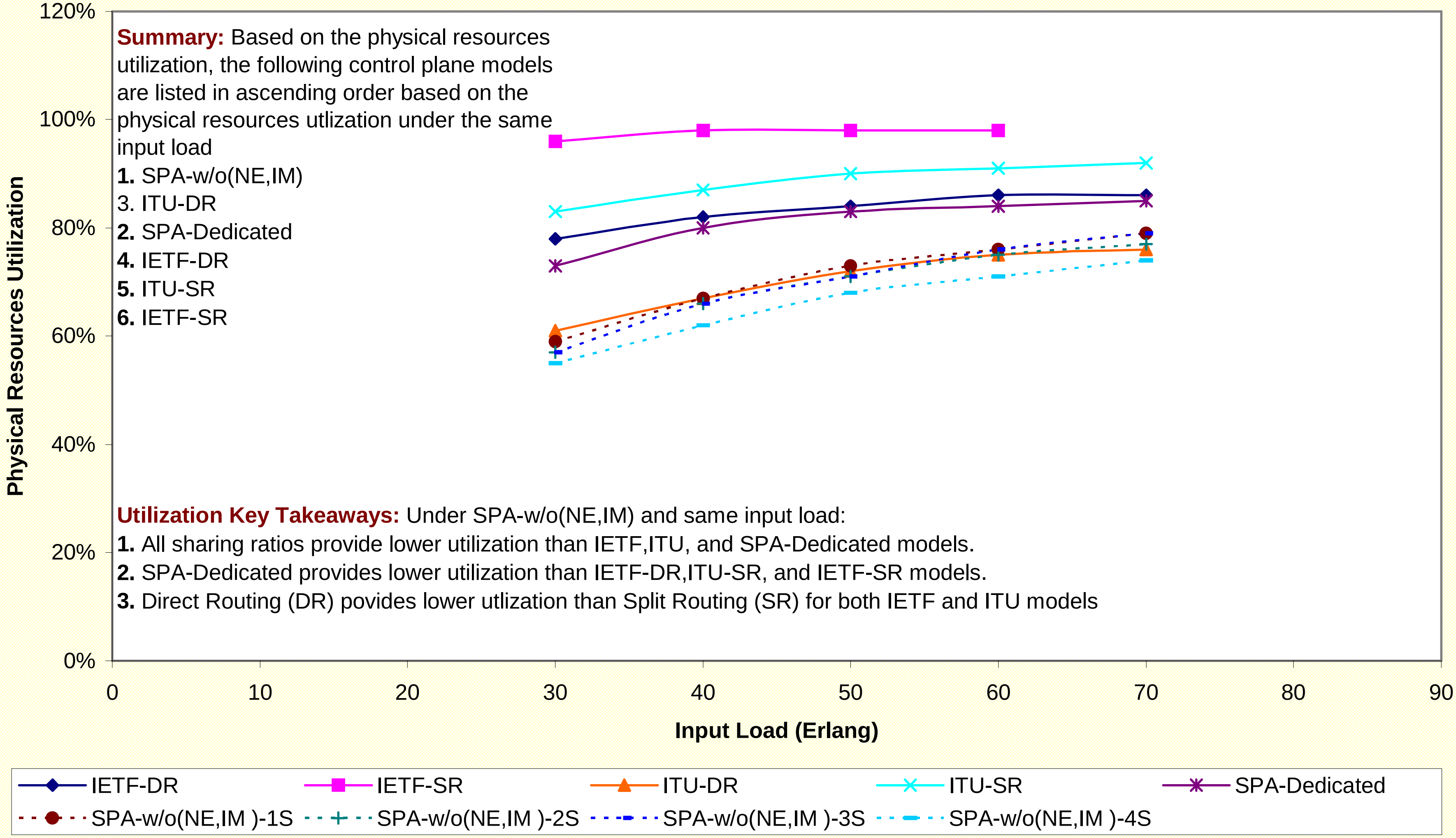
1. IETF-DR
2. ITU-DR
3. IETF-SR
4. IETF-SR
5. SPA-w/(NE,IM)-4S
6. SPA-w/(NE,IM)-3S
7. SPA-w/(NE,IM)-2S
8. SPA-w/(NE,IM)-1S

Load Key Takeaways:

1. SPA-w/(NE,IM) provides a higher permissable load compred to IETF and ITU models under both direct and split routing.
2. For SPA-w/(NE,IM) model, increasing sharing ratio leads to lower permissable load
3. The significane of sharing ratio of SPA-w/(NE,IM) on permissable load is higher than SPA-(w/oNE,w/IM) model

Appendix-C: 7 Node (2 routes) Topology Detailed Results "Utilization"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/o(NE,IM)



Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

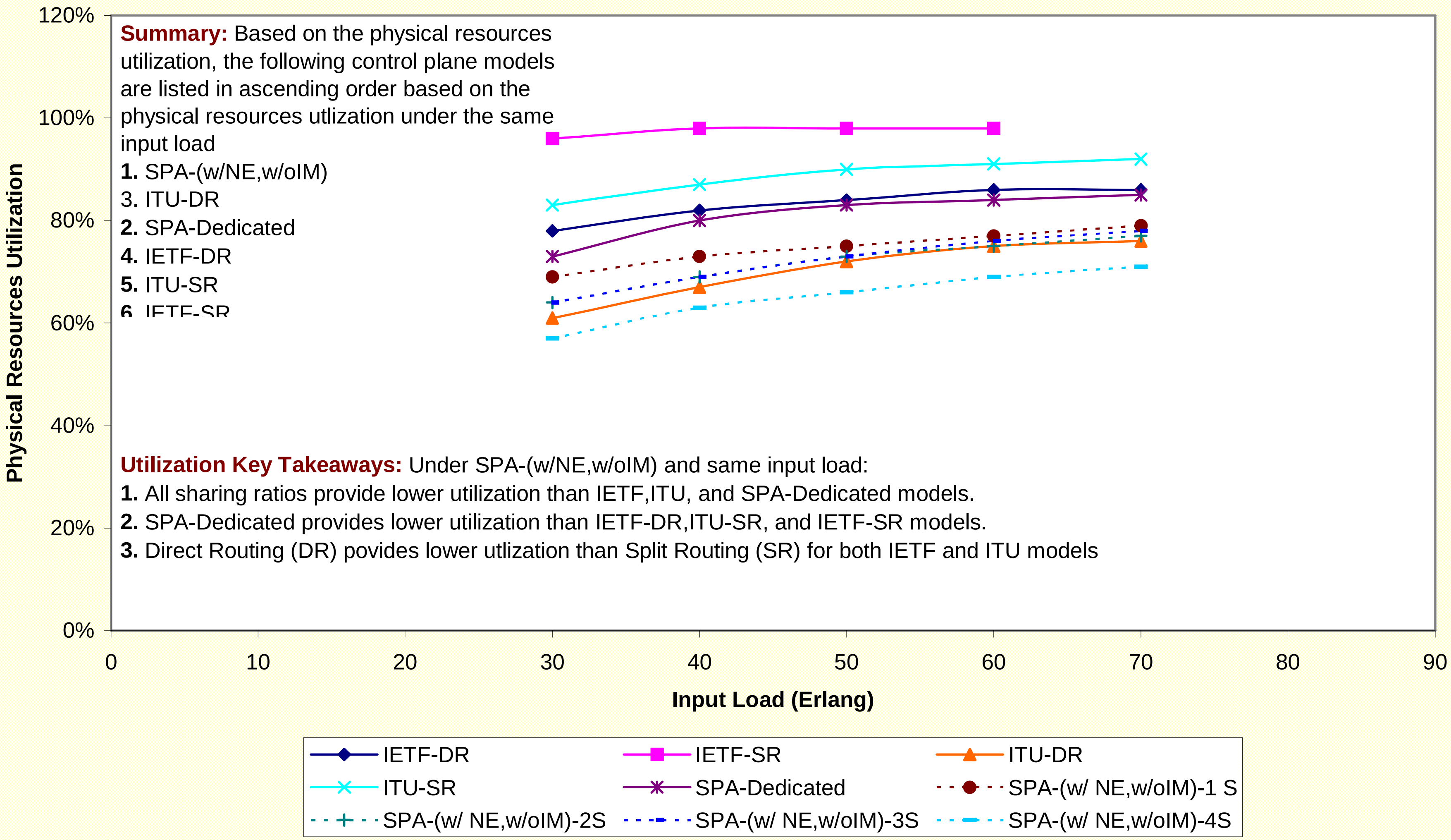
1. SPA-w/o(NE,IM)
3. ITU-DR
2. SPA-Dedicated
4. IETF-DR
5. ITU-SR
6. IETF-SR

Utilization Key Takeaways: Under SPA-w/o(NE,IM) and same input load:

1. All sharing ratios provide lower utilization than IETF,ITU, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-C: 7 Node (2 routes) Topology Detailed Results "Utilization"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/NE,w/oIM



Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

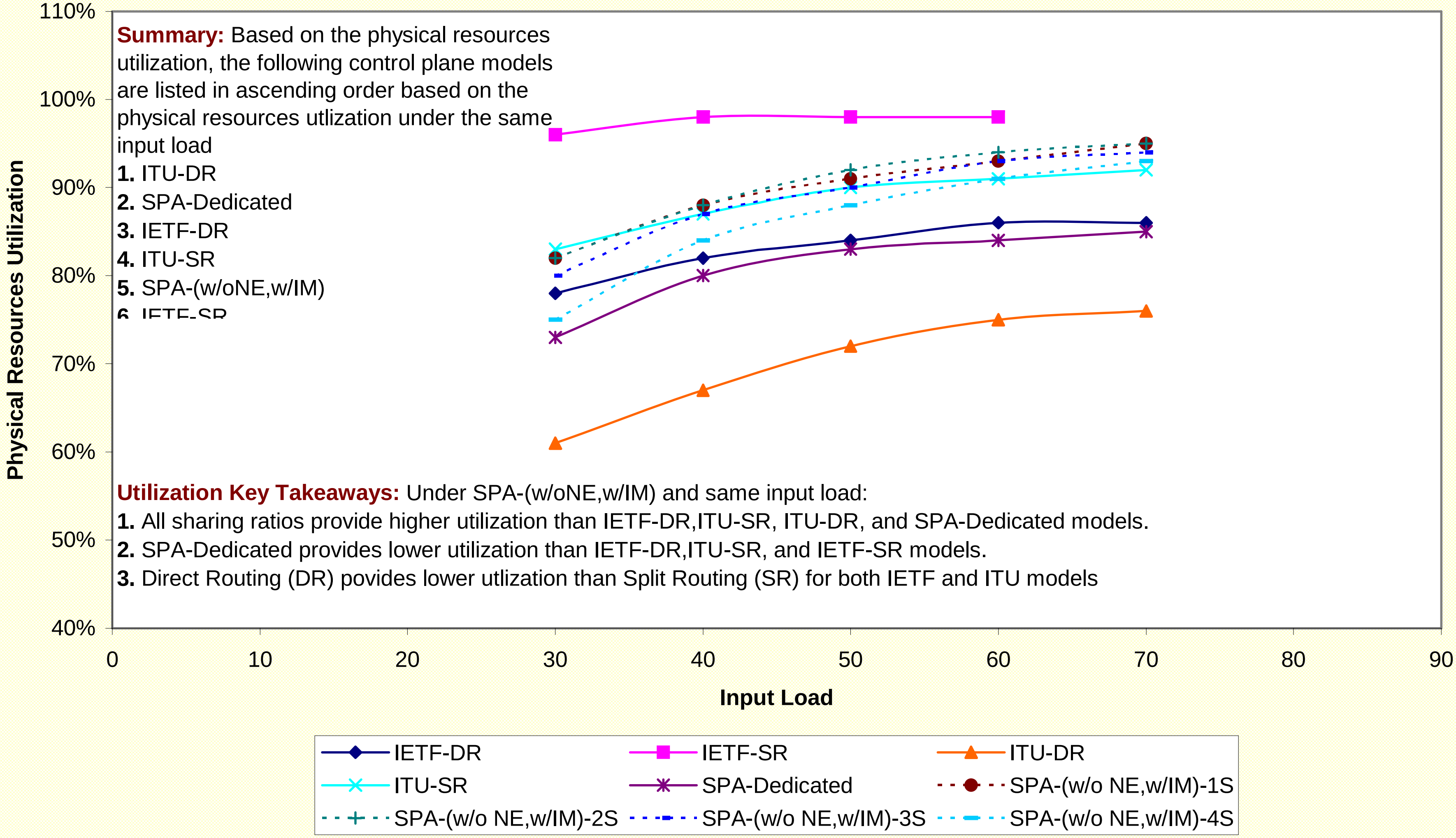
1. SPA-(w/NE,w/oIM)
3. ITU-DR
2. SPA-Dedicated
4. IETF-DR
5. ITU-SR
6. IETF-SR

Utilization Key Takeaways: Under SPA-(w/NE,w/oIM) and same input load:

1. All sharing ratios provide lower utilization than IETF,ITU, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-C: 7 Node (2 routes) Topology Detailed Results "Utilization"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/oNE,w/IM



Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

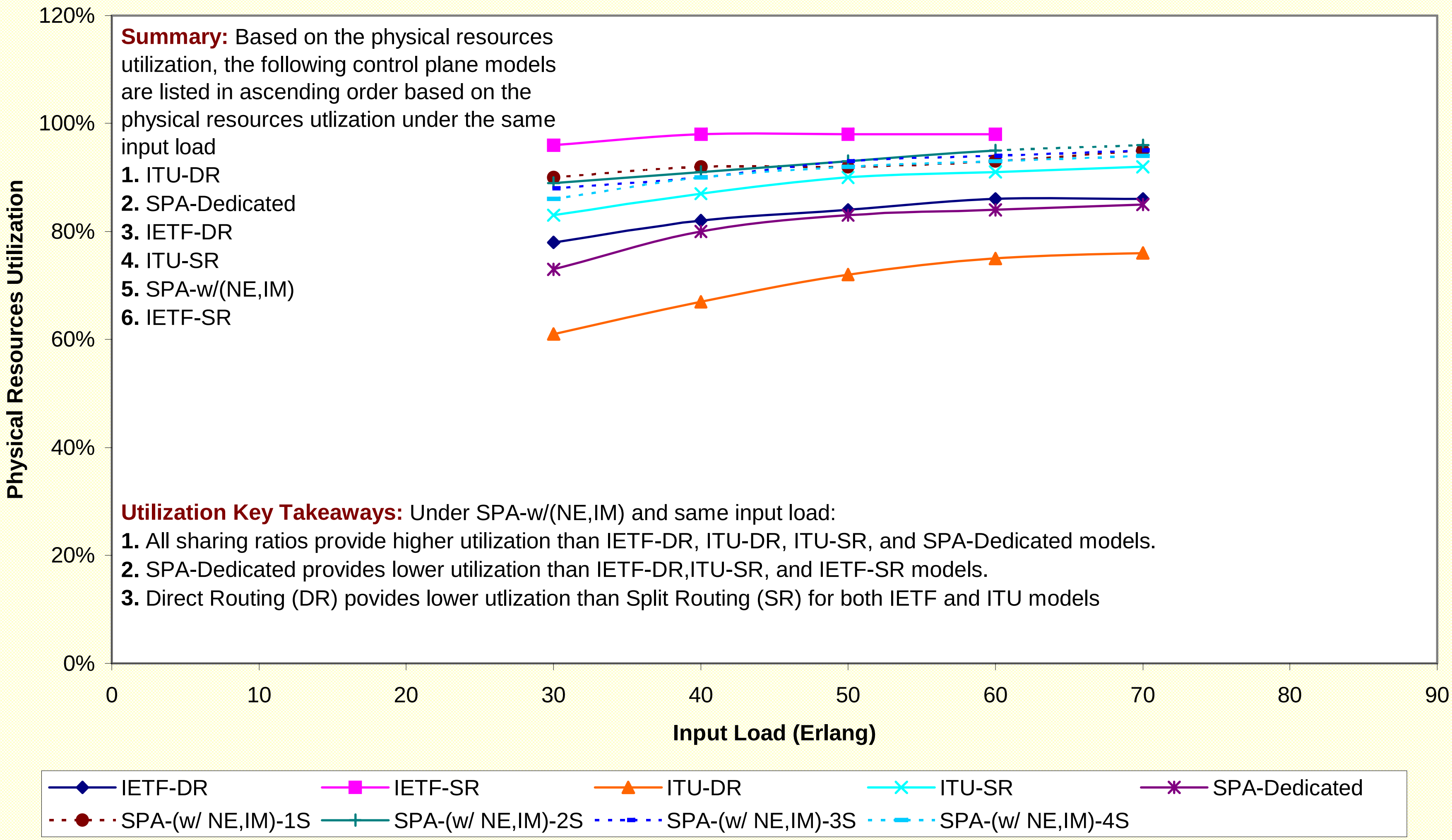
1. ITU-DR
2. SPA-Dedicated
3. IETF-DR
4. ITU-SR
5. SPA-(w/oNE,w/IM)
6. IETF-SR

Utilization Key Takeaways: Under SPA-(w/oNE,w/IM) and same input load:

1. All sharing ratios provide higher utilization than IETF-DR,ITU-SR, ITU-DR, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-C: 7 Node (2 routes) Topology Detailed Results "Utilization"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
2-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/(NE,IM)



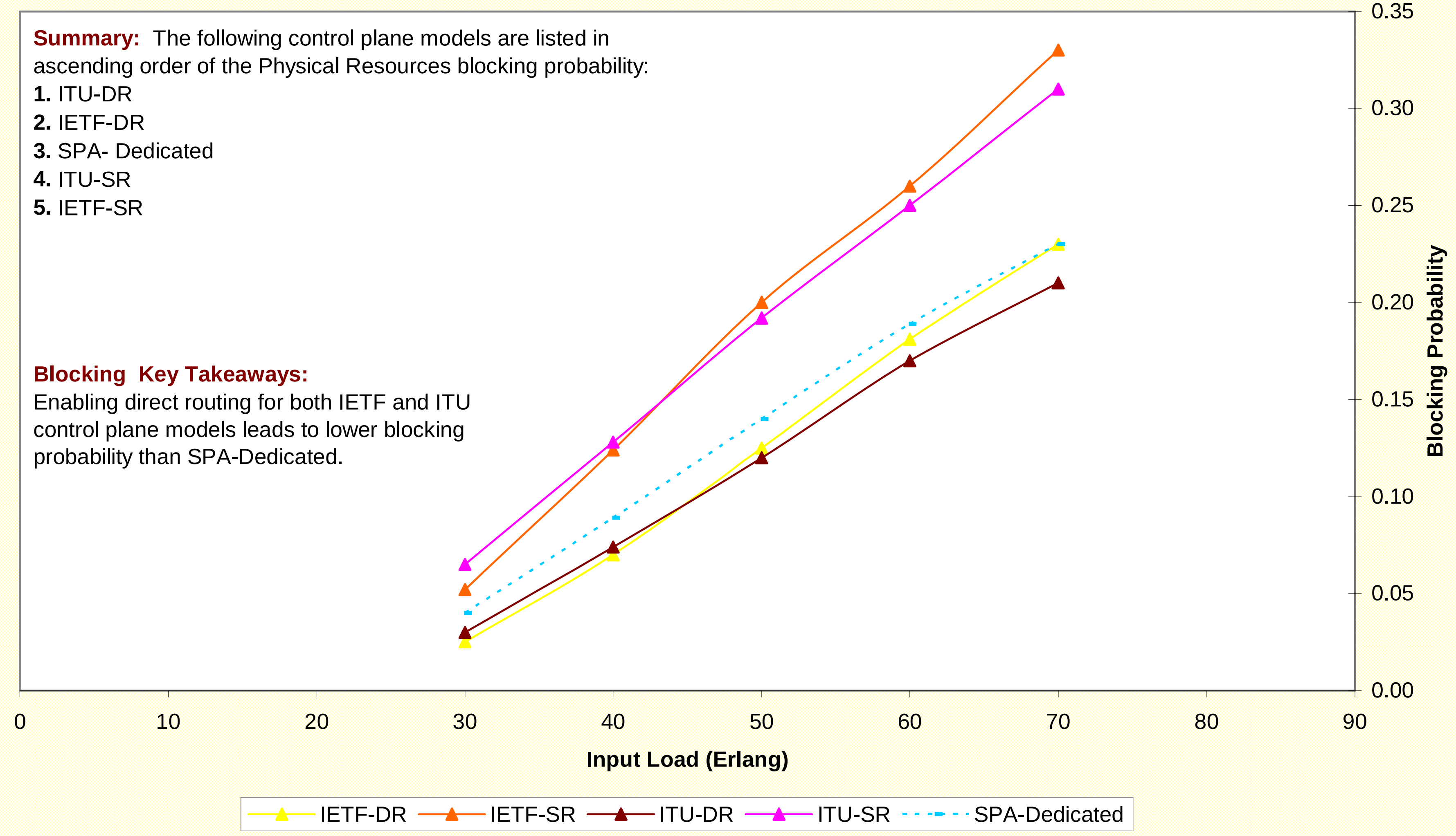
Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

1. ITU-DR
2. SPA-Dedicated
3. IETF-DR
4. ITU-SR
5. SPA-w/(NE,IM)
6. IETF-SR

Utilization Key Takeaways: Under SPA-w/(NE,IM) and same input load:

1. All sharing ratios provide higher utilization than IETF-DR, ITU-DR, ITU-SR, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physcial Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-Dedicated



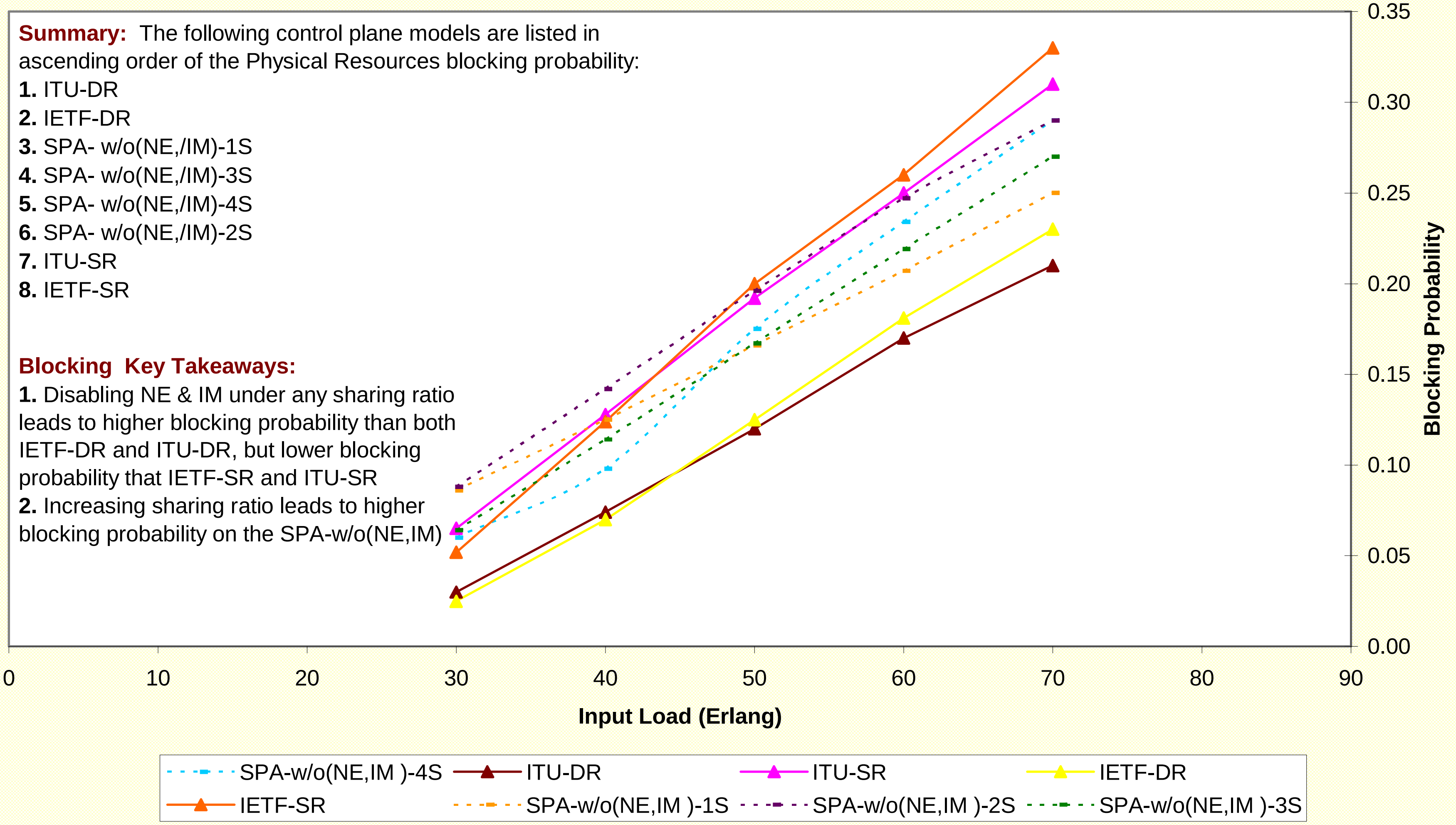
Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. ITU-DR
2. IETF-DR
3. SPA- Dedicated
4. ITU-SR
5. IETF-SR

Blocking Key Takeaways:
Enabling direct routing for both IETF and ITU control plane models leads to lower blocking probability than SPA-Dedicated.

Appendix-D: 7 Node (3 routes) Topology Detailed Results "Blocking probability"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/o(NE,IM)



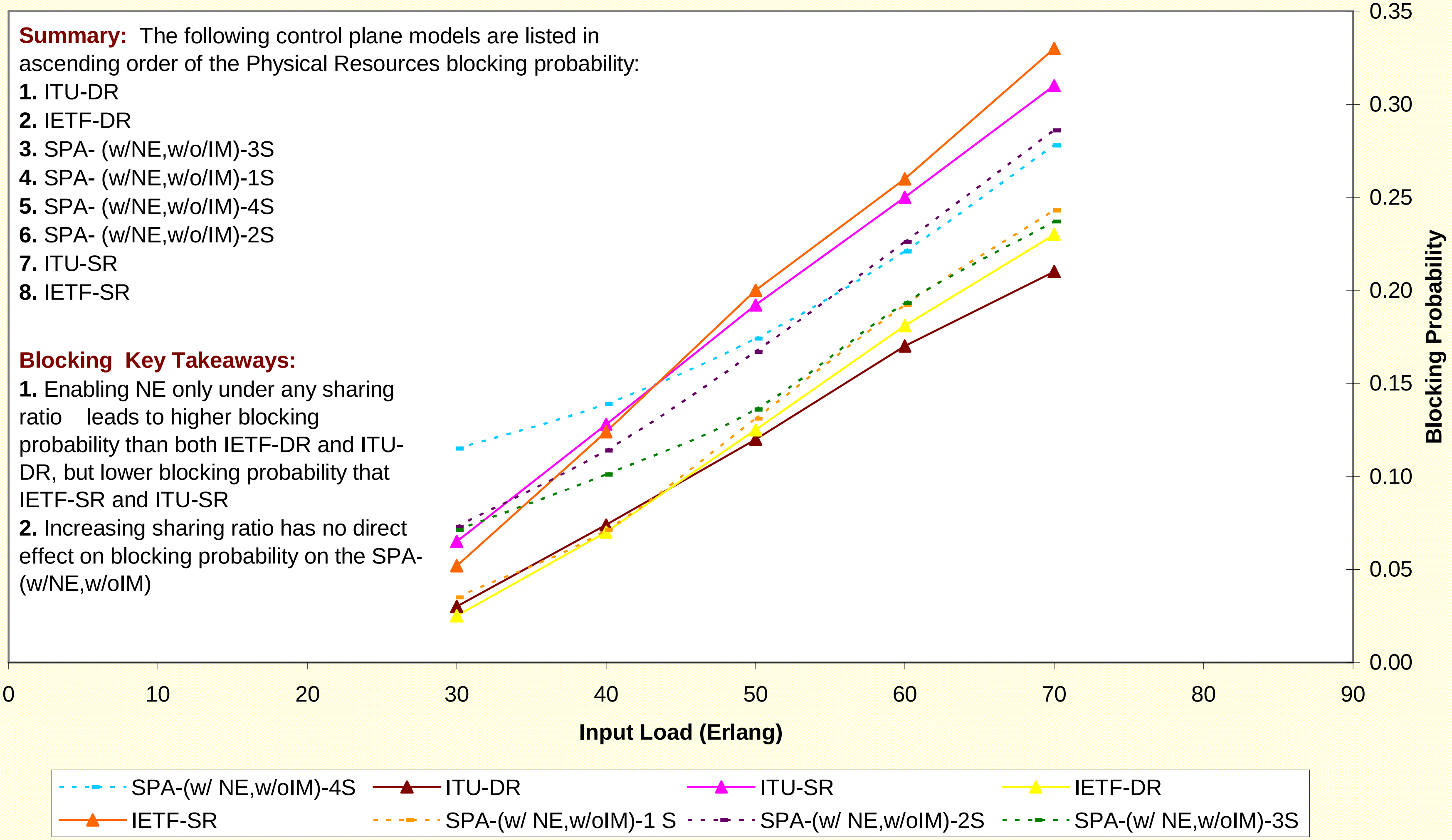
Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. ITU-DR
2. IETF-DR
3. SPA- w/o(NE,/IM)-1S
4. SPA- w/o(NE,/IM)-3S
5. SPA- w/o(NE,/IM)-4S
6. SPA- w/o(NE,/IM)-2S
7. ITU-SR
8. IETF-SR

Blocking Key Takeaways:

1. Disabling NE & IM under any sharing ratio leads to higher blocking probability than both IETF-DR and ITU-DR, but lower blocking probability that IETF-SR and ITU-SR
2. Increasing sharing ratio leads to higher blocking probability on the SPA-w/o(NE,IM)

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/NE,w/oIM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. ITU-DR
2. IETF-DR
3. SPA- (w/NE,w/o/IM)-3S
4. SPA- (w/NE,w/o/IM)-1S
5. SPA- (w/NE,w/o/IM)-4S
6. SPA- (w/NE,w/o/IM)-2S
7. ITU-SR
8. IETF-SR

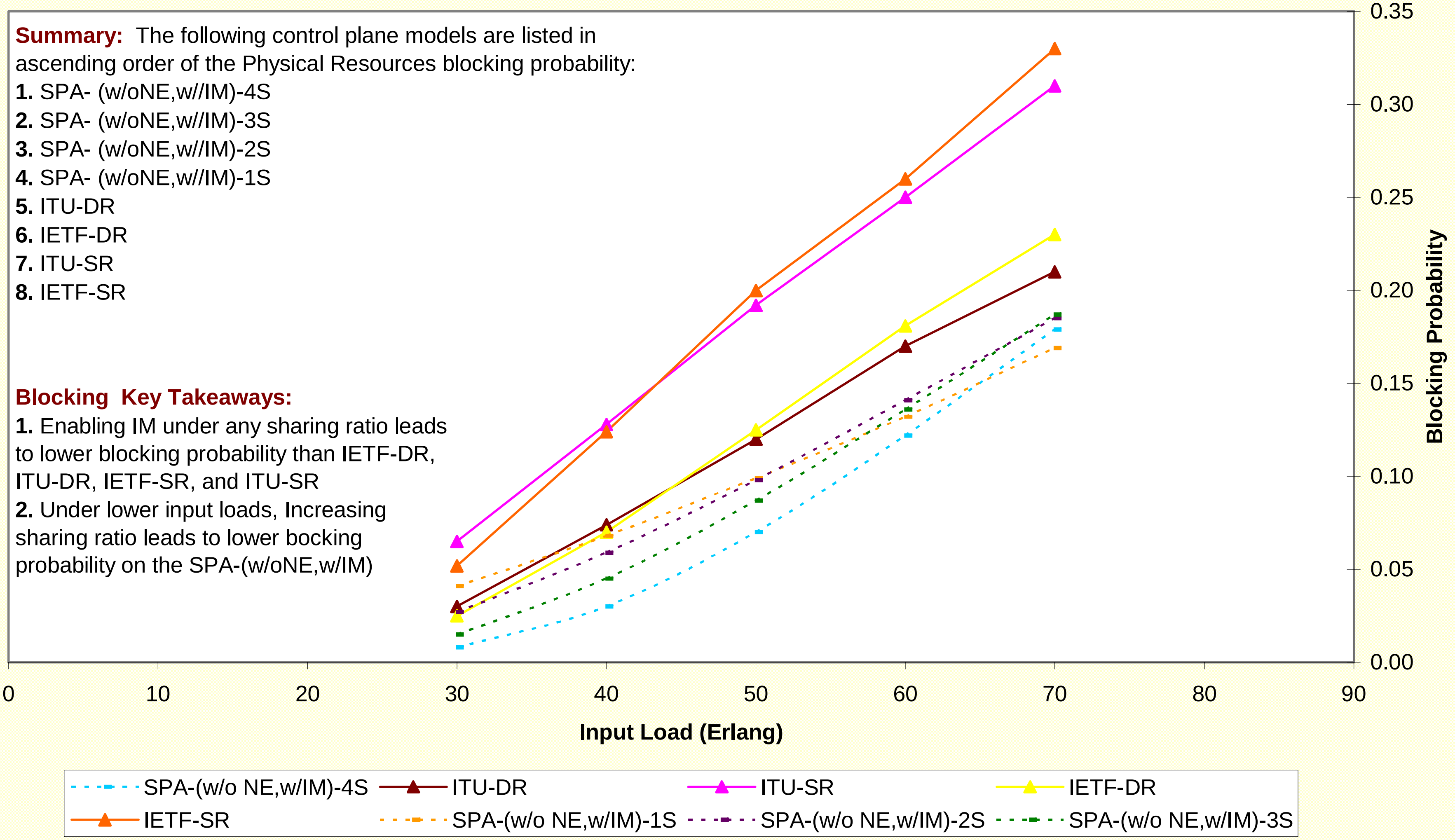
Blocking Key Takeaways:

1. Enabling NE only under any sharing ratio leads to higher blocking probability than both IETF-DR and ITU-DR, but lower blocking probability that IETF-SR and ITU-SR

2. Increasing sharing ratio has no direct effect on blocking probability on the SPA-(w/NE,w/oIM)

Appendix-D: 7 Node (3 routes) Topology Detailed Results “Blocking probability”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/oNE,w/IM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

1. SPA- (w/oNE,w//IM)-4S
2. SPA- (w/oNE,w//IM)-3S
3. SPA- (w/oNE,w//IM)-2S
4. SPA- (w/oNE,w//IM)-1S
5. ITU-DR
6. IETF-DR
7. ITU-SR
8. IETF-SR

Blocking Key Takeaways:

1. Enabling IM under any sharing ratio leads to lower blocking probability than IETF-DR, ITU-DR, IETF-SR, and ITU-SR
2. Under lower input loads, Increasing sharing ratio leads to lower bocking probability on the SPA-(w/oNE,w/IM)

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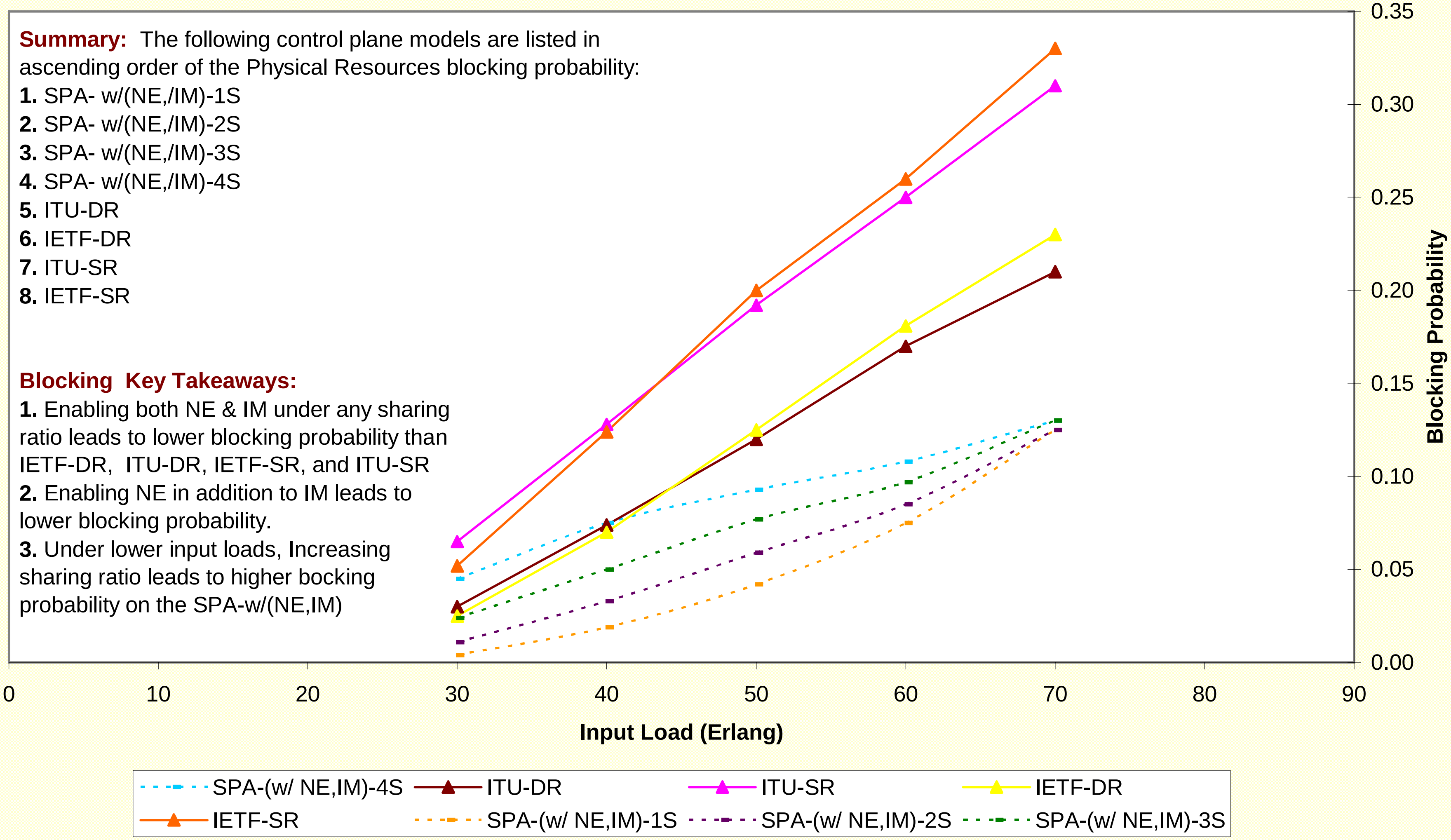
Appendix-D: 7 Node (3 routes) Topology Detailed Results "Blocking probability"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Blocking Probability (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/(NE,IM)



Summary: The following control plane models are listed in ascending order of the Physical Resources blocking probability:

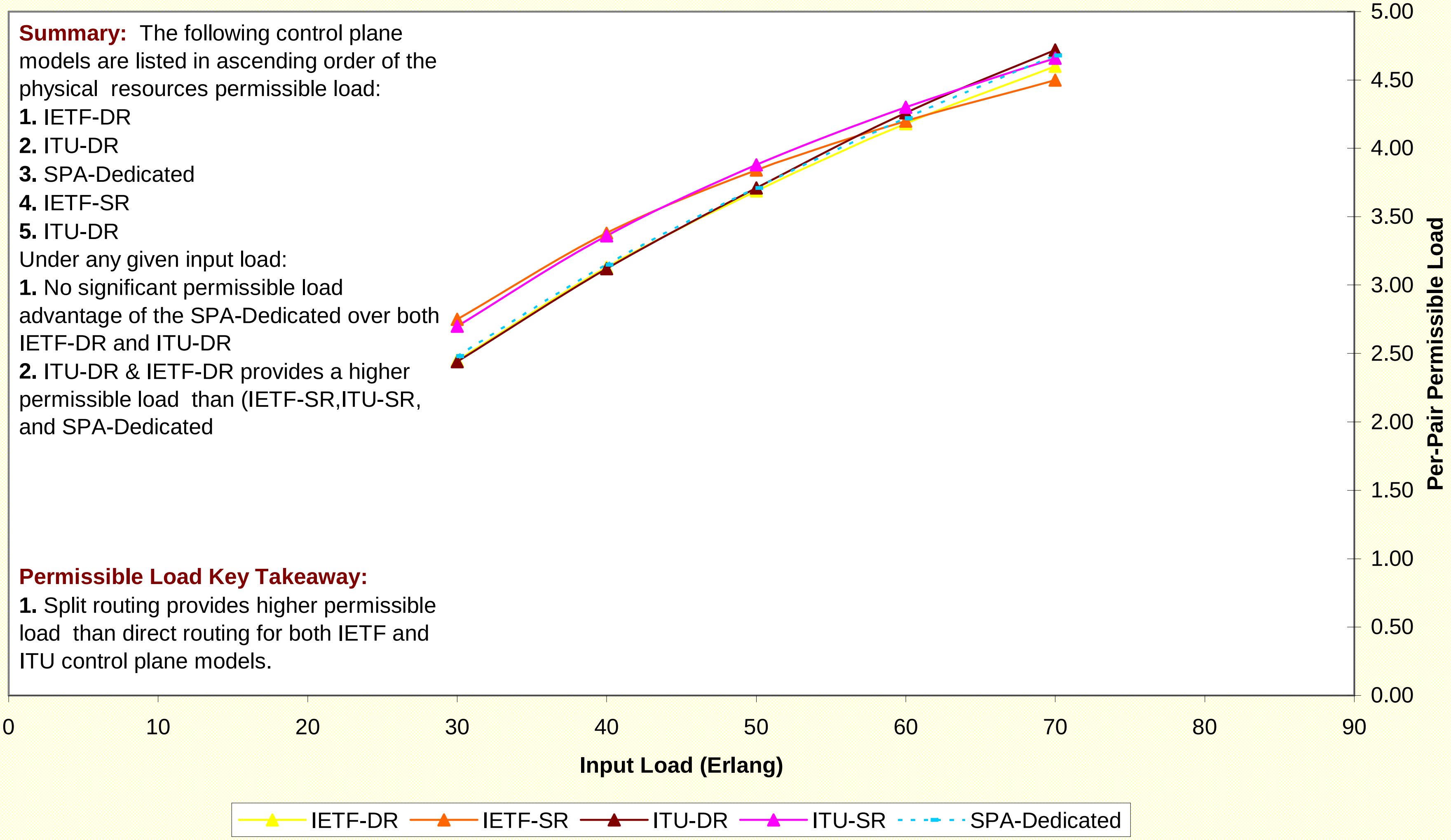
1. SPA- w/(NE,/IM)-1S
2. SPA- w/(NE,/IM)-2S
3. SPA- w/(NE,/IM)-3S
4. SPA- w/(NE,/IM)-4S
5. ITU-DR
6. IETF-DR
7. ITU-SR
8. IETF-SR

Blocking Key Takeaways:

1. Enabling both NE & IM under any sharing ratio leads to lower blocking probability than IETF-DR, ITU-DR, IETF-SR, and ITU-SR
2. Enabling NE in addition to IM leads to lower blocking probability.
3. Under lower input loads, Increasing sharing ratio leads to higher bocking probability on the SPA-w/(NE,IM)

Appendix-D: 7 Node (3 routes) Topology Detailed Results "Permissible Load"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physcial Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-Dedicated



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

1. IETF-DR
2. ITU-DR
3. SPA-Dedicated
4. IETF-SR
5. ITU-DR

Under any given input load:

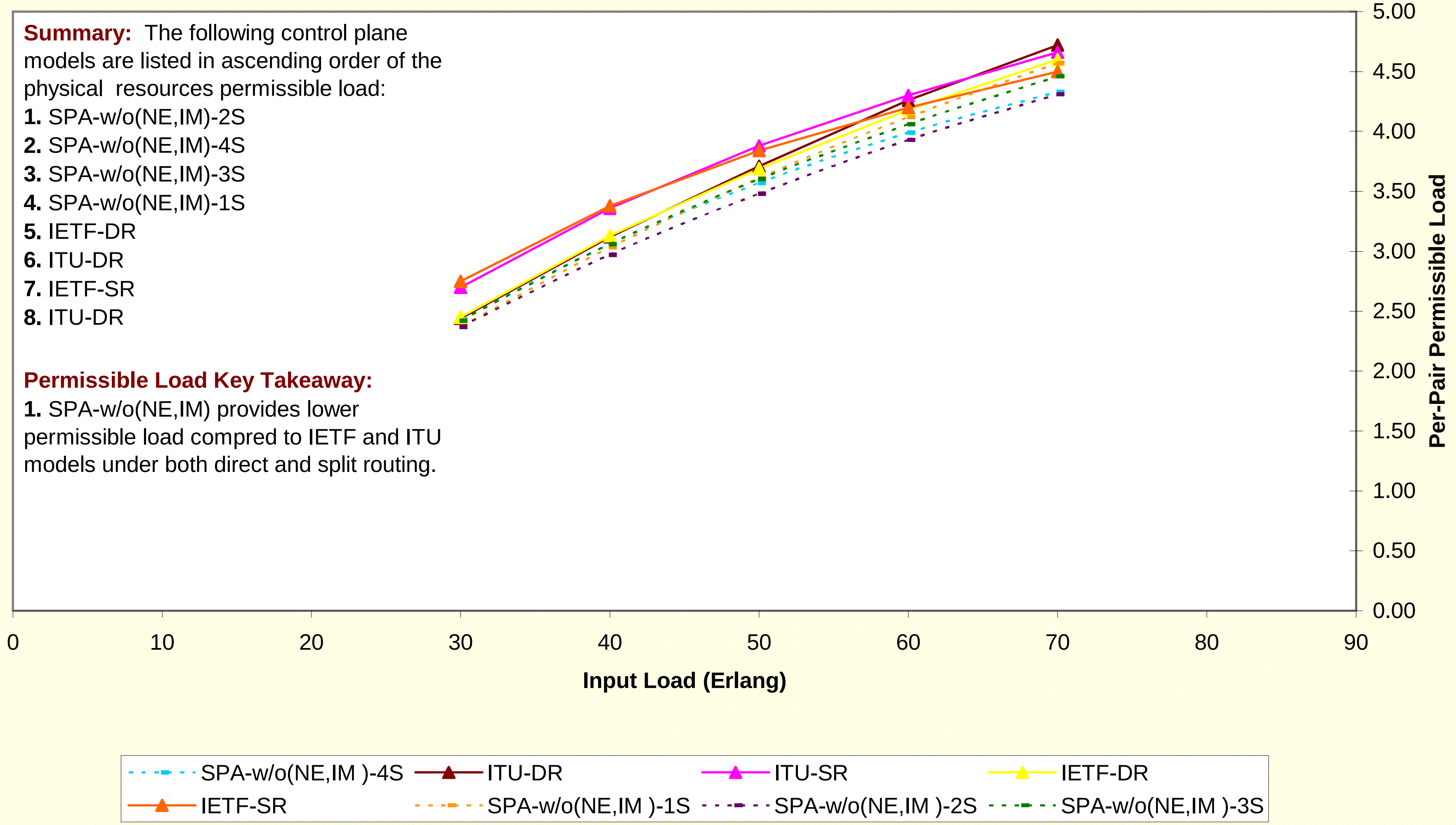
1. No significant permissible load advantage of the SPA-Dedicated over both IETF-DR and ITU-DR
2. ITU-DR & IETF-DR provides a higher permissible load than (IETF-SR,ITU-SR, and SPA-Dedicated

Permissible Load Key Takeaway:

1. Split routing provides higher permissible load than direct routing for both IETF and ITU control plane models.

Appendix-D: 7 Node (3 routes) Topology Detailed Results "Permissible Load"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/o(NE,IM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

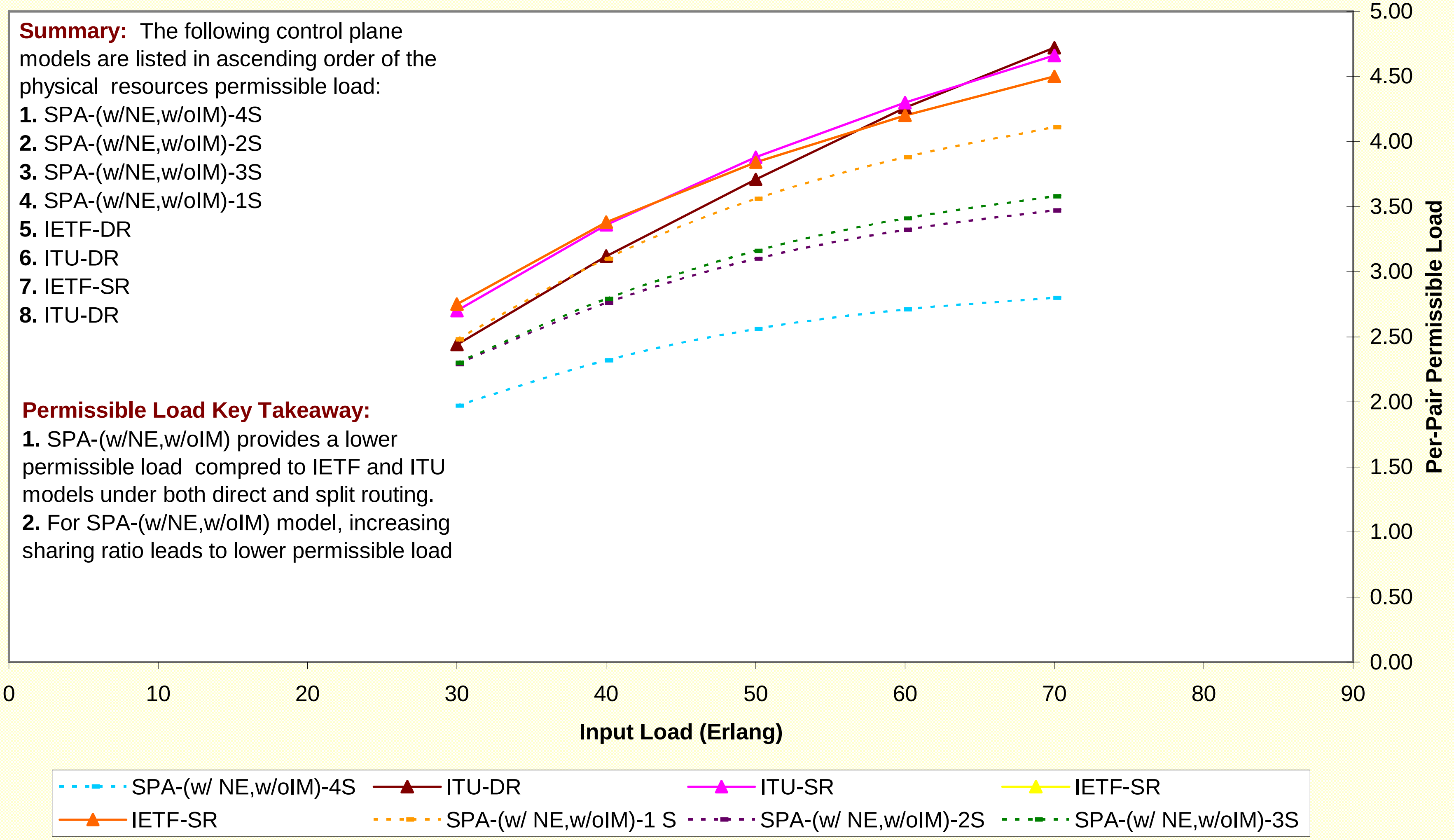
1. SPA-w/o(NE,IM)-2S
2. SPA-w/o(NE,IM)-4S
3. SPA-w/o(NE,IM)-3S
4. SPA-w/o(NE,IM)-1S
5. IETF-DR
6. ITU-DR
7. IETF-SR
8. ITU-DR

Permissible Load Key Takeaway:

1. SPA-w/o(NE,IM) provides lower permissible load compred to IETF and ITU models under both direct and split routing.

Appendix-D: 7 Node (3 routes) Topology Detailed Results “Permissible Load”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/NE,w/oIM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

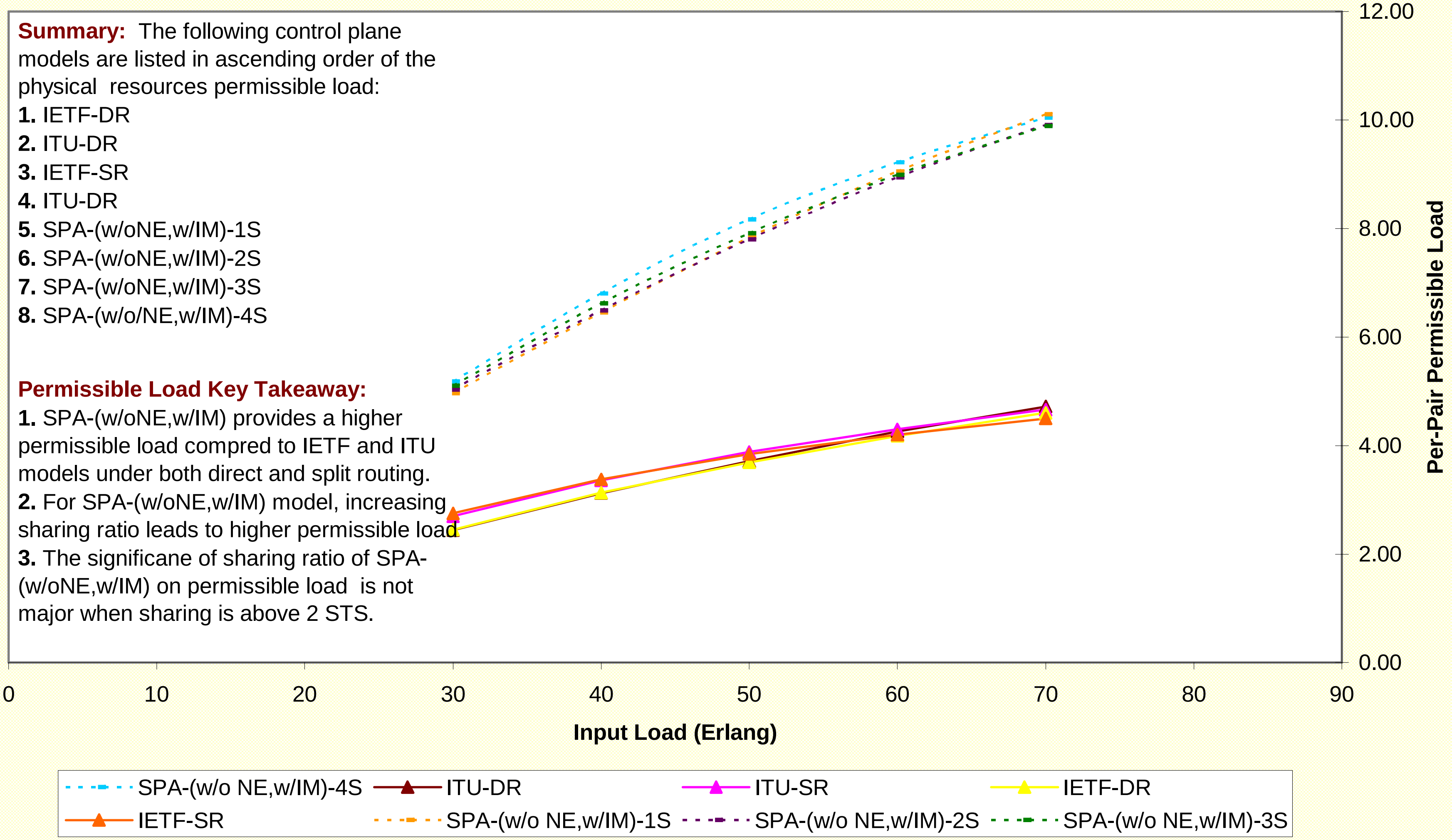
1. SPA-(w/NE,w/oIM)-4S
2. SPA-(w/NE,w/oIM)-2S
3. SPA-(w/NE,w/oIM)-3S
4. SPA-(w/NE,w/oIM)-1S
5. IETF-DR
6. ITU-DR
7. IETF-SR
8. ITU-DR

Permissible Load Key Takeaway:

1. SPA-(w/NE,w/oIM) provides a lower permissible load compred to IETF and ITU models under both direct and split routing.
2. For SPA-(w/NE,w/oIM) model, increasing sharing ratio leads to lower permissible load

Appendix-D: 7 Node (3 routes) Topology Detailed Results "Permissible Load"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-(w/oNE,w/IM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

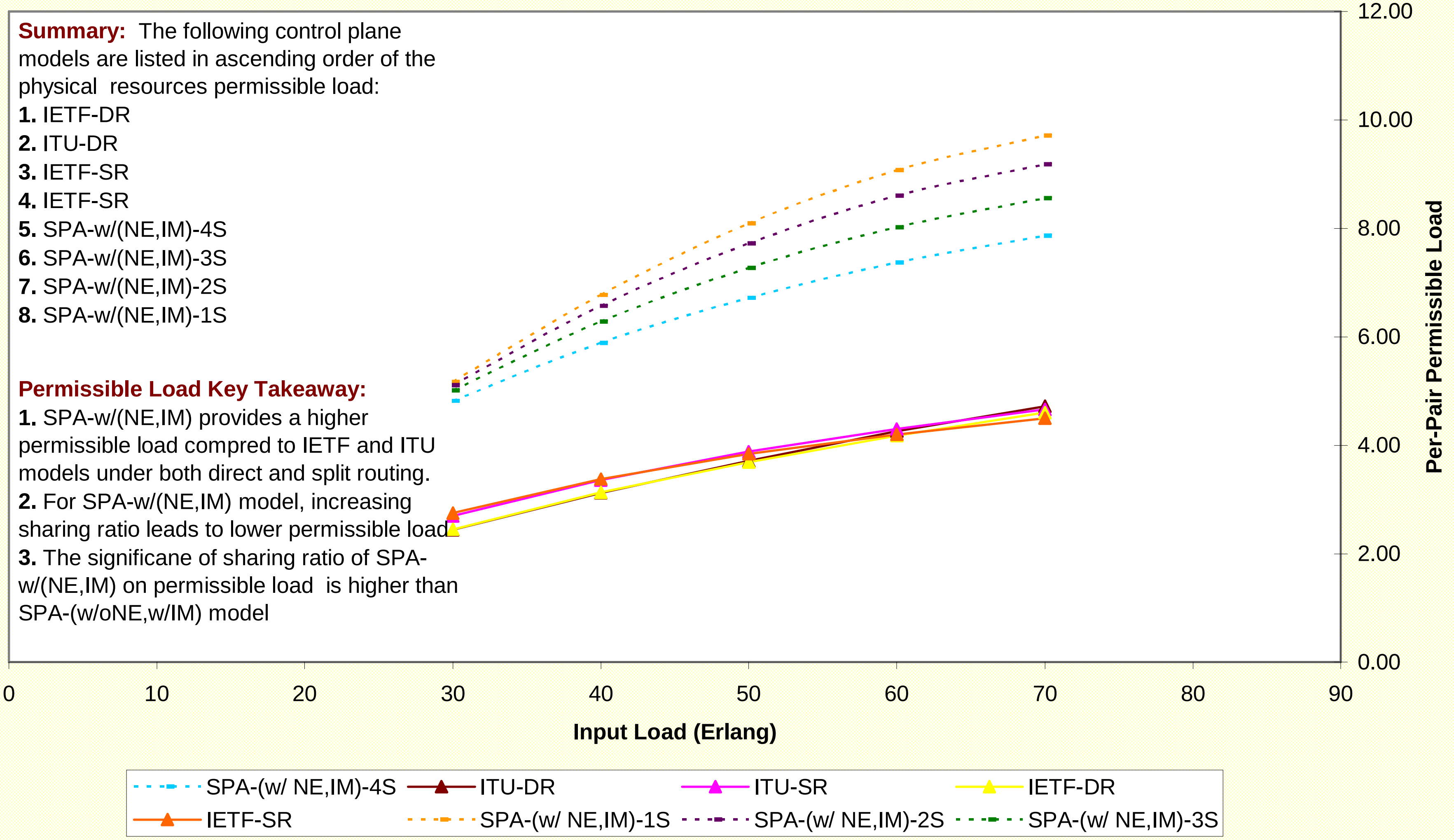
1. IETF-DR
2. ITU-DR
3. IETF-SR
4. ITU-DR
5. SPA-(w/oNE,w/IM)-1S
6. SPA-(w/oNE,w/IM)-2S
7. SPA-(w/oNE,w/IM)-3S
8. SPA-(w/o/NE,w/IM)-4S

Permissible Load Key Takeaway:

1. SPA-(w/oNE,w/IM) provides a higher permissible load compred to IETF and ITU models under both direct and split routing.
2. For SPA-(w/oNE,w/IM) model, increasing sharing ratio leads to higher permissible load
3. The significane of sharing ratio of SPA-(w/oNE,w/IM) on permissible load is not major when sharing is above 2 STS.

Appendix-D: 7 Node (3 routes) Topology Detailed Results "Permissible Load"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Permissible Load (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF(DR,SR), ITU(DR,SR), SPA-w/(NE,IM)



Summary: The following control plane models are listed in ascending order of the physical resources permissible load:

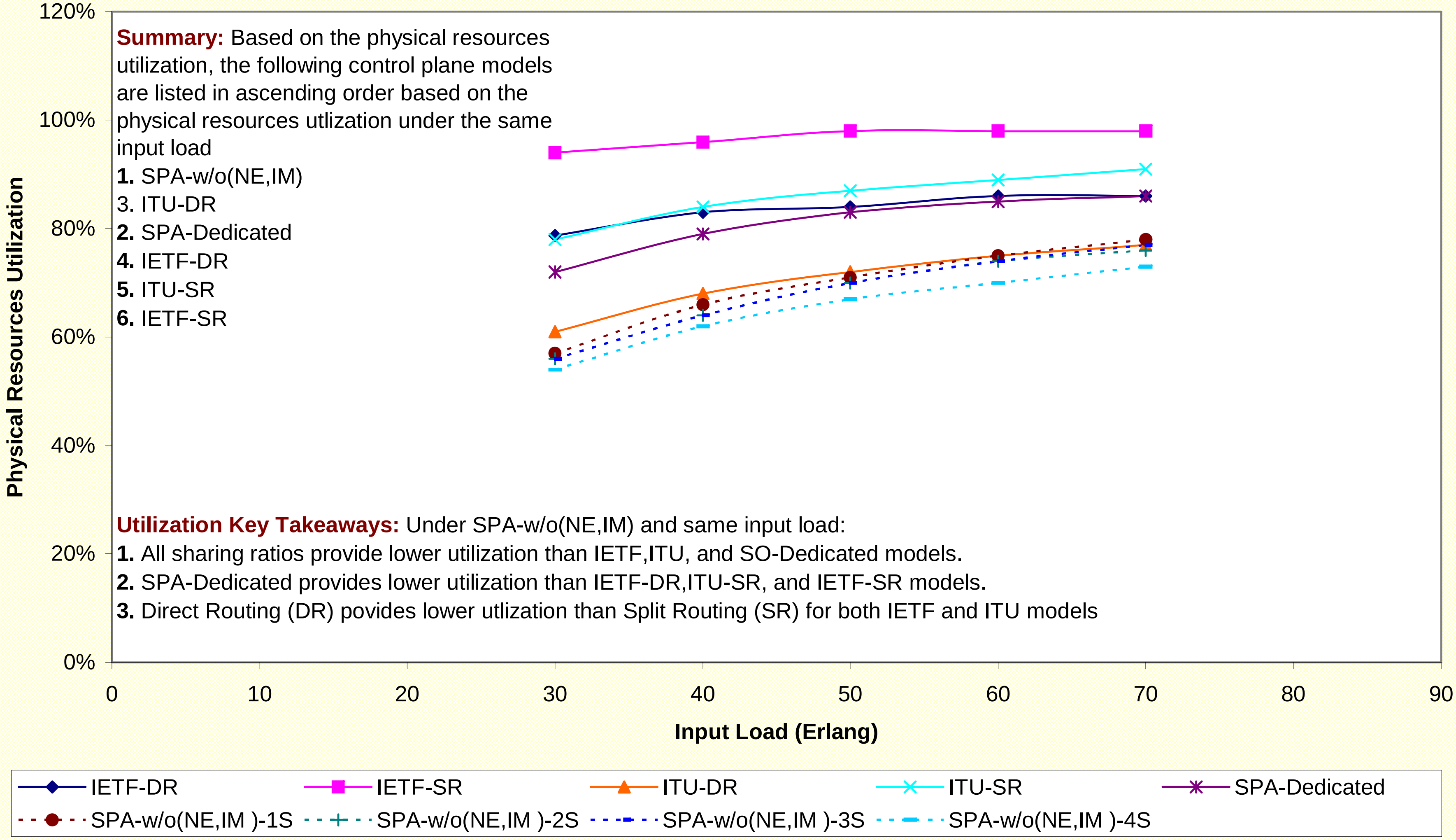
1. IETF-DR
2. ITU-DR
3. IETF-SR
4. IETF-SR
5. SPA-w/(NE,IM)-4S
6. SPA-w/(NE,IM)-3S
7. SPA-w/(NE,IM)-2S
8. SPA-w/(NE,IM)-1S

Permissible Load Key Takeaway:

1. SPA-w/(NE,IM) provides a higher permissible load compred to IETF and ITU models under both direct and split routing.
2. For SPA-w/(NE,IM) model, increasing sharing ratio leads to lower permissible load
3. The significane of sharing ratio of SPA-w/(NE,IM) on permissible load is higher than SPA-(w/oNE,w/IM) model

Appendix-D: 7 Node (3 routes) Topology Detailed Results "Utilization"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/o(NE,IM)



Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

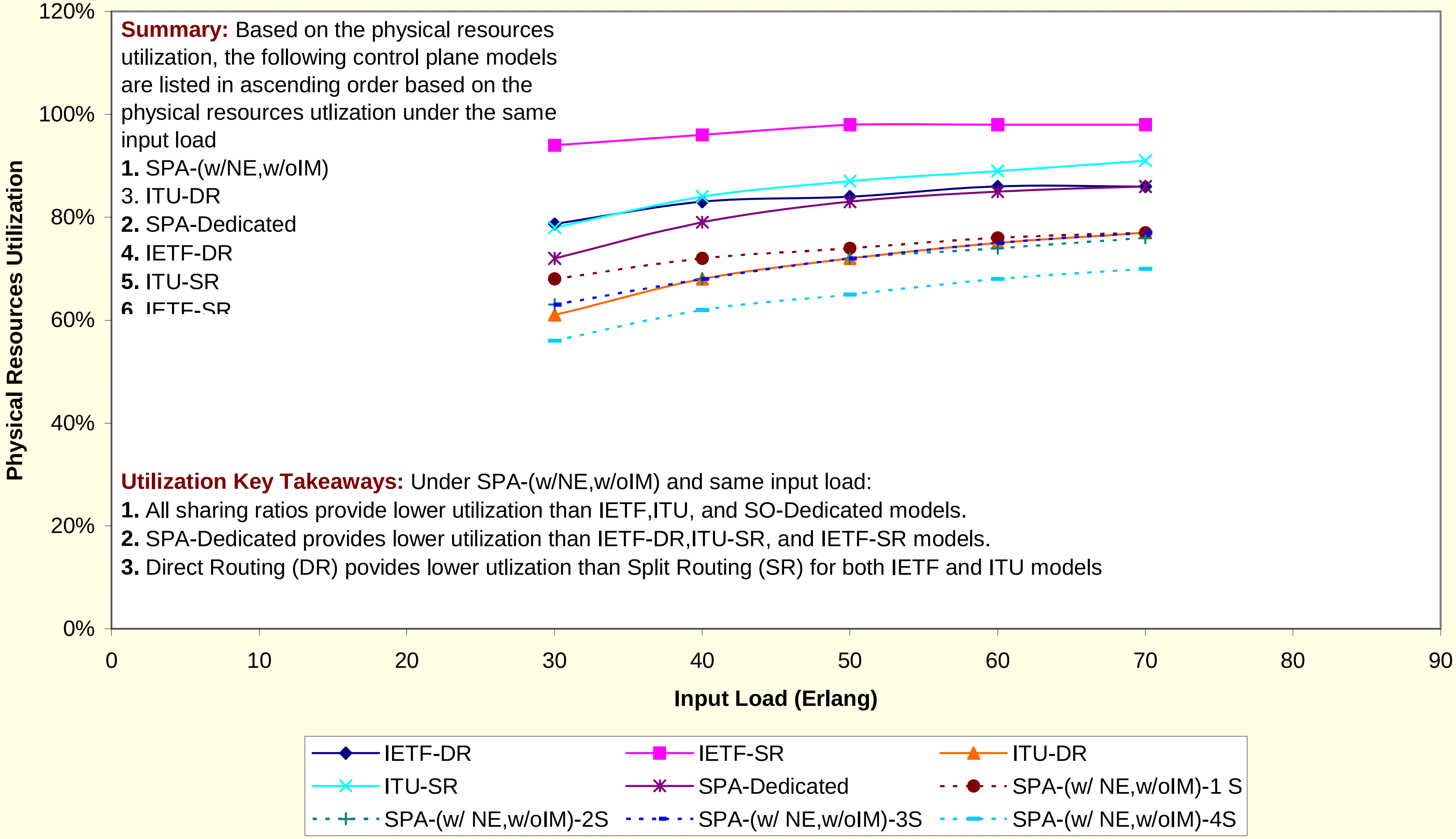
1. SPA-w/o(NE,IM)
3. ITU-DR
2. SPA-Dedicated
4. IETF-DR
5. ITU-SR
6. IETF-SR

Utilization Key Takeaways: Under SPA-w/o(NE,IM) and same input load:

1. All sharing ratios provide lower utilization than IETF,ITU, and SO-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-D: 7 Node (3 routes) Topology Detailed Results “Utilization”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/NE,w/oIM



Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

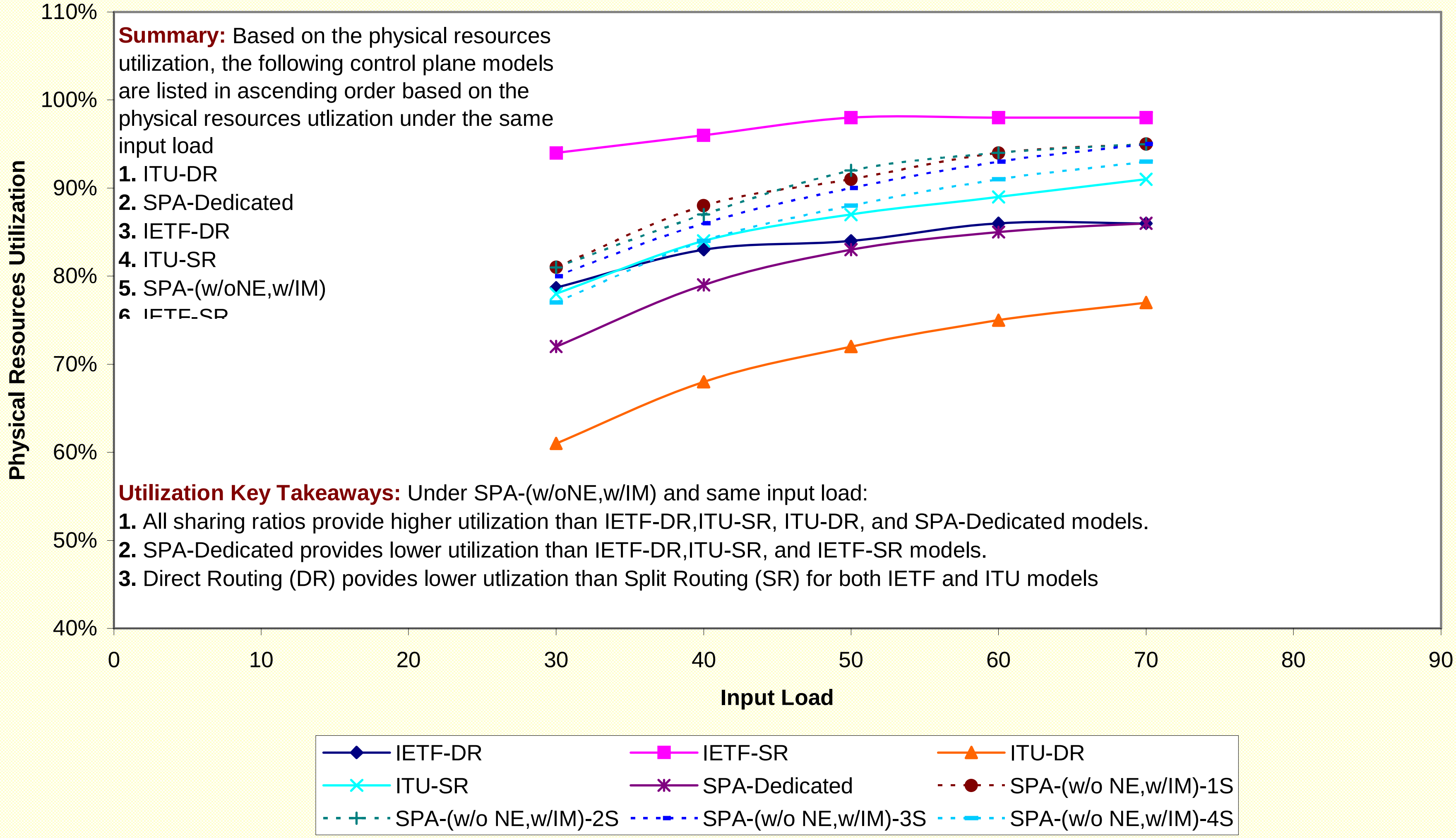
1. SPA-(w/NE,w/oIM)
3. ITU-DR
2. SPA-Dedicated
4. IETF-DR
5. ITU-SR
6. IETF-SR

Utilization Key Takeaways: Under SPA-(w/NE,w/oIM) and same input load:

1. All sharing ratios provide lower utilization than IETF,ITU, and SO-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-D: 7 Node (3 routes) Topology Detailed Results "Utilization"

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/oNE,w/IM



Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

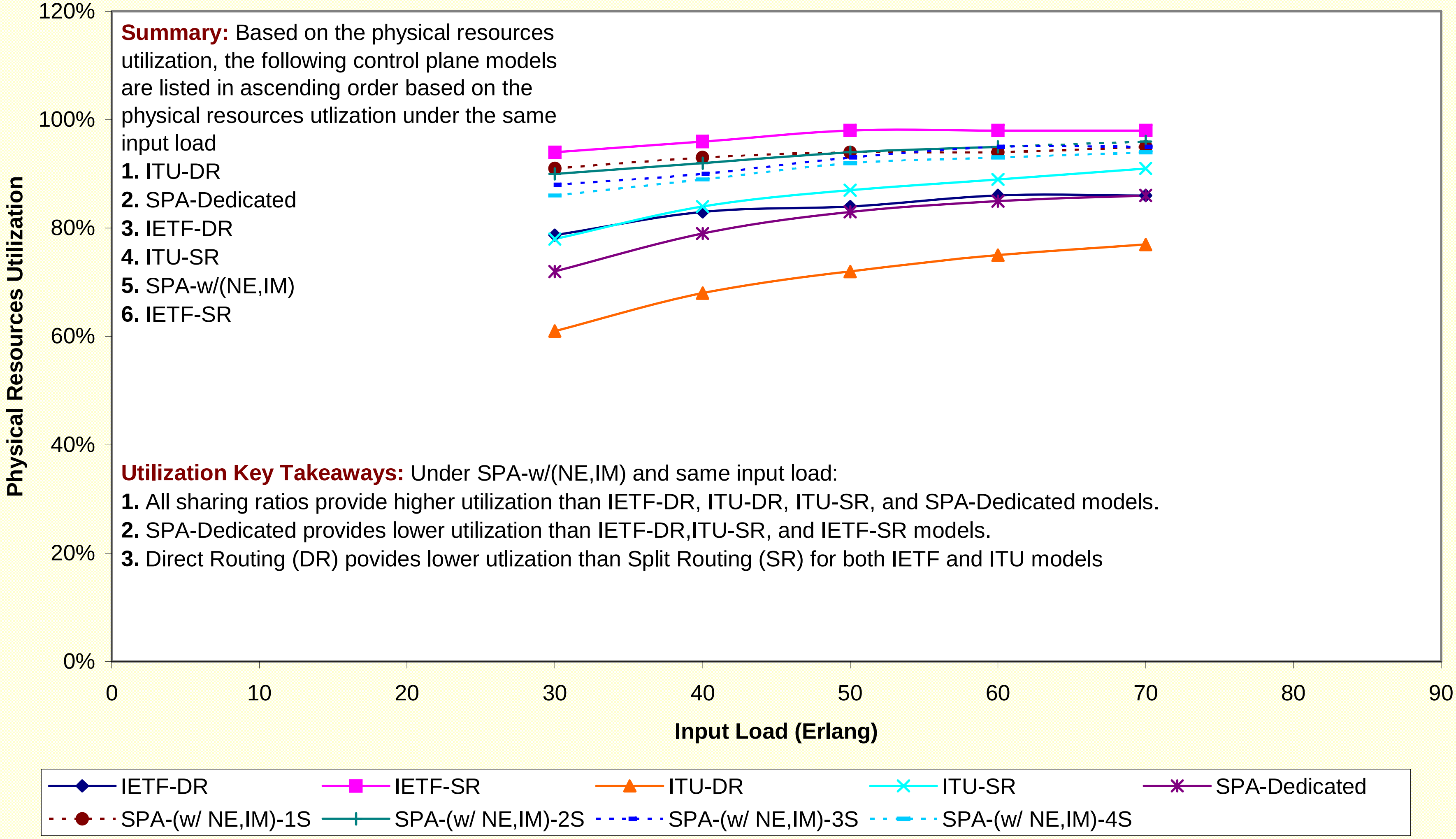
1. ITU-DR
2. SPA-Dedicated
3. IETF-DR
4. ITU-SR
5. SPA-(w/oNE,w/IM)
6. IETF-SR

Utilization Key Takeaways: Under SPA-(w/oNE,w/IM) and same input load:

1. All sharing ratios provide higher utilization than IETF-DR,ITU-SR, ITU-DR, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models

Appendix-D: 7 Node (3 routes) Topology Detailed Results “Utilization”

7-node Topology (Fully-meshed Service Configuration)
Average Network-Wide Utilization (Physical Resources)
3-Alternate Routing, Class-B Arrivals, IETF,ITU, SPA-Dedicated, SPA-w/(NE,IM)



Summary: Based on the physical resources utilization, the following control plane models are listed in ascending order based on the physical resources utlization under the same input load

1. ITU-DR
2. SPA-Dedicated
3. IETF-DR
4. ITU-SR
5. SPA-w/(NE,IM)
6. IETF-SR

Utilization Key Takeaways: Under SPA-w/(NE,IM) and same input load:

1. All sharing ratios provide higher utilization than IETF-DR, ITU-DR, ITU-SR, and SPA-Dedicated models.
2. SPA-Dedicated provides lower utilization than IETF-DR,ITU-SR, and IETF-SR models.
3. Direct Routing (DR) povides lower utlization than Split Routing (SR) for both IETF and ITU models