CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

# A Method for Estimating Air/Ground Data Capacity Requirements

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# Outline

- Background
- Data capacity estimation problem
- Average data rate analysis
- A method using priority-queueing analysis
- Results
- Observations



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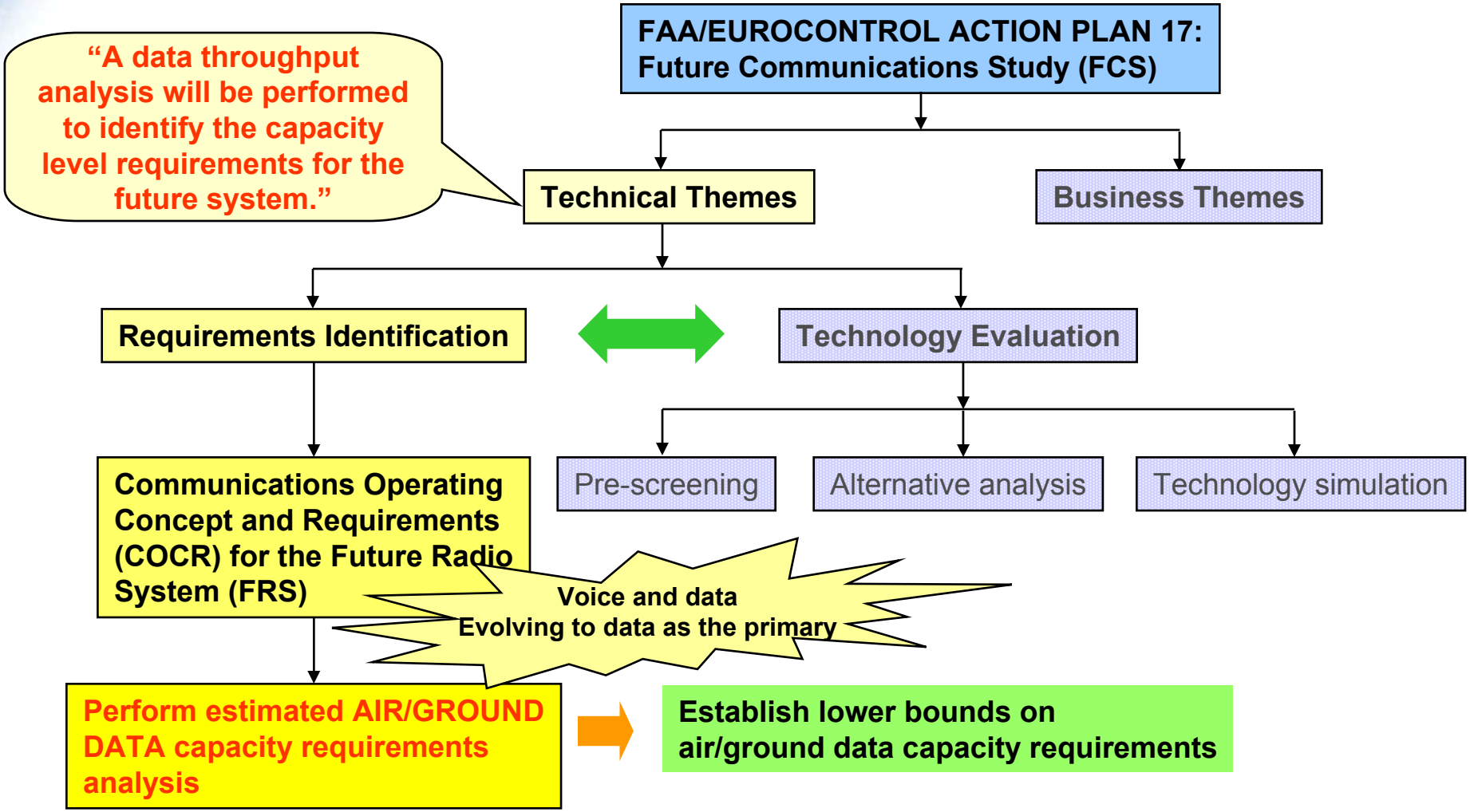
# FAA/EUROCONTROL Action Plan 17 and Air/Ground Data Capacity Requirements Analysis



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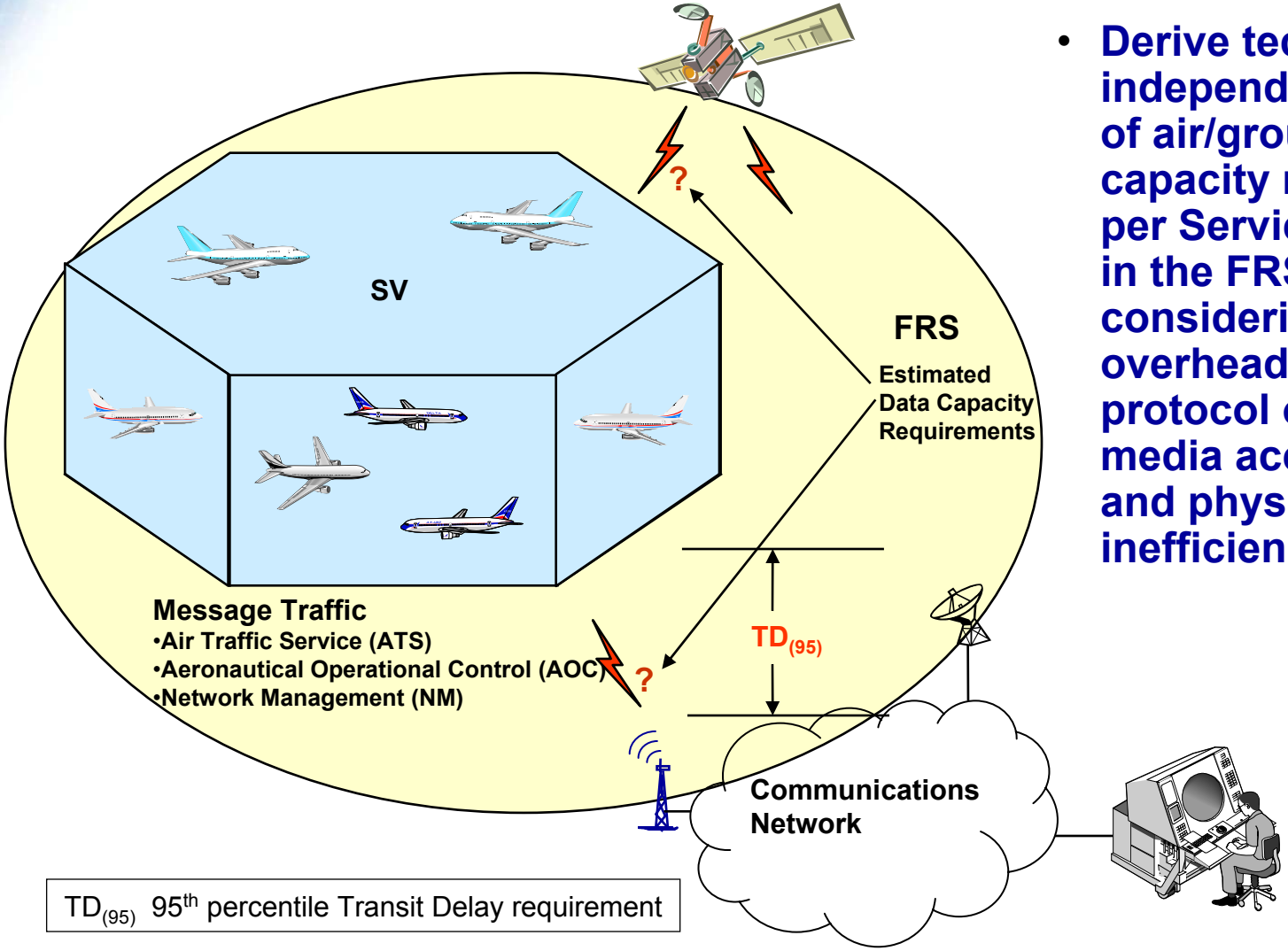
# Future Radio System (FRS) Air/Ground Data Capacity Requirements Estimation Problem




- **Derive technology-independent estimates of air/ground data capacity requirements per Service Volume (SV) in the FRS without considering subnetwork overheads, e.g., protocol overhead, media access schemes, and physical layer inefficiencies**

$TD_{(95)}$ 95th percentile Transit Delay requirement



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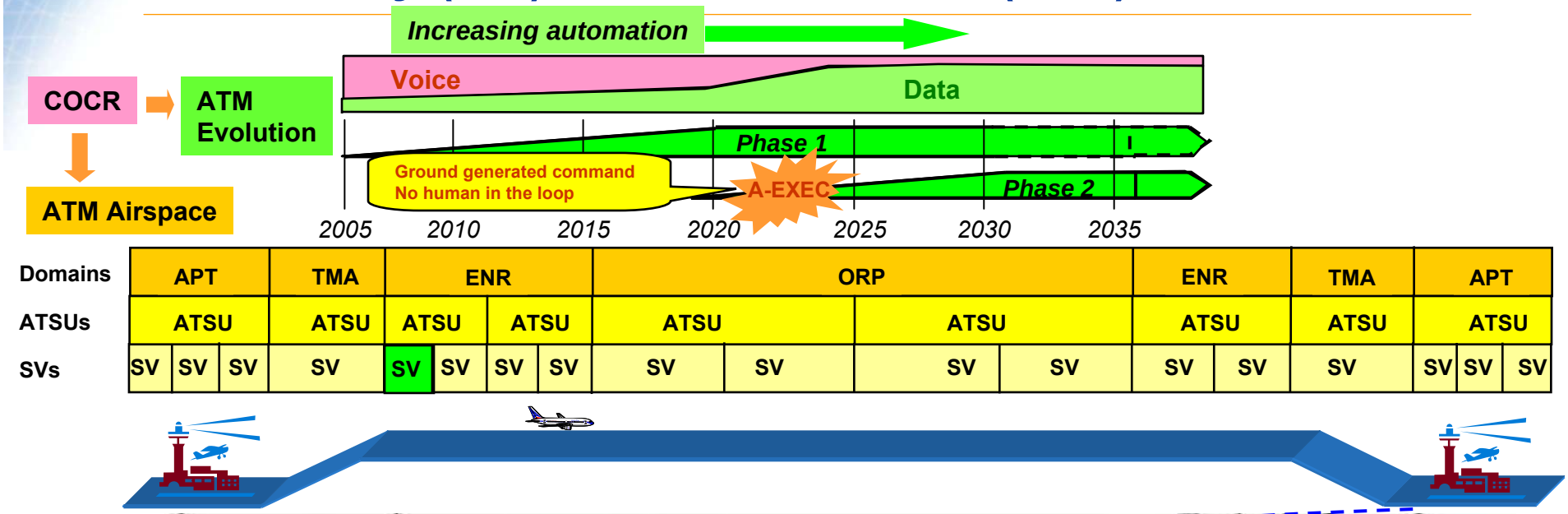
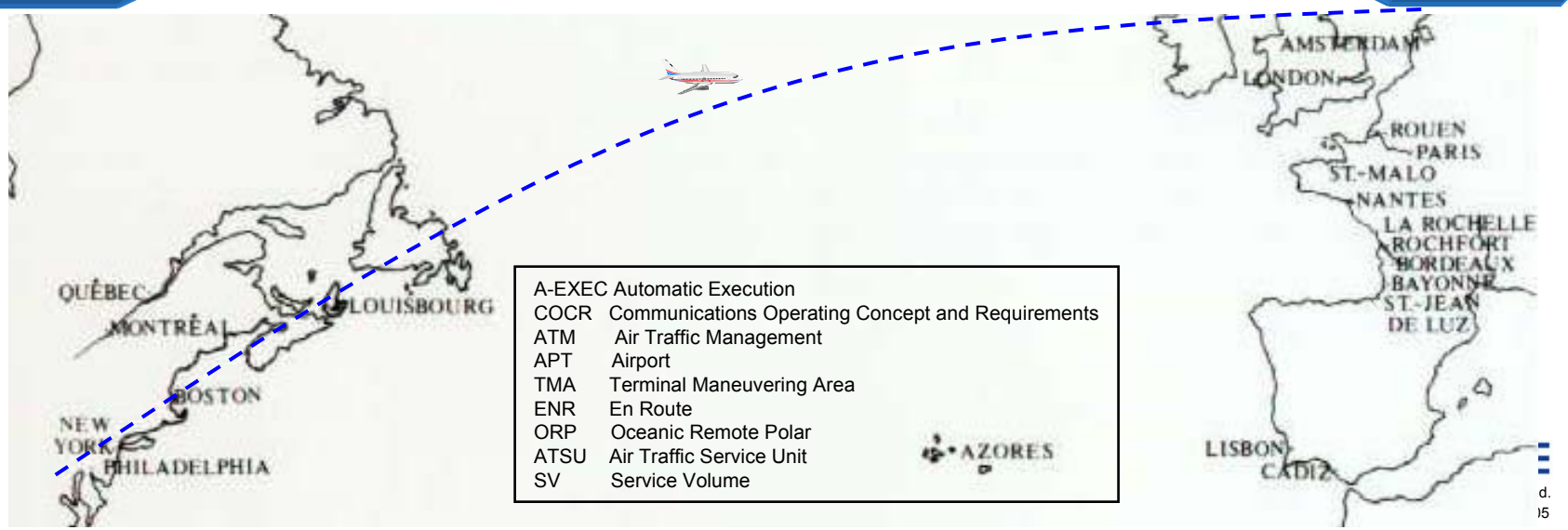
# ATM Evolution and Airspace—Focus on Phase 1 and Phase 2 En Route (ENR) Domain High-Density (HD) Service Volumes (SVs)

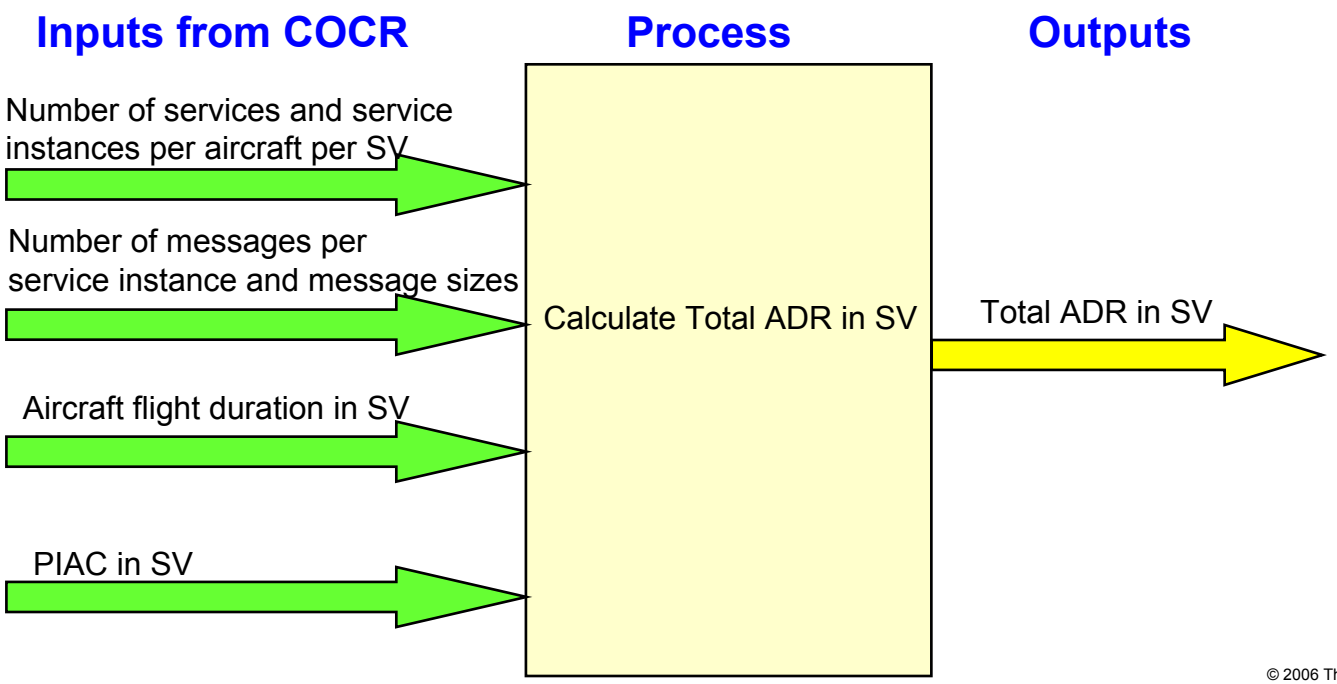



A-EXEC Automatic Execution
COCR Communications Operating Concept and Requirements
ATM Air Traffic Management
APT Airport
TMA Terminal Maneuvering Area
ENR En Route
ORP Oceanic Remote Polar
ATSU Air Traffic Service Unit
SV Service Volume

# Average Data Rate in SV Analyses—Develop Baseline Results for Comparison

- **Average Data Rate (ADR) = Amount of data transferred per unit time**
- **ADR for each aircraft in SV, $S_i$ = Total bits transmitted in SV/Flight duration in SV**
- **Total ADR in SV, $S_T$ = Peak Instantaneous Aircraft Count (PIAC) in SV*$S_i$ (each aircraft has identical traffic)**



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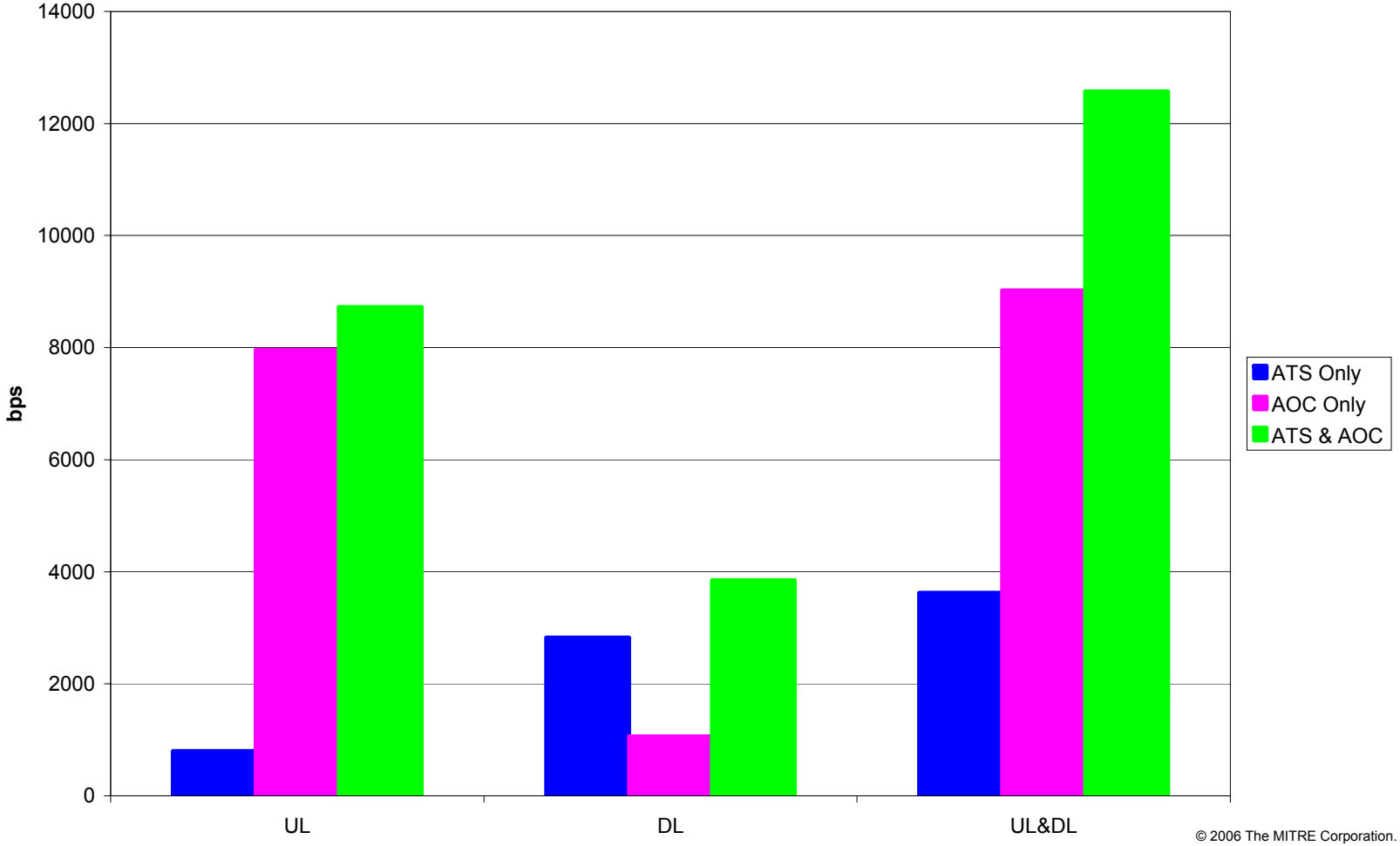
# Phase 1 En Route High-Density SV ADRs

- **AOC UpLink (UL) and UL & DownLink (DL) ADR much higher than ATS ADR**
- **ATS DL is higher than UL**



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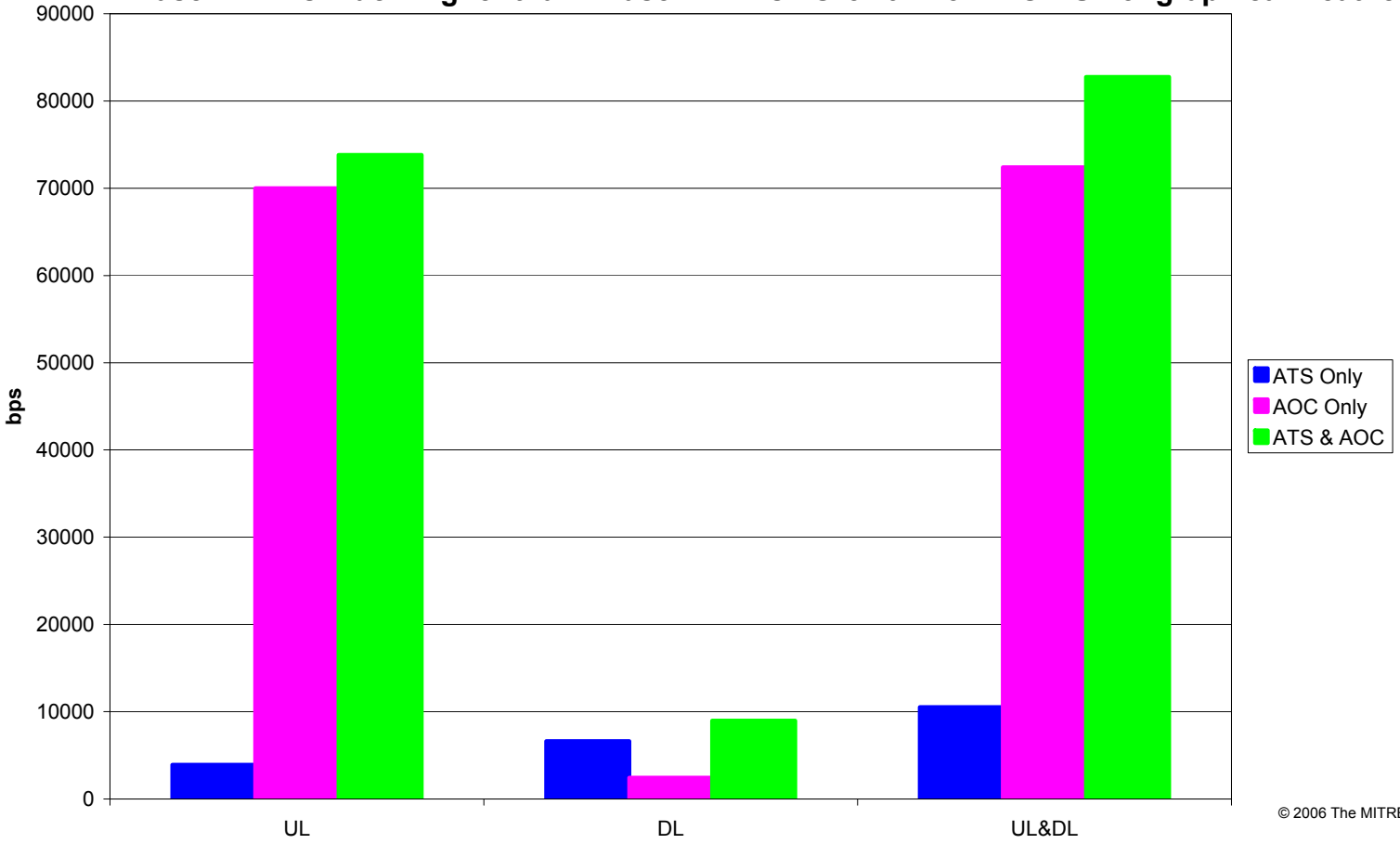
# Phase 2 En Route High-Density SV ADRs (ATS With and Without A-EXEC)

- AOC UL and UL & DL ADR much higher than ATS ADR
- ATS DL is higher than UL
- Very little difference between ATS with A-EXEC and ATS without A-EXEC results
- Phase 2 ADRs much higher than Phase 1 ADRs. Growth from AOC UL of graphical weather info.



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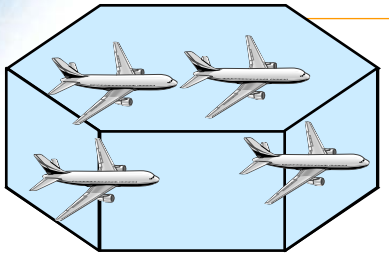
# Estimating Air/Ground Data Capacity Requirements



Aircraft
FRS Boundary

Downlink
ADR

FRS

Uplink
ADR

Ground
FRS Boundary

Total
Downlink Traffic

Msg
Size

Time

Uplink
Data
Capacity

Downlink
Data
Capacity

Total
Uplink Traffic

Msg
Size

Time

95% Transit
Delays for a
Given Traffic
and Data
Capacity

P1 P2 P3 P4
Priority

95% Transit
Delay
Requirements

P1 P2 P3 P4
Priority

95%
Transit
Delay

Existing

Required

Data Capacity



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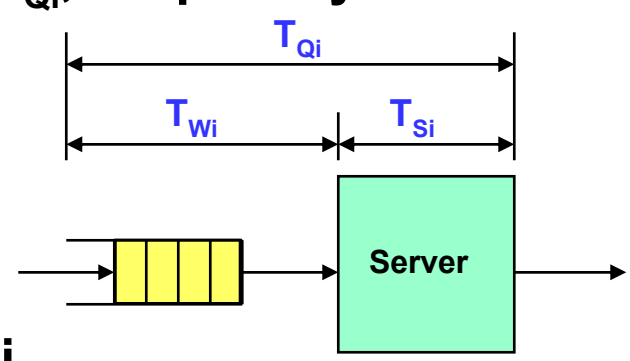
# A Method for Estimating Air/Ground Data Capacity Requirements: Priority-Queueing Analysis

- Analyze the FRS as a priority-queueing system
- N priorities, $P_1$, $P_2$, $P_3$, …, $P_N$
  - $P_1 > P_2 > P_3 > \ldots > P_N$, i.e., $P_1$ highest and $P_N$ lowest priority
  - Each with its own aggregate message length, $Msg_i$, and message arrival rate, $\lambda_i$
- 95th percentile transit delay requirements for each priority
  - $TD_{(95)1}$, $TD_{(95)2}$, $TD_{(95)3}$, …, $TD_{(95)N}$
- Average message queueing delay, $T_{Qi}$, for priority i
  - $T_{Qi} = T_{Wi} + T_{Si}$
    - Waiting Time, $T_{Wi}$
    - Service Time, $T_{Si}$
      - Time it takes to transmit a message




- Requirements: $T_{Q(95)i} \leq TD_{(95)i}$ for all i



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# Two Types of Priority-Queueing

- **Non-preemptive**
  - **No preemption of in-service message by higher priority messages**
- **Preemptive resume**
  - **Preemption of in-service message by higher priority messages**
  - **Preempted message resumes from the point where its service was suspended**



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# Priority-Queueing Analysis Process—A High-Level View

**COCR Inputs (Problem definition)**

- Service volume Network Management, ATS and AOC service instances per aircraft
- Message quantities and sizes per instance
- Flight duration in service volume
- PIAC per service volume
- 95th percentile transit delay requirements

**Process (for solving the problem)**

Priority-queueing analysis tool

**Output (Desired result)**

Estimated data capacity requirement without subnetwork overhead for service volume



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# Presentation of Results

- **Transit delays**
- **Estimated data capacity requirements**
- **Estimated data capacity requirements and ADRs**

| **Phase** | **Phase 1** | | **Phase 2** | | | |
|---|---|---|---|---|---|---|
| **A-EXEC** | NA | | ATS with A-EXEC | | ATS without A-EXEC | |
| **Type** | Non-preemptive | Preemptive | Non-preemptive | Preemptive | Non-preemptive | Preemptive |

| **Traffic** | **ATS** | | | **AOC** | | | **ATS & AOC** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Direction** | UL | DL | UL&DL | UL | DL | UL&DL | UL | DL | UL&DL |

UL UpLink
DL DownLink



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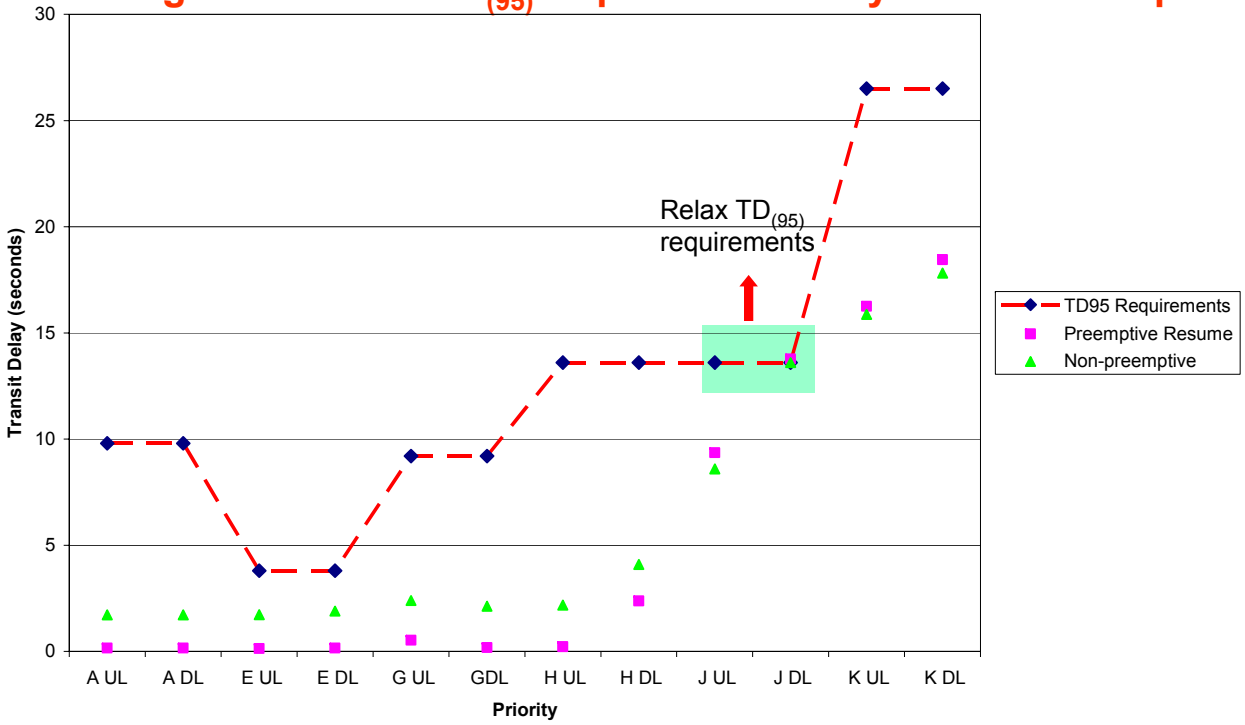
# Phase 1 Transit Delays (Same Data Capacity)

- **Preemptive priority-queueing good for high-priority messages but poor for low-priority messages**
- **Preemptive priority-queueing may require higher data capacity to meet lower priority message transit delay requirements**
  - **Transit delays for preemptive and non-preemptive: same data capacity 17,652 bps , J DL $TD_{(95)}$ = 13.6 s, TD non-preemptive = 13.6 s, TD preemptive = 13.76 s**
- **Relaxing some of the $TD_{(95)}$ requirements may lower data capacity requirements**



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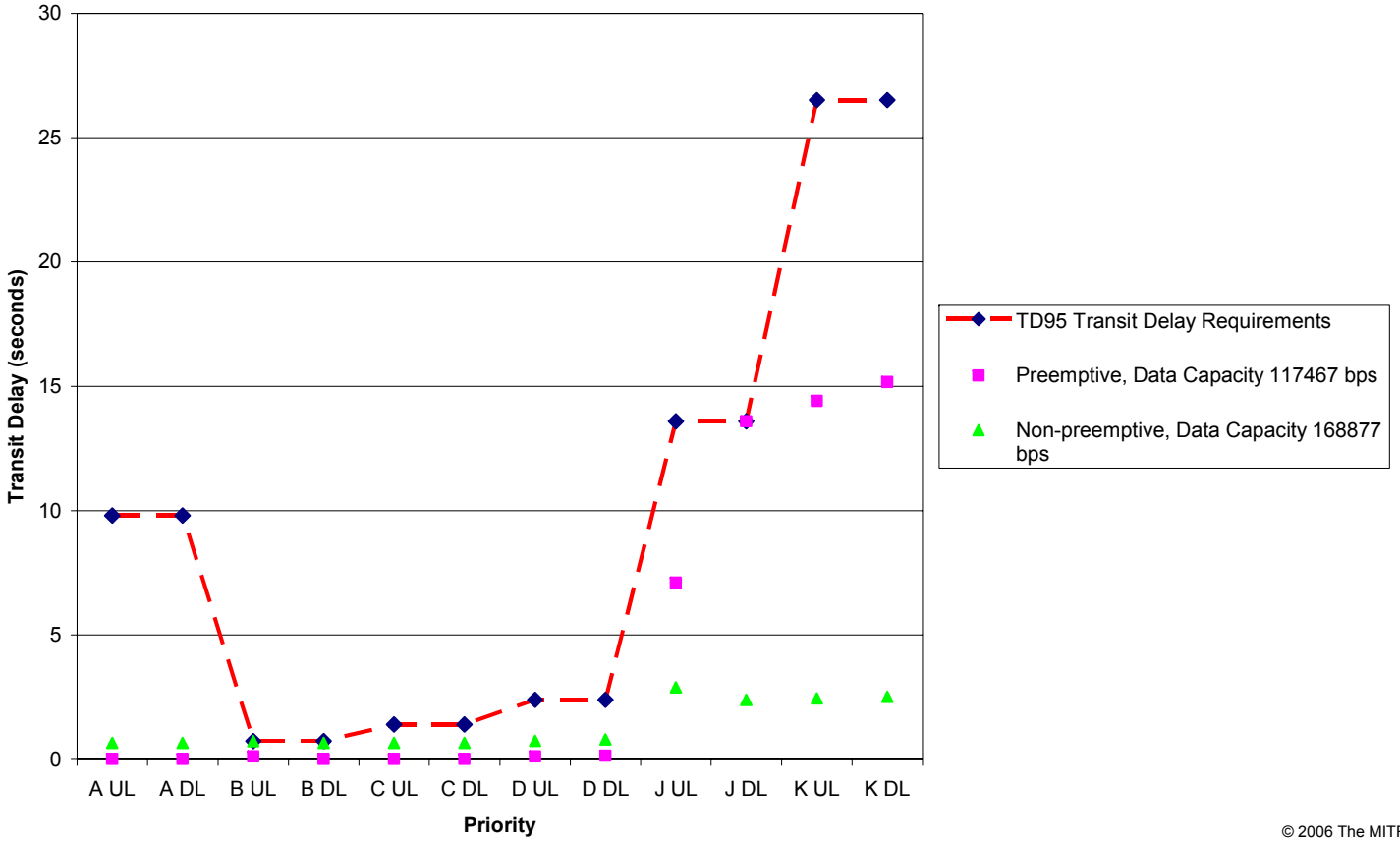
# Phase 2 Transit Delays (ATS With A-EXEC)

- **Preemptive resume priority-queueing may reduce the required data capacity**
  - **If there are sufficient TD margins for lower priority messages when the data capacity is reduced**



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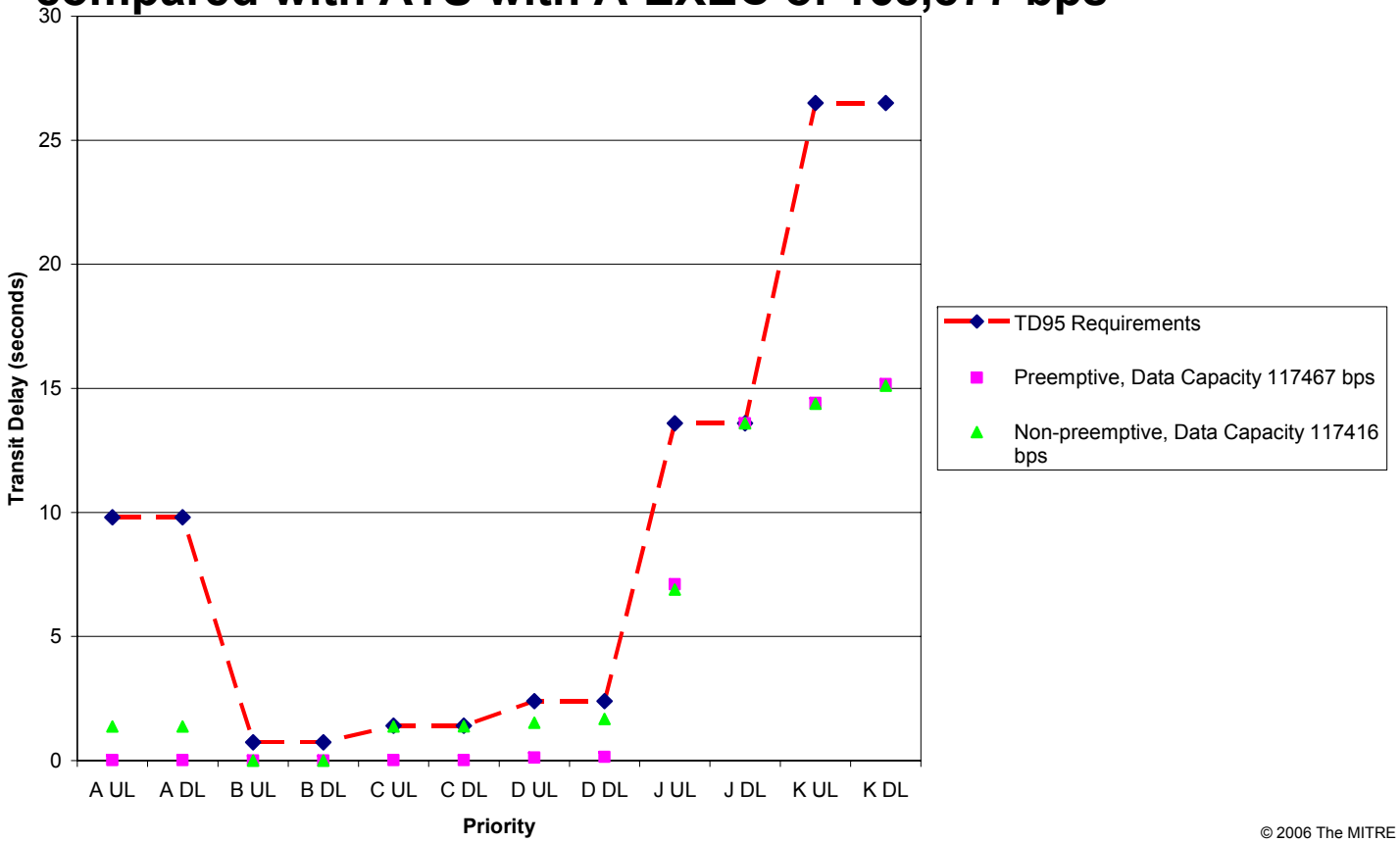
# Phase 2 Transit Delays (ATS Without A-EXEC )

- **Without A-EXEC, preemptive and non-preemptive data capacity requirements are similar**
- **Non-preemptive data capacity requirement substantially reduced compared with ATS with A-EXEC of 168,877 bps**



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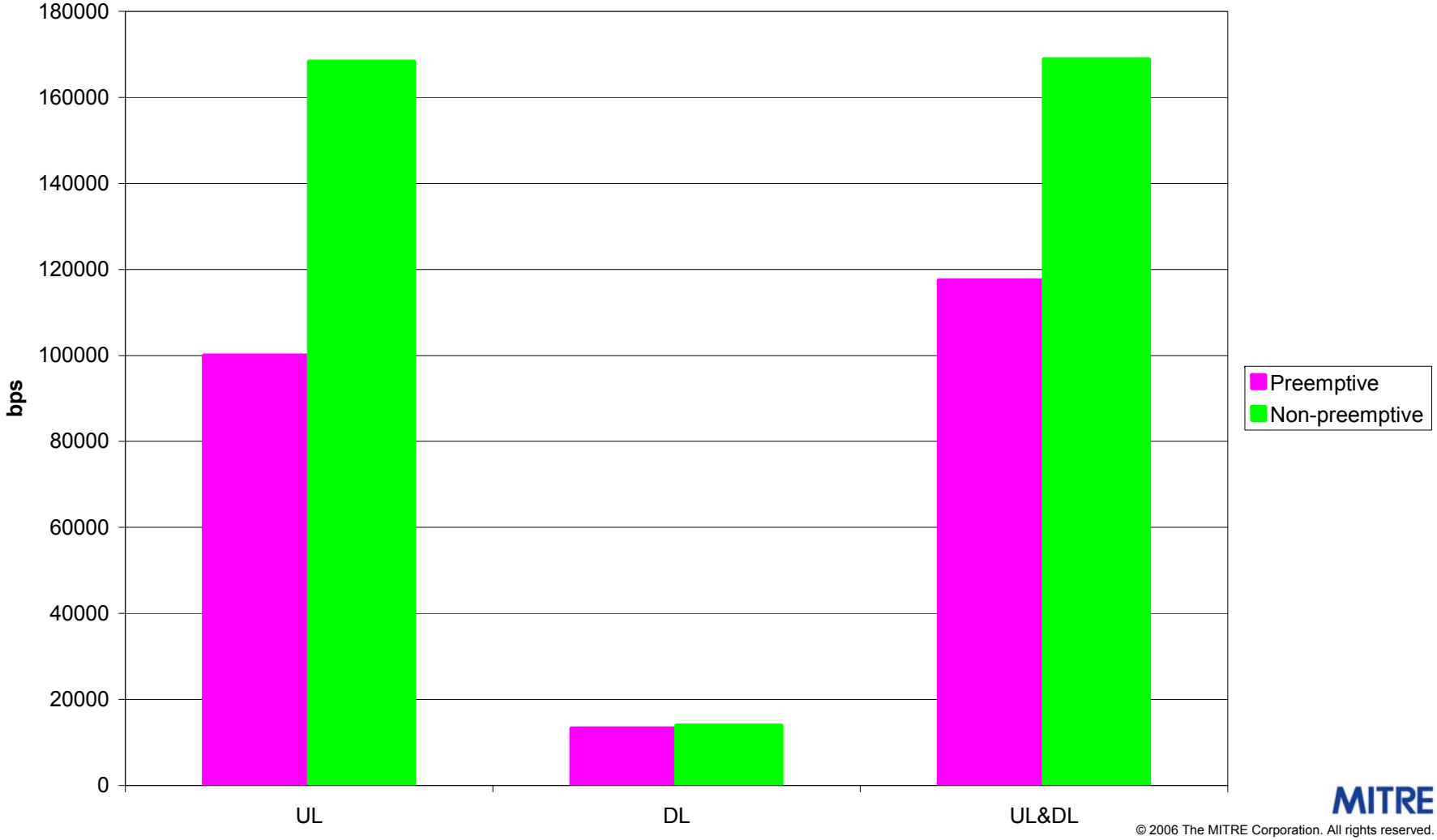
# Phase 2 Estimated Data Capacity Requirements (ATS With A-EXEC)

- **Preemptive requirements much lower in two cases**



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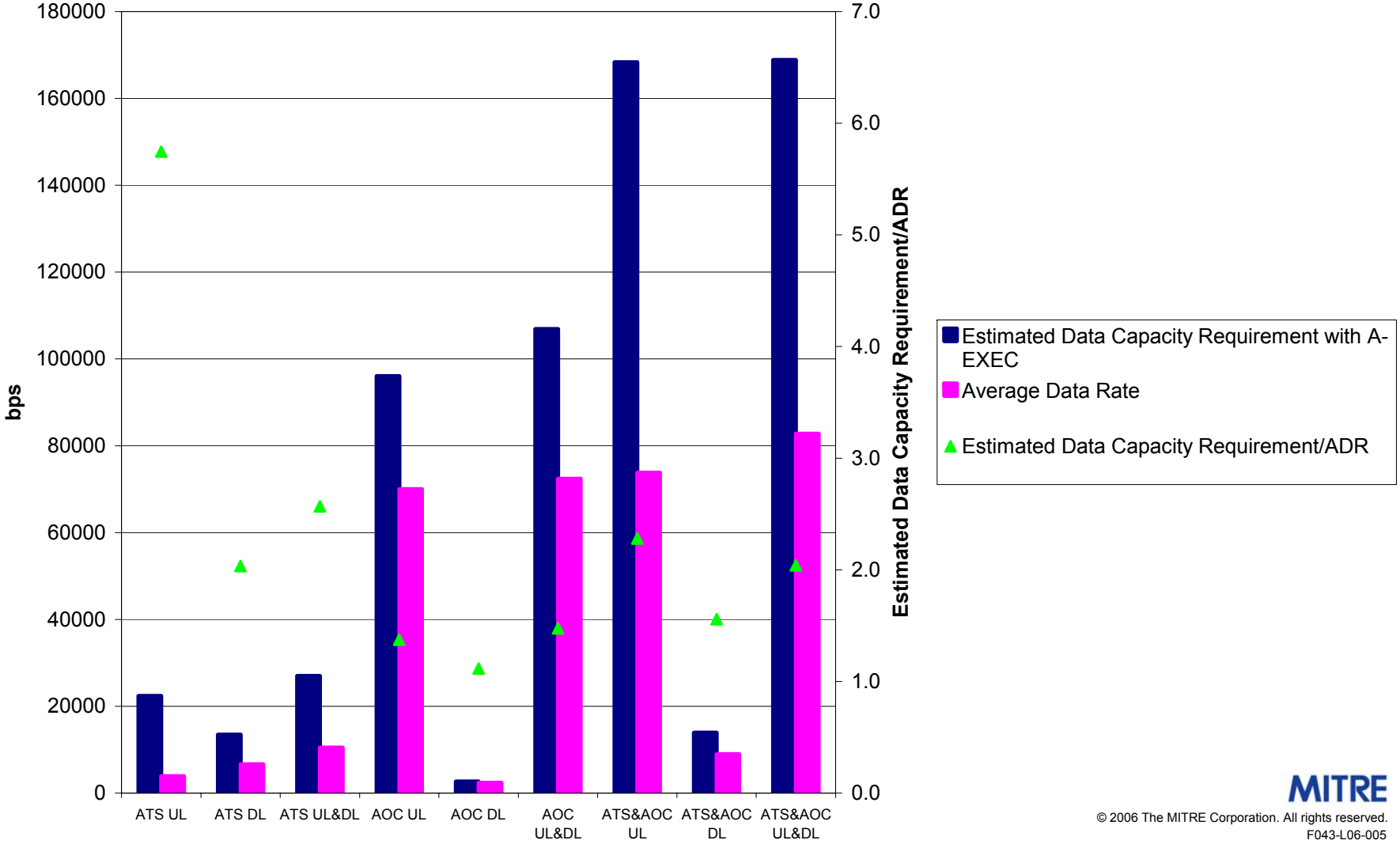
# Phase 2 Estimated Non-Preemptive Data Capacity Requirements and ADRs (ATS With A-EXEC)

- **Estimated data capacity requirement/ADR ratios — 1.1 to 5.7**



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# Observations

- With the same data capacity, preemptive good for high-priority but poor for low-priority messages compared with non-preemptive
- Potential application of priority-queueing analysis to identify transit delay requirements that can be relaxed to reduce data capacity requirements
- In most cases, the estimated data capacity requirements are similar using either types of priority-queueing
  - Preemptive requirements may be higher or lower than the non-preemptive requirements
- Estimated data capacity requirements are small multiples of ADRs when $TD_{(95)}$ requirements are large, e.g., AOC
- Estimated data capacity requirements are large multiples of ADRs when $TD_{(95)}$ requirements are small, e.g., ATS
- A-EXEC service is a data capacity requirement driver



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# Backup



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# Presentation of ADR Results

- **Phase 1 and Phase 2, ATS with A-EXEC, and ATS without A-EXEC**

| **Phase** | Phase 1 | Phase 2 | |
|---|---|---|---|
| **A-EXEC** | NA | ATS with A-EXEC | ATS without A-EXEC |

| **Traffic** | **ATS** | | | **AOC** | | | **ATS & AOC** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Direction** | UL | DL | UL&DL | UL | DL | UL&DL | UL | DL | UL&DL |

- **ATS only, Aeronautical Operational Control (AOC) only, and ATS & AOC**

UL UpLink
DL DownLink



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# Sample Phase 1 and Phase 2 En Route Air Traffic Service (ATS) Services and Service Instances

| ATS | Phase 1 | Phase 2 |
|---|---|---|
| ACL | 5 per domain | Type I: 5 per domain<br>Type II: 1 per domain |
| ACM | 1 per sector | 1 per sector |
| A-EXEC | - | 1 per year per domain |
| AMC | 1 per domain, per week | 1 per week per domain |
| ARMAND | 1 per domain, arrival only | 1 per domain, arrival only |
| C&P | 1 per domain | 1 per domain |
| COTRAC | - | 1 per sector |
| D-ALERT | 1 per aircraft per year | 1 per aircraft per year |
| D-ATIS (Arrival) | 1 per domain arrival for 70% of aircraft | 1 per domain on arrival for 30% of aircraft |
| D-ATIS (Departure) | 0 | 0 |
| DCL | 0 | 0 |
| DLL | 1 per domain 30% of the time | 1 per domain, 30% of the time |
| D-ORIS | 1 per domain | 1 per domain |
| D-OTIS | 1 per domain for 30% of aircraft | 1 per domain for arrival for 70% of aircraft |
| D-RVR | 1 per domain, 30% of the time during arrival | 1 per domain, 30% of the time, arrival only |
| DSC | 1 per domain | 1 per domain |

A-EXEC Automatic Execution



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# Sample ATS Number of Messages per Service Instance and Average Message Sizes

| ATS Addressed Services | Uplink (No Msgs x bytes) | Downlink (No Msgs x bytes) |
|---|---|---|
| ACL | 4x91 | 4x91 |
| ACM | 2x107 | 2x88 |
| A-EXEC | 1x600 | 1x100 |
| AMC | 1x89 | 0 |
| ARMAND | 1x260 | 1x88 |
| C&P | 4x91 | 4x91 |
| COTRAC (WILCO) | 2x1613 | 2x1380 |
| COTRAC (INTERACTIVE) | 3x1969 | 4x1380 |
| D-ALERT | 1x88 | 1x1000 |
| DCL | 3x98 | 3x88 |
| DLL | 1x491 | 1x222 |
| DSC | 5x165 | 5x88 |
| D-TAXI | 3x118 | 3x192 |
| DYNAV | 2x302 | 2x85 |
| FLIPCY | 2x97 | 2x131 |
| FLIPINT | 2x116 | 2x2774 |
| ITP | 4x91 | 4x91 |



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# Phase 1 and Phase 2 En Route High-Density SV Flight Duration and PIAC

| Flight Duration | |
|---|---|
| Phase 1 | Phase 2 |
| 675 s | 984 s |

| PIAC | |
|---|---|
| Phase 1 | Phase 2 |
| 41 | 95 |



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# Priority-Queueing Analysis

- **Assumptions**
  - **Identical message traffic for each aircraft**
  - **Poisson arrival process**
    - **I.e., exponential message inter-arrival times**
  - **Exponentially distributed message lengths, Msg**
  - **Message service time, $T_{Si}$, function of capacity, C, and message length, $Msg_i$**
    - **E.g., $T_{Si} = Msg_i/C$ for priority i**
- **$\lambda_i$, message arrival rate for priority i**
- **$\mu_i$, message service rate for priority i**
  - **$\mu_i = C/Msg_i$**
- **Utilization, $\rho_i = \lambda_i / \mu_i$**



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# Non-Preemptive Priority-Queueing Analysis

- **Waiting time for priority i, $T_{wi}$, function of message length, $Msg_i$, message arrival rate, $\lambda_i$, and data capacity, C**

$$T_{W_i} = \frac{\sum_{i=1}^{N} \lambda_i \overline{X_i^2} / 2}{(1-\sigma_{i-1})(1-\sigma_i)}$$

$$\sigma_{i-1} = (1-\rho_1 - \ldots - \rho_{i-1}) \qquad \sigma_i = (1-\rho_1 - \ldots - \rho_i)$$

- $\overline{X_i^2}$**, is the second moment of service time $T_{Si}$**
- **Average service time for priority i, $T_{Si} = 1/\mu_i = Msg_i/C$**
- **$T_{Qi} = T_{Wi} + T_{Si}$ ($T_{Wi}$ and $T_{Si}$ functions of variable C)**
- **Find C such that $T_{Qi} \leq TD_{(95)i}$ for all priorities**



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# Preemptive Resume Priority-Queueing Analysis

- **Waiting time for priority i, $T_{wi}$, function of message length, $Msg_i$, message arrival rate, $\lambda_i$, and data capacity, C**

$$T_{W_i} = \frac{\sum_{j=1}^{i} \lambda_j \overline{X_j^2} / 2}{(1-\sigma_i)(1-\sigma_{i-1})}$$

$$\sigma_{i-1} = (1-\rho_1 - \ldots - \rho_{i-1}) \quad \sigma_i = (1-\rho_1 - \ldots - \rho_i)$$

- $\overline{X_j^2}$, **is the second moment of service time $T_{Sj}$**
- **Average service time for priority i,** $T_{S_i} = \frac{\overline{X_i}}{1-\sigma_{i-1}}$
- $\overline{X_i}$ **, time to service priority i message without preemption,**

$$\overline{X_i} = Msg_i / C$$

- **$T_{Qi} = T_{Wi} + T_{Si}$ ($T_{Wi}$ and $T_{Si}$ functions of variable C)**
- **Find C such that $T_{Qi} \leq TD_{(95)i}$ for all priorities**



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# Calculating 95th Percentile Transit Delay from Average Transit Delay

- $P^{th}$ percentile Transit Delay (TD), $T_{(P)Q}$, can be calculated from the average TD, $T_Q$, by the following approximation:
  - $T_{(P)Q} \approx \ln(100/100-P))*T_Q$
- $95^{th}$ percentile TD, $T_{(95)Q}$, can be calculated from $T_Q$ by the following approximation:
  - $T_{(95)Q} \approx \ln(20)*T_Q$



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# FRS 95 Percentile Transit Delay, $TD_{(95)}$, Requirements for Different Priorities (Class of Service) and Priorities Used in Phase 1 and Phase 2 En Route

| | Service Type | COS | $TD_{95\text{-}FRS}$ s | Phase 1 | Phase 2 | |
|---|---|---|---|---|---|---|
| Highest priority | System/Network | A | 9.8 | √ | √ | |
| | ATS A/G Data | B | 0.74 | | √ | A-EXEC |
| | | C | 1.4 | | √ | |
| | | D | 2.4 | | √ | |
| | | E | 3.8 | √ | | |
| | | F | 4.7 | | | |
| | | G | 9.2 | √ | | |
| | | H | 13.6 | √ | | |
| | | I | 26.5 | | | |
| | AOC A/G Data | J | 13.6 | √ | √ | |
| | | K | 26.5 | √ | √ | |
| Lowest priority | | L | 51.7 | | | |



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# Priority-Queueing Analysis Process for Each Case

**Develop NM, ATS, AOC traffic model for the SV from NM, ATS, AOC service instance tables, message sizes and number of service instance tables, flight durations, and PIACs**

**Derive aggregate message sizes and arrival rates for each priority i**

↓

**Perform priority queueing analysis to estimate the required Data capacity**

**Find C such that $T_{Qi} < TD_{(95)i}$ for all priorities**



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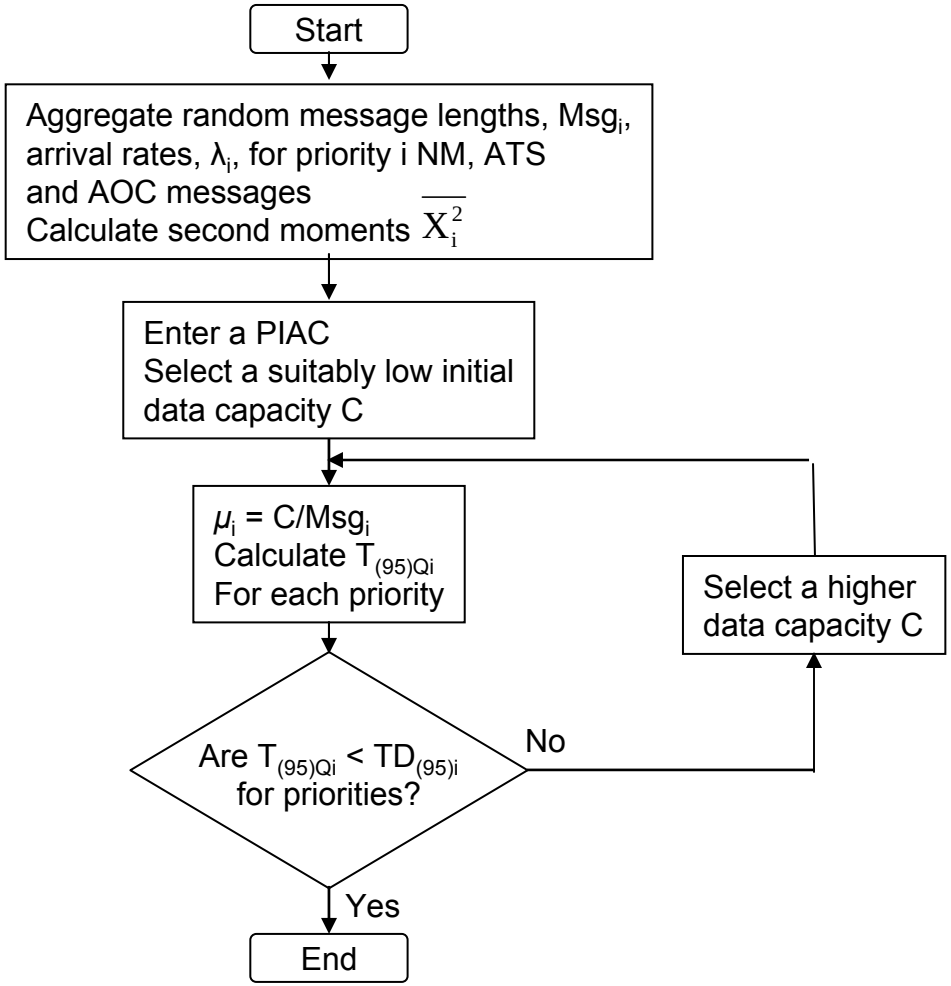
# A Procedure for Calculating Required Data Capacity $C_R$



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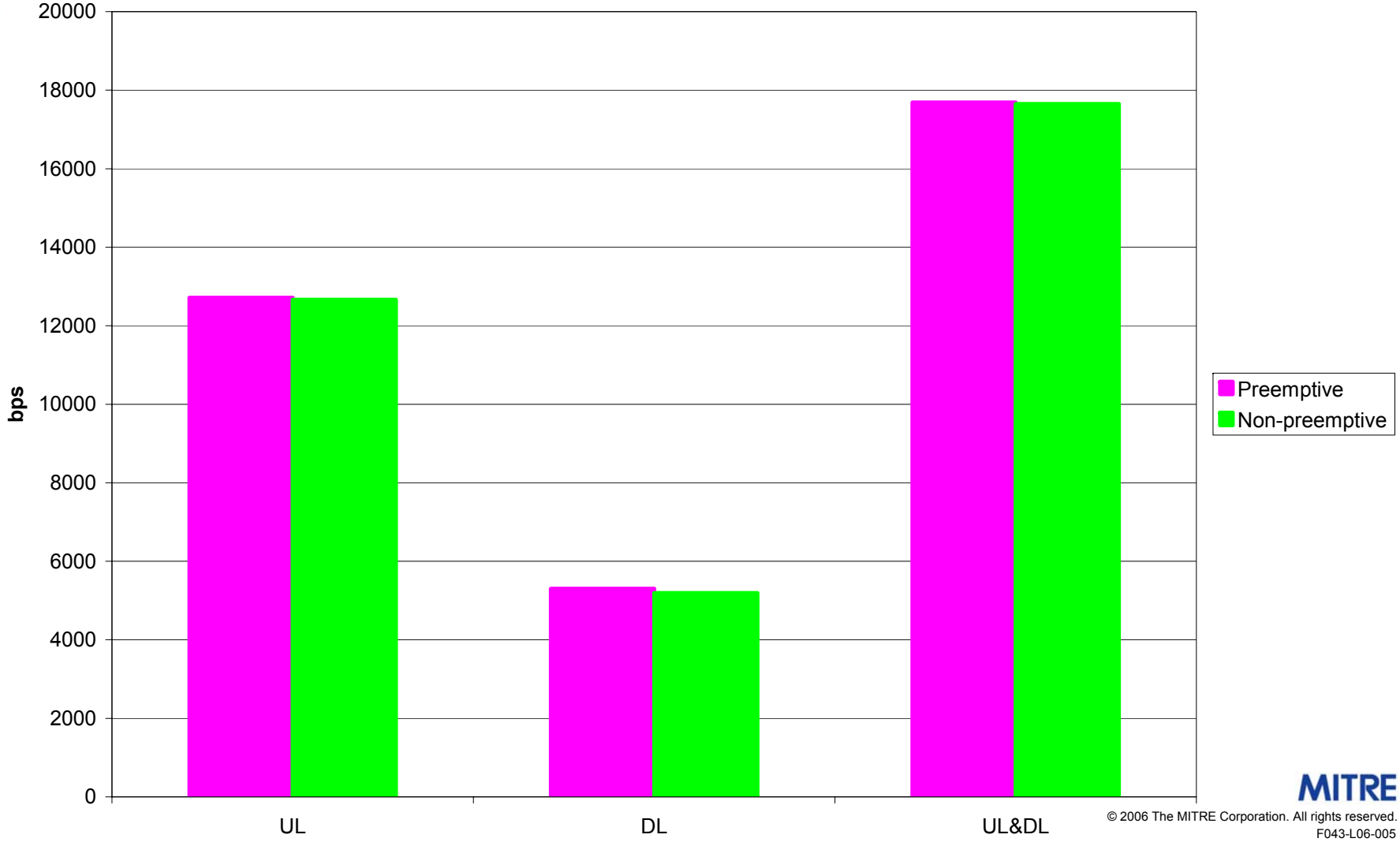
# Phase 1 Estimated Data Capacity Requirements

- **Preemptive and non-preemptive have nearly identical requirements**



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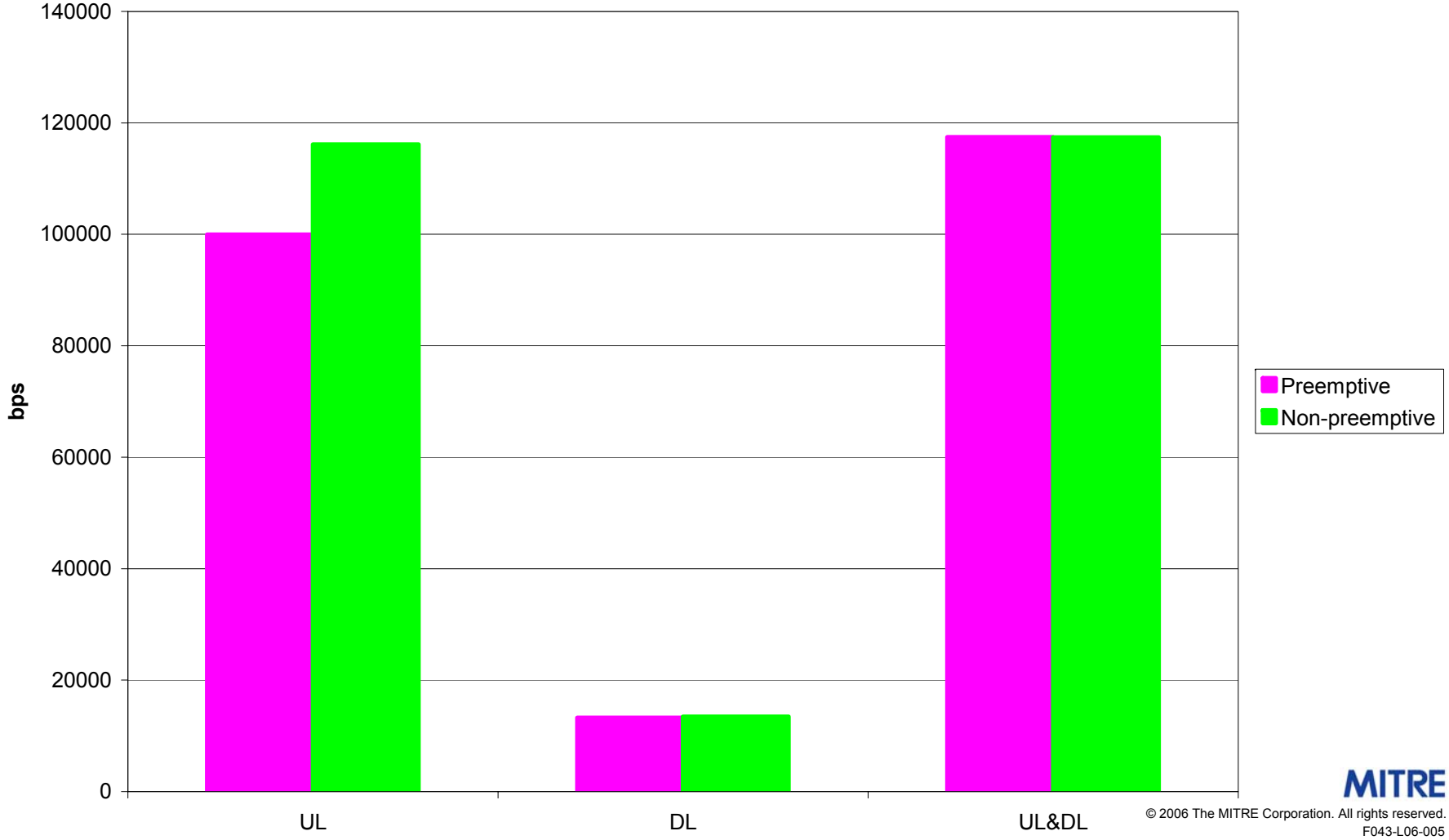
# Phase 2 Estimated Data Capacity Requirements (ATS Without A-EXEC)

- **Preemptive and non-preemptive have nearly identical requirements in two cases**



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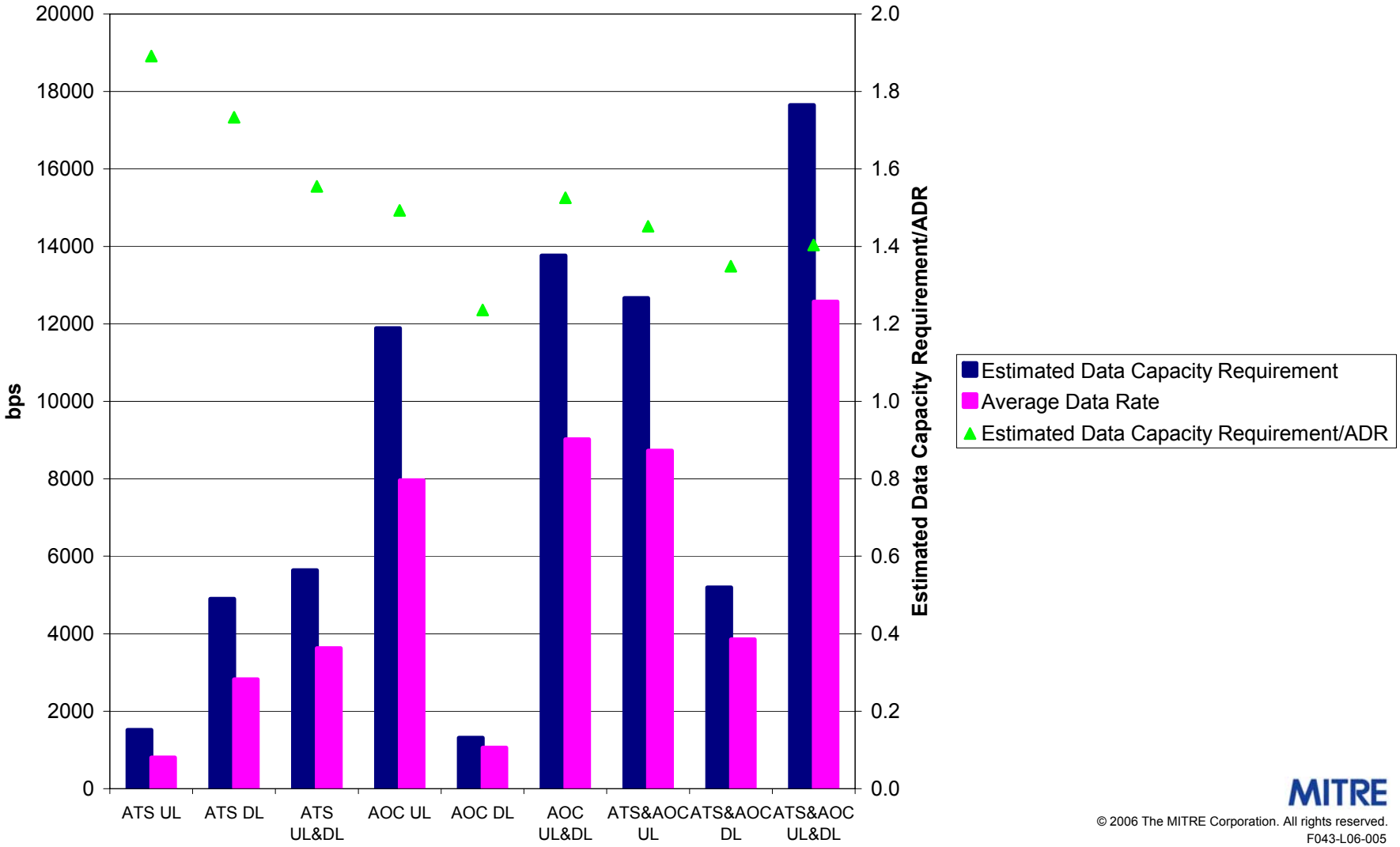
# Phase 1 Estimated Non-Preemptive Data Capacity Requirements and ADRs

- **Estimated data capacity requirement/ADR ratios — 1.2 to 1.9**



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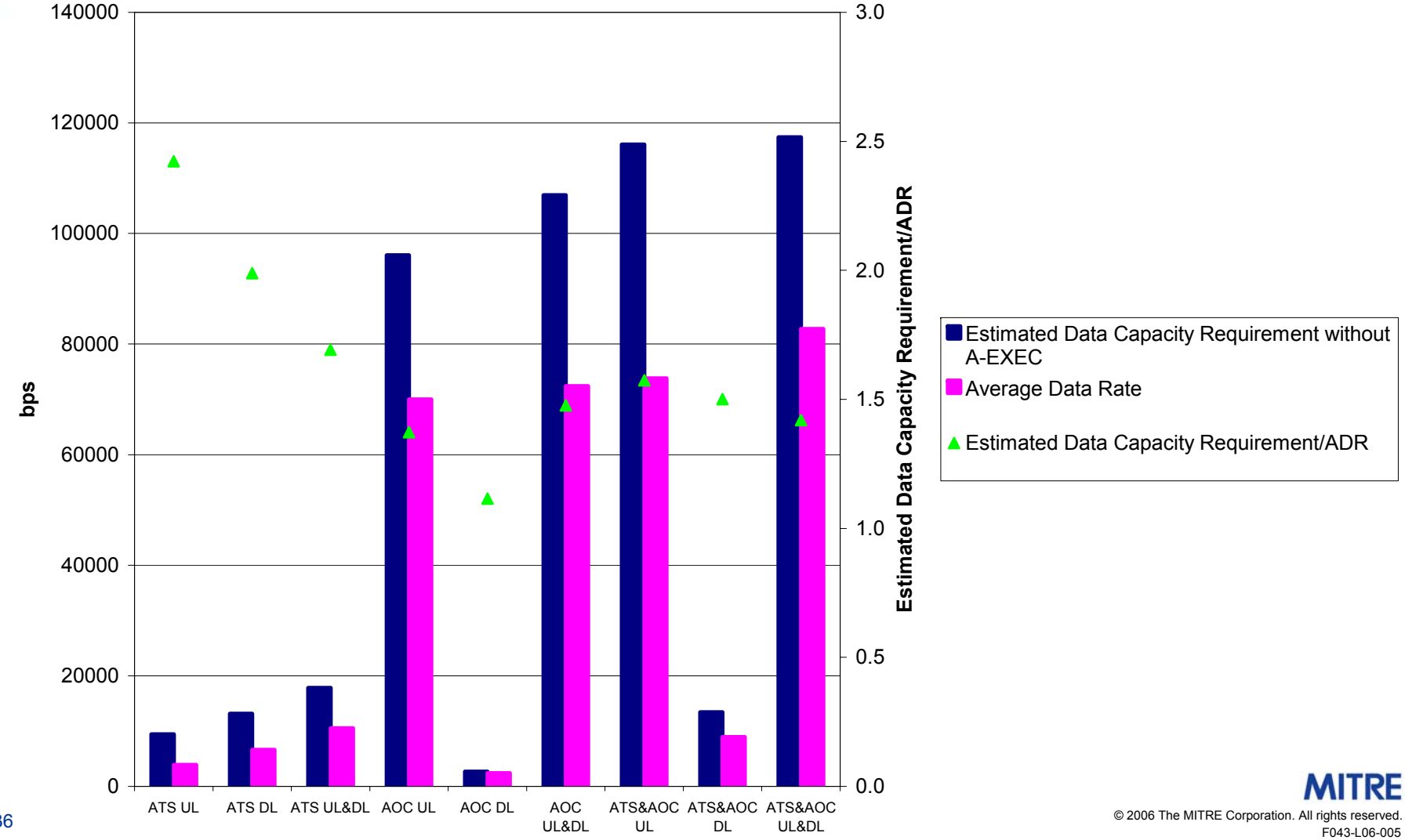
# Phase 2 Estimated Non-Preemptive Data Capacity Requirements and ADRs (ATS Without A-EXEC)

- **Estimated data capacity requirement/ADR ratios — 1.1 to 2.4**



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