

# IRI Network Analysis and Design Tools and Simulators



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# IRI Network Design Tools and Simulators



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- PLANYST
  - Burst Level Simulations
  - Analytical (Queueing) Facility
- PlanRes
  - Resource Allocation for Multi-Mission Multi-Area C4ISR Models
- MBNP (Mobile Backbone Network based Protocol oriented)
  - Mobile Ad Hoc Wireless Networks
  - Hierarchical
  - Multi tier
  - UAV and UGV aided networking
- MBNP\_Sense
  - Integrated Sensing, MBN based mobile ad hoc wireless networking and engagements
  - Multi tier UV aided network centric C4ISR system
  - Autonomous networking and sensing operations

# MBNP and MBNP\_Sense Network Design Tools and Simulators



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# Model Networks

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- Mobile Backbone Communication Network (MBN)
- Sensor Networks with Multi-tasked platforms
  - Sensing, communications, actions / firing
  - Network centric C4ISR
- Unmanned Vehicle Networks
  - Hierarchical UV (UAV, UGV, UUV) aided operations
  - Network centric C4ISR

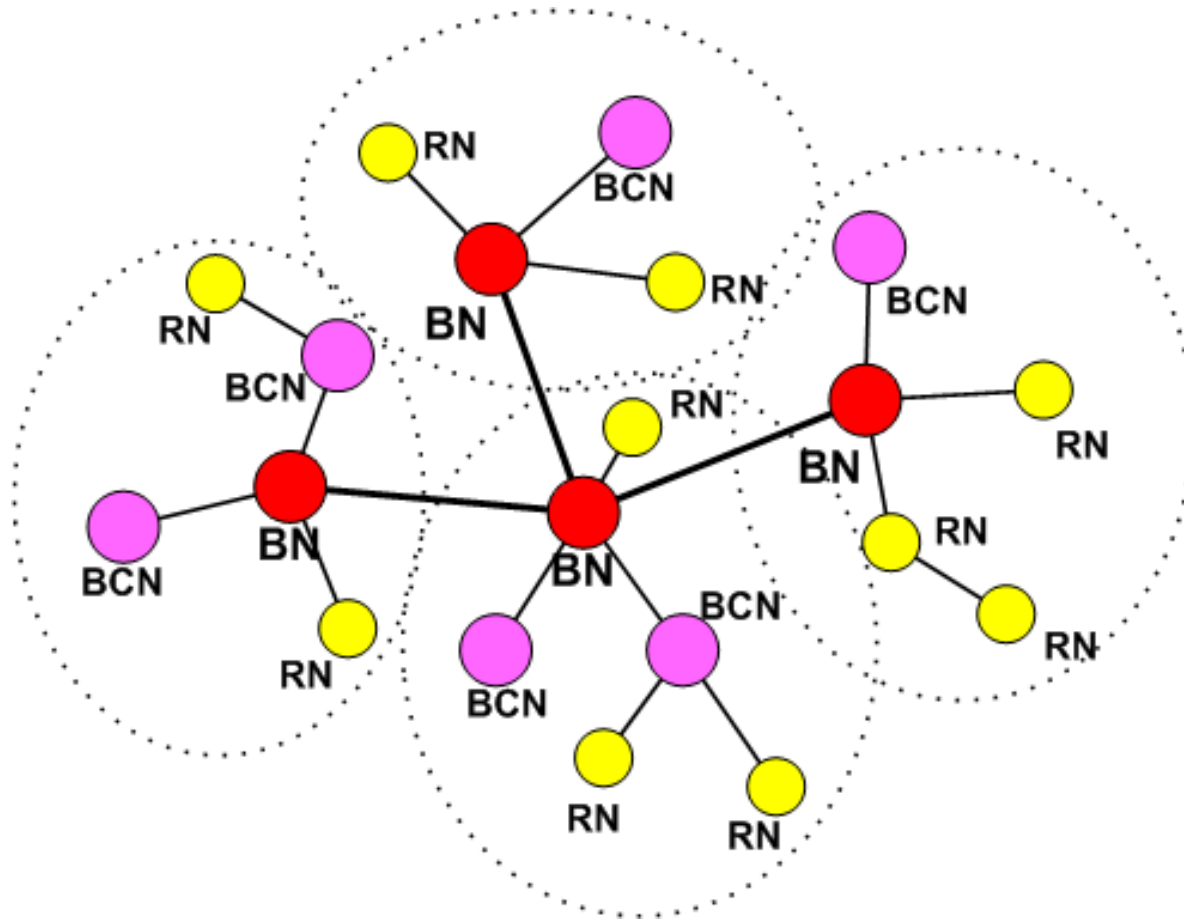


# MBN Communications Network

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- Three sub-networks
  - Bnets: Backbone Networks
  - Anets: Access Networks
  - Regular Networks
- Aiding networks:
  - UAV communication networks
  - UGV communication networks

# Mobile Backbone Network (MBN)



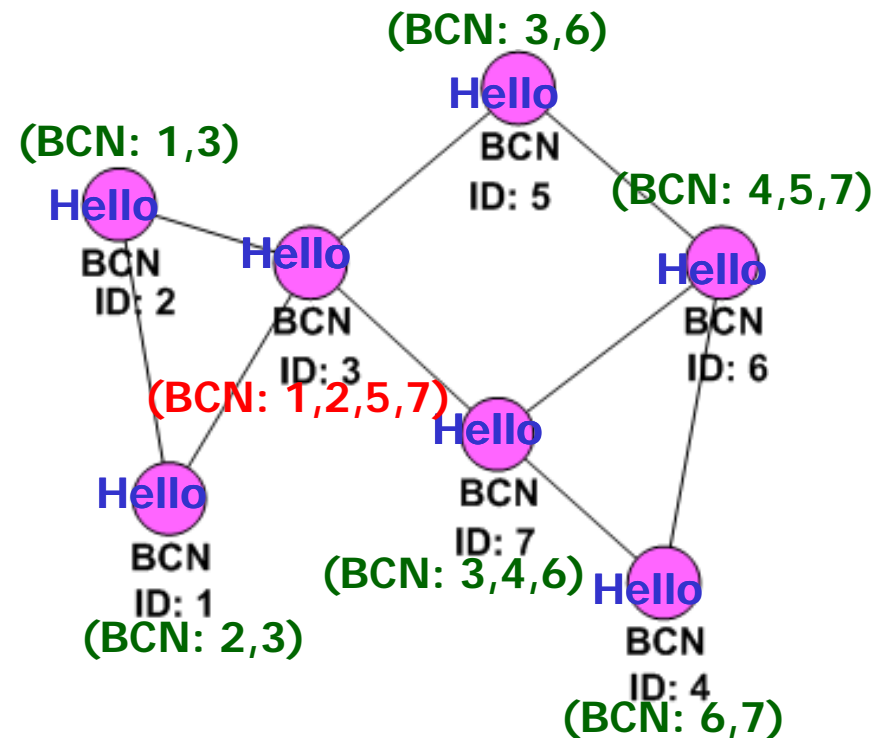
# The Extended MBN Topology Synthesis Algorithm (ETSA)

## ■ Neighbor Discovery

- Periodic Hello message exchange
- Each node learns its 1-hop neighbor information and 2-hop BN neighbor information.

## ■ Association Algorithm

- Every BCN attempts to associate with a BN with highest *Weight*.
- If no BN neighbor available, try BCNs.



Hello Message: ID, Weight, BN Neighbor List

# The Extended MBN Topology Synthesis Algorithm (ETSA)-Cont.

## ■ BCN to BN Conversion Algorithm

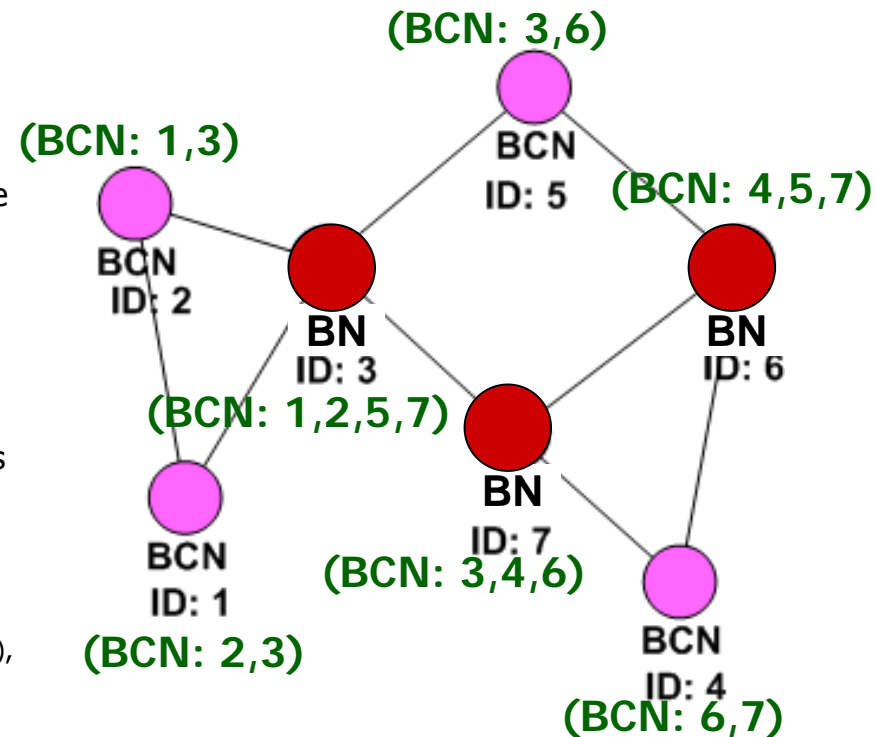
Any of the following condition is satisfied at a BCN  $u$

- **Client coverage condition:** BCN  $u$  has the highest weight among its BCN neighbors or BCN  $u$  has received at least one association request.
- **2-hop BNet connectivity:** At least one pair of its BN neighbors do not connect to each other in  $\leq 2$  hops in the BNet.
- **3-hop BNet connectivity:** At least one of its BN neighbors and one of its BCN neighbors do not connect to each other in  $\leq 2$  hops in the BNet.

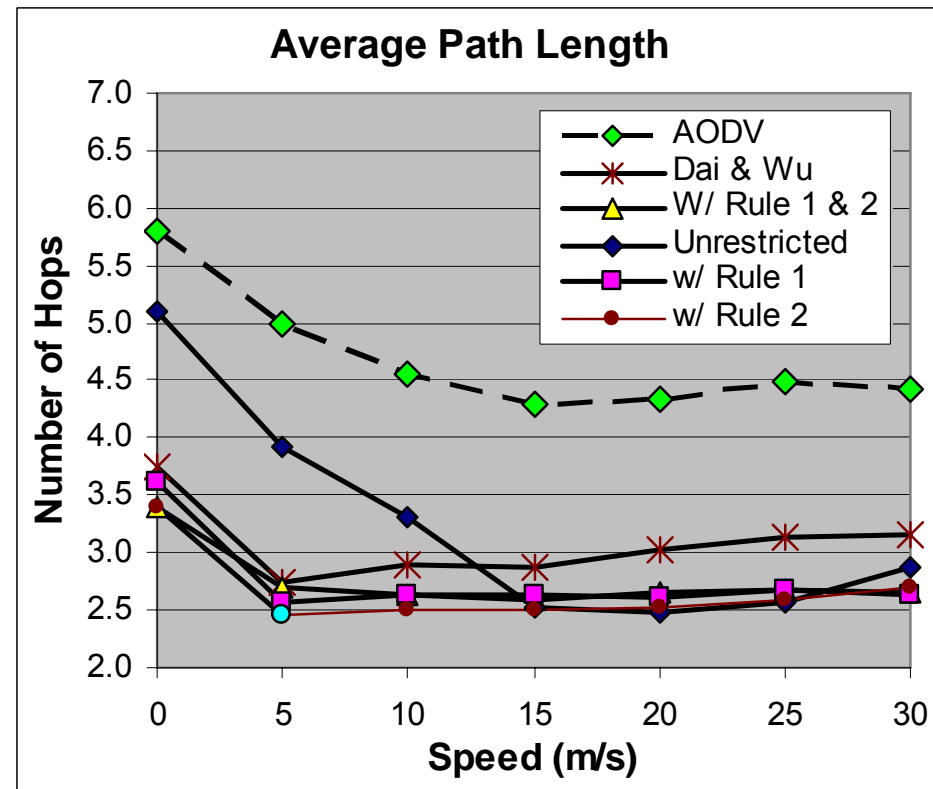
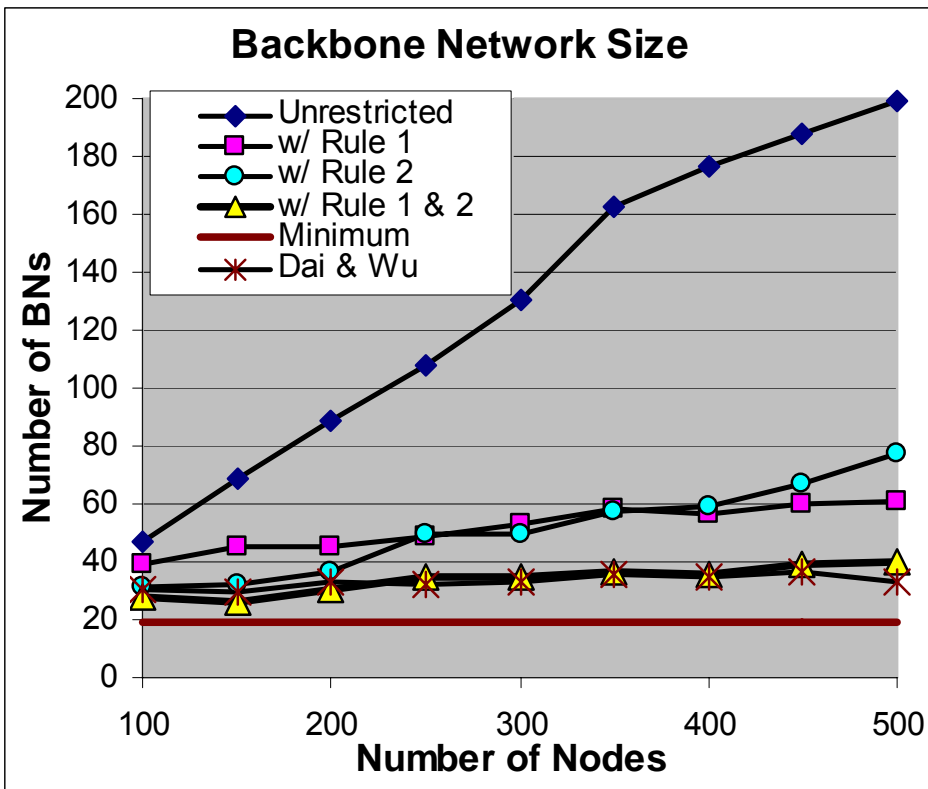
## ■ BN to BCN Conversion Algorithm

All of the following conditions are satisfied at a BN  $u$

- **Client coverage condition:** Each one of BN  $u$ 's clients has more than one BN neighbor.
- **2-hop BNet connectivity:** Any two of node  $u$ 's BN neighbors, e.g., BN node  $v$  and BN node  $w$ , either
  - (i) are directly connected to each other, and: node  $u$  has lowest highest weight among  $u, v, \text{ or } w$ , or,
  - (ii) have at least one other common BN neighbor (e.g., BN  $x$ ), and BN  $x$  has a higher weight than node  $u$  does.
- **3-hop BNet connectivity:** Any one of node  $u$ 's BN neighbors (say, BN  $v$ ) and any one of node  $u$ 's BCN neighbors (say, BCN  $w$ ) either
  - (i) are directly connected to each other, and: BN  $v$  has a higher weight than node  $u$  does, or,
  - (ii) have at least one other common BN neighbor (e.g., BN  $x$ ), and: BN  $x$  has a higher weight than node  $u$  does.



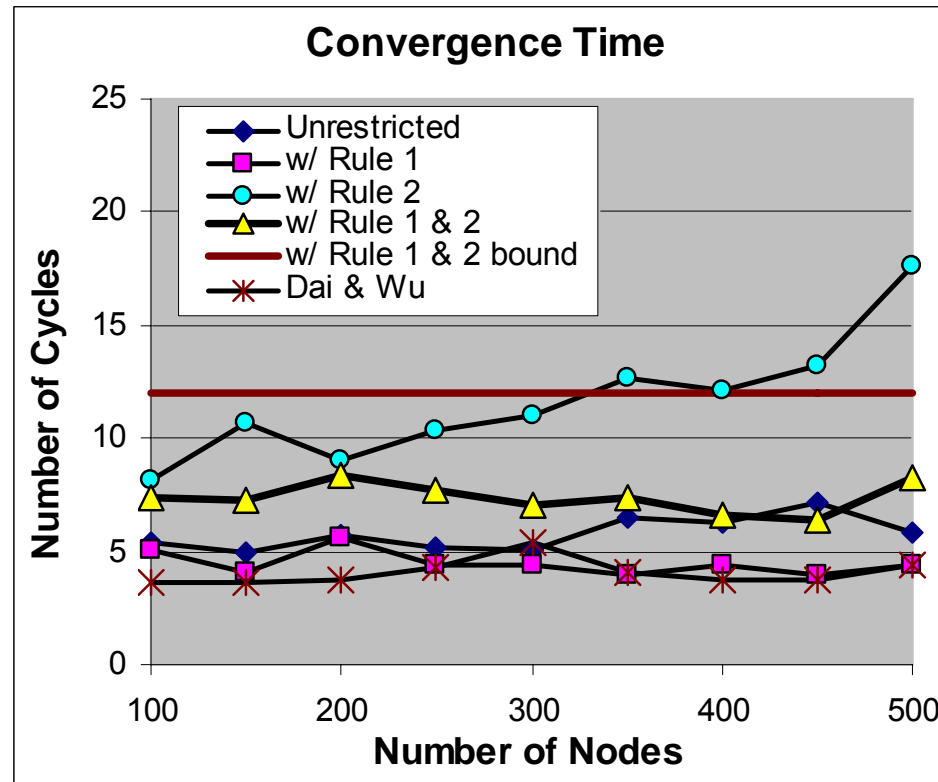
# Total number of backbone nodes (BNs) in the network



- The backbone network (BNet) size is independent of the number of nodes in the network or the nodal density.
- The backbone network (BNet) size is only proportional to the area size.

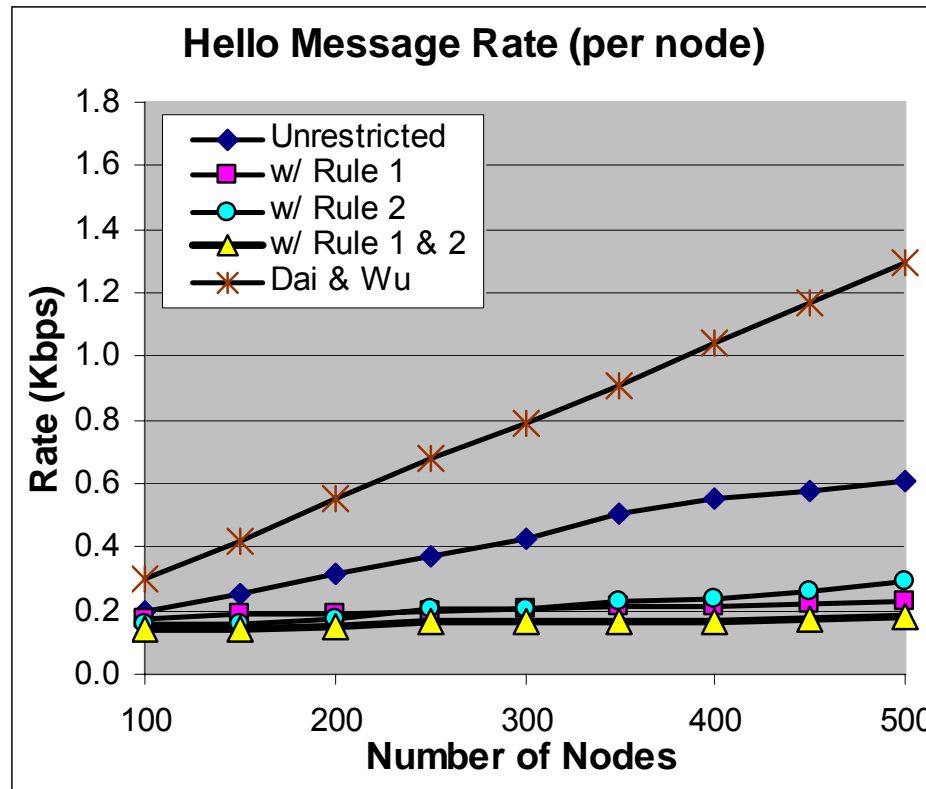
- The average data path length under ETSA is quite low. Dai and Wu's algorithm induces longer average data path length.

# MBN Topology Synthesis Algorithm Convergence Time



- The MBN topology synthesis algorithm convergence in constant time, of the order of  $O(1)$ .

# Control Message Overhead of ETSA



- The control message overhead of ETSA is independent of the number of nodes in the network or the nodal density.

# Mobile Backbone Network Routing (MBNR): Protocol and Procedures

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- Source node sends *route request* including the following information:
  - *source/destination IP*
  - *sequence number* (loop-free routing)
  - *request type* – { backbone, non-backbone } (announces the expected route type.)
  - *flooding indicator* – { source Anet, Bnet, destination Anet } (determines the flooding region.)
  - *flooding ID* – (disregards duplicate received route requests)
  - *general TTL, Anet TTL* – (flooding scope control)

# Mobile Backbone Routing: MBNR Protocol (Cont.)

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- Source Anet Flooding
  - *Anet TTL* is set to be  $n_s+1$  hops to reach the Bnet
  - The associated BN starts selective Bnet flooding if the destination node is not in the same Anet of the source node.
  - The *backbone route request* may result in a non-backbone route spanning up to  $n_s+1$  hops.
- Bnet Selective Flooding
  - No operation on *Anet TTL* in Bnet flooding
- Destination Anet Flooding
  - The associated BN of the destination node constructs the *route request*.
  - *Anet TTL* is set to be  $n_d+1$  hops.

# MBNR-FC: Incorporating Flow and Congestion Control

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## □ Congestion Control

- Objective: avoid overuse of network resources that can lead to unacceptable QoS performance for network flows; ensuring admitted flows with prescribed (per traffic class) QoS measures
  - Low message delay and delay jitter, low packet blocking ratios, high throughput rates: good delay-throughput performance.
- Each BN measures its loading level (*congested*, *heavy*, *relax*) by checking its backlogged queue size.
- Eliminate *congested* BNs from the forwarding node set.
- A BN informs its neighbor nodes about its congestion state.
- Eliminate neighbors of *congested* BN from the forwarding node set to prevent their interference with the Bnet.
- The admission control is operated at each BN by comparing the queue size with the prescribed threshold (in Route Discovery Phase).

# Flow Admission Control for QoS Performance Maintenance

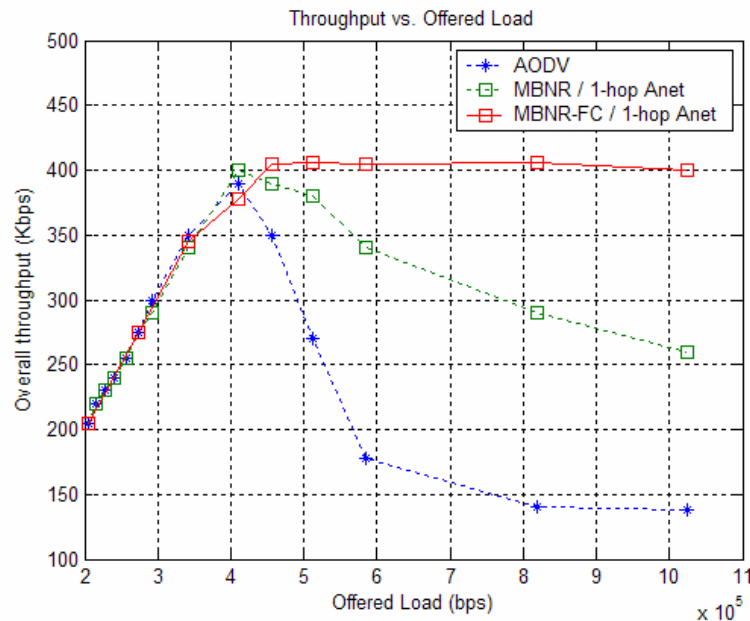
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## □ Flow Admissions

- Objective: provide and maintain Quality-of-Service (QoS) performance guarantees for admitted flows
- The source node keeps an *admitted flow table* recording its admitted flows
- For a new flow, if the route setup fails after a maximal number of route discovery tries, the flow is rejected.
- If the route setup succeeds, the new flow is recorded in the *admitted flow table*.
  - Subsequent packets can induce route re-discovery.
    - MAC layer congestion state notification is thus used by the routing mechanism
  - Flow will be blocked after a specified number of connection attempts fails
- Using IEEE 802.11e, different queues are maintained for different traffic classes, so that we can use a flow control threshold vector

# Network Throughput Performance Features

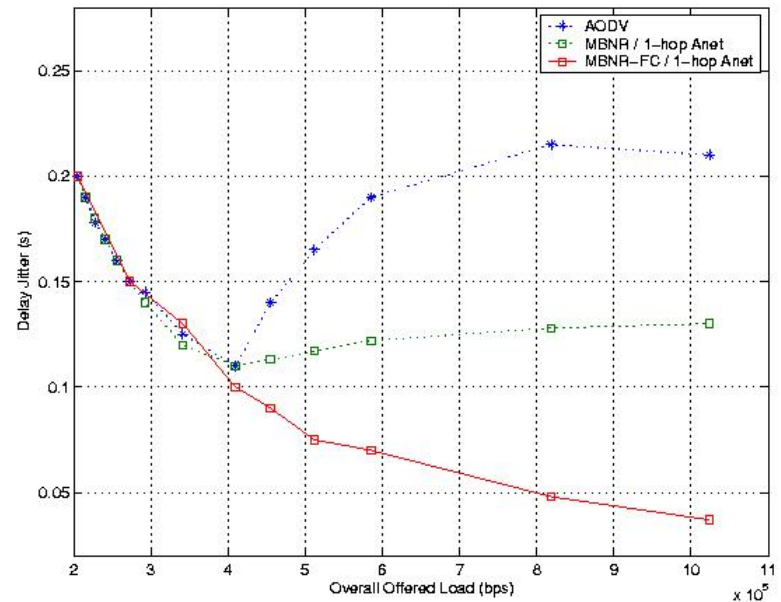
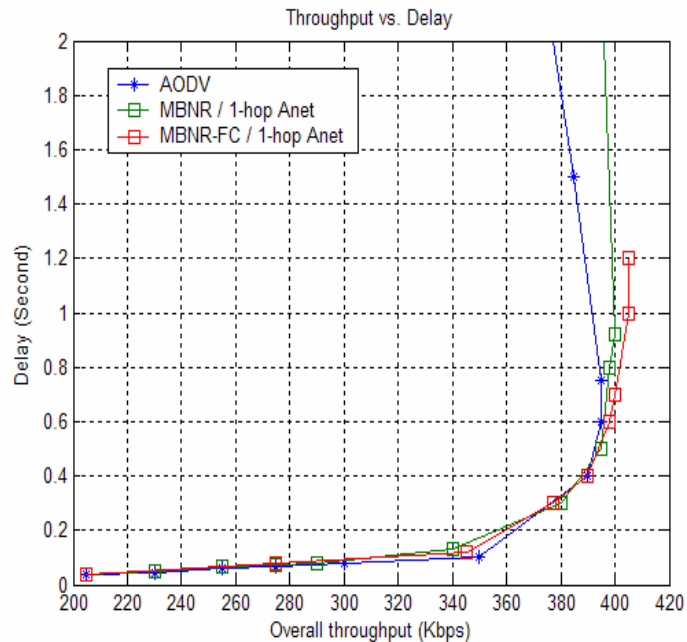
- Aggregated throughput vs. Traffic loading
  - When the network is under heavy loading, the throughput performance is much improved by reducing the flooding scope.
  - The flow admission control maintains performance behavior of admitted flows when the network operates in its saturation region.



# Network Performance: packet delay and delay jitter

## Delay jitter vs. Traffic loading

- The delay jitter is reduced as traffic loading rate is increased (when the network is not saturated).
- When the network is congested, multiple route discovery attempts can take place.



# Communication Network Nodal Types



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- BN/BCN: Backbone (Capable) Node
  - Higher capability node
  - BCNs get converted to BNs using our 'BN Election Algorithm'
  - Interconnection of BNs forms the Bnet
  - Each Anet is formed around a single BN

# Communications Network Nodal Types (Cont.)



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- RN: Regular Nodes
  - Lower Capability Nodes
  - Form Anets around a single BN in a star network topology
- UAV: Relay UAV (Unmanned Aerial Vehicle)
  - Acts as relay to aid communications operations when the network is deficient
  - Has a large coverage area, thus boosting network connectivity, coverage, mobility support and robustness to link / nodal degradations

# Communications Network Nodal Types (Cont.)



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- UGV: Relay UGV (Unmanned Ground Vehicle)
  - Acts as relay to aid communications when the network is deficient
  - Has properties similar to a permanent BN
  - Can aid the communication network to boost connectivity when required
- UAV SWARM
  - Arrangement of groups of UAVs to aid communications

# Communications Networking Algorithms



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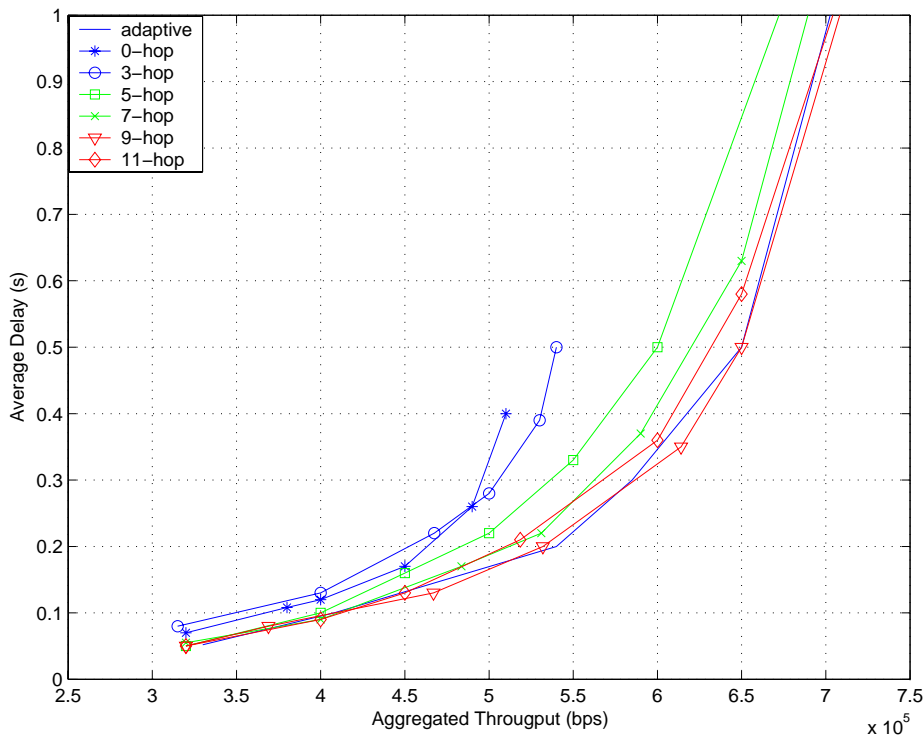
- BN election algorithm
- Anet association algorithm
- Bnet topology synthesis
- QoS routing and Robust Throughput based routing algorithms
- Optimal UAV placement algorithm
- Optimal UAV performance estimation algorithms

# Distance Awareness Routing Mechanism (MBNR-FC/DA)

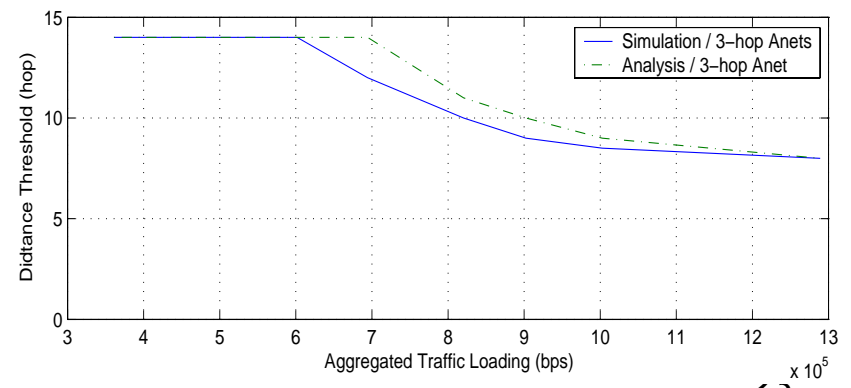
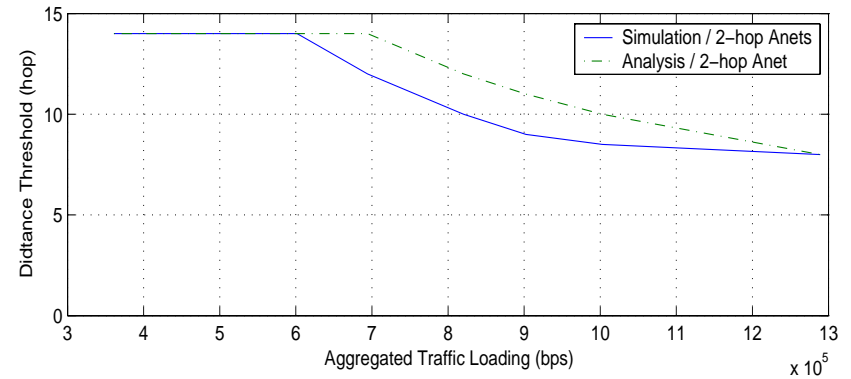
- Distance Awareness
  - A distance threshold  $d_{th}$  is selected based on the traffic loading distribution.
  - Flows with path length  $d \leq d_{th}$  use non-backbone routing procedure.
    - Route discovery messages are flooded among all types of nodes.
  - Flows with path length  $d > d_{th}$  use backbone routing procedure.
    - Pure MBNR-FC operation
- Principle:
  - For flows whose path lengths are shorter than the distance threshold level, route as much traffic as possible across the whole network (using its backbone and non-backbone segments), as long as the capacity in the non-backbone network area is not utilized beyond the specified utilization levels of the non-backbone nodal processing or energy resources.
- MBNR-FC/DA procedure
  - New generated flows first go through the non-backbone routing procedure with a distance threshold  $d_{th}$ .
  - If non-backbone routing procedure fails to discover the destination, flows switch to backbone routing procedure.

# Performance of the Hybrid Scheme

- The delay-throughput performance of MBNR-FC/DA with the adaptive scheme follows the optimal delay-throughput performance obtained by different distance thresholds under different traffic loading.

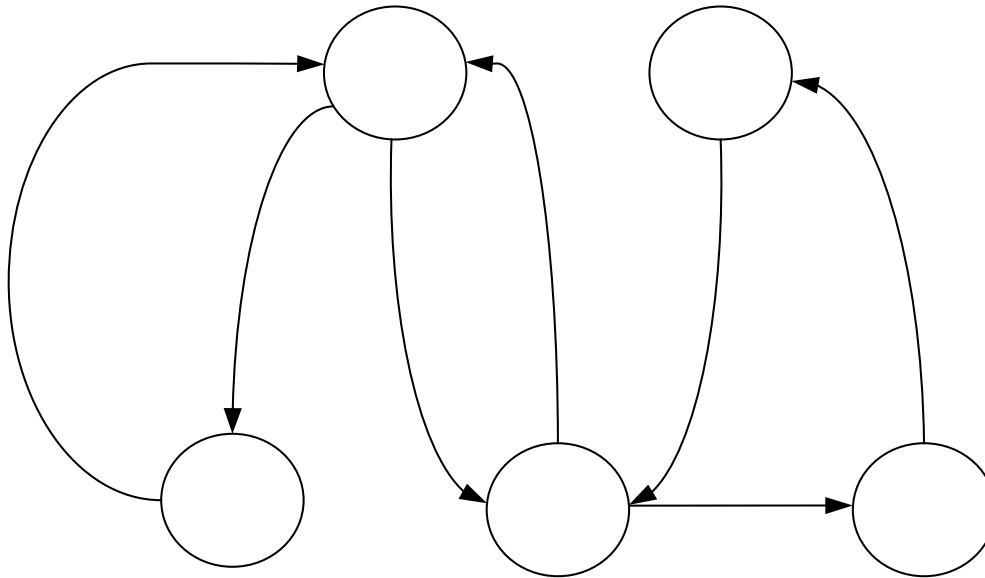


- Optimal Distance Threshold Comparison between analyse and simulations



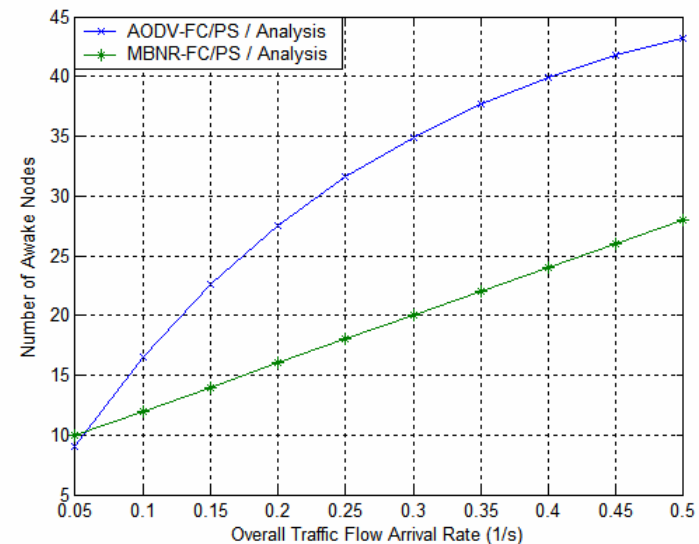
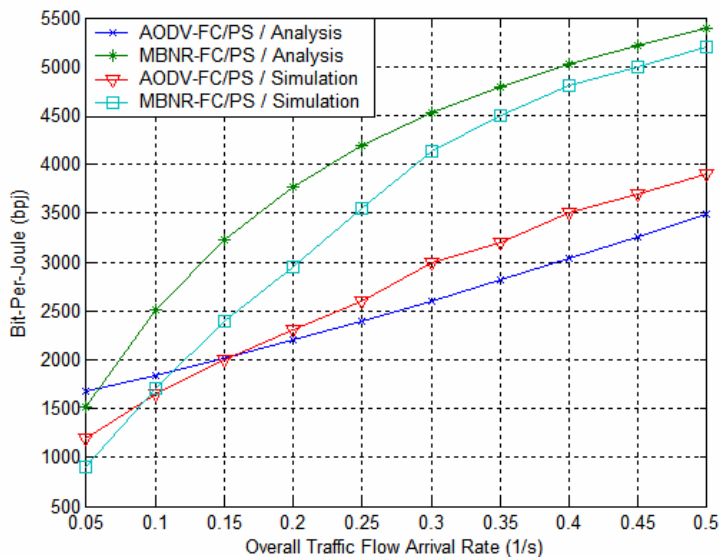
# Energy Efficient MBNR MAC

- Energy efficient MAC:
  - BNs are kept awake. BCNs and RNs wake up periodically during a common awake interval. BCNs or RNs that participate in transporting traffic flows (i.e. they serve as source/destination or relay nodes.) remain awake during the rest of the super frame. Inactive BCNs and RNs fall into sleep state after the common awake interval.



# Throughput-per-Watt Performance Comparison under Complete Back Coverage

- When the number of active network flows is above a minimal level, the Throughput per Watt efficiency attained by the MBNR-FC with Power Saving mode (MBNR-FC/PS) scheme is better than that achieved by a corresponding network that does not form a backbone structure (e.g., AODV-FC with Power Saving mode: AODV-FC/PS).
- Flat ad hoc routing distributes traffic flows among all nodes, while the MBNR concentrates the traffic flow distribution. Thus flat ad hoc routing requires more nodes to be awake than MBNR does.





# UAV communications network

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- Fixed position UAV networks
  - 2 or 4 orbiting UAVs
  - Multi-layered orbits with fixed ground communication bases
  - Can be further aided by satellite nodes
- Optimally placed UAV
  - UAV position calculated using our 'Optimal UAV placement algorithm'
  - Placed optimally to reduce flow blockage where and when needed



# Optimal UAV Placement

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- Optimal  $(x,y)$  location calculated using Blocked Flow Matrix
- Optimal  $z$  location (height) is calculated using an estimation of improvement in performance based on capacity-connectivity trade-offs:
  - Increase in height  $\rightarrow$  Increase in connectivity / coverage  $\rightarrow$  decrease in capacity
  - Decrease in height  $\rightarrow$  Increase in capacity  $\rightarrow$  decrease in connectivity / coverage



# UGV Communications Network

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- Illustrative placement pattern: Fixed position UGVs symmetrically placed in a grid
- UGVs are part of the Bnet and can access Anets through the BNs



# Sensor Network

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- Consist of a sensor gateway, sensors of different types and pursuit vehicles
- Stationary
- Arrangement
  - Individually applied
  - Multiple sensors in grid arrangements, dynamically arranged



# Sensor Network Elements

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- Sensor Gateway and Sensor Elements
  - Acoustic
  - Ultrasound
  - Electromagnetic
  - Video, as illustrative classes
- Pursuit Vehicles (PVs)
  - High speed, PV instantaneously reaches intruder's current location, e.g., stationed at center of sensor network
  - Low speed, PV tracks intruder slowly based on its speed; e.g., stationed at center of sensor network.



# Sensor Network Elements (Cont.)

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- Intruders (External Entities)
  - Illustration: 4 types of intruders, same as sensor types
  - Movement pattern of intruder is user selected / specified
- Sensor UAV
  - Similar to high speed PV, stationed at UAV base station
- Sensor UGV
  - Similar to low speed PV, stationed at UGV base station

# Sensor Network Functioning

## ■ Sensor network functions

- Detection and tracking
  - Starts when intruder enters a sensor network
  - Intruder is tracked within the sensor network
- Engagement
  - Starts when intruder is within firing range of sensor network counter element
  - May be enabled or disabled
- Pursuit
  - Performed by PV, sensor UAV or sensor UGV
  - Starts when intruder crosses PV launch line
- Communications
  - Event – based, occurs when any of the above events happens, based on traffic flow specified parameters, per flow type / traffic class
  - Communications is performed across the dynamically configured multi-tier ad hoc wireless network in accordance with our UV-MBN algorithms and protocols.



# Sensor Network Algorithms

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- Pursuit Algorithm
  - PV Pursuit
    - Fast PV
    - Slow PV
  - UAV Pursuit
  - UGV Pursuit
  - Pursuit order and priorities are user selected



# MBN Simulator Features

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- Display
  - Movement pattern of nodes is user selected
  - System display can be viewed in 3D at different elevations and view angles
- Traffic
  - Background
    - Generated randomly by software using provided distributions and user specified traffic parameters per traffic class
  - Detection
  - Engagement
  - Pursuit
    - Managed by corresponding sensor gateway, PV or sensor UAV/UGV based on the occurrence of specified events

# MBN Simulator Features: Control Variables



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- Control Variables
  - Link Fading
    - Link fading can be enabled and the fading probability and depth is user selected
  - Radios
    - The communications radios are set to follow homogeneous or heterogeneous configurations  
Under the latter, different radio modules are characterized by different effective communications transport ranges and transmission rate levels

-

# MBN Simulator Features: Illustrative Performance Displays



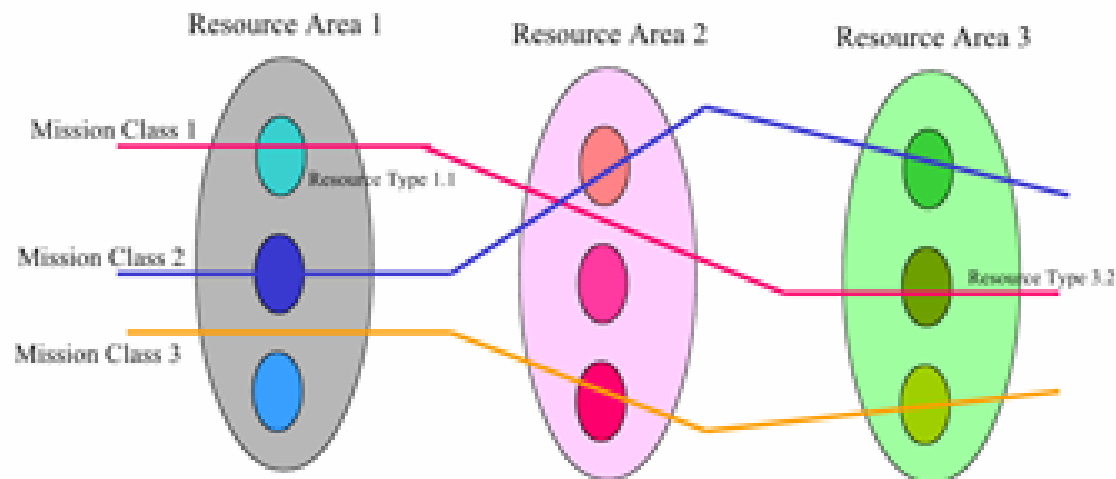
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- Performance Displays
  - Nodes coverage chart
  - Communications and Sensing based events
  - Traffic: flow blocking rate
  - Current network setting chart
  - MIB: Management Information Base
    - Node: id, type, location information
    - Flow: id, class, source-destination, route, delay information
  - Intruder survival status chart

# PlanRes: System Model

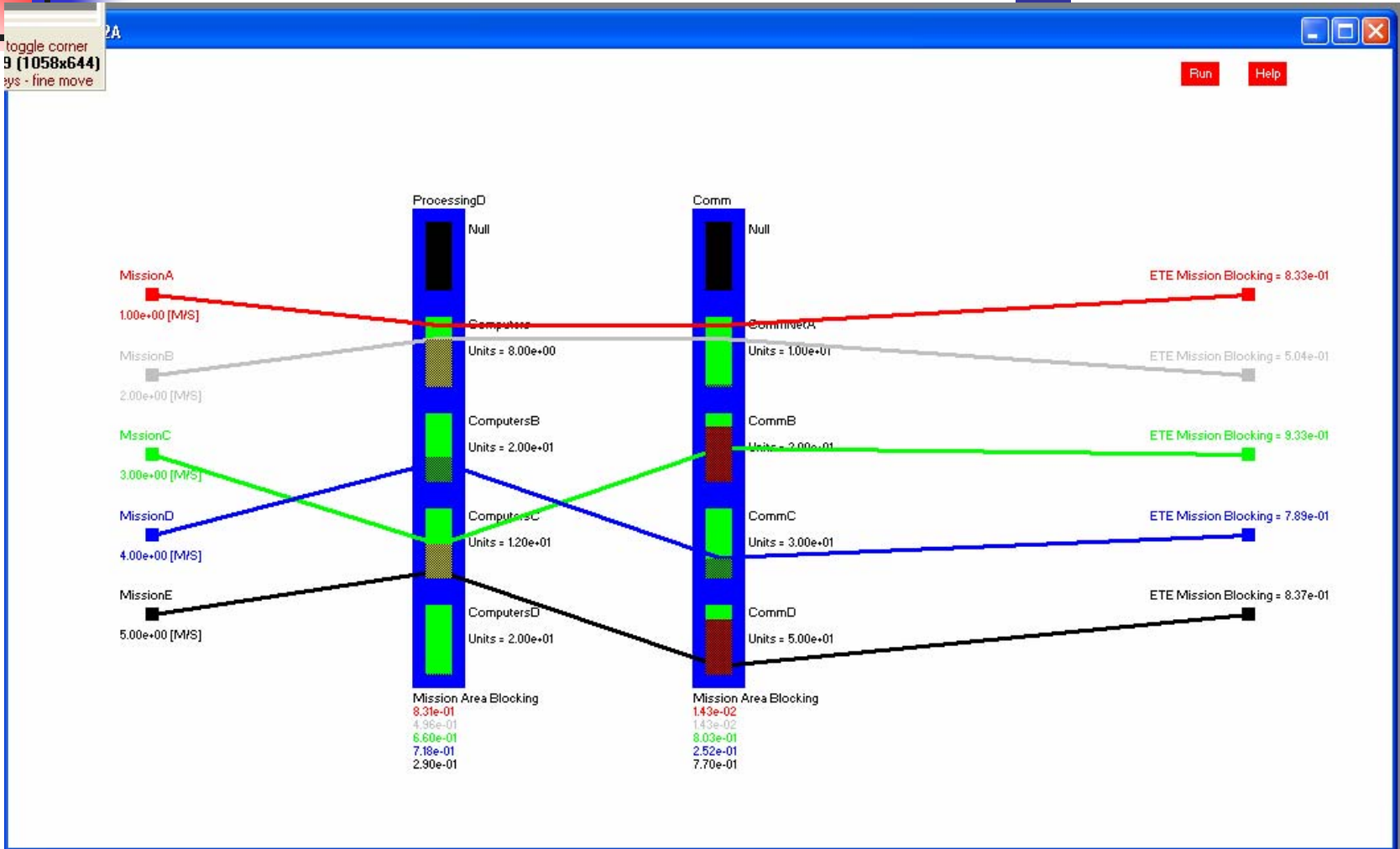
## PlayRes System Model

### System Architecture



- Mission Class 1 occupies assets of resource types 1.1 and 3.2
- Mission Class 2 occupies assets of resource types 1.2 and 2.1
- Mission Class 3 occupies assets of resource types 2.3 and 3.3

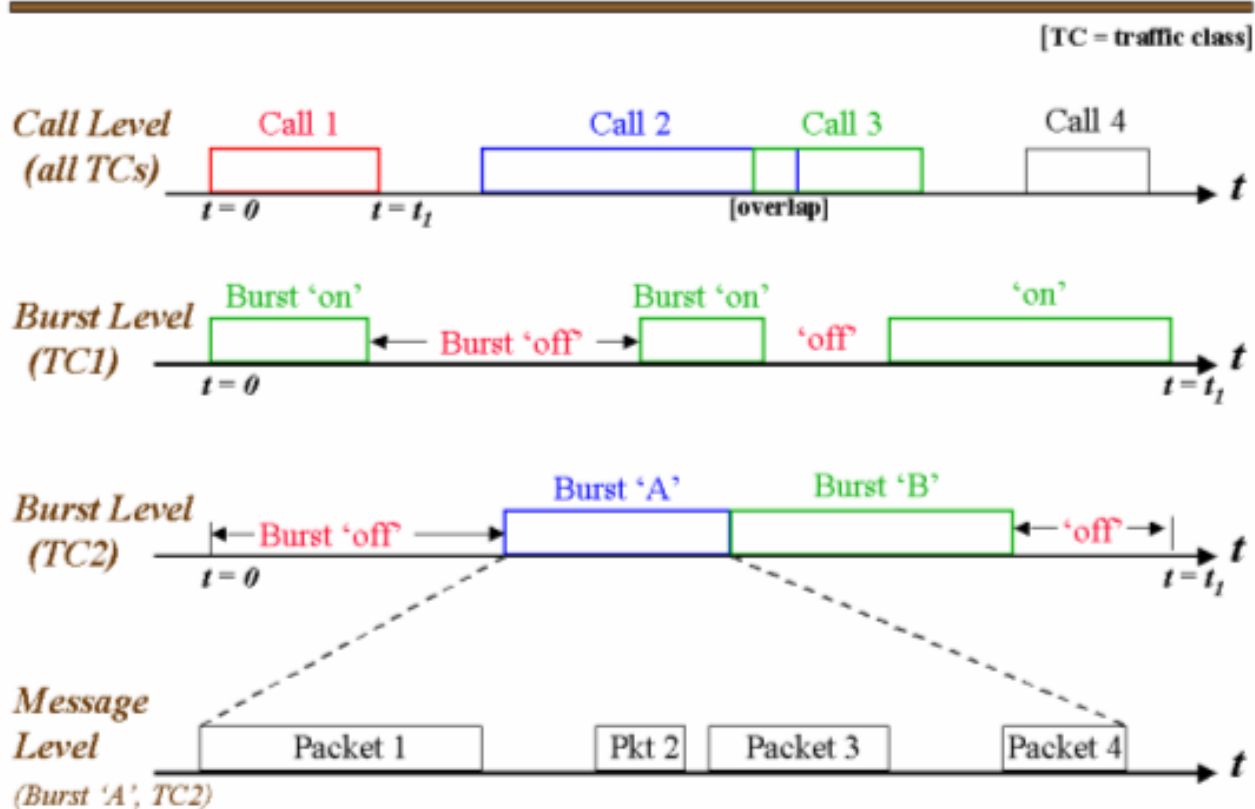
# PlanRes: Analytical Resource Allocation for MMMA\_C4ISR



# PLANYST: Traffic Process Modeling

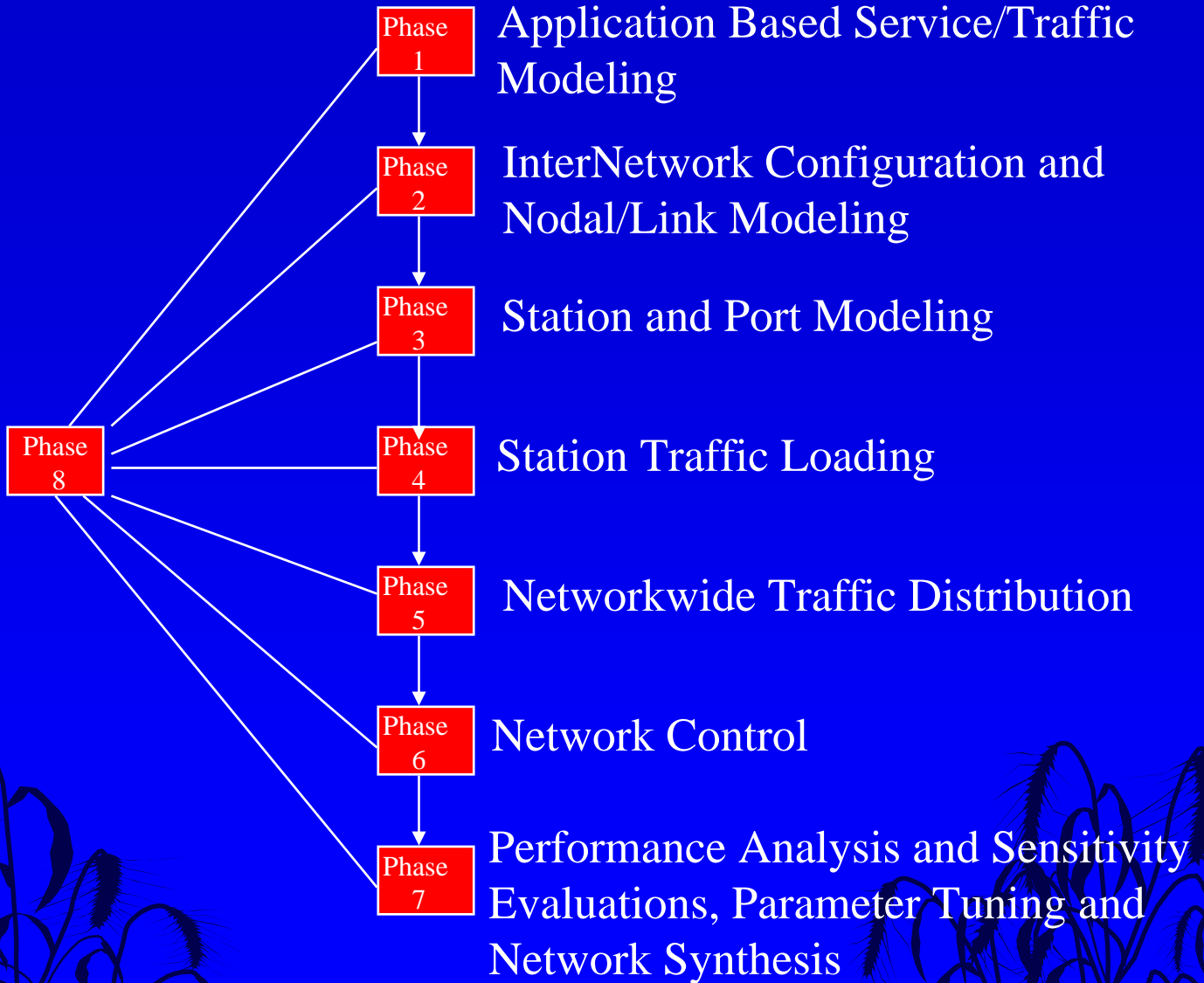
## Planyst 3-Level Model

(with multiple traffic classes and burst levels)



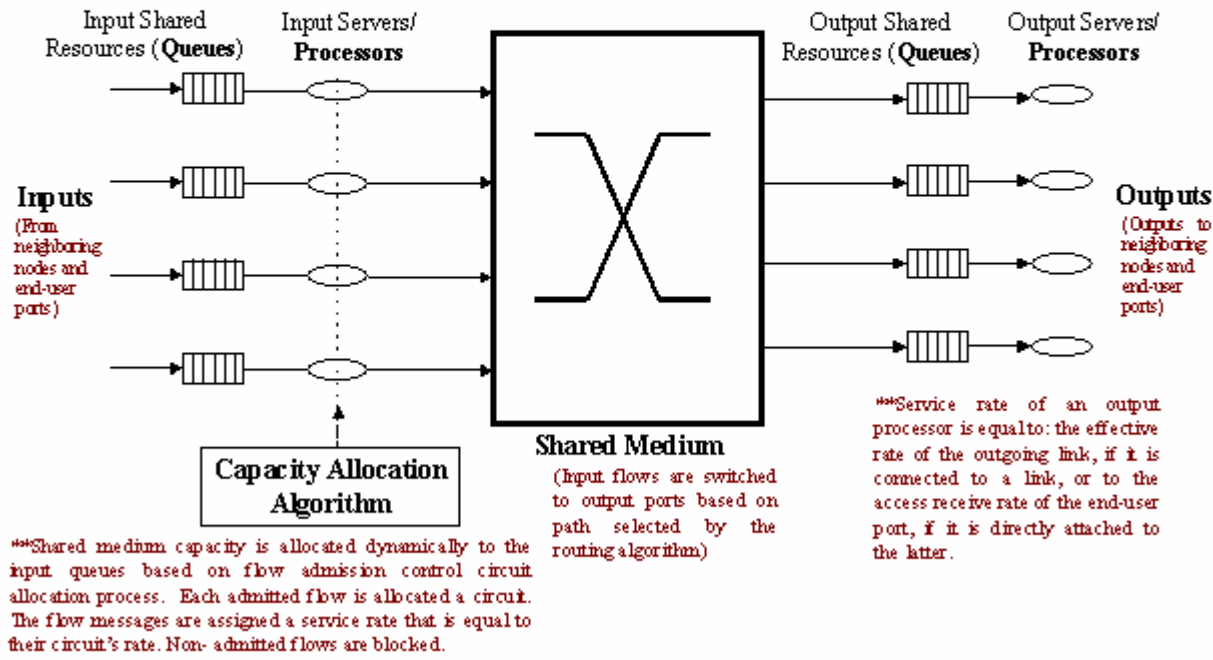
# The PLANYST Modeling and Analysis Process

Model Validation,  
Calibration and  
Testing



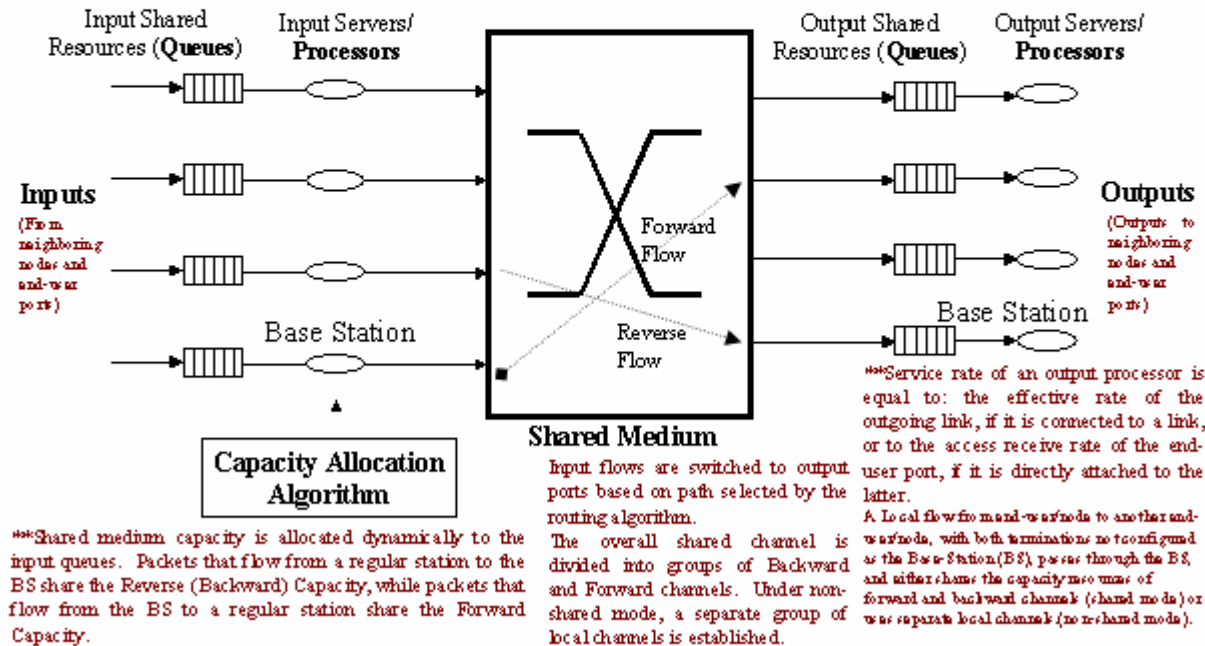
# PLANYST: CS-DAMA

## Model of a Planyst Nodal CS-DAMA Element



# PLANYST: Packet Switching Multiple Access Communications Channel

## Model of a Planyst Nodal PS-MACell Element



# PLANYST: Cloud Network Modeling

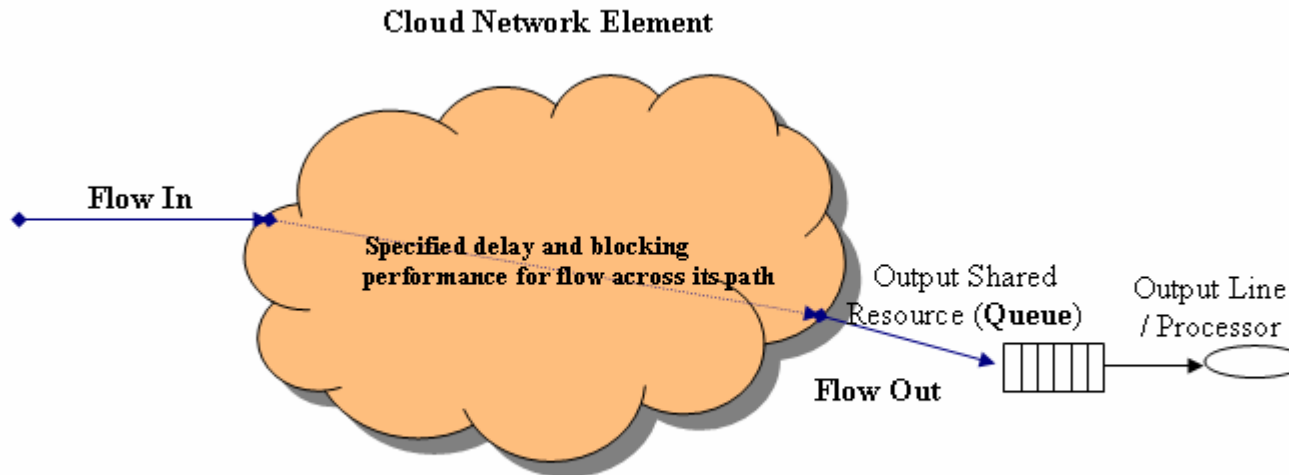
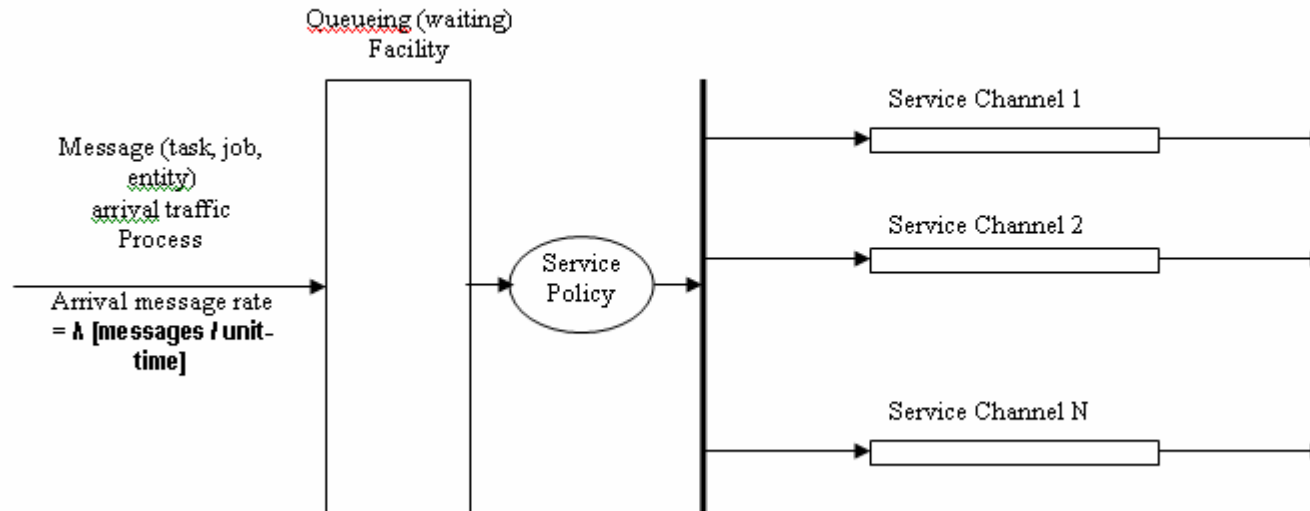


Fig. 9.2.4.1

# PLANYST: Analytical Queueing Modeling



# PLANYST: Queue Specification

**Exponential Service Time**

**Buffer Capacity**

- Unlimited
- Limited      Size (bits)

**Service Channels**

- Number of Service Channels
- Channel Service Rate (bits/sec)
- Total Throughput Capacity (bits/sec)

**Service Features**

- Average Message Length (bits)
- Average Message Service Time (sec)

**Performance Specification**

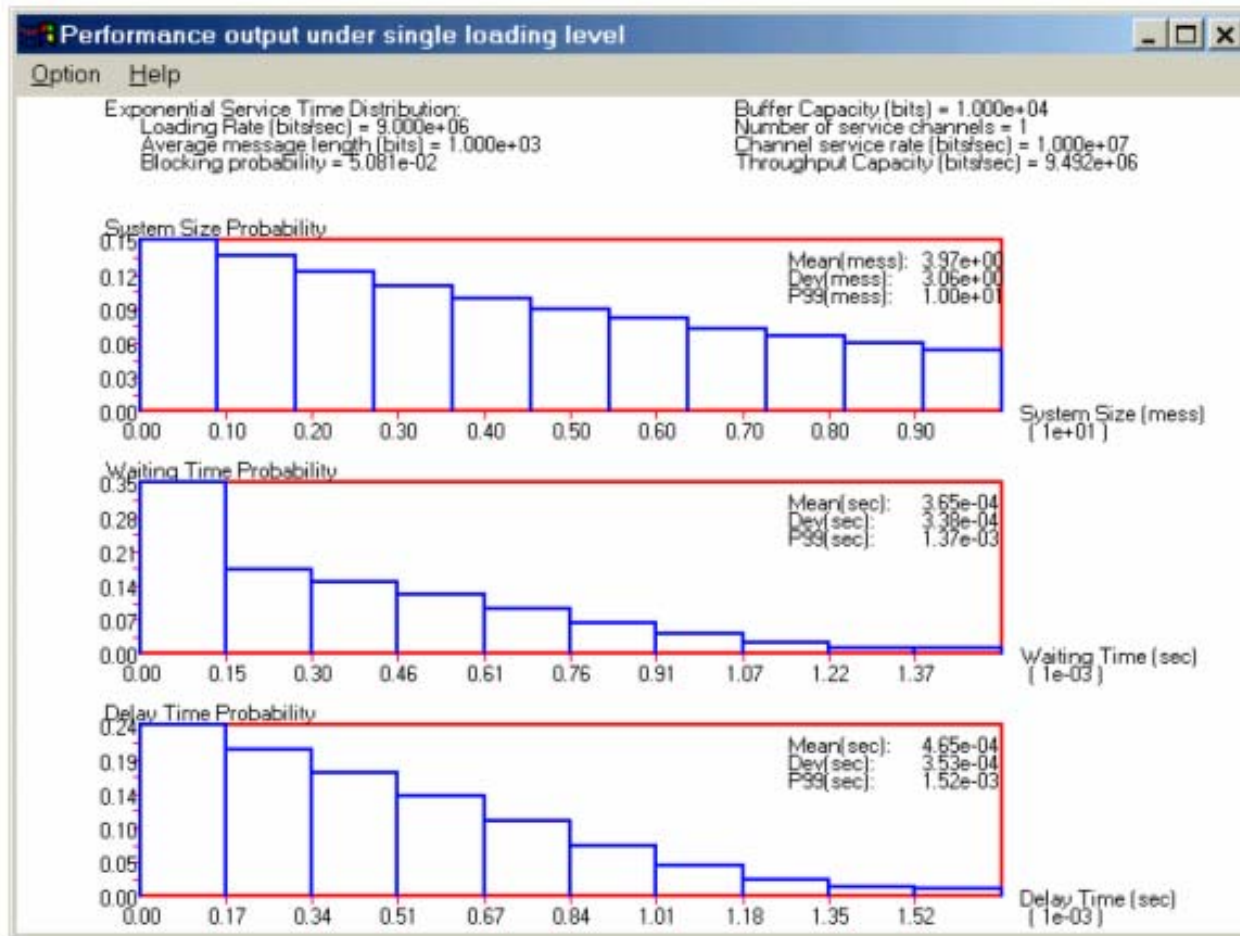
- q-ile Level Specification q (%)

**Message Arrival Rates**

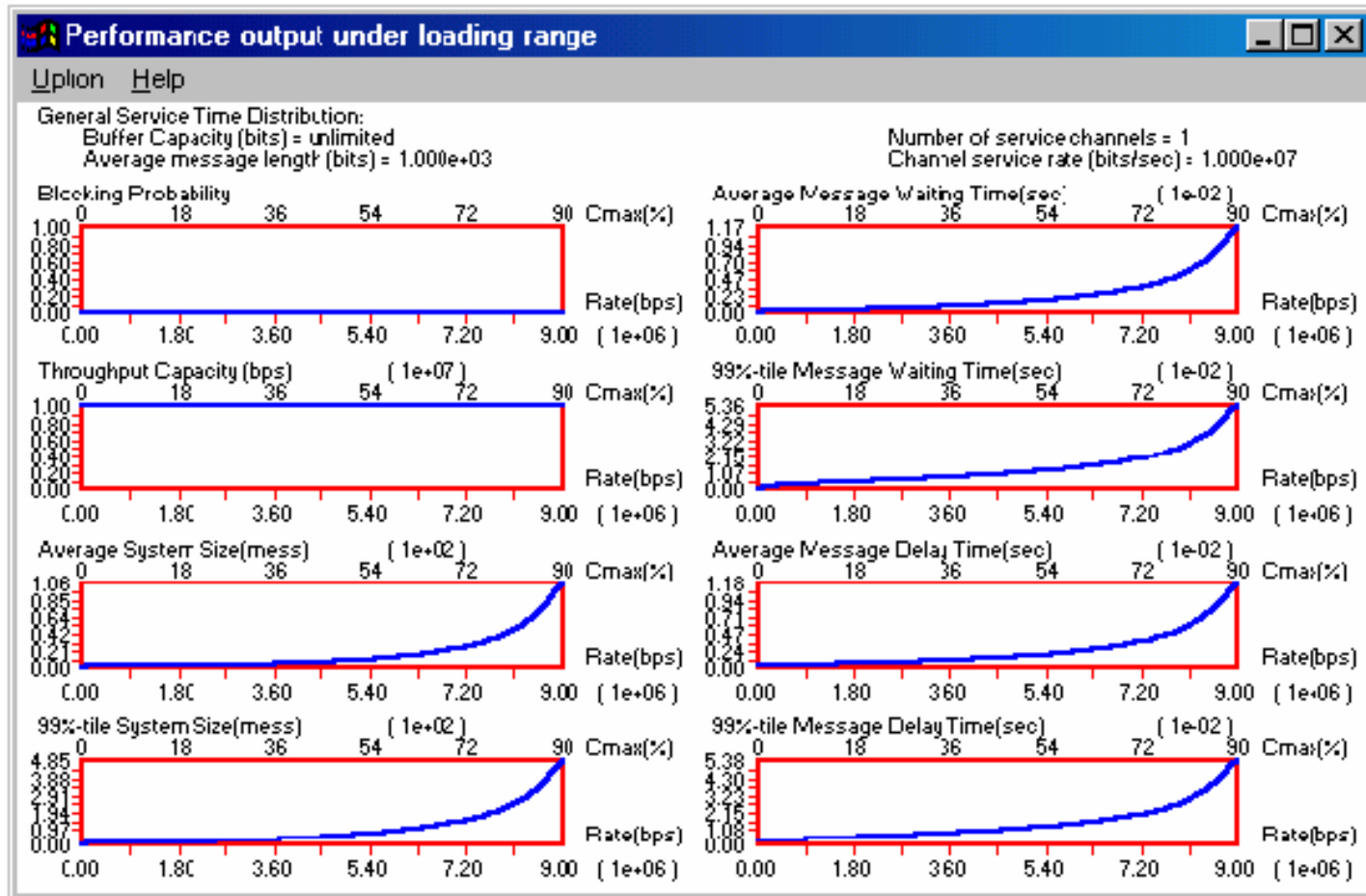
- Single Loading Level
  - Message Arrival Rate (bits/sec)
  - Message Arrival Rate (mess/sec)
- Loading Range
  - Overall Loading Range
  - Specified Range of Message Arrival Rate (bits/sec)
    - Minimum Rate (bps)
    - Maximum Rate (bps)
  - Specified Range of Message Arrival Rate (mess/sec)
    - Minimum Rate (mess/sec)
    - Maximum Rate (mess/sec)

Graph    Update    Set Default    Close    Help

# PLANYST: Design using Analytical Performance Sensitivity Evaluations



# PLANYST: Performance under Loading Range – analytical methods for the design process



# PLANYST: Performance Behavior under a loading level for multiple message priority queueing system

