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Distributed Neural Network Control of Packet Networks:
QoS, Smart Routing and DARPA's Control Plane

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The Internet Architecture: A Historical Perspective

- It was Invented "Against" the Telecoms Industry because of DoD's Dissatisfaction with Telephony for Dependable Communications

- The Initial System was Built on top of Analog Telephony

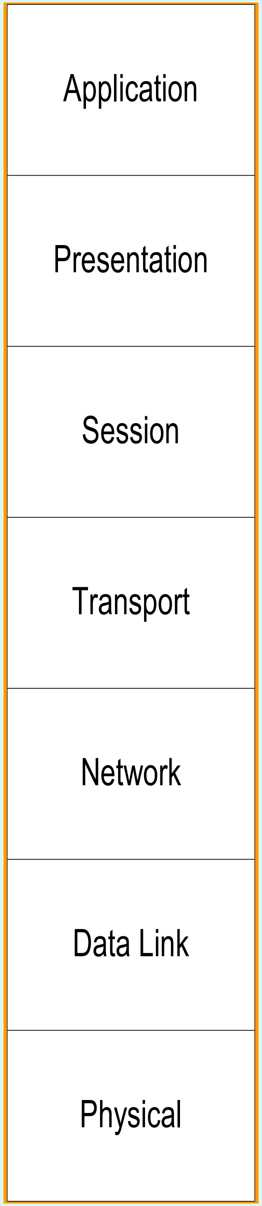
- The Telecoms Industry Fought it for Many Years and Created Competing Services (e.g. Minitel, Teletext) .. and so did some of the Computer Industry (IBM's EARN & Frame Relay)

- The First Major Application was File Transfer .. E-mail ran under FTP

- The Internet grew in a Time of Deregulation based on Loose Standardizatior (e.g. IETF)

Internet Protocols in Theory: OSI Layers

- TCP/IP is a layered protocol stack
- *Application* handles particular applications, *Presentation* handles compression and encryption of data, *Session* controls establishment, management, termination of sessions
- *Transport* provides flow of data
- *Network* handles the transmission of packets in the network
- *Data-link* is responsible for the interaction of the device driver in the operating system and the network card in the machine
- *Physical* defines electrical and mechanical specifications



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Internet Architecture in Reality: An Assembly of Inter-dependent Protocols

- The Web is one possible “Standard User Interface”
- TCP the Transmission Control Protocol: Controls Packet Flow for a Connection as a Function of Correctly Received or Lost Packets (TCP Reno, Vegas, etc.) & Retransmits Lost Packets
- BGP: Determines Paths between Clouds of Routers belonging to Autonomous Systems (AS)
- MPLS: Carries out fast Packet Switching based on Pre-determined Paths within ASs using Labels, and Implements Traffic Engineering within ASs
- IP (Internet Protocol) Implements Shortest Path Routing within ASs. Variants of IP Address QoS (e.g. IPV6), Weighted Fair Queueing, Congestion Control through Packet Drop …

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Internet Architecture: A Distributed System which has Evolved through Usage and Practice

- It has grown in a Time of Deregulation
- The Web was developed to store technical papers
- TCP is a Rudimentary Congestion Control Mechanism
- BGP Allows Different ISPs to Exchange Traffic
- MPLS Exploits ATM-like Fixed Path Routing and Reduces the Overhead of Packet Switching
- The IP (Internet Protocol) provides Router Based Staged Decisions & Shortest Paths to Minimize Overhead

Internet Traffic: Myths and Facts

- Internet Traffic is Generated by Feeders: Ethernet (business), Cable Modems (homes), Wireless Hubs (under development)
- Carrying Internet Traffic is NOT Yet Big Business: Telephony IS Big Business
- Only 10-15% of Traffic Income for Major Carriers (e.g. AT&T) Originates in the Internet
- Income is Generated in the Services, Hardware and Software Industries .. Looks just like the IT Industry
- Exponential Growth of Internet Traffic is a Myth … Telephony has Dominated the Growth in Recent Years
- Quality of Service could change all of that: e.g. Voice over IP

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The Internet in 2004: Critique from the Founding Fathers (DARPA)

- “Flaws in the basic building blocks of networking and computer science are hampering reliability, limiting flexibility and creating security vulnerabilities”

(Note that DARPA paid for most of these developments !!)

- DARPA wants to see the IP and the OSI protocol stack revamped
- “The packet network paradigm … needs to change … we must … have some mechanism for assigning capabilities to different users … today’s networks are stationary and have a static infrastructure … (mobile) nodes should be able to automatically sign on to networks in their vicinity …

The Internet: DARPA’s Main Points – and their current Research Agenda in the Control Plane Program

- Assigning capabilities to different users … How to offer Quality of Service and Service Level Guarantees to Different Users and User Classes, and how to Monitor the Outcome
- (Mobile) nodes should be able to automatically sign onto networks in their vicinity … Designing Ad Hoc Networks, either Wired or Wireless
- Specific Problems of Sensor Networks, either Wired or Wireless: Networks with Intermittent, Highly Bursty, and Urgent Needs

The Need for Quality of Service

- Identify and eliminate undesirable traffic flows (e.g. SPAM)
- Protect the System from Malicious Attacks: Viruses and Worms, Denial of Service Attacks
- Identify services and charge for them
- Provide security to connections
- Provide strict time & loss guarantees for packet delivery
- More sophisticated quantitative QoS metrics (e.g. jitter)
- Measurable service levels
- Wireless makes it all the more Urgent

The Means for Quality of Service

- Effective user interfaces into the Internet
- Pro-active interrogation and monitoring of users
- On-line monitoring of flows
- Pro-active measurement of elapsed time
- Pro-active measurement of packet losses
- Monitoring of QoS and Service Level Agreements
- Technical approaches which Cross or Combine Protocol Layers

In Theory, Global QoS Optimisation is Possible: Network Routing subject to QoS Constraints

Let $G = (N, L)$ be a graph with node set N and link set L. A link with origin node m and destination node n is denoted by (m, n). With $N_+(n)$ and $N_-(n)$ we denote the set of incoming and outgoing neighbors to node n, that is, respectively,

$$N_+(n) = \{m \in N : (m, n) \in L\},$$
$$N_-(n) = \{m \in N : (n, m) \in L\}.$$

With each link $l = (m, n)$, $m, n \in N$ there is an associated cost $c_{mn} \geq 0$ and delay $d_{mn} \geq 0$. If $p = (m_1, ..., m_k)$ is a directed path (a subgraph of G consisting of nodes $m_1, ..., m_k$, $m_i \neq m_j$ for all $1 \leq i, j \leq k$, $i \neq j$, and links (m_i, m_{i+1}), $1 \leq i \leq k-1$) then we define the cost and delay of the path respectively,

$$C(p) = \sum_{(m,n)\in p} c_{mn}.$$
$$D(p) = \sum_{(m,n)\in p} d_{mn}.$$

The set of all paths with origin node s, destination node n and delay less than of equal to d is denoted by $P_{sn}(d)$. The set of all paths from s to n is denoted simply by P_{sn}. For any d, we are interested in finding a path $p^* \in P_{sn}(d)$ such that

$$C(p^*) \leq C(p) \text{ for all } p \in P_{sn}(d).$$

Difficulties of Global Optimisation

- The network is very large – for specific users, optimisation is relevant for a subset of routes at a time
- The system is large .. information delay, control delay and combinatorial explosion: global algorithms can be very slow and come too late
- The system is highly dynamic – traffic varies significantly over short periods of time
- There are large quantities of traffic in the pipes – congestion can occur suddenly, reaction and detours must be very rapid
- Measurements local to subset of users, and adaptivity is needed which is relevant to the users most concerned by the measurements

The Alternative: On-Line Measurement and Adaptation

- Many Internet applications have QoS requirements
  - Voice over IP, video conferencing
  - Time Critical and Secure Applications
  - Network games and networked simulation
  - Web based commerce and banking
- QoS techniques based on "parameter setting" such as IntServ, DiffServ and IPv6 have not been successful
- Users should formulate their QoS Needs, smart packets can be used probe, gather measurements and select routes, dumb packets transport data, and also gather measurements

Quote from Lockheed Martin & Cisco's Report to Darpa (March 8, 2004)

… We believe the next evolution in path switching will be the employment of various infrastructure sensing devices to collect path data and allow a user, a network administrator, or an automated process to specify paths to routers within their domain authority … the cognitive router (CR) schema that was developed by Erol Gelenbe under the rubric of 'cognitive packet networks (CPN)' [2] … represents a dramatic change in the ability of a network to make intelligent routing decisions. CRs use neural networks that essentially form multi-dimensional routing tables that respond immediately to the route performance parameters captured by the packets flowing through them. CRs employ extended QoS parameters and can change routes when they recognize route degradation. Because decisions are based only on local information provided by the smart packets, CRs are not afflicted with the problems inherent in … BGP … "

The Cognitive Packet Network Approach (Patent Pending)

- Let the Measurements and On-Line Adaptation be under user control
- Let the user make his/her own QoS and economic decisions
- Remain close to, and compatible with the core IP protocol
- Allow TCP to run ABOVE CPN .. If needed

OSI Layers & CPN

- TCP/IP is a layered protocol stack
- *Application* handles particular applications, *Presentation* handles compression and encryption of data, *Session* controls establishment, management, termination of sessions
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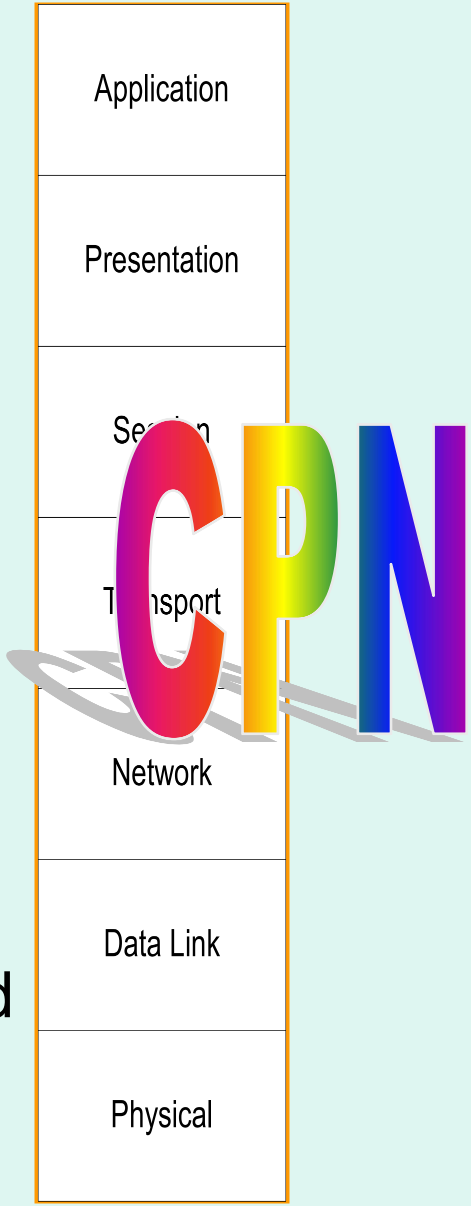
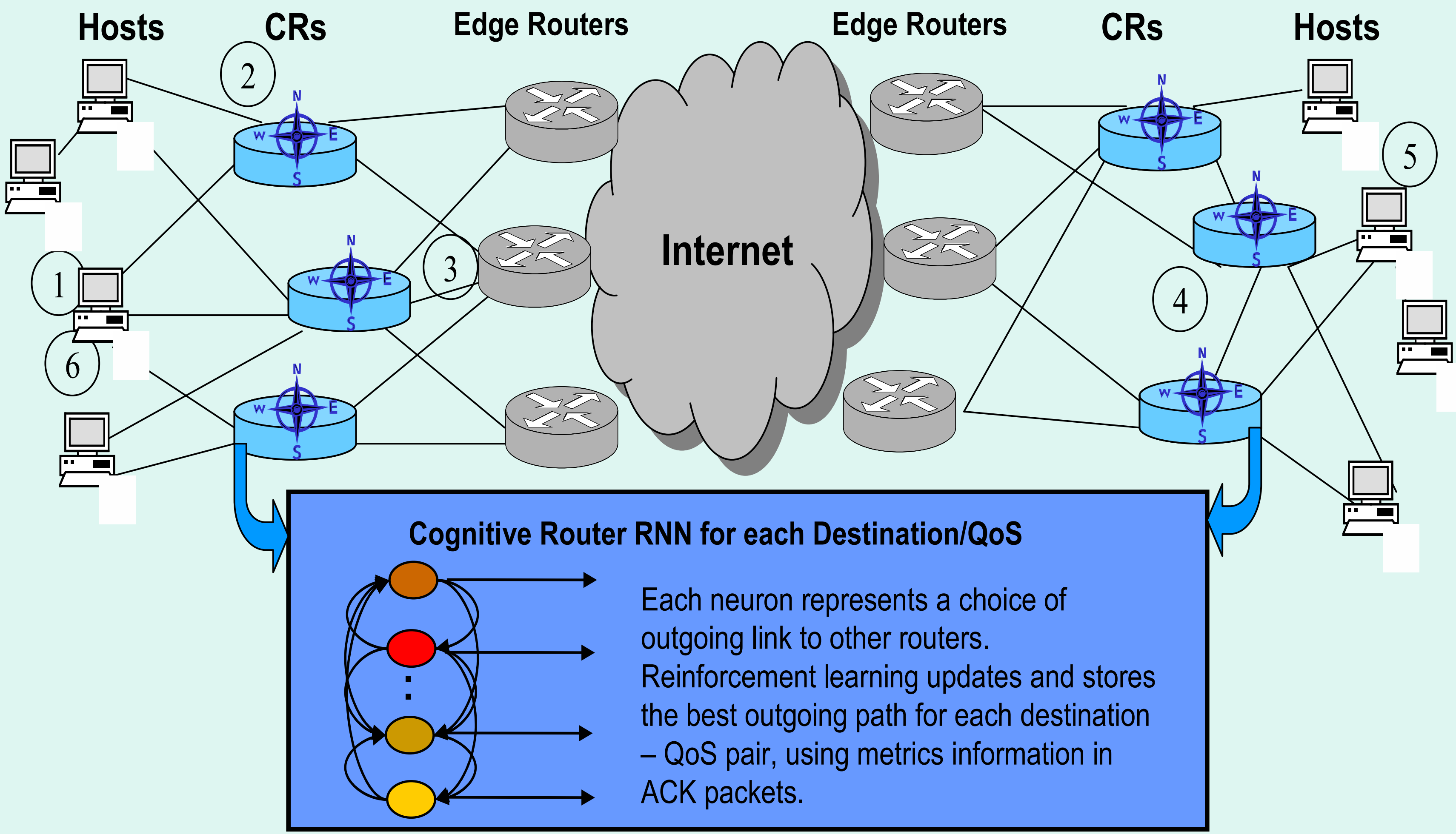


QoS in the Internet can be Controlled via CPN's Cognitive Routers Operating at the Periphery of the IP World



CPN Principles

- CPN operates seamlessly with IP and creates a self-aware network environment
- Users select QoS goals
- The User's Packets collectively learn to achieve the goals
- Learning is performed by sharing information between packets
- User Packets sharing the same goals can be grouped into *classes*
- Nodes (Cognitive Routers) are storage centers, mailboxes and processing units

CPN and Smart Packets

Smart Packets route themselves based on QoS Goals, e.g.,

- Minimise Delay or Loss or Combination
- Minimise Jitter (for Voice)
- Maximise Dispersion (for security)
- Minimise Cost
- Optimise Cost/Benefit

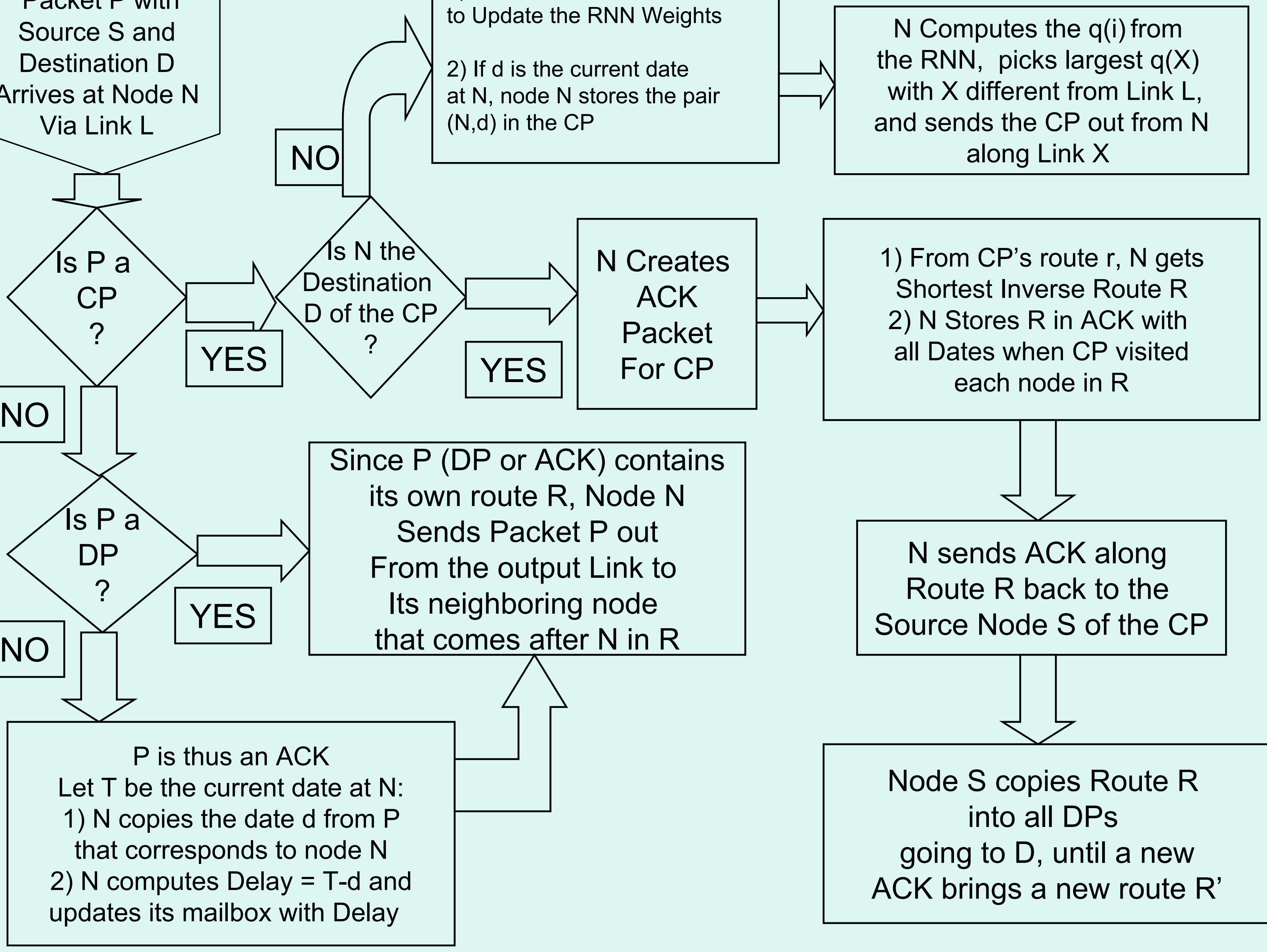
Smart Packets make observations & take decisions

ACK Packets bring back observed data and trace activity

Dumb Packets execute instructions, carry payload and also may make observations

Cognitive Adaptive Routing

- Conventional QoS Goals are extrapolated from Paths, Traffic, Delay & Loss Information – this is the "Sufficient Level of Information" for Self-Aware Networking
- Smart packets collect path information and dates
- ACK packets return Path, Delay & Loss Information and deposit W(K,c,n,D), L(K,c,n,D) at Node c on the return path, entering from Node n in Class K
- Smart packets use W(K,c,n,D) and L(K,c,n,D) for decision making using Reinforcement Learning



Packet P with Source S and Destination D Arrives at Node N Via Link L
Is P a CP ?
YES
NO
Is N the Destination D of the CP ?
NO
to Update the RNN Weights
2) If d is the current date at N, node N stores the pair (N,d) in the CP
N Computes the q(i) from the RNN, picks largest q(X) with X different from Link L, and sends the CP out from N along Link X
YES
N Creates ACK Packet For CP
1) From CP's route r, N gets Shortest Inverse Route R
2) N Stores R in ACK with all Dates when CP visited each node in R
N sends ACK along Route R back to the Source Node S of the CP
Node S copies Route R into all DPs going to D, until a new ACK brings a new route R'
Is P a DP ?
YES
NO
Since P (DP or ACK) contains its own route R, Node N Sends Packet P out From the output Link to Its neighboring node that comes after N in R
P is thus an ACK
Let T be the current date at N:
1) N copies the date d from P that corresponds to node N
2) N computes Delay = T-d and updates its mailbox with Delay

Mathematical Model of the Decision Network:

A "neural" network with n neurons

Internal State of Neuron i, is an Integer $x_i \geq 0$

Network State at time t is a Vector

$x(t) = (x_1(t), \ldots, x_i(t), \ldots, x_k(t), \ldots, x_n(t))$

Is the Internal Potential of Neuron I

If $x_i(t) > 0$, we say that Neuron i is excited and it may fire at t^+ in which case it will send out a spike

If $x_i(t)=0$, the Neuron cannot fire at t^+

When Neuron i fires: :

- It sends a spike to some Neuron k, w.p. p_{ik}
- Its internal state changes $x_i(t^+) = x_i(t) - 1$

State of Network

$x(t) = (x_1(t), \ldots, x_i(t), \ldots, x_l(t), \ldots, x_n(t)), x_i(t) \geq 0$

If $x_i > 0$, we say that Neuron i is excited

f $x_i(t) > 0$, then Neuron i will fire with probability $r_i \Delta t$ in the interval $[t, t+\Delta t]$, and as a result:

Its internal state changes $x_i(t^+) = x_i(t) - 1$

It sends a spike to some Neuron m w.p. p_{im}

he arriving spike at Neuron m is an

- Excitatory Spike w.p. p_{im}^+
- Inhibitory Spike w.p. p_{im}^-
- $p_{im} = p_{im}^+ + p_{im}^-$ with $\Sigma^n_{m=1} p_{im} \leq 1$ for all i=1,..,n

Rates and Weights

$x(t) = (x_1(t), \ldots, x_i(t), \ldots, x_l(t), \ldots, x_n(t)), x_i(t)>0$

f $x_i(t)> 0$, then Neuron i will fire with probability

$r_i\Delta t$ in the interval $[t,t+\Delta t]$, and as a result:

From Neuron i to Neuron l

- Excitatory Weight or Rate is $w_{im}^+ = r_i\, p_{im}^+$
- Inhibitory Weight or Rate is $w_{im}^- = r_i\, p_{im}^-$
- Total Firing Rate is $r_i = \Sigma^n_{m=1} w_{im}^+ + w_{im}^-$

To Neuron i, from Outside the Network

- External Excitatory Spikes arrive at rate Λ_i
- External Inhibitory Spikes arrive at rate λ_i

State Equations

$p(k,t) = \Pr[x(t) = k]$ where $\{x(t) : t \geq 0\}$ is a discrete state-space Markov process,

and $k_{ij}^{+-} = k + e_i - e_j$, $\quad k_{ij}^{++} = k + e_i + e_j$

$k_i^{+} = k + e_i$, $\quad k_i^{-} = k - e_i$:

The **Chapman** - Kolmogorov Equations

$$\frac{d}{dt} p(k,t) = \sum_{i,j} [p(k_{ij}^{+-},t) r_i p_{ij}^{+} 1[k_j(t) > 0] + p(k_{ij}^{++},t) r_i p_{ij}^{-}] + \sum_i [p(k_i^{+},t)(\lambda_i + r_i d_i) + \Lambda_i p(k_i^{-},t) 1[k_i(t) > 0]]$$

$$- p(k,t) \sum_i [(\lambda_i + r_i) 1[k_i(t) > 0] + \Lambda_i]$$

Let :

$$p(k) = \lim_{t \to \infty} \Pr[x(t) = k], \quad and \quad q_i = \lim_{t \to \infty} \Pr[x_i(t) > 0]$$

Theorem *If the* $C - K$ *equations have a stationary solution,*

then it has the "product − form" $p(k) = \prod_{i=1}^{n} q_i^{k_i} (1 - q_i)$, *where*

External Arrival Rate of Excitatory Spikes

ω^-_{ji}

Probability that Neuron I is excited

$$0 \le q_i = \frac{\Lambda_i + \sum_j q_j \overbrace{r_j p^+_{ji}}}{r_i + \lambda_i + \sum_j q_j \underbrace{r_j p^-_{ji}}} < 1$$

Firing Rate of Neuron i

External Arrival Rate of Inhibitory Spikes

ω^+_{ji}

Theorem (Gelenbe 93, Gelenbe - Schassberger 95)

The system of non-linear equations

$$q_i = \frac{\Lambda_i + \sum_j q_j r_j p_{ji}^{+}}{r_i + \lambda_i + \sum_j q_j r_j p_{ji}^{-}} \quad , \qquad 1 \le i \le n$$

has an unique solution if all the $q_i < 1$.

Theorem (Gelenbe et al. 99) *Let* $g : [0,1]^v \to R$ *be continuous and bounded. For any* $\varepsilon > 0$, *there exists an RNN with two output neurons* q_{o+}, q_{o-} *s.t.*

$$\sup_{x \in [0,1]^v} | g(x) - y(x) | < \varepsilon \qquad for \quad y(x) = \frac{q_{o+}}{1 - q_{o+}} - \frac{q_{o-}}{1 - q_{o-}}$$

Goal Based Reinforcement Learning in CPN

The Goal Function to be minimized is selected by the user, e.g.
$G = [1-L]W + L[T+W]$

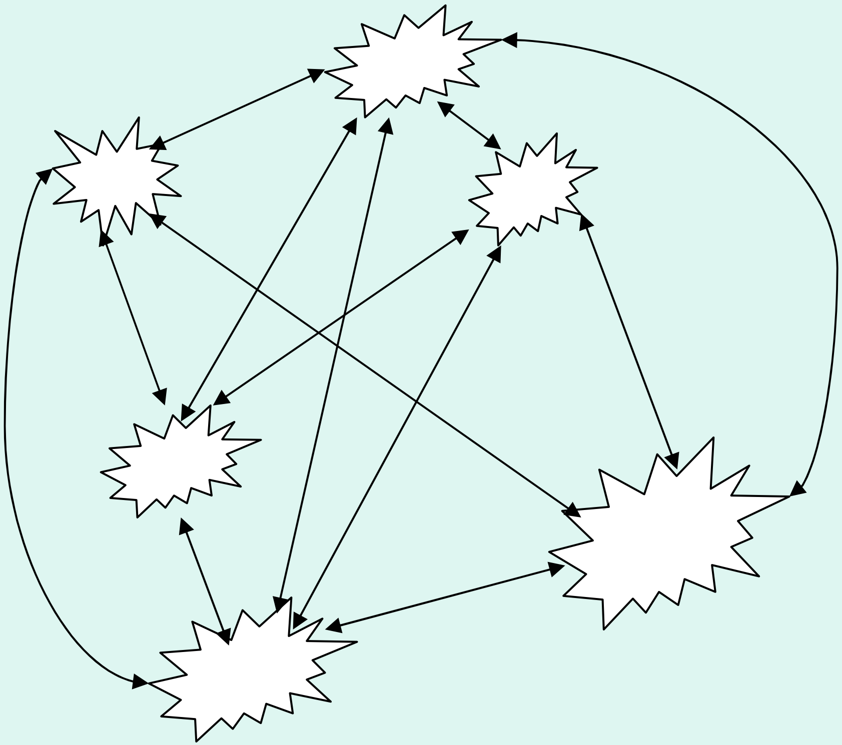
On-line measurements and probing are used to measure L and W, and this information is brought back to the decision points

The value of G is estimated at each decision node and used to compute the estimated reward $R = 1/G$

The RNN weights are updated using R stores G(u,v) indirectly in the RNN which makes a myopic (one step) decision

Routing with Reinforcement Learning using the RNN

- Each “neuron” corresponds to the choice of an output link in the node
- Fully Recurrent Random Neural Network with Excitatory and Inhibitory Weights
- Weights are updated with RL
- Existence and Uniqueness of solution is guaranteed
- Decision is made by selecting the outgoing link which corresponds to the neuron whose excitation probability is largest



Reinforcement Learning Algorithm

- The decision threshold is the Most Recent Historical Value of the Reward

$$T_l = aT_{l-1} + (1-a)R_l, R = G^{-1}$$

- Recent Reward R_l

If $T_{l-1} \leq R_l$ then

$$w^+(i, j) \leftarrow w^+(i, j) + R_l$$

$$w^-(i, k) \leftarrow w^-(i, k) + \frac{R_l}{n-2}, k \neq j$$

else

$$w^+(i, k) \leftarrow w^+(i, k) + \frac{R_l}{n-2}, k \neq j$$

$$w^-(i, j) \leftarrow w^-(i, j) + R_l$$

- Re-normalise all weights

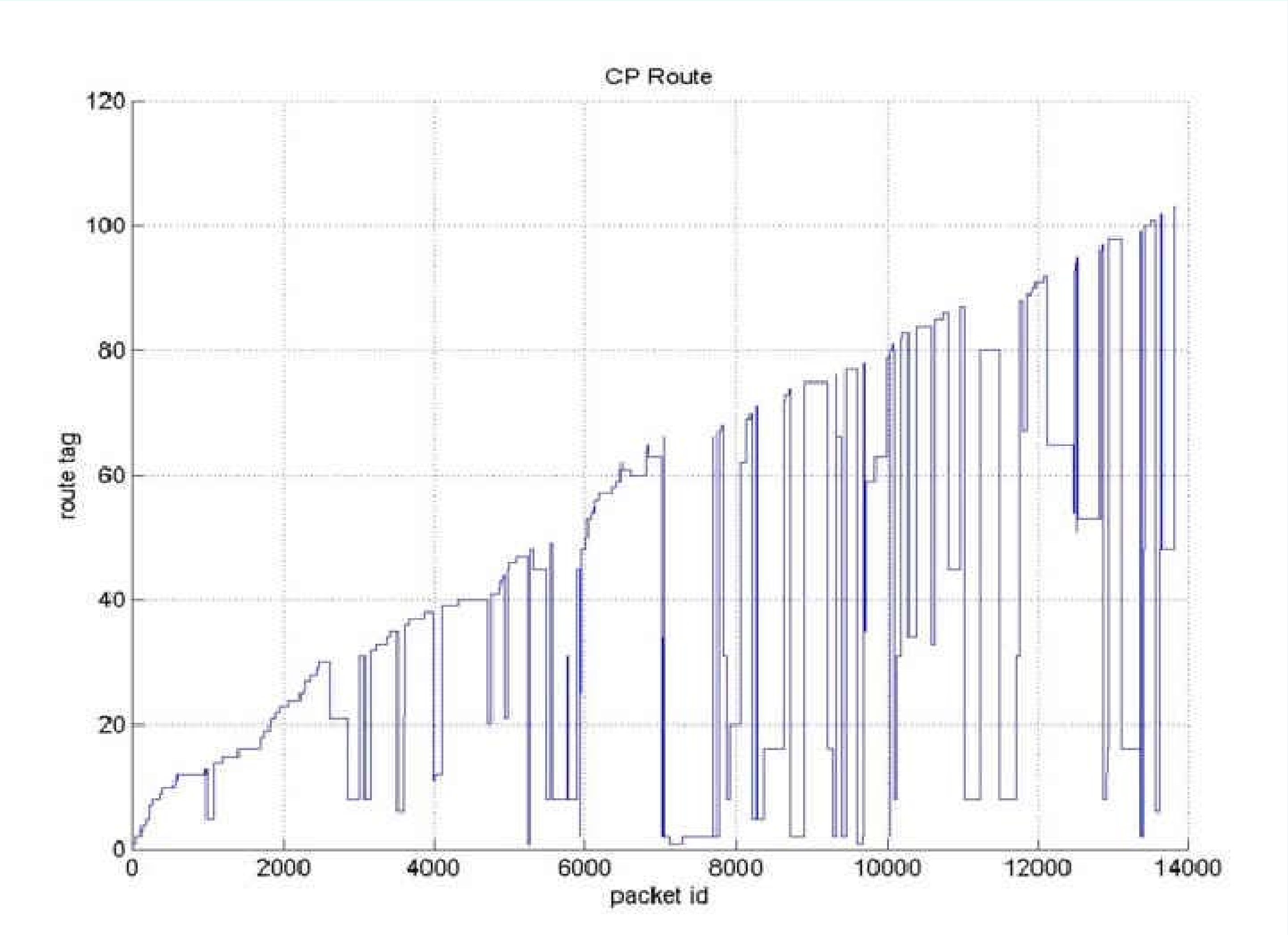
$$r_i^* = \sum_{1}^{n} [w^+(i,m) + w^-(i,m)]$$

$$w^+(i,j) \leftarrow w^+(i,j) \frac{r_i}{r_i^*}$$

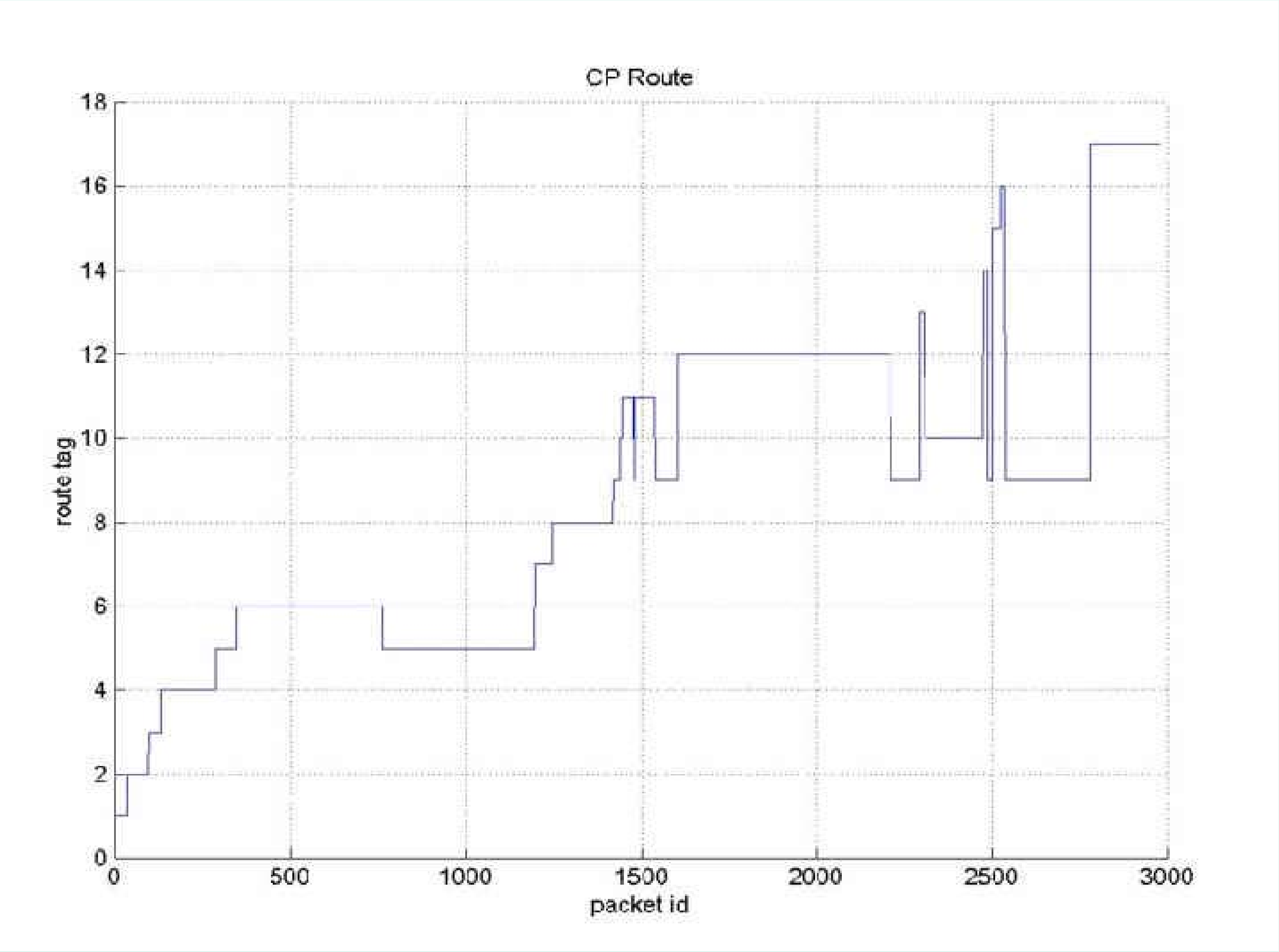
$$w^-(i,j) \leftarrow w^-(i,j) \frac{r_i}{r_i^*}$$

- Compute $q = (q_1, \ldots, q_n)$ from the fixed-point
- Select Decision k such that $q_k > q_i$ for all i=1, …, n

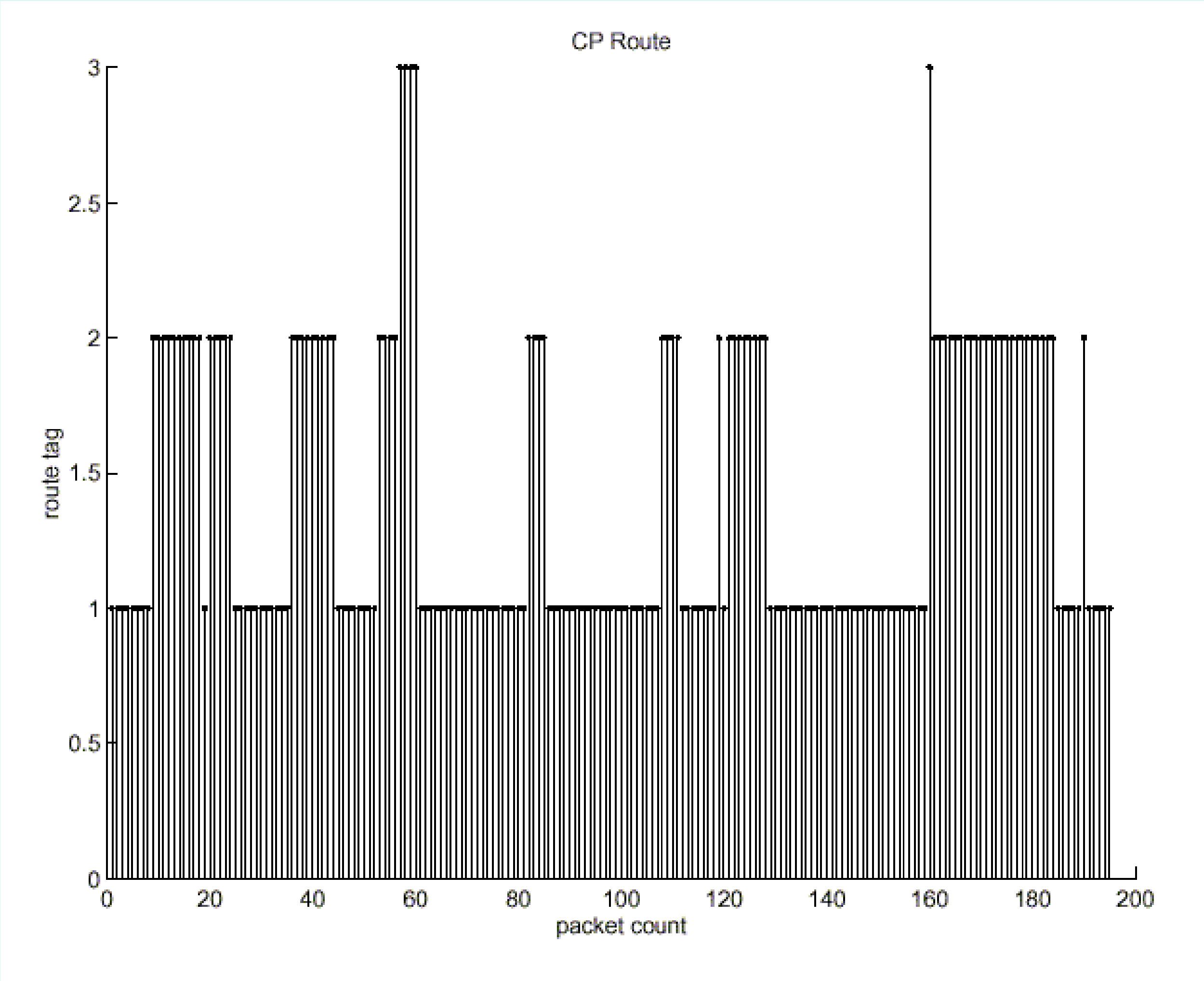
CPN Test-Bed Measurements
On-Line Route Discovery by Smart Packets



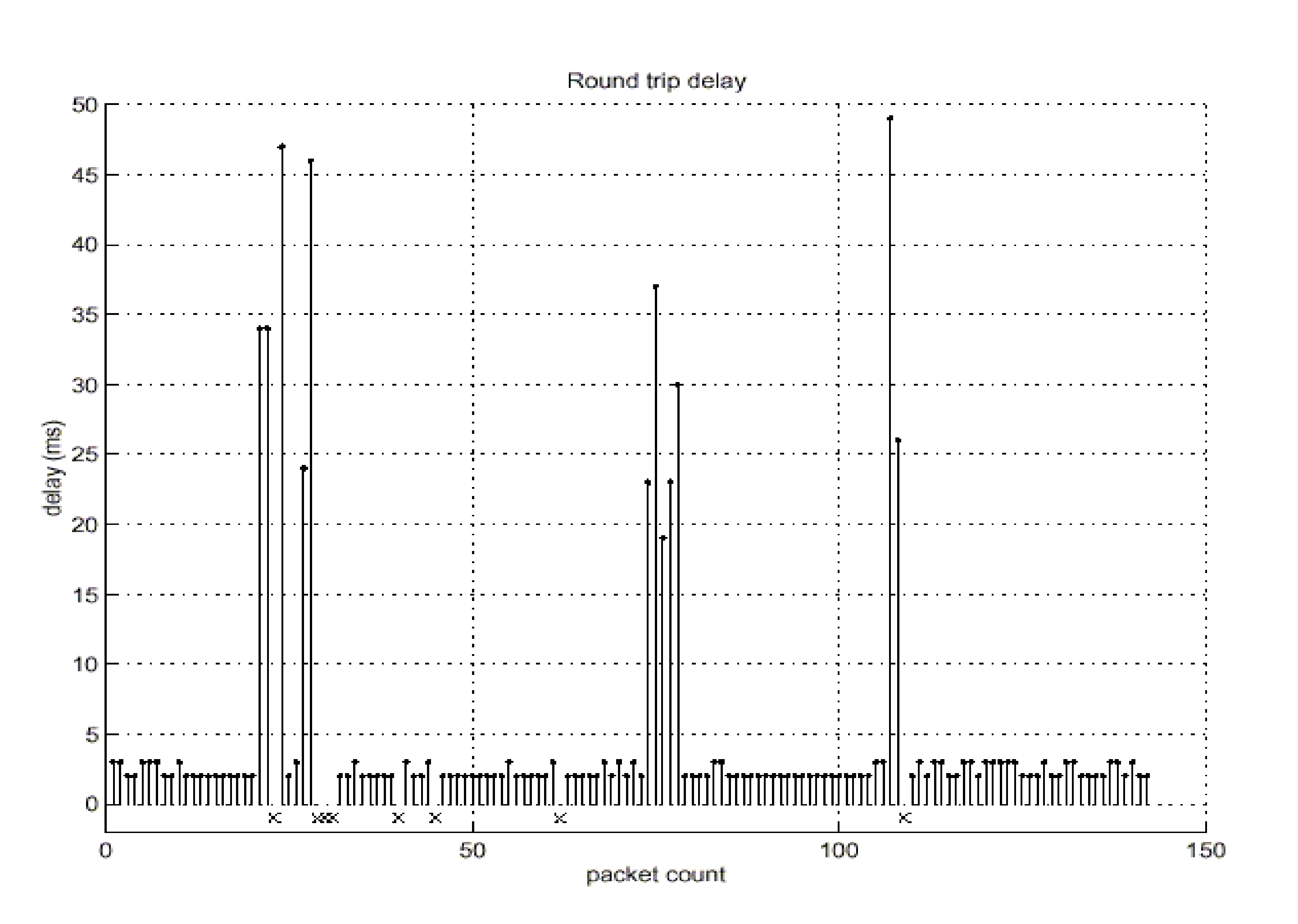
CPN Test-Bed Measurements
Ongoing Route Discovery by Smart Packets



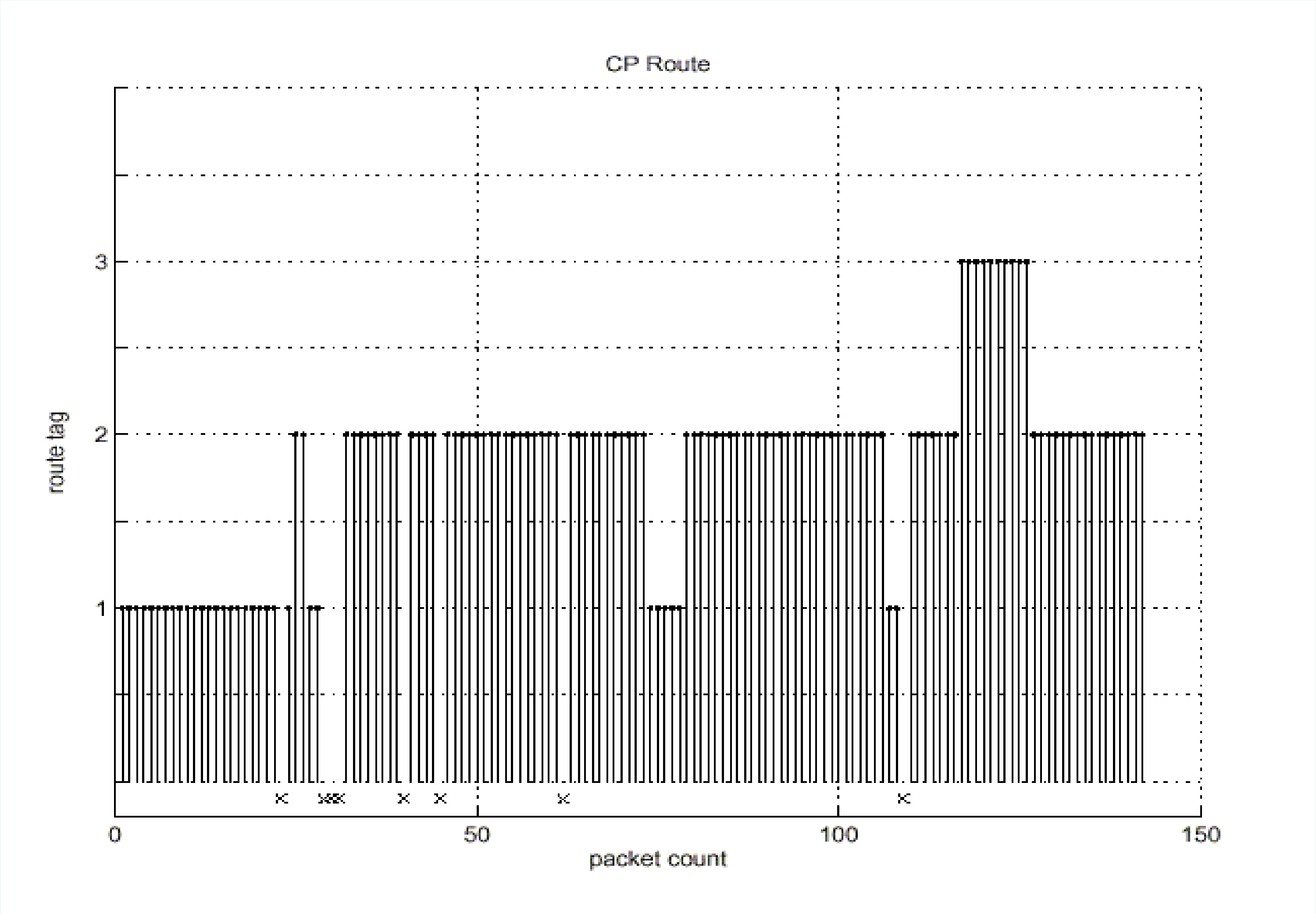
Route Adaptation without Obstructing Traffic



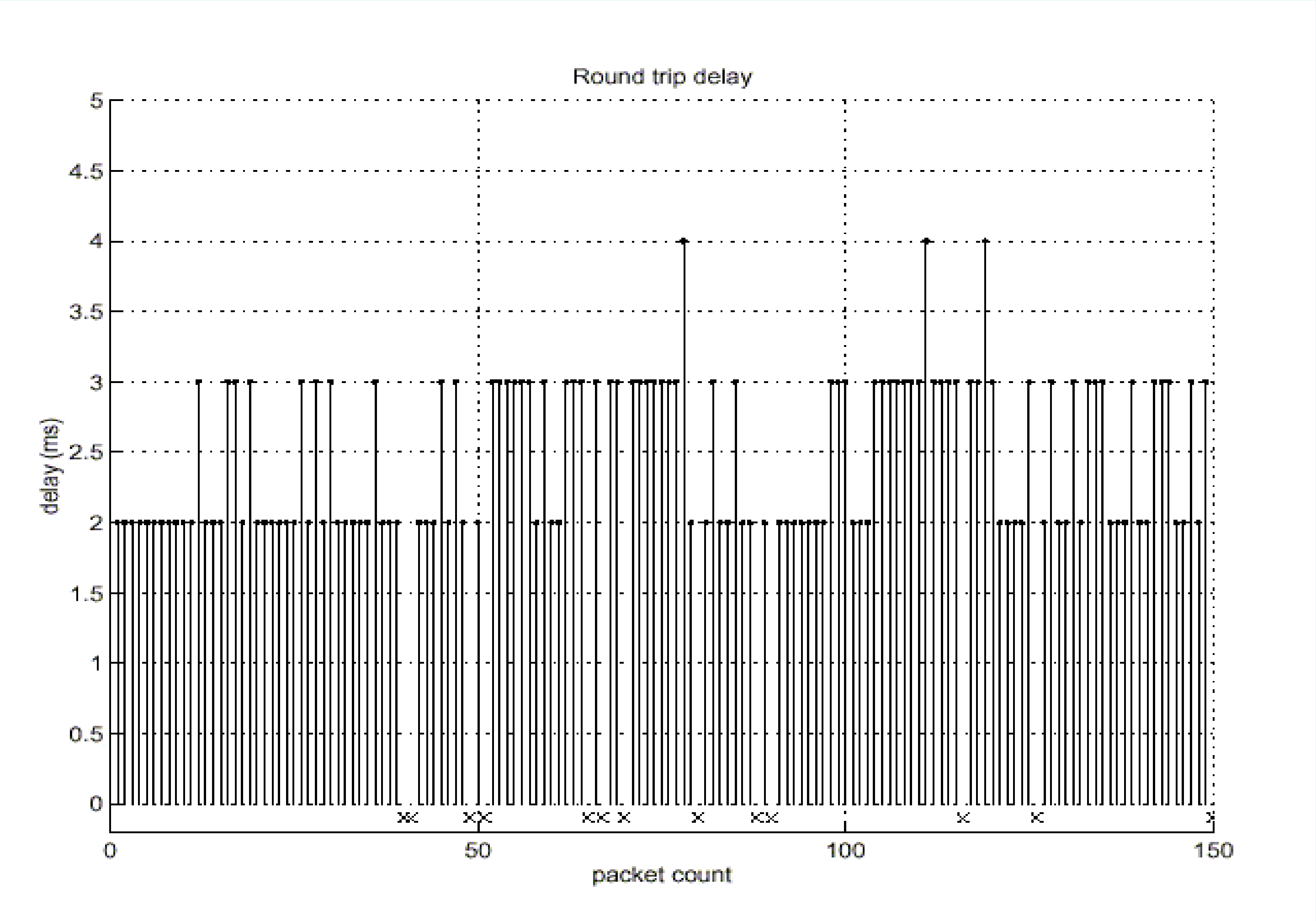
Packet Round-Trip Delay with Saturating Obstructing Traffic at Count 30



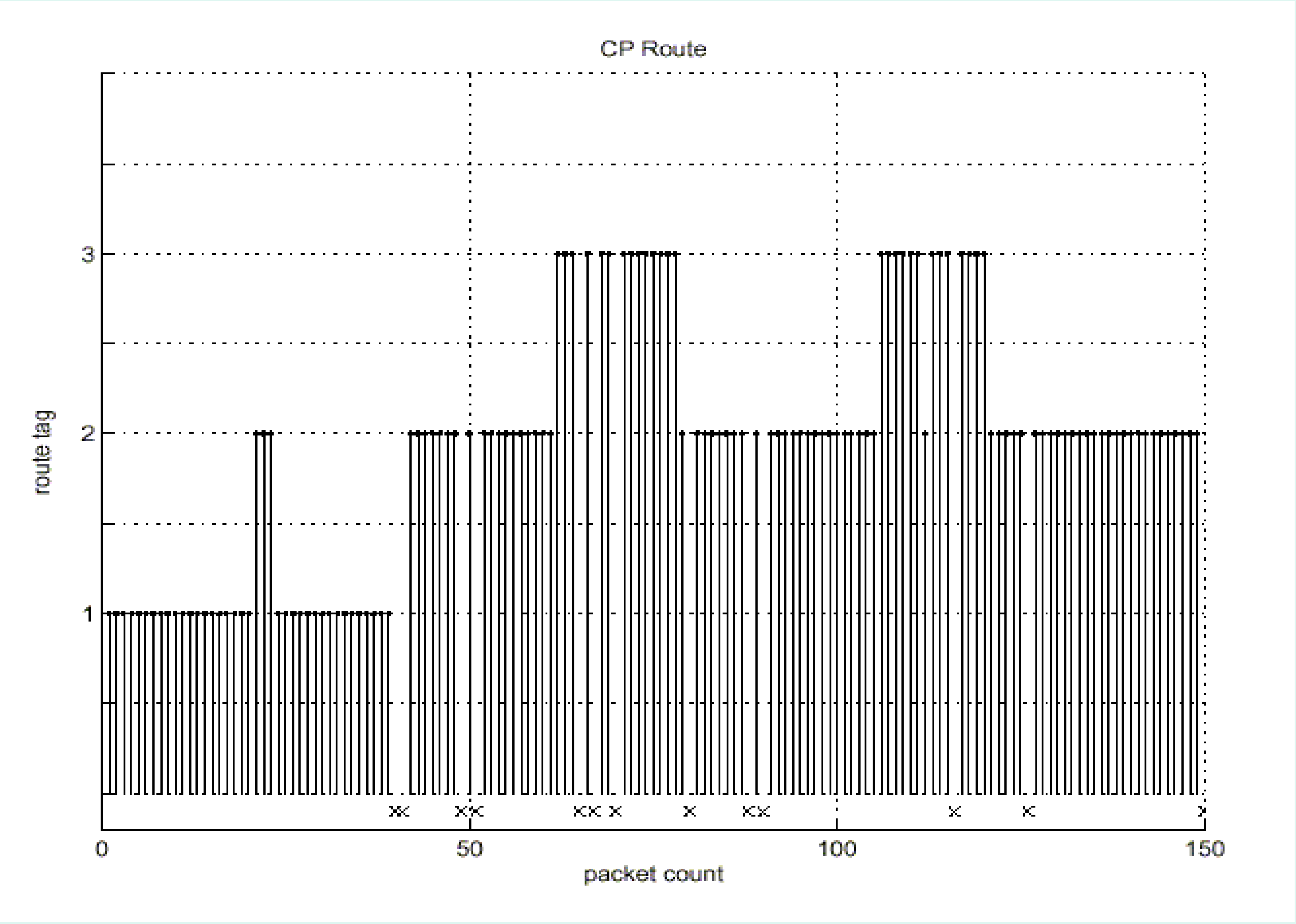
Route Adaptation with Saturating Obstructing Traffic at Count 30

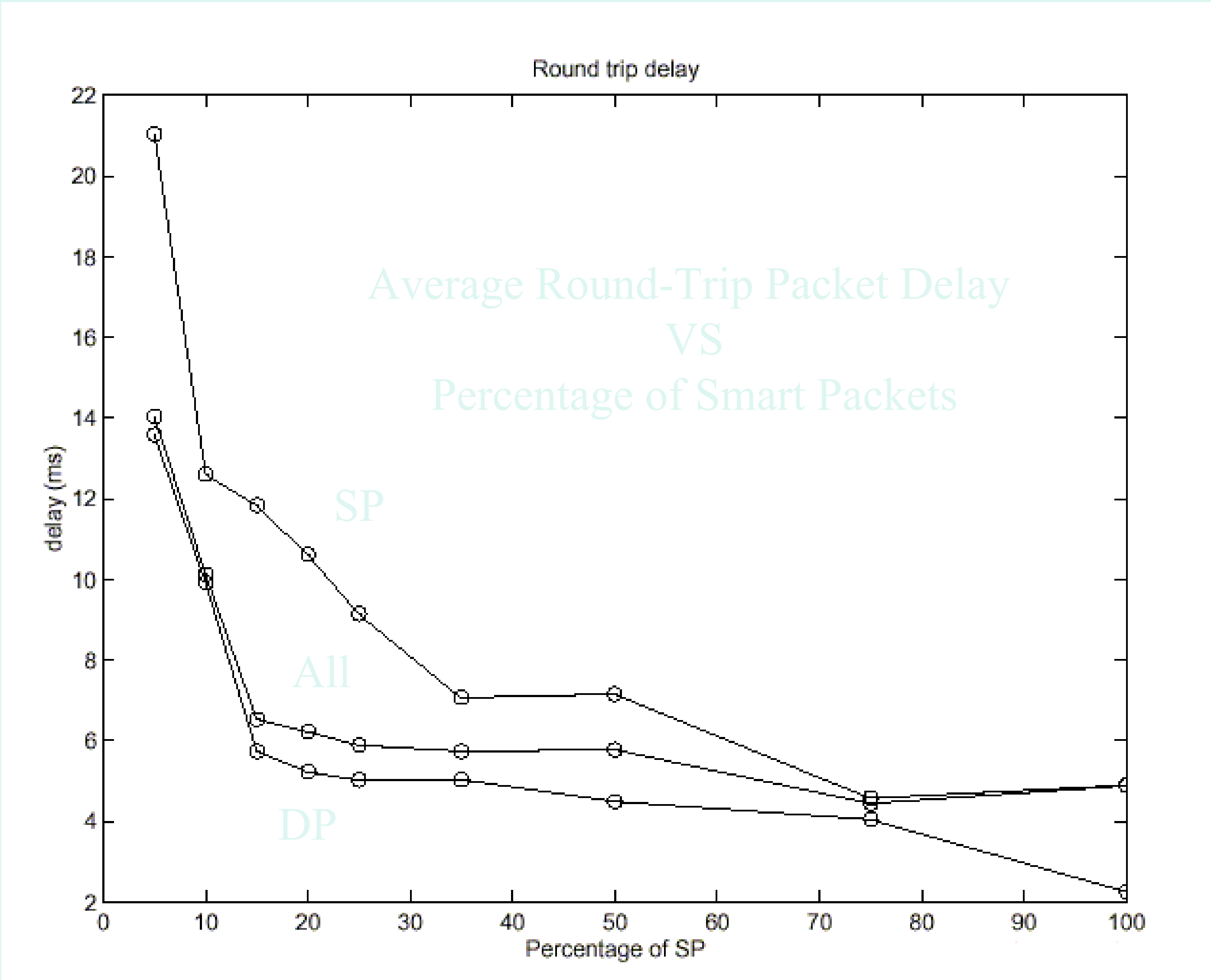


Packet Round-Trip Delay with Link Failure at Count 40



Packet Round-Trip Delay with Link Failure at Count 40




Round trip delay
Average Round-Trip Packet Delay
VS
Percentage of Smart Packets
SP
All
DP
delay (ms)
Percentage of SP
22
20
18
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90
100

A QoS Driven Application Voice over CPN

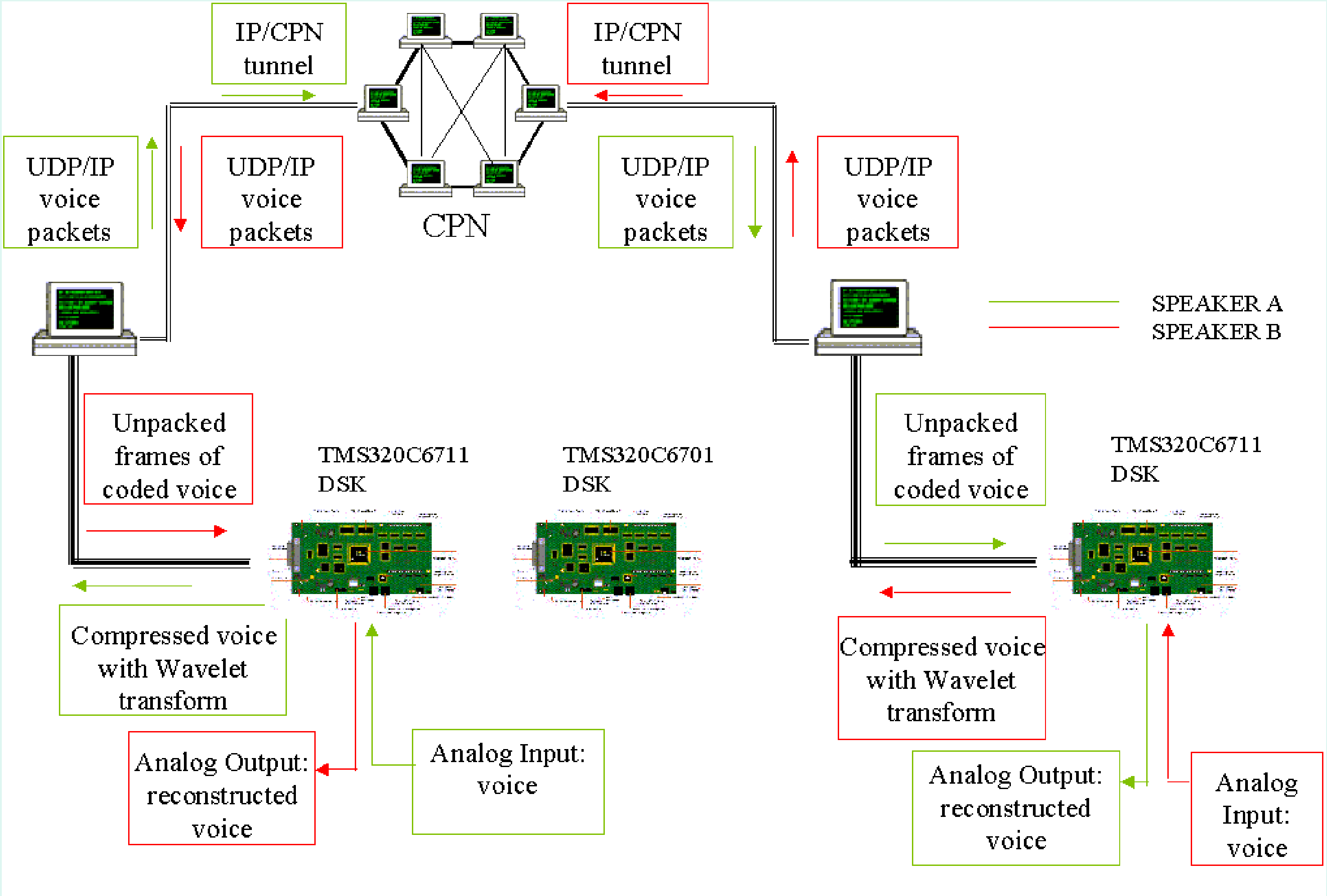


Fig. 1. Voice over CPN

Experimental Results
Voice over CPN

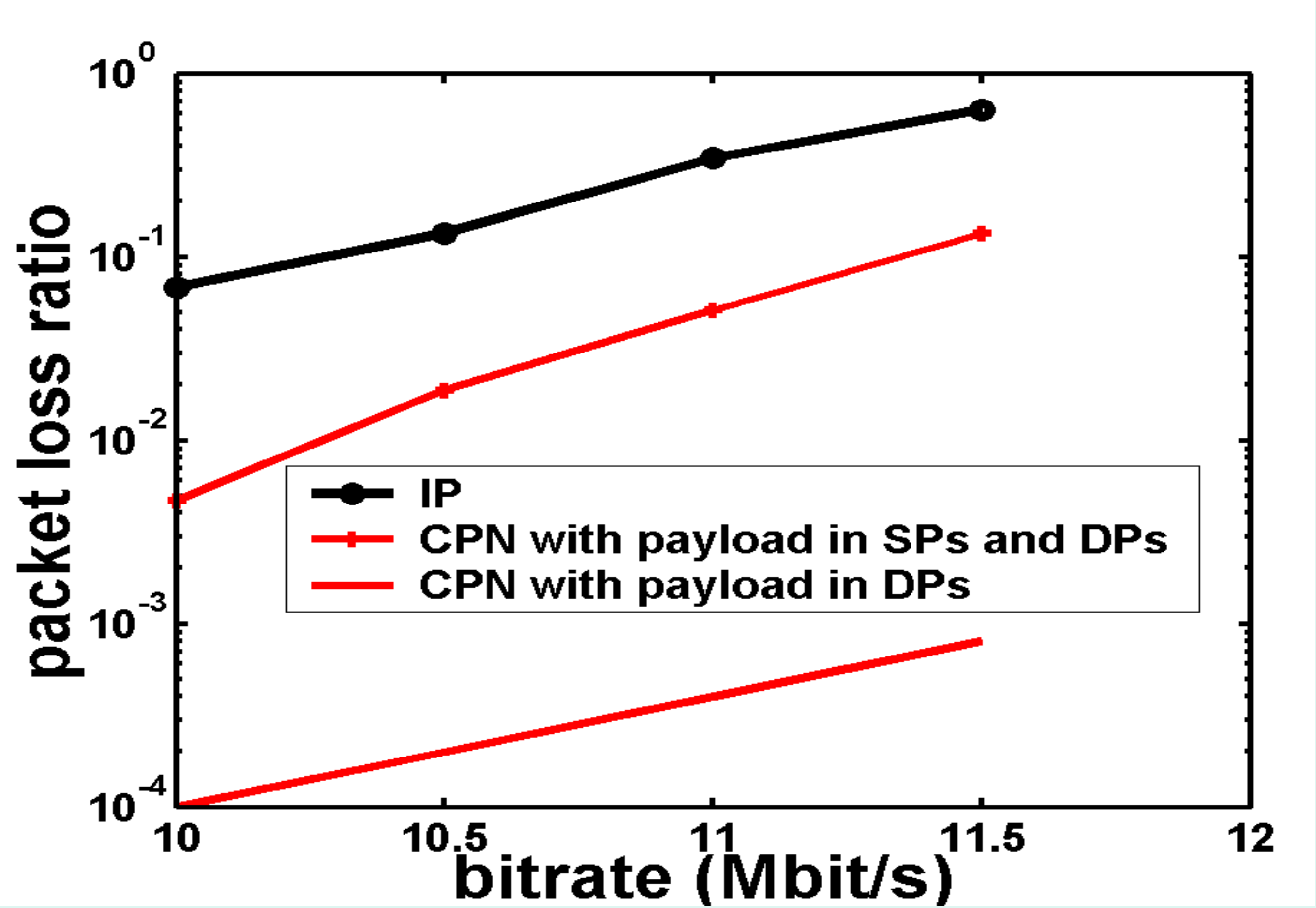
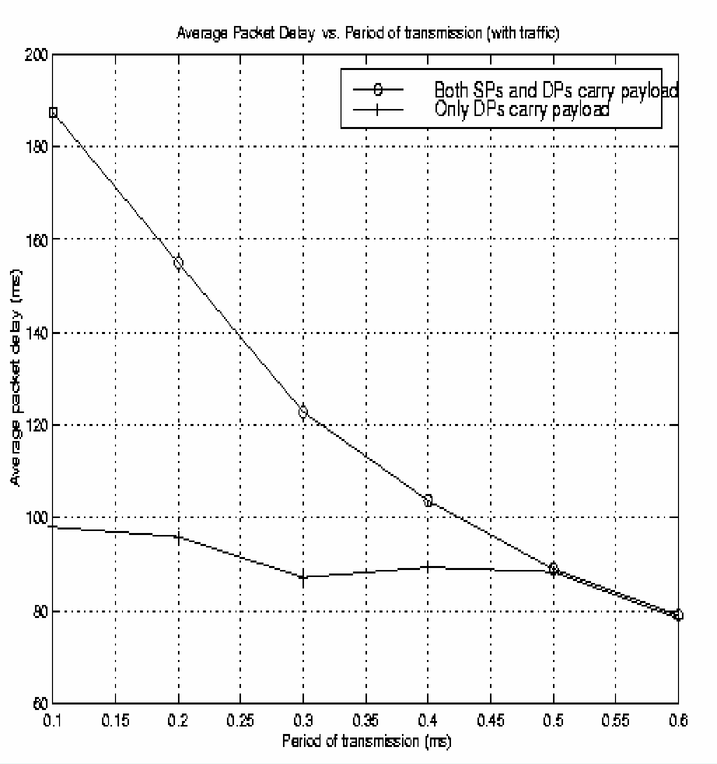


Fig. 4

Experimental Results
Voice over CPN



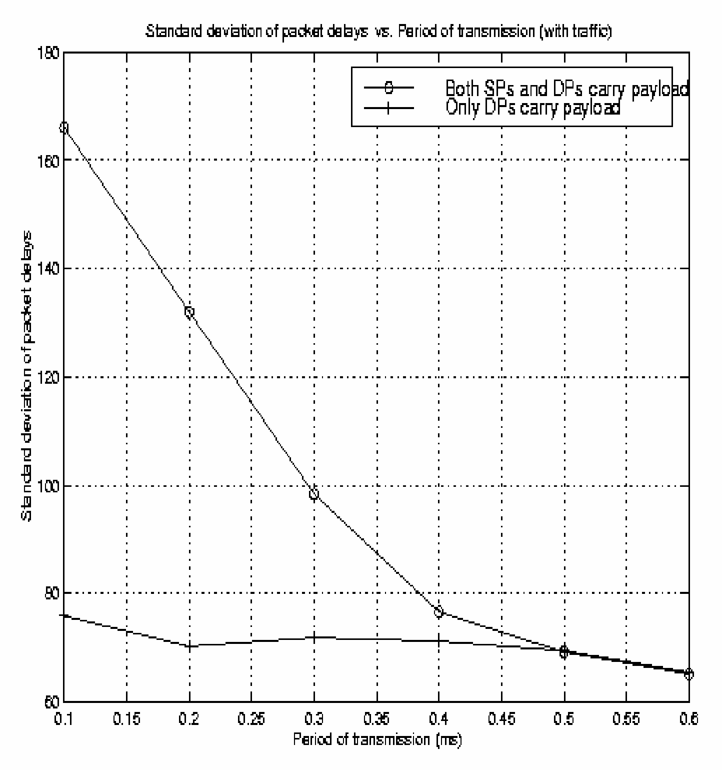


Fig. 6 : Average round-trip delay (left) and jitter (right) for user payload when only DPs are allowed to carry user payload

Experimental Results: Voice over CPN
Packet De-sequencing Probability at Receiver vs Packet Rate

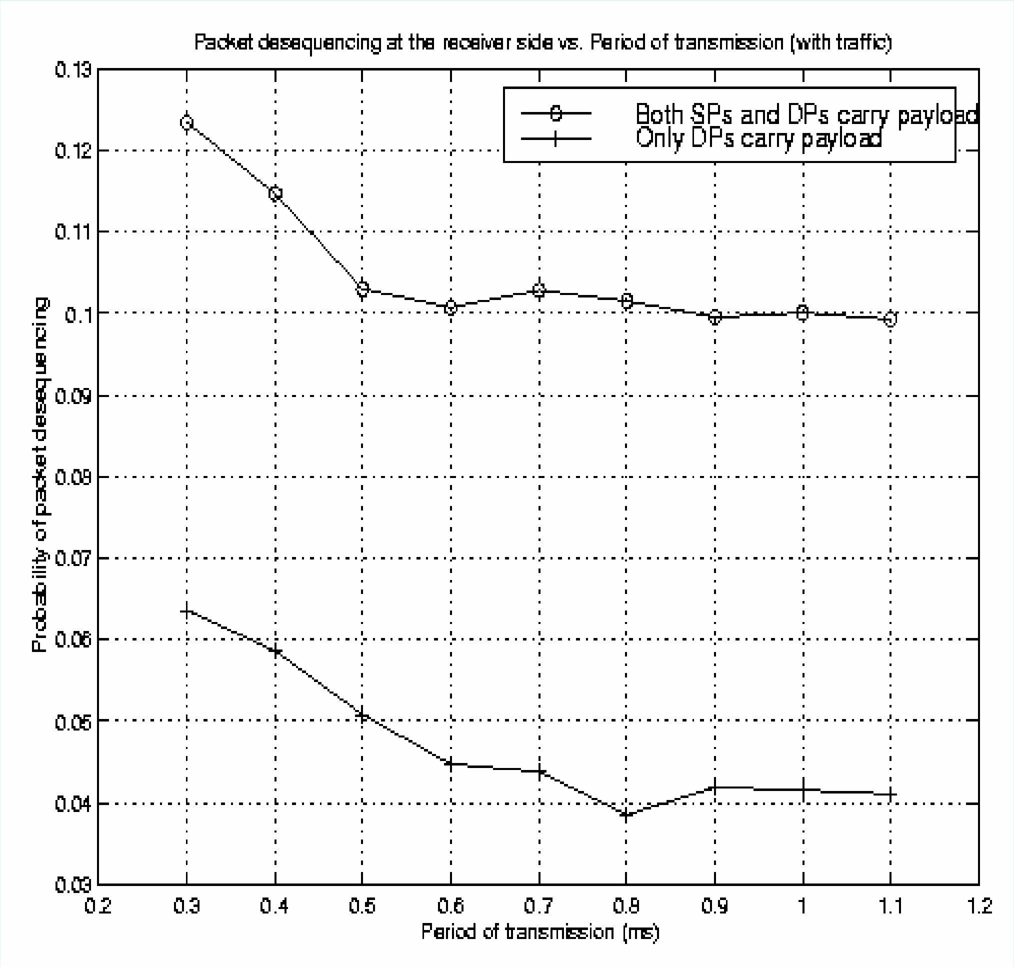
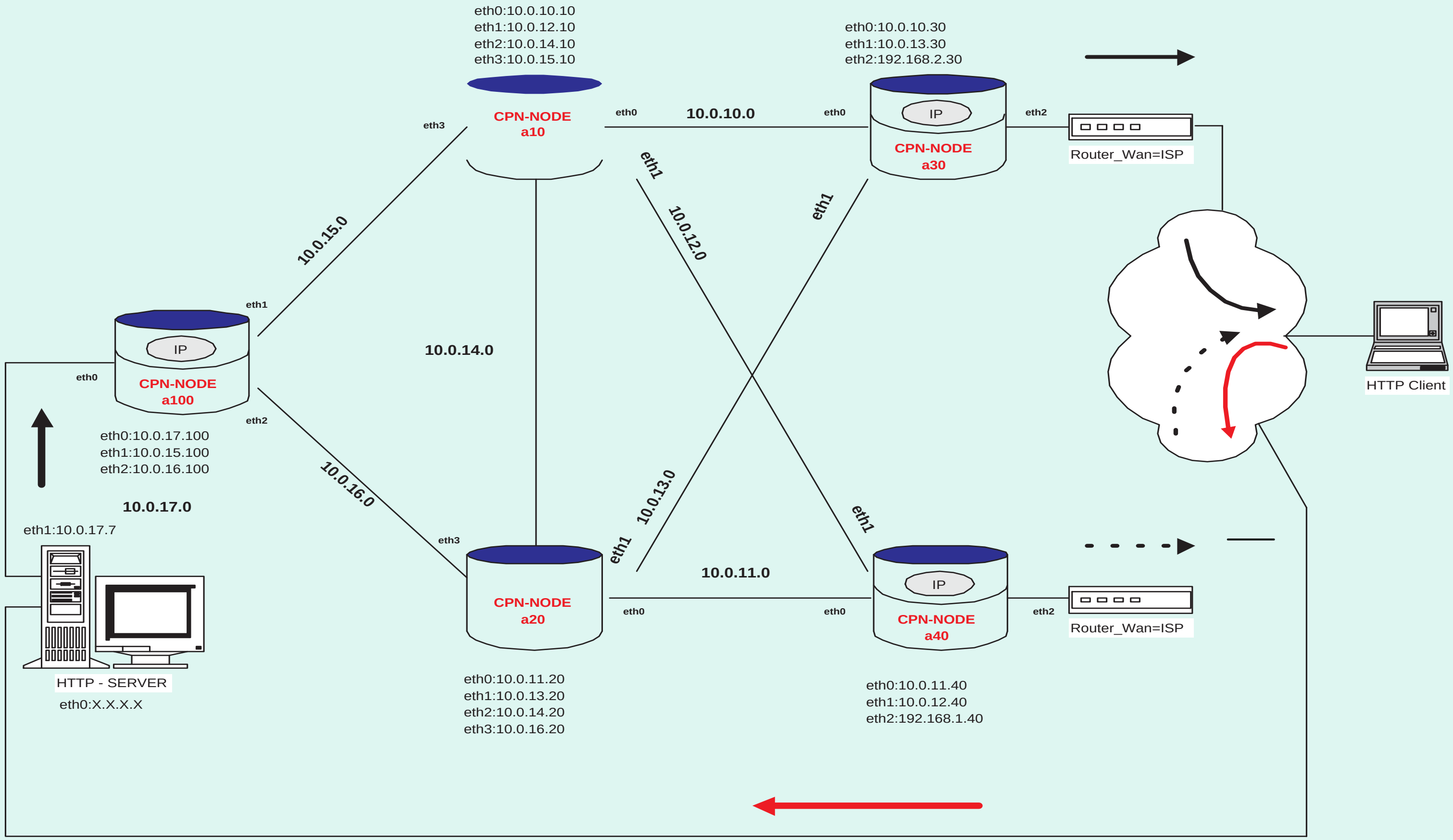
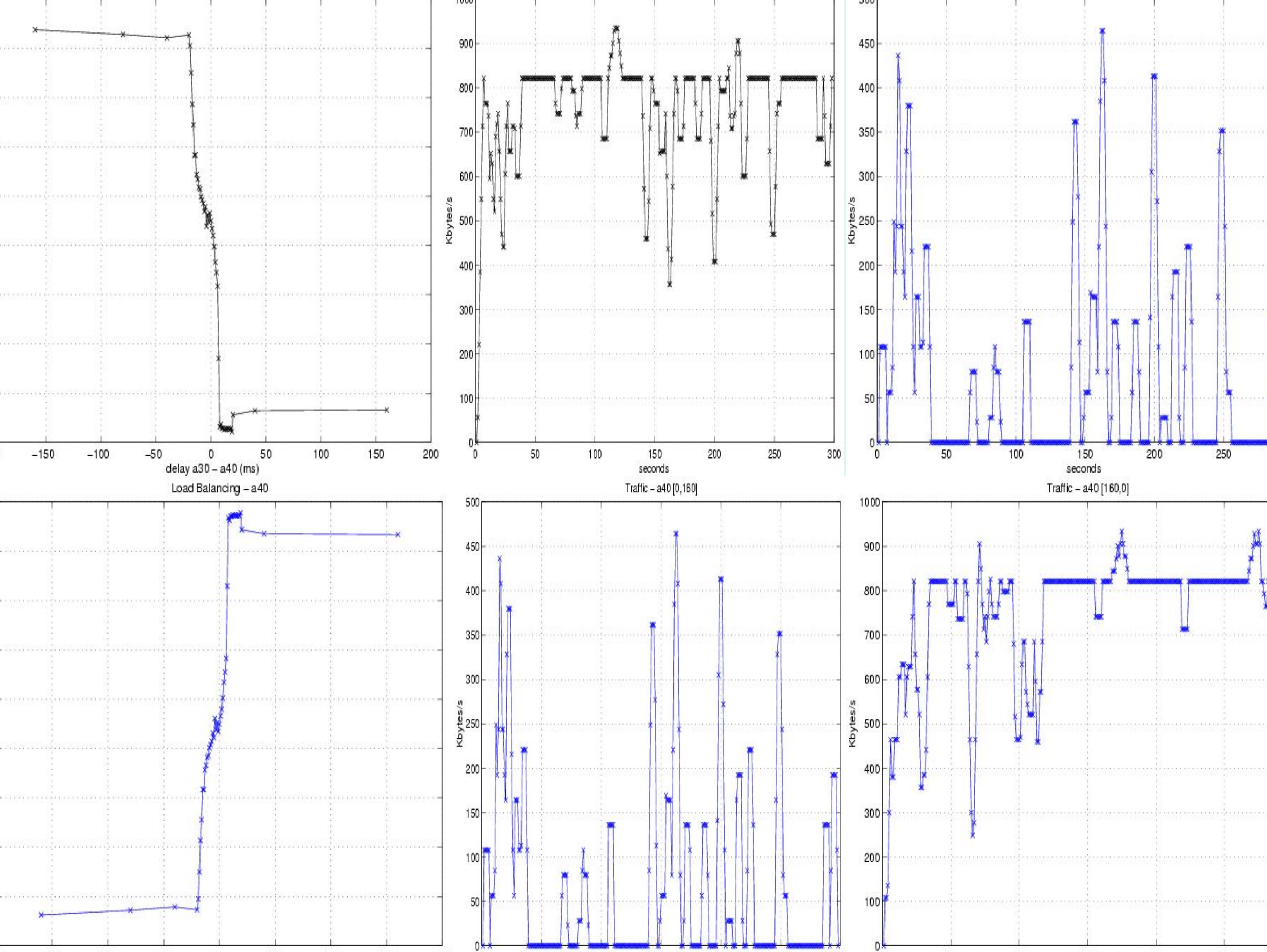


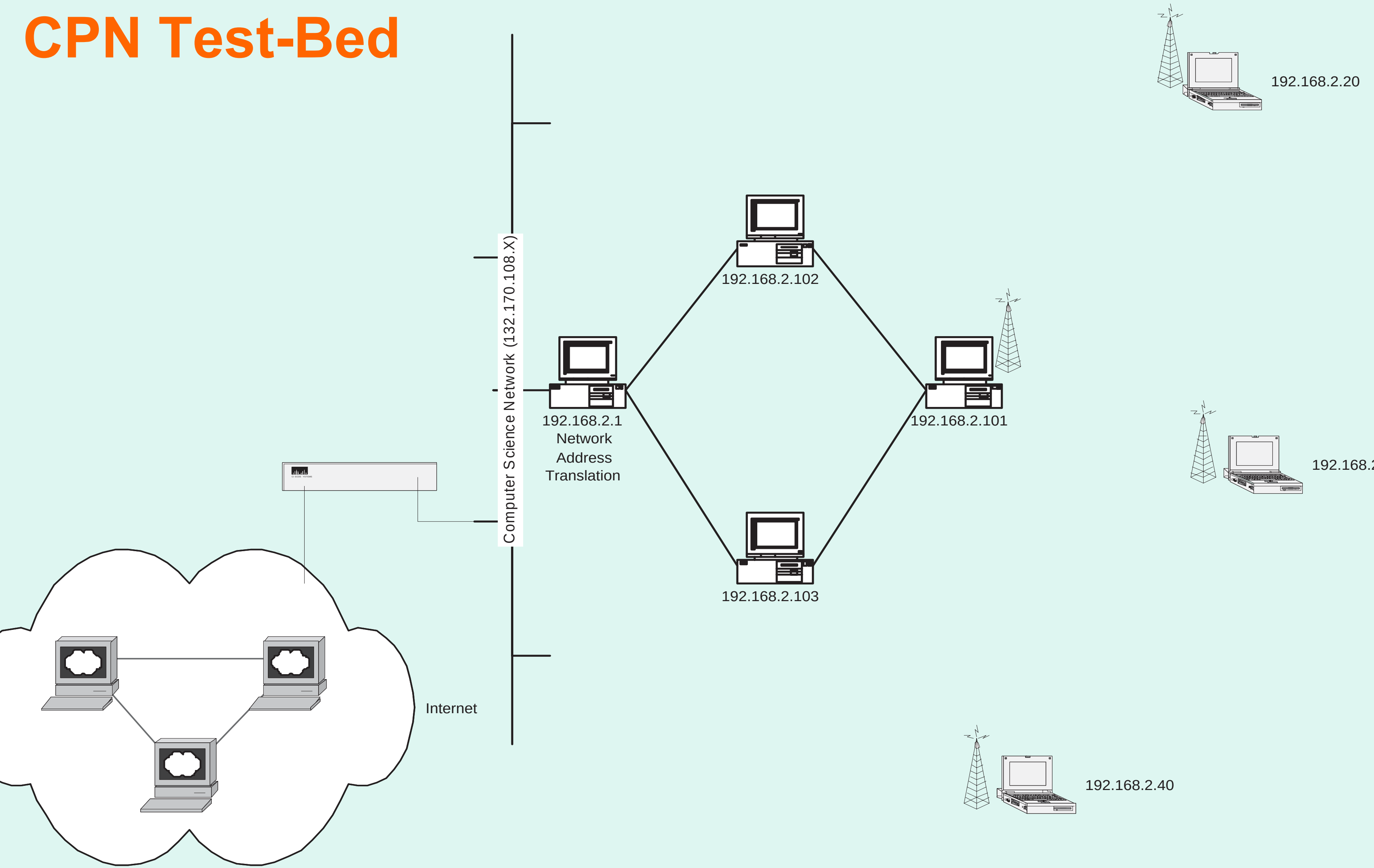
Fig. 7. Probability of packet desequencing perceived by the receiver side

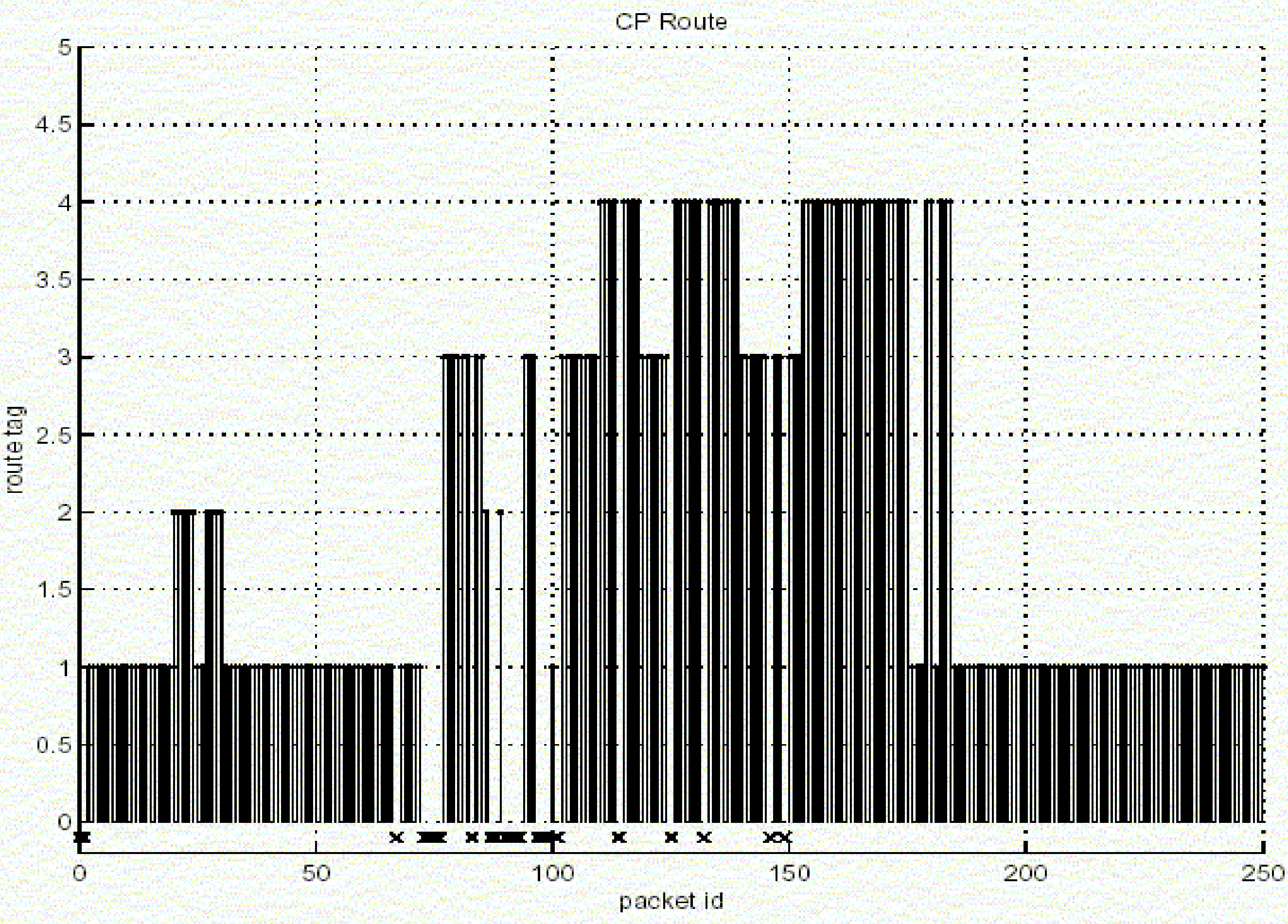
CPN for Traffic Engineering

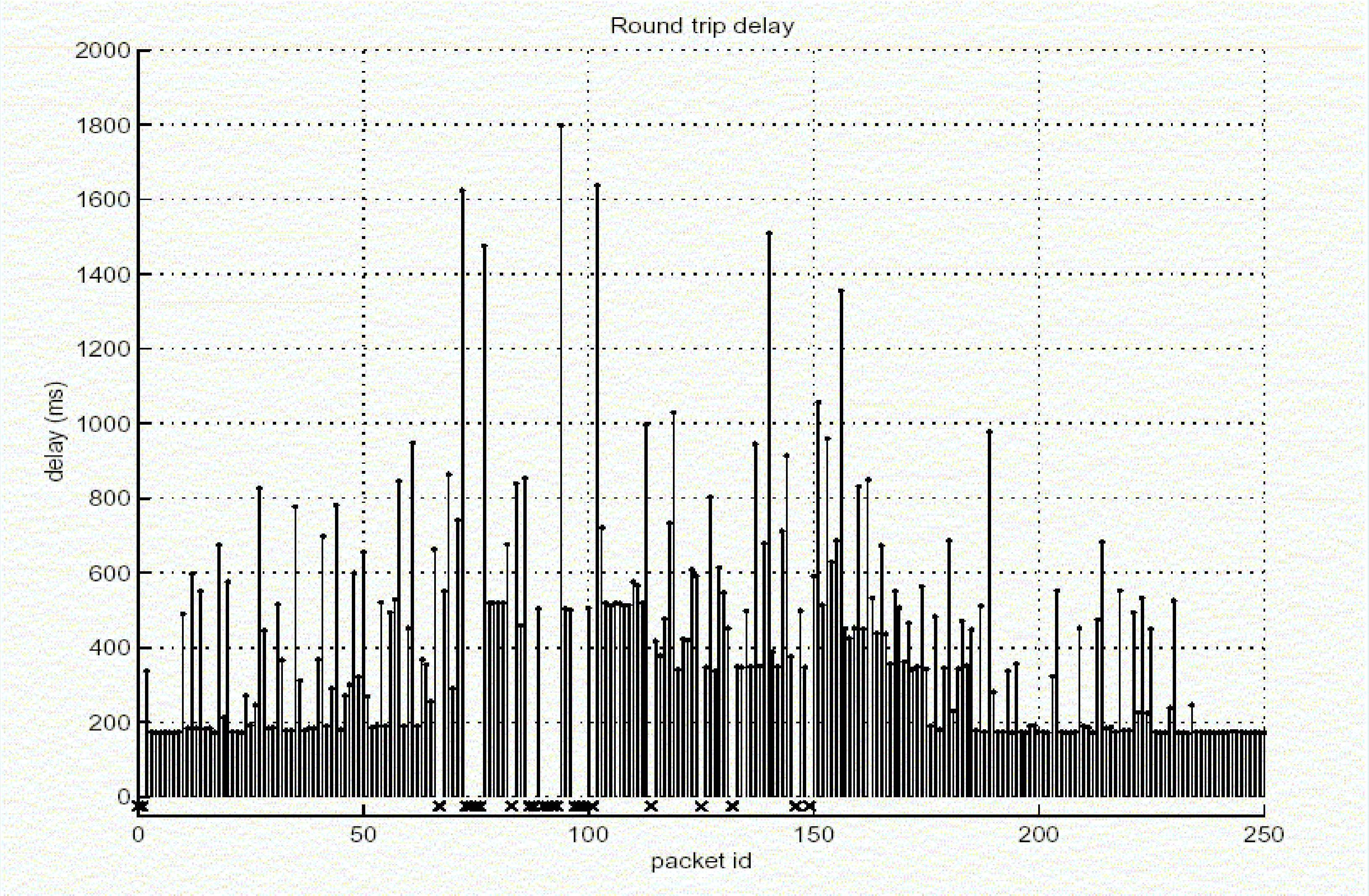



delay a30 – a40 (ms)
seconds
Kbytes/s
seconds
Kbytes/s
Load Balancing – a40
Traffic – a40 [0,160]
Kbytes/s
Traffic – a40 [160,0]
Kbytes/s

Wireless Power-Aware Adhoc CPN Test-Bed



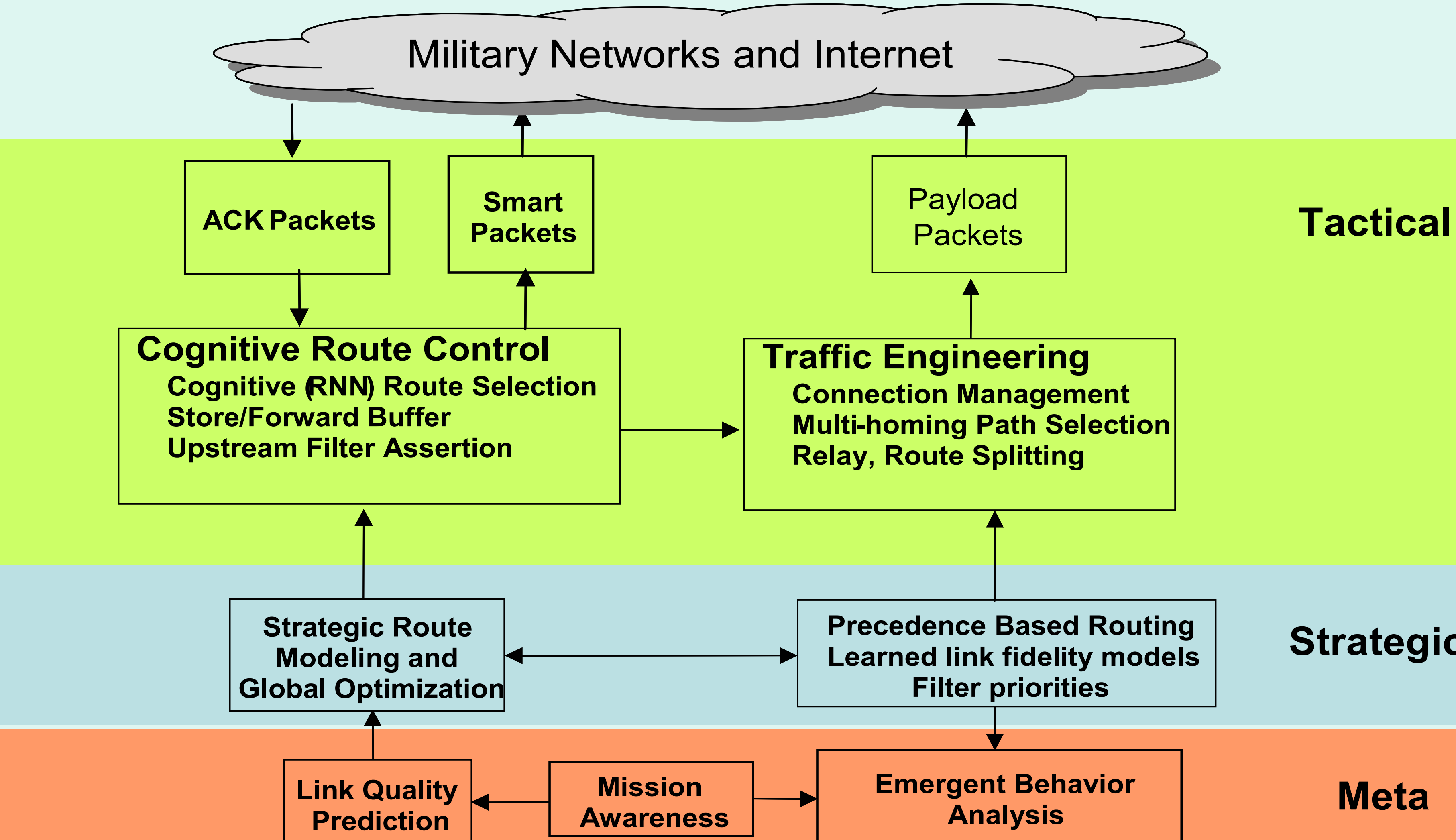

CP Route
route tag
packet id
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
50
100
150
200
250



Round trip delay
delay (ms)
packet id
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
50
100
150
200
250

Internet of the Future: CPN in the Control Plane Architecture

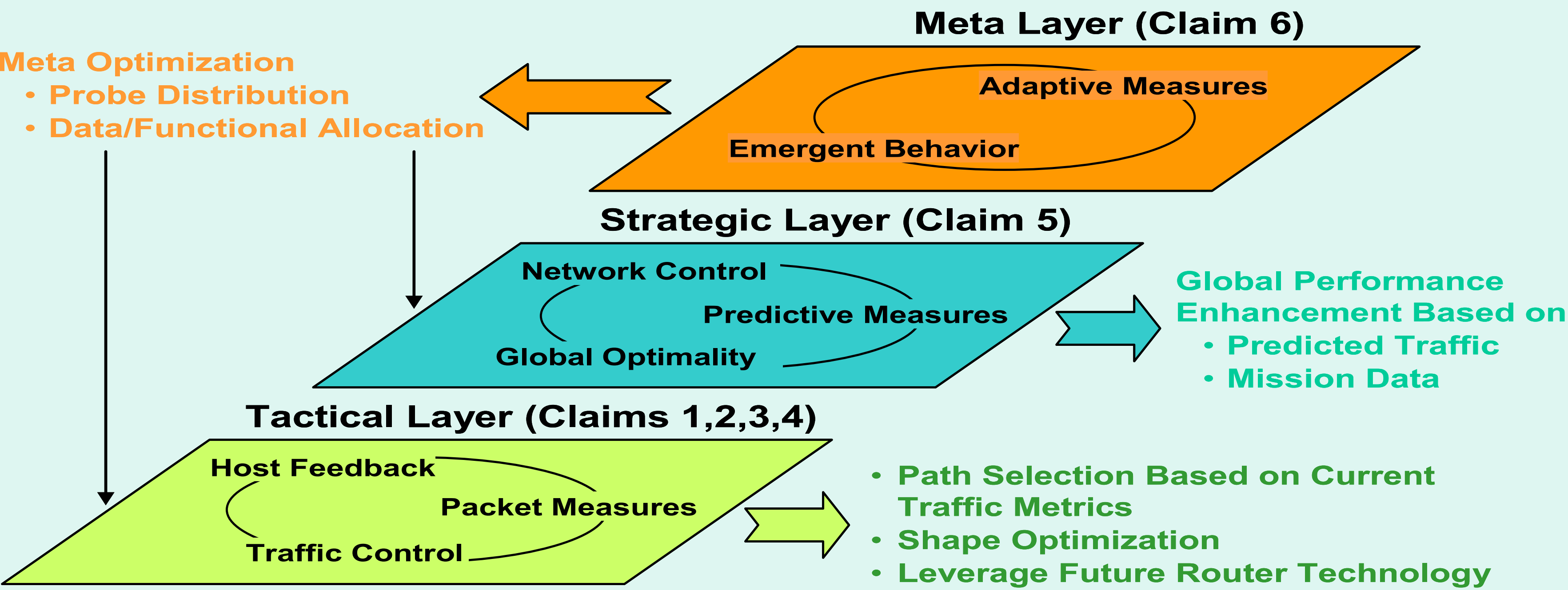
(cf. Lockheed-Martin)



Internet of the Future: DARPA's Control Plane Architecture

(cf. Lockheed-Martin)

Control Planes IN A NUTSHELL



EY – WORK ALLOCATION:

entral Florida University – Cognitive Packet Networks

an Diego State University – Packet Shaping

ristotle University – Global Optimization

ockheed Orincon IA

ISCO

Imperial College London

As We Conclude …

- The Internet and the IP Protocol Suite have emerged in a specific historic and technical context
- Some of their limitations are now become apparent
- Significant players are trying to address these issues, notably in the direction of QoS
- Our proposals and research may point to some possible solutions