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User Cooperation and Autonomy in Autonomic Networks

Project Web Page http://san.ee.ic.ac.uk

Special thanks to EPSRC, EU FP6 and ARO

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What we would like to have: A Family's Private Network (FPN)

It is a Network User and a Service for the Family

- Children and Parents have wireless PDA s
- Children use home "learning center" based on multiple external services
- Parents' cars are connected
- Infants and grand parents are being monitored
- Teen-agers' location is monitored
- The house security system is on-line
- Home temperature, sound sensors & actuators are on-line
- Home appliances, security, entertainment, heating, lighting are monitored and controlled

- Is private to family members and specific services: Home Security, the Housekeeper, the Parents, ..
- Is fully known to itself (self-aware, self-monitoring)
- Is cheap, secure, private and dependable
- Must dynamically and economically use all available communication modalities – including sensor networks, IP etc., public fixed and mobile telephony, WiFi, .. and the Rest ..

- Autonomic Self-Aware Management of Connections, Costs, QoS, Policies, Virtual Services and Network Resources, Monitoring, Upgrading ..

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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, Transpac)

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

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

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

- The Web is a 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. DiuffServ, 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

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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 still 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 …

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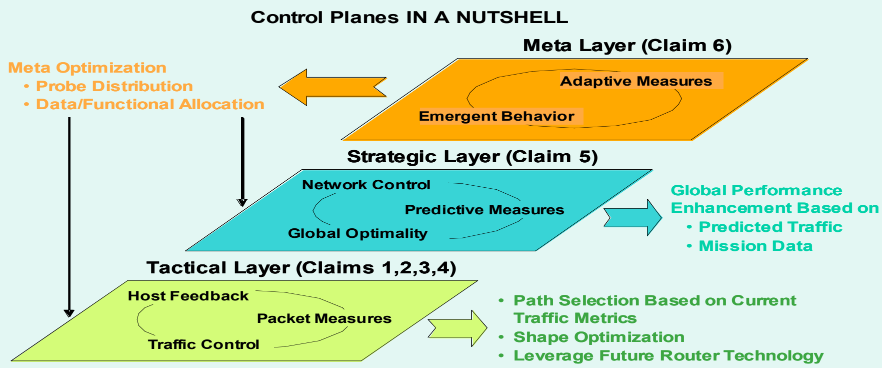
DARPA's Main Points

- 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

Future Networks and the Control Plane Architecture

(cf. Lockheed-Martin – Multiple Overlays?)



KEY – WORK ALLOCATION:
Central Florida University – Cognitive Packet Networks
San Diego State University – Packet Shaping
Aristotle University – Global Optimization
Lockheed Orincon IA
CISCO

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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

Technological Capabilities and Human Needs

- Technological Capabilities are of limited value if they do not lead to enhanced cost-effective capabilities that are of value to human users
- Fixed and mobile telephony and the Internet have been enablers for major developments that improve human existence. However advances in telecommunications have also had undesirable outcomes
- Television broadcasting was initially thought of as a wonderful medium for education. Yet in many instances it has lowered public standards for entertainment by forcing a limited number of programs upon the public; it has displaced reading, sophisticated cinema, theatrical and musical forms with facile programming
- TV Broadcasting is an example of a tremendous success in technology which has not been applied in the most broadly intelligent manner
- The ``one-to-very-many'' broadcast nature of television does not give users, or communities of users, the possibility to significantly influence the system that they use
- Other models of communications, such as the peer-to-peer model born in the Internet, can offer a greater degree of user choice
- The intelligent organisation of networks, including just compensation for services and intellectual property, should yield improved communications that enhance the cultural and humanistic environment
- Networks should allow users can to ubiquitously and harmoniously connect to offer or receive services
- We imagine an unlimited peer-to-peer world in which services, including TV and sound, voice or video telephony, messaging, libraries and documentation, live theater and entertainment, and services which are based on content, are available at an affordable cost
- Such systems can be autonomic, self-managing and self-regulating, accessible via open but secure interfaces that are compatible with a wide set of communication standards, including the IP protocol.

Premises: Users and Services

- An Network in which Users dynamically indicate requests for Services, and formulate needs in terms of Quality of Service (QoS) and price
- Users and Services are interchangeable: Services are users of other Services
- Users and Services monitor on-line the extent to which requests are being satisfied
- Services dynamically try to satisfy users as best as they can, and inform the user of the level at which the requests are being satisfied, and at what cost
- The network provides guidelines and constraints to users and services, to avoid that they impede each others' progress
- This intelligent and sensible dialogue between users, services and the network proceeds constantly based on mutual observation, network and user self-observation, and on-line adaptive and locally distributed feedback proceeding at the speed of the traffic flows and events being controlled
- We illustrate some these concepts via an experimental test-bed at Imperial College, based on the Cognitive Packet Network (CPN) that embodies some of these functionalities thanks to ``smart packets'' and reinforcement learning
- At its edges, CPN is fully compatible with IP, while internally it offers routing that is dynamically modified using on-line sensing and monitoring, based on users' QoS needs and overall network objectives

Technical and Research Problems that Follow from this Vision

- Architecture
  - Some form of Programmable Overlay Network
  - Extensible, Adaptive, Situation Aware
- Network Monitoring and Distributed Control
  - Distributed User level Monitoring
  - Distributed Control
- Quality of Service and Billing
  Composite QoS Metrics, related to R/T Monitoring and Control
- Cooperation of Users and Services
  - Cooperative Games, Agent Cooperation
- Search for Users and Services

Technical Problems

- Architecture
  A. Galis, S. Denazis, C. Brou and C. Klein (eds). Programmable networks for IP service deployment. Artech House Books, 2004.

- Monitoring and Adaptation
  A. Asgari, R. Egan, P. Trimintzios and G. Pavlou. Scalable monitoring support for resource management and service assurance. IEEE Network 18 (6), pp. 6--18, 2004.
  E. Gelenbe, R. Lent, A. Nunez. Self-aware networks and QoS. Proceedings of the IEEE, 92 (9), pp. 1478-1489, 2004.

- Quality of Service and Costing
  H. Yaiche, R.R. Mazumdar and C. Rosenberg. A game theoretic framework for bandwidth allocation and pricing in broadband networks. IEEE/ACM Transactions on Networks 8 (5), pp. 667-678, 2000.
  N. Semret, R. R.-F. Liao, A. T. Campbell and A. A. Lazar. Pricing, provisioning and peering: dynamic markets for differentiated Internet services and imlications for network interconnections. IEEE J. Sel. Areas Comms. 18 (12), pp. 2499-2513, 2000.
  E. Gelenbe, R. Lent, and Z. Xu. Cognitive Packet Networks: QoS and performance. Proc. IEEE MASCOTS Conference, pp. 3-12, Fort Worth, TX, Oct. 2002.
  N. Christin and J. Libeherr. A QoS architecture for quantitative service differentiation. IEEE Comms. Mag. 46 (6), pp. 38--45, 2003.

- Sensible Cooperation of Users and Services
  Y. Yang and A. Galis. Policy-driven mobile agents for context-aware service in next generation networks. Prof. IFIP 5th International Conference on Mobile Agents for Telecommunications, Marrakesh, ISBN 3-540-20298-6. Springer LNCS, 2003.

- Search for Users and Services
  Thoughts from robotics, target recognition, pursuit ..

In Theory, Global QoS Optimisation is Possible

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 $p = (m_1, \ldots, m_k)$ is a directed path (a subgraph of G consisting of nodes $m_1, \ldots, m_k$, $m_i \neq m_j$ 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

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

In Practice Static Optimization is Impossible

- The network is very large – for specific users, optimization 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

Hence Measurement Based Network Research

- The weak spot in computer science is software engineering – it is expensive and unreliable
- Avoid the frenzy of developing even more network software – otherwise you will get bogged down in even more bugs, impossible proofs and verifications, and layers of un-interpretable measurements
- Research and Develop small sets of network primitives that can provide both Users and Services with the ability to observe the network state and modify its behaviour adaptively in a way that suits the Users and Services
- Test variants of these primitives experimentally in a large number of coordinated test-beds
- Conduct transparent and reproducible network measurements within a large scientific community
- Couple modelling and analysis very closely with the experimental work

Some Guidelines: Measurement Based Network Research

- Determine broad classes of User/Service based QoS goals, e.g., time, loss, power, security, cost, reliability, robustness to attack
- Select relevant metrics that build in to these QoS goals
- Select measurable and observable quantities from which these metrics can be computed
- Design network primitives that can access these quantities
- Develop theoretical results which are to the extent possible free from specific assumptions about traffic characteristics
- Implement and test research in interconnected test-beds
- Provide open interfaces for access and usage of the test-beds
- Plan for reproducible network measurements within the scientific community
- Couple modelling and analysis closely with the experimental work

How about theory?

Sensible Routing Theorem

Consider any decision point x at with n choices

Let q(x,i) be a r.v. representing the QoS that results from choice i, and

W(x,i) = E[u(q(x,i))] be the expected outcome of choice i

If $p^{(k)}(x,i) = [W(x,i)]^{-k} / \Sigma^{n}_{m=1} [W(x,m)]^{-k}$

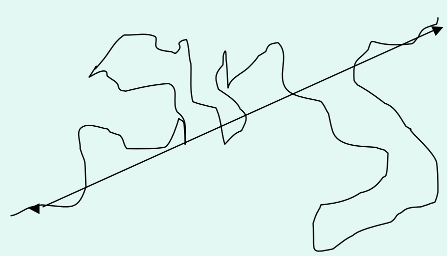
and $W^{(k)}(x) = \Sigma^{n}_{m=1} W(x,m)\, p^{(k)}(x,i)$, then

$$W^{(k+1)}(x) \leq W^{(k)}(x)$$

Time to Search

- Average Time to Search
- Drift $b \leq 0$, Second Moment
- Avg Time-Out $1/\lambda$, then

$$E[T] = 2D / [\ |b| + (b^2 + 2\lambda c)^{1/2}\ ]$$



The Cognitive Packet Network Approach

- 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

CPN Principles

Funded by UK EPSRC, and by the Math Division of ARO for the theoretical aspects

- 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 Loss of DDoS packets
- 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

- QoS Goals are obtained from Path Measurements: Traffic, Delay, Loss, Cost, Power, Security 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

Decision System: a "neural" network of networks

(neural networks embedded in each router)

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

If $x_i(t) > 0$, 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}

The 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

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

If $x_i(t) > 0$, 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 $k_{ij}^{+-} = k + e_i - e_j$, $k_{ij}^{++} = k + e_i + e_j$

$k_i^+ = k + e_i$, $k_i^- = k - e_i$:

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*

Probability that Neuron I is excited

External Arrival Rate of Excitatory Spikes

ω^{-}_{ji}

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

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.*

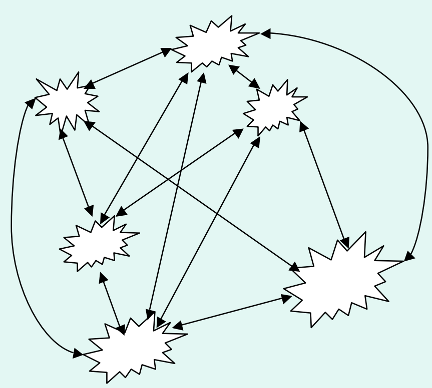
$$\sup_{x \in [0,1]^v} | g(x) - y(x) | < \varepsilon \qquad for \quad y(x) = \frac{q_{o+}}{1 - q_{o+}} - \frac{q_{o-}}{1 - q_{o-}}$$

Goal Based Reinforcement Learning in CPN

- The Goal Function to be minimized is selected by the user, for instance 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 in CPN

- 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 $T_{l-1} \le R_l$ 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

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

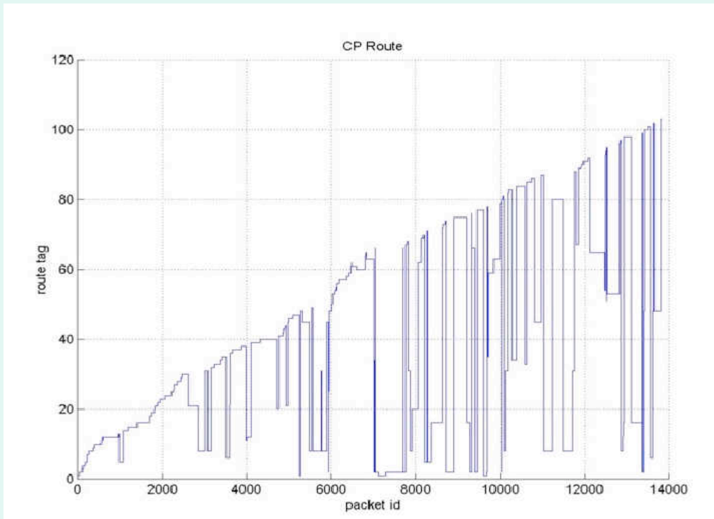
- Re-normalize all weights

$$r_i^* = \sum_1^n [w^+(i,m) + w^-(i,m)]$$

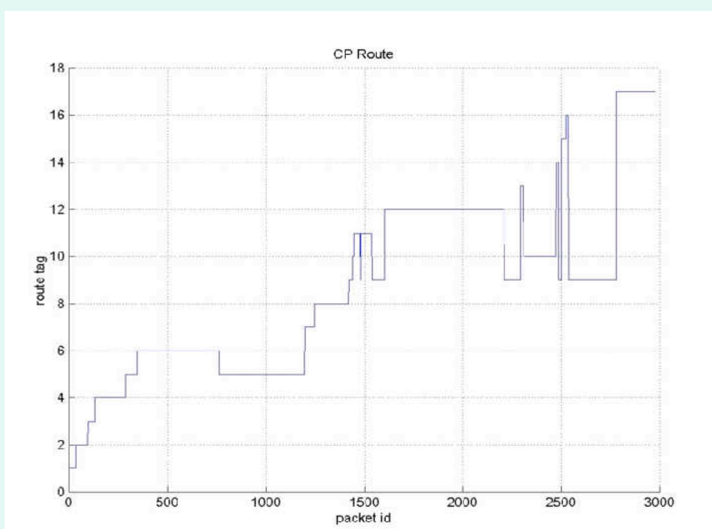
$$w^+(i,j) \leftarrow w^+(i,j)\frac{r_i}{r_i^*}$$
$$w^-(i,j) \leftarrow w^-(i,j)\frac{r_i}{r_i^*}$$

- 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

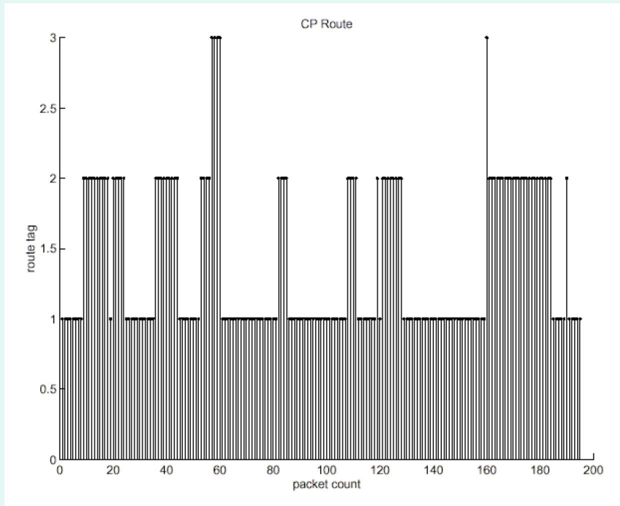
CPN Test-Bed Measurements
On-Line Route Discovery by Smart Packets



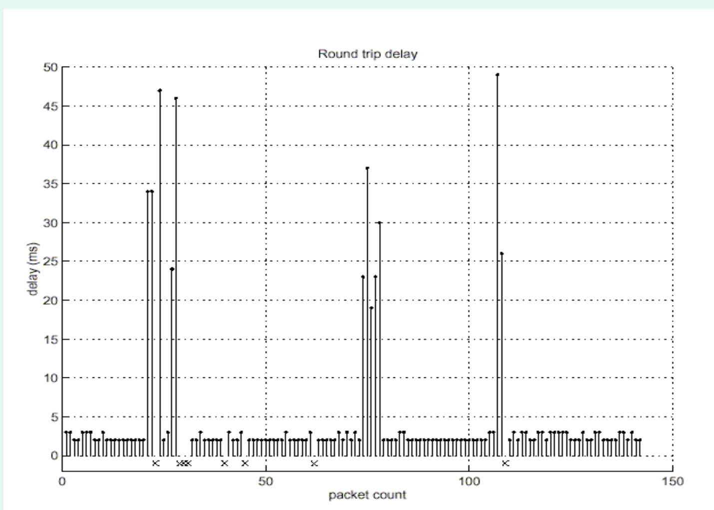
CPN Test-Bed Measurements
Ongoing Route Discovery by Smart Packets



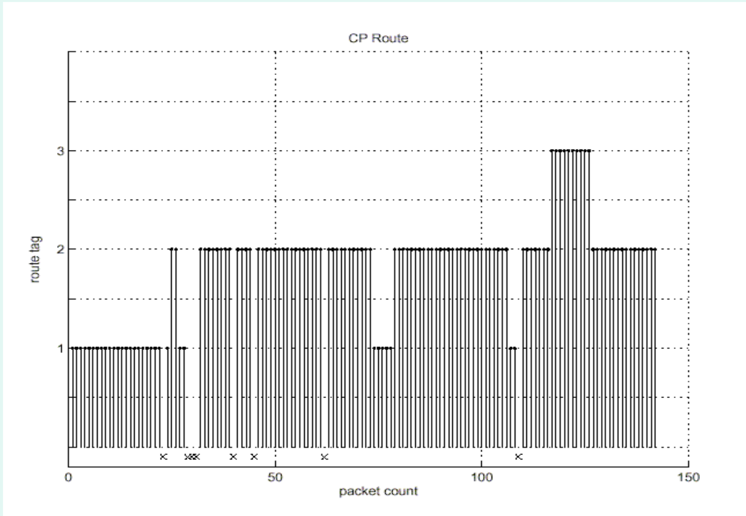
Route Adaptation without Obstructing Traffic



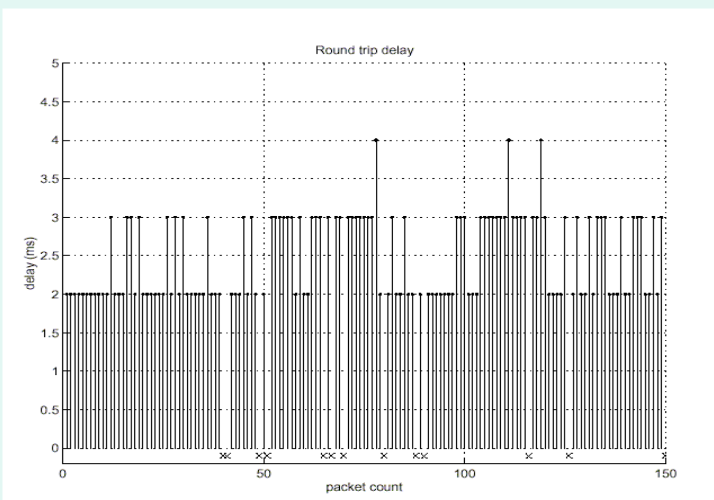
Packet Round-Trip Delay with Saturating Obstructing Traffic at Count 30



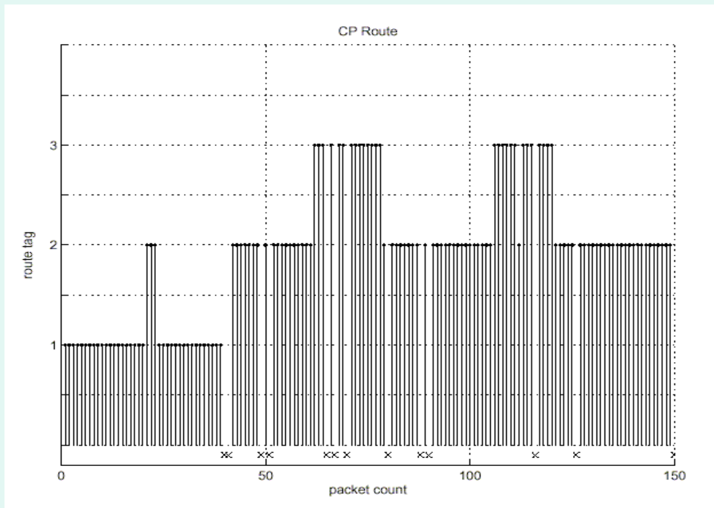
Route Adaptation with Saturating Obstructing Traffic at Count 30

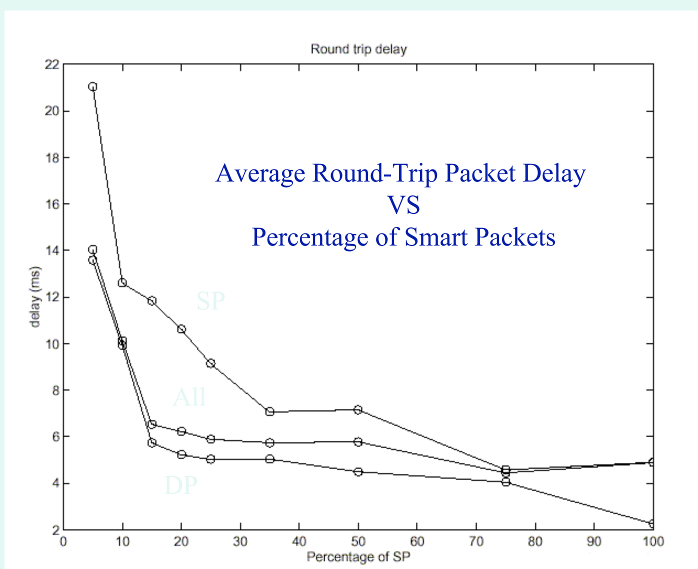


Packet Round-Trip Delay with Link Failure at Count 40



Path Tags with Link Failure at Count 40





A QoS Driven Application
Voice over CPN

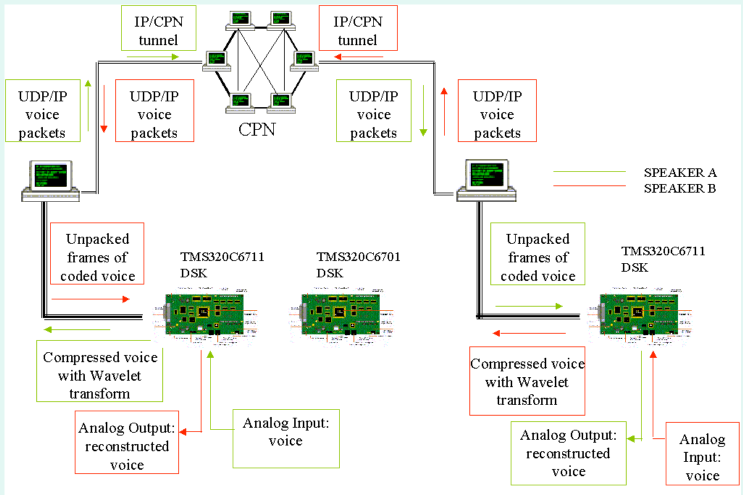


Fig. 1. Voice over CPN

Experimental Results
Voice over CPN

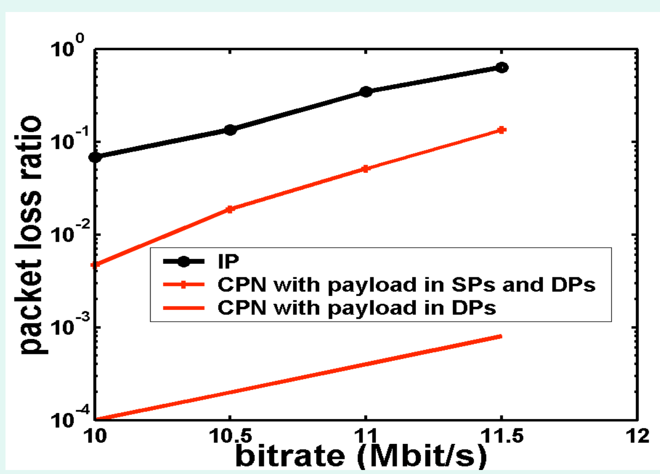
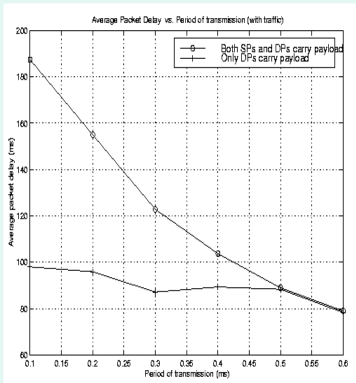


Fig. 4

Experimental Results
Voice over CPN



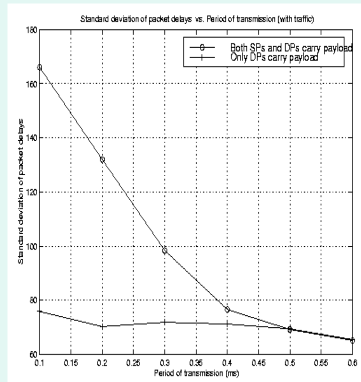


Fig. 6 : **Average round-trip delay (left) and jitter (right) for user payload when only DPs are allowed to carry user payload**

Experimental Results: Voice over CPN
Packet desequencing Probability at Receiver vs Packet Rate

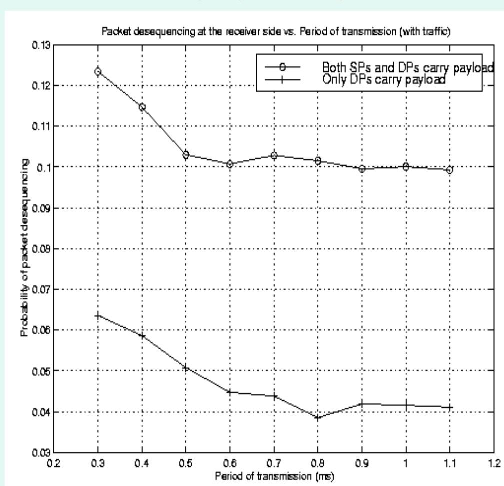
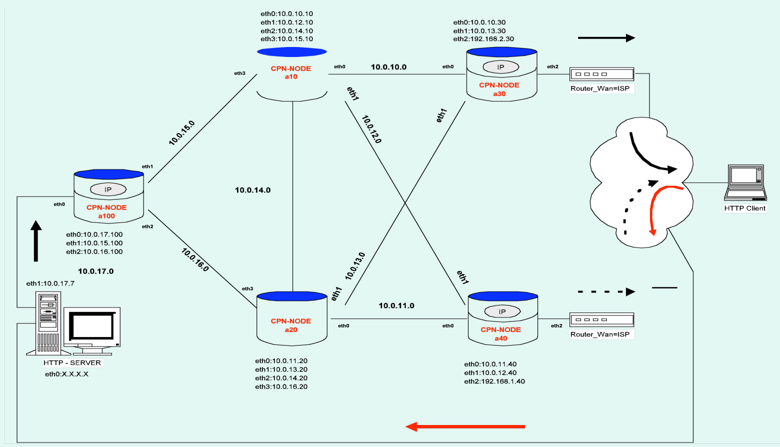
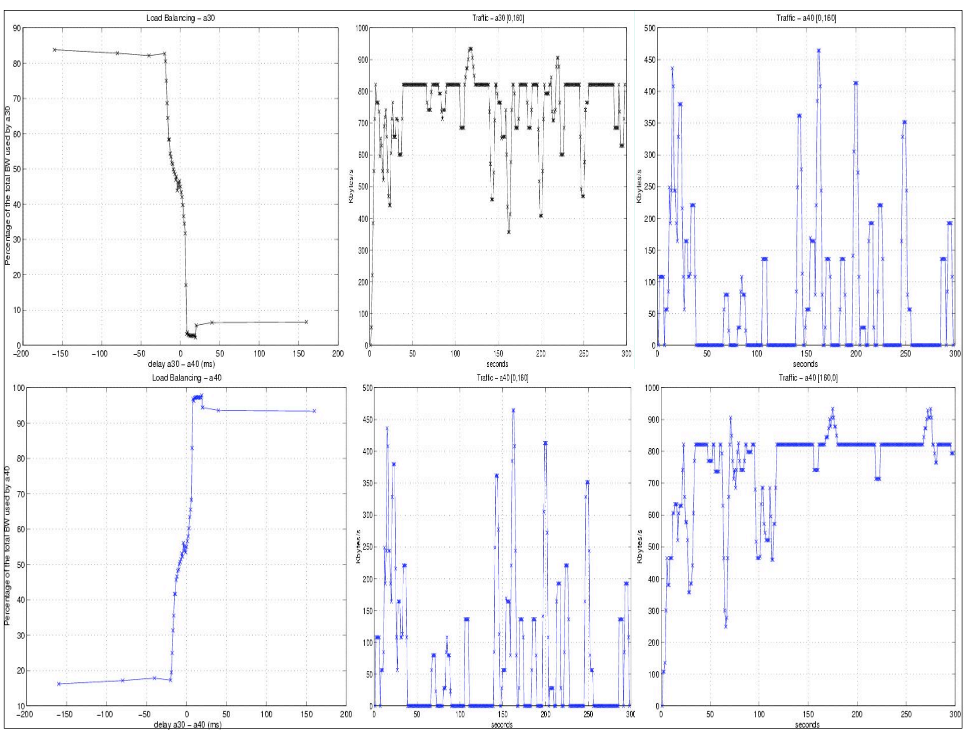


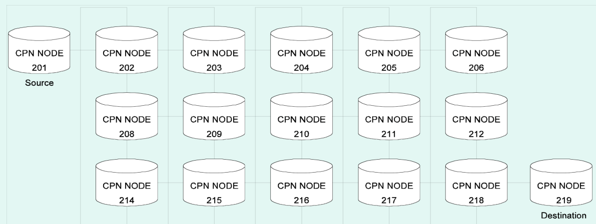
Fig. 7. Probability of packet desequencing perceived by the receiver side

CPN for Traffic Engineering





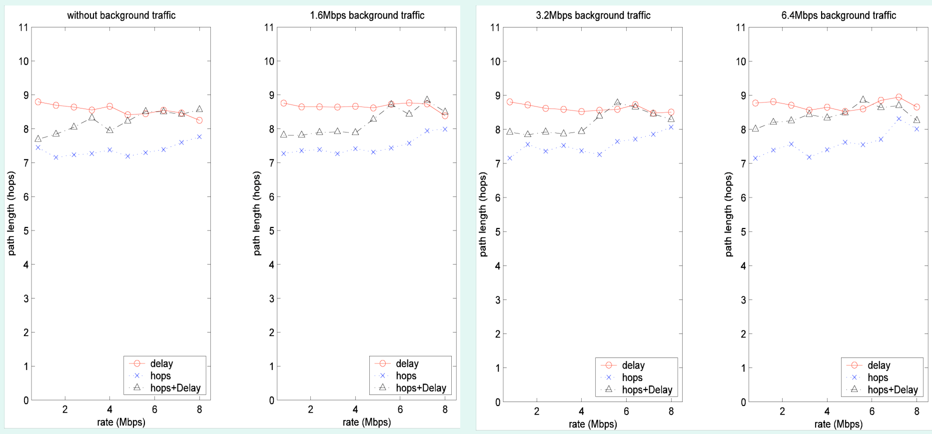
Other experiments



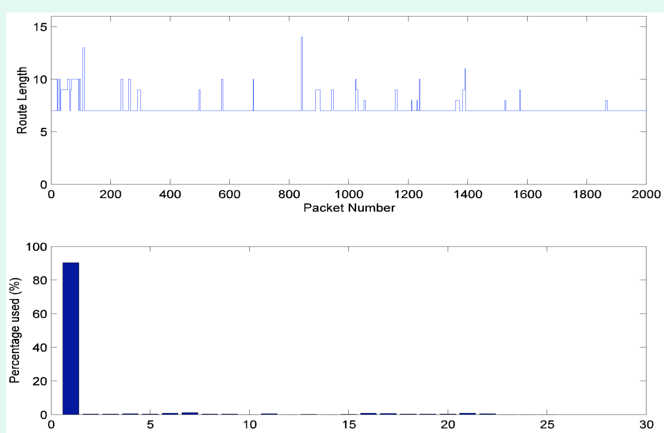
- CPN routing algorithm is used to conduct experiments using different QoS goals:
  - Delay [*Algorithm-D*]
  - Hop count [*Algorithm-H*]
  - Combination of delay and hop [*Algorithm-HD*]

- Average path length for each algorithm
- The route usage under different traffic rates
  - Low Traffic Rate (LTR)
    - 100 packets/second
  - Medium Traffic Rate (MTR)
    - 500 packets/second
  - High Traffic Rate (HTR)
    - 1000 packets/second
- The forward delay of each algorithm with different background traffic is also reported

Average path length with different levels of background traffic

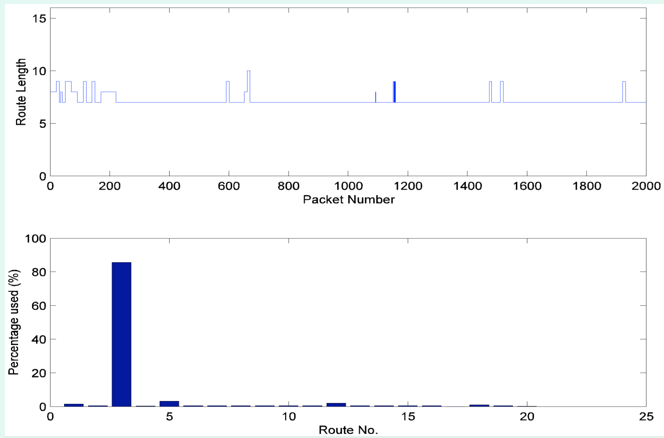


H-Algorithm Route usage with LTR



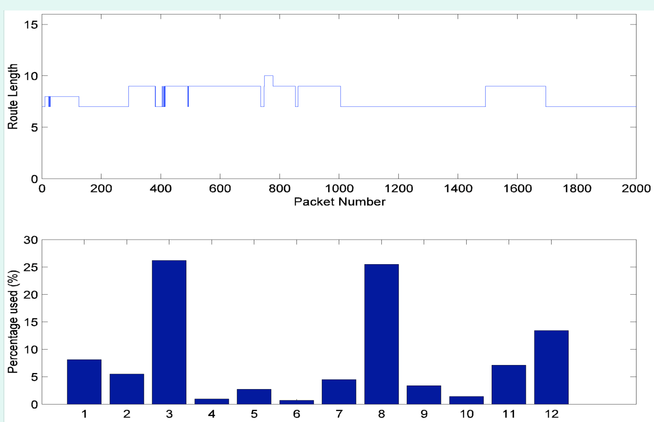
- 25 routes are discovered and one of them is the shortest path
- Above 90% of DPs use this shortest path

H-Algorithm Route usage with MTR



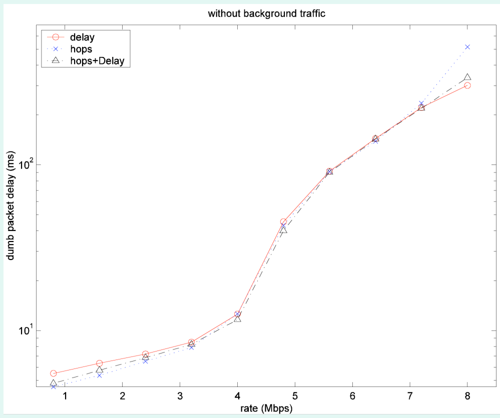
- 20 routes are discovered and 4 of them are the shortest path
- Above 85% of DPs use these 4 shortest paths

H-Algorithm Route usage with HTR

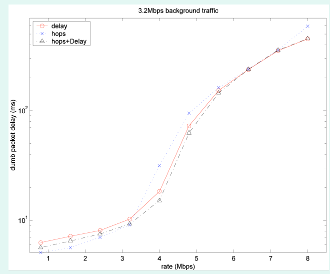


- 12 routes are discovered and 4 of them are the shortest path
- Only about 51% of DPs use these 4 shortest paths

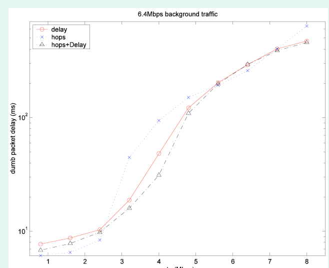
Delay with different background traffic



No background traffic



Medium

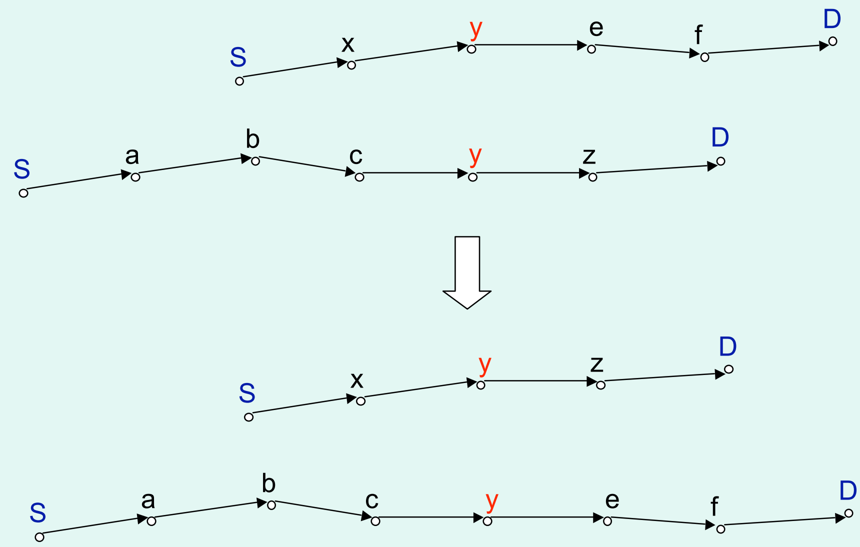


High

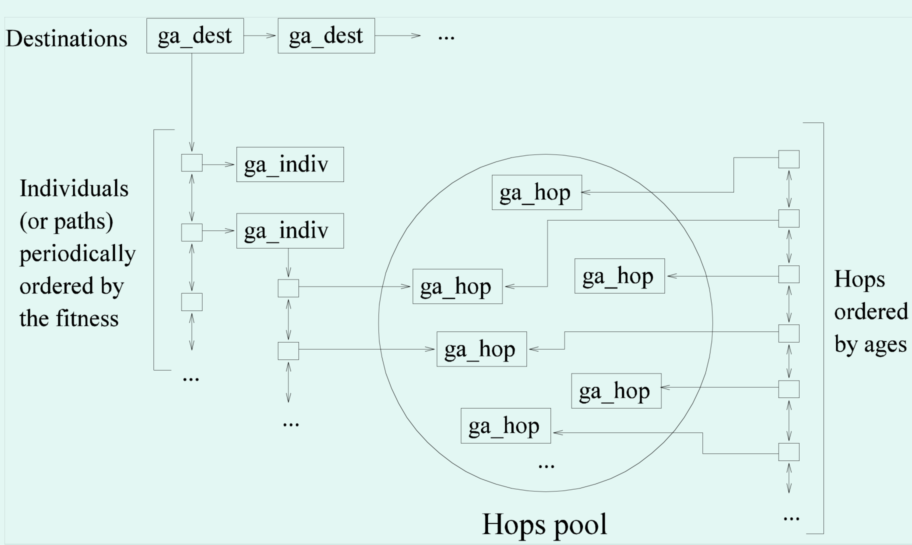
Another extension: Genetic Algorithms for CPN

- Exploit an analogy between "**genotypes**" and network paths
- The **fitness** of the individual is the QoS of the path
- **Selection function** chooses paths for reproduction based on the QoS of paths
- The genetic operation used to create new individuals is **crossover**

Crossover

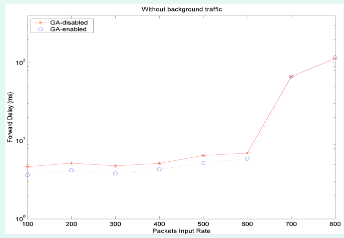


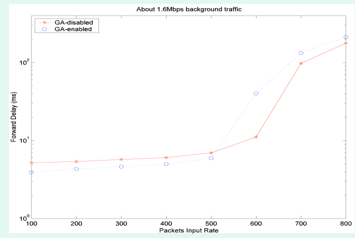
Populations in CPN



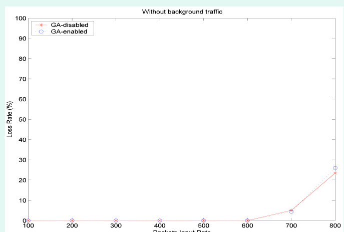
No background traffic | 2.4Mb background traffic

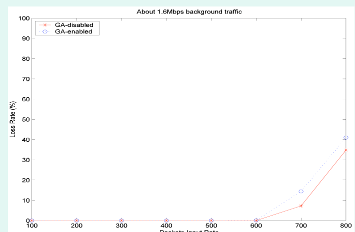
Delay





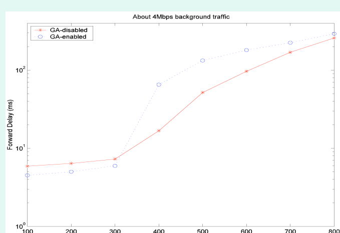
Loss

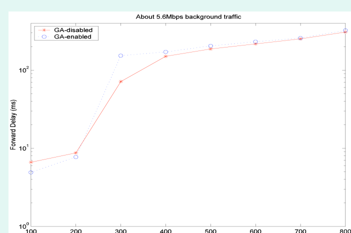




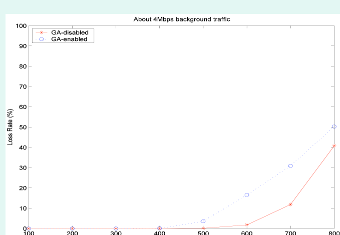
4.0Mb background traffic | 5.6Mb background traffic

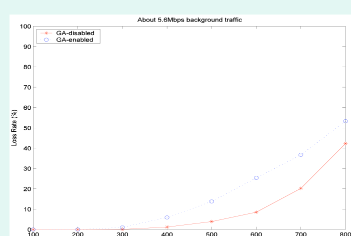
Delay



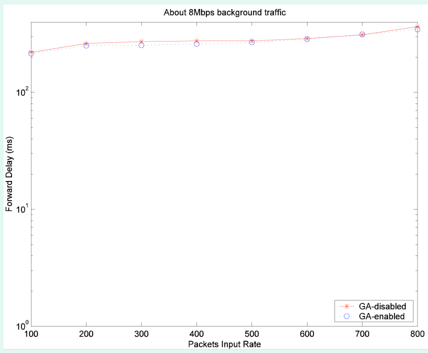


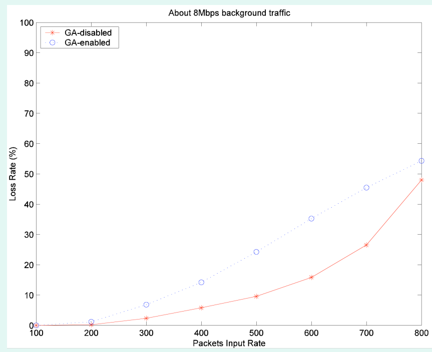
Loss



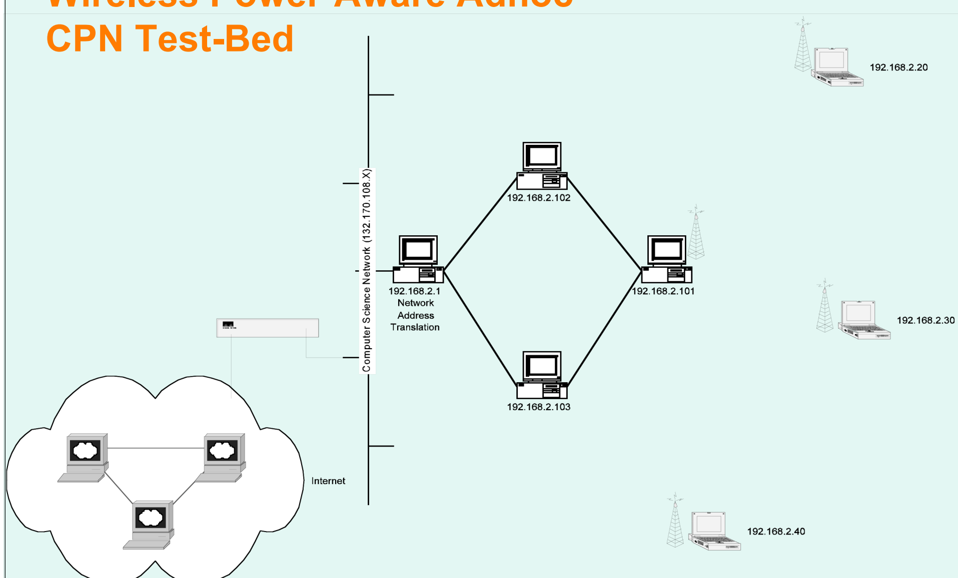


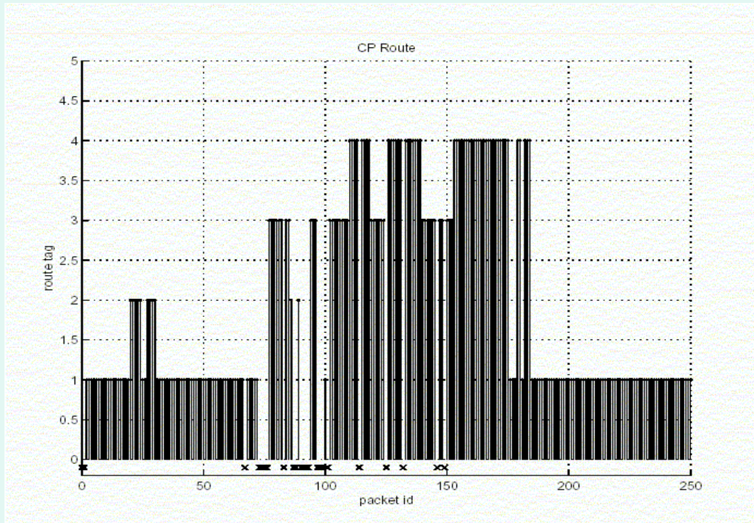
8.0Mb background traffic

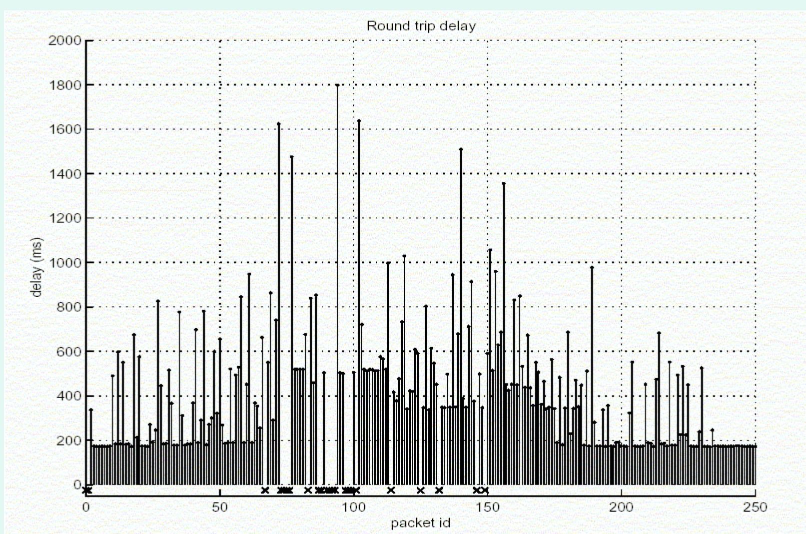




Wireless Power-Aware Adhoc CPN Test-Bed

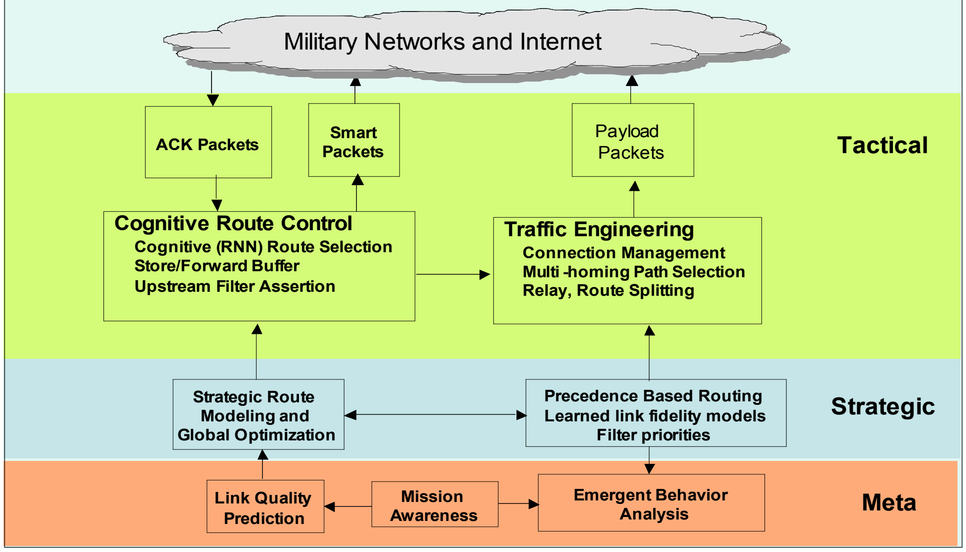


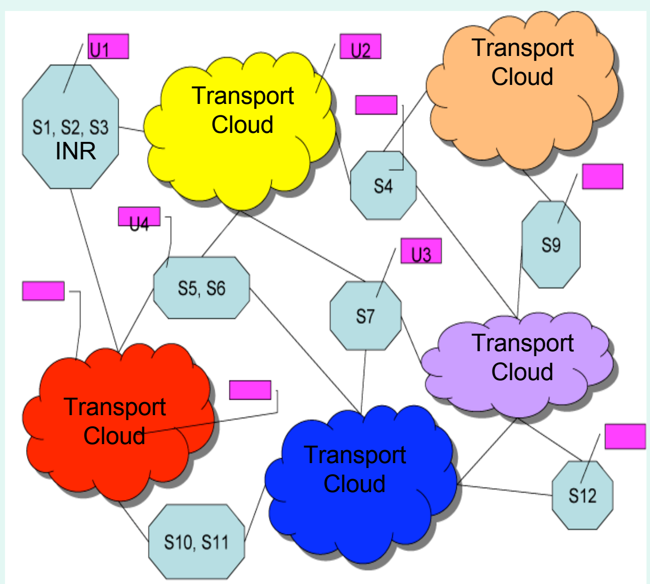

CP Route
route tag
packet id
0
50
100
150
200
250
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


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

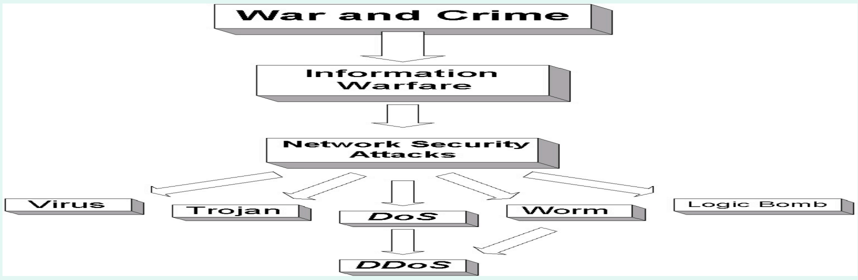
Internet of the Future: CPN in the Control Plane Architecture

(cf. Lockheed-Martin)





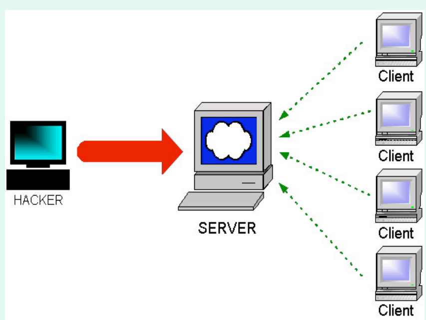
Another Example:Denial of Service Protection using CPN



- 1996. Panix
- 1998. “Analyzer” attacks the Pentagon
- 2000. “Mafiaboy” attacks Amazon, Yahoo etc.
- 2001. Port of Houston
- 2002. 13 Root Servers
- 2003. American hackers attack Al Jazeera

What is a DoS Attack

An attack with the purpose of preventing legitimate users from using a specific network resource

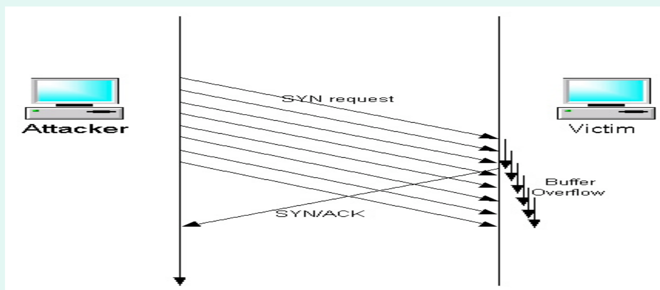


Is it a new threat?

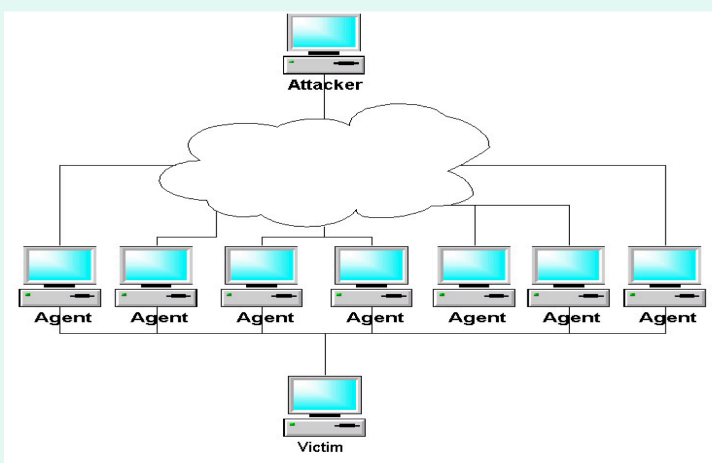
1985, R.T. Morris writes:

“The weakness in the Internet Protocol is that the source host **itself** fills in the IP source host id, and there is no provision in TCP/IP to discover the true origin of a packet” .. IP Spoofing

SYN Flood Attack



Distributed DoS



Issues that have been Examined

- Detection
  - Pattern detection
  - Anomaly detection
  - Hybrid detection
  - Third-party detection
- Response
  - Agent identification
  - Rate-limiting
  - Filtering
  - Reconfiguration

The CPN DDoS Defence Scheme

- The CPN architecture traces flows using smart and ACK packets
- A DoS produces QoS degradation
- The user(s) and victim(s) detect the attack and inform nodes upstream from the victim(s) using ACK packets
- These nodes drop possible DoS packets
- The detection scheme is never perfect (false alarms & detection failures)

Mathematical model (1)

- Analyses the impact of DDoS protection on overall network performance
- Measures traffic rates in relation to service rates and detection probabilities

Mathematical model

$$I^{n}_{n_j,\mathbf{n}} = \lambda^{n}_{n_j,\mathbf{n}} \prod_{l=1}^{j-1} ((1 - L_{n_l})(1 - f_{n_l,\mathbf{n}}))$$

$$I^{d}_{d_j,\mathbf{d}} = \lambda^{d}_{d_j,\mathbf{d}} \prod_{l=1}^{j-1} ((1 - L_{d_l})(1 - d_{d_l,\mathbf{d}}))$$

$$L_i = \rho_i^{B_i} \cdot \frac{1 - \rho_i^{B_i+1}}{1 - \rho_i}$$

$$\rho_i = s_i\left(\sum_{\mathbf{n}} I^{n}_{i,\mathbf{n}}(1 - f_{i,\mathbf{n}}) + \sum_{\mathbf{d}} I^{d}_{i,\mathbf{d}}(1 - d_{i,\mathbf{d}})\right)$$

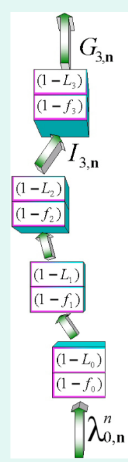
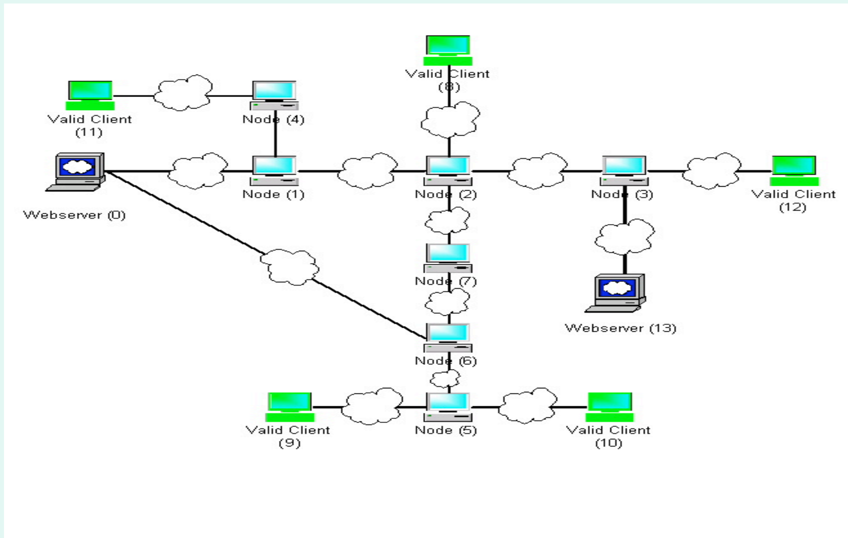
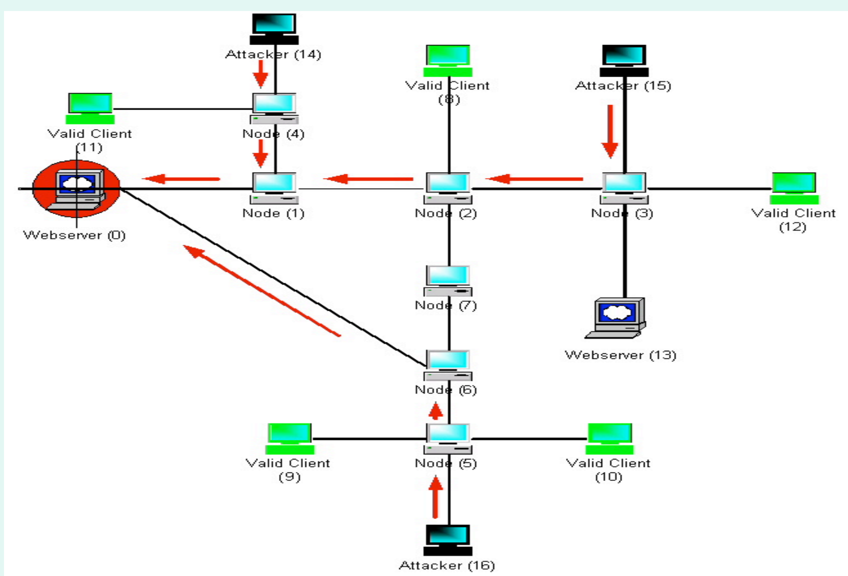
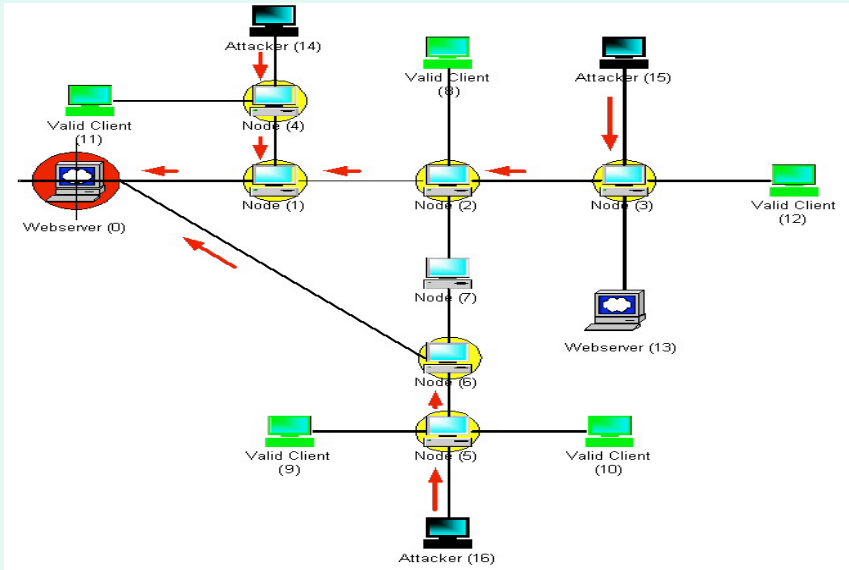


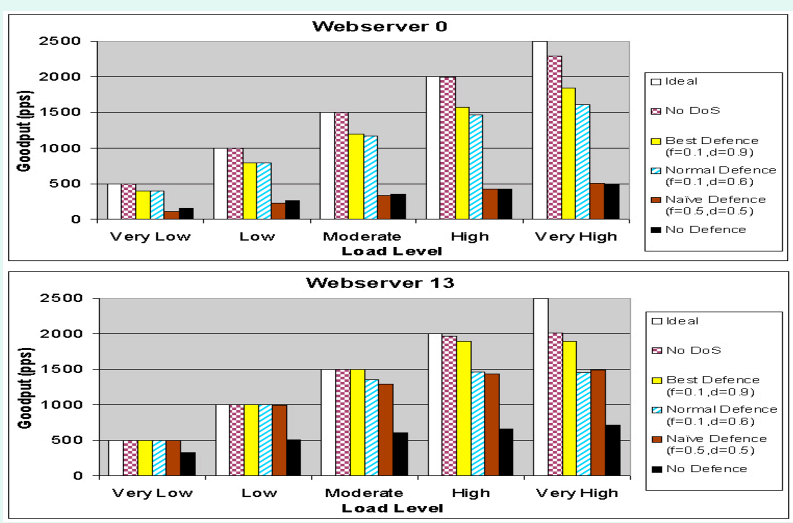
Illustration on an Experimental CPN Test-Bed



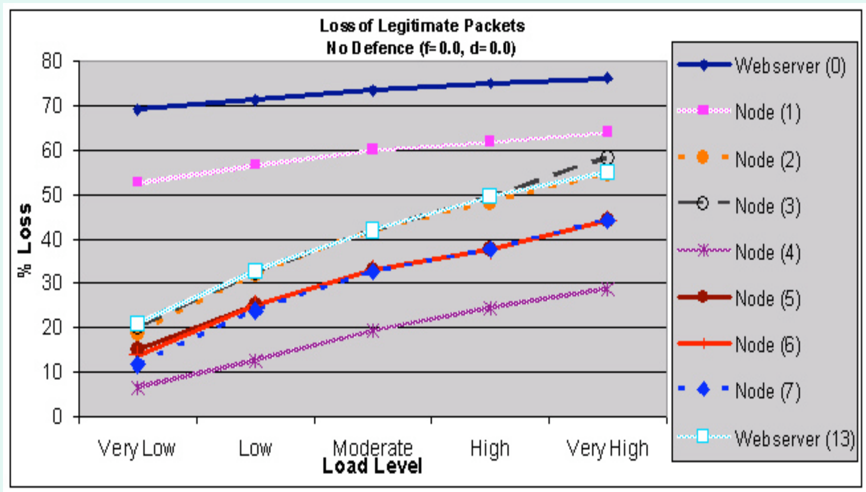




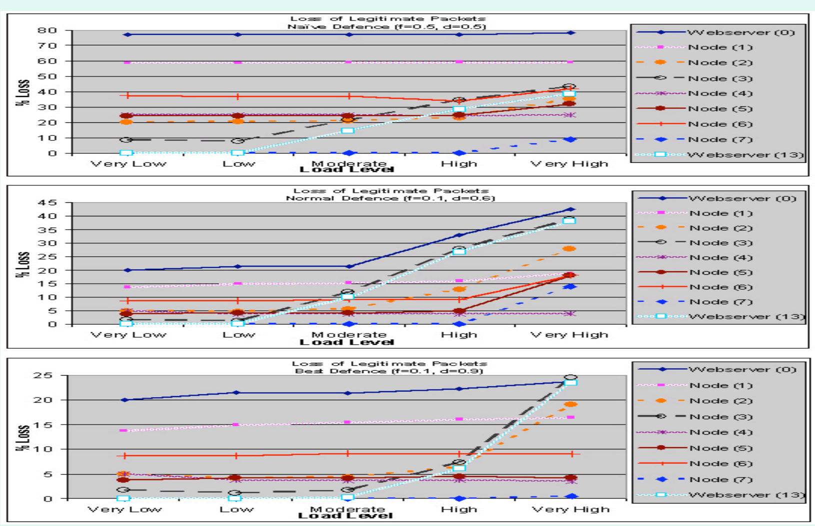
Predictions of Mathematical Analysis



Impact on the nodes
(without Defence)



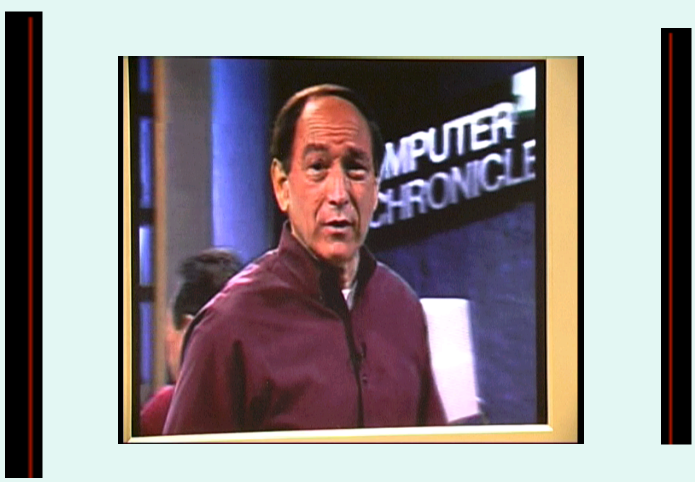
Impact of the Defence on the Nodes



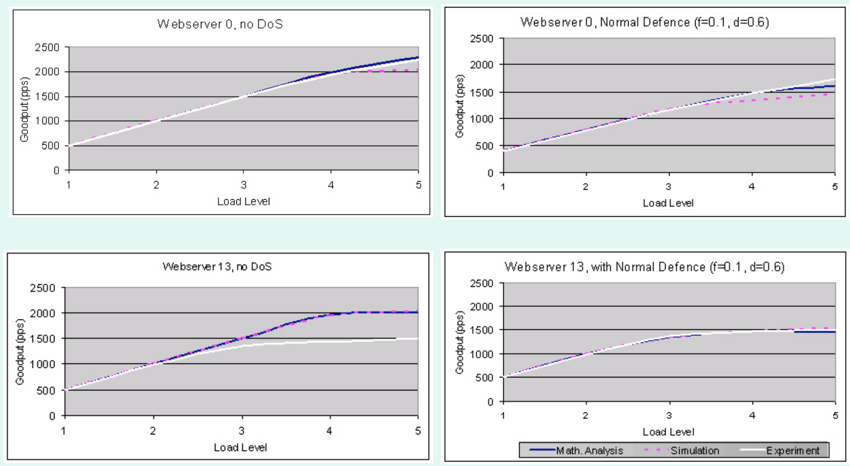
Experiment

- 2.4GHz P4 PCs, Linux kernel 2.4.26, CPN
- Different QoS protocols for normal and attack traffic
- Delay-based FIFO queuing
- 60 sec

DoS on a streaming video



Math. Analysis, Simulation and Experiment Comparison



Network Research for Users and Services A Pragmatic Approach

- Consider architectures that support open, extensible, human centric networks
- Investigate broad classes of User/Service based QoS goals, e.g., time, loss, power, security, cost, reliability, robustness to attack
- Investigate relevant metrics that can be built into these QoS goals
- Select measurable and observable quantities from which these metrics can be computed
- Design network primitives that can access these measurable quantities and report them to Users/Services
- Illustrate the above in experimental test-beds
- Design and provide open interfaces for access and usage of the test-beds
- Couple modelling and analysis with the experimental work