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FIT 4 GREEN

Energy Aware Routing in Packet Networks

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- ICT uses up as much energy as air travel and 2% of the world's CO_2 imprint
- This is bound to grow: smart grid, smart homes, distance learning, home-work ..
- Much of this is inevitably consumed in packet networks
- e.g. BT's electricity bill for ICT exceeds £1B/yr

➔ Improve Energy Efficiency in Networks

Energy efficiency in wired networks

- Techniques for energy savings in wireless (sensor) networks have been very widely studied
- Wired networks have been largely neglected even though they are massive consumers of power
- In a wired packet network the problem is to:
    - Minimize total power consumption, and obviously ...
    - Respect users' QoS needs

Previous Work

- M. Gupta and S. Singh [1] : Routing modifications and putting devices to sleep.
- J. Chabarek et al. [2]: Offline optimization where components can be powered on/off in combination with multi-commodity network-flow problem
- Energy-aware online technique [3] based on a step-like model of power consumption and assumption of hardware rate adaptation
- Rate adaptation and a burst traffic technique at edge routers [4]
- Energy savings through routing in wireless Ad-Hoc networks [5]
- Energy savings in Cloud Computing (Processing+Networking) [6]
- Experiments with power-aware routing using CPN [7,8]
- Various heuristics for power savings [10]
- Power consumption measurements in routers [13]
- *No general systematic principled approach yet developped that can examine all the parameters of the problem*

Our Work

- Experiments on a test-bed to seek the way forward
- Build a model that will allow formally defined routing algorithms to be designed and evaluated – use the theory of G-networks
- Design a heuristic based on the Cognitive Packet Network routing algorithm and evaluate on a test-bed with respect to power savings and QoS

Preliminary Experiments

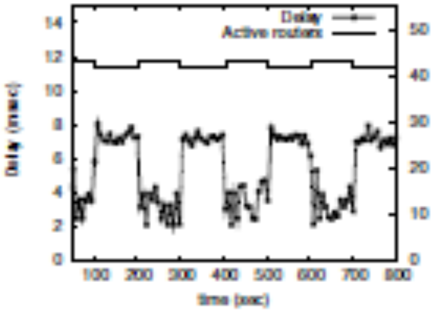
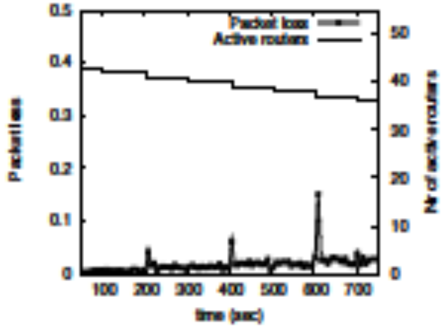


Fig. 5. Delay - second experiment



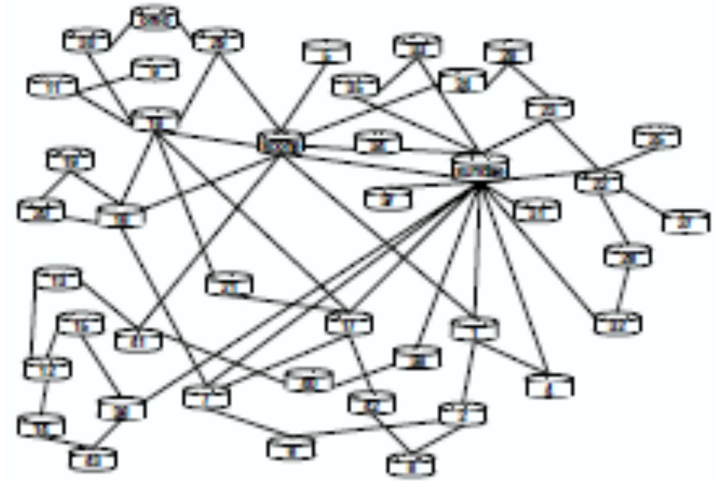


Fig. 1. Topology of the test-bed in use

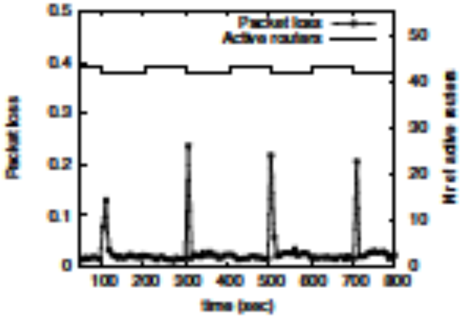
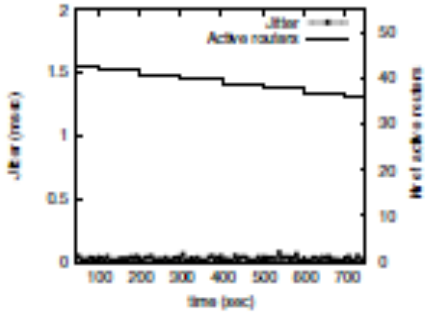
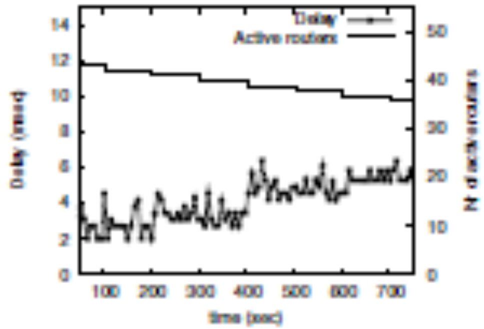
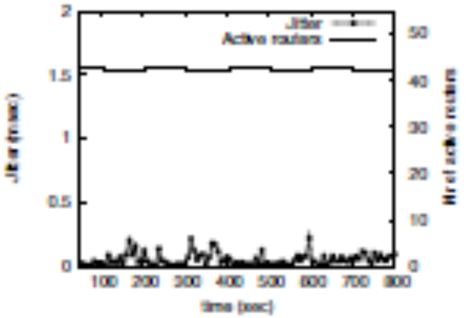


Fig. 6. Packet loss - second experiment



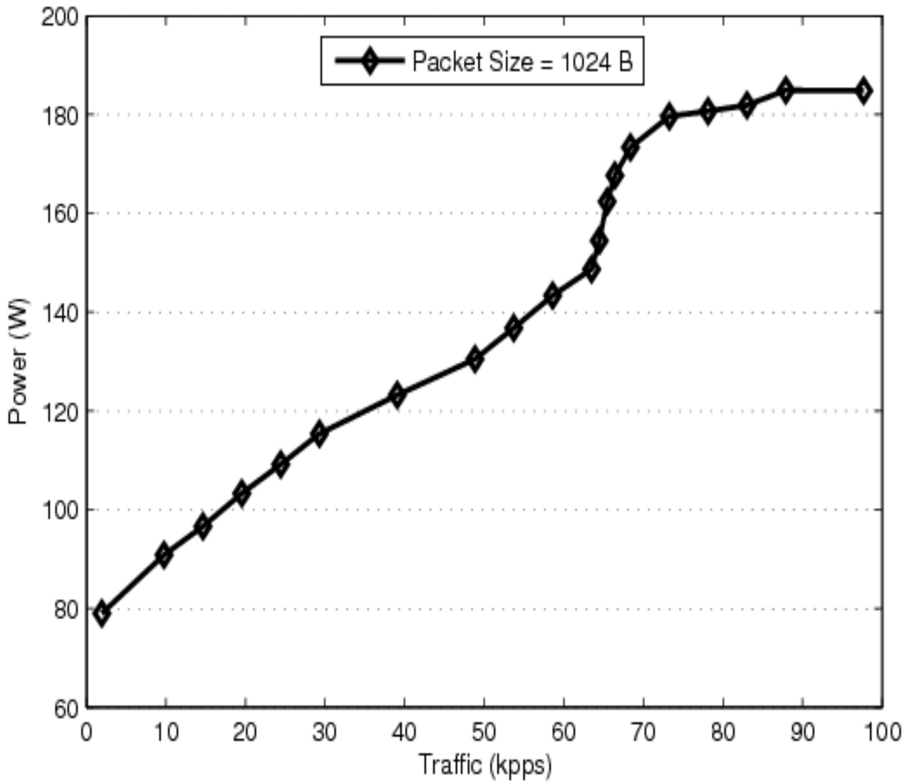


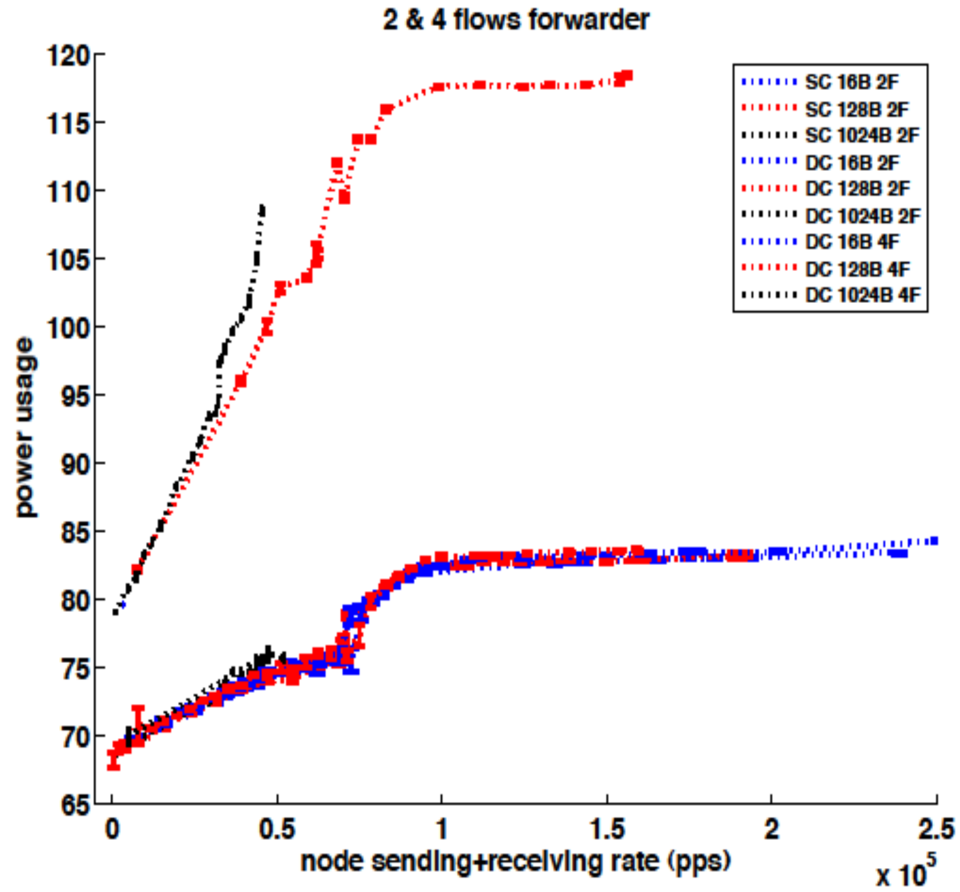


Measurements on Feasibility Using our 46-node Laboratory Packet Network Test-Bed:

E. Gelenbe and S. Silvestri, ``Optimisation of Power Consumption in Wired Packet Networks,'' Proc. QShine'09, 22 (12), 717-728, LNICST, Springer Verlag, 2009.

Power Measurement on Routers





[14] R. Lent, "Power measurements of processors for routing," Intelligent Systems and Networks Group, Tech. Report, Imperial College London, May 2010.

G-networks allow product form solutions that include the effect of routing control

Rerouting controls occur infrequently (seconds) as compared to individual packet service times (1ms) and end-to-end packet travel times (10ms)

- The system attains steady-state between the control instants
- G-networks [11,12,13] with triggered customer movement and multiple classes are a convenient modelling paradigm for packet networks with controls
- Network with **N** queues, **R** routers and **L** links, **N=R∪L**
- Set of **user traffic classes *U***
- The default routing decision of a user of class *k* from node *i* to node *j* is represented by the probability ***P(i,k,j)***
- The external arrival rate of packets of class k to router r is denoted by ***λ(r,k)***

G-networks allow product form solutions that include the effect of re-routing

*C*urrent default routing decision of a user of class *k* from neighbouring queues *i* to *j* is ***P(i,k,j)***

- **Control traffic class *(r,k):*** *acts at router r on traffic class k*
- A control packet of class *(r,k)* moves from queue *i* to *j* with probability ***p((r,k),i,j)***
- Control function ***Q(r,k,j)*** : probability that user of class *k* at router *r* is directed by the corresponding control packet of type *(i,k)* to link j.
- External arrival rate of control packets of class *(r,k)* to router i : $\boldsymbol{\lambda^{-}(i(r,k))}$

Traffic in the Network

- The steady state probability that a router *r* or a link *l* contains at least one packet of user class *k* is given by

$$q(r,k)=\frac{\Lambda_R(r,k)}{\mu_r+\Lambda^-(r,(r,k))}, \text{if } r\in\mathbf{R} \qquad q(l,k)=\frac{\Lambda_L(l,k)}{\mu_l}, \text{if } l\in\mathbf{L}$$

- The total arrival rates of user packets of class k to the routers and links are given by

$$\Lambda_R(r,k)=\lambda(r,k)+\sum_{l\in\mathbf{L}} q(l,k)P(l,k,r)\mu_l, \text{if } r\in\mathbf{R}$$

$$\Lambda_L(l,k)=\sum_{r\in\mathbf{R}}[q(r,k)P(r,k,l)\mu_r+\Lambda^-(r,(r,k))q(r,k)Q(r,k,l)], \text{if } l\in\mathbf{L}$$

- *f* is the fraction of control actions (e.g. 10^{-2}) that actually need to be communicated via a new control packet

Control Traffic

- The total arrival rate to router or link j of control traffic of class (i,k) is given by

$$\Lambda^-(j,(i,k)) = \lambda^-(j,(i,k)) + \sum_{l \in \mathbf{L}} p((i,k),l,j)c(l,(i,k))\mu_l, \text{if } i, \text{j} \in \mathbf{R}$$

$$\Lambda^-(j,(i,k)) = \sum_{r \in \mathbf{R}} p((i,k),r,j)K(r,(i,k))\mu_r, \text{if } i \in \mathbf{R}, j \in \mathbf{L}, i \neq r$$

- The steady-state probability that a router r contains at least one packet of class k is

$$c(l,(i,k)) = \frac{\sum_{r \in \mathbf{R}} p((i,k),r,l)K(r,(i,k))\mu_r}{\mu_l}, \text{if } l \in \mathbf{L}$$

- And for the routers

$$K(r,(i,k)) = \frac{\lambda^-(r,(i,k)) + \sum_{l \in \mathbf{L}} p((i,k),l,r)c(l,(i,k))\mu_l}{\mu_r}, \text{if } r \in \mathbf{R}, r \neq i$$

Average Queue Length

- Each user class is assumed to be handled by separate queues in routers, so the average queue length in router *r* is given by

$$N(r,k) = \frac{q(r,k)}{1-q(r,k)}, r \in \mathbf{R}$$

- On the other hand, all packets within a link are handled in a first-come-first-serve order, so the average queue length at link *l* is given by

$$N(l) = \frac{B(l)}{1-B(l)}, l \in \mathbf{L}$$

where $B(l) = \sum_{k \in \mathbf{U}} [q(l,k) + \sum_{i \in \mathbf{R}} c(l,(i,k))]$ is the steady state probability that link *l* is busy

QoS metrics

- We can now derive the relevant QoS metrics, e.g.
  - Total average delay through the network for a packet of class *k*

$$T(k) = \sum_{l \in \mathbf{L}} \pi(l,k) \frac{N(l)}{\Lambda_L(l,k)} + \sum_{r \in \mathbf{R}} \pi(r,k) \frac{N(r,k)}{\Lambda_R(l,k)}, \quad \bar{T} = \sum_k T(k)$$

where $\pi(r,k) = \frac{\Lambda_R(r,k)}{\lambda^+(k)}, r \in \mathbf{R}$, $\pi(l,k) = \frac{\Lambda_L(l,k)}{\lambda^+(k)}, l \in \mathbf{L}$ are the probabilities that a packet of class k enters router r or link l respectively,
and $\lambda^+(k) = \sum_{r \in \mathbf{R}} \lambda(r,k) = \lambda(s,k)$ is the total traffic of class k, s being the source router of this class

Power Consumption Model

- Consider nodes separately as routers and links: their power consumption is modelled separately
- Power consumption is an increasing function of load

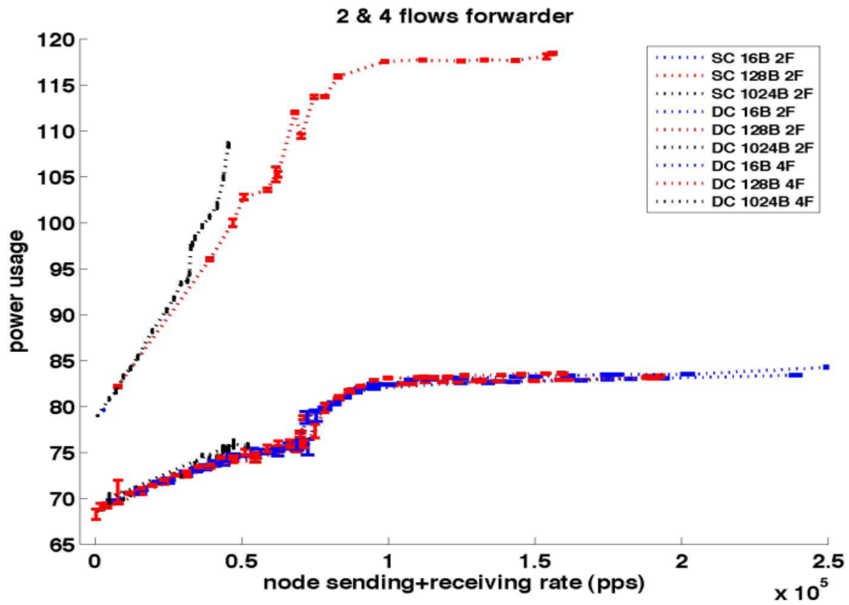


Figure 1 Router power consumption in Watts as a function of packet rate in pkts/sec [14]

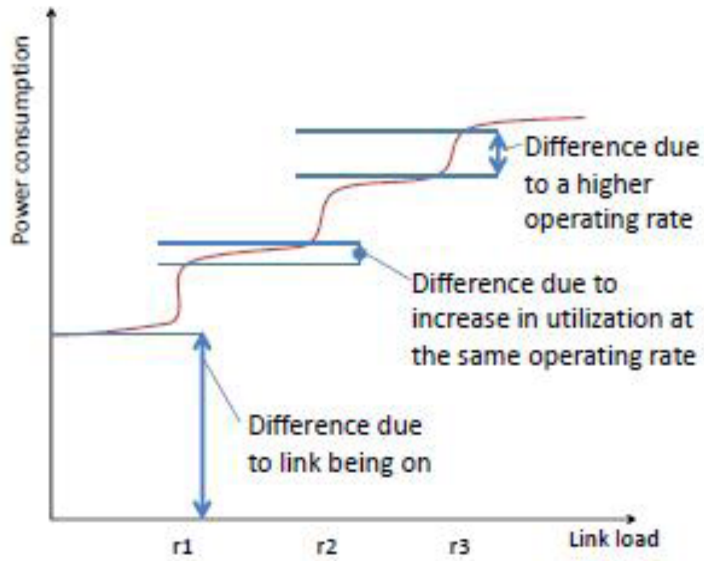


Figure 2 Link power consumption in Watts as a function of traffic rate in bytes/sec [3]

Power Consumption Model

- Routers

$$P_i = \alpha_i + g_R(\Lambda_i) + c_i \sum_{k \in \mathbf{U}} \Lambda_R^-(i,(i,k)), i \in \mathbf{R}$$

where α_i is the static router power consumption, $g_R(.)$ is an increasing function of the packet processing rate as in Figure 1 and $c_i > 0$ is a proportionality constant related to the power consumed for the processing of the rerouting control

- Links

$$P_i = \beta_i + g_L(\Lambda_i), i \in \mathbf{L}$$

where β_i is the static power consumption when the link interface is on and $g_L(.)$ is an increasing function of the data transmission rate on the link as in Figure 2

Gradient Descent Optimisation

- The routing optimisation can be expressed as the minimization of a function that combines power consumption and (e.g.) the network average delay :

Minimize $G = c\sum_{i \in N} P_i + \overline{T}$

Using the $Q(i,k,j)$

- We therefore need to design algorithm to obtain the parameters $Q^o(i,k,j)$ at the operating points of the network

$$\underline{X} = [\underline{\lambda}, \underline{\lambda}^-, \underline{\mu}, \underline{P}^+, \underline{p}]$$

A. Gradient Descent Optimization

- Algorithm of O(|***U***|.|***N***|^3) complexity [High!!]
  - Initialize the values *Q(i,k,j)* and choose *η*>0
  - Solve |***U***| systems of |***N*** | non-linear equations to obtain the steady state probabilities *q(i,k) from G-network theory*
  - Solve |***U***| systems of |***N*** | linear equations for gradient descent using G-network theory

$$\frac{\partial \mathbf{q}_k}{\partial Q(x,m,y)} = \boldsymbol{\gamma}_k^{xmy}(\mathbf{I} - \mathbf{W}_k)^{-1}$$

  - Update the values of *Q(i,k,j)* using the nth computational step $Q_{n+1}(i,k,j) = Q_n(i,k,j) - \eta \frac{\partial G}{\partial Q(i,k,j)} \Big|_{Q(i,k,j)=Q_n(i,k,j)}$

Optimisation Through Network Balancing

- Simpler cost minimising algorithm when the cost is expressed as

$$C = \sum_{r \in \mathbf{R}} \frac{\Lambda_r}{\Lambda_T} F_r(\Lambda_r) + \sum_{l \in \mathbf{L}} \frac{\Lambda_l}{\Lambda_T} F_l(\Lambda_l)$$

  where Λ_r, Λ_l are the traffic rates at the routers and links and Λ_T is the total traffic carried by the network.

- *Two paths of length u,v with v≤u are perfectly balanced,* if there exist traffic rates x_i *,1≤i≤u* such that

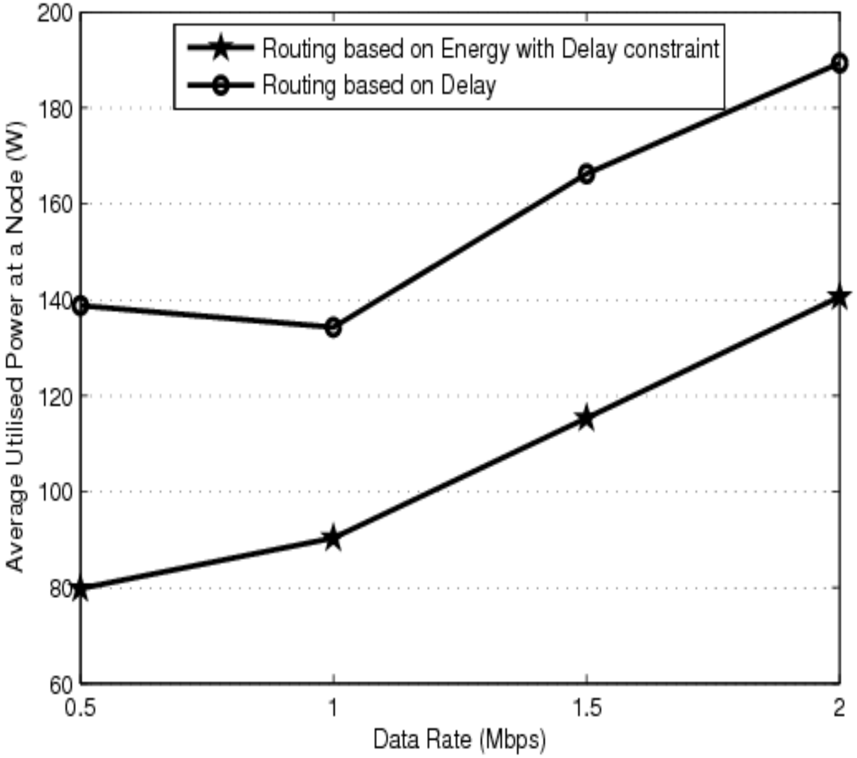
$$F_r(x_i) = F'_{r_i}(x_i), \quad 1 \le i \le v$$

We show that by better balancing paths the Power plus QoS cost of the network is reduced provided that the functions F are continuous, differentiable, increasing

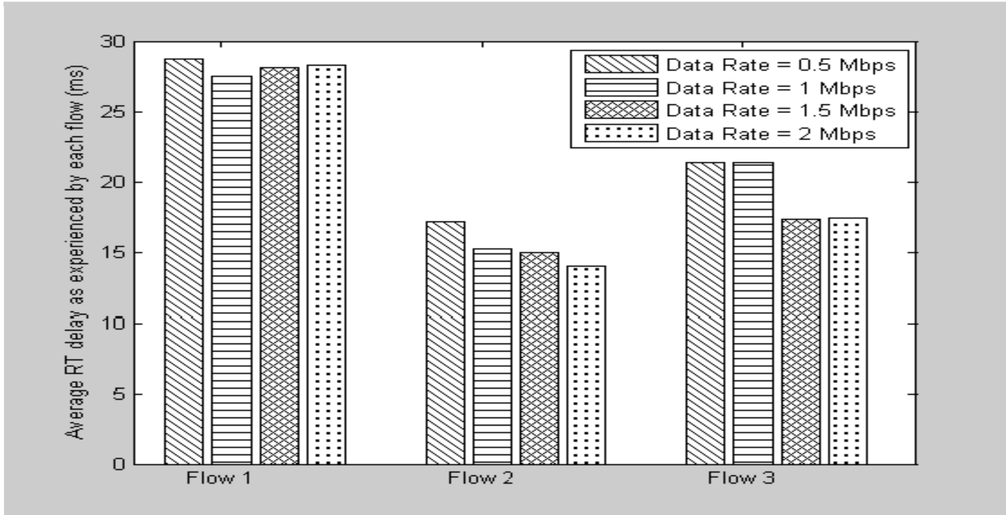
Experiments with a Self-Aware Approach
Minimise Power subject to End-to-End Delay (80ms) Constraint

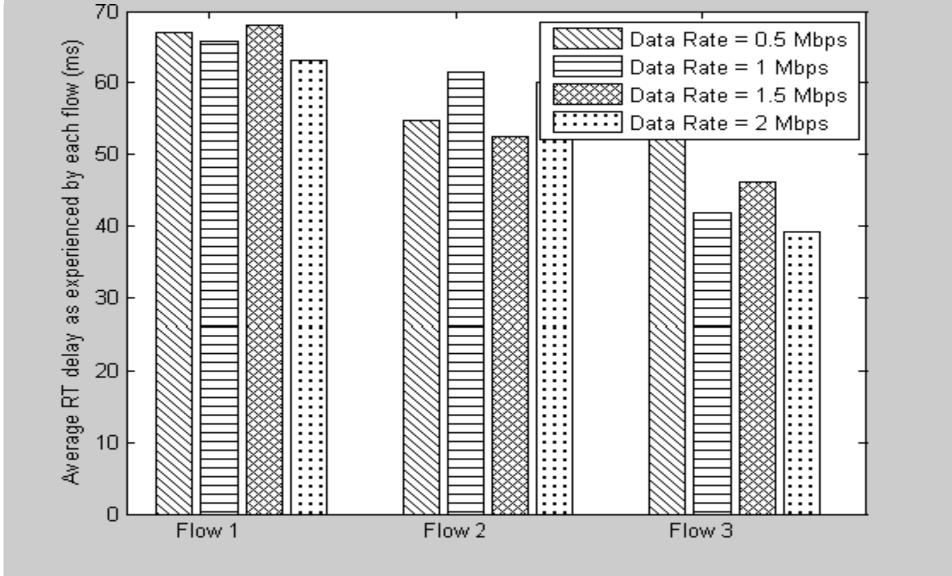
[10] **E. Gelenbe, ``Steps Toward Self-Aware Networks,'' Comm. ACM, 52 (7), pp. 66-75, July 2009.**

[15] E. Gelenbe and T. Mahmoodi "Energy aware routing in the Cognitive Packet Network", presented at NGI/Coseners,

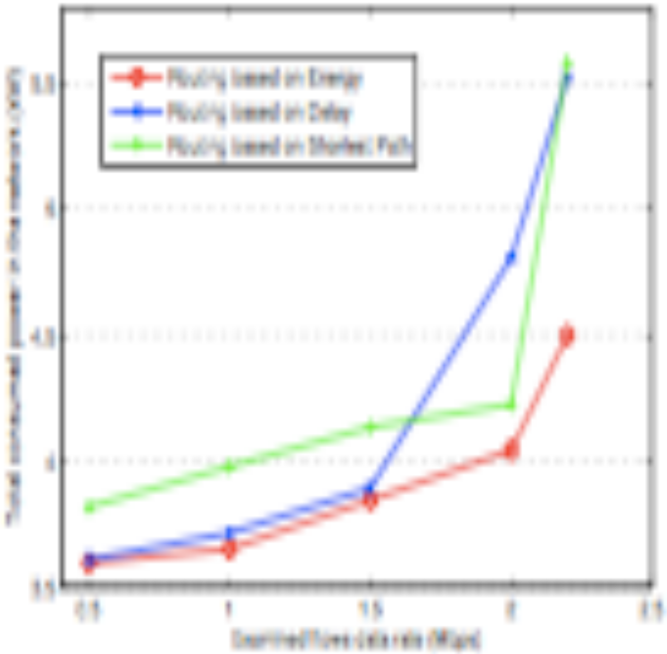


Measuring Avg Power Over All Routers
Vs Average Traffic per Router

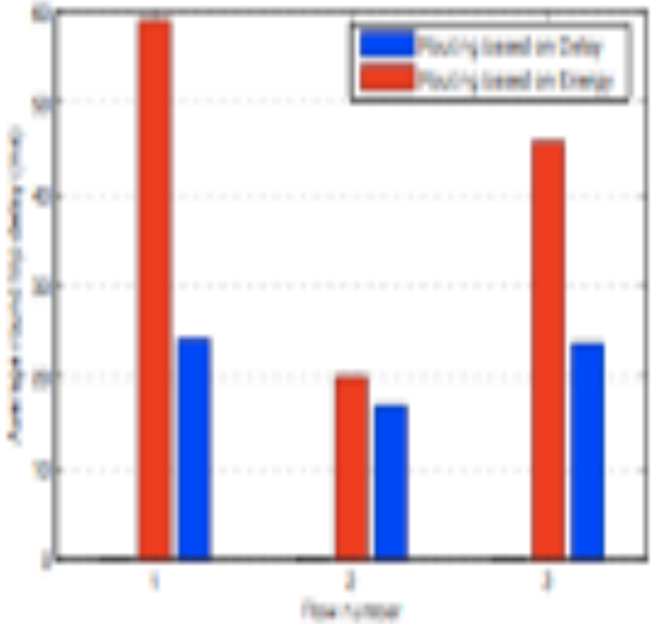




Power and Delay with EARP
Energy Aware Routing Protocol



(a) Total power consumption in the network vs. traffic rate



(b) Average round trip delay

Power Savings and QoS using EARP

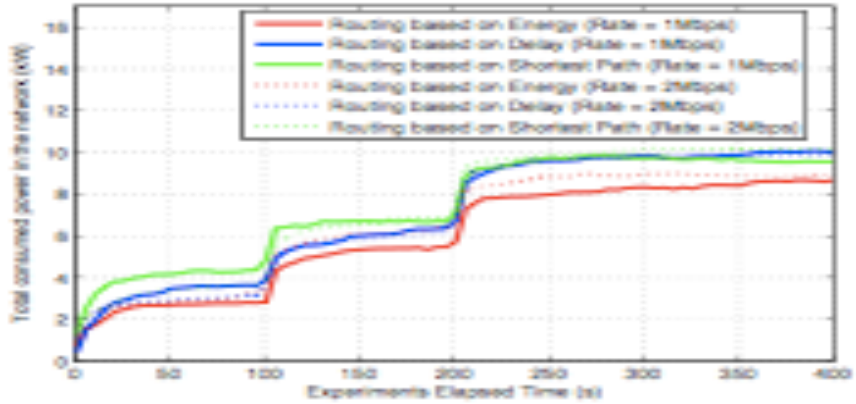
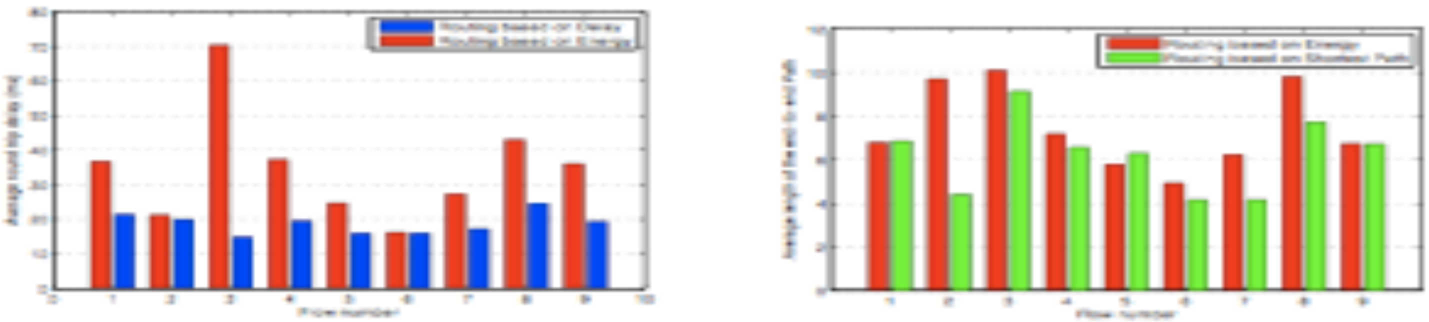


Fig. 2. Scenario two: Total power consumption in the network Vs. the experiment's elapsed time.



(a) Average round trip delay

(b) Average length of the end-to-end path

Fig. 3. Scenario two: round trip delay and the route length of the active flows.

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