An Energy-Aware Routing Protocol in Cognitive Networks

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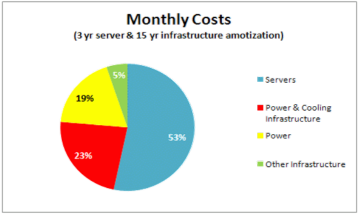
Outline

Global View Vs. Holistic View

- ICT itself is a large power consumer,
  - total energy consumption for ICT and for air travel are comparable.
- Significant fraction of the total energy used for ICT systems is consumed in the network,
  - Amazon has evaluated its data centre expenses, showing that server costs account for 53%.



Wired and Wireless Networks

- In wireless networks,
  - sources of energy are scarce.
  - in most cases the aim is to increase the life-time of wireless nodes.
  - energy efficient protocols have been extensively studied in this area.
- In wired networks, although the availability of power is not an issue,
  - power is yet costly, and thus optmisation of the power consumption is desired.
  - research on energy consumption is relatively new.

Energy-Aware Routing Protocol

- Routing protocols per se could be optimised based on energy consumption, mainly because nodes may have,
  - various energy related characteristics.
  - different sources of power generation at different cost and/or Greenhouse Gas (GHG) emission.
- An Energy-Aware Routing Protocol (EARP) is presented here that,
  - attempts to minimise the total power consumption in the network,
  - and also respects the requested QoS by each incoming flow.
  - cost of power at any node in the network can be introduced as a function that capture the above mentioned parameters.

Power Consumption as a Function of Traffic

- Assuming flow k carries traffic t_k, T_i denotes the traffic level at node i, $F(i)$ denotes the set of flows that use node i in their end-to-end path.

$$T_i = \sum_{k \in F(i)} t_k. \qquad (1)$$

- Let $p_i(T)$ and $Q_i(T)$ the power consumption and QoS of node i when the traffic it carries is T,
  - adding a new flow k to node i will result in a change of power consumption and QoS at that node,
  - this also affects the other flows that are using the node in their end-to-end path.

Power Cost Function

- The *Power Cost* of the $k-th$ flow at node i can be defined as,

$$m_i^k(t_k, T_i) = c \cdot p_i(t_k + T_i) + d \cdot [p_i(t_k + T_i) - p_i(T_i)]. \quad (2)$$

- Here the first term is the total power (watts) used by the $k-th$ flow, multiplied by some constant c. The second term represents the increase in wattage for the other flows, multiplied by some constant d.
- Constant values c and d are defined such that $c, \ d \geq 0$,
  - if $d = 0$, we are ignoring the effect of adding a new flow to node i on the other flows that are using the node.
  - if $c = d = 1$ both the elements have an equal weight.

Distributed Algorithm

- Given $m_i^k(t_k, T_i)$ cost as associated to the consumed power of flow k at node i, our routing protocol aims to minimise the total cost of power in the network as the whole entity.
- This algorithm can be implemented in a centralised manner such that,
  - a single node of the network has access to the total information,
  - therefore routing decisions can be made accordingly.
- On the other hand, the distributed algorithm requires the information of power consumption at the nodes locally.
- To enable the distributed implementation of the algorithm, EARP relies on the underlying Cognitive Packet Network (CPN) for the information it requires.

Cognitive Packet Network

- CPN allows a network with an arbitrary topology to observe its state in a distributed manner and exploit the data being gathered to improve different QoS metrics.
- Smart Packets (SPs) are constantly generated by each of the source users of CPN, in order to,
  - seek paths to the destination that minimise the desired QoS.
  - update the QoS information of different paths used by the source.
  - allow the source node to make informed decisions.
- ACKnowledgement packets (ACK) bring back information that has been discovered by SPs to all the nodes within the corresponding path.
  - these packets follow back the selected rout by SPs.

Energy and QoS Driven Routing

- EARP attempts not only to minimise the total consumed power in the network but also to respects the requested QoS by each incoming flow.
  - CPN's smart packets are used to gather information about the power usage and QoS at the nodes.
  - CPN's source routing scheme is modified to include power consumption as a decision criterion.
- Reinforcement Learning (RL) algorithm is used in CPN to find the optimal rout according to the predefined goal function.
  - Since EARP is expected to minimise the overall cost of power while satisfying the requested QoS, the goal G_i to be optimised will combine the power consumption with the QoS constraint.

Reinforcement Learning in EARP

- The goal function at node i is defined as,

$$G_i = m^k_{\pi(i)}(t_k, \overline{T_{\pi(i)}}) + \beta \cdot 1[Q^k_{\pi(i)}(t_k, \overline{T_{\pi(i)}}) - Q^k_o > 0](Q^k_{\pi(i)}(t_k, \overline{T_{\pi(i)}}))^{\nu}, \tag{3}$$

where:

- $m^k_{\pi(i)}(t_k, \overline{T_{\pi(i)}})$ is the total power cost function on the path going from the $i-th$ node to the destination of flow k.
- $Q^k_{\pi(i)}(t_k, \overline{T_{\pi(i)}}))$ is the total QoS value measured from this node to the destination by the SPs, while Q^k_o is the QoS value that *should not be exceeded* for flow k.

Power and QoS on the Path $\pi(i)$

- The power related cost functions for the k-th traffic flow of rate t_k on a path $\pi(i)$ originating at node i is written as:

$$m^k_{\pi(i)}(t_k, \overline{T_{\pi(i)}}) = \sum_{n \in \pi(i)} m^k_n(t_k, T_n), \tag{4}$$

- Similarly, we would have the QoS criterion, such as loss, delay or some other metric:

$$Q^k_{\pi(i)}(t_k, \overline{T_{\pi(i)}}) = \sum_{n \in \pi(i)} Q^k_n(t_k, T_n) \tag{5}$$

Reinforcement Learning in EARP

- Each router stores a specific Random Neural Network (RNN) for each flow that is active at that node,
- The arrival of a SP will trigger the interrogation of the RNN to determine the next hop for the SP.
- The output port of the node is selected based on the neuron of the RNN which is the most excited.
- Arrival of an ACK packet back from the destination of that flow, will trigger the execution of the RL process.

Reinforcement Learning in EARP

- In this RL process, the reward function of $R = G^{-1}$ and its sliding average is used i.e., if the R_θ are the successive measured values of the reward function R at some node, then the RNN weights are updated based on the threshold Θ_θ, which captures a historical (but sliding window) average of the reward,

$$\Theta_\theta = \alpha\Theta_{\theta-1} + (1-\alpha)R_\theta, \tag{6}$$

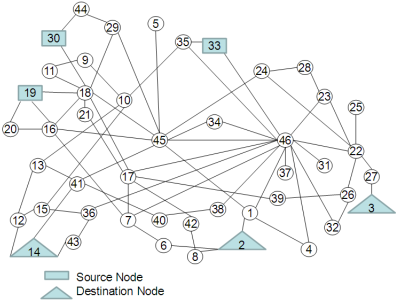
- Constant value $0 \le \alpha \le 1$ tunes the responsiveness of the algorithm, i.e. $\alpha = 0.8$ represents an "average sliding window" of the five past values

Reinforcement Learning in EARP

- Weights are increased or reduced based on the difference between the current reward R_θ and the previous threshold $\Theta_{\theta-1}$.
- If R_θ is larger than $\Theta_{\theta-1}$, then this results in,
  - significant increase in the excitatory weights from all neurons to the previously selected output link.
  - slight increase in the inhibitory weights leading to other neurons.
- If R_θ is smaller than $\Theta_{\theta-1}$,
  - all excitatory weights leading to all neurons are moderately increased, except for the previous winner.
  - the inhibitory weights leading to the previous winning neuron are significantly increased, in order to “punish” it for not being successful.

Networking Testbed: Topology

- Our topology resembles that of the Swiss Education and Research Network, and artificial delays are used to replicate the link-level delays of the real network.

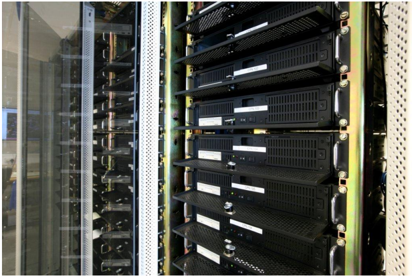
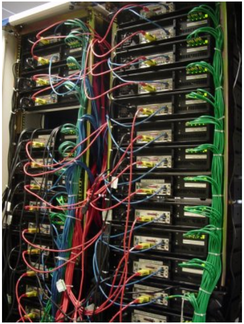


Networking Testbed: Parameters

- Our experimental testbed consists of 46 nodes,
  - nodes are Pentium IV-machines with up to fifteen Ethernet interfaces running Linux Kernel 2.6.15.
  - nodes are connected with the full-duplex links at 10 Mbps.
- The requested QoS value of delay is 80 ms, i.e. $Q_o^k = 80$, which has been chosen based on the actual delay of a flow in the network.
- In the implementation, the constant $\nu = 8$, and $\beta = 1$ are chosen in the goal function so that its second term can become so large that the delay constraint is rarely violated.

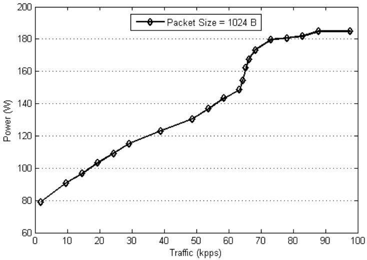
Networking Testbed

- ISN Networking Testbed.

Power Consumption Model

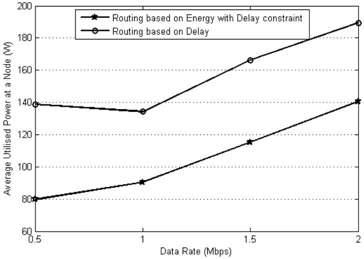
- Power consumption as a function of packet rate as measured in a router is plotted in this curve.



- We assume that all the nodes have the same power consumption characteristic as shown above.

Experimental Results: Power

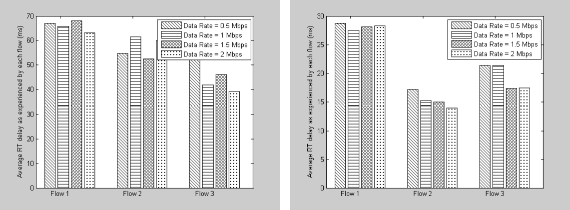
- Average consumed power in a node is decreased using EARP as compared with the delay minimisation scheme.



- It can be seen that using only delay as the QoS goal, nodes are quite close to operating at their maximum power.

Experimental Results: Delay

- The average delay values as experienced by the three active flows show an increase, which is fairly expected.
  - although delay may increase with EARP, each flows round trip delay remains within the prescribed limit.

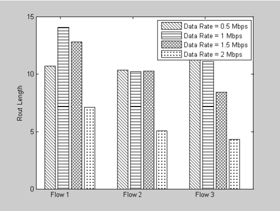


(c) Routing based on energy with delay constraint.

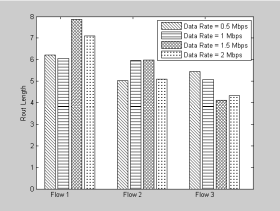
(d) Routing based on delay.

Experimental Results: Rout Length

- The increase in delay is mainly due to the longer paths taken by EARP to avoid nodes that may carry more traffic,
  - examining the average length of the end-to-end paths reveals that routs selected by delay minimisation protocol are 40% shorter than those selected by EARP.



(e) Routing based on energy with delay constraint.



(f) Routing based on delay.

Conclusions

- ICT is a large consumer of energy, and a big emitter of GHG. Therefore, providing energy efficient solutions are desired.
- An Energy-Aware Routing Protocol (EARP) is presented that minimises the total cost of power in the network, and at the same time respects the requested level of QoS.
- EARP is implemented in a fully distributed fashion, and for its required information relies on the functionality of Cognitive Packet Network.
- Performance investigations that carried out in an experimental testbed reveals a significant savings in the power consumption of the network.

Questions?

Thanks for your attention.

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