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Energy Efficient Network Resource Allocation Scheme for Hose Model

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Abstract

Given the exponential growth in telecommunication networks, more and more attention is being paid to their energy consumption. However, the often over-provisioned wired network is still overlooked. In core networks, pairs of routers are typically connected by multiple physical cables that form one logical bundled link participating in the intra-domain routing protocol. To reduce the energy consumption of hose-model networks with bundled cables, we propose a scheme to deactivate the maximum number of cables, and associated equipment, possible. A similar approach has been presented for the pipe model, where the exact traffic matrix is assumed to be known. Due to traffic uncertainty, however, it is difficult for operators to have exact knowledge of the traffic matrix. This traffic uncertainty can be avoided by using the hose model, which specifies only the upper bounds of the egress/ingress traffic from/to a node. We introduce a mixed integer linear problem formulation that yields the optimal solution and a more practical and near optimal heuristic algorithm for large networks. Our performance evaluation results show that it offers up to 50% power reduction compared to shortest path routing.

Acknowledgements

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Contents

Chapter 1

Introduction

The traffic in telecommunication networks has, in recent years, seen continuous exponential growth due to the increasing number of connection demands and higher capacity requirements. The actual trends offer no end in sight, the volume of traffic and the resources needed to accommodate it will most likely continue to increase rapidly. This impacts the energy consumption of telecommunication networks and its share of global consumption. Given the energy crisis and the greenhouse effect, power saving is a real concern.

Greening networks has become an important part of networking research recently. Power awareness is a big part of mobile networking; studies have been conducted for both ad-hoc and wireless as Jones et al. show in [1]. Also, the computer architecture community has come up with different approaches to limit energy consumption (e.g., [2], [3]). Unfortunately, the power consumption of the underlying wired networks has been overlooked. We note that the capacity of core networks is traditionally over-provisioned in order to accommodate traffic shifts, and to permit re-routing when links fail.

Power reduction can be achieved by adopting a strategy similar to computers, idle resources can be put into sleep mode or even shut off for some time. In core networks, pairs of routers are typically connected by multiple physical cables to accommodate more traffic or for extension purposes. The cables connecting two routers form one logical bundled link participating in the intra-domain routing protocol [4]. Measurements reveal that less than 30% of backbone capacity is utilized [5]. As a result, cables can be powered down selectively to achieve energy savings, essentially during period of low traffic utilization.

One approach to power down unused individual cables in each bundle for the pipe model has been published [6]. In pipe-model traffic, the exact traffic demand between any source and destination is assumed to be known, the full traffic matrix is considered as given. However in actual networks, due to traffic uncertainty, it is difficult to determine the exact traffic matrix.

The hose model presents an pallative to traffic uncertainty and offers more flexibility to network operators [7]-[8]. Unlike the pipe-model traffic, it does not require the exact traffic matrix to be known. In hose-model traffic, only the upper bound of the total incoming/outgoing (ingress/egress) traffic for each user's edge node is specified. While it is difficult to predict the exact traffic demand for each end user of a network at any given time, network operators can estimate the upper bound of the total incoming/outgoing traffic for each edge node. According to its definition, hose-model traffic covers all sets of traffic demands that are likely to be routed between the edge nodes. To the best of our knowledge, no study has considered reducing the power consumption of bundled cable networks under the hose model.

This paper proposes a power consumption reduction scheme for bundled cable networks under the hose model. Our approach is to selectively deactivate as many cables as possible while still guaranteeing that the network can route the traffic loads. To achieve an optimal solution, we introduce a mixed integer linear problem (MILP) formulation that minimizes the energy consumption of bundled cable networks under the hose model while retaining robust routing performance. Since the MILP problem is NP-hard, and therefore is not tractable for large networks, we develop a heuristic algorithm that yields near optimal solutions; its linear programming (LP) formulation ensure that there is enough headroom for the traffic that is likely to offered within the hose-model limits.

The rest of the paper is organized as follows. Chapter 2 explores related works on greening networks as well as on hose-model networking. We formulate an MILP problem for determining optimal solutions in Chapter 3 assuming the use of the hose-model. Chapter 4 describes our proposed heuristic algorithm and the related LP problem. Chapter 5 presents the performance of our heuristic algorithm as compared to the shortest path routing (SPR) and maximum throughput formulation in several networks. The conclusions appear in chapter 6.

Chapter 2

Related works

Reducing the energy consumption of telecommunication networks by moving toward green networks is receiving a lot of attention from the research community. With the exponential increase in resource consumption by telecommunication networks, their share in worldwide energy consumption has become more and more important.

2.1 Link deactivation technology

Current networks do not have the systems that would make it possible to deactivate/activate individual cables within a bundled link. Given the energetic research into telecommunication networks, and the importance of power saving, this omission will be rectified quite soon. The architecture closest to our working model was presented by Chabarek et al. [9]. They investigated the power consumption of a router and its distribution among its components, chassis, and line cards. We assume that in bundled cable networks, cables are powered by line cards and the line cards are attached to several chassis. A router can consist of multiple chassis, but in this work, we do not consider the number of chassis. Our approach is to switch off individual cables and their controlling line cards for each link, particularly during periods of low traffic.

For the remainder of this work, we assume that network operators intend to dynamically switch on/off cables and the associated line cards for a given period of time. The hose model parameters are specified for the same given period.

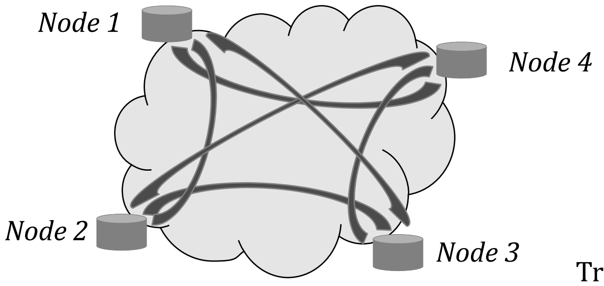
2.2 Greening pipe model network

In [9], Chabarek et al. advocated for a new concern about power awareness in wire line networks. They consider that it should be taken as a primary objective in the design of networks and the implementation of routing protocols. After addressing generic modeling for reducing the power consumption of network devices, they investigate the power demand associated to the traffic matrices in network design. Their identification of system configurations that minimize power consumption while meeting performance and robustness requirements allows them to assess the potential impact of power awareness in routing and network design.

In [10], the authors further these considerations with more emphasis on the protocol level. Their approach is, with granted support for power management at hardware level, to use adequate network protocols to put network components to sleep during idle times and adapt the rate of network operation to the offered workload. The two methods provide substantial power savings with simple power management algorithms.

The works presented in [6] and [12] are the closest to ours as they consider switching off, for certain periods of time, some components of the network, entire routers and links in [12], idle bundle cables in [6]. In that, the approach used in [6] is more advantageous as it offers the possibility of deactivating idle cables within a bundled link without disabling it, therefore avoiding the all or nothing situation at the link level. The authors first formulate the problem as an MILP before introducing heuristics that are practical for large networks. We will proceed similarly in this work.

All the before mentioned power reduction approaches show that substantial power savings can be achieved for green networks. However, their impact is limited since the



-	h_{12}	h_{13}	h_{14}
h_{21}	-	h_{23}	h_{24}
h_{31}	h_{32}	-	h_{34}
h_{41}	h_{42}	h_{43}	-

Traffic matrix (T): Sets of traffic demands

Figure 2.1: Pipe-model network

traffic matrix must be known in advance. In addition to the fact that actual traffic demands are difficult to know at any time, their implementation will need to consider the changes driven by dynamic traffic demands.

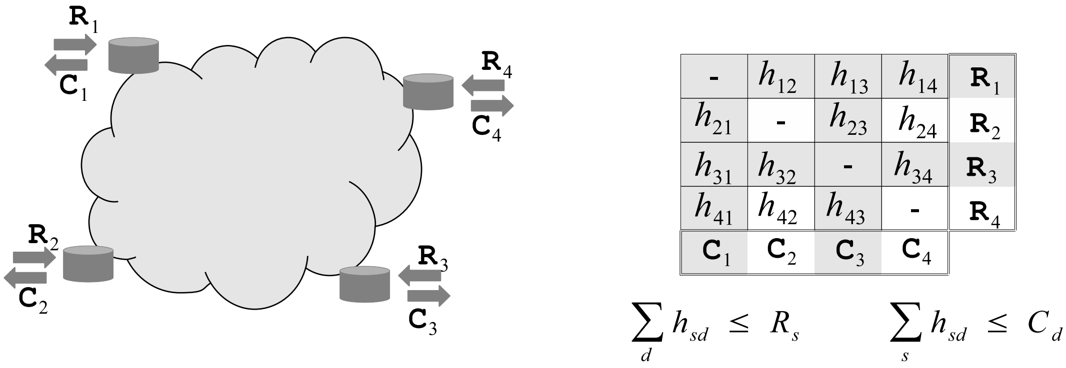
2.3 Research on hose model

2.3.1 Hose model definition

A hose-model traffic model is defined by the sets of maximum allowed outgoing / incoming traffic from/to a node [7]. Opposite to the pipe model, hose model does not require the exact traffic matrix to be known. In pipe model, the traffic matrix denoted by $T = \{h_{sd}\}$, where h_{sd} is a traffic demand between source node s and destination node d, is fully expressed (Fig. 2.1). However it is difficult for network operators to measure and predict the actual traffic matrix.

On the other hand, it is easy for network operators to specify the traffic as just the total outgoing/incoming traffic from/to node s and node d (Fig. 2.2). The total outgoing traffic from node s is represented as $R_s = \sum\limits_{d} h_{sd}$, where R_s is the traffic that node s can send into the network. The total incoming traffic to node d is represented as $C_d = \sum\limits_{s} h_{sd}$, where C_d is the traffic that node d can receive from the network.

By this definition, any traffic matrix that fit within its boundaries (R_s, C_d) is cov-



-	h_{12}	h_{13}	h_{14}	R_1
h_{21}	-	h_{23}	h_{24}	R_2
h_{31}	h_{32}	-	h_{34}	R_3
h_{41}	h_{42}	h_{43}	-	R_4
C_1	C_2	C_3	C_4	

$$\sum_d h_{sd} \le R_s \qquad \sum_s h_{sd} \le C_d$$

Figure 2.2: Hose-model network

ered by the hose model. It offers to network operator a certain flexibility regarding traffic uncertainty and an easy way to define the traffic demand for the clients.

2.3.2 Previous researches

Due to the range of possible traffic demands the hose-model must cover, providing robust routing with strong performance is the top priority. To reach that objective, several approaches have been considered.

With regard to the efficient use of network resources, one may think that shortest path routing (SPR) is a viable candidate. However, under hose-model traffic condition, the network will most likely be over-provisioned to support worst case scenarios. In fact, as presented in [13], a tree based resource sharing approach yields better provisioning. The example presented in Fig. 2.3 illustrates this. In this example network, the maximum outgoing/incoming traffic that can be sent/received, respectively at each node is given. Also, we assume that all links share the same cost. Therefore, in the shortest path routing scheme, all neighbor nodes use their connecting link as the default routing path and the traffic from node X to node W (respectively, from node W to node X) are routed through node Y. Under this condition, node Y is defined as the root node in the tree routing approach. The reserved capacity for a directed link

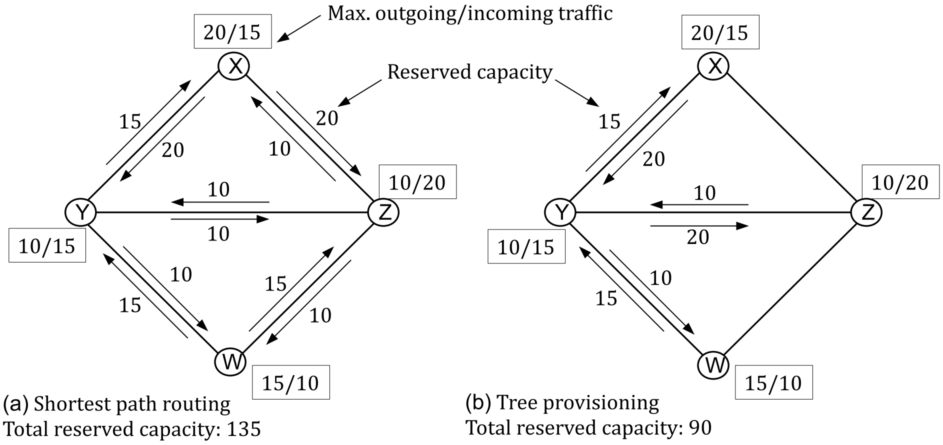


Figure 2.3: Hose model provisioning example

is determined by the minimum between the total incoming capacity of the nodes at its receiving end and the total outgoing capacity of the nodes at its sending end [13]. The resulting total reserved bandwidth is up to 135 for the shortest path routing approach while tree provisioning needs only 90.

Among other previous approaches, the approach with the least congestion ratio [14]-[15] provides robust routing and even better performance than tree provisioning under hose-model traffic. In the least congestion ratio approach, the objective is to limit the network's highest link utilization ratio; the lower this ratio is, the more likely the network is to accept additional traffic demands without dropping any. This results in increased network capacity. In [14], the authors introduced an LP formulation for the maximum throughput of traffic in the hose model. Their formulation is equivalent to finding the minimum multiplier (least congestion ratio) such that its product with a link's capacity is more than or equal to the traffic induced through that link under any set of traffic demands bounded by the hose specification. We find that none of works published to date satisfy our aim of deactivating the maximum number of cables possible. The fact is, those works ignore some factors that are critical in reducing the number of cables used. In the case of the least congestion ratio, only the used capacity of the most congested link is minimized. Thus, the other links may be used as long as their congestion ratio is lower than the highest one. Since our objective is to achieve power savings by deactivating bundle cables, we cannot afford to overlook any salvageable resource.

2.4 Thesis main contribution

The work presented in this thesis is driven by the target to efficiently deactivate idle cables in networks even if the traffic demands are not exactly known. This leads us to consider hose-model traffic. With the hose model, specific traffic demands are not needed, only the upper bounds of the total incoming/outgoing traffic to/from a node are needed, and they can be estimated by networks operators for a given period of time.

In this work, we adapt the problem formulation to meet our aim to minimize the number of active cables. The objective function that is minimized is the total resource utilization and for that we have to minimize the spare capacity. The main issue dealt with is imposing tight constraints on link utilization rates.

Regardless of the possible exponential number of traffic demands and link capacity quantization (individual cables), the number of active cables has to be just that number necessary to handle the hose-model traffic at its worst case. Meanwhile, we will provide robust routing with the performance metrics of bandwidth utilization and power saving.

Chapter 3

Optimal problem formulation

To reduce the energy consumption of networks under hose-model traffic, we deactivate unused cables while keeping enough cables active to ensure routing of all traffic demands. Minimizing the power utilization is achieved by minimizing network resource activation; this requires solving the optimization problem of minimizing the total number of active cables over the network.

3.1 Network model

The network is represented as directed graph $G(V, E)$ that consists of a set, V, of routers and a set, E, of links, where each link $[uv] \in E$ between two routers $u, v \in V$ has capacity c_{uv}. Each link consists of B cables that can be shut down independently. The traffic demand between a pair of routers, source and destination (sd), is represented by h_{sd}, and the total outgoing/incoming traffic for node s by R_s and C_s, respectively. Let D denote the collection of all source and destination pairs (sd) that currently have a traffic demand. Network topology $G(V, E)$, link capacity c_{uv}, link granularity B, and traffic demands h_{sd} for pipe model and/or R_s and C_s for hose model are the inputs to the optimization problem. The network model is summarized in Table 3.1.

Table 3.1: Summary of notation

$G(V, E)$:	Directed graph with $\lvert V\rvert$ nodes, $\lvert E\rvert$ links
c_{uv}:	Capacity of link $[uv]$
B:	Number of cables in a bundle, Link granularity
D:	Set of source/destination (sd)
h_{sd}:	Demand (sd) from source s for destination d
R_s :	Total outgoing traffic from node s
C_d :	Total incoming traffic to node d
x_{sd}^{uv}:	0 to 1, ratio of traffic (sd) on edge $[uv]$
f_{sd}^{uv}:	Binary, 1 if traffic (sd) on edge $[uv]$, 0 else
f_{uv}:	total flow on edge $[uv]$
n_{uv}:	number of powered cables in link $[uv]$

3.2 MILP for minimizing energy consumption

To achieve optimal energy savings, we formulate an MILP problem in which the network characteristics and the traffic demands are given parameters.

3.2.1 For pipe model

The following formulation can be used for pipe-model traffic in which the exact traffic matrix $\{h_{sd}\}$ is given as a parameter. The decision variables are n_{uv}, which is the number of active cables in a bundle, and x_{sd}^{uv}. Compared to Fisher et al.'s formulation [6], we use x_{sd}^{uv} to define the ratio of traffic demand h_{sd} on edge $[uv]$ instead of f_{sd}^{uv} corresponding to the actual flow on edge $[uv]$ from demand h_{sd}. This will facilitate the use of the dual problem formulation to derive a hose-model MILP problem from the pipe-model formulation.

MILP formulation for pipe model

$$\min \quad \sum_{(u,v)\in E} n_{uv} \tag{3.1}$$

Subject to

$$\sum_{v\in V:(u,v)\in E} x_{sd}^{uv} - \sum_{v\in V:(v,u)\in E} x_{sd}^{vu} = 1 \qquad \forall\ (sd) \in E, u \in V, u = s \tag{3.1a}$$

$$\sum_{v\in V:(u,v)\in E} x_{sd}^{uv} - \sum_{v\in V:(v,u)\in E} x_{sd}^{vu} = 0 \qquad \forall\ (sd) \in E, u \in V, u \neq s, d \tag{3.1b}$$

$$\sum_{(sd)\in D} h_{sd} x_{sd}^{uv} \leq n_{uv} \frac{C_{uv}}{B} \qquad \forall\ (u,v) \in E \tag{3.1c}$$

$$n_{uv} \leq B \qquad \forall (u,v) \in E \tag{3.1d}$$

$$x_{sd}^{uv} \geq 0 \qquad \forall\ (u,v) \in E, (s,d) \in D \tag{3.1e}$$

$$n_{uv} = 0, 1, 2, \cdots \qquad \forall\ (u,v) \in E \tag{3.1f}$$

The objective function to be minimized for this MILP problem is the total number of active cables over the network. Eqs. (3.1a)-(3.1b) represent the traffic flow constraint and Eq. (3.1c) the link capacity constraint.

3.2.2 For hose model

When the traffic matrix is not fully expressed, in other words the exact $\{h_{sd}\}$ is unknown, the hose model expresses the total egress/ingress (R_i/C_i) for node i as:

$$R_i = \sum_{d\in V} h_{id}, \qquad C_i = \sum_{s\in V} h_{si}. \tag{3.2}$$

Since the traffic matrix can vary within the hose boundary, one way to deal with the hose model is to consider the worst case scenario. In this case, using the given routing paths, the maximum traffic under hose conditions is carried by the network. With given parameters of the routing, $\{x_{sd}^{uv}\}$, and the hose boundary, R_s/C_d, and taking $\{h_{sd}\}$ as decision variables, we can formulate the problem as follows:

$$\max \sum_{(s,d)\in D} h_{sd} x_{sd}^{uv} \tag{3.3}$$

Subject to

$$\sum_{d\in V} h_{sd} \leq R_s \quad \forall\, s \in V \tag{3.3a}$$

$$\sum_{s\in V} h_{sd} \leq C_d \quad \forall\, d \in V \tag{3.3b}$$

$$h_{sd} \geq 0 \quad \forall\, (s,d) \in D \tag{3.3c}$$

A solution to this problem covers the hose-model worst case scenario due to the constraints (3.3a)-(3.3b). Also, since this problem has the same optimal solution as its dual problem, it can be replaced by the latter formulated in (3.4)-(3.4b). The dual approach has the advantage of dispensing with the potentially exponential variables $\{h_{sd}\}$.

$$\min \sum_{s\in V} R_s \theta_s^{uv} + \sum_{d\in V} C_d \delta_d^{uv} \tag{3.4}$$

Subject to

$$\theta_s^{uv} + \delta_d^{uv} \geq x_{sd}(p,q) \quad \forall\, (s,d) \in D, (u,v) \in E \tag{3.4a}$$

$$\theta_s^{uv},\ \delta_s^{uv} \geq 0 \quad \forall\, (u,v) \in E, s \in V \tag{3.4b}$$

θ_i^{uv} and δ_j^{uv} are introduced variables.

We replace Eq. (3.1c) by its dual equivalent in Eq. (3.4) and include the hose-model constraint by adding Eq. (3.4a) to the pipe formulation constraints. We obtain the following MILP formulation corresponding to hose-model traffic. This process is demonstrated in [16].

MILP formulation for hose model

$$\min \quad \sum_{(u,v)\in E} n_{uv} \tag{3.5}$$

Subject to

$$\sum_{v\in V:(u,v)\in E} x_{sd}^{uv} - \sum_{v\in V:(v,u)\in E} x_{sd}^{vu} = 1$$

$$\forall\ (sd) \in E, u \in V, u = s \tag{3.5a}$$

$$\sum_{v\in V:(u,v)\in E} x_{sd}^{uv} - \sum_{v\in V:(v,u)\in E} x_{sd}^{vu} = 0$$

$$\forall\ (sd) \in E, u \in V, u \neq s, d \tag{3.5b}$$

$$\sum_{s\in V} R_s \theta_s^{uv} + \sum_{d\in V} C_d \delta_d^{uv} \leq n_{uv}\frac{c_{uv}}{B} \qquad \forall\ (u,v) \in E \tag{3.5c}$$

$$n_{uv} \leq B \qquad \forall (u,v) \in E \tag{3.5d}$$

$$\theta_s^{uv} + \delta_d^{uv} \geq x_{sd}^{uv} \qquad \forall\ (s,d) \in D, (u,v) \in E \tag{3.5e}$$

$$x_{sd}^{uv}, \theta_s^{uv}, \delta_s^{uv} \geq 0 \quad \forall\ (u,v) \in E, (s,d) \in D \tag{3.5f}$$

$$n_{uv} = 0, 1, 2, \cdots \qquad \forall\ (u,v) \in E \tag{3.5g}$$

The above formulation represents an MILP problem whose objective function is determining the optimal set of active cables in order to minimize the total number of active cables over the network. The traffic flow constraints are represented by Eqs. (3.5a)-(3.5b). For a given set of hose-model traffic, the worst case scenario is considered as in fixed routing; we maximize the traffic flow over the active links with constraints (3.5c)-(3.5e). Eq. (3.5c) also ensures that the traffic over link $[uv]$ does not exceed its capacity.

Unfortunately the MILP problem is NP-Hard and cannot be solved in practical time when the number of variables is large. Therefore, it is not tractable for large networks. To achieve near optimal solutions in practical time, we introduce the hose-model minimum power consumption (HMPC) heuristic algorithm; it deactivates cables one by one and uses an LP formulation to ensure that enough cables remain active to carry all the network traffic.

Chapter 4

Hose-model Minimum Power Consumption (HMPC) scheme

Our proposal introduces a heuristic algorithm that aims to approach, in realistic computation time, the optimal solution obtained by the MILP for the hose model. We deactivate as many cables as possible applying our heuristic algorithm.

4.1 Heuristic algorithm

This heuristic algorithm deactivates, one by one, cables until the remaining active cables are only just able to carry all worst-case traffic. In order to verify that the active network cables are able to handle all traffic demands, we solve the LP problem formulated to minimize the total traffic flow with hose-model traffic. We assume that the traffic demands cannot exceed the initial network capacity.

Our heuristic algorithm consists of three steps. First we solve the LP problem for the network's initial capacity, and then deactivate all idle cables. This will not change the network traffic flow.

Second, we deactivate the cables that can be deactivated while maintaining an optimal solution to the LP problem. In this condition, we have the same LP objective value (minimizing total link activation) while part of the traffic routing is changed.

Third, we deactivate the remaining cables that can be deactivated. Even though deactivation of these cables increases the LP objective value (now sub-optimal), it may reduce the number of active cables and thus total power consumption.

We describe the processing of the three steps of our algorithm in detail below.

Step 1: After initially solving the hose-model LP problem and deactivating all idle cables, we save the LP problem's optimal solution and update link capacity of the actives cables.

Step 2: We test if cable deactivation is feasible for each and every link of the network by solving the LP problem. Depending on the returned result, we define:

- *Normal* state links: The links for which a cable removal does not change the LP result. We shut off a cable from each of them and update their capacity.
- Links at *final* state: The links for which cable deactivation is not possible, e.g. results in an infeasible LP problem. They are ignored by the algorithm.
- Links at *hold*: The links for which the LP problem can be solved but whose deactivation would result in a sub-optimal solution are put in a stand-by state (hold). We reconsider deactivation of these links in step 3.

Step 2 is repeated until all links reach their *final* state or are placed in *hold*.

Step 3: We finally deactivate the remaining cable. We solve the LP problem for all links in *hold* and compare the results. The cable from the link for which cable deactivation results in the smallest sub-optimal solution is deactivated. The links for which a cable deactivation results in an infeasible LP problem are updated to *final* state as defined in step 2.

Step 3 is repeated until all links are *final*.

HMPC heuristic Algorithm

```
Ensure: The minimum total link utilization
Solve LP problem with initial capacity
     Remove all idle cables
while Link not final nor at Hold do
    for any link not final nor at Hold do
        Remove cable then Solve LP problem
        if Infeasible solution then
            Cancel cable removal, Update link as Final
        else if Sub-optimal solution then
            Cancel cable removal, Update link as on Hold
        end if
    end for
end while
while Link at Hold do
    minSolution = $\infty$
    for Any link at Hold do
        Remove cable then Solve LP problem
        if solution < minSolution then save link,
            minSolution = solution
        else if Infeasible solution then Update link as Final
        end if
        Cancel cable removal
    end for
    Remove cable for link with min sub-optimal solution
end while
```

4.2 LP formulation

Using the above presented MILP obtained after dual formulation for the hose-model, worst case scenario, we define the LP formulation for the hose model as follows.

LP formulation for hose model

$$\min \quad \sum_{(u,v)\in E} f_{uv} \tag{4.1}$$

Subject to

$$\sum_{v\in V:(u,v)\in E} x_{sd}^{uv} - \sum_{v\in V:(v,u)\in E} x_{sd}^{vu} = 1 \qquad \forall\ (s,d) \in D, u \in V, u = s \tag{4.1a}$$

$$\sum_{v\in V:(u,v)\in E} x_{sd}^{uv} - \sum_{v\in V:(v,u)\in E} x_{sd}^{vu} = 0 \qquad \forall (s,d) \in D, u \in V, u \neq s, d \tag{4.1b}$$

$$\sum_{s\in V} R_s \theta_s^{uv} + \sum_{d\in V} C_d \delta_d^{uv} \leq f_{uv} \qquad \forall\ (u,v) \in E \tag{4.1c}$$

$$f_{uv} \leq c_{uv} \qquad \forall\ (u,v) \in E \tag{4.1d}$$

$$\theta_s^{uv} + \delta_d^{uv} \geq x_{sd}^{uv} \qquad \forall\ (s,d) \in D, (u,v) \in E \tag{4.1e}$$

$$x_{sd}^{uv}, f_{uv}, \theta_s^{uv}, \delta_s^{uv} \geq 0 \quad \forall\ (u,v) \in E, (s,d) \in D \tag{4.1f}$$

In this formulation, the objective function, which is to be minimized, is the total link activation over the network (TLAN). For a given hose-model traffic, the worst case scenario is considered as for fixed routing; we maximize the traffic flow over the active links (Eqs. (4.1d)-(4.1e)). The problem has a solution when the network has enough capacity to route all traffic demands that satisfy the hose-model traffic boundary. Our heuristic uses this problem to test if cables can be deactivated.

4.3 Computational complexity

Our proposed scheme solves the LP problem $O(|E|B)$ times. In fact, we have defined the algorithm so that the main processing is done in step 2 where we solve the LP problem once for each deactivated cable. Thus, the maximum number of iterations equals the total number of cables in the network, $|E| * B = O(|V|^2 B)$.

If the algorithm presented in [17] by Gonzaga et al. is adopted to solve the LP problem, it can be done in a $O(n^3 L)$ computation time, with n the number of constraints and L the total number of bits of the input. Since our LP problem defined in Eqs. (4.1)-(4.1f) has $O(|V|^4)$ constraints, its computation complexity is $O((|V|^4)^3 L) = O(|V|^{12} L)$.

The overall computation complexity of our proposed scheme is therefore $O(|V|^{14} BL)$.

Note that, in practice, the computation time depends on the LP solver.

Chapter 5

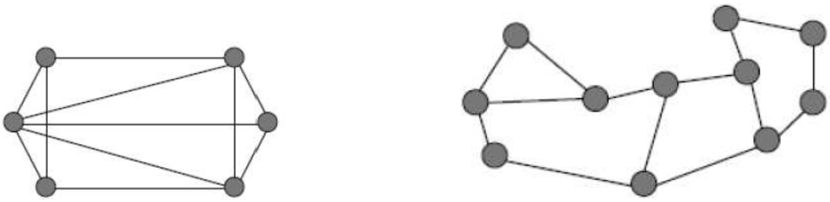
Performance Evaluation

5.1 Simulation setups

We evaluate the performance of the proposed scheme in terms of TLAN as a lower TLAN value represents better power savings. This evaluation uses the four different networks in Fig. 5.1. The traffic demands, $\{h_{sd}\}$, are randomly generated and then from the returned values we fix the hose boundary values R_s and C_d by summing, respectively, the outgoing traffic from node s and the incoming traffic toward node d.

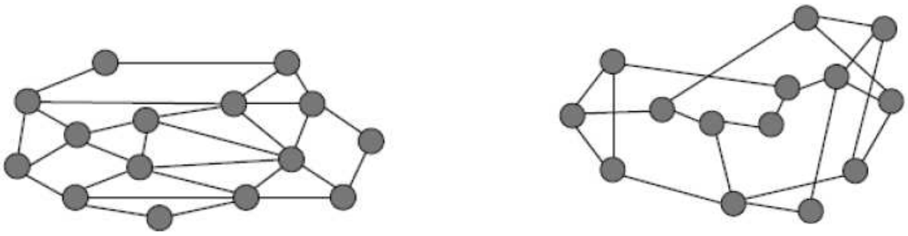
Regarding the shortest path routing simulation, we first determine the routing for each couple $(sd) \in D$, then update f_{sd}^{uv} to 1 for each link $[uv]$ in path (sd). From there we proceed to hose provisioning by reserving, at each link $[uv]$, resources for the maximum traffic according to the routing and the hose specification. The simulation approach used for the least congestion ratio is similar to our presented approach in the process, but differs in LP formulation used. In the least congestion ratio case, we use the maximum throughput (MTP) formulation presented in [14].

We use a CPLEX solver [18] installed in a dedicated Ubuntu server (Intel(R) Core(TM) 2 Quad CPU Q9550 @ 2.83GHz, 4 GB memory) to execute our formulated LP and MILP problems. Table 5.1 shows some computation times achieved by our scheme as compared to the time needed to solve the MILP problem.



(a) Network 1

(b) Network 2



(c) Network 3

(d) Network 4

Figure 5.1: Used Networks

Table 5.1: Example of Computation time

Networks	**Network1**			**Network2**		
Granularity	**G=2**	**G=12**	**G=24**	**G=2**	**G=12**	**G=24**
HMPC	<1s	<1s	1s	3s	5s	8s
MILP	10s	12s	19s	12mn	7h	*

5.2 Result comparison to conventional approaches

Our heuristic algorithm (HMPC) outperforms the SPR by as much as 50% in terms of power reduction, for all the networks examined (Fig. 5.2). It performs better than the least congestion ratio approach as well. Notice that the difference from the shortest path is more pronounced for networks in which the average neighboring node numbers are higher. This can be explained by the fact that SPR will most likely result in more disjoint paths when the number of neighboring nodes allows such paths, therefore resulting in more resource reservation for hose provisioning.

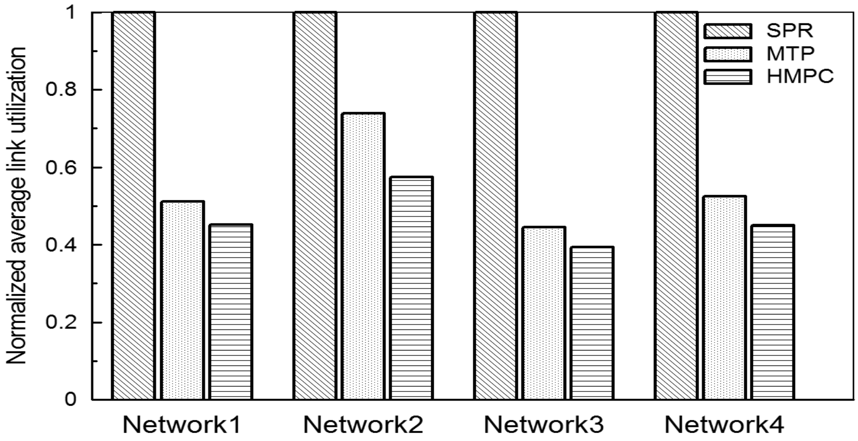
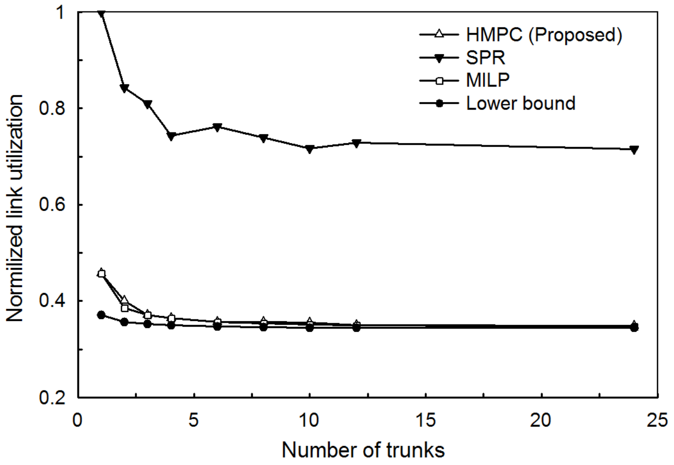


Figure 5.2: HMPC comparison with SPR and MTP on different networks

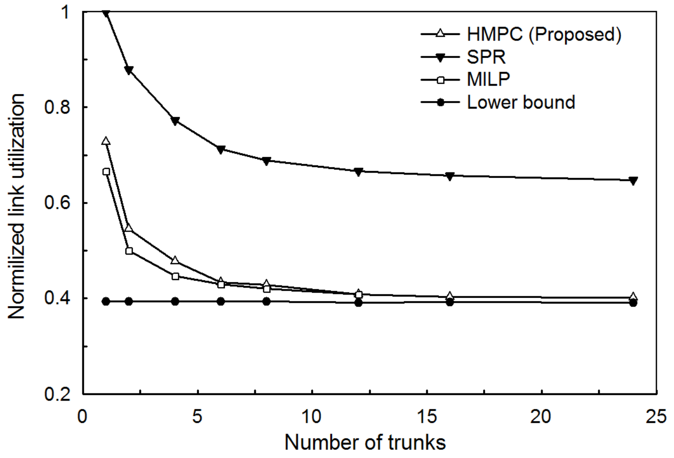
5.3 Heuristic efficiency

Figure 5.3 shows that the HMPC algorithm solutions are close to the optimal solutions obtained by the MILP formulation when they are tractable. Although these solutions can differ from the theoretical lower bound, they are the best achievable. This is due to the constraints imposed by on the network configuration such as the traffic flow continuity when the lower bound is defined by the strict minimum number of cables theoretically needed. The latter is given by the lowest multiple of the cable capacity (c_{uv}/B) greater than the total traffic flow; it may not be a feasible solution. In addition, we can see that we achieve better results as the number of cables increases. With more cables, the granularity of load assignment increases, hence idle capacity is decreased.

Our results also confirm that SPR is definitely not efficient when dealing with hose-model traffic. In fact, it is outperformed by some margin by our HMPC algorithm even with fine granularities. For a comparison, for pipe-model traffic, with fine granularities, the optimal result is the one achieved by SPR. Figure 5.4 illustrates this fact.



(a) Network 1

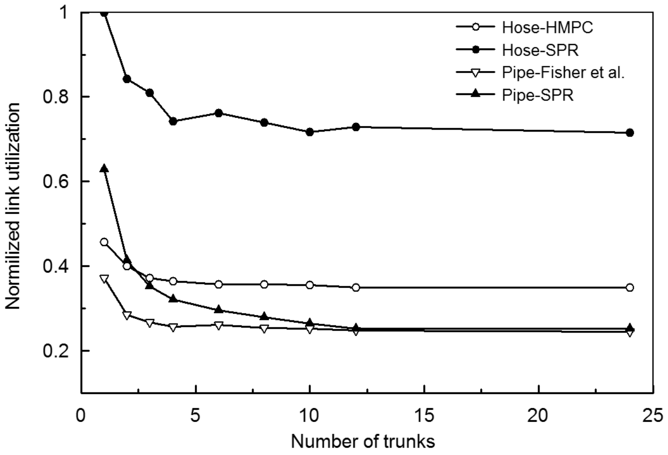


(b) Network 2

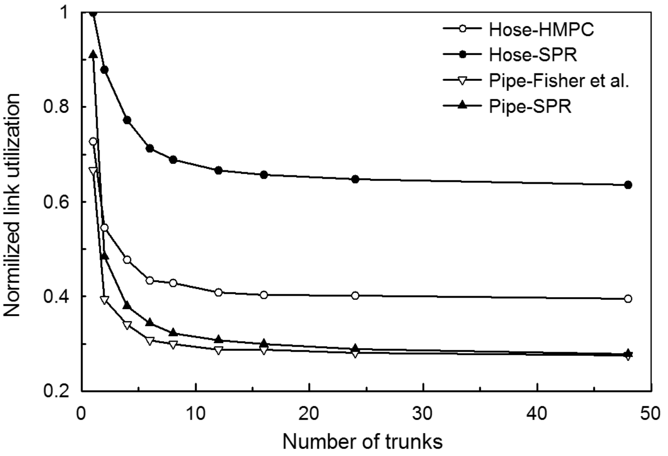
Figure 5.3: Heuristic efficiency and granularity dependency

5.4 Performance comparison with pipe model

Meanwhile, given the choice between the different traffic models, pipe and hose models, one factor determining their usage is their performance. For that purpose, we compare the average link utilization of HMPC to the pipe model approach presented by Fisher et al. [6]. We take the average results of 100 simulations for both models. At each simulation, we use the same traffic data for the pipe model and the hose model; the hose model boundaries are derived from the pipe model traffic. Figure 5.5 compares



(a) Network 1



(b) Network 2

Figure 5.4: HMPC and SPR comparison for hose and pipe model

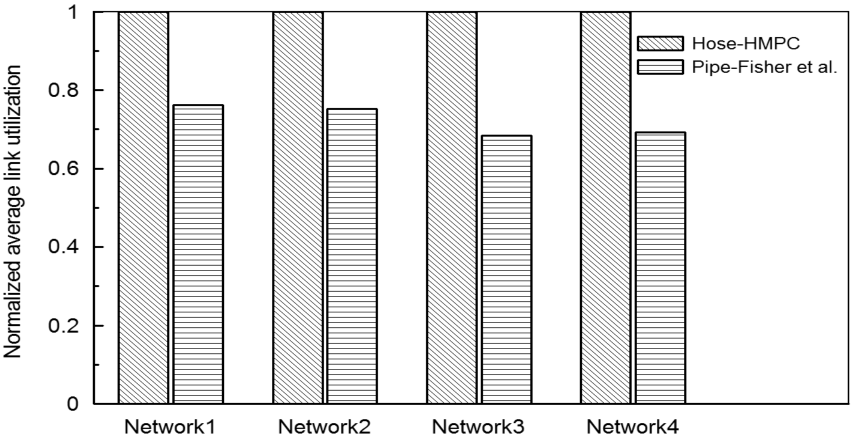


Figure 5.5: Performance comparison with pipe

the results of our HMPC for hose model to the pipe model result. It shows that our performance does not equal that of the pipe model. However, this was to be expected; the hose model does not perform as well as the pipe model. In fact the hose model has to use more resources in anticipation of the worst case scenario due to traffic uncertainty. In [15]-[19], Oki et al. presented a more detailed comparison to prove that. In their work, they compare the routing performances of hose, pipe and intermediate models in networks with no bundled cable consideration. As shown in Fig. 5.5, the performance margins in this work (25% – 35%) fit into the performance range they presented.

Even with lower efficiency, than the pipe model, in terms of resource utilization, the hose model offers more flexibility to network operators and makes it easier for network clients to define the traffic loads.

Chapter 6

Conclusion

This paper has proposed a scheme to reduce energy consumption by deactivating unused cables individually in bundled cable networks while considering hose-model traffic. We show that a conventional approach such as shortest path routing may not be suitable for the hose model and then formulate an MILP problem to identify the optimal solution. Since the MILP problem is not tractable for large networks, we have introduced a heuristic algorithm that uses an LP formulation to produce near optimal solutions.

The performance evaluation results have shown that our scheme outperforms the shortest path routing by as much as 50% in term of power savings.

The obtained results suggest that our proposed scheme can be implemented by network operators wanting to reduce their power consumption in bundled cable networks while keeping some traffic flexibility with the hose model.

Publications

Conference Proceedings Publications

- S. Ba, I. A. Ouedraogo, E. Oki, *"A Power Consumption Reduction Scheme in Hose-Model Networks with Bundled Links,"* Green Computing and Communications (GreenCom), 2013 IEEE and Internet of Things (iThings/CPSCom), IEEE International Conference on and IEEE Cyber, Physical and Social Computing , vol., no., pp.40,45, 20-23 Aug. 2013

Journal Publications (Submitting)

- S. Ba, I. A. Ouedraogo, E. Oki, *"Reducing the Power Consumption of Hose-Model Networks with Bundled Links"*

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