Dynamic topologies for sustainable and energy efficient traffic routing

Alexander A. Kist *, Abdelnour Aldraho

The University of Southern Queensland, Toowoomba, Queensland, Australia

1. Introduction

Energy efficiency and greenhouse gas (GHG) emission footprint have become major concerns for environmental, as well as economic reasons. This is particularly relevant to the Information and communication technology (ICT) sector as it is both, an enabler for energy reductions, as well as an industry with its own GHG emissions footprint [1]. In 2007, the IT sector was responsible for approximately 2% of the global carbon footprint [2]. This figure includes all components, such as personal computers and network infrastructure and is comparable in size to the global aviation industry. Furthermore, it is expected that the contribution will grow at 6% each year until 2020 [1]. It is estimated that network related GHG emissions account for 30% [2] to 37% [1] of the sector's contributions. In contrast, telecommunication networks operate at utilisation of below 30% [3] to below 50% [4]. The main reason for this is the cyclic nature of traffic and the practise to over provision systems to support QoS requirements at peak loads. In light of global warming and GHG emissions, green information and communication technology is receiving growing attention, both, in the business as well as the research community. In the ICT research community, energy efficiency has been a concern for low powered devices such as wireless networks [e.g. 5–7], sensor networks [e.g. 8] and general mobile and battery powered devices. Recent studies have approached the topic of energy efficiency from a variety of different angles and span all aspects of computing and communication, from software development to packet forwarding and switching fabric. For example, [9] investigates the carbon footprint of the Internet and potential carbon reductions by replacing car and air travel by Internet-based telecommuting and teleconferencing services.

Increased energy consumption of computing hardware is multiplied by increased energy use of cooling infrastructure. To reduce energy consumption of computer networks, a number of areas have to be addressed: infrastructure, such as cooling and power delivery; server hardware and software, such as dense packing and power efficient processors; as well as intelligent resource management, such as virtualisation and traffic engineering. This research focuses on teletraffic engineering and inves-
tigates the possibility of reducing the number of active routers and links at times of lesser load and therefore reduces the overall power consumption. Networks actively change their topology to adapt to current traffic conditions. There are two main aspects to this problem: the potential savings by dynamically changing the network topology and the dynamics of routing protocols including the detection of network changes and traffic measured. This paper focuses on the former and aims to classify potential savings of dynamic topologies. Mathematical programming is used to evaluate potential savings in current networks.

The contribution of this work can be summarised as follows: The node bypass transformation is proposed that allows optimisation problems that automatically reduce the number of nodes in the network, if these are not required to accommodate traffic loads. A number of optimisation problems are formulated as mixed integer linear programs (MIP) and these can be used to evaluate energy savings of networks with reduced topologies. An eight node and a twenty node topology are tested with a large data set of traffic matrices as examples for Australian and North American backbone networks. It is concluded that reduced topologies provide feasible solutions for a wide range of traffic matrices and reduce network power consumption considerably. The remainder of the paper is organised as follows: Section 2 discusses related research. Section 3 introduces a number of mixed integer mathematical programs that allow the identification of optimal sets of routers for given traffic loads. Section 4 discusses numerical results that show the advantages of dynamic topologies in the context of energy efficient traffic forwarding. The paper concludes with Section 5.

2. Related work

For server and router systems, energy consumption has been a concern, in regards to the ability of supplying sufficient power, heat dissipation and cooling. Roth and Kleinman [10] provide detailed data on energy consumption of office and telecommunication equipment in the US, as of the year 2000. Gupta and Singh [11] use this data to estimate energy consumption of Internet infrastructure to 6.05 TWh in 2000. Several opportunities are discussed as to how to reduce power consumption including sleep modes. Changes to routing protocols are outlined to support this. Ethernet has become ubiquitous across a wide range of network applications. However, it is not energy efficient, as the energy used is almost independent of traffic load [11]. Gunaratne et al. [12] quote a figure of 3 W power difference for idle line cards operating at 10 Mb/s and 1 Gb/s. Ethernet link shutdown [13], low power modes of LAN networks [14] and a feasibility study [15] are investigated by the same group to introduce algorithms and mechanisms to achieve the dynamic link shutdown and the low power modes. Power savings in LAN switches are addressed by Ananthanarayanan and Katz [16]; and rate adaptation and sleeping stages in networks are targeted in [3]. Baliga et al. [17] compare energy consumption of various technologies in the access network and concludes that optical-access is the most energy efficient.

The term dynamic topology has been used by the networking community in the past, in particular, in context of circuit switched networks. Noakes et al. [18] present "... an adaptive link assignment algorithm for distributed optimisation of dynamically changing network topologies..." and a related routing algorithm is discussed by [19]. Moose [20] investigates dynamic hierarchical networks that employ adaptive behaviour for variable demands. White et al. [21] introduce an analytical approach that addresses activation and deactivation of links in response to changed traffic conditions. In broad terms, these studies address the problem of dynamically changing network configuration; however, these address different technologies and optimisation problems and these are not directly applicable to energy efficient network configuration.

A few studies directly relate to dynamic topologies and a number of authors have identified power consumption as a main issue in high performance router design [e.g. 22]. Solutions include the use of optics in routers [23] and energy efficient switching fabric design [24]. Power awareness in network design and routing to mitigate power consumption of high speed network equipment is advocated by Chabarek et al. [25]. The authors undertake benchmarking of two routers to estimate power use. Based on these measurements they develop a general model for router energy consumption and formulated the network design problem as a power aware mixed integer program. Optimisation focuses on allocation of line cards per chassis and chassis over the target network. The optimisation problem is different from this paper, as routers do not inject or consume traffic. This research uses the reported measurement results to formulate the device power model in Section 4.1. Furthermore, the work in this paper differs as it does not target a design problem and does not focus on the same level of detail in device configuration, but a generic solution that use a set of predefined router energy states.

Chiaraviglio et al. [26] introduce a network design problem with the aim to reduce the total power consumed by the network. It outlines the optimisation problem as a linear program and proposes heuristics to solve the problem. The main difference of this approach is that nodes are unable to consume or inject traffic. In the discussed scenario, only nodes and links that are redundant in a particular scenario can be turned off. The problem formulation is similar to classic network design problems with an energy consumption objective. Chiaraviglio et al. [27] use the results of [26] and evaluates an operator topology with realistic power usage figures for devices and proposes a new algorithm that accounts for power consumption of devices. As for the first paper, node capabilities are different. Furthermore, the study focuses on a specific star network topology with three different aggregation levels, whereas this work looks at a generic network topology. Chiaraviglio et al. [28] focus on a much larger scale and uses analytical and simulation results to estimate redundant network resources worldwide, that could be turned off to save power. Recent publications also investigate energy efficient routing. Giroire et al. [29], for example, focus on topologies where line cards can be turned off and investigate routing that minimises the number of active links. Bianzino et al. [30] evaluate energy efficient routing for various topologies and traffic matrices. In both cases...
network nodes cannot be turned off. A number of studies target specific applications or techniques. Chiaraviglio et al. [31] target energy aware network management in radio access networks. Vasic and Kostic [32] presents an “online energy-aware traffic management technique” that assumes equipment is able to adapt its power use to utilisation using rate adaptation and sleep states. This approach provides a solution for energy efficient traffic management; it does not address the dynamic topology problem. Wu et al. [33] discuss the routing and wavelength assignment problems with the new objective of reducing network energy consumption. The authors introduce an ILP formulation and a number of heuristics to solve the problem. Node and link power down for unused connections in IP over WDM networks is also discussed by Idzikowski et al. [34]. This research project focuses on traffic engineering of IP networks and investigates the possibility of reducing the number of active routers at times of lesser load.

3. Generic problem formulation

To evaluate the energy reduction potential of dynamic topologies in backbone networks, a set of mathematical models are introduced in this section. Traffic flows in an IP network can be modelled as multi-commodity flow problems expressed in path or link flow formulation [35]. In this case, the demands between source and destination nodes are commodities. The dynamic topology problem, discussed in this paper, is based on the link flow formulation.

In general terms, the aim is to find a minimal topology that can satisfy given traffic demands. The generic optimisation problem can be summarised as follows: given a network topology of routers and links with known capacities, a traffic matrix including all demands and the fixed and variable power consumptions of routers and links. The aim is to find a network topology, i.e. a set of active nodes and links, so that the overall power consumption is minimised. This solution is subject to the conservation of flow and maximum link utilisation constraints.

3.1. Notation

The following notation is used throughout this paper: A network \( G(N,M) \) consist of \( N \) nodes and \( M \) directed arcs. The flow of commodity \( k \) on arc \((i,j)\) is denoted as \( x^k_{ij} \) and the unit costs of commodity \( k \) using arc \((i,j)\) as \( c^k_{ij} \). Arc \((i,j)\) has also a fixed cost \( g^k_{ij} \). This cost is encountered if link \((i,j)\) is active and it is independent of the traffic \( x^k_{ij} \). The capacity of arc \((i,j)\) is denoted by \( u^k_{ij} \). Similarly, node has costs \( c^k_i \) and \( g^k_i \) and capacities \( u^k_i \). \( h^k_i \) denotes the nodes standby cost. The constant \( b^k(i) \) denotes supplies or demands at node \( i \), \( b^k(i) \) is the sum of all supplies at node \( i \) and \( b^k(i) \) is the sum of all demands at node \( i \). The variables \( \delta^k_i \) and \( \delta^k_i \) are Boolean values that indicate if arc \((i,j)\) and node \( i \) are in use, respectively. Integer constants \( \gamma_i \) and \( \beta_i \) indicate the maximum out-degree and in-degree of nodes, respectively.

3.2. Intuitive network model

An intuitive formulation of the dynamic topology problem that only accounts for fixed costs, leads to an instance of the capacitated multicommodity minimum cost flow (CMCF) problem defined by Eqs. (1)–(4) [26]. This problem is closely related to the optimal network problem [36]. The aim is to minimise the cost \( Z \) of operating nodes and links.

Minimise \( Z = \sum_{ij} \delta^k g_{ij} + \sum_i \delta^k g_i \) \hspace{1cm} (1)

The minimum is subject to balance constraints, Eq. (2), and bundle constraints, Eq. (3).

\[ N x^k = b^k \quad \text{for all} \quad k = 1,2,\ldots,K, \] \hspace{1cm} (2)

\[ \sum_k x^k_{ij} \leq u^k \delta^k \quad \text{for all} \quad (i,j) \in A. \] \hspace{1cm} (3)

\( N \) is the node-arc incidence matrix and \( b \) is the right hand side vector, the vector that specifies supplies and demands. The balance constraint expresses the conservation of flow, as the sum of all elements \( b(i) \) in \( b \) must be equal to zero. In the case of network traffic flows, there are only two non zero elements for each \( b^k \): the flow source \( b(s) \) and the flow destination \( b(t) \). The commodities, \( k \), correspond to the demands between source and destination nodes. Eq. (3) limits the flows on links to the link capacity \( u^k_i \). If links are not active, the capacity is zero. Eq. (4) imposes the additional constraint that if a node is turned off, all connected links are disconnected as well.

\[ \sum_{j=1}^{N} \delta^k_j + \sum_{j=1}^{N} \delta^k_j \leq M \delta^k_i, \quad \text{where} \quad M \geq 2N. \] \hspace{1cm} (4)

This formulation leads to practical solutions for core networks, where nodes do not consume or inject traffic. If nodes have demands assigned, the above formulation produces solutions, where nodes with demands are always active. Only unused arcs can be powered off. If nodes inject and consume traffic, an additional mechanism is required that handles local demands for nodes that are in standby; emanating and terminating demands have to be assigned to alternative nodes.

3.3. Node standby power models

Modern router architectures are complex and vendor specific. Design also varies with the size and purpose; for example, core routers are different from edge routers. This makes it difficult to develop a generic router power model that is general enough to allow for innovation and changes in architecture; and at same time specific enough to be realistic for currently used hardware. To overcome these issues, this work proposes a number of router standby modes that are informed by current router hardware and proposes subtle changes to enable power reductions. As suggested by Chabarek et al. [25] there are opportunities for low power/hibernation modes. For the discussion in this paper, it is assumed that routers feature a number of line cards, switching fabric, main processor and power supply. Line cards are itself complex and may use network processors, memory and line drivers. In-
pendently of the router’s power saving state, it is assumed that links can be turned on and off individually. This assumption is also used by Chabarek et al. [25], for example. Furthermore, for discussion in this paper, it is assumed that components can be powered down automatically.

At a conceptual level, points of presence (PoP), or individual Internet service providers’ locations, have to handle three types of traffic: terminating traffic, emanating traffic, and transit traffic. At a router level this can be translated into local and transit traffic. For network modelling this relates to the ability of nodes to inject or consume traffic. For a practical router this means that a specific, local interface handles terminating and emanating traffic. This research suggests that without major redesign, routers could support a number of low power modes, that essentially mean they are in a “switching only” mode which bridges the local connection to a neighbouring router. This mode largely relies on line cards and switching fabric. Such a configuration would be much closer to flow based routers, suggested by Roberts [37] and it is suggested that such routers operate at 20% of the power of conventional routers. This proposal is further supported by the fact that such modes do not require routing functionality and that lightly loaded switching fabric consumes less power [38]. For the modelling in this paper, a generic device is assumed. It has been widely acknowledged that power saving options are very limited in current devices, but emerging hardware will implement diverse energy management features [e.g. 32,27]. A number of options are plausible as to how routers in low power modes handle terminating, emanating and transit traffic.

The following alternatives have been identified that reduce router forwarding and routing functionality which in turn leads to reduced power consumption:

(a) **router inactive** — Neither local nor transit traffic is forwarded.

(b) **router active** — All local traffic is sent and received, transit traffic is forwarded via any outgoing interface.

(c) **links-only** — Only links can be turned off, all nodes remain active.

(d) **bridged-all** — Local demands are bridged to one link, terminating traffic is received on one interface only.

(e) **bridged-local** — Local demands are bridged to one link, terminating traffic is received on all interfaces.

(f) **default-gateway** — Local traffic and all transit traffic is forwarded via one link only.

(g) **bridged-many** — Multiple bridged interfaces, incoming and outgoing links are bridged, including the local to an outgoing link.

Fig. 1 depicts alternative configurations (b)–(g). Arcs on the left of the nodes symbolise terminating traffic, arcs on the right symbolise emanating traffic and arcs on top of nodes indicate local demands. Options (d) suggest a simple bridge between ports, requiring the least functional support. Option (e) is similar; additionally it allows for multiple terminating interfaces bridged locally. It does not require intelligence as all traffic is forwarded to the same local interface. Options (f) further allows for transit traffic. It does not require complex routing functionality, as all traffic is forwarded to the default gateway. Option (g) allows for additional interfaces to be bridged that only accommodate transit traffic and is outside the scope of this paper. This work focuses on the bridged-all option for routers in power saving modes as it requires the least functional support in routers. Reduced versions of the mathematical model that is developed in Section 3.6 can be applied to bridged-local and default gateway as well. Option (c) is covered by the model discussed in Section 3.2. The key aim of this paper is not to propose new router designs, but to evaluate potential gains that dynamic topologies could offer if such standby modes are to be supported by routers. None of the suggested standby options require major redesigns of router hardware and are achievable with minor changes to existing systems.

### 3.4. Generic link flow formulation

The dynamic topology problem, discussed in this paper, is based on the link flow formulation of a multicommodity flow problem. It is extended by a bypass transformation, used to formulate an optimisation problem that minimises the number of routers for a given network load. The generic multicommodity flow problem can be formulated as a mathematical program, Eqs. (5)–(7) [35]. The aim is to minimise the cost $Z$ of the objective function shown in Eq. (5).

$$\text{Minimise } Z = \sum_k c^k x^k. \quad \text{(5)}$$

$c^k$ is the row vector of link costs, $c^k_i$; and $x^k$ is the column vector of link flows, $x^k_{ij}$. As outlined above, for telecommunication networks, all $c^k$ are equal. The minimum is subject to balance constraints, Eq. (6), and bundle constraints, Eq. (7), respectively.

$$\mathcal{N}x^k = b^k \quad \text{for all } k = 1, 2, \ldots, K, \quad \text{(6)}$$

$$\sum_k x^k_{ij} \leq u_{ij} \quad \text{for all } (i, j) \in A. \quad \text{(7)}$$

As before, $\mathcal{N}$ is the node-arc incidence matrix and $b$ is the right hand side vector. Without the constraints shown in Eq. (7), the problem reverts to $k$ single commodity flow problems.

This formulation does not impose capacity restrictions on nodes, however, in computer networks, nodes or routers are the main power consumers. To include node costs $c_n$, $g_n$ and node capacities $u_i$, the node splitting transformation can be applied [35]. Nodes, $i$ are replaced by a set of additional nodes, $i^r$ and $i^p$, connected by a new arc $(i^r, i^p)$. This transformation does not affect the problem formulation, Eqs. (5)–(7); however, it changes the problem size. As a consequence of the transformation, the number of nodes is doubled and $n$ additional arcs are introduced. Fig. 2(a) depicts an example network with nodes 1, 2 and 3 and the corresponding unit costs $c_{12}$, $c_{13}$, fixed costs $g_{12}$, $g_{13}$, and capacities $u_{12}$, $u_{13}$, respectively. Node 1 has also costs $c_1$, $g_1$ and capacity $u_1$ assigned. To include these node constraints, Node 1 is replaced by a capacitated link.
(1', 1''), as depicted in Fig. 2(b). Node costs and capacities are reassigned to the new link accordingly.

3.5. Node bypass transformation

The aim of this research is to develop a model that minimises the number of nodes in the network required to service a given network load. It also assumes that nodes are injecting and consuming traffic. If nodes are switched to a standby mode, they are no longer able to route traffic. Therefore, it is necessary to bridge local demands to one of the neighbouring nodes. As discussed in Section 3.3, this can be done by disconnecting all but one interface. To reflect this in the network model, an extended node transformation in combination with modified problem formulation is proposed. The goal is to introduce an alternative connection to neighbouring nodes that does not rely on routing at the node level. To achieve this, a set of additional arcs are added to the node splitting transformation and additional constraints are introduced that limit the number of active arcs. The algorithm to transform the network is depicted in Fig. 3.

The first main loop (Line 1) is executed for all network nodes: the arc (i0, i00) is generated and the node cost and capacity are assigned to the new arc. The loop over all demands k (Lines 4–8) sums emanating and terminating demands at the current node i, respectively. All demands are reassigned to the corresponding dashed nodes in the same loop; emanating demands to once-dashed nodes, terminating demands to twice-dashed nodes. The next loop (Lines 9–15) iterates through all arcs that are leaving node i. The source node is changed to the twice-dashed node and the out-degree of node i00 is increased by one. In the next step, bypass links are generated by duplicating the original link and connecting it to the once-dashed node. Costs are also duplicated; however, the capacity is reduced to the size of the emanating demands (Line 15). This limits the traffic on the bypass links to local demands. Half of the node standby power consumption hi is assigned to the bypass link (Line 13). The final loop iterates through all arcs that are terminating at node i. The terminating end of the link is connected to node i0 and the in-degree of node i0 is increased by one. The arc is duplicated and its destination node is set to node i00. Half of the standby cost is added to the link’s fixed cost and the link capacity is limited to the received traffic (Line 22).

This transformation has the following effect: If a node is not in a standby mode, traffic is routed via the router link (i0, i00), all newly added bypass links are deactivated. If a node is in power saving mode, arc (i0, i00) is deactivated and the node does not forward any transit traffic. Locally generated traffic is forwarded via bypass arcs emanating at node i0 which are included between the router ingress (dashed node) and the destination nodes of the transformed network. As routed and bypass traffic are exclusive, only one arc leaving a dashed node can be used at one
The additional arcs have the same capacities and costs than the original links. The same applies for terminating traffic: It is either forwarded via the route when it is active; or via one of the bypass arcs terminating at node 0, if the router is in standby mode. As above, only one terminating link at node 0 can be active at one time. A router in standby-mode encounters the fixed cost $h_i$. This transformation implements the bridge-all option discussed in Section 3.3.

Fig. 2(c) depicts an example of this extended transformation. For simplicity, only emanating arcs are shown. If the arc $(i', i'')$ is active, Fig. 2(b) is replicated, if either arc $(i, 2)$ or $(i, 3)$ is active, all traffic, originally routed via node 1 is routed via node 2 or 3, respectively. Traffic that originated at node 1 in the original network originates at the ingress, node 1. The proportional costs of the transformed network are given by Eq. (8)

$$c_{i'2} = c_{i2} = c_{i12}, \quad c_{i'3} = c_{i3} = c_{i13}, \quad c_{i''1} = c_1$$

and the fixed costs by Eqs. (9) and (10).

$$g_{i'2} = g_{i2} + h_i/2, \quad g_{i'3} = g_{i3} + h_i/2, \quad g_{i''1} = g_1, \quad (9)$$

$$g_{i'2} = g_{i2}, \quad g_{i'3} = g_{i3}. \quad (10)$$

To make the transformed network equivalent to the original network additional constraints are required: only one arc emanating from a once-dashed node can be used at one time and only one arc can terminate at a twice-dashed node at one time. If all arcs $(i', i'')$ are used the original network is replicated. If for node $i$ another emanating arc $(i', j)$ is active and the corresponding termination arc is active, it is equivalent to a network without router $i$ present. The demands of node $i$ are assigned to node $j$ in this case. To enforce this limitation, the problem formulation has been adapted as discussed below.

### 3.6. Node bypass MIP

This section outlines the changes to the mathematical program of the multicommodity flow problem, Eqs. (5)–(7) that are necessary to accommodate the network transformation. This formulation uses two additional constants $\gamma_i$ and $\beta_i$ that limit the out- and in-degree of nodes, respectively. For once-dashed nodes, $\gamma_i$ equals one and for other nodes it is equal to the out-degree that corresponds to their connectivity. For twice-dashed nodes, $\beta_i$ equals one, for all other nodes $\beta_i$ is equal to the in-degree. The resulting
mixed integer program is given below. The new objective function, Eq. (11), includes an additional fixed cost $g_{ij}$ for active links.

Minimise $\sum_{ij} c_{ij} x^k_{ij} + \sum_y \delta_y g_{ij}$. \hspace{1cm} (11)

Restrictions that are required for the extended transformation are enforced by two additional constraints given in Eqs. (12) and (13).

$$\sum_j \delta_{ij} = \gamma_i \hspace{1cm} \text{for all } i \in N.$$

$$\sum_i \delta_{ij} = \beta_j \hspace{1cm} \text{for all } j \in N. \hspace{1cm} (13)$$

As before the formulation requires mass balance constraints, given in Eq. (14).

$$\mathbf{AX} = \mathbf{b}$$

for all $k = 1, 2, \ldots, K. \hspace{1cm} (14)$

If router $i$ is active, traffic is routed via arc $(i, j)$; otherwise, traffic is forwarded directly between $i$ and one of the connected nodes. To enforce this, the variable $\delta_{ij}$ has also to be included in the bundle constraint, Eq. (15).

$$\sum_k x^k_{ij} \leq u_i \delta_{ij} \hspace{1cm} \text{for all } i \in N. \hspace{1cm} (15)$$

If feasible solutions exist, these models will find an optimal solution. The problem formulation above has one limitation; demands can only be bridged for one hop. Therefore, only one router between demand and next router can be turned off. This limitation is intrinsic to the overall problem formulation. If demands have to be forwarded for more than one hop, this requires routing functionality in the intermediate node and therefore violates the overall problem constraints. This problem formulation provides a solution for the bridged-all standby option. Relaxed versions of the problem formulation can be used to implement bridged-local and default-gateway options as well.

To enable the bridged-local standby option, the following changes are required: Additional arcs for terminating demands are not necessary; therefore, Lines 18–22 in Fig. 3 can be ignored and the in-degree constraint in Eq. (13) is redundant. Terminating demands have to be connected to once-dashed nodes. Therefore, Line 8 has to be changed to $b^k(i) = b^k(i)$ and the standby power consumption has to be assigned to one link only; hence, Line 13 has to be changed to $g_{ij} = h_i$.

To support the default-gateway standby option, the demand limitation of the bypass arcs has to be removed in addition to the changes outlined above; i.e. Lines 14 and 15 have to be removed. As the definitions are less restrictive than the original problem, they lead to simplified transformations and problem formulations. To minimise the network power consumption, costs correspond to energy use and constraints are link and node capacities. Using this model, the number of routers and links that are necessary to accommodate the traffic can be determined.

4. Evaluation and analysis

The previous section introduced a set of mathematical models that assist in determining optimal topologies for given traffic loads. This section discusses numerical results found by analysing two test networks with large sets of traffic matrices. The aim is to highlight the implications of the models and show sample results, it does not provide a comprehensive analysis of all possible network configurations.

4.1. Device power model

Network energy consumption has to be calculated for various traffic loads to evaluate performance of the mathematical models. The power consumption of routers varies depending on capacity, vendor and features. To demonstrate the impact of the model, arbitrary, but realistic values for a generic router and links are required. A set of basic assumptions are used to motivate the choice of power demands of network devices. The power model for these evaluations is based on the discussion in Section 3.3. It is assumed that 10% of the router energy consumption is load dependent; i.e. caused by function, such as routing table lookups, queuing, and forwarding; and 90% of the total power consumption is load independent. These assumptions are supported by measurements undertaken by Chabarek et al. Moreover, it is assumed that routers without line cards consume a maximum of 600 W, i.e. 540 W are independent of load. A single, fixed power ratio has been used as variations have no direct impact on the principal outcome. Implications of altered power ratios are discussed in Section 4.6. In line with the discussions in Section 3.3, it is assumed that routers have two modes of operation, independent of line card configurations: A fully functional mode and a standby mode that does not support routing functionality. It is assumed that in standby mode, the router consumes 10% of the maximum power. Load dependent power consumption in low power modes is assumed to be negligible.

For calculations, it is assumed that the power consumption of line cards is attributed to links; i.e. two line cards are required per link. Each line card has only one port and line cards can be individually activated and deactivated. For the calculations in this section, it is assumed that links have a maximum power consumption of 80 W.\footnote{3} As

3. The magnitude of this value is based on [25]. The authors report absolute power values of unloaded systems of 430 W. As nodes in this model inject and consume traffic, node power consumption has to also account for an access link.

4. Chabarek et al. report 26 W for a 1 port Fast Ethernet line card, 30 W for a 1 port Gigabit Ethernet line card and 92 W for a 4 port Gigabit card (23 W per port). Further discussions in the remainder of this paper assume a total of 32 W fixed power consumption per port (40 W total) for generic links. The power consumption of a link is the sum of the power of the two line cards at the link endpoints. The power consumption of network interfaces is decreasing as technology advances, these values reflect conservative assumptions.
the utilisation of network processors depends on traffic load, a higher variability of 20% is assumed. Furthermore, for calculations in this paper, it is assumed that link capacity is not a major factor in power consumption, i.e. technology at a similar level of maturity, have similar power requirements. Overall, power density increases with link speed. These assumptions are supported by Gupta and Singh [11] and Gunaratne et al. [12]. These references refer to PC network cards and absolute power values are not directly applicable. Variable power consumption is scaled to link speed. An unloaded link consumes 80% of the total power and a fully loaded link consumes 100% of the link power. The numerical values are only indicative and changes in the absolute values are inconsequential to the overall trends that are discussed in the remainder of the paper. If these models are applied to specific scenarios and technologies, assumptions can be revised accordingly.

4.2. Test networks and ILP solver

Evaluations use two networks, one with 8 nodes and 24 unidirectional links; and one with 22 nodes and 86 unidirectional links. The former is inspired by the Australian Telstra network (AS1221) and the latter by a North American backbone. The networks are similar to the topologies that have been identified by the rocket fuel project [39] without including stub networks. The topologies are depicted in Figs. 4 and 5, respectively. For the 8 node network, links have nominal capacities of 1 Gbps (dashed lines) and 10 Gbps (full lines), respectively. If link \((ij)\) exists, link \((ji)\) also exists. Nodes in this network have a capacity of 100 Gbps and do not pose a bottleneck. Traffic matrices include 56 demands, i.e. traffic between all routers. The experiment uses 3327 instances of traffic matrices which have been generated randomly. The matrices include traffic demands between origin and destination nodes and not link traffic. Realistic traffic matrices feature a demand distribution that reflects the size of the nodes in terms of connected link capacities. For the problem of dynamic topologies such a traffic distribution is advantageous as it accumulates traffic at fewer, highly loaded nodes. This results in more opportunities to put unloaded nodes into standby modes. A set of randomly generated traffic matrices therefore underestimates energy saving potential of a given topology. For the 8 node network, random traffic matrices were chosen as a worst case scenario.

To generalise the results, instances are grouped into 31 sets, according to the total demand of each instance. This traffic data has been used by a number of other studies including [e.g. 40]. For the investigations in this paper, only traffic matrices that have feasible solutions for the 8 node network are used. Fig. 6 depicts the number of instances included in each group. Most groups include more than 100 instances. Fig. 6 shows the mean of total traffic demands per instance and corresponding 95% confidence intervals. The total demand changes from 2.64 Gbps to 10.21 Gbps, simulating different network load conditions. The maximum total sustainable demand for this network is approximately 10 Gbps. The theoretical network capacity, i.e. the sum of all link capacities, is much higher, 78 Gbps. The difference is due to the situation that demands between origin and destination nodes are routed via a number of links. Furthermore, demands do not exactly match available link capacities. In absence of any traffic engineering or optimisation, a network is fully loaded once one or more links become congested. The minimum power consumption of this network is bound by the fix power consumption of 8 nodes (8 \(\times\) 540 = 4320 W) and 24 links (24 \(\times\) 64 W = 1536 W), 5856 W. A fully loaded network would consume 6720 W.\(^5\)

The 22 node topology, depicted in Fig. 5, features link capacities between 256 Mbps and 8192 Mbps. Nodes have a capacity of 128 Gbps and therefore do not pose a bottleneck. Traffic matrices for the large network include 462 demands and are based on a gravity model; i.e. highly connected nodes attract more traffic. The process of how these traffic matrices where generated is described in [41]. These traffic matrices follow the gravity assumption; however, this does not necessarily mean that they have feasible solutions for the network. The traffic matrix instances are scaled with a load factor to cover the complete range of potential operating conditions. Previous work [41] has indicated that this network reaches saturation at total traffic loads of about 60 Gbps. Above this load, individual links become overloaded. The theoretical capacity of this network is 212 Gbps. As above, only traffic matrices that had feasible solutions for the unmodified network where included. An unloaded network will consume 17,384 W, 11,880 W by nodes and 5504 W by links. If all network nodes and links are fully loaded, the network consumes 20,080 W. These two values mark the performance baseline of the unmodified network.\(^5\)

\(^5\) This marks only an upper bound and not a practical value as it implies that all nodes and links are 100% loaded.
The open source mathematical programming toolkit GNU LP Solver (GLPK) [42] and the SCIP tool [43] are used to solve the mathematical programs for the test networks. For the 22 node network, the commercial IBM ILOG CPLEX Optimizer 12.2 has been used as a solver with reduced runtimes. Practical times to solve the problems vary greatly. On an Intel Core 2 Duo Processor P8600, 2.4 GHz with 4 GB RAM it took at most minutes for the 8 node network and on average about 1.6 h (median 1.1 h) for the 22 node network using the bridged-all standby option. Runtimes for the links-only option were much higher, on average 6.8 h (median 3.5 h) for highly loaded networks, lightly loaded networks take 24 h and more. The lower median values indicate that there are a few problems that take a long time to solves. The longest instance that was included required 45 h.

This limits the scenarios for the link-only option. These are only provided as benchmarks for algorithms that have been discussed in literature and are not the main interest in this paper. The average runtime decreases with higher...
total traffic load as higher loads result in fewer feasible solutions that need to be evaluated. As these problems are known to be NP hard, only limited size problems can be solved. The solution times indicate that this approach is unsuitable for online implementations. However, the aim of this paper is to evaluate performance thresholds, online algorithms will have to rely on suitable heuristics.

To evaluate performance in this study, it is assumed that link utilisation is a sufficient measure for network performance. This assumption is widely used [e.g. 44,45]. If the effective link utilisation is below 100%, performance is acceptable; above this threshold performance is insufficient. If links are over provisioned, this assumption does not necessarily imply that the actual link utilisation is 100%. All discussions in this paper refer to effective link utilisation and not the real link utilisation.

4.3. Results

This section presents results that have been found by applying the mathematical model, introduced in Section 3, to the test setup discussed above. Numerical results are presented for the bridged-all, bridged-local and default-gateway standby options for the 8 node network. The results are also compared to the links-only options which corresponds to the optimisation model that has been introduced by Chiaraviglio et al. [26]. For the 22 node network, results for the bridged-all and link-only standby options are presented.

4.3.1. 8 Node network – bridged-all

For nodes in standby, locally emanating and terminating traffic is bridged to individual links. Fig. 7 depicts the network power consumption versus total traffic demand, as a scatter plot for all traffic instances. The cloud on top (●) shows the energy consumption of an unmodified 8 node network. In this case all 8 nodes are active and the slope shows the impact of the variable network power consumption. As the nodes in this network are over provisioned and variable power consumption is scaled by capacity, the impact of variable power consumption is less than the theoretical maximum would suggest. This baseline depicts the minimum power consumption for an unmodified network. The cloud below (▼) shows the results for the link-only option. In this case all nodes remain active and only links can be turned off. At lower loads more links can be powered down, which leads to an increased slope. It shows improvement in comparison with the unmodified network. In both cases, the energy-use increases linearly with demand. For higher loads, most links are required and power values approach the baseline. The lower clouds (■) show the energy consumption for the bridged-all option. Five distinct clouds and an additional single value can be identified. The figure also shows the impact of deactivated links (various, distinct levels per cloud) and the influence of variable power consumption (slope).

Fig. 8 depicts the number of active nodes versus the total demands for the same data set. The graph shows similar patterns to Fig. 7. Individual clouds correspond to the number of active nodes. Lightly loaded networks require only three nodes; highly loaded networks require 7 nodes. Three nodes result in a fixed power consumption of 1620 W, 5 nodes in standby consume 5 \times 60 W = 300 W. The fixed power consumption for a network with three active nodes is therefore 1920 W for nodes; approximately 950 W are due to links and loads. For each additional activated node, the fixed power consumption is raised by 480 W. The power consumption is reduced considerably in relation to the unmodified network as well as the links-only power option. The ability to reduce the network power consumption of the various standby options is discussed in Section 4.4 in more detail.
Fig. 9 depicts grouped results for the number of active nodes that are required to accommodate given traffic loads for the bridged-all standby option. The graph shows the average number of nodes that are required for a particular demand group and the corresponding 95% confidence intervals. The graph is similar to Fig. 8, but also indicates how general the number of active network nodes is for a particular demand group. Groups with large confidence interval have no specific network representations. There are three traffic levels that result in a constant number of active nodes. For this particular example, topologies with three, four and seven routers provide topologies that cover a wide range of traffic conditions. Furthermore, it can be observed that for most cases, seven active nodes are sufficient to service demands. Only one out of 3327 instance requires 8 nodes. These results indicate that implementation of an active dynamic topology network is feasible, especially, if network load levels can be detected, and effects of dynamic traffic rerouting are minimised.

These observations are further supported by Table 1. The table shows frequency of active nodes in relation to the number of active nodes for the 8 node network and the bridged-all standby option. The second column shows how many instances feature a particular number of active nodes.
which are listed in the first column. The remaining columns show a matrix of how often a node was active as part of the total node count in each row. The table gives an indication of how important nodes are for the overall topology. In this network configuration, Node 1 is only used 12 times. In contrast, Node 3 is always active. Nodes 7 and 8 are active most of the time; and Node 6 is active for most of the higher loaded instances. This indicates that there are key nodes that are essential to maintain connectivity and are unlikely to be switched off. This information can be used to design online algorithms and create node priority list that could be used to determine the order of router shutdowns, an issue to be addressed by future studies.

4.3.2. 8 Node network – bridged-local and default gateway

This section discusses the power consumption (Figs. 10 and 11) and active node count (Figs. 12 and 13) for the other two alternative standby options.

A scatter plot of the network power consumption versus the total demand for the bridged-local standby option is depicted in Fig. 10. In this case, locally originating demands of nodes in standby are forwarded via one bridged link; terminating traffic can be received via all terminating links. This does not lead to fewer active nodes than the first option as could be expected. Surprisingly, there is no major difference between both bridged options in terms of network power consumption. Fig. 12 depicts the number of active nodes versus the demand groups for the same data set. These results are also very similar to the bridged-all standby option. The only difference occurs at higher network loads for demand groups 25–30. In this case, for several instances, 6 nodes are sufficient, whereas the bridged-all option requires 7 nodes.

Fig. 11 depicts the power consumption for the default gateway node standby option and Fig. 13 shows the corresponding active nodes versus demand groups plot. This option provides the greatest saving and low demands up to group 6 require only 2 active nodes; however, the number of nodes are not as specific as they were for the first two standby examples, indicated by the higher confidence intervals in Fig. 13. A detailed comparison of the energy use is discussed below.

![Fig. 10. Power consumption versus total demand; 8 node network; original network and bridged-local standby option.](image-url)
4.4. Comparison of power consumption

Table 2 shows the mean power consumption for every fifth group for various standby options and quantifies improvements compared to the unmodified network. All three standby power options perform at a similar level for medium to highly loaded networks. For modestly loaded networks, bridged-all and bridged-local operate at a similar level, default gateway offers greater savings. Once the network reaches a load of about 50–60%, the number of active nodes increases rapidly and power reductions decrease. Power consumption and active node graphs also support this observation. The effect is the same for all standby options. The overall results support the choice of bridged-all as the best option. It requires the lowest level of functionally in the forwarding path and it offers excellent power savings. The additional effort to implement bridged-local or default gateway options is not justified. The difference to the links-only option shows the potential for dynamic topologies to reduce the networks energy footprint in comparison to approaches that are unable to turn off nodes that have demands attached.
4.5. 22 node network – bridged-all

Comprehensive results were discussed for the 8 node network topology above, this section introduces a smaller set of results for the 22 node network using the links-only and the bridged-all standby options. This shows that the model applied to a larger network, with more realistic traffic matrices, yields similar outcomes. Fig. 14 depicts the network power consumption versus the total demand as a scatter plot for the 22 node network. The top row of data points (\(C7\)) show the energy consumption of an unmodified 22 node network with all nodes active. This marks the baseline power consumption for the original network. The data points below (\(N\)) show the results for the links-only option and the lowest set of data points (\(j\)) show the energy consumption for the bridged-all option. There is a difference in the number of samples between the links-only and the bridged-all results, 266 and 141, respectively. This is due to the much longer runtime to solve the problems that feature the links-only option, as mentioned above. As these results are only included to offer a comparison to other optimisation approaches, this is not a concern. There is a trend that can be identified and that will be the similar for the other samples.

The graphs in Fig. 14 follow the same general pattern than the results for the eight node network. The power savings for lightly to moderately loaded networks (below a total load of approximately 32 Gbps) are considerable. The network energy-use is reduced by approximately 60%. As the network load increases, the number of active nodes increases and the power consumption rises. The curve for the bridged-all standby option shows a clear step-change that marks a rapid increase. This occurs at a total load of approximately 32 Gbps. Such a step-change, also less pronounced, can also be seen in Fig. 7 that depicts the results for the 8 node network, as well.

Fig. 15 depicts the number of active nodes and active links versus the total demand for the same data set. The lower sets show the number of active nodes for bridged-all (\(C15\)) and links-only (+) options. The number of node for the links-only option is constant at 22, for the bridged-all option it changes with load. The minimum number of nodes that were encountered in this topology is 6. The two upper plots show the number of active links for the bridged-all (■) and links-only (▲) options. In both cases the number of active links increases steadily with network load. The bridged-all option has at least 42 active links.

Fig. 16 depicts the network topology for one example instance of the 22 node network with 6 active nodes and 42 active links. Active nodes and links are highlighted in the graph. In this example Nodes 2, 4, 6, 12, 14 and 20 are active. Node 11, in the bottom right corner, is bridged to Node 2, for example. At least 6 nodes and 42 links are necessary to provide sufficient connectivity to service all network endpoints with the bridged-all standby option.

Table 2
Power consumption of the 8 node network.

<table>
<thead>
<tr>
<th>Group number</th>
<th>1</th>
<th>6</th>
<th>11</th>
<th>16</th>
<th>21</th>
<th>26</th>
<th>31</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original [W]</td>
<td>5906</td>
<td>5929</td>
<td>5953</td>
<td>5977</td>
<td>6000</td>
<td>6024</td>
<td>6049</td>
</tr>
<tr>
<td>links-only [W]</td>
<td>5071</td>
<td>5155</td>
<td>5288</td>
<td>5425</td>
<td>5532</td>
<td>5674</td>
<td>5778</td>
</tr>
<tr>
<td>Savings</td>
<td>14%</td>
<td>13%</td>
<td>11%</td>
<td>9%</td>
<td>8%</td>
<td>6%</td>
<td>5%</td>
</tr>
<tr>
<td>bridged-all [W]</td>
<td>2848</td>
<td>3280</td>
<td>3455</td>
<td>3552</td>
<td>4663</td>
<td>5214</td>
<td>5328</td>
</tr>
<tr>
<td>Savings</td>
<td>52%</td>
<td>45%</td>
<td>42%</td>
<td>41%</td>
<td>22%</td>
<td>13%</td>
<td>12%</td>
</tr>
<tr>
<td>bridged-local [W]</td>
<td>2847</td>
<td>3135</td>
<td>3453</td>
<td>3550</td>
<td>4419</td>
<td>5173</td>
<td>5322</td>
</tr>
<tr>
<td>Savings</td>
<td>52%</td>
<td>47%</td>
<td>42%</td>
<td>41%</td>
<td>26%</td>
<td>14%</td>
<td>12%</td>
</tr>
<tr>
<td>default gateway [W]</td>
<td>2115</td>
<td>2297</td>
<td>2950</td>
<td>3402</td>
<td>4398</td>
<td>5156</td>
<td>5300</td>
</tr>
<tr>
<td>Savings</td>
<td>64%</td>
<td>61%</td>
<td>50%</td>
<td>42%</td>
<td>27%</td>
<td>14%</td>
<td>12%</td>
</tr>
</tbody>
</table>
2(n − 1) unidirectional links are required. Once the minimum network configuration is reached, there are no more changes in topology; here for loads below 23 Gbps the network topology is static. The depicted instance has a total traffic demand of 21.8 Gbps and the network consumes 7159 W. The minimum fixed power consumption of 6 active and 16 standby nodes is 5160 W, the minimum fixed power of 42 links is 1280 Watt and additional 719 W are due to load. Fig. 15 also shows that the number of active nodes decreases below 42 unidirectional links for the links-only standby option. This is possible since all nodes are active and not all links have to be bidirectional to provide sufficient connectivity.

4.6. Discussion and practical implications

The aim of this paper is to address a generic networking problem that is grounded in currently available hardware. However, standby options of reduced functionality in routers are envisaged, that yield a lower energy footprint.
These do not require major architectural changes; however, some systems have to be adapted. For example, power supplies currently consume approximately 30% of the total energy of a router, and options are required that these scale with load.

Current routers waste a lot of energy in standby and there is great potential for improvement. Some of the techniques that have been discussed in Section 2 will help to address this problem. More advanced devices will have a load proportional power profile. In terms of the models discussed in this paper, this means that the load-proportional power component is higher. The proportion of fixed to variable power consumption has no direct impact on the accuracy of the model. The model will work equally for all proportions. However, if the power consumption only has a variable component, there is no need to turn any nodes off as the network always operates at the most power efficient level if traffic flows are optimal. As future devices are likely to have higher load dependent power components, this model can be used to evaluate thresholds that make it uneconomical to turn nodes off. If the variable power component increases, the slope of the lines in the graphs will increase as well. At the same time, the gap between optimised and original network will diminish.

If networks are able to adapt to traffic demands, network power consumption can be reduced considerably. To allow router standby modes, minor modifications to routers are required. It is worthwhile looking into the protocol dynamic aspects of dynamic topologies, as the mechanism allows for substantial power savings in communication networks. As these problems are NP hard, applications are limited to medium sized networks. However, these models can be used in network planning applications and to benchmark the performance of heuristic which can be applied to larger networks. Practical online applications of the dynamic topology problem have to rely on local information, as other approaches are not scalable. This point has also been made by Vasic and Kostic [32] and has driven their approach to the problem.

5. Conclusion

This paper presented generic models and numerical results that indicate dynamic topologies are able to reduce power consumption of communication networks by adapting topologies to traffic conditions. The mathematical models can be modified in the future to take other aspects into account, including performance guarantees, service levels, and resilience. This study indicates that dynamic topologies can offer significant power reductions and that it is feasible to investigate dynamic aspects of this proposal. Traditional routing protocols are insufficient, as they can take several minutes to converge, leading to traffic loss and service disruptions. Questions that require further research include, but are not limited to how the transitions between states are managed; how load information is obtained and distributed; and how the networks are dynamically reconfigured. These aspects are left for further study; however, the numerical results that have been presented in this paper show that dynamic topologies can offer significant improvements in network power consumption. In practice, this effect will be more pronounced as networks operate most of the time at low utilisation levels, where savings are the greatest. Deploying dynamic topologies can introduce average energy saving between 30% and 50% which translates into major reductions in the GHG emission footprint of communication networks. Dynamic
reconfiguring networks can also be combined with other efforts to reduce the carbon footprint of equipment such as hardware optimisation, micro sleep states or other alternatives.

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Alexander A. Kist received the Ph.D. degree in Communication and Electronic Engineering from RMIT University, Melbourne, Australia in 2004. His research focused on performance modelling and evaluation of SIP Protocol based 3G Signalling IP networks and the development of methodologies to enable QoS Signalling in multi-service IP networks. He received the Bachelor degree, Diplom-Ingenieur (FH), in telecommunications engineering from the University of Applied Science Offenbarg, Germany in 2000. The thesis on the problem of synthesising of partially link-disjoint paths in a network was completed at the Centre for Advanced Technology in Telecommunications (CATT), RMIT University, Melbourne Australia. From 2004 to 2006 he was a Postdoctoral Research Fellow with the Australian Telecommunications Cooperative Research Centre (ATrc) and RMIT University, Melbourne, Australia. From 2005 he was the ATrc networking program project leader. Since May 2006 he was a Lecturer and since January 2011 is a Senior Lecturer in Telecommunications at the University of Southern Queensland, Toowoomba, Australia. His research interests include green IT, teletraffic engineering, performance modelling and QoS provisioning. He is the author of more than 30 scientific articles and one patent. He is a member of the Telecommunication Society of Australia and Engineers Australia; and he is a senior member of the Institute of Electrical and Electronics Engineers (IEEE).

Abdelnour Aldraho received the B.Sc. and M.Sc. Degree in Electrical and Computer Engineering from Sebha University, Sebha, Libya, and network mobile systems from Leeds metropolitan University, Leeds, UK, in 1998 and 2003, respectively. He is a Ph.D. candidate at University of Southern Queensland. He was a networking engineer in Information and Communication Technology at Eni Oil Company, Tripoli, Libya from 1999. He was a faculty member in computer science department at Sebha University, Sebha, Libya from 2006. His research interests and expertise are in communication networks, wireless/mobile networks, and artificial neural networks. His current focus and specific interest is in Green communication networks.