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Résumé

Les systèmes larges bandes ubiquitaires permettant de répondre à l'accroissement des demandes de services multimédia mobiles sont au c ur des préoccupations académiques et industrielles. Les réseaux de communications satellitaires et plus particulièrement les systèmes basses orbites LEO (Low Earth Orbit), tels Iridium, Iridium-NEXT jouent un rôle essentiel dans le déploiement de ces systèmes. Cependant leur déploiement et maintenance s'avère être un processus très coûteux qui induit un défi tant de recherche que d'ingénierie pour augmenter leur durée de vie.

L'axe majeur développé dans cette thèse s'appuie sur le fait que la durée de vie du service satellite peut être significativement augmentée en gérant le niveau de décharge des batteries. Les batteries sont utilisées par les satellites lorsqu'ils ne sont pas en visibilité solaire, ce qui selon le type de constellation peut atteindre 30% du temps. Bien que les batteries se rechargent par l'énergie solaire le niveau de décharge atteint au cours de la période d'éclipse affecte leur durée de vie et par conséquent la durée de vie du service satellite. Les batteries utilisées par Irridium next peuvent diminuer de moitié leur durée de vie lorsque le niveau de décharge augmente de 15%.

Nos travaux ont pour objectif de diminuer le niveau de décharge des batteries des constellations satellites LEO. Plusieurs techniques sont proposées. En premier lieu nous considérons le routage des communication au sein de la constellation satellitaire avec un relayage en fonction du niveau de batterie. L'objectif est de concilier la performance en terme de délai et la performance énergétique. L'originalité de ce routage est d'exploiter la configuration spécifique de la topologie en favorisant le travail des satellites exposés au soleil devant ceux en éclipse. Nous proposons deux métriques de routage, LASER et SLIM, l'une nécessitant des échanges additionnels l'autre non, qui permettent

d'augmenter la durée de vie des batteries de respectivement 75% et 100%.

Dans un deuxième temps nous étudions une approche de consolidation. Il s'agit d'élaborer une topologie économe, en sélectionnant un nombre de ressources suffisant pour acheminer le trafic tout en laissant en état d'endormissement les ressources inutilisées. Nous proposons deux approches nécessitant des prérequis de connaissance de trafic différents. L'approche trafic s'appuie sur la métrique MLU(Maximum Link Utilisation) pour quantifier la qualité de la topologie économe. Pour résoudre le problème NP difficile de recherche du maximum de nombre de noeuds pour une contrainte de MLU donnée, nous élaborons les heuristiques BASIC et SNAP ayant des caractéristiques performance/simplicité opposées. L'approche sans connaissance de trafic qualifie la qualité de la topologie économe par une métrique calculée selon la connectivité algébrique de la topologie. Ayant montré que la résolution est NP difficile nous proposons une heuristique. Les résultats que nous obtenons en utilisant des requêtes de trafics et une topologie réelles, permettent de doubler la durée de vie de la batterie.

La dernière partie de la thèse étend le problème de consolidation de ressources aux réseaux filaires. L'intérêt n'est pas d'augmenter la durée de vie du service mais de diminuer les coûts d'exploitation tout en répondant au défi écologique de réduction d'empreinte carbonne. Nous étendons la métrique ADI aux réseaux filaires et proposons des heuristiques, en temps polynomial, avec un calcul de la connectivité algébrique, ou un calcul de centralité plus simple à obtenir sur des topologies importantes. Nous les évaluons sur 3 topologies de réseaux représentatifs (Geant, SPRINT, IBM watson) avec des traces de trafic réelles. Les résultats obtenus montrent que les heuristiques sont aussi efficaces qu'une approche trafic de temps exponentiel et, comparées à la solution polynomiale classique de la littérature, améliorent les résultats d'environ 80%

Abstract

To meet the exponential growth in demand for multimedia services on mobile devices and to support connectivity anywhere on the planet, the development of ubiquitous broadband systems has attracted a lot of interest from both academia and industry. Satellite networks in general and Low Earth Orbit (LEO) satellite constellations in particular are expected to play an essential role in the deployment of such systems. However, LEO satellite constellations like Iridium or Iridium-NEXT are extremely expensive to deploy and maintain. As a result, extending their service lifetime has emerged as a crucial research and engineering challenge.

The key observation in this thesis is that one can significantly increase the satellite service life by managing the Depth of Discharge (DoD) of its batteries. Satellites in LEO constellations can spend over 30% of their time under the earth's umbra, time during which they are powered by batteries. While the batteries are recharged by solar energy, the depth of discharge they reach during eclipse significantly affects their lifetime – and by extension, the service life of the satellites themselves. For batteries of the type that power Iridium and Iridium-NEXT satellites, a 15% increase to the DoD can practically cut their service life in half.

In the main part of this thesis, we propose different techniques for reducing the battery depth of discharge in LEO constellations. Thanks to the highly uniform and symmetric nature of these constellations, there exist many paths between any two satellites, opening up the possibility of selecting the path to forward the data based on battery levels. In this context, we first focus on routing and propose two new routing metrics – LASER and SLIM – that try to strike a balance between the performance and battery DoD. Our basic approach is to leverage the deterministic

movement of satellites so as to favor routing traffic over satellites exposed to the sun as opposed to those eclipsed, thereby decreasing the average battery DoD – all without taking a significant penalty in performance. Using realistic LEO topologies and traffic requests, we show that LASER and SLIM can increase the battery lifetime by as much as 75% and 100%, respectively.

Then, we turn our attention to resource consolidation – a new paradigm for the reduction of the power consumption. It involves having a carefully selected subset of network links entering a sleep state while using the rest, a frugal version of the original network topology, to transport available traffic. We propose two different methods to perform resource consolidation in LEO networks. First, we propose a traffic-aware metric for quantifying the quality of frugal topologies, the Maximum Link Utilization (MLU). With the problem of finding the maximum number of nodes that can be put to sleep subject to a given MLU threshold being NP-hard, we introduce two heuristics – BASIC and SNAP – representing different tradeoffs in terms of performance and simplicity. Second, we propose a lightweight, traffic-agnostic metric for quantifying the quality of frugal topologies, the Adequacy Index (ADI). After showing that the problem of finding the most frugal topology subject to a given ADI threshold is NP-hard, we propose a heuristic named AvOId. We evaluate both forms of resource consolidation using realistic LEO topologies and traffic requests. The results show that the schemes we developed can double the satellite battery lifetime.

The second part of this thesis focuses on extending the resource consolidation schemes to wired networks. In this context, the challenge is not extending the network lifetime but reducing the operating costs and carbon footprint. The potential savings are significant. Powering wired networks in the United States alone costs an estimated 0.5 - 2.4 billion dollars per year. Meanwhile, several studies have shown that the ICT industry is responsible for 2% of the world's CO2 emission. We extend the traffic-agnostic metric, ADI, to the wired networks. We model the problem of finding the most frugal topology subject to the ADI threshold and show that it is NP-hard. Then, we propose two polynomial time heuristics – ABStAIn and CuTBAck. We assess their behavior under real traffic loads and topologies from 3 different networks. Our results show that ABStAIn and CuTBAck are as effective as an exponential time traffic based solution at creating frugal topologies and outperform a state of the art polynomial time traffic based solution by about 80%.

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Acronyms

ABStAIn **A**lgebraic **B**a**S**ed **A**lgorithm for Frugal**I**ty.

ADI Adequacy Index.

AvOId **A**lgebraic based alg**O**r**I**thm for frugality.

BASIC **BASIC** Link Pruning.

BPL Broadband over Powerlines.

CDF Cumulative Distribution Function.

CDMA Code Division Multiple Access.

CEMR Compact Explicit Multi-path Routing.

CFDAMA Combined Free/Demand Allocation Multiple Access.

CMCF Capacitated Multi-commodity minimum Cost Flow.

CuTBAck **C**en**T**rality **B**ased **A**lgorithm for Frugality.

DAFDM Demand-Assigned Frequency Division Multiplexing.

DAMA Demand Assignment Multiple Access.

DoD Depth of Discharge.

DSL Digital Subscriber Line.

DSP Dijkstra's Shortest Path.

ESOL Energy Saving in the Internet based on Occurrence of Links.

FDMA Frequency Division Multiple Access.

FSA Finite-state Automaton.

GEO Geostationary Orbit.

GRiDA GReen Distributed Algorithm.

ICT Information and Communication Technologies.

ILP Integer Linear Programming.

IP Internet Protocol.

ISL Inter-Satellite Link.

ISLs Inter-Satellite Links.

ISPs Internet Service Providers.

LASER **L**oc**A**tion and loAd **SE**nsitive **R**outing.

LEO Low Earth Orbit.

MAC Multiple Access Control.

MEO Medium Earth Orbit.

MLU Maximum Link Utilization.

MRPC Maximum Residual Packet Capacity.

NGI Next-Generation Internet.

OSPF Open Shortest Path First.

PoPs Point of Presences.

QoS Quality of Service.

REFWA Recursive, Explicit, and Fair Window Adjustment.

RIP Routing Information Protocol.

SLIM **S**igna**L**-free rout**I**ng for **M**aximizing satellite service life.

SNAP Po**S**itio**N** **A**ware **P**runing.

TCP Transmission Control Protocol.

TDMA Time Division Multiple Access.

UDP User Datagram Protocol.

VN Virtual Node.

VT Virtual Topology.

WSNs Wireless Sensor Networks.

Introduction

Recent studies estimate that as many as 4.2 billion people, over 60 % of the world's population, still lack internet access [1]. Bringing the Web to every corner of the globe is sure to be a highly ambitious undertaking and a very challenging task for current terrestrial technologies. According to Cisco [2], the current access networks are very unlikely to cope with the tremendous increase in Internet Protocol (IP) traffic in the next years. Therefore, new Internet technologies are required to accommodate the emerging wide-band Internet services with diverse Quality of Service (QoS) requirements.

Satellite communication systems offer many advantages over traditional terrestrial networks. In addition to their inherent multicast capabilities, wide bandwidth and flexible deployment features, they are able to provide coverage to wide geographical areas and interconnect remote terrestrial networks [3]. Therefore satellite technology can enable many civilian and military applications, such as disaster and environmental monitoring, managing large systems, effective data collection, disaster prevention and Internet of things. Satellites are also very effective at broadcasting information. Anyone can receive the data the satellites transmit, and each user can decode and use the subset of information that he/she is interested in and authorized to receive, given that he/she is equipped and configured correctly [4]. As a result, satellite networks are expected to be an essential part of Next-Generation Internet (NGI) [5]. LEO satellite systems in particular are of great interest as they provide lower propagation delay as well as higher throughput than Geostationary Orbit (GEO) and Medium Earth Orbit (MEO) satellites [6]. On the other hand, LEO satellites have a much shorter lifetime when compared to MEO and GEO satellites [7]. Therefore, as LEO satellite constellations like Iridium or Iridium NEXT are extremely expensive to deploy and maintain, extending their service lifetime is of crucial importance.

In the main part of this thesis, we present different approaches for reducing energy consumption in the LEO satellite constellations, with the aim of extending their service lifetime, without causing major disruptions to network activities. In the second part, we present additional work on energy efficiency in the wired networks. In the following, we motivate these approaches and enumerate our main contributions.

A Energy E ciency in LEO Satellite Constellations

LEO satellites are equipped with solar panels and rechargeable batteries as their energy source and storage. Both are complementary to each other during two alternate phases. First, when a satellite is exposed to the sun, solar panels convert sunlight into electrical energy, The generated power is used to operate the satellite`s components with the remaining power stored in battery cells. Second, during eclipse, the energy stored in the batteries is used to operate the satellite components. For a constellation like Iridium, for example, satellites spend about 30% of their time in the earth's umbra [8, 9], time during which they are powered by batteries. This, coupled with the fact that it is impractical to replace the satellite batteries, makes the battery lifetime essential to the service lifetime of the LEO satellite.

Far and away, the dominant variable affecting the battery lifetime is the Depth of Discharge (Depth of Discharge (DoD)). For nickel hydrogen batteries, the kind powering the current Iridium constellation satellites, studies have shown that as little as 15% reduction in Depth of Discharge (DoD) can double their lifetime [10, 11]. Similar behavior is observed with lithium-ion batteries [12, 13], the kind of which will power Iridium NEXT [14].

Thanks to the highly uniform and symmetric nature of LEO satellite constellations, there may be several minimum hop paths between two nodes in a satellite network. Selecting which path to use for sending data can have an important effect on the network lifetime. A lot of effort has been put into designing routing protocols for LEO satellite constellations [15–18]. Unfortunately, all of these routing protocols share a quest for performance. The underlying assumption being that, with LEO satellites being powered by solar energy and batteries, rechargeable by solar energy, the communication protocols need not be concerned with energy efficiency. However, a routing protocol that in addition to the traditional performance metrics is sensitive to the energy consumption of eclipsed nodes, can reduce the Depth of Discharge and, thus, significantly increase the lifetime of the batteries onboard the satellites.

Furthermore, the LEO satellite constellations are designed to cover the entire globe almost uniformly even if the traffic distribution on earth is not homogeneous. For the Iridium satellite constellation, it is estimated that between 81% and 85% of the traffic comes from the continents [19]. The population density, and by extension the customer base, is high in cities, low in rural areas and almost zero over the oceans (around 70% of the earth's surface) [20] - leaving large sections of the constellation significantly underutilized. Therefore, selectively shutting down a significant fraction of the constellation during periods of low demand so as to reduce the overall energy consumption is entirely conceivable.

B Energy E ciency in Terrestrial Wired Networks

For billions of people around the world, the Internet has become an essential component of their everyday social and business lives. According Cisco [21], the peak global throughput increased by 41% through 2014 year alone. It is estimated that the global wire-line Internet traffic will increase by a factor of 16 over the decade 2010-2020 [22]. Moreover, the global mobile Internet traffic will grow even faster. To keep pace, Internet Service Providers (ISPs) have to rely on similar growth in bandwidth and capacities in routers and switches. This can lead to a huge rise in energy consumption and CO_2 emission [23]. Studies show that the power consumption related to Information and Communication Technologies (ICT) varies between 2 % to 10% of the worldwide power consumption [24], making the ICT industry responsible for 2% of the world`s CO_2 emission [25]. Therefore, the ICT is expected to play a major role in the effort to reduce the worldwide energy consumption through the adaptation of green networking technologies.

Currently, network operators overprovision their networks. Most ISPs upgrade their infrastructures when the link utilization reaches above 40% [26, 27], leading to a significant waste of energy. Reducing this waste, however, is challenging. First, a network operator has to build its infrastructure for the worst case and the rule of thumb value of 40% is based on average utilization. Network traffic is inherently variable, with high and low peaks often re ecting human activity. Second, the coarse granularity of the current transmission technology forces network providers to install high bandwidth links during any incremental upgrade [28]. Therefore, designing large networks with average link utilization approaching 100% is infeasible. Given this, resource consolidation has emerged as the default paradigm for the reduction of power consumption in wired networks. It consists of having a carefully selected subset of network links entering “sleep" state, while using the rest to transport the available traffic.

This thesis introduces several approaches for energy efficiency in the wired terrestrial networks. Since the energy consumption of wired networks has been traditionally overlooked, the potential savings in this area are significant. Powering the wired networks in the United States, for example, costs an estimated 0.5 - 2.4 billion dollars per year [29].

C Thesis Contributions and Organization

The remainder of this thesis is organized around my contributions, as follows.

Chapter 1: Networking with LEO Satellite and Energy E ciency

This chapter covers the state of the art. It first presents the context of this dissertation by giving a brief introduction to LEO satellite design and architecture. We study the entry/exit positions and times through the earth shadow for LEO satellites. Issues related to MAC mechanisms, routing strategies, and transport protocols are presented. Then, existing energy management approaches in terrestrial wireless/wired networks and satellite systems are reviewed.

Chapter 2: On Routing for Extending Satellite Service Life

In this chapter, we introduce LASER and SLIM, two routing metrics that strike a balance between the battery lifetime and performance. The basic mechanism employed by both metrics is to disfavor routing data over satellites that have spent the most time in the earth's umbra in order to reduce the DoD, without stretching the paths too much so as to limit the penalty in performance. LASER leverages the specifics of the LEO satellite constellation to compute the propagation delay and combines it with the satellite battery level, acquired via signaling, into a single link metric. SLIM drops all requirements for signaling and instead combines the propagation delay and the time spent in the shadow, both of which can be computed, into a single routing metric. Simulation results show that LASER and SLIM can increase the satellite service life by as much as 75% and 100%, respectively.

The results of this chapter have been accepted for publication to IEEE GLOBECOM 2014 [30].

Chapter 3: Traffic-Aware Network Pruning for Extending Satellite Service Life

In this chapter, we study the problem of switching off network links while still guaranteeing full connectivity and meeting QoS (in term of link utilization) constraints. Since finding the optimal solution is a NP-hard problem, we propose two heuristics – BASIC and SNAP. BASIC is based on the observation that constellation links not on shortest path trees are highly unlikely to carry traffic and thus can be safely shut down. SNAP improves upon BASIC by leveraging the deterministic movement of satellites so as to prune only links that are in eclipse and from areas with light traffic. Simulation results show that BASIC and SNAP can increase the satellite service life by as much as 40% and 80%, respectively.

The results of this chapter have been accepted for publication to IEEE GreenCom 2015.

Chapter 4: Traffic-Agnostic Network Pruning for Extending Satellite Service Life

In this chapter, we propose a new traffic-agnostic metric for quantifying the quality of a frugal version of a network topology, the ADI. ADI is based on the concept of algebraic connectivity from spectral graph theory [31]. We formalize the problem of minimizing the power consumption of a network subject to a given ADI threshold and prove that the problem is NP-hard. Then, we propose a heuristic named - AvOId, which removes links that have low impact on network connectivity by keeping the ADI threshold above a given value. Results show that AvOId algorithm can increase the average satellite lifetime by 85%.

The results of this chapter have been accepted for publication to the Journal of Wireless Networks (WINET) [32].

Chapter 5: Extending the Network Pruning Techniques to Terrestrial Wired Networks

In this chapter, we extend the traffic-agnostic metric, ADI 4, to the terrestrial wired networks infrastructure. We show that the problem of finding the most frugal topology satisfying a specific ADI value is NP-hard. Then, we propose two polynomial time heuristics – ABStAIn and CuTBAck. We perform extensive simulations using topologies and traffic matrices from 3 real networks. Our results show that ABStAIn and CuTBAck are as effective as an exponential time traffic-aware solution at creating frugal topologies and outperform a state of the art polynomial time traffic based solution by about 80%. Furthermore, the median link utilization observed with ABStAIn and CuTBAck is similar to that with traffic based solutions, with the maximum link utilization never exceeding 80%.

The results of this chapter have been accepted for publication to IEEE LCN 2015 [33].

Chapter 6: Conclusions and Perspectives

Chapter 6 concludes this manuscript by summarizing our contributions and presenting future research directions.

Chapter 1

Networking with LEO Satellite and Energy E ciency

Contents

In this chapter, we present the state of the art related to this thesis. First, we discuss the importance of the satellite systems and why we believe they could be a fundamental part of the Internet infrastructure in the near future. Then, we describe in detail the LEO satellite constellation architecture and related protocols. We study the entry/exit positions and times through the earth shadow for LEO satellites. As there is no work on energy efficiency for LEO satellite constellations, we discuss techniques for reducing energy consumption in traditional terrestrial wireless and wired networks and their applicability to the LEO satellite context. We present a taxonomy of existing energy efficient techniques in wireless networks. and a review of energy efficient techniques for wired networks. Finally, techniques for reducing the energy consumption of a single satellite are discussed.

1 Importance of Satellite Communication Systems

Despite the recent advances in terrestrial communication technologies, the demand for Internet services is growing in terms of both the number of users and the services to be supported, which poses serious challenges to current terrestrial networks. To cope with this issue, network technicians and telecommunication operators have considered temporary solutions such as Digital Subscriber Line (DSL), Fiber Optic, or Broadband over Powerlines (BPL) technologies. However, as the demand for advanced multimedia services is growing to metropolitan areas with large number of users, applying such solutions to bridge the last mile between local service providers and end-user's/customer's premises will require extremely large investment in terms of time, infrastructure, and human resources. These developments demand rethink of network designs and architectures, to support ubiquitous broadband access to all kinds of heterogeneous and customized Internet based services and applications [34].

Satellite communication systems exhibit unique features and offer an array of advantages over traditional terrestrial networks. In addition to their inherent multicast capabilities and exible deployment features, they are able to provide coverage to extensive geographic areas and to interconnect among remote terrestrial networks. Coupled with the fact that more than half of the world lacks a terrestrial networks infrastructure, satellite communication systems are seen as an attractive solution to accommodate these high bit-rate services with different QoS requirements [35].

Satellites also prove attractive for the rapid deployment of telecommunication services between or with isolated communities. Hence several countries, where populated areas are separated by wide distances or difficult terrain or sea, use satellites on trunk routes. In such cases, satellites also provide a useful back-up for existing terrestrial services [36]. The satellite can act as a safety valve for terrestrial networks. Fiber failure or network congestion problems can be recovered easily by routing traffic through a satellite channel. Furthermore, given the recent advances and ongoing improvements in next generation of satellite technologies, broadband satellite based Internet services are likely to open a promising market for service providers in the near future [37].

2 LEO Satellite Network Architecture

Communications over satellites began successfully with the use of single satellite in the geostationary orbits. Inmarsat [38], a prime example of GEO satellite networks, provides satellite telecommunication services. Since 80's, GEO satellite networks have been commercially successful in providing different services, such as television broadcasting, weather forecasting and long distance communications. However, due to high propagation delay caused by the high altitude of GEO satellites, and to provide global communication with much lower latency, higher throughput and low terminal power requirements, focus has been directed towards LEO satellite communication systems [39].

In general, a LEO network consists of a number satellites organized as a constellation in orbits of 500 - 2000 km above the earth`s surface. Communication between any two points within the constellation coverage is possible via the LEO network at any time. There are two types of LEOs - little LEOs and Big LEOs, which are launched to support a wide range of communication services. Big LEOs are used for technology devices such as high-speed, high-bandwidth data communications, and video conferencing. Little LEOs are required to offer non-voice services for example vehicle tracking, environmental monitoring and two-way data communication [40]. The design and development of LEO satellite constellations have been thus the subject of extensive research in the recent literature (e.g. Skybridge [41], Iridium-NEXT [42]). Table 1.1 lists most of the proposed worldwide LEO satellite constellations and the distinguishing features of their orbits. [43] proposes in detail most of the LEO satellite constellations listed in the table. Motorola proposed Celestri constellation consist of 63 ka and V-band satellites at 1400 km altitude. The system delivers connectivity to its subscribers at high data rate access ranging between 64 kbps to 155 Mbps. Uplinks and downlinks use Demand-Assigned Frequency Division Multiplexing (DAFDM)/Time Division Multiple Access (TDMA)and the system provides transmission at rates 2.048, 51.84 and 155.52 Mbps for uplinks, and 16.384, 51.84, 155.52 Mbps for downlinks. The capacity for the satellites can reach 1.83 Gbps [43]. The Globalstar second-generation constellation consists of 32 LEO satellites. Each satellite consists of a communication system of both S and L-band antennas, a trapezoidal body, two solar arrays and each satellite operates at an altitude of 1,414km. The second-generation satellites are manufactured by Thales Alenia Space in France. On any given call, several satellites transmit a caller's signal via Code Division Multiple Access (CDMA) scheme to a satellite dish at the suitable gateway where the call is then routed locally through the terrestrial telecommunications system [44]. It is considered that the available or future LEO networks with ubiquitous coverage and generous bandwidth are particularly attractive for wide-band multimedia services.

System	Organization	No. of Satellites	Altitude (kms)	Min. Elvation Angle	Coverage (%)	ISLs
Iridium	Motorola	66	780	8.2°	100	Yes
Globalstar	Global Star Co.	48	1406	10°	83	Yes
Teledesic	Teledesic Co.	288	1375	40°	100	Yes
Skybridge	Alcatel	80	1469	10°	86	No
NeLS	Japan NiCT	120	1200	20°	79	Yes
Celestri	Motorola	63	1400	16°	73	Yes

Table 1.1: Main LEO satellite constellations

2.1 LEO Network Model

Consider a polar-orbiting LEO satellite constellation consisting of N evenly separated (angular separation of 180°/N) polar orbits (planes $p_1, p_2, \ldots, p_N$) which cross each other over the pole areas and each orbit has M evenly separated satellites (angular separation of 360°/M) [45]. In this thesis, we assume that each satellite, $s_{i\,j}$ (the j^{th} satellite on the i^{th} plane), in the constellation has Inter-Satellite Links (ISLs) with its four neighboring satellites: two intra-plane (L_a) ISLs connecting to vertically adjacent satellites in the same plane, $s_{i\,j\pm1}$, and two inter-plane (L_e) ISLs connecting to the closest neighboring satellites in the adjacent planes, $s_{i\pm1\,j}$. As shown in Fig. 1.1, these ISLs forms a mesh network with a seam between the first plane (p_1) and last plane (p_N), where satellites in planes along the seams rotate in opposite directions.

On the same plane, all satellites move in the same circular direction. The intra-plane ISLs are maintained at all times and their lengths are fixed and can be computed as noted in [46]:

$$L_a = \quad \overline{2}R\sqrt{1 \quad \cos(360^\circ\frac{1}{M})} \tag{1.1}$$

Between planes, the inter-plane ISLs are operated only outside the polar region and their lengths vary over time with the satellite movement [46]:

$$L_e = \quad \overline{2}R\sqrt{1 \quad \cos(360^\circ\frac{1}{2N})}\cos(lat) \tag{1.2}$$

Where R is the radius of the plane and lat stands for the latitude at which the interplane Inter-Satellite Link (ISL) resides.

Using Eq. 1.1 and 1.2, one can compute the propagation delay of a given path.

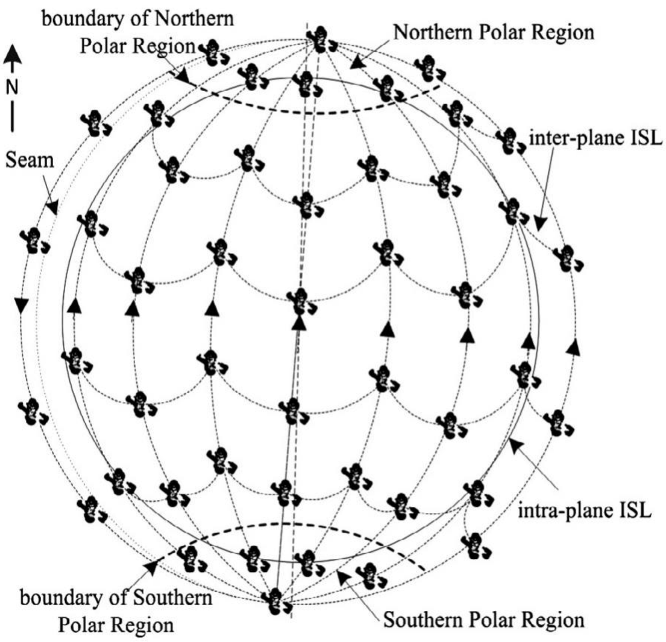


Figure 1.1: Iridium-like polar LEO constellation

Let $L\left(S_{is\,js}, S_{id\,jd}\right)$ be the length of ISL between satellite $S_{is\,js}$ and satellite $S_{id\,jd}$. The propagation delay of a multihop path can be computed as follows:

$$T_p = \frac{\sum_{j=1}^{h(p)} L\left(S_{is\,js}, S_{id\,jd}\right)}{V} \tag{1.3}$$

Where h(p) is the number of hops on a specific path and V the speed of light.

Compared with GEO systems, the LEO satellite constellation implies a significant smaller footprint per satellite which means more satellites are needed for global coverage. According to [47], the approximate number of satellites, $N.M$, to obtain continuous global coverage between any latitude X and the pole can be obtained by equation 1.4. The number of satellites needed as a function of orbital altitude h (600 km to 2000 km) is presented in table 1.2 (assuming $\quad = 10°$).

$$
\begin{aligned}
N.M &= \frac{4.\cos X}{1 \quad cos} \\
1.3.N < M.\cos X &< 2.2.N \\
&= \arccos\left(\frac{R}{R+h}.\cos \quad\right)
\end{aligned}
\tag{1.4}
$$

Where and are the Earth-centred half-cone-angle of coverage for each satellite and the minimum elevation angle, respectively.

h (km)	N	M_{orbit}	M_{total}
600	7	15	105
800	7	11	77
1000	6	10	60
1200	6	8	48
1400	5	8	40
1600	5	7	35
1800	4	8	32
2000	4	7	28

Table 1.2: The number of LEO satellite for global coverage

2.2 Powering LEO Satellites

Every satellite in space requires electrical power. Therefore, satellites are usually equipped with solar panels and rechargeable batteries as their energy source and storage. Both are completing to each other during two alternate periods [48]. First, when a satellite exposed to the sun, solar panels convert sunlight into electrical energy; the generated power is used to operate the satellite`s components, and then the remaining power is stored in the batteries. Second, during the eclipse time when satellites pass through a shadow region on the opposite side of the earth from the sun. A part from the occultation of the sun by the earth (see Fig.1.2) – time during which they need to be powered by batteries. The frequent charge/discharge cycles typical of earth observation satellites go to limit the batteries service life - and also the satellite`s. A GEO satellite experiences eclipses only during two near-equinox periods a year (March, September) and these eclipses last no more than 72 minutes a day, or 5% of the total orbit time. For LEO satellites, circling the Earth once every 100 minutes, satellites spend about 30% of their time in the earth`s umbra, which means the batteries are used much more frequently. Therefore, when a LEO satellite is eclipsed scientists and researchers become very keen in the time of shadow entrance and exit [9]. Such information is very benefical for various utilizations e.g. the sizing of the solar panel, thermal control requirements and satellite service life.

2.3 Computing the LEO Satellite Eclipse Time

We revisit quickly standard textbook material [49] that can be used to determine, at any given time, whether a particular satellite is under the earth's shadow, and if yes, for how long it has been there. We will use this information in designing routing metrics that will disfavor sending packets through satellites that have spent the most time in the earth's shadow.

The LEO satellite location can be computed using the satellite orbital parameters. According to the Kepler model for the circular orbit, we need three quantities to determine the shadow conditions of earth satellites: The orbital size, the orbit inclination i, and the right ascension of the ascending node (RAAN), denoted by . The orbit inclination is simply the angle between the orbit plane and the equatorial plane, while RAAN is the angle measured from the vernal equinox along the earth

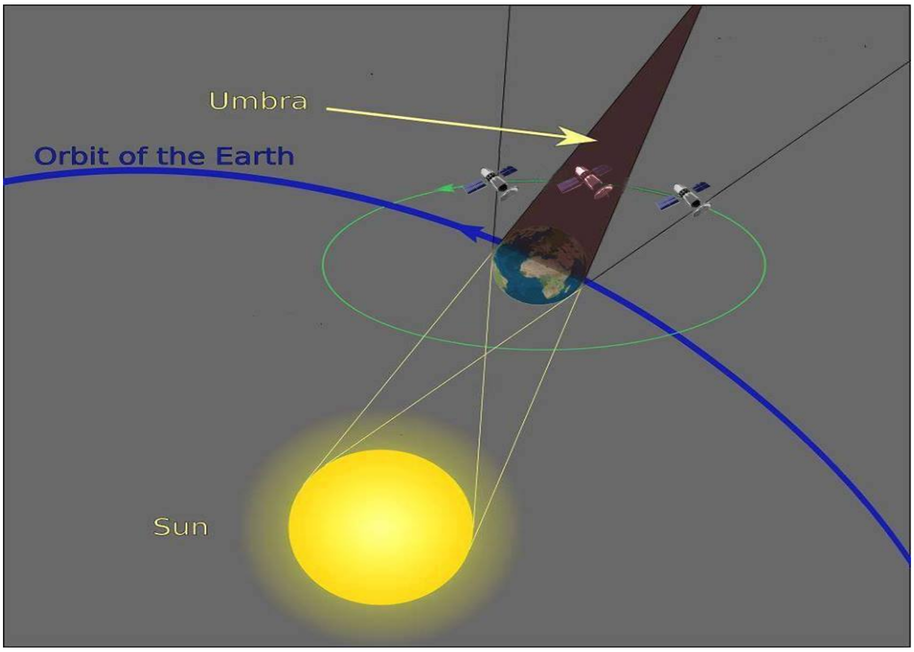


Figure 1.2: LEO satellite shadow

equator to the point at which the satellite ascends from south to north. With this information one can compute the time a particular satellite enters and exits the earth's umbra (shadow) [9, 50].

We have coded the algorithm in a Matlab script and in Fig. 1.3 we illustrate how the script works for a particular Iridium satellite. Based on data publicly available [8], we use the following parameters: altitude 780 kilometers, orbit inclination 86.4°, eccentricity zero, RAAN 235.47°, argument of perigee zero. The analysis begins on September 1, 2013 at 11:00:00 UTC and is carried out for a 24h period. For clarity, only a few hours are depicted in Fig. 1.3. We observed that an Iridium satellite performs a full circle around the earth in around 100 mins and spends about 36 minutes in the earth's umbra. Considering the significant portion of time the satellite is eclipsed, the battery operation and life are very important to the service life of the satellite itself.

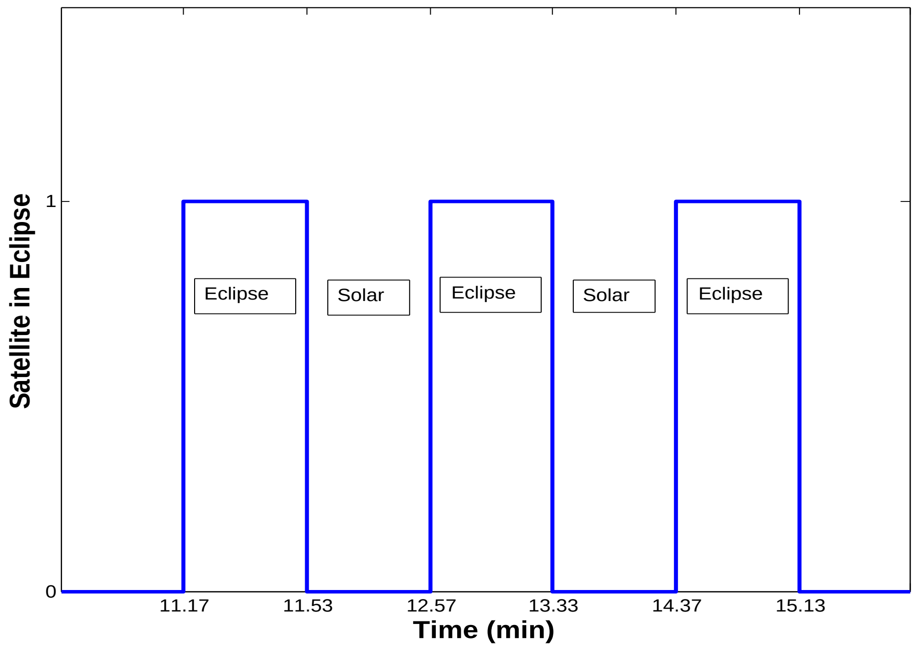


Figure 1.3: The analysis is for 24 hours but for clarity of presentation only a few hours are depicted. This satellite performs a full circle around the earth around 14 times over 24h, with average cycle duration of around 100 minutes. Out of the 100 minute cycle, around 36 minutes are spent in the earth's umbra.

3 MAC, Routing and Transport Protocols for LEO Constellations

In this section, we study the Multiple Access Control (MAC), routing and transport protocols for LEO satellite communications. In this thesis, we do not provide a new MAC or transport layer schemes. However, understanding these schemes is necessary to have a complete picture on networking over LEO satellite constellation.

3.1 Multiple Access Control

MAC protocols are designed to coordinate transmission of packets, retransmission of damaged packets, resolution of collisions during contention periods among stations. The long propagation delay of the earth-satellite link and the large number of users terminals scattered within the satellite footprint further impose severe demands and constraints on MAC protocols that can be employed in a satellite network. MAC protocols have been studied and classified into three categories. Fixed, random and demand assignments. In section 4.3 some MAC protocols will be presented in reducing the energy consumption of single satellite. [51] survey in detail most of the MAC protocols used in satellite networks.

In fixed assignment protocols, the allocation of the channel bandwidth to a station is a static assignment, and it is independent of stations activities. The fixed allocation systems consist of Frequency Division Multiple Access (FDMA), TDMA, and CDMA. In FDMA and TDMA systems, each user utilizes its own dedicated channel. They are contention-free, and can provide QoS services. However, they make inefficient utilization of satellite resources and are inappropriate in the case where numerous terminals are allocated. In a CDMA system, each user is given a unique code sequence to use for transmission the data. Thus, in a CDMA the whole bandwidth is used by all users, making it more exible to network expansion.

Random access (e.g. ALOHA), in ALOHA, each terminal in the surface sends its data at any time when the data is generated. ALOHA minimizes the transmission time and the processing complexity, however, in the case where a large number of terminals are deployed, the probability of data collisions increase drastically. It is common to ALOHA scheme to has data collisions especially with numerous number of terminals. Data collisions required the data to be retransmitted which reduce the system overall throughput and increase the average packet delay. A more effective use of the burst repetition is provided by contention resolution diversity slotted ALOHA (CRDSA) [52], whose basic idea is the adoption of interference cancellation (IC) to resolve collisions. An enhanced version of the CRDSA protocol named CRDSA++ has been presented in [53]. CRDSA++ provides two main enhancements compared to the original version of the protocol: a) increased (optimized) number of packet repetitions (2 in CRDSA 3-5 in CRDSA++); b) exploitation of the received packets power unbalance to further boost the random access performance.

Demand Assignment Multiple Access (DAMA) schemes have been widely used in satellite systems. The random access may better accommodate a large number of terminals with bursty traffic, it provides no guarantee in QoS services. DAMA schemes attempt to solve this problem by allocating dynamically the system bandwidth to user requests [54]. A resource request must be granted before actual data transmission. Which are handled according to a random access technique. After a successful reservation, actual data transmission starts for the entire connection time. Bandwidth is allocated using FDMA or TDMA for actual data transmission. Resource reservation can be made either explicitly or implicitly. Explicit reservation: a terminal send a request to occupy certain time slots. It is on per-transmission basis and usually a dedicated reservation channel is shared among all terminals. The drawbacks of this method is the extra time required for explicit reservation. In implicit reservation, there is no explicit reservation message, in this method reservation is made by occupation; an occupied slot by the packet from a given terminal remains assigned to the terminal for the consecutive frames. The absence of extra time needed for explicit reservation is an advantage in implicit reservation. However, the disadvantage of this method is that a terminal is in a position to capture all the time slots for itself. Several DAMA resource reservation techniques have been proposed in literature. Combined Free/Demand Allocation Multiple Access (CFDAMA) is a famous example [55]. The main idea behind the CFDAMA freely assigns remaining channel to the users without reservation requests, simlarly to random access without throughput reduction caused by collisions.

3.2 Routing

Current terrestrial internet routing protocols, such as Routing Information Protocol (RIP) and Open Shortest Path First (OSPF), rely on exchanging topology information when network connections are established or changed. Applying such schemes to the rapidly and regularly changing LEO satellite network topologies, if not done properly, can induce substantial overhead. One thing to be taken into account is that, although the topology of LEO satellite network rapidly changes, these changes are periodic and predictable due to the deterministic motion of LEO satellites. Therefore, several routing schemes have been proposed for utilizing this inherent attribute.

The Virtual Topology (VT) mechanism and the Virtual Node (VN) mechanism are the best known concepts [20]. With VT, based on to the periodicity of the LEO satellite network, the system period, T, is divided into n time intervals during each interval the network remains unchanged. The advantage of this mechanism is that, in each time interval, every satellite knows about the link state of the whole constellation. One of the main drawbacks of this mechanism is that ISLs are not always active but inactive when satellites are located in the polar areas due to adverse pointing and tracking conditions. Thus, the path might be disconnected if one of its ISLs is inactive while the connection is still live. In [56], a LEO satellite network is represented as a Finite-state Automaton (FSA), where the system period, T, is divided into states. These states are derived from the ISLs connectivity data so that the LEO network has a fixed topology in each state. Due to the periodicity of the LEO constellation topology a finite number of states can be found. Then, it is proposed to execute an optimal routing strategy on each of these fixed topologies for the best use of ISLs in the system. A number of routing tables are stored on-board and retrieved when topology changes. Although the messaging overhead and computational complexity is reduced, large storage capacity is required on the satellites.

Another concept worth explaining that is tailored to dynamic LEO satellite constellations is the VN[57]. In this routing mechanism the whole earth area is split into different regions and each region is given a single fixed logical address. At each fixed time point, the satellite that is closest to the center of the region is given the logical address of this region. The data packets are routed simply by including the logical address in their headers. So with the VN mechanism, a fixed virtual topology is superimposed over the physical topology to hide the mobility of the satellites from the routing protocols. Even as satellites are moving across the sky, the virtual topology remains unchanged. Each VN keeps state information, such as routing tables and information of users within the VN's coverage area. As this satellite handoff, the state information is transferred from the first satellite to the second satellite. A routing decision is performed on the virtual topology, and the routing protocols are hidden of the dynamic satellite constellation in state transfers.

Based on the two concepts presented so far, several onboard routing strategies have been proposed in literature. In [15], a centralized routing scheme that relies on the Dijkstra's shortest path algorithm to compute the optimal path for any pair of satellites is proposed and evaluated. A centralized scheme can be simple to be deployed and implemented, be that at the ground station or the ingress satellite. However, as with any centralized scheme, it offers low fault-tolerance, and it can impose additional overhead, in the form of larger headers in source routing for example, to deliver the routing information from the centralized node to all satellites.

On the other hand, in distributed schemes, routes can be calculated onboard every satellite, based on almost real-time network state information, including link states, ISLs bandwidth, queue state, traffic distribution etc. Henderson et al [16] proposed a distributed routing algorithm which selects the next hop based on the remaining distance to the destination. Numerical results showed that their solution offered yields good routes , with an average latency degradation of less than 10 msec when compared with the optimal routes. However, in certain cases, such as around the seams and the polar regions the scheme was shown to perform poorly. Also, Ekici et. al. developed onboard distributed routing algorithms for minimizing the propagation delay [46].

The schemes described above use the propagation delay as the main metric. This is to be expected considering the large link lengths in satellite constellations. However, focusing on propagation delay alone can lead to over-utilization of and congestion on certain links while leaving other links under-utilized. LAOR, the location assisted on-demand routing protocol for LEO satellite networks [17] tries to remedy this by adapting the AODV [58] protocol to take into account the queueing delay in addition to the propagation delay. However, in an effort to limit the signaling overhead, LOAR limits the scope of RREQs to a specific area between the source and destination. This leads to higher congestion in this particular area resulting in a drop in performance under high loads. In [59], the authors propose an onboard Compact Explicit Multi-path Routing (CEMR) algorithm based on a cost metric that includes both propagation and queuing delay. The propagation delay is deterministic and can be computed in advanced, while, the queuing delay is predicted by monitoring the number of packets in the outgoing queue of the satellite over a time interval. It is assumed that the network state over each time interval is updated before routing calculation is carried out. T.Taleb. et al [18] claim that a better load balancing algorithm can be achieved by having satellites explicitly notify their neighbors when congestion takes place. Neighboring satellites will respond by decreasing their sending rates and searching for alternative paths. This algorithm is shown to reduce the packet dropping probability, however, it is not protected from signaling congestion due to frequent feedback packets. Although congestion-signaling packets are sent only when necessary, they could indeed exacerbate congestion in high load scenarios.

In [60], Rao *et al.* propose an Agent-based Multi-Service Routing (AMSR) algorithm based on a cost metric that involves unfair traffic distribution, link utilization level, constellation geometry characteristics, call duration and periodic changes in the network topology. The authors used all the factors to implement QoS routing. Three separate FIFO queues are implemented for each outgoing link, one for each traffic class. With a queue scheduling policy, different priorities are allocated to the three traffic classes: delay-sensitive, bandwidth sensitive and best effort. Another policy [61] is based on the Markov process theory to develop a blocking probability analysis model. To avoid the congestion, the authors used the available bandwidth and the blocking probability as link cost metric for throughput sensitive traffic. While, the routing cost metric is decided by the propagation and queuing delay for delay sensitive traffic. Best effort traffic is forwarded randomly using k-shortest paths. In [62], is a three layered satellite architecture. Traffic is usually differentiated based on the distance between the source and the destination satellite. For routing purposes, LEO satellites covered by a MEO satellite belong to the same domain. For the intra-domain communication, packets are transferred only through the links between LEO satellites. For the inter-domain communication, packets are transferred via the MEO layer. In the proposed routing algorithm, short distance dependent traffic is transmitted through lower layer satellites while long distance dependent traffic is transmitted through inter-orbital links (IOL) up to the MEO layer to minimize the average number of satellite hops and resource consumption.

What all the routing protocols described above have in common is their quest for performance. The general understanding has been that, with LEO satellites being powered by solar energy and batteries – rechargeable by solar energy when under the earth's eclipse – the communication protocols need not be concerned with energy consumption. However, satellites in LEO constellations like Iridium can be under the earth's eclipse around 30% of the time, making batteries essential to their operation. While the batteries are recharged by solar energy, their lifetime is highly affected by the depth of discharge [12, 13]. A routing protocol that, in addition to the performance, is sensitive to the energy consumption of eclipsed nodes, can reduce the depth of discharge and, thus, significantly increase the lifetime of the batteries onboard the satellites.

In chapter 2, we propose two novel routing metrics aiming to strike a balance between performance and battery DoD in LEO satellite constellations.

3.3 Transport

Transmission Control Protocol (TCP)/IP and User Datagram Protocol (UDP)/IP are the protocols suite on which the Internet depends. Therefore, the Internet over LEO satellite networks is expected to continue to serve applications based on TCP and UDP. However, both protocols performance over satellite networks is impaired by the characteristics of the satellite radio link, specifically by link asymmetry and higher propagation delay and bit error rate due to physical channel errors. The impact on TCP will be much greater, and heated debates have been spawned concerning the feasibility of TCP in satellite context [63]. Moreover, TCP controls about 95% of the bytes and 90% of the packets sent over the Internet, according to different studies [64]. We refer the reader to section 4.3 for more related works on energy efficient transport protocols of single satellite.

TCP uses the concept of the acknowledgement of the received data to achieve reliable delivery. When the end-to-end delay is very high, as when a satellite link is part of the path, the performance of TCP is quickly decreases since the congestion window (cwnd) takes a long time to increase as well as the pipe to be filled. A number of possible solutions have been presented in the literature, ranging from limited modifications of TCP to completely alternative protocol and network architectures [65]. In this context, [66] proposes modification to current TCP, the congestion window is intially set to value larger than one packet and smaller than four packets in size, to decrease the negative impact of the TCP performance. Although the advantages of this modification in improving TCP performance, there are many problems. An increased value of the initial window would increase the burstiness of the sender and could increase the existing congestion in the network. Initial Spreading [67, 68] is a fast start-up TCP mechanism designed to reduce the round-trip time (RTT) dependency in the beginning of a connection. Added to regular TCPs, it significantly speeds up short-lived connections while not damaging other kind of connections. Originally designed to answer satellite problems.

In [69], Taleb et al. introduces Recursive, Explicit, and Fair Window Adjustment (REFWA) method to improve the TCP efficiency over multihops space networks. The key concept of the REFWA scheme is to match the aggregate window size of all active TCP flows to the effective network bandwidth-delay product. REFWA scheme improves the system fairness, reduces the number of packet drops, and makes better utilization of the bottleneck link.

4 Green Networking Strategies

To the best of our knowledge, no satellite-specific approach has been proposed yet in the literature for reducing energy consumption in LEO satellite networks. We therefore review the techniques developed so far for terrestrial networks and GEO satellites and discuss their applicability to the LEO satellite context.

4.1 Terrestrial Wireless

The energy efficient network techniques can be classified into five classes in wireless environment, namely, data reduction, protocol overhead reduction, energy efficient routing, duty cycling and topology control. Taxonomy of energy efficient techniques in terrestrial wireless is illustrated in Figure 1.4 [70].

1. Data reduction: focuses on reducing the amount of data produced, processed and transmitted and, thereby, reducing the required power consumption at the mobile node. Several techniques are used for data reduction in wireless environment, ranging from data compression [71], to data aggregation techniques [72].

2. Protocol overhead reduction: most protocols require control packets to be exchanged. Since these packets contain no application data, we consider their transmission and reception as overhead. Several techniques are proposed in the literature to reduce protocol overhead. The proposed algorithms range from the optimized flooding to avoid unnecessary retransmissions, as in [73], to cross-layer with the lower and upper layers to optimize network resources while meeting the requirements of the application [74].

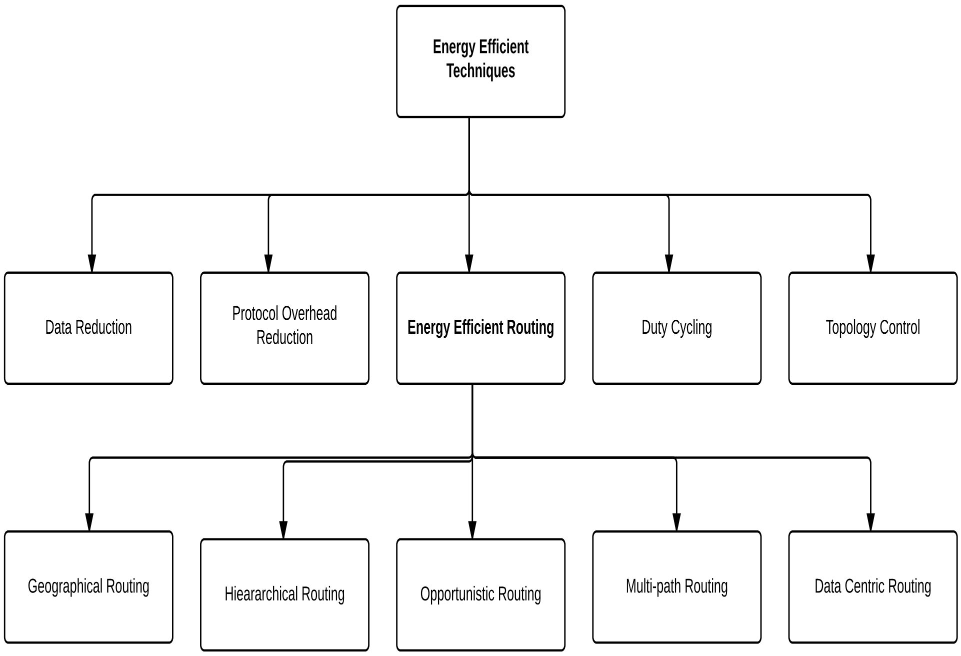


Figure 1.4: Taxonomy of energy efficient techniques in terrestrial wireless.

3. Energy efficient routing: the main purpose of energy efficient algorithm is to maximize the network lifetime. These algorithms are not just related to minimize the total energy consumption of the route but also to maximize the lifetime of each node in the network to increase the network lifetime. Some protocols use geographical coordinates of nodes to build an efficient route toward the destination [75]. Others are opportunistic, it benefits from the node mobility and the broadcast characteristic of wireless mediums to improve energy efficiency by a transmission to the sink [76]. Others build a hierarchy of nodes to reduce the routing algorithm overhead and, thereby, maximize the network lifetime [77]. Multi-path routing algorithms use multiple paths to achieve load balancing and more robustness against routes failures [78]. Finally, data centric routing protocols send the data only to interested number of nodes for reserving useless transmissions [79].

4. Duty cycling: duty cycling is the proportion of time during which a node is operated i.e., each wireless node alternates between active and sleep states to conserve energy with an average

sleep period (much) longer than the active period. This approach can be divided into two techniques. High duty cycling focuses on switching off redundant nodes to achieve a high level of energy saving while a frugal set are kept in power on mode to meet application requirements [80]. A low duty cycling deals with scheduling activity of nodes which have been selected as active mode to guarantee network functionality i.e., switching off the radio of the active nodes when no communication is required [81].

5. Topology control: topology control aims at tuning the topology of highly dynamic networks to provide better control over network resources and to increase the efficiency of communication. It increases the energy efficiency by adjusting transmission power while maintaining network connectivity [82].

We now focus on energy efficient routing that is closer to our work in chapter 2.

4.1.1 Energy Efficient Routing Protocols

Routing protocols in wireless nodes have a common objective of efficiently utilizing the limited resources of nodes in order to extend the lifetime of the network. Different routing techniques can be adopted for different applications based on their requirements. We present a few representative works in energy efficient routing in Wireless Sensor Networks (WSNs) to demonstrate the progress in the field, while highlighting the need for an energy aware routing in LEO satellite constellations.

Reliable Energy Aware Routing (REAR) [83] by Hassanein and Luo is an on-demand routing protocol that ensures that each ow has enough energy on the selected path: the nodes with low residual energy are avoided. However, the path selected does not minimize the energy needed to transmit a ow packet from its source to its destination. Therefore, the network lifetime may not be maximized. In [84] K.Akkaya et al. proposed an energy-aware QoS routing protocol for WSNs. It finds a least cost, delay-constrained path for real-time data. The link cost used is a function that captures the nodes' energy reserve, transmission energy, error rate and other communication parameters. Extension the battery lifetime in WSNs is addressed in [85]. The key idea is that wireless nodes equipped with renewable energy sources handle much more data than wireless nodes with batteries. A hierarchical network architecture is designed, where nodes with renewable energy sources (denoted as primary nodes) carry out most message delivery tasks, and nodes equipped with batteries (denoted as secondary nodes) are those with less communication demands. The Maximum Residual Packet Capacity (MRPC) protocol is proposed in [86], which considers battery charge as well as link reliability during route selection. MRPC depends on the fact that, selecting the path with the least transmission energy for reliable communication may not always maximize the lifetime of the ad hoc network. On the other hand, MRPC identifies the capacity of a node not just by the residual battery capacity, but also by expected energy spent in reliable forwarding a packet over a specific link. Eu et al. [87] studied optimal routing in an energy-harvesting WSNs with optimal relay node placement and investigated the impact of routing and node placement on the network activities. In [88], the multipath routing is formulated as a linear programming problem with an objective to maximize the time until the first sensor node runs out of energy. The sources are assumed to be transmitting data packets at a constant rate. Directed Diffusion (DD) [89] in which sinks broadcast an interest message to sensors, only interested nodes reply with a gradient message. Hence, both interest and gradients establish paths between sink and interested sensors.

The routing algorithms presented so far have well addressed the problem of reducing the energy consumption in WSNs. Unfortunately, these approaches can not be straightforwardly applicable to the satellite context as they ignore the specifics of LEO satellite constellations specifically the fact that, batteries are recharged periodically. In chapter 2, we propose two new routing metrics that try to strike a balance between performance and battery Depth of Discharge (DoD) in LEO satellite constellations. The two routing metrics take into their account the specificities of LEO satellite constellations.

4.2 Terrestrial Wired

The energy efficient network techniques can be classified into two classes in wired environment, namely, rate-adaptation and sleeping. These techniques are already popular in other fields, in particular data centers and mobile networks. Table 1.3 summarizes the related works on energy efficient techniques in terrestrial wired networks.

Reference	Implementation Type	Branch	Online/O ine Computation	Approach	Network Layer	Performance Constraint
[28] Chiaraviglio et al.	Centralized	Sleeping	O ine	Traffic-aware	Network	MLU
[90] Zhang et al.	Centralized	Sleeping	O ine	Traffic-aware	Network	MLU and Path length
[91] Fisher et al.	Centralized	Sleeping	O ine	Traffic-aware	Network	–
[92] Lin et al.	Centralized	Sleeping	O ine	Traffic-aware	Network	MLU and Path length
*[93] Gupta et al.	Centralized	Sleeping	O ine	Traffic-aware	Network	–
*[93] Gupta et al.	Distributed	Rate Adaptation	Online	–	Data Link	–
*[94] Nedevschi et al.	Distributed	Sleeping	Online	Traffic-agnostic	Data link	–
*[94] Nedevschi et al.	Distributed	Rate Adaptation	Online	–	Data link	–
[95] Bianzino et al.	Distributed	Sleeping	Online	Traffic-agnostic	Network	–
[96] Cuomo et al.	Centralized	Sleeping	O ine	Traffic-agnostic	Network	–
[97] Cianfrani et al.	Distributed	Sleeping	Online	Traffic-agnostic	Network	–

Table 1.3: Taxonomy of green networking research. Item with * appear in multiple branches

1. Rate-Adaptation in Networks: in general, operating a device at a lower frequency can reduce the energy consumption for two reasons. First, clearly operating more slowly offers some fairly important savings. For instance, Ethernet links consume between 2 - 4 W when operating between 100 Mbps - 1 Gbps compared to 10 - 20 W between 10 Gbps [98]. Second, operating at lower frequency allows the use of Dynamic Voltage Scaling (DVS) that allow a corresponding reduction in the supply voltage. This allows power scale cubically, therefore, energy consumption quadratically, with operating frequency [99]. Dynamic rate adaptation of the transmission link speed has been proposed in [94] and [100]. In [94], adapts the transmission rate to arbitrary values between the typical 10/100/1000 Mbps modes of Ethernet. The work in [100] uses a queue to determine transmission rates for each interface.

2. Putting Network Elements to Sleep: this approach is based on an efficient deployment of routers over a set of Point of Presences (PoPs) such that the aggregate power demand is minimized while

QoS requirements are satisfied. In [101] Chabarek et al. have showed that being aware of power consumption when designing network topologies can result in significant power reductions. For example, with a given set of demands and link capacities, there are likely to be many router-level network topologies that can satisfy a level of QoS. The capacity of backbone networks is overprovisioned in order to accommodate traffic shifts, and over-redundant to deal with link and node failures [91]. As a result, many links are underutilized, especially during off-peak hours when traffic is low, which provides opportunities for energy reduction. This can be accomplished by distributing the traffic in a way that minimizes the overall network's energy consumption by putting specific nodes and links to sleep mode.

We now focus on sleeping strategy that is closer to our work in chapters 3, 4, 5.

4.2.1 Putting Network Elements to Sleep

In the literature, there are two approaches that have been proposed to put network elements into sleep mode [102]: the traffic-aware approach that rely on the joint control of network topology and instantaneous and global knowledge of the traffic matrix and network congestion levels, and traffic-agnostic approach, that based on knowledge of the network topology, without traffic awareness.

1. Traffic-aware solutions, which are the most common, are based on the joint control of network topology and traffic matrix. The general method for addressing this problem has been to adopt the Capacitated Multi-commodity minimum Cost Flow (CMCF) problem formulation so that the objective function depends on the power consumption [28, 90–92, 103–107]. With the problem being NP-complete, various heuristics have been proposed for creating frugal topologies by switching off the maximum number of links[1] possible subject to the maximum link utilization – the main quality metric used – being below a threshold. The implementation for most of the traffic-aware solutions in the literature is centralized, supposing the presence of a central unit with a network global view. However, as with any centralized solution, it offers low fault-tolerance, and it can impose additional overhead, in the form of larger headers in

[1] Line cards represent a majority of the routers energy consumption [108].

source routing for example, to deliver the routing information from the centralized unit to all nodes in the network. In [28], the authors considered different approaches for switching off a specific number of network elements (nodes and links) while still ensuring full connectivity and QoS constraint for backbone networks. Cianfrani et al. propose an OSPF-compliant approach called ESIR [109] (Energy Saving IP Routing) where the main goal is to share the Shortest Path Trees (SPTs) between neighbor routers so that the overall set of active network links is minimized. ESIR uses heuristic algorithms to solve the NP-complete problem of sharing SPTs and reduces the number of active links in a percentage of 40%. In [90] the authors define the problem of maximizing the number of links in the network that can be switched off subject to fulfilling specific link utilization and packet delay constraints. The problem is modeled as a mixed integer program and several heuristics capable of reducing the reducing power consumption by 27% to 42% are proposed. In [101] a hybrid routing/network design scheme is proposed. However, it depends on solving a mixed integer program and thus is applicable only to very small topologies. A heuristic for switching off links is introduced in [91].

While the works presented so far are shown to handle well the problem of traffic-aware pruning in wired terrestrial, non of them can be straightforwardly applicable to the satellite context as they ignore the specifics of LEO satellite constellations. In chapter 3, we highlight the need of traffic-aware pruning scheme that, in addition to the performance, is sensitive to the energy consumption of eclipsed nodes. Therefore we present the design and evaluation of traffic-aware pruning that takes into account the specificities of LEO satellite constellations.

2. The traffic-agnostic solutions are based on knowledge of the network topology, without traffic awareness. These solutions do not consider knowledge of the actual and past/future traffic matrices, being able to run in real-time and distributed manner, where this information would not be available. The first topology oriented solution was proposed in [110] and extended in [97], where the authors propose an OSPF compliant energy saving algorithm based on a modified version of Dijkstra's algorithm. The authors in [96] propose Energy Saving in the Internet

based on Occurrence of Links (ESOL). This technique represents green approaches that only place links to sleep without modifying link weights. ESOL runs on top of OSPF and uses LSAs to determine the occurrence of nodes and links in all calculated shortest paths. Network links with low frequency are placed into sleep mode. Bianzino et al. propose the GReen Distributed Algorithm (GRiDA) [95], a distributed approach to energy-aware problem. It has been designed to automatically adapt the energy consumption of IP based networks to their current load, by switching off/on links in a distributed fashion. The nodes take an independent decisions on the off/on state of incidents links. In particular, GRiDA is run at random intervals (typically in the order of minutes).

While, the works presented so far are shown to reduce the energy consumption in wired networks, none of them guarantee a certain level of resilience and/or robustness of the network. Further, these solutions need to modify the protocols at the heart of IP networks so as to reduce their energy footprints. In chapter 4 we propose a new lightweight traffic-agnostic metric for quantifying the quality of a frugal topology relative to the full-on network. This metric takes into its consideration the specificities of LEO satellite constellations. In chapter 5, we extend the traffic-agnostic approach presented in chapter 4 to reduce energy consumption in wired IP networks.

4.3 GEO Satellites

The problem of energy consumption of a single satellite has been studied in the literature. In [111], the authors address the issue of energy allocation and admission control problem of a single satellite in its orbit. The objective is to choose which transmission requests to serve so that the expected total rewards is maximized for the system. It uses a dynamic programming approach to minimize a cost related to energy, subject to various delay constraints, such as a deadline by which all packets must be sent. Satellite NDMA (S-NDMA) [112] assumes a DAMA MAC protocol, and uses the channel statistical information to define the number of packets transmissions separated by a round trip times (RTTs), such that the energy consumption is minimized and a set of QoS requirements is met. However, these schemes discuss the energy allocation of the single satellite, not the whole satellite constellation. In [113], a cross layer design is proposed for the packet scheduling on a forward link that implements adaptive coding and modulation (ACM). A cross layer approach is considered where the physical and MAC layers share some knowledge of the channel dynamics in presence of ACM. These capabilities increase the probability of successful wireless transmissions and decrease the unnecessary retransmissions and thus improve energy efficiency. An energy-efficient of TCP packet transmission over satellite channels is presented in [114, 115]. We refer the interested reader to [116] for more details on energy savings of a single satellite.

The schemes presented so far discuss the energy allocation of the single satellite, not the whole satellite constellation. To the best of our knowledge, this the first work that considers the problem of energy efficiency on satellite constellations.

5 Summary

In this chapter, we addressed the importance of LEO satellite systems in providing ubiquitous Internet access and showed that they would be an integral part of infrastructure during the current millennium. We provided also a brief overview on the general LEO satellite design and architecture. Also, we studied the entry/exit location and times through the earth shadow for LEO satellites. In this context, issues related to MAC mechamisms, routing strategies, and transport protocols in LEO constellations are presented. Finally, techniques for reducing energy consumption are portrayed in detail.

Chapter 2

On Routing for Extending Satellite Service Life

Contents

In the previous chapter we have presented the context of this work and reviewed the state of the art on the design and implementation of routing algorithms in LEO satellite constellations. Our analysis has shown that existing routing algorithms do not take into account the energy consumption of the eclipsed satellites. To address this limitation, we design, implement, and evaluate a novel routing algorithm which improves the lifetime of LEO satellite constellations.

This chapter proposes **L**oc**A**tion and loAd **SE**nsitive **R**outing (LASER) and **S**igna**L**-free rout**I**ng for **M**aximizing satellite service life (SLIM) – two new routing metrics aiming to strike a balance between extending the LEO satellites service life and performance. The key intuition underlying LASER and SLIM is that eclipsed satellites should be less favored for routing data traffic when compared to satellites exposed to the sun.

The results of this chapter have been accepted for publication to IEEE GLOBECOM 2014 [30].

1 Introduction

Reliable operation of LEO satellite constellations with guaranteed QoS for real-time broadband multimedia traffic mostly depends upon its power subsystem. Integral part of the power subsystem is its rechargeable batteries. During the eclipse period the stored energy in the batteries is used to operate the satellite components also augments the solar panels during the solar period, when there is not enough solar power to operate the satellite components. The LEO satellite is subjected to varying communication traffic for its on-board processing and routing act as a varying load on the rechargeable batteries which is subjected to many thermal and power cycles during its operation in the orbit. The charging and discharging regime is affected by the traffic patterns and the amount of traffic determines the Depth of Discharge level of the battery. Therefore, in LEO satellite constellations the efficient traffic path finding is essential for a longer lifetime for the batteries.

However, building and maintaining high performing LEO satellite networks is a daunting challenge– mainly because of two aspects. First, the very environment in which LEO networks operate greatly restricts the processing power and storage capacity of the LEO satellite equipments – and it is difficult to upgrade and replace hardware once the satellites are launched. Secondly, the high speed movement of LEO satellites results in a highly dynamic, multi-hop topology [117, 118]. As a result, a lot of effort has been put into designing routing protocols for LEO satellite constellations [15–18].

The emphasis so far has been on traditional performance metrics, such as delay and throughput. However, satellite batteries do not last forever and their lifetime is highly affected by the DoD [12, 13]. A routing protocol that, in addition to the performance, is sensitive to the energy consumption of eclipsed nodes, can reduce the DoD and, thus, significantly increase the lifetime of the batteries onboard the satellites.

In this chapter, we propose two novel routing metrics to reduce the DoD in the eclipsed satellites– thus, extending constellation lifetime. In summary, we make the following contributions:

- We present LASER routing metric that combine the propagation delay with the satellite battery level–acquired via signaling–into a single link metric.

- We present SLIM routing metric which drops all requirements for signaling, and instead combines the propagation delay and the time spent in the shadow–both of which can be computed–into a single routing metric.

- Using publicly available data about the Iridium constellation, we show that LASER and SLIM can increase the battery lifetime by as much as 75% and 100%, respectively.

2 Routing for Extending Satellite Service Life

We present LASER and SLIM, two new routing metrics aiming to strike a balance between performance and battery lifetime in LEO satellite constellations.

As mentioned previously, the DoD can have a significant impact on the lifetime of batteries deployed onboard satellites. Therefore, our basic approach is to favor routing traffic over satellites exposed to the sun as opposed to the eclipsed satellites functioning on battery energy alone, thereby decreasing the battery DoD - all without taking a high penalty in performance.

The two proposed metrics present different tradeoffs in terms of signaling overhead and DoD gains. LASER uses signaling for acquiring the level of battery discharge at every satellite and include that information in the routing metric. SLIM, on the other hand, requires zero signaling and relies solely on the approach described in Section 2.3 for predicting if a given satellite is in eclipse and for how long.

2.1 LASER: Location and loAd SEnsitive Routing

LASER combines the battery's level of discharge and the propagation delay in creating a new link metric for routing in LEO satellite constellations. Since the motion of satellites is deterministic, the propagation delay can be computed in advance, according to the parameters of selected constellation. The only non-deterministic parameter - the battery level of discharge - will have to be distributed through the network via a ooding mechanism. Once that information is collected, every LEO satellite can compute the LASER value on every link (normalized by the differences of optimal function values [119]) as follows:

$$laser_{i\,j}(t) = w_1 \frac{T_{i\,j}(t) \quad T^{min}}{T^{max} \quad T^{min}} + w_2 \frac{D_{i\,j}(t) \quad D^{min}}{D^{max} \quad D^{min}} \tag{2.1}$$

Where $T_{i\,j}(t)$ is the propagation delay between two satellites, i,j, at given time t, and w_1 and w_2 represent weighting factors that one can tune depending on the application needs[1]. For example, setting $w_2 = 0$ will reduce LASER to a propagation-delay metric. Finally, $D_{i\,j}(t)$ is a quantity that depends on the battery levels of the satellites i and j at time t and is computed as follows:

$$D_{i\,j}(t) = \frac{e_i}{B_i(t)} + \frac{e_j}{B_j(t)} \tag{2.2}$$

In which

- $e = \begin{cases} 1 & \text{if Satellite is eclipsed by the earth.} \\ 0 & \text{if Satellite is exposed to the sun.} \end{cases}$
- B is the residual battery capacity for a given satellite.

As we can see from Eq. 2.2, the $D_{i\,j}$ part of LASER is designed to capture the cost of routing data over satellites whose batteries have higher levels of discharge. Since the goal of LASER is to increase the constellation's service life, it tries to minimize the maximum DoD in the network. To accomplish this, it assigns a higher cost ($D_{i\,j}$) to batteries with higher levels of discharge while obviously assigning zero cost if the solar panels recharging the batteries are exposed to the sun.

Note that, for a given path, its LASER cost is simply the summation of the LASER costs of the links constituting the path.

2.2 SLIM : SignaL-free routIng for Maximizing satellite service life

LASER is a first effort at designing a routing metric for minimizing the depth of discharge. However, just like the terrestrial metrics from which it was inspired [86], it requires up-to-date knowledge

[1] In our simulations we got promising results by setting $w_1 = w_2 = 0\ 5$.

of battery levels of all satellites – something that can only be possible with periodic network-wide signaling. This is costly for the eclipsed satellites.

To address this shortcoming of LASER , we introduce SLIM, a metric for SignaL-free routIng for Maximizing satellite lifetime. The key insight behind the SLIM metric is that, unlike many terrestrial networks, the movements of the satellites is deterministic. Thus, at any given time, one can compute for every satellite if it is in eclipse, and if yes, for how long. SLIM uses this information to make less attractive links over satellites that have been in the shadow the most and whose batteries – on average – must have the highest level of discharge:

$$slim_{i\,j}(t) = w_1 \frac{T_{i\,j}(t) \quad T^{min}}{T^{max} \quad T^{min}} + w_2 \frac{S_{i\,j}(t) \quad S^{min}}{S^{max} \quad S^{min}} \tag{2.3}$$

Where $S(t)$ is the time that a particular satellite has spent in shadow and can be calculated as shown in Section 2.3. As with LASER, the SLIM cost of a path is imply the summation of the SLIM costs of the links constituting the path.

LASER vs. SLIM : The energy consumption of an eclipsed satellite does not depend only on how long it has been eclipsed but also the amount of data traffic it has transmitted and received during this period. LASER, who uses the actual battery levels, is more accurate than SLIM. However, LASER requires signaling for acquiring this information, making it heavier than SLIM.

2.3 Routing with SLIM and LASER

There is a rich literature in routing protocols for mesh-like topologies in general and LEO constellations in particular. Our goal in this work is not to propose a new routing protocol but rather to propose two routing metrics that can be utilized by current and future routing protocols. Both metrics are additive and thus can be utilized by any routing protocol that uses a minimum-weight algorithm for computing paths. Computing LASER minimum paths requires the battery level of all satellites, which can be acquired by including this information in link state updates, for a link state protocol, or the routing discovery packets (RREQ/RREP), for an on-demand protocol like LAOR [17]. For computing SLIM minimum paths no periodic information is necessary, except for the initial information to bootstrap the shadow-time computations for every satellite. The periodicity at which SLIM or LASER minimum paths are computed and updated will depend on the particular routing protocol.

3 Experimental and Evaluation Results

We use the network simulator (ns2.34) [120] as simulation platform and evaluate the performance of LASER and SLIM in terms of battery level of discharge, average end-to-end delay, packet delivery ratio and load distribution.

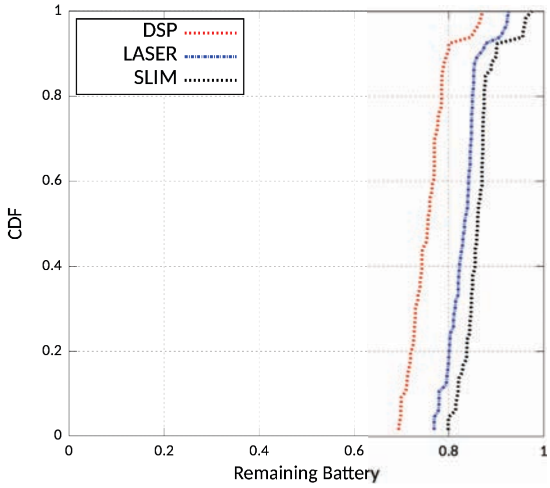
3.1 Experimental Setup

LEO constellation parameters: Our performance analysis is based on the Iridium constellation [8]. There are 6 orbital planes with 11 satellites each and inter-plane separation of 31.6°; each satellite is assumed to have four ISLs with two intra-orbits ISLs and two inter-orbits ISLs. The bandwidth of Uplink-Downlink (UDL) and ISL links are 1.5 Mbps and 10 Mbps, respectively. We do not consider the seams where two ISLs are switched off due to the motion in opposite direction. Satellite orbits are 780 km in altitude with an orbit inclination angle of 86.4° and the minimum elevation angle of ground stations is 8.2°. Mission started September 1, 2013 at 11:00:00 UTC.

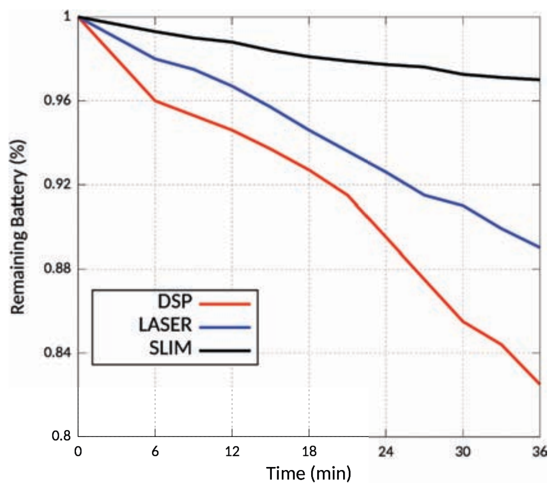
Battery parameters: To make the simulations as realistic as possible, we use publicly available data for the Iridium satellites. Specifically, the battery capacity is set to 250Wh, transmission power to 11 watt, reception power to 6 watt and the nominal operation power to 4 watt, idle power to 3 watt and sleeping mode to 0.3 watt (10% of idle mode).

Routing protocols: While the SLIM and LASER metrics can be implemented over any routing protocol, we implemented them over Dijkstra's Shortest Path (DSP) for simplicity. For LASER we implement a standard link state update protocol [121] for collecting the battery levels of all satellites.

Basic for comparison: We compare SLIM and LASER to pure DSP, for two reasons. First, DSP remains one of the most popular routing methods for LEO satellite networks [62]. Second, comparing to a protocol that ignores the battery lifetime helps quantity the potential for improvement and tradeoffs involved in switching to protocols that do take the battery lifetime into account.



(a) The CDF of battery levels for all satellites. The $x - axis$ represents the battery level just before exiting eclipse



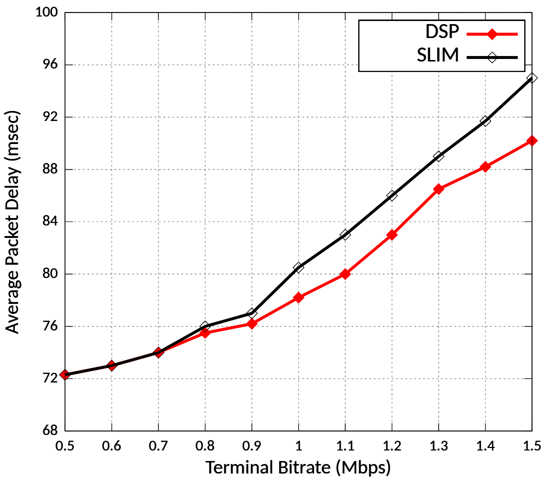
(b) Battery level for one satellite as it goes through eclipse. Out of the 100 minute cycle, around 36 minutes are spent in shadow

Figure 2.1: LASER and SLIM reduce the depth of discharge (DoD) by as much as 11% and 16% (median 10% and 14%), respectively, over a metric that does not take battery discharge into account. Considering that reducing a nickel hydrogen battery's DOD by 15% almost doubles its lifecycle, using SLIM can significantly extend the LEO satellites service life. The data also shows that SLIM's “lightness" outperforms LASER's accuracy

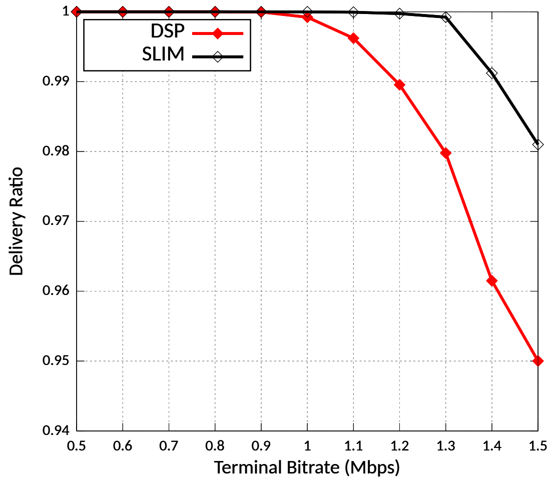
3.2 Experiment 1: Battery Depth of Discharge

We start with an experiment for evaluating LASER and SLIMin terms of battery DoD. For this, 100 terminals are distributed over six continents according to the distribution used in [122] and a CBR traffic generator transmitting at 1.5 Mbps is attached to each one of them. The average packet size is set to 210 Byte. Unlike DSP and SLIM, LASER requires extra control packets for acquiring the battery levels so to make the comparison fair we have associated a cost in terms of energy to every control packet.

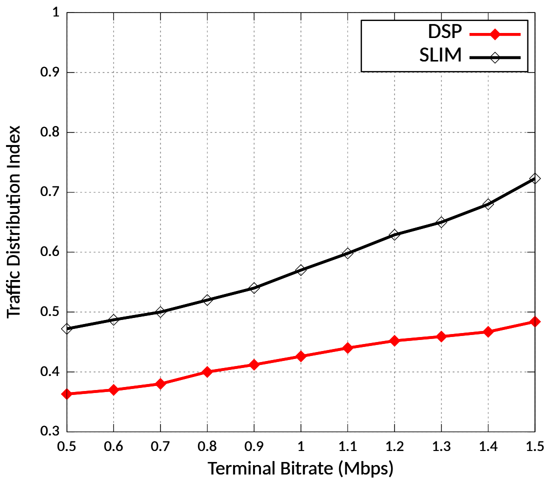
Figure 2.1(a) compares the CDFs of the battery levels at the end of the eclipse period for all satellites when using LASER, SLIM and DSP. The data shows that LASER and SLIMreduce the level of discharge by as much as 11% and 16%, respectively, when compared to DSP. Considering



(a) Average packet delay for di erent terminal bitrates.



(b) Packet delivery ratios for di erent terminal bitrates.



(c) Load distribution Index for di erent terminal bitrates.

Figure 2.2: SLIM adapts to the location and battery level of satellites while DSP always selects the shortest paths. As a result, with SLIM there is a slight increase in end-to-end delay, however, using SLIM leads to better delivery ratio, and better load distribution index.

the effect the depth of discharge has on the battery lifetime [11] [13], a 16% reduction in the depth of discharge can double the satellite service life in LEO constellations. For further clarity, in Figure 2.1(b) we zoom into an arbitrarily satellite as it goes through the eclipse period. Note that, an Iridium

LEO satellite rotates around the earth in 100 minutes, with eclipse period around 36 minutes, which explains the x-axis going from 0 to 36 mins. As shown in Fig. 2.1(b), once the satellite enters the eclipse its battery level starts dropping. However, the drop is less pronounced for LASER and SLIM.

Finally, the data shows that SLIM`s “lightness outperforms LASER accuracy.

3.3 Experiment 2: Impact of Energy-aware Routing on Path Length

In this experiment, we evaluate the effect of energy-aware routing on the shortest paths. Towards this, we run a second experiment with similar settings as the first except that we vary the traffic input rate from 0.5 to 1.5 Mbps to simulate different levels of traffic load. During the simulations we measure the end-to-end delay SLIM and DSP. We omit LASER for this part of the evaluation since SLIM was shown to clearly outperform it.

Figure 2.2(a) shows the results for the end-to-end delay. As expected, the SLIM’s improvement to the battery DoD does not come entirely for free – a slight increase in end-to-end delay over the DSP is observed. Nevertheless, the biggest increase is observed in the high loads and is due to the fact that SLIM delivers more packets (as shown in Fig. 2.2(b) and elaborated below). The data indicates that setting $w_1 = w_2 = 0.5$ for SLIM (see Eq. 2.3) strikes a good balance between performance and service life.

3.4 Experiment 3: Impact of Energy-aware Routing in Packet Delivery Ratio

To investigate the abilities of the SLIM in supporting QoS, we evaluate its performance in terms of the achieved packet delivery ratios. Figure 2.2(b) shows that using SLIM leads to a much better packet delivery ratios over the LEO constellation when compared to DSP. This is to be excepted since SLIM adapts to the position and battery level of the satellites while DSP always uses the shortest path to the destination. This performance is attributable to the fact that DSP algorithm bases its routing strategy on only finding paths with the shortest delay.

3.5 Experiment 4: Impact of Energy-aware Routing in Load Distribution Index

The SLIM scheme results also in a more balanced distribution of traffic over the entire constellation. To illustrate the idea at hand, we plot the traffic distribution index for different transmission rate in Figure 2.2(c). To investigate how well traffic is distributed over the entire constellation, the following traffic distribution index is used f [18]:

$$f = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2} \tag{2.4}$$

Where n is the number of satellites and x_i denotes the number of packets that traversed the i^{th} satellite.

Figure 2.2(c) shows that SLIM leads to a better and more efficient distribution of traffic among the constellation links. Since DSP sends the data over single paths during the entire transmission time.

4 Summary and Discussion

In this chapter, we proposed two new routing metrics – LASER and SLIM– striking a balance between performance and battery DoD in LEO satellite constellations. Our basic approach is to leverage the deterministic movement of satellites for favoring routing traffic over satellites exposed to the sun as opposed to the eclipsed satellites, thereby decreasing the average battery DoD– all without taking a significant penalty in performance.

The methods take advantage of some specific attributes of LEO satellite constellations to calcualte the exact location of each satellite and the highly symmetric and uniform structure of the topology. Unlike other networks such as sensor networks where battery lifetime is also essential, the movement of the satellites in a LEO constellation, such as Iridium, is deterministic. The location of any satellite can be computed and so can if a satellite is eclipsed, and if yes, for how long. Moreover, the LEO constellation topology is highly symmetric and uniform, there can be many alternate paths between two satellites. Selection of the most appropriate path can effectively increase the utilization of the system.

We demonstrated through extensive simulation results that LASER and SLIM have the potential to extend satellite service life, lowering packet drops, and increase the traffic distribution index while trading off very little in terms of end-to-end delay.

CHAPTER 3

Tra c-Aware Network Pruning for Extending Satellite Service Life

Contents

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In the previous chapter, we have shown the benefit brought by using energy efficient routing to improve the satellite service life in LEO satellite constellation. However, the energy dissipated in receive and send states is small when compared to the energy dissipated in the idle state. As satellite constellation are typically over-provisioned, selectively shutting down idle satellite links during off-peak hours has the potential to reduce energy consumption and, thus, extend constellation lifetime.

In this chapter, we address the problem of identifying the optimal set of links that can be shut down in a satellite constellation subject to maintaining full connectivity and bounding the maximum link utilization. With the problem being NP-hard, we introduce two heuristics, **BASIC** Link Pruning (BASIC) and Po**S**itio**N** **A**ware **P**runing (SNAP), which represent different tradeoffs in terms of performance and simplicity.

The remainder of this chapter corresponds to Network Pruning for Extending Satellite Service Life in LEO Satellite Constellations by Mohammed Hussein, Gentian Jakllari and Beatrice Paillassa which has been accepted to the journal of Wireless Networks (WINET), 2015 [32]. This is an extended version of the work with the same title and authors accepted for publication to IEEE GreenCom 2015 [123].

1 Introduction

Once a network has been designed (i.e., the resources that will compose it have been chosen), a periodical, off-line, process decides how the network resources will be optimized. This process is referred to as "network dimensioning". One of the most common practices for acting in a green fashion in network dimensioning consists in resource consolidation [93]: this technique aims at reducing the energy consumption due to devices underutilized at a given time. The traffic matrix in a given network approximately follows a well known daily behavior. Therefore, there is an opportunity to aggregate traffic ows over a subset of the network links, allowing other links to be temporarily turned off. However, the network connectivity and QoS, e.g., by limiting the maximum utilization over any link must be preserved. In other words, the required level of performance will be guaranteed, but using network resources that is dimensioned over the actual traffic demand, rather than for the peak demand.

As mentioned earlier, there is some researche focusing on the energy saving problems in satellite networks [111, 112]. However, the energy consumption reduction schemes proposed so far have focused on the satellite as a single entity not the constellation as a whole. Compared to the duration solar-coverage of GEO satellite, the LEO satellite would move into the earth umbra every orbit cycle and then only battery can be available, which is the same condition as WSNs.

In this chapter, we ask whether considering the satellite constellations as a whole could lead to better approaches for reducing the energy consumption of eclipsed satellites. Our question is rooted in the fact that LEO constellations are designed to cover the entire globe almost uniformly when the traffic distribution on earth is not homogeneous. Users tend to cluster around major urban areas (see Figure. 3.1) – for the Iridium satellite constellation, it is estimated that between 81% and 85% of the traffic comes from continents [19] – leaving large sections of the constellation significantly underutilized. Therefore, selectively shutting down a significant fraction of the constellation during periods of low demand so as to reduce overall energy consumption is entirely conceivable. In summary, the contributions of this chapter are the following:

- We have implemented a Matlab script to determine the real traffic matrix in a LEO satellite constellations.

- We formally define and formulate the traffic-aware energy saving problem using Integer Linear Programming (ILP). The objective is to minimize the total power consumption of the eclipsed satellites.

- We propose BASIC heuristic algorithm that is effective for large networks. BASIC is based on the observation that constellation links not on shortest path trees are highly unlikely to carry traffic and thus can be safely shut down.

- Also, we propose SNAP heuristic algorithm which improves upon BASIC by leveraging the deterministic movement of satellites so as to prune only links that are in eclipse and from areas with light traffic.

- Simulation results based on a realistic LEO satellite constellation and traffic matrices show that BASIC and SNAP can increase the average satellite lifetime by 40% and 80%, respectively, under the constraint that the maximum link utilization never exceeds 50%.

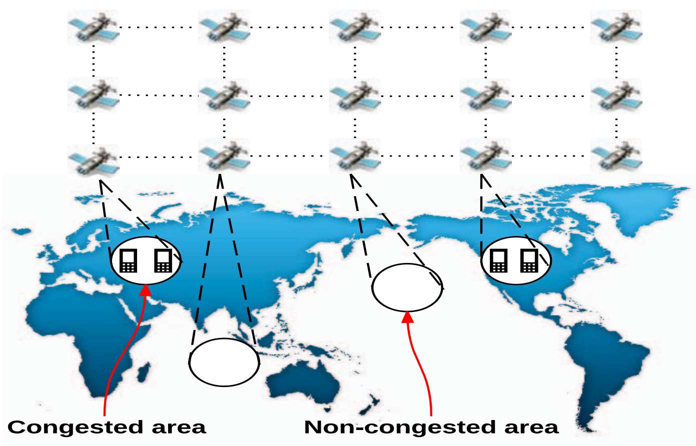


Figure 3.1: A LEO satellite network with non-homogeneous traffic distribution

2 Tra c Modeling and Problem Formulation

2.1 Tra c Model

The LEO satellite network carries unbalanced traffic load, which leads that parts of satellite links are congested while others are unused due to population distribution over the Globe. Therefore, in this section we describe how to determine the real traffic matrix in a LEO satellite constellation [124, 125], in order to put forward the satellites utilization.

Using the Virtual Node concept, the whole world is divided into 6 12 cells; each cell occupies 30° latitude and 30° longitude. This traffic approach depends on the statistics about the user density levels per cell, Internet host density levels per continent, and user activity levels per hour.

The inter-satellite traffic requirement between satellites s and d, i.e, t^{sd}, depends on the user traffic density level, u_s, the host density level, h_d, and the distance, $l(s,d)$, between the satellites:

$$t^{sd} = \frac{(u_s \quad h_d)}{(l(s,d))} \tag{3.1}$$

Where s corresponds to the LEO logical location (n, m), with $n = \frac{s}{M_L}$, $m = s\ MOD\ M_L$ and M_L being the number of satellites in a LEO plane. The distance between two zones can be calculated using the longitude and latitude for the center of that zones. Finally, we use the values $= 0.5$ and $= 1.5$ recommended in [125]. To adapt the generated traffic model to practical wideband LEO satellite network, we use t^{sd} as the proportional coefficient for obtaining the average traffic values T^{sd} between two satellites.

$$T^{sd} = \frac{t^{sd}}{\sum\limits_{\forall s}\sum\limits_{\forall d} t^{sd}} \quad \frac{\text{total offered traffic}}{3600} \quad \frac{a_h}{100} \tag{3.2}$$

Here, the total offered traffic represents the total traffic generated worldwide per day, with a_h representing the activity percentage during hour h. Note that, the average traffic demand is not only a function of the location of the source-destination pair but it is also a function of the time slot.

We have implemented the traffic generation algorithm in Matlab and in Fig. 3.2 we depict the results for the arrival rates for different traffic zones at a given time when the total offered traffic is 500Tb/day [126]. As the results show, many satellites in the constellation are underutilized, especially satellites covering the Southern Hemisphere. This represents a clear opportunity for saving energy, since many ISLs are powered on without fully utilization, while a carefully selected subset of them can be powered off without affecting major disruption to network activities.

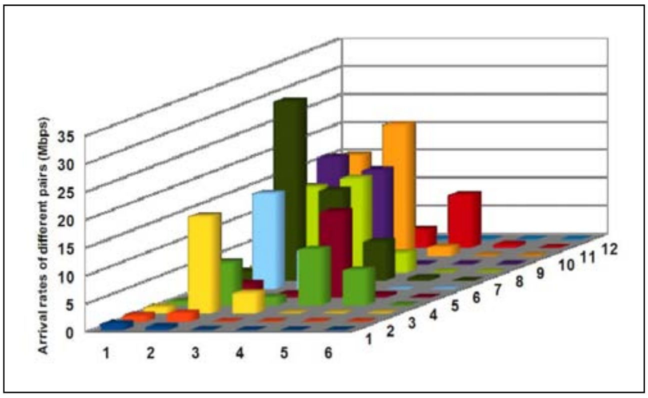


Figure 3.2: Distribution of traffic arrival rates at a given time for each of the 72 satellites comprising the LEO constellation.

2.2 The Problem Formulation

The problem of resource consolidation may be formalized as an optimization problem, where the objective is to minimize total power consumption of the eclipsed links in the constellation, and the constraints include the classical connectivity constraints and the QoS constraints. Formally, we model the LEO network as un undirected weighted graph $G(V, E)$, where V is the set of $N = |V|$ nodes and E is the set of $L = |E|$ links. Each link $(u, v) \in E$ between two nodes $u, v \in V$ has a capacity c_{uv}. Satellite nodes can be divided into two categories based on whether they are exposed to the sun or eclipsed by the earth. Our interest is obviously on the eclipsed satellites powered by batteries.

The objective is to find the network configuration (i.e., the working point of the eclipsed links of the network) that minimizes the total power consumption of the eclipsed links in the constellation, expressed as the sum of the consumption of all eclipsed links. Let p_{uv} be the power consumption of the eclipsed link (u, v) and x_{uv} be a binary variable denoting whether link (u, v) is pruned or not.

$\mathbf{L}_{eclipse}$ is the set of the eclipsed links. With this model, the network total energy consumption may be represented by the following expression:

$$minimize\ P_{total} = \sum_{uv=1}^{size(\mathbf{L}_{eclipse})} p_{uv} x_{uv} \tag{3.3}$$

The load imposed to the network is defined by a Traffic Matrix that specifies, for every couple of ingress and egress satellites (s, d), the traffic owing from s to d, denoted by T^{sd} hereafter. Each traffic requests from s to d is routed across the network, generating a traffic of f^{sd}_{vu} over any link (v, u). This Traffic Matrix defines the following set of constraints:

$$\sum_{v=1}^{N} f^{sd}_{uv} \quad \sum_{v=1}^{N} f^{sd}_{vu} = \begin{cases} T^{sd} & s, d, \ \ u = s \\ \ \ T^{sd} & s, d, \ \ u = d \\ 0 & s, d, \ \ u = s, d \end{cases} \tag{3.4}$$

To preserve QoS , no link should reach 100% utilization, or more in general, an arbitrary value that the network manager considers safe enough. This defines the following constraints:

$$\sum_{s=1}^{N} \sum_{d=1}^{N} (f^{sd}_{uv} + f^{sd}_{vu}) \qquad c_{uv} x_{uv} \qquad u, v \tag{3.5}$$

This problem formulation falls in the class of CMCF, well-known to be NP-hard [127]. Therefore, we propose heuristics for computing approximate solutions in polynomial time.

3 Topology and Tra c-aware Heuristics

Traffic-aware energy saving problem is known to be NP-complete [28]. Solving the ILP to find optimal solution is time consuming and it only works for small networks. Therefore, we present two heuristics designed to find an admissible solution to the problem defined by Equation 3.3. The heuristics remove network links in certain order until no further links can be removed. The first heuristic, BASIC, has been inspired by work on backbone networks [128]. It removes satellite links regardless of their spatial location. The second heuristic, SNAP, takes the satellite position in consideration when selecting which links to prune.

3.1 BASIC Link Pruning (BASIC)

The goal of BASIC, Algorithm 1, is to directly remove the maximum number of satellite links such that all ows are satisfied. BASIC starts with a simple observation: it is highly unlikely that links not belonging to any shortest path will be used for forwarding traffic [1]. Thus, pruning these links will have no adverse impact on network performance. BASIC starts by first computing the set of the shortest path links given the traffic demand, D_{in} (lines 2-4). Once the non-shortest-path links are excluded from the set of links to be kept on[2], LS, BASIC proceeds with pruning shortest-path links. In each iteration, the considered link is removed from the graph (line 7), and traffic is then rerouted on the residual graph. After rerouting, if a violation occurs (equation 3.5), then the specific link is put back on the graph (line 10).

As the names implies, this algorithm is straightforward. It is introduced here as basis for a more sophisticated algorithm as well as to demonstrate the value of an approach that takes into account the specifics of the satellite constellations, as we show in the performance evaluation in Section 4.

3.2 PoSitioN Aware Pruning (SNAP)

SNAP, Algorithm 2, improves upon BASIC by making two key observations. First, unlike the terrestrial networks, from which BASIC is inspired, where shutting down any networking component improves the energy profile, in LEO constellations that is not always the case. When exposed to the sun, satellites are powered by solar energy so shutting them down is unnecessary. Second, in LEO constellations there is a high correlation between geographical location and traffic level. Most satellite traffic hot spots are located in the Northern Hemisphere, especially between 0°and 50°N [129]. There is nothing this clear cut in terrestrial networks.

However, turning these two observations into a pruning algorithm raises the challenge of determining each satellite's location every time SNAP needs to make a pruning decision. Therefore, SNAP starts off by computing the location of every constellation link (lines 2-5). Then, based on the traffic demand, it computes the links belonging to some shortest path tree (lines 7-8). SNAP prunes

[1]We use a simple shortest path algorithm to route the tra c.

[2]BASIC returns the set of links that are to be kept on; the rest of the links are pruned. Thus, not including non-shortest-path links in the set LS is equivalent to pruning them.

Algorithm 1: BASIC Link Pruning (BASIC)

input : Complete LEO Network Graph: $G(N\ L)$
Input Deamands List: D_{in}

output : Un-Pruned Links

begin
  $Links\_Set(LS)$;
  for $i = 1$ *to sizeof*(D_{in}) **do**
    SP $links\_of\_all\_shortest\_paths\_(D_i)$ LS LS SP
  for $i = 1$ *to sizeof*$(Links\_Set)$ **do**
    $Link_i$ $LS(i)$;
    LS $LS -$ $Link_i$;
    $Violated$ $Demands\_Constraints(D_{in}\ LS)$;
    if $Violated == True$ **then**
      LS LS $Link_i$;
  return LS
  //Final network topology $G^f(N\ LS)$

shortest-path *eclipsed* links by considering them in order of geographic priority. Eclipsed links in the Southern Hemisphere (SEL) are more likely to be lightly loaded so they are considered for pruning first (lines 12-17); followed by the eclipsed links in the Northern Hemisphere (NEL) (lines 18-23). Finally, the set of links to be kept on is returned (line 24).

4 Experimental and Evaluation Results

We use CPLEX and Matlab as simulation tools and a real satellite traffic demand matrix to evaluate the performance of BASIC and SNAP in terms of number of links pruned, battery level of discharge, average path stretch and link load distribution.

4.1 Experimental Setup

LEO Constellation: We consider a constellation with 6 orbital planes, each orbited by 12 satellites. Satellite orbits are 780 km in altitude with an orbit inclination angle of 86.4°. We do not consider

Algorithm 2: poSitioN Aware Pruning (SNAP).

input : Complete LEO Network Graph: $G(N\ L)$
Input Deamands List: D_{in}

output : Un-Pruned Links

begin
- $EL \quad Eclipse\_Links\_List(G(N\ L))$;
- $SunL \quad Sun\_Links\_List(G(N\ L))$;
- $SL \quad Southern\_Hemisphere\_Links(G(N\ L))$;
- $NL \quad Northern\_Hemisphere\_Links(G(N\ L))$;
- $Links\_Set(LS)$;
- **for** $i = 1$ *to sizeof*(D_{in}) **do**
  - $SP \quad links\_of\_all\_shortest\_paths\_(D_i)\ LS \quad LS \quad SP$
- $Candidate\_Eclipse\_Links(CEL) \quad LS \quad EL$;
- $Northern\_Eclipse\_Links(NEL) \quad CEL \quad NL$;
- $Southern\_Eclipse\_Links(SEL) \quad CEL \quad SL$;
- **for** $i = 1$ *to sizeof*(SEL) **do**
  - $Link_i \quad SEL(i)$;
  - $LS \quad LS - \ Link_i$;
  - $Violated \quad Demands\_Constraint(D_{in}\ LS)$;
  - **if** $Violated == True$ **then**
    - $LS \quad LS \quad Link_i$;
- **for** $i = 1$ *to sizeof*(NEL) **do**
  - $Link_i \quad NEL(i)$;
  - $LS \quad LS - \ Link_i$;
  - $Violated \quad Demands\_Constraint(D_{in}\ LS)$;
  - **if** $Violated == True$ **then**
    - $LS \quad LS \quad Link_i$;
- **return** $LS \quad SunL$;
- //Final network topology $G^f(N\ LS \quad SunL)$

the seams where two ISLs are switched off due to motions in opposite directions. Hence, we assume each satellite maintains four ISLs to its neighboring satellites at all times. The capacity of every ISLs is set to 155 Mbps.

Traffic matrix: We generate traffic matrices starting from real user levels, u_s, and real Internet host density levels, h_d, collected for each zone in 2005 [125]. Using the traffic model described in Section 2.1 , we transform u_s and h_d into hourly traffic levels, a_h, for every LEO constellation link. We assume the traffic level does not change significantly within an hour. However, during a 24 hour cycle there is a significant difference in traffic level between peak and off-peak hours. In the traffic matrices we use in this study off-peak traffic is between 10%–20% of the peak traffic level.

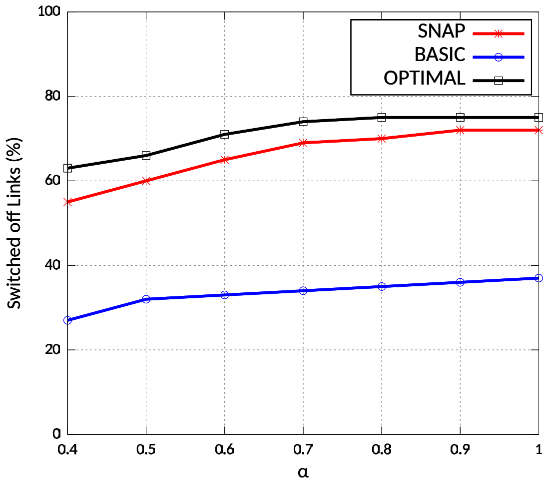
Basis for comparison: To the best of our knowledge, there is no other work that tackles the problem of network pruning in satellite constellations so we use the optimal solution as benchmark. To get optimal values, we solve the ILP problem formulation (Section 2.2) in CPLEX. The CPLEX computations are performed on a Linux PC with eight 3.4 GHz CPUs and 16 GB of RAM. However, even for a small input such as the Atlanta network [130] consisting of 15 nodes and 22 links CPLEX takes several hours to converge. Therefore, we force CPLEX to stop once it converges to within 95% of the optimal, which on our platform took about 300 seconds per point.

4.2 Experiment 1: Pruning Performance During O -Peak Hours

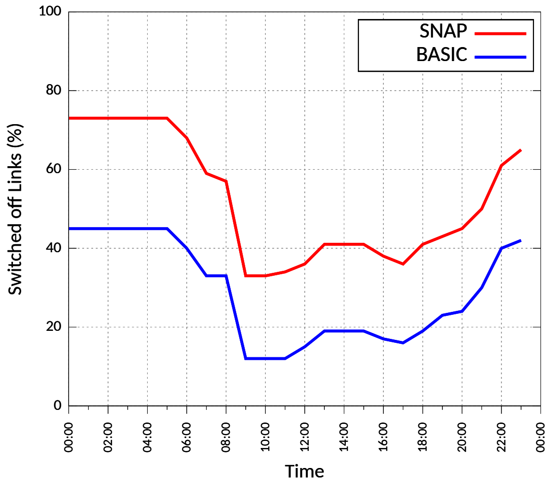
We study the pruning performance of BASIC and SNAP under the constraint that the maximum link utilization in the network never exceeds the QoS parameter (Eq. 3.5). Fig. 3.3(a) shows the number of eclipsed links switched off for $\in [0.4, 1]$. The results show that SNAP is able to prune a remarkably high percentage of links, as high as 72%, while meeting the QoS constraint. What makes this results the more remarkable is that it is very close to the optimal solution. On the other hand, BASIC barely prunes half as many links as SNAP. This validates our approach of taking into account the LEO constellations characteristics when designing an efficient networking pruning algorithm.

4.3 Experiment 2: Pruning Performance During a 24-Hour Cycle

In this experiment, we evaluate BASIC and SNAP during a 24-h cycle on a week day. Fig. 3.3(b) shows the percentage of switched off links when the maximum link utilization limit, , is set to 0.6. As expected, during the night hours the data traffic is low so BASIC and SNAP manage to prune as much as 45% and 72% of the eclipsed links, respectively. This significant amount of links is pruned



(a) Percentage of eclipsed links pruned as a function of QoS,



(b) Percentage of eclipsed links pruned during a 24-h cycle

Figure 3.3: BASIC barely prunes half as many links as SNAP. This validates our approach of taking into account the LEO constellations characteristics when designing an efficient networking pruning algorithm.

despite the fact that the maximum link utilization is never allowed to exceed 60%. Between 10:00 am and 6:00 pm, the data traffic level is at its highest, explaining why the percentage of pruned links by both heuristics drops. Nevertheless, SNAP still manages to prune over 30% of the eclipsed links.

4.4 Experiment 3: Battery Depth of Discharge

In this experiment, we evaluate the impact of BASIC and SNAP on the level of battery discharge in the eclipsed satellites, according to energy model described in chapter 2. Fig. 3.4 shows the results of the experiment. To keep the graph simple to read we show the results of a single satellite, which is representative of the average behavior observed during the simulation on all satellites. The results of the experiment show that the network pruning with BASIC and SNAP reduce the battery DoD by 6 and 12%, respectively, compared to doing no pruning (consider the original topology). Considering the effect the DoD has on the battery lifetime [11] [13], a 6% and 12% reduction in DoD can lead to 40% and 80% increase in the battery lifetime, respectively.

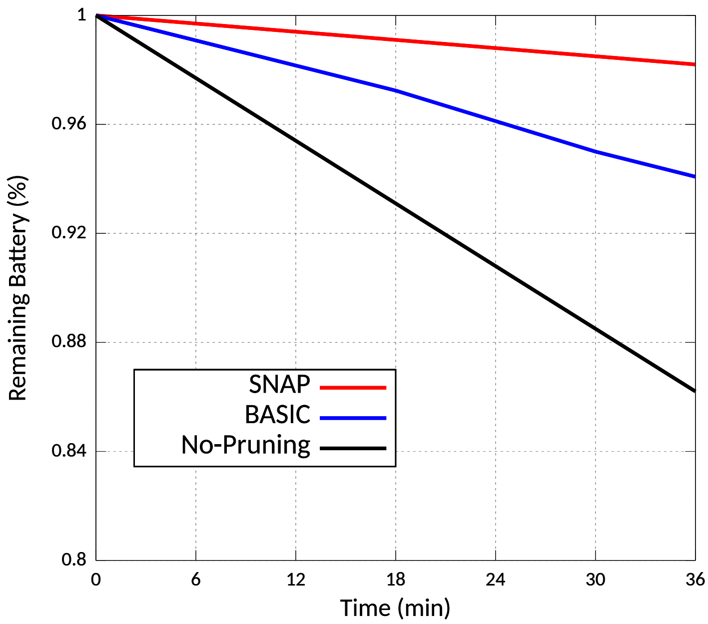


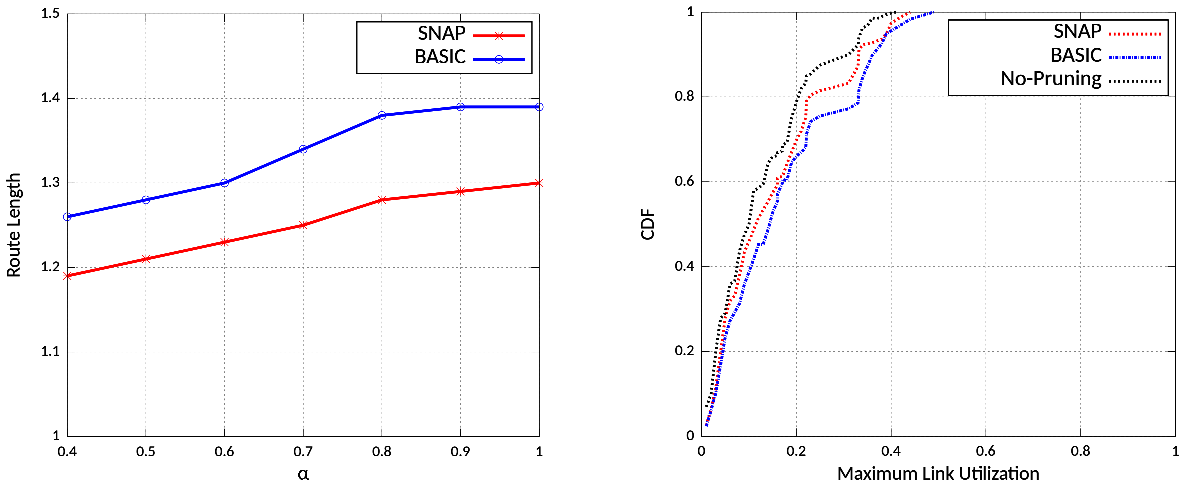
Figure 3.4: Battery level for one satellite as it goes through eclipse with $= 0.5$. Of the 100 minute cycle, around 36 minutes are spent in eclipse.

4.5 Experiment 4: Impact of Pruning on Path Length

In this experiment, we evaluate the effect of pruning on the shortest paths. Removing links inevitably leads to longer routes and the end-to-end delay depends not only on buffer delay but also on the number of hops a packet has to cross on the way to the destination. The path stretch is defined as the ratio between a shortest path on the pruned topology divided by the shortest path between the same source destination pair in the original graph. Fig. 3.5(a) shows that, while pruning the network using BASIC and SNAP does have the side effect of increasing the average path length, the increase with SNAP is very limited. The average path length with SNAP is increased by only 21% when $= 0.5$.

4.6 Experiment 5: Impact of Pruning on Link Utilization

Fig. 3.5(b) shows the CDF of maximum link utilization using BASIC and SNAP. Note that, pruning links increases the congestion level on the links left because of two reasons. First, there are less links



(a) Impact of BASIC and SNAP on the average path length in the network as a function of QoS constraint .

(b) The CDF of maximum links utilization for all the active links with = 0 5. The $x-$axis represents the maximum links utilization.

Figure 3.5: Effect of pruning on network performance.

to forward the same amount of traffic. Second, as the paths between any pair of nodes increase, every data packet will have to be transmitted over more hops before it reaches the destination, thereby it increases the level of congestion on the network. Nevertheless, Fig. 3.5(b) shows that the maximum link utilization in the network with SNAP closely follows the levels observed when no pruning was performed.

5 Summary and Discussion

In this chapter, we considered the problem of extending the service life of LEO satellite constellations. Our aim was to find the minimum set of links to satisfy a given traffic demand under general connectivity and QoS constraints. We first formulated the problem using an ILP formulation. Then, we proposed two heuristics, BASIC and SNAP, which strike a balance between extending the LEO satellite service life and traditional network performance. BASIC is based on the observation that constellation links not on shortest path trees are highly unlikely to carry traffic and thus can be safely shut down. SNAP improves upon BASIC by leveraging the deterministic movement of satellites so as to prune only links that are in eclipse and from areas with light traffic.

Simulations using realistic LEO topologies and traffic matrices showed that BASIC and SNAP are able to achieve considerable power savings and, thus, extend constellation lifetime by 40% and 80%, respectively. This significant improvement in service life is achieved while trading off very little in terms of congestion and average path length.

The work in this chapter and chapter 2 face the same challenge: extending the service life of satellite constellations. However, addressing this common challenge was approached in two different ways. In chapter 2 we assume no capability of controlling when and if the transceiver of a satellite can be put to sleep. As a result, the proposed approach relies on modifications to the routing software. In this chapter, we assume greater control, including the capability to put satellite transceivers to sleep, making it possible to work on the best possible solution – using only the capacity necessary to satisfy the traffic demand. Unfortunately, finding this solution is NP-hard, forcing us to rely on heuristics. This explains the fact that while BASIC and SNAP do increase the constellation lifetime significantly, their performance is slightly inferior to that of SLIM and LASER from chapter 2.

As future work, we intend to work on better performing heuristics and extend BASIC and SNAP to take into account link failures and sudden traffic bursts.

Chapter 4

Tra c-Agnostic Network Pruning for Extending Satellite Service Life

Contents

All previously analyzed solutions for energy-aware pruning assume perfect knowledge of the traffic matrix; i.e., the amount of traffic sent from each node to every other node at any given time. This strong assumption limits their applicability to limited scenarios.

In this chapter, we propose a traffic-agnostic approach. It relies on a novel metric for quantifying the quality of frugal topologies, the Adequacy Index (ADI). After showing that the problem of finding the most frugal network topology subject to a given ADI is NP-complete, we propose a polynomial time heuristic to solve it. Extensive simulations using a real LEO satellite network scenarios show that the proposed heuristic is able to achieve energy savings comparable to traffic-aware solutions.

The results of this chapter have been accepted to the Journal of Wireless Networks (WINET) [32].

1 Introduction

Although green networking has been attracting a growing attention during the last years (see the surveys [102, 131]), we found a limited number of works devoted to traffic-agnostic approaches [95, 97, 110, 132]. The key advantages of these traffic-agnostic solutions are that they can be applied without knowledge of the actual traffic in the network. However, these works need to modify the protocols at the heart of IP networks so as to reduce their energy footprints. Further, none of them guarantees a certain level of resilience and/or robustness of the network.

In this chapter, we argue for using a quality metric for frugal topology that does not depend on instantaneous traffic and congestion levels and yet is highly correlated with the quality of the network as a whole. We introduce the Adequacy Index (ADI), a metric for quantifying the quality of the frugal version of the full-on network. ADI is based on the concept of algebraic connectivity from spectral graph theory [31]. Compared with more intuitive graph concepts, such as the vertex/edge connectivity – the minimum number of vertices/edges whose deletion from a graph disconnects it – the algebraic connectivity better captures the robustness of a graph [133–135]. Consider the two simple graphs in Fig 4.1. Removing any single edge from the star topology would only result in a single isolated node. Removing a link from the middle of the line topology would split the network in two. While the vertex and edge connectivity fail to capture the difference in robustness between the star and line topology, the algebraic connectivity does.

We formalize the problem of minimizing the power consumption of a network subject to a given ADI and prove that the problem is NP-Complete. Then, we propose a heuristic named- **A**lgebraic based alg**O**r**I**thm for frugality (AvOId), which removes links that have low impact on network connectivity.

Simulation results based on a realistic LEO satellite constellation and traffic matrices show that AvOId can increase the average satellite lifetime by 85%. Fundamentally, AvOId provides a novel control option to LEO network operators- it can be programmed to be enabled during off-peak hours for creating energy frugal topology and disabled during peak hours.

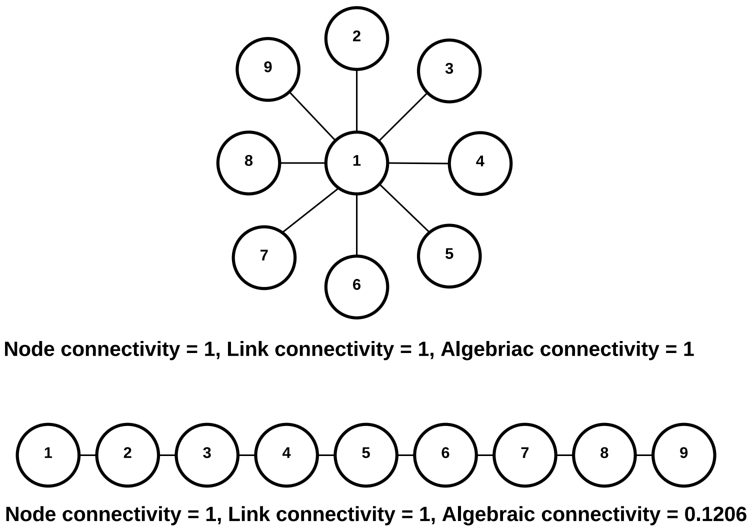


Figure 4.1: Algebraic connectivity is a better indicator of network robustness.

2 Primer on Algebraic Connectivity

"How well connected is a graph?" This is a fundamental question to any problem modeled using graphs and that unfortunately defies a simple answer. Even producing a simple definition as to what well connected exactly means is challenging. The algebraic connectivity – the second smallest eigenvalue of the graph's Laplacian matrix – was established by Fiedler in his seminal work [31] as an elegant answer to this fundamental question.

Let $G = (V, E)$ be a simple graph with $|V|$ vertices and $|E|$ edges; its algebraic connectivity is a function of its adjacency and degree matrices. In the following, we introduce formal definitions for all these quantities along with some key results on algebraic connectivity.

Definition 1 (Adjacency Matrix). *Given a simple graph $G = (V, E)$ with $|V| = n$, its adjacency matrix $A(G)$ is a $n \quad n$ binary matrix where the entry a_{ij} is equal to 1 if $\ i, j \ \in E$ and 0 otherwise.*

Definition 2 (Degree Matrix). *Given a simple graph $G = (V, E)$ with $|V| = n$, its degree matrix $D(G)$ is a $n \quad n$ diagonal matrix where the entry d_{ii} is equal to the degree of vertex i.*

Definition 3 (Laplacian Matrix). *Given a simple graph $G = (V, E)$ with $|V| = n$, its Laplacian* *matrix $L(G)$ is a $n \quad n$ matrix defined as:*

$$L(G) = D(G) \quad A(G)$$

From Definition 3, it follows that the entry $l_{i\,j}$ of the Laplacian matrix for graph G is

$$l_{i\,j} = \begin{cases} deg(i) & \text{if } i = j \\ \quad 1 & \text{if } i = j \text{ and } \quad i, j \quad \in E \\ 0 & \text{otherwise} \end{cases}$$

where $deg(i)$ is the degree of vertex i.

The eigenvalues of the Laplacian matrix are usually referred to as the graph spectra. The number of zero-valued eigenvalues of the Laplacian matrix is equal to the number of connected components in the graph G. Consequently, the *second smallest* eigenvalue being 0 is equivalent to the graph having at least two connected component and thus being disconnected. Therefore, this eigenvalue is referred to as the algebraic connectivity of the graph [31]. More formally:

Definition 4 (**Algebraic Connectivity** $a(G)$)**.** *Let $N \quad 2$ and $0 = \ _1 \quad \ _2 \quad\quad \ _N$ be the eigenvalues of the Laplacian matrix $L(G)$. The algebraic connectivity $a(G)$ of the graph G is equal to the second smallest eigenvalue, $\ _2$.*

The algebraic connectivity has become essential to the study of the network robustness not only because a non-zero value proves end-to-end connectivity but more importantly because of Lemma 1 proved by Fiedler [31]. It connects the algebraic connectivity to two important graph properties. One, the *vertex connectivity*, the minimum number of vertices whose deletion from a graph disconnects it. Two, the *edge connectivity*, the minimum number of edges whose deletion from a graph G disconnects it.

Lemma 1 (Bound on Connectivity)**.** *Let $k(G)$ and $\ (G)$ be the vertex and edge connectivity of the graph G, respectively. Then*

$$a(G) \quad k(G) \quad\quad (G).$$

Finally, we present a property that will be useful in Section 3.

Lemma 2. *The function $a(G)$ is non-decreasing for graphs with the same set of vertices, i.e.* $a(G_1)\quad a(G_2)$*, if* $V_1 = V_2$*, and* $E_1 \quad E_2$.

3 New Metric and Problem De nition

In this section we propose a new metric, ADI, for quantifying the quality of a LEO network topology. We then use this metric to formally define the problem of computing frugal LEO topology.

3.1 Adequacy Index

Our goal is to compute a frugal yet adequate version of an LEO satellite network topology. For this, we first need to quantify the notions of **frugal** and **adequate**. The notion of frugal is easy to quantify – it is the non-trivial version of the full network topology that minimizes energy consumption. Adequate has been traditionally defined as a topology whose maximum link utilization is bounded by a given threshold (chapter 3). The advantage of this definition is that it guarantees a given level of congestion and quality of service in the network. Unfortunately, guaranteeing a given level of link utilization requires accurate and instantaneous information as to the level of congestion and traffic matrix in the network. To circumvent this impractical requirement, in this section we propose a new definition for adequate:

Definition 5 (Adequacy Index, ADI). *Let $G = (V, E)$ be a simple graph. Let $G^f = (V, E^f)$ such that $E^f \quad E$ be a frugal version of graph G. The adequacy index, ADI, of the frugal graph G^f is defined as follows:*

$$ADI(G^f) = \frac{a(G^f)}{a(G)} \tag{4.1}$$

where $a()$ denotes the algebraic connectivity.

The following lemma describes a basic property of the Adequacy Index.

Lemma 3. *Let $G = (V, E)$ be a simple graph and $G^f = (V, E^f)$ such that $E^f \quad E$ a frugal version of graph G. Then*

$$0 \quad ADI(G^f) \quad 1.$$

Proof. Follows from Lemma 2. □

The Adequacy Index has the advantage of depending on the topological properties of the LEO network and not on the instantaneous traffic level. At the same time, as it depends on the algebraic connectivity it is related to the level of connectivity and redundancy. In Section 5, using real LEO topology and traffic matrices, we show that the ADI provides a knob that enables changing the level of frugality as well as congestion in the network.

3.2 The Problem Formulation

We model the LEO network as un undirected weighted graph $G(V, E)$, where V is the set of $N = |V|$ nodes and E is the set of $L = |E|$ links representing the physical links between satellite nodes. Satellite nodes can be divided into two categories based on whether they are exposed to the sun or eclipsed by the earth. Our interest is obviously on the eclipsed satellites which are powered by batteries.

Let p_{uv} be the power consumption of the **eclipsed** link (u, v) and x_{uv} be a binary variable denoting whether link (u, v) is pruned or not. The objective is to turn off as many eclipsed links as possible so as to create a frugal yet adequate topology of satellite nodes. The problem can be formulated as follows:

$$minimize\ P_{total} = \sum_{uv=1}^{size(\mathbf{L}_{eclipse})} p_{uv} x_{uv} \tag{4.2}$$

$$\text{s.t. } ADI(G^f) \quad Threshold \tag{4.3}$$

Where $\mathbf{L}_{eclipse}$ is the set of the eclipsed links. Equation 4.2 minimizes the total power consumption of the LEO network. Equation 4.3 forces the ADI of the reduced LEO graph to be above a threshold value. Finally, Theorem 1 shows the difficulty of solving this problem.

Theorem 1. *The problem of finding the most frugal LEO network topology subject to a given ADI threshold is NP-hard.*

Proof. The proof is simple so we provide a sketch. We show that our problem is NP-Hard by reducing the maximum algebraic connectivity augmentation problem [136], hereto $P2$, to our problem, hereto $P1$. To this end, we consider the instance of $P1$ in which once the most frugal topology is found, we are asked whether the number of edges in this topology is higher than a non-negative integer k. Solving this instance of $P1$ consists of solving an instance of $P2$. Since $P2$ has been shown to be NP-Hard [136] that concludes the proof. □

Therefore, we propose heuristic algorithms for computing approximate solutions in admissible time.

4 Topology-aware Heuristics

In this section, we present heuristics for computing the most frugal LEO network topology subject to a given ADI threshold. At first, we propose a generic approach that uses the ADI metric. Then, we present a specific instantiations of the generic approach, which leverages algebraic connectivity. The generic approach, Algorithm 5, uses a greedy strategy for solving the problem. It starts with the complete LEO topology and renders it frugal by removing eclipse links iteratively (lines 5-11). In every iteration it selects the most expendable eclipse link (line 6) and checks weather removing it would not lower the ADI of the frugal graph below a given threshold, ADI_T, given as input (line 9). If this the case the eclipse link e can be removed, then, the remaining links are resorted (line 12) - removing an eclipse link changes the LEO graph structure and the relative importance of the remaining links. Otherwise, the link is kept. Obviously, the key part of this approach is sorting the eclipse links from the most to the least expendable. Depending on how the sorting procedure is implemented, we can have a rich set of solutions for the most frugal adequate LEO topology problem. Algorithm 4 proposes a sorting algorithm called **A**lgebraic based alg**O**r**I**thm for frugality (AvOId) that establishes a direct link between every eclipse link and the ADI.

Algorithm 4 orders the eclipse links based on their impact on the algebraic connectivity, since the aim is to switch off those links that have low impact on the network connectivity. The straightforward approach to determine each satellite's location would be to add periodic signaling for exchanging location information among all satellites. However, this would add extra overhead, negating some, if not all, of the very benefit brought about by pruning. Instead, AvOId solves this challenge by leveraging the fact that the satellite movement is deterministic and, thus, the location of a satellite at any given time can be computed as explained in chapter 1.

The input for Algorithm 4 is the complete LEO topology $G(N, L)$, and the output of the algorithm is an ordered list of eclipsed links. The algorithm associates to each eclipse link $e \in E$ the variation $\;^{e} = a(G) \quad a(G^{e})$, where $a(G)$ is the algebraic connectivity for the input graph G and $a(G^{e})$ is the algebraic connectivity after removing the eclipse link e (lines 7-11). We name Z a vector containing the Eclipsed Links (E) and `SE_List` is the ordered obtained from Z sorting in increasing order of $\;^{e}$ (line 12).

5 Experimental Evaluation

In this section, we evaluate the performance of AvOId in terms of number of links pruned, battery level of discharge, path stretch and link load distribution.

5.1 Experimental Setup

Implementation: A custom simulator is written in Matlab to implement the AvOId heuristic. While, the optimization toolbox OPTI in Matlab is used for generating the optimal frugal topology.

Basic for comparison: To the best of our knowledge, there is no other work that tackles the problem of network pruning in satellite constellations so we use the optimal solution as benchmark. We named this method “OPTIMAL . Also, we defined another algorithm which switches off eclipsed links randomly. We named this method “RANDOM .

5.2 Experiment 1: Pruning Performance

As a first performance analysis we observe, the AvOId behavior as a function of the Adequacy Index Threshold. Fig. 4.2(a) shows the number of switched off eclipsed links for different values of the Adequacy Index Threshold. It can be noticed that as the Adequacy Index Threshold increases, the number of links that can be switched off decreases, due to the connectivity constraints. AvOId is

Algorithm 3: Generic Approach.

input : Complete LEO Network Graph: $G(N\ L)$
Adequacy Index Threshold: ADI_T
Sorting Function: $SortEclipseEdges()$

output : Frugal LEO Graph: $G^f(N\ L^f)$

begin
  $G^f(N\ L^f)\quad G(N\ L)$;
  $a(G)\quad$ AlgebraicConnectivity $(G(N\ L))$
  `//Sorted list of eclipse links obtained from Algorithm 4`
  $SE\_List\quad$ SortEdges $(G(N\ L^f))$;
  `//Remove eclipse links starting from the most expendable if doing so does not lower the adequacy index below the threshold,` ADI_T.
  for $i = 1$ *to sizeof*(SE_List) **do**
    $e\quad MostExpendable(SE\_List)$;
    $L^f\quad L^f -\ e$;
    $a(G^f)\quad$ AlgebraicConnectivity $(G^f(N\ L^f))$
    if $\frac{a(G^f)}{a(G)}\quad ADI_T$ **then**
      `//Do not remove this eclipse edge.`
      $L^f\quad L^f +\ e$;
    else
      `//Removing an edge changes the structure of the graph and the relative importance of the remaining edges. Thus, the edges queue is re-sorted.`
      $SE\_List\quad$ SortEdges $(G(N\ L^f))$;
  return $G^f(N\ L^f)$;

very competitive when compare to the optimal solution. Also, while AvOId, built on the algebraic connectivity, it is able to switch off a large number of eclipsed links, between 30%-40%, several times more than the strategy of switching links off at random.

5.3 Experiment 2: Battery Depth of Discharge

In this experiment, we evaluate the impact of AvOId on the level of battery discharge. Fig. 4.2(b) shows the results of the experiment. The results of the experiment show that, the network pruning

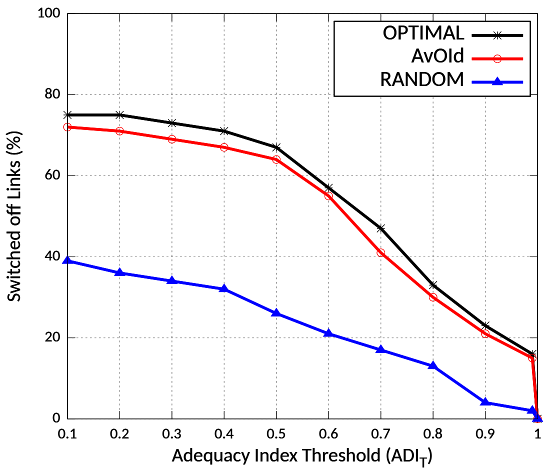
Algorithm 4: AvOId's Method for Sorting Eclipse Links.

```
input   : Complete LEO Network Graph: G(N  L)
output  : A sorted list of eclipsed links.
begin
    //Compute the eclipse links using the method described in chapter  2
    E = Compute_Eclipse_Links_List(G(N  L))
    a(G)    AlgebriacConnectivity (G(N  L))
    E_length =  E
    Z̄ = zeros(SE_length)
    e = 1
    for e   E do
        Z̄[e] = e:
        compute a(G^e) where G^e = (N  L −  e );
        Δ^e = a(G) − a(G^e);
        e = e + 1;
    //Sort eclipse links based on their effect of algebraic connectivity (from the least effect
      to the most effect)
    SE_List= sort Z̄ in increasing order based on values Δ^e;
    return SE_List;
```

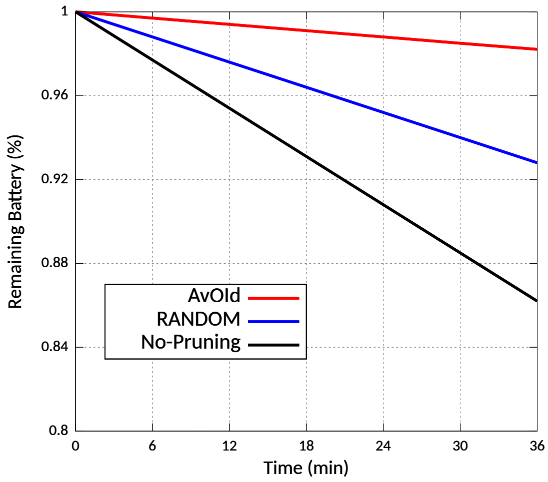
with AvOId reduces the battery depth of discharge by 12.5%, compared to doing no pruning (consider the original topology). Considering the effect the depth of discharge has on the battery lifetime [11] [13], a 12.5% reduction in depth of discharge can lead to 85% increase in the battery lifetime. In case of RANDOM the percentage of of lifetime increasing is 40%.

5.4 Experiment 3: Impact of Pruning on Path Length

Using the same traffic matrix generated in chapter 3, we first route all ows in the original topology using DSP, then we use the same ows to calculate the average path length in the frugal topology using DSP. Fig 4.3(a), we see that the impact of the route lengths is limited. Fig 4.3(a) indicates that we can turn off 65% of the eclipsed links when $ADI_T = 0.5$ while, the consequent percentage of path increasing reaches only 15%. Moreover, the average distance between two satellites is inversely



(a) Percentage of eclipsed links pruned as a function of Adequacy Index Threshold



(b) Battery level for one satellite as it goes through eclipse with $ADI_T = 0\ 5$.

Figure 4.2: While AvOId, built on the algebraic connectivity, is able to switch off a large number of eclipse links, between 30%-40% , several times more than the strategy of switching links off at random.

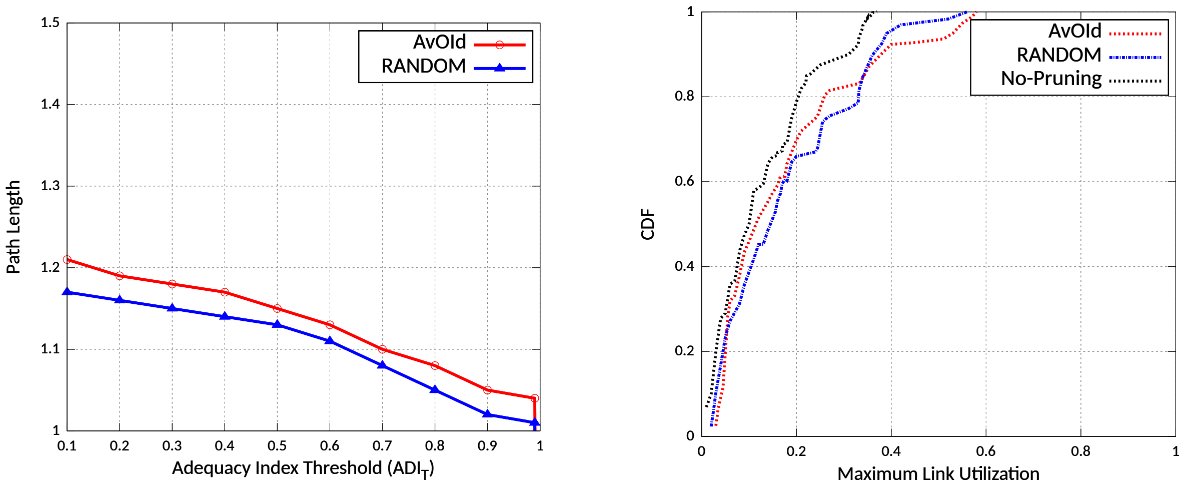
proportional to the algebraic connectivity, so by choosing the Adequacy Index Threshold, we can determine the percentage of path increasing.

5.5 Experiment 4: Impact of Pruning on Link Utilization

In this section, we evaluate the impact of pruning on link utilization using the same traffic matrix generated in chapter 3. We draw the Cumulative Distribution Function (CDF) of maximum link utilization on the active links. Fig. 4.3(b) shows that the ADI correlates very well with the maximum link utilization measured in the network. With AvOId the maximum link utilization will never exceed 58% - in spite of, AvOId is traffic un-aware solution.

5.6 Experiment 5: Comparison with Tra c Based Solutions

We now compare the traffic-aware heuristics BASIC and SNAP presented in chapter 3, to the traffic-agnostic heuristics RANDOM and AvOId presented in this chapter. For BASIC and SNAP we set



(a) Impact of AvOId on the average path length in the network as a function of QoS constraint .

(b) The CDF of maximum links utilization for all the active links with $ADI_T = 0\ 5$.

Figure 4.3: Effect of pruning on network performance.

the Maximum Link Utilization Threshold, to 0.5 for both heuristics. While, for RANDOM and AvOId the Adequacy Index Threshold, ADI_T, is set to 0.5. Table 4.1 shows that AvOId switches off the most eclipse links, followed closely by SNAP. Furthermore, AvOId performance is better than SNAP in terms of path stretch. BASIC and SNAP are greedy heuristics that iteratively select the least loaded link in the network as a candidate for being switched off, just because a particular link is lightly loaded does not necessarily mean it is expandable from the perspective of the whole network. This explains why AvOId showed superior performance in our experiments in terms of power savings and path stretch. However, there is no guarantee in maximum link utilization when using traffic-agnostic solutions.

The traffic-agnostic solution requires knowledge of global topology on a centralized server or on each on-board router. It is fairly easy to satisfy this requirement by runing a link state routing protocol such as OSPF [97]. However, the traffic-aware approach requires the knowledge of network topology and traffic information as input - a requirement that can be impractical for many network operators. Therefore, from the numerical results and the implementation applicability we see that the traffic-agnostic approach can open new era of energy savings for eclipsed satellites in LEO constellations. It could represent a good starting point to implement a future algorithm where traffic QoS aspects are taken into account.

Algorithm	**Switched-off(%)**	**DoD(%)**	**Path Stretch(%)**	**Maximum Link Utilization(%)**
SNAP ($= 0.5$)	60	80	21	40
BASIC ($= 0.5$)	25	40	29	44
AvOId ($ADI_T = 0.5$)	64	85	15	58
RANDOM ($ADI_T = 0.5$)	25	40	17	56

Table 4.1: Comparisons traffic vs topology.

6 Summary and Discussion

We present AvOId, a polynomial time heuristic for creating frugal LEO satellite networks. The new heuristic is based on the ADI, a novel metric that leverages spectral graph theory for quantifiying the quality of a frugal graph.

Simulations using realistic LEOtopologies and traffic matrices showed that AvOId is able to achieve considerable power savings and, thus, extend constellation lifetime by 85%. This significant improvement in service life is achieved while trading off very little in terms of congestion and average path length. Moreover, we compare the performance of our algorithm with more complex traffic-aware solution presented in chapter 3 and we show that, our traffic-agnostic approach achieves slightly better performance even if it is “blind with respect to traffic.

Differently from other approaches, AvOId does not rely on instantaneous and global knowledge of the traffic matrix and network congestion levels - a reqirement that can be impractical for many satellite operators.

Intersting directions that can be studied are how to implement the traffic-agnostic algorithm "AvOId where QoS aspects are taken into account.

Chapter 5

Extending the Network Pruning Techniques into Terrestrial Wired Networks

Contents

In this chapter, we extend our work on energy efficiency to the wired networks infrastructure. We demonstrate how the spectral graph theory information presented in chapter 4 can be used again to reduce the energy consumption in IP wired networks. We show that the problem of minimizing the power consumption of a network subject to a given ADI threshold (introduced in chapter 4) is NP-hard and present two polynomial time heuristics – **A**lgebraic **B**a**S**ed **A**lgorithm for Frugal**I**ty (ABStAIn) and **C**en**T**rality **B**ased **A**lgorithm for Frugality (CuTBAck). We perform extensive simulations using topologies and traffic matrices from 3 real networks. Our results show that ABStAIn and CuTBAck are as effective as an exponential time traffic- aware solution at creating frugal topologies and outperform a state of the art polynomial time traffic-aware solution by about 80%. Furthermore, the median link utilization observed with ABStAIn and CuTBAck is similar to that with traffic-aware solutions, with the maximum link utilization never exceeding 80%.

The results of this chapter have been accepted for publication to IEEE LCN 2015 [33].

1 Introduction

One of the most promising developments in the telecommunications industry has been the integration of terrestrial and satellite networks. Effectively exploiting multiple heterogeneous access networks in parallel, as described in Fig. 5.1, can be a potential solution to organizations that demand ever-present broadband connectivity–covering every application, every geography and every moment in time. In the previous chapters of this thesis, we presented different techniques to reduce the energy consumption in LEO satellite networks. In this chapter, and to make our solution complete, we extend the novel approach presented in chapter 4 to reduce the energy footprints in IP networks. Moreover, more energy-efficient network architectures would allow network deployments in less developed parts of the world. In this chapter, we describe optimization techniques that allow significant energy savings in IP networks.

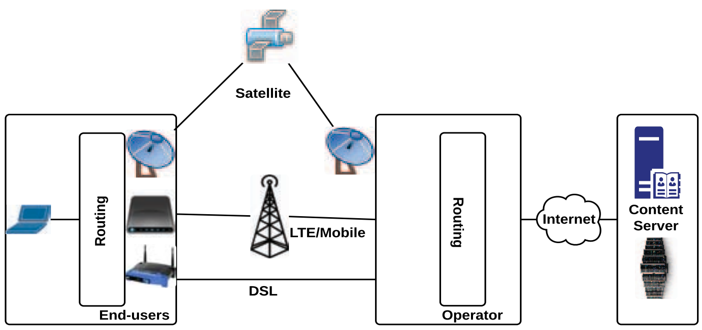


Figure 5.1: Multiple connection scenario overview.

The Internet has become a major source of power consumption due to its exponential growth. European telecommunication operators currently consume 21.4 TWh per year, a quantity projected to soon reach 35.8 TWh, if no green networking technologies are adapted [137]. British Telecom reported that its overall energy consumption during the 2008 year to be 2.6 TWh, making it the biggest single energy consumer in the United Kingdom [102]. In US, small network equipments in homes, that is modems, gateways and routers, consumed approximately 8.3 TWh of electricity during 2012 year, which resulted in 5 million metric tonnes of CO_2 [138]. Qureshi et al. [139] projected that even smaller systems like Akami consume approximately 10M $ worth of elctricity annually.

As mentioned earlier, network operators overprovision their networks to accommodate traffic bursts, and to allow rerouting when links or routers fail. Most ISPs upgrade their infrastructures when the link utilization reaches above 40% [140, 141], leading to a significant waste of energy. Further, the power consumption of backbone routers and their line cards is essentially independent of link load [101]. Therefore, in order to reduce the energy consumption, the authors in [28, 90] switch off router line cards and reroute traffic during off-peak periods. In this respect, Intel corporation has introduced the 0BASE-X concept [142], by which line cards are able to quickly switch from active mode to idle mode and vice vera.

In this chapter, we extend the traffic-agnostic solution presented in chapter 4 to reduce the energy footprints in IP networks. In summary, we make the following contributions:

- We use the Adequacy Index (ADI), a metric for quantifying the quality of the frugal topology relative to the full-on network. ADI is based on the concept of algebraic connectivity from spectral graph theory [133].

- We formalize the problem of minimizing the power consumption of a network subject to a given ADI is NP-complete.

- We introduce a generic approach for solving the problem and present two polynomial time instantiations: ABStAIn and CuTBAck. ABStAIn and CuTBAck follow the generic approach of creating frugal topologies by removing links in some order until a given ADI threshold is reached. They differ on how the network links are ordered from the most expendable, the first to be switched off for frugality, to the most important. ABStAIn relies on the algebraic connectivity for deciding how important a particular link is, while CuTBAck on the notion of the link betweenness centrality [143].

- We evaluate CuTBAck and ABStAIn using real topologies and traffic matrices from 3 networks representing a mixture of academic, commercial and educational usage, and compare them to two popular traffic based solutions: Benchmark-MLU [90] and Least-Flow [28]. The data shows that CuTBAck and ABStAIn switch off as many links as the exponential time Benchmark-MLU and 80% as many as the Least-Flow. The median link utilization observed in the frugal topologies generated by CuTBAck and ABStAIn was similar to what was observed in the topologies generated by Benchmark-MLU and Least-Flow, with the maximum link utilization never exceeding 80%.

- ABStAIn and CuTBAck are the first polynomial time schemes that do not require accurate traffic information nor a modification to the IP network protocols, can easily be implemented on a central controller, such as an SDN controller [141], and enable large network operators to reduce their energy footprints.
- Fundamentally, CuTBAck and ABStAIn provide a novel control option to network operators – it can be programmed to be enabled during off-peak hours for creating energy frugal topologies and disabled during peak hours.

2 The Problem Formulation

We model a network of IP routers, such as an Autonomous System or backbone network, as a simple graph $G = (V, E)$, with V the set of vertices representing the routers and E the set of edges representing the physical links between routers.

Let $p_{(u\ v)}$ be the power consumption of the link from router u to v. Let $x_{(u\ v)}$ be a binary variable denoting whether link (u, v) is switched off for saving energy. The objective is to turn off as many links as possible so as to create a frugal yet adequate topology of routers. The problem can be formulated as follows:

$$\text{minimize} \quad P_{tot} = \sum_{(u\ v) \in E} p_{(u\ v)} x_{(u\ v)} \tag{5.1}$$

$$\text{s.t. } ADI(G^f) \quad Threshold \tag{5.2}$$

Equation 5.1 minimizes the total power consumption of the network. Equation 5.2 forces the Adequacy Index of the frugal graph to be above a threshold value. Finally, Theorem 2 shows the difficulty of solving this problem.

Theorem 2. *The problem of finding the most frugal network topology subject to a given adequacy index threshold is NP-hard.*

We refer the reader to chapter 4 for the details on Adequacy Index (ADI) and its relations. In section 3, we focus on designing heuristic approaches to solve our problem.

3 Creating Frugal Topologies

In this section, we present heuristics for computing the most frugal network topology subject to a given adequacy index threshold. At first, we introduce a generic approach that uses the adequacy index metric. Then, we present two specific instantiations of the generic approach. The first leverages the algebraic connectivity while the second leverages concepts from the network centrality [144].

3.1 Generic Approach

The generic approach, Algorithm 5, uses a greedy strategy for solving the problem. It starts with the complete topology and renders it frugal by removing edges iteratively (lines 5-12). In every iteration it selects the most expendable edge (line 6) and checks whether removing it would lower the adequacy index of the frugal graph below a given threshold, ADI_T, given as input (line 8). If not, the edge is removed and the remaining edges are re-sorted (line 12) – removing an edge changes the graph structure and the relative importance of the remaining edges. Otherwise the edge is kept. Obviously, the key part of this approach is sorting the edges from the most to the least expendable (lines 4,12). Depending on how the sorting procedure is implemented, we can have a rich set of solutions for the most frugal adequate topology problem. In the following we show two such examples.

Algorithm 5: Generic Approach.

input : Complete Network Graph: $G(V\ E)$
Adequacy Index Threshold: ADI_T
Sorting Function: $SortEdges()$

output : Frugal Graph: $G^f(V\ E^f)$

```
begin
    G^f(V E^f)    G(V E);
    a(G)    AlgebraicConnectivity (G(V E))
    //Sort the edges from least to most important using the specific ordering algorithm.
    SE_List    SortEdges (G(V E^f));
    //Remove edges starting from the most expandable if doing so does not lower the adequacy
      index below the threshold, ADI_T.
    for i = 1    sizeof(SE_List) do
        e    MostExpendable(SE_List);
        E^f    E^f −  e ;
        a(G^f)    AlgebraicConnectivity (G^f(V E^f))
        if a(G^f)/a(G)    ADI_T then
            //Do not remove this edge.
            E^f    E^f +  e ;
        else
            //Removing an edge changes the structure of the graph and the relative importance of
              the remaining edges.  Thus, the edges queue is re-sorted.
            SE_List    SortEdges (G(V E^f));
    return G^f(V E^f);
```

3.2 ABStAIn: *A*lgebraic *B*a*S*ed *A*lgorithm for Frugal*I*ty

To implement the generic approach, ABStAIn proposes a sorting algorithm that establishes a direct link between every edge and the ADI. The straightforward approach would be to remove every edge, compute the impact this would have on the Adequacy Index and sort edges based on this impact. This, however, would entail computing the algebraic connectivity of the graph as many times as there are edges – a costly proposition given that a single computation of the eigenvalues using the popular

QR algorithm [145] takes $O(|V|^3)$ operations. Instead, we present an approach that requires a single calculation of the algebraic connectivity. To accomplish this, ABStAIn relies on what we refer to as the *Fiedler Factor*. Before defining the Fiedler Factor we introduce the definition of the Fiedler Vector.

Definition 6 (Fiedler Vector)**.** *Let $G = (V, E)$ be a simple graph and $L(G)$ its Laplacian matrix. The eigenvector of $L(G)$ corresponding to its second smallest eigenvalue is known as the Fiedler Vector.*

Definition 7 (Fiedler Factor). *Let F be the Fiedler Vector resulting from the Laplacian matrix of the simple graph $G = (V, E)$. For every edge $e(u, v) \in E$ its Fiedler Factor is*

$$FF(e(u,v)) = |F[u] \quad F[v]| \,.$$

The following Lemma shows how the Fiedler Factor is related to the algebraic connectivity.

Lemma 4. *Let $G = (V, E)$ be a simple graph and $a(G)$ its algebraic connectivity. Then for all edges $e \in E$ the following holds [31]:*

$$a(G \quad e) \quad a(G) \quad FF(e)^2 \tag{5.3}$$

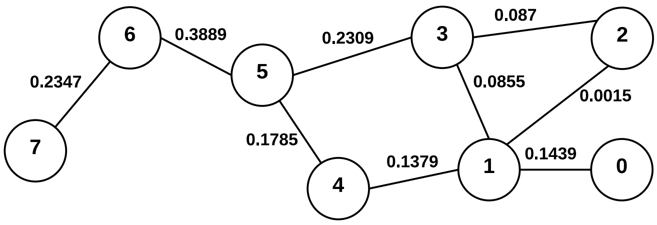
Algorithm 6: ABStAIn's Method for Sorting Edges.

input : Complete Network Graph: $G(V\ E)$

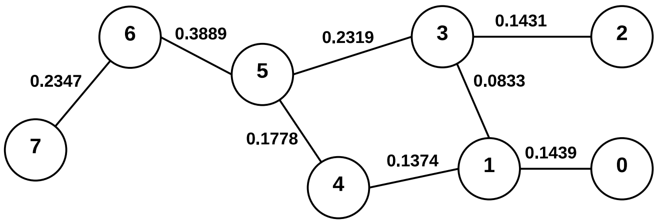
output : A sorted list of the graph edges.

begin
  $F[V]$ ComputeFiedlerVector ($G(V\ E)$)
  `//Compute the Fiedler Factor,`FF`, for all edges.`
  for $e(u\ v)$ E **do**
    $FF(e(u\ v)) = F[u] - F[v]$;
  `//Sort edges in nonincreasing order of Fiedler Factor.`
  SE_List Sort ($E\ FF[E]$ *nonincreasing*);
  return SE_List;

Eq. 5.3 indicates that removing the edge whose Fiedler Factor is smallest will have the least negative impact on the algebraic connectivity and, by extension, the ADI of the frugal graph. Therefore,



(a) Initial state.



(b) After ABStAIn s rst iteration.

Figure 5.2: Edge $(5, 6)$ has the highest weight, consistent with the fact that it is the only edge whose removal would lead to two non-trivial connected components. Fig. a – ABStAIn removes edge $(1, 2)$ first and then recalculates the edge weights. Fig. b – $(2, 3)$ is what now connects vertex 2 to the rest of the graph so its weight has increased significantly, leaving $(1, 3)$ as the next most expendable edge.

ABStAIn's sorting function, Algorithm 6, starts by assigning every edge a weight equal to its Fiedler Factor (lines 3-4). It then simply uses a standard sorting algorithm for sorting edges in non-increasing order of Fiedler Factor (line 5).

Fig. 5.2 shows an illustration of how ABStAIn works on a simple 8-node graph, shown in its initial state (Fig. 5.2(a)) and after one iteration of ABStAIn (Fig. 5.2(b). Every edge is given a weight equal to its Fiedler Factor. ABStAIn considers edge $(5, 6)$ the least expendable, consistent with the fact that it is the only edge whose removal would create two non-trivial connected component. On the other hand, ABStAIn considers edge $(1, 2)$ the most expendable – removing it would still leave the graph connected and vertices 1,3,4,5 would still have two edge-disjoint paths – and gives it the smallest weight. ABStAIn's implementation of the Generic Approach selects edge $(1, 2)$ first (line 6, Algorithm 5), removes it, recalculates the weights and re-sorts the edges.

3.3 CuTBAck: *C*en*T*rality *B*ased *A*lgorithm for Frugality

ABStAIn provides an elegant sorting method working directly with the algebraic connectivity on which the ADI is founded. However, for matrices of order 5 or more, the eigenvalues and eigenvectors cannot be obtained by an explicit algebraic formula, and must therefore be computed by approximate numerical methods. The popular QR Algorithm takes $O(|V|^3)$ operations per iteration even though in most cases it converges in two iterations [145]. CuTBAck relaxes the requirement for eigenvalue calculations by relying on the edge betweenness centrality – the fraction of all-pairs shortest paths passing through a particular edge [144]. More formally:

Algorithm 7: CuTBAck's Method for Sorting Edges.

input : Complete Network Graph: $G(V\ E)$

output : A sorted list of the graph edges.

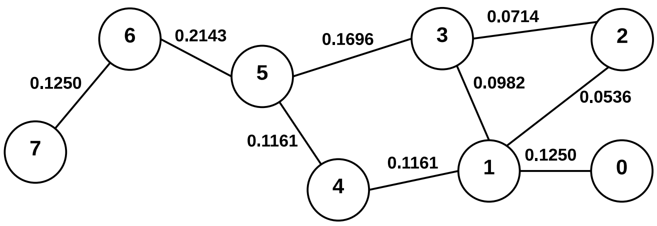
begin
  `//Compute edge betweenness using Eq.5.4.`
  for $v\quad V$ **do**
    Dijstra $(G(V\ E)\ v)$;
    for $e\quad E$ **do**
      if $e\quad ShortestPathTree$ **then**
        `//As G is connected there are` $V - 1$ `paths on the shortest-path tree.`
        $btwn(e)\quad btwn(e) + \frac{1}{(|V|-1)}$;
  `//Sort edges in nonincreasing order of betweenness.`
  SE_List Sort $(E\ btwn[E]\ nonincreasing)$;
  return SE_List;

Definition 8 (Link Betweenness Centrality). *Let $G = (V, E)$ be a simple graph. For every edge $e \in E$ its betweenness centrality is given by the expression:*

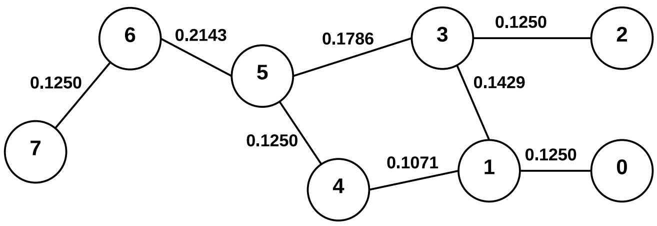
$$btwn(e) = \sum_{s \in V} \frac{(s|e)}{(s)} \tag{5.4}$$

where (s) is the total number of shortest paths on G rooted at vertex s and $(s|e)$ the number of shortest paths in (s) passing through edge e.

The betweenness centrality captures the importance of an edge to the shortest paths. The higher the betweenness centrality the higher the disruption will be to the transfer of the data in the network should the link be removed. On the other hand, a link with small betweenness centrality could be removed for frugality without significantly affecting the graph's adequacy. Therefore, CuTBAck builds its sorting algorithm, Algorithm 7, around the betweenness centrality. The algorithm starts by computing the betweenness centrality of all the edges (lines 2-6). This computation is simple – it suffices to run Dijkstra's algorithm from every vertex in the graph. Finally, the edges are sorted in non-increasing order of centrality betweenness by using a standard sorting algorithm (line 7).



(a) Initial state.



(b) After CuTBAck s rst iteration.

Figure 5.3: Edge $(5, 6)$ has the highest weight as all the shortest paths to vertices 6 and 7 have to pass through it. Removing link $(1, 2)$ will have the minimal effect of increasing the shortest path between vertices 1 and 2 by a hop. Fig. a – CuTBAck removes edge $(1, 2)$ first and then recalculates the edge weights. Fig. b – $(2, 3)$ is what now connects vertex 2 to the rest of the graph so its weight has increased significantly, leaving $(1, 4)$ as the next most expendable edge.

Fig. 5.3 shows an illustration of how CuTBAck works on a simple 8-node graph, shown in its initial state (Fig. 5.3(a)) and after one iteration of CuTBAck (Fig. 5.3(b). Every edge is given a weight equal to its betweenness centrality. CuTBAck considers edge $(5, 6)$ the least expendable in the graph. This is consistent with the fact that removing edge $(5,6)$ would cut the flow of data to two nodes, 5 and 6, more than any other edge. On the other hand, removing edge $(1,2)$ would cause a minimal disruption to the data flow in the network and thus this link is given the smallest weight by CuTBAck. CuTBAck's implementation of the Generic Approach selects edge $(1,2)$ first (line 6, Algorithm 5), removes it, recalculates the weights and re-sorts the edges.

4 Experimental and Evaluation Results

In this section, we evaluate the performance of ABStAIn and CuTBAck in terms of network links switched off, path stretch and link utilization distribution using real network topologies and traffic matrices. In summary, we make the following main observations:

1. In Section 4.2, we show that ABStAIn and CuTBAck, when applied on real network topologies, can switch off between 20%-30% of the network links. For Adequacy Index values between 0.4 and 1, the percentage of switched off links is very close to the optimal solution.

2. In Section 4.3, we show that the Adequacy Index correlates very well with the maximum link utilization in the network.

3. In Section 4.4, we show that despite the high number of links switched off by ABStAIn and CuTBAck, the shortest paths are only stretched by around 20% on average.

4. In Section 4.5, comparing to two well known traffic based solution, the exponential time Benchmark-MLU [90] and polynomial time Least-Flow [28], ABStAIn and CuTBAck are shown to perform as well as Benchmark-MLU and clearly outperform Least-Flow.

5. In Section 4.6, using the power model from [95], ABStAIn and CuTBAck are shown to perform as well as Benchmark-MLU and clearly outperform Least-Flow.

6. ABStAIn, as expected, outperforms CuTBAck but the gap is small enough to justify selecting the latter in applications where running time is a primary concern.

4.1 Experimental Setup

Network	**Usage**	**Location**	**Nodes**	**Links**
IBM-Watson	Research	USA	16	49
SPRINT	Commercial	USA	44	212
GÉANT	Academia	Europe	23	74

Table 5.1: Network topologies used in the performance evaluation.

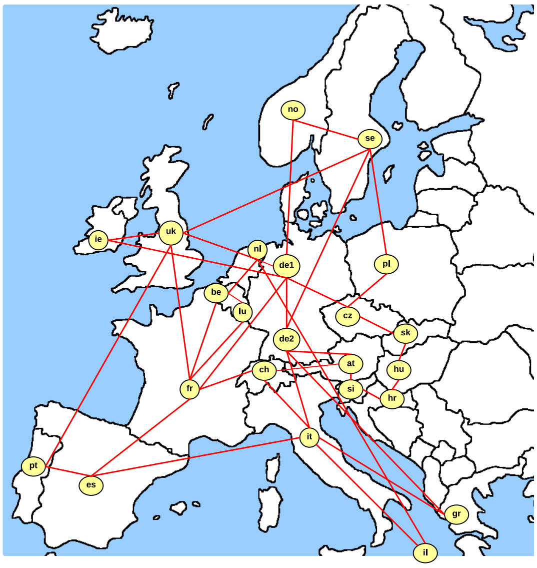


Figure 5.4: The GÉANT network.

Implementation: A custom simulator is written in Matlab to implement ABStAIn and CuT-BAck while the MATLAB code for the solutions proposed in [90] was provided by the authors. The optimization toolbox “OPTI in Matlab is used for generating optimal frugal topologies.

Topologies and Traffic Matrices: We use 3 real network topologies, representing a mixture of research, education and commercial applications (Table 5.1): IBM-Watson selected from SNDLib [130], SPRINT selected from Rocketfuel [146] and GÉANT, a pan-European (see Fig. 5.4) research and education network [147].

SND-lib provides real traffic matrices for the IBM-Watson topology but does not provide the link capacities. Thus, we select the link capacities using the method described in [140] – high degree nodes have high capacity links (10Gb/s) with the rest having smaller capacity links (2.5Gb/s). Since Rocketfuel does not provide link capacities and traffic matrices, we assign capacities to links using the same method as for IBM-Watson and generate traffic matrices using the gravity model [148]. In particular, we assume that each router generates traffic for all the other routers: 40% of it is high bit-rate traffic, between 1 Mbit/s and 80 Mbit/s, and the remaining 60%, low bit-rate traffic, up to 1 Mbit/s. For GÉANT, the topology and traffic matrices, measured every 15 minutes, are provided by the authors of [147].

Basis for Comparison: We compare ABStAIn and CuTBAck with the optimal solution computed using the MATLAB “OPTI tool and two well known traffic based solutions [28, 90]. To measure the value of a carefully designed solution we also compare to a solution that simply removes links at random.

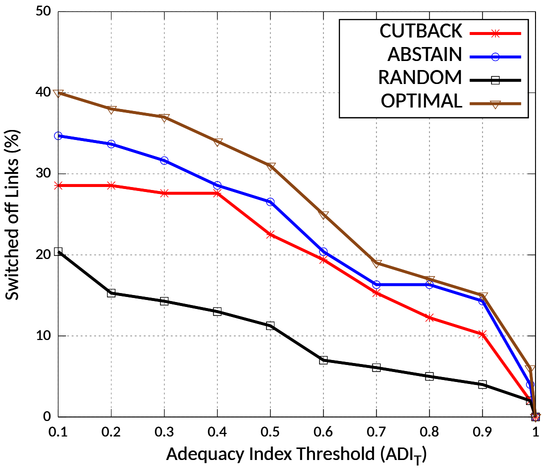
4.2 Experiment 1: Frugality

Fig. 5.5 shows the number of switched off links on all 3 topologies for different values of the Adequacy Index threshold. The data points to three interesting conclusions. First, ABStAIn and CuTBAck are able to switch off a large number of links, between 20%-30%, several times more than the strategy of switching links off at random. Second, ABStAIn and CuTBAck are very competitive when compare to the Optimal solution – for Adequacy Index threshold between 0.4 and 1 ABStAIn and CuTBAck are almost as good as the Optimal and only for values under 0.3 does the Optimal start performing significantly better. Third, while ABStAIn, built on the algebraic connectivity, is expected to outperform CuTBAck, built on the betweenness centrality and simpler to compute, the difference is small.

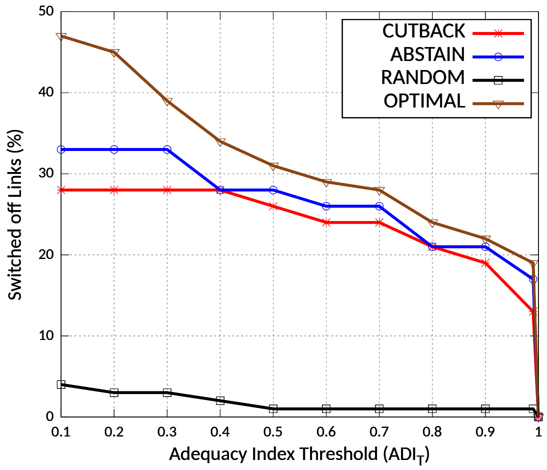
4.3 Experiment 2: Adequacy Index vs. Maximum Link Utilization

In this experiment, we evaluate the relation between the Adequacy Index and maximum link utilization in the network.

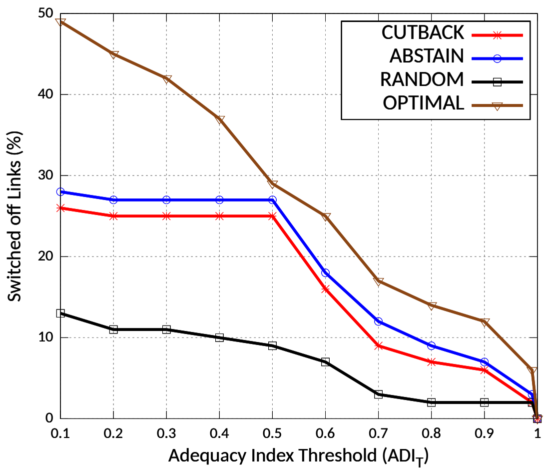
Method: Optimal frugal topologies for IBM-Watson, Sprint and GÉANT are generated using MATLAB’s “OPTI" tool using Adequacy Index threshold values varying from 0.1 to 1. The Optimal



(a) IBM-Watson



(b) SPRINT



(c) GÉANT

Figure 5.5: The percentage of switched off links as function of the Adequacy Index threshold.

solution is favored over using our heuristics so as to focus on the value of Adequacy Index as a metric without the results being biased by the way a particular heuristic works. Once the optimal frugal topology is generated, we introduce off-peak hour[1] traffic using the traffic matrices described in Section 4.1 and measure the maximum link utilization in the network.

[1]We recommend disabling the mechanism for creating frugal topologies during peak hours.

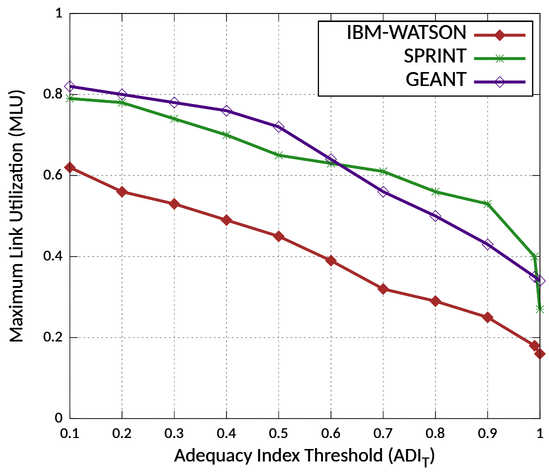


Figure 5.6: ADI is shown to correlated well with the maximum link utilization. The data is collected on frugal topologies generated by the Optimal solution so as to isolate the {ADI, link utilization} relation from any bias the particularities of a heuristic may introduce.

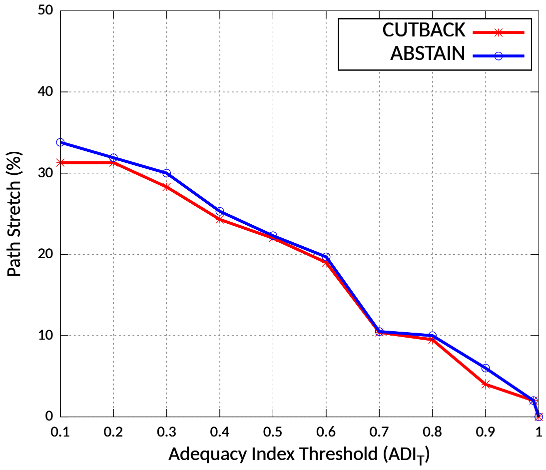
Results: Fig. 5.6 shows that the Adequacy Index correlates very well with the maximum link utilization measured in the network. What is more, the data for $ADI_T = 1$, equivalent to no frugality (see Eq. 4.1 in chapter 4), demonstrates that networks are severely underutilized, leaving substantial room for saving energy. Indeed, reducing the Adequacy Index threshold leads to more frugal topologies (as shown in Fig. 5.5) without any link getting saturated. Even for very aggressive values of the Adequacy Index threshold the maximum link utilization is around 80% for GÉANT and Sprint, and only 60% for IBM-Watson.

4.4 Experiment 3: E ect of Frugality on Shortest Paths

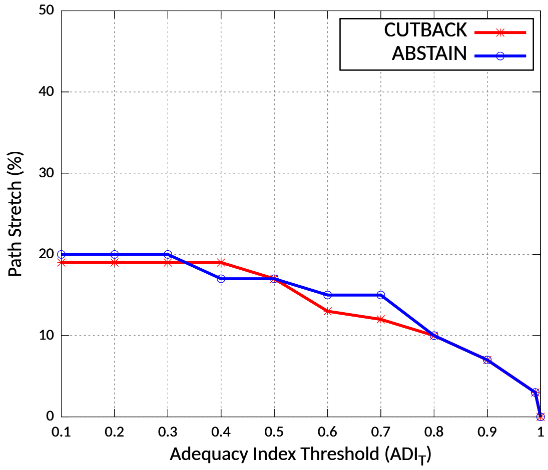
In this experiment, we evaluate the effect of being frugal on the shortest paths. Most works in the subject quantify the effect of frugality by measuring link utilization. However, removing links inevitably leads to longer routes and the end-to-end delay depends not only on buffer delay but also the number of hops a packet has to cross on the way to the destination.

Method: For all 3 topologies under consideration, we compute all-pairs shortest paths before and after applying ABStAIn and CuTBAck. The *path stretch* is defined as the ratio between a shortest path on the frugal topology divided by the shortest path between the same source destination pair on the original graph.

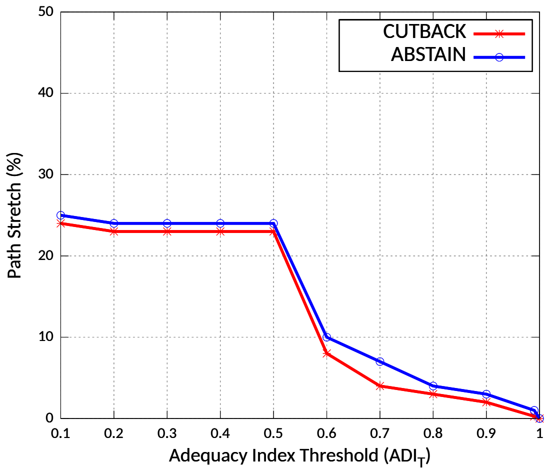
Results: Fig. 5.7 shows that while there is a price to be paid in terms of expected end-to-end delay for being energy frugal, it is quite low. Even for very aggressive Adequacy Index threshold values the path stretch is between 20% and 30%.



(a) IBM-Watson



(b) SPRINT



(c) GÉANT

Figure 5.7: The impact of frugality on the path stretch.

4.5 Experiment 4: Comparison with Tra c Based Solutions

In this experiment we compare ABStAIn and CuTBAck to two well known traffic based solutions: Least-Flow [28] and what we refer to as Benchmark-MLU [90]. The authors of [90] have proposed a solution to the problem of computing the most frugal topology subject to a maximum link utilization threshold relying on multiple calls to the CPLEX optimizer. Therefore, while shown to be one of the best traffic based solutions, it can only be used as a benchmark[2].

Algorithm	**Switched-off (%)**	**Path Stretch (%)**
Benchmark-MLU ($MLU_T = 0.5$)	24.4	28.8
Least-Flow ($MLU_T = 0.5$)	15	20
ABStAIn ($ADI_T = 0.5$)	27.7	24.6
CuTBAck ($ADI_T = 0.5$)	25	23

Table 5.2: Comparisons with traffic based approaches.

Method: For this set of experiments we use only the GÉANT network as it is the only network for which we have complete information as to the link capacities as well as real traffic matrixes at 15 mins granularity. For Least-Flow and Benchmark-MLU we use the best settings proposed by their authors. In particular, the maximum link utilization threshold, MLU_T, is set to 0.5 for both. For ABStAIn and CuTBAck the Adequacy Index threshold, ADI_T, is also set to 0.5. We run all solutions on the GÉANT topology using off-peak traffic matrices and measure the link utilization in the network, number of links switched off and the path stretch.

Results: Table 5.2 shows that ABStAIn switches off the most links, followed closely by CuTBAck and Benchmark-MLU. Least-Flow is a distant forth. Similar results are observed for the path stretch. The fact that ABStAIn and CuTBAck outperform Benchmark-MLU, albeit by a little, is

[2] On a Linux PC with eight 3.4 GHz CPUs and 16 GB of RAM a single run of Benchmark-MLU takes from a few hours on GÉANT to around 20 hours on the SPRINT topology.

surprising considering the latter uses the CPLEX optimizer for computing topologies very close to the optimal. On the other hand, Benchmark-MLU clearly outperforms all other solutions in terms of traffic distribution in the network, as shown in Fig. 5.8. As expected, the link utilization never reaches beyond 50% with Least-Flow and Benchmark-MLU. Nevertheless, ABStAIn and CuTBAck, without requiring instantaneous traffic information, still achieve the same median link utilization and no link ever reaches saturation – the maximum link utilization is 80%.

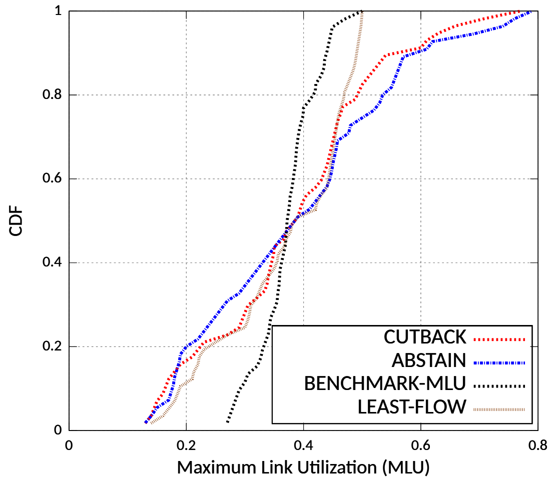


Figure 5.8: CDF of the link utilization for all heuristics –IP networks

4.6 Experiment 5: Illustration Using a Power Model

As there is no universally accepted power model and to avoid having results biased by a particular model so far we avoid having results biased by a particular model so far we quantifying the power savings. To demonstrate the potential for power savings in real life, in this experiment we repeat the same experiment as in 4.5 while using the following power model [95]:

Power Model: In this section, we are interested in the power consumption related to links, i.e., the power consumption of the linecards, and the optical amplifiers along the link. In particular, we consider ports consuming $P_{nic} = 50$ W for each $c_{ref} = 10$ Gbps of link capacity, and amplifiers consuming $P_a = 1$ KW for each $c_{ref} = 10$ Gbps of link capacity, with an amplifier every $m_a = 70$ km. Therefore, we compute the power consumption P_l of a link l, with capacity c_l and length m_l, as: $P_l = \left\lceil \frac{c_l}{c_{ref}} \right\rceil \left(\left\lfloor \frac{m_l}{m_a} \right\rfloor P_a + 2P_{nic} \right)$.

Algorithm	**Power Saving (%)**	**Path Stretch (%)**
Benchmark-MLU ($MLU_T = 0.5$)	33	28.8
Least-Flow ($MLU_T = 0.5$)	19	20
ABStAIn ($ADI_T = 0.5$)	38	24.6
CuTBAck ($ADI_T = 0.5$)	34.5	23

Table 5.3: Comparisons using a specific power model.

Table 5.3 shows that the results are consistent with those in Table 5.2. ABStAIn and CuTBAck are shown to reduce the power consumption by an impressive 38% and 34.5%, respectively, further underscoring the potential for reducing the energy footprint of IP networks.

5 Summary and Discussion

We presented ABStAIn and CuTBAck, two polynomial time heuristics for creating frugal IP networks. The new heuristics are based on the Adequacy Index (ADI), a novel metric that leverages spectral graph theory for quantifying the quality of a frugal graph. Using topologies and traffic matrices from 3 real networks – IBM-Watson, SPRINT and GÉANT - we showed that ABStAIn and CuTBAck are able to switch off about 25% of the links in the network – 80% as many links as a state of the art polynomial time solution and as many as an exponential time approach. This significant frugality was achieved with the median and maximum link utilization in the network below 40% and 80%, respectively. We believe ABStAIn and CuTBAck give network operators a new option for managing the energy consumption of their infrastructure.

Chapter 6

Conclusions and Perspectives

In recent years, the issue of energy efficiency has emerged as one of the main scientific and engineering challenges of our time. In the main part of this thesis, we proposed several methods for extending satellite service life in LEO satellite constellations by reducing the energy consumption of eclipsed satellites following the routing and the resource consolidation principles. In the second part of this thesis, we proposed solutions to push energy-awareness into wired networks.

1 Conclusions

To provide global communication with reasonable latency and low terminal power requirements, constellations made of low earth orbit (LEO) satellites have been the focus of several research works in the recent literature [149]. A LEO satellite performs approximately a full circle around the earth around 14 times over 24 hours, with average cycle duration of around 100 minutes. Out of the 100 minute cycle, around 36 minutes are spent in the earth's umbra – time during which they need to be powered by batteries [9]. As outlined in this thesis, the dominant variable affecting the battery lifetime is the depth of discharge (DoD). For nickel hydrogen and lithium-ion batteries, the kind of which power most of LEO satellite constellations, a 15% reduction in depth of discharge can double their lifetime [11–13].

Since the LEO satellite constellation topology is highly symmetric and uniform, there can be many alternate paths between two satellites. With this in mind, in chapter 2, we presented two new routing metrics – LASER and SLIM– that aim to strike an equilibrium between the network lifetime and performance in LEO satellite constellations. Our basic approach was to leverage the deterministic movement of satellites so as to favor routing traffic over satellites exposed to the sun as opposed to those eclipsed, thereby decreasing the average battery depth of discharge – all without taking a significant penalty in performance. We carried simulations with realistic LEO topology and traffic traces. The results showed that LASER and SLIM can reduce the DoD by about 11% and 16%, respectively, leading to as much as 100% increase in the satellite batteries lifetime. This was accomplished by trading off very little in terms of end-to-end delay.

Given the non-uniform distribution of users in LEO satellite footprints, due to several geographical and/or climatic constraints, some Inter-Satellite Links (ISLs) are expected to be loaded while others remain underutilized. Indeed, LEO satellites covering urban areas dense with users will have more data packets than satellites serving rural regions. The traffic density variance, along with the capacity over-provisioning of the LEO constellations, makes it possible to shut down entire sections during periods of low demand. This has the potential to significantly reduce energy consumption – thus, extending constellation lifetime – without causing major disruptions to network activities. LASER and SLIM do not fulfill all this potential as they only re-route traffic. Ideally, one would identify the minimum set of resources to satisfy the traffic demand and shut down the rest of the network, even though this requires capabilities, such as shutting down satellite transceivers, superior to those assumed in chapter 2. Therefore, in chapter 3, we addressed the problem of identifying the optimal set of links that can be shut down in a satellite constellation subject to maintaining full connectivity and bounding the maximum link utilization. With the problem shown to be NP-hard, we introduced two heuristics, BASIC and SNAP, which represent different tradeoffs in terms of performance and simplicity. We evaluated BASIC and SNAP using realistic LEO topologies and traffic matrices. The results show that BASIC and SNAP can increase the satellite service life by as much as 40% and 80%, respectively. This is accomplished by trading off very little in terms of average path length and congestion. While these results represent significant progress, they are inferior to what we accomplished with LASER and SLIM in chapter 2, which is the opposite of what we expected. The reason for this is that with the problem NP-hard we had to resort to heuristics. As part of future work, we intend to look for better performing heuristics.

In chapter 4, we extended the resource consolidation model presented in chapter 3 by proposing a solution that does not need global knowledge of the network traffic ows. In particular, we proposed a new traffic-agnostic metric for quantifying the quality of the reduced topology, the Adequacy Index (ADI). After showing that the problem of finding the most frugal topology of a LEO network subject to a given ADI is NP-complete, we proposed a polynomial time heuristic to solve it. The proposed solution resulted in battery lifetime improvement comparable to traffic-aware solutions.

In this thesis, we also explored extending the resource consolidation technique presented in chapter 4 to IP wired networks. Our motivation stems from the encouraging results obtained in chapter 4 along with the fact that energy consumption in wired networks has been traditionally overlooked. The potential savings in this area are significant powering wired networks in the United States alone costs an estimated 0.5 - 2.4 billion dollars per year [29]. In chapter 5, we presented ABStAIn and CuTBAck, two polynomial time heuristics for creating frugal IP wired networks. The new heuristics are based on the Adequacy Index (ADI). Simulations using several real network topologies, showed that the ABStAIn and CuTBAck can achieve 38% and 34.5% of energy savings, respectively, compared to the classical DSP model.

2 Perspectives

In the following, we discuss issues we think represent open problems that we would like to pursue in the future.

Energy-Aware Routing and Tra c Class Di erentiation

LEO satellite networks will be called to support many applications in the future. Similarly to traditional Internet, the applications in the next generation satellite network can be categorized into three types: delay sensitive, throughput sensitive, and best effort. However, we have designed LASER and SLIM for the case of a single traffic class. Furthermore, additional research is needed on the sensitivity of traffic to delay. LASER and SLIM schemes can extend satellite service life by detouring traffic to the satellites exposed to the sun as opposed to the eclipsed satellites. As a result, the detoured packets may incur extra delay due to the increase in hop count. This aspect may be unfavorable for delay sensitive traffic such as real-time applications. To deal with this issue, delay sensitive traffic must be differentiated from delay tolerant background traffic. In this regard, an analysis of such scenarios may be interesting, especially to evaluate the trade off between energy saving and quality of service.

Traffic-Aware Pruning and Traffic Granularity

The current traffic-aware pruning techniques are based on the off-peak traffic requests. It would be interesting to evaluate the algorithms to sudden traffic surges and traffic variations. A high number of network reconfigurations may actually degrade the network performance (i.e., each reconfiguration needs a new convergence period for the routing protocol). Analyzing the tradeoffs between the energy efficiency and the number of network reconfigurations may hence be an interesting research problem. Also, the impact of the network reconfigurations on traffic losses should be evaluated.

Traffic-Agnostic Pruning and Maximum Link Utilization

The traffic-agnostic solutions are based on knowledge of the network topology, without traffic awareness, so they do not guarantee specific traffic requirements. As also pointed in this thesis, having an accurate picture of the link utilizations in the network is very difficult not least because traffic levels depend on an intricate set of actors, including the routing and traffic engineering policies. Therefore, traffic-agnostic solutions may be defined considering different levels of available information. For example, higher level of information may be considered the current load of links and the history of the past decisions.

Network Pruning Schemes and Device Failures

Methods to protect energy-aware pruning solutions from network failures will be necessary. Different working statuses can be defined, each corresponding to a specific set of devices being shut down due to failure. It is possible to define and optimize the design formation as a global optimization over possible different working statuses. A detailed analysis of the performance and robustness of the pruning solutions formulation with the probability of devices failing could be an interesting direction to pursue.

It is our hope that the findings in this thesis may contribute to a better understanding of Energy Efficiency in LEO satellite constellations and IP networks while stimulating further work in this area.

Publications

International Journals with Peer Review

- Hussein, Mohammed, Gentian Jakllari, and Beatrice Paillassa. "Network pruning for extending satellite service life in LEO satellite constellations." Wireless Networks (2015): 1-13.

International Conferences with Peer Review

- Mohammed Hussein, Gentian Jakllari, Beatrice Paillassa. On Routing for Extending Satellite Service Life in LEO Satellite Networks (regular paper). Dans :

  IEEE Global Communications Conference (GLOBECOM 2014), Austin, TX, USA, 08/12/2014-12/12/2014, IEEE, p. 2832-2837, 2014.

- Mohammed Hussein, Gentian Jakllari, Beatrice Paillassa. Frugal Topologies for Saving Energy in IP Networks (regular paper). Dans :

  IEEE Conference on Local Computer Networks (LCN 2015), Clearwater Beach, Florida, USA, 26/10/2015-29/10/2015, IEEE, 2015.

- Mohammed Hussein, Gentian Jakllari, Beatrice Paillassa. Network Pruning for Extending Satellite Service Life in LEO Satellite Constellations (regular paper). Dans :

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