Data-Plane Energy Efficiency of a Next-Generation Internet Architecture

Seyedali Tabaeiaghdaei
Department of Computer Science
ETH Zürich, Switzerland

Adrian Perrig
Department of Computer Science
ETH Zürich, Switzerland

***Abstract*—In the face of the ever-increasing power consumption of the information and communication technology sector, next-generation Internet architectures offer an opportunity to improve the energy consumption of the Internet. The SCION architecture is unique in that it has reached commercial deployment and thus opens up opportunities for estimating and understanding the promised energy efficiency from a realistic perspective.**

In this work, we introduce a method that uses the available energy consumption models for the current Internet architecture to estimate the energy efficiency of SCION's data plane. By applying this method to the best available power consumption models of the Internet, we show that while providing advanced security and availability guarantees, SCION can reduce global data plane power consumption by around 700 MW. We further investigate the impact of the SCION's quality of service (QoS) extension on data plane's power consumption and conclude that SCION with its QoS extension can reduce the power consumption of the Internet by up to 2.88 GW. Therefore, SCION, with its QoS extension, reduces the power consumption of the Internet and the whole ICT sector by up to 9.4% and 1.3%, respectively.

***Index Terms*—Power consumption, next-generation Internet architecture, Quality of Service, QoS**

I. INTRODUCTION

It is estimated that the information and communication technology (ICT) sector consumed 2000 TW h electrical energy in 2020 (which is around 7% of global electricity generation) and is responsible for 2.7% of global CO_2 emissions [1]–[5]. The electricity consumption impact of the ICT sector is expected to grow to 21% in 2030 [6], of which networks account for a 27% share in 2030 (13% in 2020) [1].

Given the rising concerns regarding climate change and the environmental impact of the ICT sector, numerous researchers have studied the power consumption and energy efficiency of the Internet [1], [4], [6]–[10], trying to estimate the power consumption of the Internet and predict the future trend by proposing various models. These models, however, do not take into account the potential changes to the Internet's operation proposed by next-generation Internet architectures.

Several next-generation architectures have been proposed, typically substantially modifying the Internet's operation. These modifications can significantly impact energy efficiency, necessitating investigation prior to large-scale deployment. SCION [11] is a next-generation Internet architecture that provides strong security and availability guarantees. SCION uses packet-carried forwarding state to forward packets, a fundamental architectural change with a tremendous potential impact on the Internet's energy efficiency. Furthermore, SCION's inter-domain bandwidth reservation system can simplify congestion control algorithms, affecting the power consumption of both networks and end hosts significantly. As SCION has reached commercial deployment [12], it is important to study its power impact.

In this paper, we introduce a method to analyze SCION's impact on the data-plane power consumption. Using this method we first identify all modifications required by SCION to all different types of devices in the Internet. Then, we investigate how these modifications change the power consumption of each device by taking into account the available power consumption models for those devices. Finally, we investigate how the change in the power consumption of each device changes the power consumption of the whole Internet using the available power consumption models. This methodology is independent of the available power consumption models of the Internet and network devices and therefore can be applied to any available power consumption model. However, the accuracy of the analysis depends on the accuracy of the underlying models.

In Section III we describe this method in more detail by applying it to the available power consumption models of the Internet, and providing an estimate of how SCION changes the power consumption of the Internet. Furthermore, in Section IV we investigate how the inter-domain QoS extension of SCION impacts the Internet's power consumption.

II. BACKGROUND ON SCION

SCION is a path-aware Internet architecture providing routing security, availability, path transparency, and path control.

A. Architecture

To improve scalability, SCION groups ASes into *isolation domains (ISDs).* An ISD is administered by its ISD core, typically consisting of several core ASes. Core ASes provide connectivity to core ASes in other ISDs, and issue certificates for non-core ASes in their own ISD. In each ISD, all non-core ASes are either direct or indirect customers of core ASes.

B. Data plane

SCION uses packet-carried forwarding state to forward packets: the inter-domain forwarding path is included in packet headers, and routers forward packets using this information.

978-1-6654-9792-3/22/$31.00 ©2022 IEEE

Thus, SCION border routers can thus avoid storing and accessing large global (inter-domain) forwarding tables.

SCION paths consist of at most three *path segments*: an up-, a core- and a down-path segment. Up-path segments connect non-core ASes to core ASes within an ISD, core-path segments connect core ASes (within or between ISDs), and down-path segments connect core ASes to non-core ASes within an ISD. Each path segment contains one *info field* and a variable number of *hop field*s. An info field contains information about the path segment. A hop field contains information about an AS hop on the path segment, such as the interface identifiers from which the packet should enter and exit the AS and a message authentication code (MAC) generated by the AS's secret key (during path-segment construction in the control plane) to prevent hosts from using unauthorized paths. The SCION header contains two pointers called *current info field* and *current hop field* pointing to the info field and hop field the packet is currently being forwarded on.

Upon receiving a packet, each border router first verifies the current hop field's MAC, then forwards the packet to the next inter-domain interface specified in the current hop field.

C. Control plane

SCION introduces a hierarchical control plane with two levels: among all core ASes, and between core and non-core ASes within an ISD.

In the first level, which is called *core beaconing*, core ASes' *beacon servers* collaborate to construct core-path segments by periodically 1) initiating *path-segment construction beacons (PCBs)*, 2) appending their AS hop to PCBs received from other core ASes, and 3) sending initiated and extended PCBs to their neighboring core ASes. Core beacon servers periodically select a subset of received PCBs, extract their core-path segments, and register them to the core *path server* in the same AS.

In the second level, which is called *intra-ISD beaconing*, the beacon server of each core AS periodically initiates PCBs towards its AS, and sends them to its customers. Non-core beacon servers, however, do not initiate PCBs. They periodically append their own AS hop to the PCBs received from their providers and disseminate them to their customers. Non-core beacon servers periodically select a subset of received PCBs, extract their up- and down-path segments, and register them at the local and the core path servers, respectively.

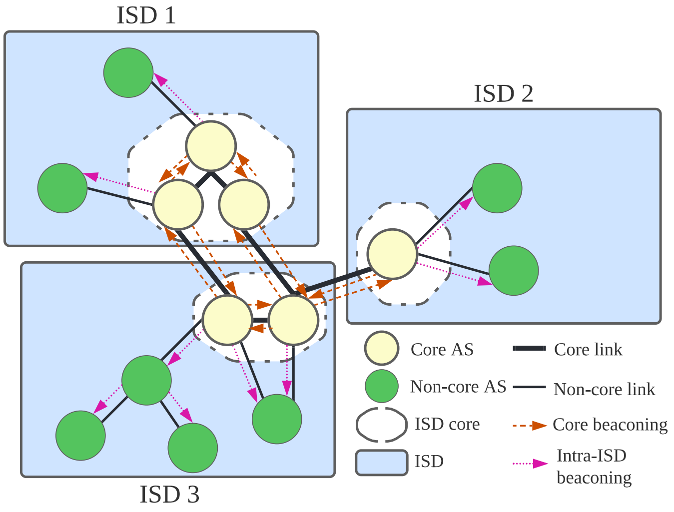

Fig. 1: Overview of the SCION Internet architecture.

To construct end-to-end paths, SCION hosts need to iteratively fetch up-, core-, and down-path segments by requesting them from path servers.

D. COLIBRI

As a path-aware Internet architecture, SCION enables inter-domain QoS by reserving bandwidth on inter-domain paths. COLIBRI [13] is the SCION QoS extension that provides end-to-end bandwidth reservation through reserving bandwidth on up-, core-, and down-path segments.

III. THE IMPACT OF SCION ON THE POWER CONSUMPTION OF THE INTERNET'S DATA PLANE

In this section, we describe our method to analyze the impact of SCION on the power consumption of the Internet's data plane and apply it to the available models for the power consumption of the Internet to provide an estimation of how SCION would change the data plane's power consumption. This method consists of the following steps:

- identifying how SCION modifies packet processing on network devices (e.g., routers' forwarding engine, or queuing),
- identifying how SCION modifies each data packet's structure and length,
- identifying which devices are affected by the aforementioned modifications and analyzing how these modifications change their power consumption according to the available power consumption models for each network device type,
- estimating the global power consumption impact of the required changes in each type of network devices based on available models for the power consumption of the Internet, and
- accumulating the global power impacts resulting from changing all different types of affected network devices.

In the remainder of this section, we use this methodology to provide an estimation of how SCION (without its QoS extension) would change the power consumption of the Internet. In this analysis, we use the currently available models for the power consumption the Internet and various network devices.

To model the power consumption of the Internet, researchers segment it into the core network, metro/edge networks, and access networks [7], [9], [10], [14]. The core network is an optical multi-layer network known as an IP-over-WDM network consisting of high-capacity core routers, and wavelength division multiplexing (WDM) links that provide a broadband physical connection between the routers [15], [16]. Metro and edge networks are the interfaces between access networks and the core network [7]. Access networks provide end-hosts with an Internet connection using a wide variety of wired or wireless technologies.

SCION reduces the power consumption of the Internet's data plane by not performing longest-prefix matching on (core) routers, but increases power consumption because of increasing packet size (forwarding path is included in packet header), and routers perform per-packet MAC verification.

In the following sections, we analyze how these modifications to the Internet's data plane affect the power consumption of core routers, WDM links, metro/edge networks and access networks. Then, we estimate the net impact of SCION on the Internet's power as the sum of its partial impacts.

A. Impact on a single core router

We estimate SCION's impact on a core router's power by analyzing how it changes different router components' power. In this analysis, we use the model Hinton et al. [9] propose for the core router power. According to this model, a core router's power (P_{CR}) consists of four main power components: control plane ($P_{Control}$), data plane (P_{Data}), power supply and internal cooling ($P_{P\&C}$), and input/output ($P_{I/O}$).

We can further decompose the data plane power into three power components: forwarding engine (P_{FE}), switching fabric (P_{SF}), and buffer (P_B), see Table I.

Each power component decomposes into idle and dynamic (traffic-dependent) power components. By analyzing how SCION affects different idle and dynamic power components, we estimate the router power in SCION relative to IP. A fundamental assumption in our analysis is that each component's relative contribution to the idle, dynamic and total power of a router are equal.

1) Impact on the forwarding engine: According to Table I, the forwarding engine, which makes forwarding decisions, is responsible for 32% of a core router power. Almost all this power is consumed by the forwarding-table lookup process in which the forwarding engine performs longest-prefix matching over a large forwarding table. IP routers store the global IP forwarding table in ternary content-addressable memory (TCAM), enabling longest-prefix matching over large forwarding tables at line speed. TCAMs are among the most power-hungry memory technologies, at least 75 times more power-intense than other technologies (like SRAM) [17]. They are the main reason that the forwarding engine consumes a significant share of router power. As the global IP prefix space increases to almost one million prefixes in 2021 [18], IP routers need larger TCAM chips to store ever-larger forwarding tables.

TABLE I: A Pareto analysis breakdown of power consumption of a core router, from Hinton et al. [9].

Router component	Share of total power consumption (%)
Power supply & cooling ($P_{P\&C}$)	33
Forwarding engine (P_{FE})	32
Switching fabric (P_{SF})	15
Control plane ($P_{Control}$)	10
Input/output ($P_{I/O}$)	6
Buffers (P_B)	4

SCION uses packet-carried forwarding state. Thus, its routers do not perform per-packet longest-prefix matching over a large forwarding table. Instead, they parse each packet's current hop field, verify its MAC, and look up the exact match of its egress interface in a small table. Therefore, SCION changes the inter-domain table match type from longest-prefix matching to exact matching and reduces the size of the forwarding table from almost a million (the same order as the global IP prefix space size) to thousands for large ASes and hundreds for small ASes (the same order as the number of interfaces of a single AS).

Performing exact matching instead of longest-prefix matching, TCAM chips can be completely turned off or removed from SCION routers as performing exact matching does not need a TCAM. With memory technologies (like SRAM) at least 75 times more power-efficient than TCAMs [17], and at least two orders of magnitude smaller tables, the inter-domain table lookup process on a SCION router is around 7500 times more power-efficient than on an IP router. These modifications to the forwarding engine affect both dynamic and idle power components, reducing the router power by $\approx 31\%$. We denote the change in the core router power because of removing TCAM by ΔP_{CR}^{TCAM}. Therefore, $\Delta P_{CR}^{TCAM} = -0.31 P_{CR}$.

On the other hand, the forwarding engine of a SCION router computes an AES-CMAC [19] over the path's current hop field to verify whether it is generated by the current AS or not. This operation increases the forwarding engine power (P_{FE}) of the router. To estimate this increase, we use the 128-bit AES implementation on a Virtex-6 [20] FPGA proposed by Soltani et al. [21], which consumes 2.8 W at 100 Gbps throughput.

To estimate the power overhead of the AES-CMAC operation for a SCION router, we calculate the number of such AES modules a router needs by dividing the router's maximum packet-throughput by the AES module's.

We calculate the maximum packet-throughput of the AES module by dividing its throughput (i.e., 100 Gbps) by the number of bits per packet over which the forwarding engine computes the MAC (i.e., 128 bits), yielding a packet-throughput of 780 Mpps.

We calculate the maximum packet-throughput of a typical core router by dividing the throughput of a Cisco CRS 16-slot single shelf system [22] (i.e., 12.8 Tbps) by the size of the smallest SCION frame (i.e., 78 bytes, a frame containing only layer 2 and SCION headers with a one-hop path), resulting in a maximum packet-throughput of 20.5 Gpps.

Therefore, verifying MACs at the peak rate introduces

$$\frac{20.5\,\text{Gpps}}{780\,\text{Mpps}} \times 2.8\,\text{W} \approx 75.6\,\text{W} \tag{1}$$

power overhead to such a router, corresponding to 0.5% of its total power ($\Delta P_{CR}^{MAC} = +0.005 P_{CR}$), given that the Cisco CRS 16-slot single shelf system consumes 16.8 kW power.

The net change SCION introduces to the forwarding engine power of a router (ΔP_{CR}^{FE}) is

$$\begin{aligned}\Delta P_{CR}^{FE} &= \Delta P_{CR}^{MAC} + \Delta P_{CR}^{TCAM} \\ &= +0.005P_{CR} - 0.31P_{CR} \\ &= -0.305P_{CR},\end{aligned} \tag{2}$$

indicating that the router power decreases by 30.5%.

2) Impact on switching fabrics and buffers: By including forwarding paths in packet headers, SCION increases packet size, which increases the dynamic switching fabric and buffer power as routers consume more energy to switch and queue larger packets. The increased packet size increases their idle power as well since a router needs higher-capacity switching fabrics and buffers. We assume that the idle and dynamic power components increase proportionally with SCION's communication overhead.

The header-size overhead of SCION depends on the length of the path a packet carries. According to Huston [23] the average IPv4 AS-path length in the Internet is 5.3. For such an AS-path length, the SCION header with three path-segments (up- core- and down-path segments) is 107.6 bytes longer on average than the IPv4 header according to the SCION header specification [24]. By calculating the average IP frame size (i.e., 583 bytes) using the Internet packet-size distribution provided by Sinha et al. [25], we conclude that the 107-byte header-size overhead of SCION results in 18.4% communication overhead relative to the current Internet.

This 18.4% communication overhead corresponds to an 18.4% increase in the power of switching fabrics (P_{SF}) and buffers (P_B). According to Table I switching fabrics and buffers together consume 19% of the router power. Hence, the communication overhead of SCION increases the total power of a router by

$$\Delta P_{CR}^{SF\&B} = +0.184 \times 0.19P_{CR} = +0.035P_{CR}, \tag{3}$$

indicating that the router power increases by 3.5%.

3) Impact on the control plane and I/O: SCION separates the data plane from the inter-domain control plane by delegating control plane tasks to beacon and path servers in each AS, shifting control plane power from routers to these servers. Previous work demonstrates that the SCION control plane performs around 200 times less work on a per-path basis than BGP [12], thus we consider the overhead to be negligible and conservatively assume the power of control plane and I/O ($\Delta P_{CR}^{Ctrl\&I/O} = 0$).

4) Impact on the power supply and cooling: SCION does not directly change the power supply and cooling power component. However, this component is proportional to other components [15], which are affected by SCION.

The net change SCION introduces to all power components, excluding power supply and cooling is

$$\begin{aligned}\Delta P_{CR} - \Delta P_{CR}^{P\&C} &= \Delta P_{CR}^{FE} + \Delta P_{CR}^{SF\&B} + \Delta P_{CR}^{Ctrl\&I/O} \\ &= -0.305P_{CR} + 0.035P_{CR} + 0 \\ &= -0.27P_{CR} \\ &= -0.27 \times \frac{P_{CR} \times (P_{CR} - P_{P\&C})}{P_{CR} - P_{P\&C}} \\ &= -0.27 \times \frac{P_{CR} \times (P_{CR} - P_{P\&C})}{0.67P_{CR}} \\ &\approx -0.4 \times (P_{CR} - P_{P\&C}),\end{aligned} \tag{4}$$

indicating that the sum of all other components decreases by 40%. Therefore, power supply and cooling component is reduced by 40% as well:

$$\Delta P_{CR}^{P\&C} = -0.4P_{P\&C}. \tag{5}$$

By substituting $\Delta P_{CR}^{P\&C}$ with $-0.4P_{P\&C}$ in eq. (4) we obtain the total change in the router power:

$$\begin{aligned}\Delta P_{CR} - (-0.4P_{P\&C}) &\approx -0.4 \times (P_{CR} - P_{P\&C}) \\ \Delta P_{CR} &\approx 0.4P_{CR}.\end{aligned} \tag{6}$$

Equation (6) suggests that SCION decreases the total power consumption of a core router by 40%. Figure 2 illustrates cumulative router components' power in IP, standard SCION, and SCION with COLIBRI (see Section IV), and Figure 3 illustrates the standard SCION's power savings and overheads in a router.

B. Global impact on all core routers' power

In this section, we analyze how using SCION core routers changes the Internet's power. Baliga et al. [7] have proposed models for the global power consumption of core routers, WDM devices, metro/edge and access networks as functions of the number of users and their average access rate. We use their predictions for the devices' power efficiency in 2020.

In 2021, there are 4.3 and 1.2 billion mobile and fixed broadband Internet users [26], [27] with average access rates of

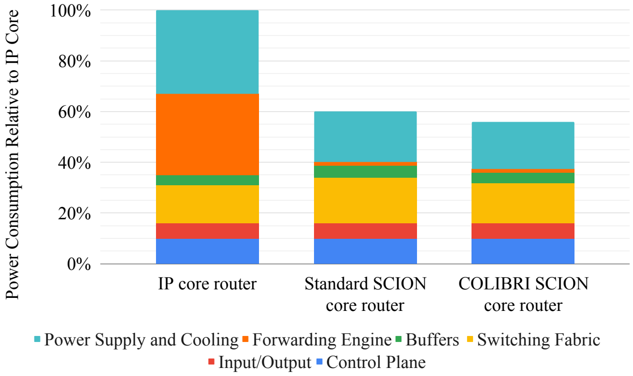

Fig. 2: Cumulative power consumption of a core router's components in IP, standard SCION and SCION with COLIBRI relative to the total power consumption of an IP core router.

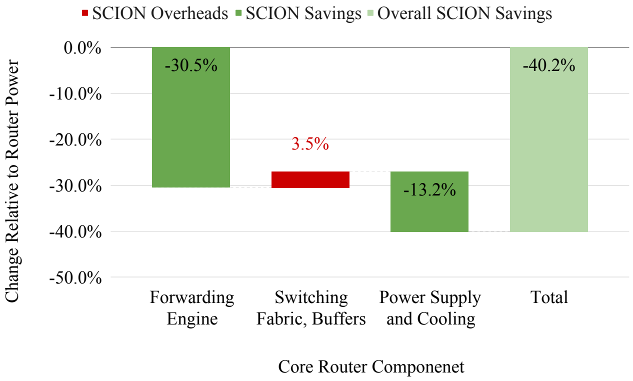

Fig. 3: Power savings and overheads the standard SCION (without COLIBRI) introduces to a core router.

54 Mbps and 105 Mbps, respectively [28]. According to Baliga et al.'s model, core routers consume 1.3 W and 2.07 W per user at the 50 Mbps and 100 Mbps access rates, respectively. Therefore, all core routers consume

$$\begin{aligned} P^{CR}_{Global} &= P^{CR}_{user,rate=50\,\mathrm{Mbps}} \times Users_{Mobile} \\ &+ P^{CR}_{user,rate=105\,\mathrm{Mbps}} \times Users_{Fixed} \\ &= 2.07 \times 1.2 \times 10^9 + 1.3 \times 4.3 \times 10^9 \\ &= 8.074\,\mathrm{GW}. \end{aligned} \tag{7}$$

Since SCION reduces each router's power by 40%, it reduces their global power consumption by

$$\Delta P^{CR}_{Global} = -0.4 \times 8.074\,\mathrm{GW} = -3.23\,\mathrm{GW}. \tag{8}$$

C. Impact on WDM devices

1) Impact on a single WDM device: Since WDM devices do not perform longest-prefix matching, SCION does not reduce that overhead. However, SCION's communication overhead increases the WDM power. Similar to switching fabrics and buffers in core routers, idle and dynamic power of a WDM device proportionally increase with the communication overhead. Therefore, SCION increases WDM power by 18.4% ($\Delta P_{WDM} = +0.184 P_{WDM}$).

2) Global impact: To estimate the absolute increase in the global WDM power, we use the model proposed by Baliga et al. [7] for the WDM power per user per access rate similar to the one for core routers in Section III-B. According to this model, WDM devices consume 0.3 W and 0.5 W per user at the 50 Mbps and 100 Mbps access rates, respectively, resulting in a global power consumption of 1.9 GW. Therefore, the 18.4% communication overhead of SCION increases the global WDM power by 0.35 GW ($\Delta P^{WDM}_{Global} = +0.35\,\mathrm{GW}$).

D. Impact on metro/edge routers

1) Impact on a single metro or edge router: SCION does not modify the forwarding engine power of metro/edge routers because 1) these routers do not store the global forwarding table, so packet-carried forwarding state does not reduce their power significantly, and 2) SCION does not modify intra-domain forwarding.

However, SCION's communication overhead increases their switching fabric and buffer power by 18.4%, similar to core routers. According to the model proposed by Vishwanath et al. [29], metro and edge router power is dominated by switching fabric power, resulting in approximately 18% router power increase by SCION. ($\Delta P_{ER} = +0.18 P_{ER}$ and $\Delta P_{MR} = +0.18 P_{MR}$).

2) Global impact: According to Baliga et al. [7], metro/edge networks consume 0.67 W and 1 W per user at the 50 Mbps and 100 Mbps access rates, respectively. Using the same method as in Section III-B results in a global power consumption of 4.08 GW for metro/edge networks. Therefore, the 18% power increase corresponds to an absolute power increase of 0.74 GW. ($\Delta P^{ER}_{Global} + \Delta P^{MR}_{Global} = +0.74\,\mathrm{GW}$).

E. Impact on access networks

Due to the same reasons we mentioned in Section III-D, eliminating longest-prefix matching by SCION does not change the access network power. However, its communication overhead introduces power-consumption overhead to the access network.

1) Wired access: SCION's communication overhead does not change the power of most wired access network technologies as their power does not vary by increasing access rate according to the model proposed by Baliga et al. [7].

2) Mobile access: In mobile access networks, however, the communication overhead of SCION increases power proportionally. Pihkola et al. [8] have estimated the energy intensity of mobile access networks to be 0.3 kW h/GB in 2017 and predicted that it would reduce to 0.1 kW h/GB in 2020. Using their predicted energy intensity and the global mobile traffic (i.e., 55 EB per month in 2021 [30]), the 18.4% communication overhead of SCION would result in a global power overhead of 1.41 GW ($\Delta P^{Mobile}_{Global} = +1.41\,\mathrm{GW}$).

However, we can alleviate this overhead using header compression where the mobile device and the base station negotiate paths for each flow, and the base station fills the packet headers with the negotiated paths. Therefore, the header size of the packet sent from/to the end host to/from the base station would be close to the IP header size, resulting in negligible overhead.

F. Global impact on networks' power

We estimate the net change SCION introduces to communication networks' power by accumulating changes it introduces to different network segments:

$$\begin{aligned} \Delta P_{Global} &= \Delta P^{WDM}_{Global} + \Delta P^{ER}_{Global} + \Delta P^{MR}_{Global} \\ &+ \Delta P^{Mobile}_{Global} + \Delta P^{CR}_{Global} \\ &= 0.35 + 0.74 + 1.41 - 3.23 \\ &= -0.73\,\mathrm{GW}. \end{aligned} \tag{9}$$

Figure 4 illustrates power savings and power overheads of standard SCION (without QoS extension) in different parts of communication networks.

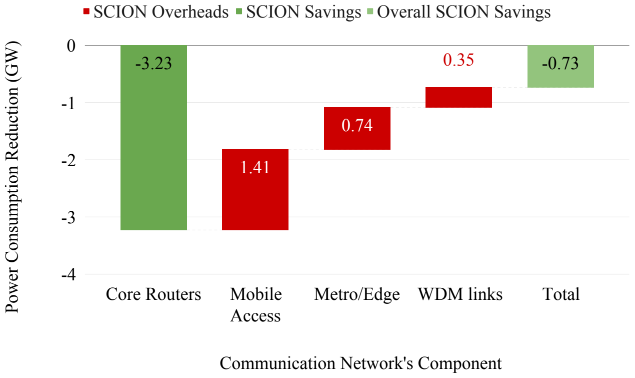

Fig. 4: SCION's global power savings and overheads without COLIBRI.

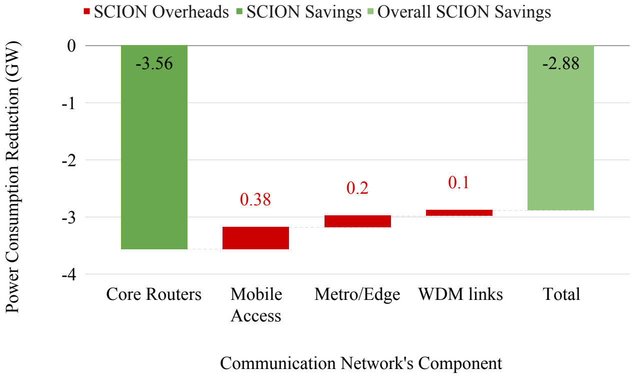

Fig. 5: SCION's global power savings and overheads with COLIBRI.

IV. IMPACT OF QOS ON POWER CONSUMPTION OF THE INTERNET

As COLIBRI [13] (the QoS extension of SCION) does not introduce any significant change to the core router forwarding engine, it enables the same reduction in its power component as standard SCION.

On the other hand, COLIBRI reduces the communication overhead of SCION mainly in two ways: 1) reducing number of ACK messages, and 2) reducing the size of hop fields and the number of info fields in SCION paths.

Since COLIBRI guarantees end-to-end bandwidth reservation, the number of ACK messages can be reduced in the transmission layer. Here, we analyze the best case where no ACK message is needed. The packet-size distribution of the Internet [25] suggests that 32% of packets on the Internet are as small as the minimum packet size. As these packets do not contain any application-layer payload, we assume they are ACK messages. Removing ACK messages increases the average frame size on the Internet from 583 to 833, decreasing the header to payload ratio, thus lowering SCION's communication overhead.

Furthermore, COLIBRI paths consist of only one path segment (instead of at most three in standard SCION), and their hop fields are 4 bytes shorter than standard SCION paths' hop fields, which reduces the average header-size overhead of SCION from 107.6 bytes to 70.4 bytes for the average IPv4 AS-path length (i.e., 5.3 [23]).

Therefore, the expected communication overhead of SCION with COLIBRI relative to IP is

$$\begin{aligned} &\frac{\text{\# of COLIBRI packets}}{\text{\# of Internet packets}} \times \frac{\text{Avg COLIBRI frame size}}{\text{Avg Internet frame size}} \\ &\quad = (1 - 0.32) \times \frac{833 + 70.4}{583} = 1.05, \end{aligned} \tag{10}$$

reducing the communication overhead from 18.4% to 5%.

Using the same methodology as in Section III, we calculate the global impact of SCION with COLIBRI by substituting the 18.4% communication overhead with 5% in all formulae. Our calculations suggest that the full deployment of SCION with COLIBRI reduces networks' power by up to 2.88 GW ($\Delta P_{Global,COLIBRI} = -2.88\,\text{GW}$). Figure 5 illustrates the global impact of SCION with COLIBRI on the power consumption of communication networks.

The up to 2.88 GW power saving of SCION corresponds to almost 9.4% and 1.3% of the networking (excluding data centers) and the whole ICT sectors' power consumption in 2020, respectively, given the estimated 270 TW h and 1990 TW h energy consumed by those sectors in 2020, respectively [1].

V. FUTURE IMPACT ON THE POWER CONSUMPTION

Assuming TCAM's relative contribution to the core router power remains the same, SCION can save 9.3 GW in 2030 according to Andrae's prediction [1]. However, with growing IPv6 adoption and the expected slow down in network devices' power-efficiency improvement rate, it is expected that TCAM chips will have an even more significant share of the core router power [6], [31], [32], increasing the power savings by SCION beyond the estimated 9.3 GW in 2030.

VI. RELATED WORK

Several prior works propose different methods for analyzing or modeling the energy intensity of the Internet. These works fall into three categories: top-down approaches, bottom-up approaches, and model-based approaches [33].

1) Top-down approaches: researchers divide the total electricity consumption of the Internet (or a part of it) by the Internet traffic of that part within a period of time, providing the average energy consumption of the Internet per transferred data. These methods usually lead to overestimating the energy intensity of the Internet as they do not take the idle energy consumption of network devices into account, which is responsible for the majority of the energy consumption of network devices. Studies conducted by Koomey et al. [34], Taylor et al. [35], Weber et al. [36], Lanzisera et al. [37], and Andrae et al. [6] fall into this category.

2) Bottom-up approaches: researchers generalize the energy intensity values they have obtained from case studies through direct measurement or observation. For example, Coroama et al. [38] present a pure bottom-up assessment of the energy intensity of a video conference between Switzerland and Japan. Their study achieves high accuracy, as they knew the exact path and all the network devices between the end domains. However, the generalization to the whole Internet may lead to considerable error.

3) Model-based approaches: researchers model parts of the Internet based on network design principles and then apply vendor-provided energy consumption of each device in that part of the Internet to their model to determine the total energy consumption of that part. In one of the earliest studies in this area, Baliga et al. [39] propose a model for core routers' and WDM links' energy consumption as a function of the number of Internet subscribers and their access rate. In their later work [40] they propose models for the energy consumption of core, metro/edge, and access networks. Vishwanath et al. [41] propose a model for power consumption of high-capacity switches and routers in metro and edge networks taking both idle and dynamic power into account, and verify their model with direct measurements. In another work [42], they predict the future trends in the power consumption of different parts of the Internet with and without considering the improvement in devices' energy efficiencies.

In the context of next-generation Internet architectures, Lee et al. [43] estimate the power consumption of Content-Centric Networking (CCN). Chen et al. [44] compare power consumption of SCION with Named Data Networking (NDN [45]), but they only analyze SCION's impact on the dynamic power consumption of core routers' forwarding engine, ignoring the impact of SCION on idle power consumption, on other parts of a core router, and on other network components.

VII. Conclusion and Future Work

In this work, we propose a method to analyze the power consumption of the SCION next-generation Internet architecture's data plane and its QoS extension based on the models for the power consumption of communication networks. A major advantage of this method is its generality that makes it applicable to different power consumption models of different parts of the communication networks.

However, the accuracy of the final results derived by the proposed method depends on the accuracy of the underlying power consumption models. To the best of our knowledge, the power consumption models we use are the currently latest and most reliable. Nonetheless, not all changes in the Internet infrastructure in recent years are reflected, which could have an impact on the power consumption models of the Internet. In particular, two changes should be considered in future work:

- the transition from the conventional hierarchy of the Internet in which most of the Internet traffic used to carried by carrier ISPs towards a more flat model due to the deployment of edge computing, direct peerings at IXPs, and intra- and inter-datacenter communications,
- the deployment of multi-protocol label switching (MPLS) in core networks, which reduces their power consumption considerably as the longest-prefix matching is only performed once per ISP at the (core) border router and all other (core) routers within the ISP only perform label matching which is more energy efficient than longest-prefix matching. The available models do not differentiate between IP and MPLS core routers for modeling their power consumption.

As the Internet continues to evolve, it is clear that the power consumption models of the Internet require continuous updates. Nevertheless, our analysis based on the method we propose and using the best available power consumption models, indicates that a secure Internet architecture like SCION could reduce the power consumption of the Internet while providing strong security guarantees. Interestingly, our analysis suggests that a QoS extension can decrease the power consumption of an Internet architecture. Our results indicate SCION with its QoS extension can decrease the power consumption of the Internet (excluding data centers) by up to 9.4%.

These results open up exciting research directions to study next-generation architectures' energy consumption. An open problem in this context is the question of how to construct an Internet architecture to minimize power consumption. We hope that this paper provides an early indication about the energy reduction potential of architectural mechanisms, and encourages further research on this important topic.

VIII. Acknowledgments

We are grateful to Daniel Bertolo, Claude Hähni, Fabian Mauchle, and Dave Oran for stimulating discussions and inputs on the power consumption of network devices. We gratefully acknowledge support from ETH Zurich, and from the Zurich Information Security and Privacy Center (ZISC).

References

[1] A. Andrae, "New perspectives on internet electricity use in 2030," *Engineering and Applied Science Letters*, vol. 3, pp. 19–31, 06 2020.

[2] International Energy Agency (IEA). (2020) Data and Statistics. [Online]. Available: https://perma.cc/72QW-26D9

[3] A. Andrae, L. Hu, L. Liu, J. Spear, and K. Rubel, "Delivering Tangible Carbon Emission and Cost Reduction through the ICT Supply Chain," *International Journal of Green Technology*, vol. 3, pp. 1–10, Nov 2017.

[4] A. Andrae, "Projecting the Chiaroscuro of the Electricity Use of Communication and Computing from 2018 to 2030," Feb 2019.

[5] J. Lorincz, A. Capone, and J. Wu, "Greener, Energy-Efficient and Sustainable Networks: State-Of-The-Art and New Trends," *Sensors*, vol. 19, p. 4864, Nov 2019.

[6] A. Andrae and T. Edler, "On Global Electricity Usage of Communication Technology: Trends to 2030," *Challenges*, vol. 6, no. 1, pp. 117–157, 2015. [Online]. Available: https://www.mdpi.com/2078-1547/6/1/117

[7] J. Baliga, R. Ayre, K. Hinton, W. V. Sorin, and R. S. Tucker, "Energy consumption in optical ip networks," *Journal of Lightwave Technology*, vol. 27, no. 13, pp. 2391–2403, 2009.

[8] H. Pihkola, M. Hongisto, O. Apilo, and M. Lasanen, "Evaluating the Energy Consumption of Mobile Data Transfer—From Technology Development to Consumer Behaviour and Life Cycle Thinking," *Sustainability*, vol. 10, p. 2494, 07 2018.

[9] K. Hinton, J. Baliga, M. Feng, R. Ayre, and R. S. Tucker, "Power consumption and energy efficiency in the Internet," *IEEE Network*, vol. 25, no. 2, pp. 6–12, 2011.

[10] D. Schien, V. C. Coroama, L. M. Hilty, and C. Preist, “The Energy Intensity of the Internet: Edge and Core Networks,” in *ICT Innovations for Sustainability*, ser. Advances in Intelligent Systems and Computing. Springer, 2015, vol. 310, pp. 157–170.

[11] A. Perrig, P. Szalachowski, R. M. Reischuk, and L. Chuat, *SCION: A Secure Internet Architecture*, ser. Information Security and Cryptography. Cham: Springer International Publishing, 2017.

[12] C. Krähenbühl, S. Tabaeiaghdaei, C. Gloor, J. Kwon, A. Perrig, D. Hausheer, and D. Roos, “Deployment and Scalability of an Inter-Domain Multi-Path Routing Infrastructure,” in *Proceedings of ACM International Conference on Emerging Networking EXperiments and Technologies (CoNEXT)*, 2021.

[13] G. Giuliari, D. Roos, M. Wyss, J. A. Garcia-Pardo, M. Legner, and A. Perrig, “Colibri: A Cooperative Lightweight Inter-domain Bandwidth-Reservation Infrastructure,” in *Proceedings of ACM International Conference on Emerging Networking EXperiments and Technologies (CoNEXT)*, 2021.

[14] K. Hinton, F. Jalali, and A. Matin, “Energy Consumption Modeling of Optical Networks,” *Photonic Netw. Commun.*, vol. 30, no. 1, p. 4–16, Aug 2015.

[15] W. Heddeghem, F. Idzikowski, W. Vereecken, D. Colle, M. Pickavet, and P. Demeester, “Power consumption modeling in optical multilayer networks,” *Photonic Network Communications*, vol. 24, 10 2012.

[16] A. Ahmad, A. Bianco, E. Bonetto, L. Chiaraviglio, and F. Idzikowski, “Energy-Aware Design of Multilayer Core Networks,” *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 5, pp. A127–A143, Oct 2013.

[17] C. Chen, D. Barrera, and A. Perrig, “Modeling data-plane power consumption of future Internet architectures,” in *Proceedings of the IEEE Conference on Collaboration and Internet Computing (CIC)*, Nov. 2016.

[18] T. Bates. (2020) CIDR report. [Online]. Available: https://perma.cc/H2BM-LGK9

[19] J. Song, R. Poovendran, J. Lee, and T. Iwata, “The AES-CMAC Algorithm,” RFC 4493 (Informational), RFC Editor, Fremont, CA, USA, Jun. 2006.

[20] XILINX. (2015) Virtex-6 Family Overview. [Online]. Available: https://perma.cc/V3VA-SVHP

[21] A. Soltani and S. Sharifian, “An ultra-high throughput and fully pipelined implementation of aes algorithm on fpga,” *Microprocessors and Microsystems*, vol. 39, no. 7, pp. 480–493, 2015.

[22] CISCO. (2016) Cisco CRS 16-Slot Single-Shelf System Data Sheet. [Online]. Available: https://perma.cc/V8YW-XD9X

[23] G. Huston. BGP in 2020 – The BGP Table. [Online]. Available: https://perma.cc/UMJ9-Q4QA

[24] Anapaya. (2021) SCION Header Specification. [Online]. Available: https://perma.cc/2DQH-NXSU

[25] R. Sinha, C. Papadopoulos, and J. Heidemann, “Internet Packet Size Distributions: Some Observations,” USC/Information Sciences Institute, Tech. Rep. ISI-TR-2007-643, May 2007.

[26] Statista. (2021) Number of fixed broadband Internet subscriptions worldwide from 2005 to 2020. [Online]. Available: https://perma.cc/FZ7Q-B9DS

[27] ——. (2021) Global digital population as of January 2021. [Online]. Available: https://perma.cc/VF2U-A7FT

[28] ——. (2021) Average mobile and fixed broadband download and upload speeds worldwide as of May 2021. [Online]. Available: https://perma.cc/W4D8-CK56

[29] A. Vishwanath, K. Hinton, R. Ayre, and R. Tucker, “Modeling Energy Consumption in High-Capacity Routers and Switches,” *Selected Areas in Communications, IEEE Journal on*, vol. 32, pp. 1524–1532, 08 2014.

[30] Statista. (2020) Global mobile data traffic from 2017 to 2022. [Online]. Available: https://perma.cc/4B9Q-QL9X

[31] A. Andrae, “New perspectives on internet electricity use in 2030,” *Engineering and Applied Science Letters*, vol. 3, pp. 19–31, 06 2020.

[32] B. Aebischer and L. Hilty, *The Energy Demand of ICT: A Historical Perspective and Current Methodological Challenges*, 08 2015, vol. 310, pp. 71–103.

[33] V. Coroama and L. Hilty, “Assessing Internet energy intensity: A review of methods and results,” *Environmental Impact Assessment Review*, vol. 45, pp. 63–68, 02 2014.

[34] J. Koomey, H. Chong, W. Loh, B. Nordman, and M. Blazek, “Network Electricity Use Associated with Wireless Personal Digital Assistants,” *Journal of Infrastructure Systems*, vol. 10, no. 3, pp. 131–137, 2004. [Online]. Available: https://ascelibrary.org/doi/abs/10.1061/%28ASCE%291076-0342%282004%2910%3A3%28130%29

[35] C. Taylor and J. Koomey, “Estimating Energy Use and Greenhouse Gas Emissions of Internet Advertising,” Jan 2008.

[36] C. L. Weber, J. G. Koomey, and H. S. Matthews, “The Energy and Climate Change Implications of Different Music Delivery Methods,” *Journal of Industrial Ecology*, vol. 14, no. 5, pp. 754–769, 2010. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1530-9290.2010.00269.x

[37] S. Lanzisera, B. Nordman, and R. E. Brown, “Data Network Equipment Energy Use and Savings Potential in Buildings,” *Energy Efficiency*, vol. 5, no. 2, p. 149–162, 2011.

[38] V. C. Coroama, L. M. Hilty, E. Heiri, and F. M. Horn, “The Direct Energy Demand of Internet Data Flows,” *Journal of Industrial Ecology*, vol. 17, no. 5, pp. 680–688, 2013. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12048

[39] J. Baliga, K. Hinton, and R. Tucker, “Energy Consumption of the Internet,” Jul 2007.

[40] J. Baliga, R. Ayre, K. Hinton, W. Sorin, and R. Tucker, “Energy Consumption in Optical IP Networks,” *Journal of Lightwave Technology*, vol. 27, no. 13, pp. 2391–2403, 2009.

[41] A. Vishwanath, K. Hinton, R. W. A. Ayre, and R. S. Tucker, “Modeling Energy Consumption in High-Capacity Routers and Switches,” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 8, pp. 1524–1532, 2014.

[42] K. Hinton, J. Baliga, M. Feng, R. Ayre, and R. Tucker, “Power Consumption and Energy Efficiency in the Internet,” *Network, IEEE*, vol. 25, pp. 6 – 12, May 2011.

[43] U. Lee, I. Rimac, D. Kilper, and V. Hilt, “Toward Energy-Efficient Content Dissemination,” *Netwrk. Mag. of Global Internetwkg.*, vol. 25, no. 2, p. 14–19, Mar. 2011.

[44] C. Chen, D. Barrera, and A. Perrig, “Modeling Data-Plane Power Consumption of Future Internet Architectures,” in *Proceedings of the IEEE Conference on Collaboration and Internet Computing (CIC)*, Nov. 2016.

[45] V. Jacobson, D. K. Smetters, J. D. Thornton, M. F. Plass, N. H. Briggs, and R. L. Braynard, “Networking Named Content,” in *Proceedings of the 5th International Conference on Emerging Networking Experiments and Technologies*, ser. CoNEXT ’09, 2009, p. 1–12.