Challenges and Opportunities in Management for Green Networking

Abstract

Reducing mankind's carbon footprint and making technology more
sustainable are among the big challenges of our age. While networks
are an enabler of applications that help to reduce this footprint,
they also contribute to this footprint in no insignificant way
themselves. Methods to make networking technology itself "greener"
and to manage networks in ways that reduces their carbon footprint
without impacting their utility therefore need to be explored. This
document outlines a corresponding set of opportunities, along with
associated research challenges, for networking technology in general
and management technology in particular to become "greener", i.e.
more sustainable, with reduced greenhouse gas emissions and carbon
footprint.

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1. **Introduction**

   Climate change and the need to curb greenhouse emissions have been
   recognized by the United Nations and by most governments as one of
   the big challenges of our time. As a result, curbing those emissions
   is becoming of increasing importance for society and for many
   industries. The networking industry is no exception.

   The science behind greenhouse gas emissions and it relationship with
   climate change is complex. However, there is overwhelming scientific

consensus pointing towards a clear correlation between climate change and a rising amount of greenhouse gases in the atmosphere. One greenhouse gas of particular concern, but by no means the only one, is carbon dioxide (CO_2). Carbon dioxide is emitted in the process of burning fuels to generate energy that is used, for example, to power electrical devices such as networking equipment. Of particular concern here is the use of fossil fuels, such as oil, which releases CO_2 that had long been removed from the earth's atmosphere, as opposed to the use of renewable or sustainable fuels that do not "add" to the amount of carbon in the atmosphere.

Greenhouse gas emissions are in turn correlated with the need to power technology, including networks. Reducing those emissions can be achieved by reducing the amount of fossil fuels needed to generate the energy that is needed to power those networks. This can be achieved by improving the energy mix to include increasing amounts of renewable (and hence sustainable) energy sources such as wind or solar. It can also be achieved by increasing energy savings and improving energy efficiency so that the same outcomes can be achieved while consuming less energy in the first place.

The amount of CO_2 that is emitted in burning fossil fuels to generate energy is also referred to as carbon footprint. Reducing this footprint to net-zero is hence a major sustainability goal. However, sustainability encompasses also other factors beyond carbon, such as sustainable use of other natural resources, the preservation of natural habitats and biodiversity, and the avoidance of any form of pollution.

In the context of this document, we refer to networking technology that helps to improve sustainability simply as "green". Green, in that sense, includes technology that helps to lower networking's carbon footprint, which turn includes technology that helps to increase efficiency and realize energy savings as well as facilitating managing networks towards stronger use of renewables.

Arguably, networks can already be considered a "green" technology in that networks enable many applications that allow users and whole industries to save energy and become more sustainable in a significant way. For example, it allows (at least to an extent) to replace travel with teleconferencing; it enables many employees to work from home and "telecommute," thus reducing the need for actual commute; IoT applications that facilitate automated monitoring and control from remote sites help make agriculture more sustainable by minimizing the application of resources such as water and fertilizer; networked smart buildings allow for greater energy optimization and sparser use of lighting and HVAC (heating, ventilation, air conditioning) than their non-networked not-so-smart counterparts.

The IETF has recently initiated a reflection on the energy cost of hosting meetings three times a year (see for instance https://www.ietf.org/blog/towards-a-net-zero-ietf/). It conducted a study of the carbon emissions of a typical meeting, and found out that 99% of the emissions were due to the air travel. In the same vein, [framework] compared an in-person with a virtual meeting and found a reduction in energy of 66% for a virtual meeting. These findings confirm that networking technology can reduce emissions when acting as virtual substitution for physical events.

That said, networks themselves consume significant amounts of energy. Therefore, the networking industry has an important role to play in meeting sustainability goals not just by enabling others to reduce their reliance on energy, but by also reducing its own. Future networking advances will increasingly need to focus on becoming more energy-efficient and reducing carbon footprint, both for economic reasons and for reasons of corporate responsibility. This shift has already begun and sustainability is already becoming an important concern for network providers. In some cases such as in the context of networked data centers, the ability to procure enough energy becomes a bottleneck prohibiting further growth and greater sustainability thus becomes a business necessity.

For example, in its annual report, Telefónica reports that in 2021, its network's energy consumption per PB of data amounted to 54MWh [telefonica2021]. This rate has has been dramatically decreasing (a seven-fold factor over six years) although gains in efficiency are being offset by simultaneous growth in data volume. In the same report, it is stated as an important corporate goal to continue on that trajectory and aggressively reduce overall carbon emissions further.

Perhaps the most obvious gains in sustainability can be made with regards to improving the efficiency with which networks utilize power, reducing the amount of energy that is required to provide communication services. However, for a holistic approach other aspects need to be considered as well. Perhaps most importantly, carbon footprint is determined not by it power consumption alone. The sustainability of power sources needs to be taken into account as well. A deployment that includes devices that are less energy-efficient but that are powered by a sustainable energy source can arguably be considered "greener" than a deployment that includes highly-efficient device that are powered by Diesel generators. In fact, in the same Telefónica report, extensive reliance on renewable energy sources is emphasized.

Similarly, deployments can take other environmental factors into account that affect carbon footprint. For example, deployments in which factors such as the need for cooling are reduced will be

considered greener than deployments where this is not the case.
Examples include deployments in cooler natural surroundings (e.g. in
colder climates) where that is an option. Finally, manufacturing and
recycling of networking equipment are also part of the
sustainability equation, as the production itself consumes energy
and results in a carbon cost embedded as part of the device itself.
Extending the lifetime of equipment may in many cases be preferable
over replacing it earlier with equipment that is slightly more
energy-efficient but that requires the embedded carbon cost to be
amortized over a much shorter period of time.

From a technical perspective, multiple vectors along which networks
can be made "greener" should be considered:

  *At the equipment level. Perhaps the most promising vector for
   improving networking sustainability concerns the network
   equipment itself. At the most fundamental level, networks (even
   softwarized ones) involve appliances, i.e. equipment that relies
   on electrical power to perform its function. However, beyond
   making those appliances merely more energy-efficient, there are
   other important ways in which equipment can help networks become
   greener. This includes aspects such as support for port power
   saving modes allowing to reduce power consumption for resources
   that are not fully utilized, but also management instrumentation
   that allows to precisely monitor power usage at different levels
   of granularity (for example, accounting separately for the
   contributions of CPU, memory, or different ports. This enables
   (for example) controller applications that aim to optimize energy
   usage across the network. (As a side note, the term "device", as
   used in the context of this draft, is used to refer to networking
   equipment. We are not taking into consideration end-user devices
   and endpoints such as mobile phones or computing equipment.)

  *At the protocol level. Energy-efficiency and greenness are
   aspects that are rarely considered when designing network
   protocols. This suggests that there may be plenty of untapped
   potential. Some aspects involve designing protocols in ways that
   reduce the need for redundant or wasteful transmission of data to
   allow not only for better network utilization, but greater
   goodput per unit of energy being consumed. Techniques might
   include approaches that reduce the "header tax" incurred by
   payloads as well as methods resulting in the reduction of
   wasteful retransmissions. Likewise, aspects such as restructuring
   addresses in ways that allow to minimize the size of lookup
   tables and associated memory sizes and their energy use can play
   a role as well. Another role of protocols concerns the enabling
   of functionality to improve energy efficiency at the network
   level, such as discovery protocols that allow for quick
   adaptation to network components being taken dynamically into and

out of service depending on network conditions, as well as
protocols that can assist with functions such as the collection
of energy telemetry data from the network.

*At the network level. Perhaps the greatest opportunities to
 realize power savings exist at the level of the network as whole.
 For example, optimizing energy efficiency may involve directing
 traffic in such a way that it allows for isolation of equipment
 that may at the moment not be needed so that it could be powered
 down or brought into power-saving mode. By the same token,
 traffic should be directed in a way that requires bringing
 additional equipment online or out of power-saving mode in cases
 where alternative traffic paths are available for which the
 incremental energy cost would amount to zero. Likewise, some
 networking devices may be rated less "green" and more power-
 intensive than others or powered by less-sustainable energy
 sources. Their use might be avoided unless required to meet peak
 capacity demands. Generally, incremental carbon emissions can be
 viewed as a cost metric that networks should strive to minimize
 and consider as part of routing and of network path optimization.

*At the architecture level. The current network architecture
 supports a wide range of applications, but does not take into
 account energy efficiency as one of its design parameters. One
 can argue that the most energy efficient shift of the last two
 decades has been the deployment of Content Delivery Network
 overlays: while these were set up to reduce latency and minimize
 bandwidth consumption, from a network perspective, retrieving the
 content from a local cache is also much greener. What other
 architectural shifts can produce energy consumption reduction?

We believe that network standardization organizations in general,
and IETF in particular, can make important contributions to each of
these vectors. In this document, we will therefore explore each of
those vectors in further detail and for each point out specific
challenges for IETF. As our starting point, we borrow some material
from a prior paper, [GreenNet22]. For this document, this material
has been both expanded (for example, in terms of some of the
opportunities) and pruned (for example, in terms of background on
prior scholarly work). In addition, this document focuses on and
attempts to articulate specific challenges relating to work that
could be championed by the IETF to make a difference.

2. Definitions and Acronyms

Below you find acronyms used in this draft:

Carbon footprint: as used in this document, the amount of carbon emissions associated with the use or deployment of technology, usually correlated with the amount of energy consumption.

CDN: Content Delivery Network.

CPU: Central Processing Unit, that is the main processor in a server.

DC: Data Center.

FCT: Flow Completion Time.

GPU: Graphical Processing Unit.

HVAC: Heating, Ventilation, Air Conditioning.

ICN: Information Centric Network.

IGP: Interior Gateway Protocol.

IoT: Internet of Things.

IPU: Infrastructure Processing Units.

LEED: Leadership in Energy and Environmental Design, a green building rating system.

LEO: Low Earth Orbit.

LPM: Longest Prefix Match, a method to look up prefixes in a forwarding element.

MPLS: Multi-Path Label Switching

MTU: Maximum Transmission Unit, the largest packet size that can be transmitted over a network.

NIC: Network Interface Card.

QoS, QoE: Quality of Service, Quality of Experience.

QUIC: Quick UDP Internet Connections.

SDN: Software-Defined Networking.

TCP: Transport Control Crotocol.

TE: Traffic Engineering.

TPU: Tensor Processing Unit.

WAN: Wide Area Network.

3. Contributors to Network Energy Consumption

Carbon footprint and, with it, greenhouse gas emissions are
determined by a number of factors. A main factor is network energy
consumption, as the energy consumed can be considered a proxy for
the burning of fuels required for corresponding power generation.
Network energy consumption by itself does not tell the whole story,
as it does not take the sustainability of energy sources and energy
mix into account. Likewise, there are other factors such as hidden
carbon cost reflecting the carbon footprint expended in
manufacturing of networking hardware. Nonetheless, network energy
consumption is an excellent predictor for carbon footprint and its
reduction key to sustainable solutions. Exploring possibilities to
improve energy efficiency is hence a key factor for greener, more
sustainable, less carbon-intensive networks.

For this, it is important to understand which aspects contribute to
power consumption the most and hence where the greatest potential
not just for power savings but also sustainability improvements
lies.

3.1. Power Consumption Characteristics

Power is ultimately drawn by devices. The power consumption of the
device can be divided into the consumption of the core device - the
backplane and CPU, if you will - as well as additional consumption
incurred per port and line card. In addition, GPU and TPU may be
used as well in the network and may have different power consumption
profiles. Furthermore it is important to understand the difference
between power consumption when a resource is idling versus when it
is under load. This helps to understand the incremental cost of
additional transmission versus the initial cost of transmission.

In typical networking devices, only roughly half of the energy
consumption is associated with the data plane [bolla2011energy]. An
idle base system typically consumes more than half of the power over
the same system running at full load [chabarek08], [cervero19].
Generally, the cost of sending the first bit is very high, as it
requires powering up a device, port, etc. The incremental cost of
transmission of additional bits (beyond the first) is many orders of
magnitude lower. Likewise, the incremental cost of incremental CPU
and memory needed to process additional packets becomes fairly
negligible. This means that a device's power consumption does not
increase linearly with the volume of forwarded traffic. Instead, it

resembles more of a step function in which power consumption stays roughly the same up to a certain volume of traffic, followed by a sudden jump when when additional resources need to be procured to support a higher volume of traffic. By the same token, generally speaking it is more energy-efficient to transmit a large volume of data in one burst (and turning off the interface when idling), instead of continuously transmitting at a lower rate. In that sense it can be the duration of the transmission that dominates the energy consumption, not the actual data rate.

3.2. Dimensioning for Peak Usage

The implications on green networking from an energy-savings standpoint are significant: Potentially the largest gains can be made when network resources can effectively be taken off the grid (i.e. isolated and removed from service so they can be powered down while not needed). Likewise, for applications where this is possible, it may be desirable to replace continuous traffic at low data rates with traffic that is sent in burst at high data rates, in order to potentially maximize the time during which resources can be idled.

At the same time, any non-idle resources should be utilized to the greatest extent possible as the incremental energy cost is negligible. Of course, this needs to occur while still taking other operational goals into consideration, such as protection against failures (allowing for readily-available redundancy and spare capacity in case of failure) and load balancing (for increased operational robustness). As data transmission needs tend to fluctuate wildly and occur in bursts, any optimization schemes need to be highly adaptable and allow for very short control loops.

As a result, emphasis needs to be given to technology that allows for example to (at the device level) exercise very efficient and rapid discovery, monitoring, and control of networking resources so that they can be dynamically be taken offline or back into service, without (at the network level) requiring extensive convergence of state across the network or recalculation of routes and other optimization problems, and (at the network equipment level) support rapid power cycle and initialization schemes. There may be some lessons that can be applied here from IoT, which has long had to contend with power-constrained end devices that need to spend much of their time in power saving states to conserve battery.

4. Challenges and Opportunities - Equipment Level

We are categorizing challenges and opportunities to improve
sustainability at the network equipment level along the following
lines:

  *Hardware and manufacturing. Related opportunities are arguably
   among the most obvious and perhaps "largest". However, solutions
   here may lie largely outside IETF's scope.

  *Visibility and instrumentation. Instrumenting equipment to
   provide visibility into how they consume energy is key to
   management solutions and control loops to facilitate optimization
   schemes.

4.1. Hardware and Manufacturing

Perhaps the most obvious opportunities to make networking technology
more energy efficient exist at the equipment level. After all,
networking involves physical equipment to receive and transmit data.
Making such equipment more power efficient, have it dissipate less
heat to consume less energy and reduce the need for cooling, making
it eco-friendly to deploy, sourcing sustainable materials and
facilitating recycling of equipment at the end of its life-cycle all
contribute to making networks greener. More specific and unique to
networking are schemes to reduce energy usage of transmission
technology from wireless (antennas) to optical (lasers).

One critical aspect of the energy cost of networking is the cost to
manufacture and deploy the networking equipment. This is outside of
the scope of this document: we only consider the energy cost of
running the network, as this is where the IETF can play a role.
However, a holistic approach would include into this the embedded
energy that is included in the networking equipment. One aspect for
the IETF may be to consider impact of deploying new protocols on the
rate of obsolescence of the equipment. For instance, incremental
approaches that do not require to replace equipment right away - or
even extend the lifetime of deployed equipment - would have a lower
energy footprint. This is one important benefit also of technologies
such as Software-Defined Networking and Network Function
Virtualization, as they may allow support of new networking features
through software updates without requiring hardware replacements.

An attempt to compute not only the energy of running a network, but
also the energy embedded into manufacturing the equipment is
described in [emergy] . This is denoted by "emergy", a portmanteau
for embedded energy. Likewise, an approach to recycling equipment
and a proof of concept using old cell phones recycled into a
"junkyard" data center are described in [junkyard].

One trade-off to consider at this level is the selection of a platform that can be hardware-optimized for energy efficiency vs a platform that is versatile and can run multiple functions. For instance, a switch could run on an efficient hardware platform, or run as a software module (container) over some multi-purpose platform. While the first one is operationaly more energy efficient, it may have a higher embedded energy from a smaller scale, less efficient production process, as well as a shorter shelf life once new functions need to be added to the platform.

4.2. Visibility and Instrumentation

Beyond "first-order" opportunities as outlined in the previous subsection, network equipment just as importantly plays an important role to enable and support green networking at other levels. Of prime importance is the equipment's ability to provide visibility to management and control plane into its current energy usage. Such visibility enables control loops for energy optimization schemes, allowing applications to obtain feedback regarding the energy implications of their actions, from setting up paths across the network that require the least incremental amount of energy to quantifying metrics related to energy cost used to optimize forwarding decisions. Absent an actual measurement of energy usage (and until such measurement is put in place), the network equipment could advertise some proxy of its power consumption (say, a labelling scheme as silver, gold, platinum similar to the LEED sustainability metric in building codes or the Energy Star label in home appliances; or a description of the type of the device as using CPU vs GPU vs TPU processors with different power profiles).

One prerequisite to such schemes is to have proper instrumentation in place that allows to monitor current power consumption at the level of networking devices as a whole, line cards, and individual ports. Such instrumentation should also allow to assess the energy efficiency and carbon footprint of the device as a whole. In addition, it will be desirable to relate this power consumption to data rates as well as to current traffic, for example, to indicate current energy consumption relative to interface speeds, as well as for incremental energy consumption that is expected for incremental traffic (to aid control schemes that aim to "shave" power off current services or to minimize the incremental use of power for additional traffic). This is an area where the current state of the art is sorely lacking and standardization lags behind. For example, as of today, standardized YANG data models [RFC7950] for network energy consumption that can be used in conjunction with management and control protocols have yet to be defined.

To remedy this situation, an effort to define sets of green networking metrics is currently under way

[I.D.draft-cx-green-metrics]. An agreed set of such metrics will provide the basis for further steps such as the implementation of corresponding data models as part of management and control instrumentation.

Instrumentation should also take into account the possibility of virtualization, introducing layers of indirection to assess the actual energy usage. For example, virtualized networking functions could be hosted on containers or virtual machines which are hosted on a CPU in a data center instead of a regular network appliance such as a router or a switch, leading to very different power consumption characteristics. For example, a data center CPU could be more power efficient and consume power more proportionally to actual CPU load. Instrumentation needs to reflect these facts and facilitate attributing power consumption in a correct manner.

Beyond monitoring and providing visibility into power consumption, control knobs are needed to configure energy saving policies. For instance, power saving modes are common in endpoints (such as mobile phones or notebook computers) but sorely lacking in networking equipment.

The following summarizes some challenges and opportunities that can provide the basis for IETF-led advances:

  *Basic equipment categorization as "energy-efficient" (or not) as
   a first step to identify immediate potential improvements, akin
   to the EnergyStar program from the US's Environmental Protection
   Agency.

  *Equipment instrumentation advances for improved energy-awareness;
   definition and standardization of granular management
   information.

  *Virtualized energy and carbon metrics and assessment of their
   effectiveness in solutions that optimize carbon footprint also in
   virtualized environments (including SDN, network slicing, network
   function virtualization, etc.).

  *Certification and compliance assessment methods that ensure that
   green instrumentation cannot be manipulated to give false and
   misleading data.

  *Methods that allow to account for energy mix powering equipment,
   to facilitate solutions that optimize carbon footprint and
   minimize pollution beyond mere energy efficiency [Hossain2019].

5. Challenges and Opportunities - Protocol Level

There are several opportunities to improve network sustainability at the protocol level. We characterize them along three main categories: protocols that enable carbon footprint optimization schemes at the network level, protocols designed to optimize data transmission rates under energy considerations, and protocols designed to reduce the volume of data to be transmitted. A fourth category concerns aspects related to network addressing schemes.

There is also substantial work in the area of IoT, which has had to contend with energy-constrained devices for a long time. Much of that work was motivated not by sustainability concerns but practical concerns such as battery life. However, many aspects appear to also apply in the context of sustainability, such as reducing chattiness to allow IoT equipment to go into low-power mode. Accordingly, there is opportunity to extend IoT work to more generalized scenarios. The use of power-constrained protocols into the wider Internet happens regularly. For instance, ARM-based chipsets initially designed for energy-efficiency in battery-operated mobile devices have been embraced in data centers for a similar trajectory.

5.1. Protocol Enablers for Carbon Optimization Mechanisms

As will be discussed in Section Section 6, energy- and pollution-aware schemes can help improve network sustainability but require awareness of related data. To facilitate such schemes, protocols are needed that are able to discover what links are available along with their energy efficiency. For instance, links may be turned off in order to save energy, and turned back on based upon the elasticity of the demand. Protocols should be devised to discover when this happens, and to have a view of the topology that is consistent with frequent topology updates due to power cycling of the network resources.

Also, protocols are required to quickly converge onto an energy-efficient path once a new topology is created by turning links on/off. Current routing protocols may provide for fast recovery in the case of failure. However, failures are hopefully relatively rare events, while we expect an energy efficient network to aggressively try to turn off links.

Some mechanism is needed to present to the management layer a view of the network that identifies opportunities to turn resources off (routers/links) while still providing an acceptable level of Quality of Experience (QoE) to the users. This gets more complex as the level of QoE shifts from the current Best Effort delivery model to more sophisticated mechanisms with, for instance, latency, bandwidth or reliability guarantees.

Similarly, schemes might be devised in which links across paths with a favorable energy mix are preferred over other paths. This implies that the discovery of topology should be able support corresponding parameters. More generally speaking, any mechanism that provides applications with network visibility is a candidate for scrutinization as to whether it should be extended to provide support for sustainability-related parameters.

The following summarizes some challenges and opportunities that can provide the basis for IETF-led advances:

  *Protocol advances to enable rapidly taking down, bring back online, and discover availability and power saving status of networking resources while minimizing the need for reconvergence and propagation of state.

  *Assess which protocols could be extended with energy- and sustainability-related parameters in ways that would enable "greener" networking solutions, and exploring those solutions.

5.2. Protocol Optimization

The second category involves designing protocols in such a way that the rate of transmission is chosen to maximize energy efficiency. For example, Traffic Engineering (TE) can be manipulated to impact the rate adaptation mechanism [ren2018jordan]. By choosing where to send the traffic, TE can artificially congest links so as to trigger rate adaptation and therefore reduce the total amount of traffic. Most TE systems attempt to minimize Maximal Link Utilization (MLU) but energy saving mechanisms could decide to do the opposite (maximize minimal link utilization) and attempt to turn off some resources to save power.

Another example is to set up the proper rate of transmission to minimize the flow completion time (FCT) so as to enable opportunities to turn off links. In a wireless context, [TradeOff] studies how setting the proper initial value for the congestion window can reduce the FCT and therefore allow the equipment to go faster into a low-energy mode. By sending the data faster, the energy cost can be significantly reduced. This is a simple proof of concept, but protocols that allow for turning links into a low-power mode by transmitting the data over shorter periods could be designed for other types of networks beyond WiFi access. This should be done carefully: in the limit, a high rate of transmission over a short period of time may create bursts that the network would need to accommodate, with all attendant complications of bursty traffic. We conjecture there is a sweet spot between trying to complete flows faster while controlling for burstiness in the network. It is probably advisable to attempt to send traffic paced yet in bulk

rather than spread out over multiple round trips. This is an area of worthwhile exploration.

The following summarizes some challenges and opportunities that can provide the basis for IETF-led advances:

   *Protocol advances that allow greater control over traffic pacing to account for fluctuations in carbon cost, i.e. control knobs to "bulk up" transmission over short periods or to smoothen it out over longer periods.

   *Protocol advances that allow to optimize link utilization according to different goals and strategies (including maximizing minimal link utilization vs minimizing maximal link utilization, etc).

   *Assessments of the carbon impact of such strategies.

5.3. Data Volume Reduction

The first category involves designing protocols in such a way that they reduce the volume of data that needs to be transmitted for any given purpose. Loosely speaking, by reducing this volume, more traffic can be served by the same amount of networking infrastructure, hence reducing overall energy consumption. Possibilities here include protocols that avoid unnecessary retransmissions. At the application layer, protocols may also use coding mechanisms that encode information close to the Shannon limit. Currently, most of the traffic over the Internet consists of video streaming and encoders for video are already quite efficient and keep improving all the time, resulting in energy savings as one of many advantages (of course being offset by increasingly higher resolution). However, it is not clear that the extra work to achieve higher compression ratios for the payloads results in a net energy gain: what is saved over the network may be offset by the compression/decompression effort. Further research on this aspect is necessary.

At the transport protocol layer, TCP and to some extent QUIC react to congestion by dropping packets. This is a highly energy inefficient method to signal congestion, since the network has to wait one RTT to be aware that the congestion has occurred, and since the effort to transmit the packet from the source up until it is dropped ends up being wasted. This calls for new transport protocols that react to congestion without dropping packets. ECN[RFC2481] is a possible solution, however not widely deployed. DC-TCP [alizadeh2010DCTCP] is tuned for Data Centers, L4S is an attempt to port similar functionality to the Internet [RFC9330]. Qualitative Communication [QUAL] [westphal2021qualitative] allows the nodes to

react to congestion by dropping only some of the data in the packet,
thereby only partially wasting the resource consumed by transmitted
the packet up to this point. Novel transport protocols for the WAN
can ensure that no energy is wasted transmitting packets that will
be eventually dropped.

Another solution to reduce the bandwidth of network protocols by
reducing their header tax, for example applying header compression.
An example in IETF is [RFC3095]. Again, reducing protocol header
size saves energy to forward packets, but at the cost of maintaining
a state for compression/decompression, plus computing these
operations. The gain from such protocol optimization further depends
on the application and whether it sends packets with large payloads
close to the MTU (the header tax and any savings here are very
limited), or whether it sends packets with very small payload size
(making the header tax more pronounced and savings more
significant).

An alternative to reducing the amount of protocol data is to design
routing protocols that are more efficient to process at each node.
For instance, path based forwarding/labels such as MPLS [RFC3031]
facilitate the next hop look-up, thereby reducing the energy
consumption. It is unclear if some state at router to speed up look
up is more energy efficient that "no state + lookup" that is more
computationally intensive. Other methods to speed up a next-hop
lookup include geographic routing (e.g. [herzen2011PIE]). Some
network protocols could be designed to reduce the next hop look-up
computation at a router. It is unclear if Longest Prefix Match (LPM)
is efficient from an energy point of view or if constitutes a
significant energy burden for the operation of a router.

The following summarizes some challenges and opportunities that can
provide the basis for IETF-led advances in this space:

  *Assessments of energy-related tradeoffs regarding protocol design
   space and tradeoffs, such as maintaining state versus more
   compact encodings or extra computation for transcodings versus
   larger data volume.

  *Protocol advances for improving the ratio of goodput to
   throughput and to reduce waste: reduction in header tax, in
   protocol verbosity, in need for retransmissions, improvements in
   coding, etc.

5.4. Network Addressing

There are other ways to shave off energy usage from networks. One
example concerns network addressing. Address tables can get very
large, resulting in large forwarding tables that require

considerable amount of memory, in addition to large amounts of state
needing to be maintained and synchronized. From an energy footprint
perspective, both can be considered wasteful and offer opportunities
for improvement. At the protocol level, rethinking how addresses are
structured can allow for flexible addressing schemes that can be
exploited in network deployments that are less energy-intensive by
design. This can be complemented by supporting clever address
allocation schemes that minimize the number of required forwarding
entries as part of deployments.

Alternatively, the address could be designed so as to allow for more
efficient processing than LPM. For instance, a geographic type of
addressing (where the next hop is computed as a simple distance
calculation based on the respective position of the current node, of
its neighbors and of the destination) [herzen2011PIE] could be
potentially more energy-efficient.

The following summarizes some challenges and opportunities that can
provide the basis for IETF-led advances in this space:

   *Devise methods to assess the magnitude of the carbon footprint
    that is associated with addressing schemes.

   *Devise methods to improve addressing schemes, as well as address
    assignment schemes, to minimize their footprint.

6. Challenges and Opportunities - Network Level

6.1. Network Optimization and Energy/Carbon/Pollution-Aware Networking

   Networks have been optimized for many years under many criteria, for
   example to optimize (maximize) network utilization and to optimize
   (minimize) cost. Hence, it is straighforward to add optimization for
   "greenness" (including energy efficiency, power consumption, carbon
   footprint) as important criteria.

   This includes assessing the carbon footprints of paths and
   optimizing those paths so that overall footprint is minimized, then
   applying techniques such as path-aware networking or segment routing
   [RFC8402] to steer traffic along those paths. (As mentioned earlier,
   other proxy measures could be used for carbon footprint, such as an
   energy-efficiency ratings of traversed equipment.) It also includes
   aspects such as considering the incremental carbon footprint in
   routing decisions. Optimizing cost has a long tradition in
   networking; many of the existing mechanisms can be leveraged for
   greener networking simply by introducing carbon footprint as a cost
   factor. Low-hanging fruit include the inclusion of carbon-related
   parameters as a cost parameter in control planes, whether
   distributed (e.g. IGP) or conceptually centralized via SDN
   controllers. Likewise, there are opportunities in right-placing

functionality in the network. An example concerns placement of
virtualized network functions in carbon-optimized ways - for
example, cohosted on fewer servers in close proximity to each other
in order to avoid unnecessary overhead in long-distance control
traffic.

Other opportunities concern adding carbon-awareness to dynamic path
selection schemes. This is sometimes also referred to as "energy-
aware networking" (respectively "pollution-aware networking"
[Hossain2019] or "carbon-aware networking", when carbon footprint
related parameters beyond pure energy consumption are taken into
account). Again, considerable energy savings can potentially be
realized by taking resources offline (e.g. putting them into power-
saving or hibernation mode) when they are not currently needed under
current network demand and load conditions. Therefore, weaning such
resources from traffic becomes an important consideration for
energy-efficient traffic steering. This contrasts and indeed
conflicts with existing schemes that typically aim to create
redundancy and load-balance traffic across a network to achieve even
resource utilization. This usually occurs for important reasons,
such as making networks more resilient, optimizing service levels,
and increasing fairness. One of the big challenges hence concerns
how resource weaning schemes to realize energy savings can be
accommodated while preventing the cannibalization of other important
goals, counteracting other established mechanisms, and avoiding
destabilization of the network.

An opportunity may lie in making a distinction between "energy
modes" of different domains. For instance, in a highly trafficked
core, the energy challenge is to transmit the traffic efficiently.
The amount of traffic is relatively fluid (due to multiplexing of
multiple sessions) and the traffic is predictable. In this case,
there is no need to optimize on a per session basis nor even at a
short time scale. In the access networks connecting to that core,
though, there are opportunites for this fast convergence: traffic is
much more bursty, less predictable and the network should be able to
be more reactive. Other domains such as DCs may have also more
variable workloads and different traffic patterns.

The following summarizes some challenges and opportunities that can
provide the basis for IETF-led advances in this space:

  *Devise methods for carbon-aware traffic steering and routing;
   treat carbon footprint as a traffic cost metric to optimize.

  *Apply ML and AI methods to optimize networks for carbon
   footprint; assess applicability of game theoretic approaches.

*Articulate and, as applicable, moderate tradeoffs between carbon
   awareness and other operational goals such as robustness and
   redundancy.

  *Extend control-plane protocols with carbon-related parameters.

  *Consider security issues imposed by greater energy awareness, to
   minimize the new attack surfaces that would allow an adversary to
   turn off resources or to waste energy.

6.2. Assessing Carbon Footprint and Network-Level Instrumentation

As an important prerequisite to capture many of the opportunities
outlined in [Section 6.1](), good abstractions (and corresponding
instrumentation) that allow to easily assess energy cost and carbon
footprint will be required. These abstractions need to account for
not only for the energy cost associated with packet forwarding
across a given path, but related cost for processing, for memory,
for maintaining of state, to result in a holistic picture.

Optimization of carbon footprint involves in many cases trade-offs
that involve not only packet forwarding but also aspects such as
keeping state, caching data, or running computations at the edge
instead of elsewhere. (Note: there may be a differential in running
a computation at an edge server vs. at an hyperscale DC. The latter
is often better optimized than the latter.) Likewise, other aspects
of carbon footprint beyond mere energy-intensity should be
considered. For instance, some network segments may be powered by
more sustainable energy sources than others, and some network
equipment may be more environmentally-friendly to build, deploy and
recycle, all of which can be reflected in abstractions to consider.

Assessing carbon footprint at the network level requires
instrumentation that associates that footprint not just with
individual devices (as outline in [Section 4.2]() but relates it also to
concepts that are meaningful at the network level, i.e. to flows and
to paths. For example, it will be useful to provide visibility into
the carbon intensity of a path: Can the carbon cost of traffic
transmitted over the path be aggregated? Does the path include
outliers, i.e. segments with equipment with a particularly poor
carbon footprint?

Similarly, how can the carbon cost of a flow be assessed? That might
serve many purposes beyond network optimization, from the option to
introduce green billing and charging schemes to the ability to raise
carbon awareness by end users.

The following summarizes some challenges and opportunities that can
provide the basis for IETF-led advances in this space:

   *Devise methods to assess, to estimate, to predict carbon-
    intensity of paths.

   *Devise methods to account for carbon footprint of flows and
    networking services.

6.3. Convergence Schemes

One set of challenges of carbon-aware networking concerns the fact
that many schemes result in much greater dynamicity and continuous
change in the network as resources may be getting steered away from
(when possible) and then leveraged again (when necessary) in rapid
succession. This imposes significant stress on convergence schemes
that results in challenges to the scalability of solutions and their
ability to perform in a fast-enough manner. Network-wide convergence
imposes high cost and incurs significant delay and is hence not
susceptible to such schemes. In order to mitigate this problem,
mechanisms should be investigate that do not require convergence
beyond the vicinity of the affected network device. Especially in
cases where central network controllers are involved that are
responsible for aspects such as configuration of paths and the
positioning of network functions and that aim for global
optimization, the impact of churn needs to be minimized. This means
that, for example, (re-) discovery and update schemes need to be
simplified and extensive recalculation e.g. of routes and paths
based on the current energy state of the network needs to be
avoided.

Challenges and opportunities for IETF-led advances in this space
include:

   *Protocols that facilitate rapid convergence (per section
    Section 5.1).

   *Investigate methods that mitigate effects of churn, including
    methods that maintain memory or state as well as methods relying
    on prediction, inference, and interpolation.

7. Challenges and Opportunities - Architecture Level

Another possibility to improve network energy efficiency is to
organize networks in a way that they can best serve important
applications so as to minimize energy consumption. Examples include
retrieval of content or remote computation. This allows to minimize
the amount of communication that needs to take place in the first
place, although energy savings within the network may at least in
part be offset by additional energy consumption elsewhere. The

following are some examples that suggest that it may be worthwhile reconsidering the ways in which networks are architected to minimize their carbon footprint.

For example, Content Delivery Networks (CDNs) have reduced the energy expenditure of the Internet by downloading content near the users. The content is sent only a few times over the WAN, and then is served locally. This shifts the energy consumption from networking to storage. Further methods can reduce the energy usage even more [bianco2016energy][mathew2011energy][islam2012evaluating]. Whether overall energy savings are net positive depends on the actual deployment, but from the network operator's perspective, at least it shifts the energy bill away from the network to the CDN operator.

While CDNs operate as an overlay, another architecture has been proposed to provide the CDN features directly in the network, namely Information Centric Networks [ahlgren2012survey], studied as well in the IRTF ICNRG. This however shifts the energy consumption back to the network operator and requires some power-hungry hardware, such as chips for larger name look-ups and memory for the in-network cache. As a result, it is unclear if there is an actual energy gain from the dissemination and retrieval of content within in-network caches.

Fog computing and placing intelligence at the edge are other architectural directions for reducing the amount of energy that is spent on packet forwarding and in the network. There again, the trade-off is between performing computation in a an energy-optimized data center at very large scale, but requiring transmission of significant volumes of data across many nodes and long distances, versus performing computational tasks at the edge where the energy may not be used as efficiently (less multiplexing of resources, and smaller sites are inherently less efficient due to their smaller scale) but the amount of long-distance network traffic is significantly reduced. Softwarization, containers, microservices are direct enablers for such architectures, and the deployment of programmable network infrastructure (as for instance Infrastructure Processing Units - IPUs or smartNICs that offload some computations from the CPU onto the NIC) will help its realization. However, the power consumption characteristics of CPUs are different from those of NPUs, another aspect to be considered in conjunction with virtualization.

Other possibilities concern taking economic aspects into consideration impact, such as providing incentives to users of networking services in order to minimize energy consumption and emission impact. An example for this is given in [wolf2014choicenet], which could be expanded to include energy incentives.

Other approaches consider performing a late binding of data and
functions to be performed on the data [krol2017NFaaS]. The COIN
Research Group in IRTF focuses on similar issues. Jointly optimizing
for the total energy cost, taking into account networking and
computing (and the different energy cost of computing in an
hyperscale DC vs an edge node) is still an area of open research.

In summary, rethinking of the overall network (and networked
application) architecture can be an opportunity to significantly
reduce the energy cost at the network layer, for example by
performing tasks that involve massive communications closer to the
user. To what extend these shifts result in a net reduction of
carbon footprint is an important question that requires further
analysis on a case-by-case basis.

The following summarizes some challenges and opportunities that can
provide the basis for IETF-led advances in this space:

  *Investigate organization of networking architecture for important
   classes of applications (examples: content delivery, right-
   placing of computational intelligence, industrial operations and
   control, massively distributed machine learning and AI) to
   optimize green foot print and holistic approaches to trade off
   carbon footprint between forwarding, storage, and computation.

  *Models to assess and compare alternatives in providing networked
   services, e.g. assess carbon impact relative to alternatives
   where as to where to perform compute, what information to cache,
   and what communication exchanges to conduct.

8. Conclusions

How to make networks "greener" and reduce their carbon footprint is
an important problem for the networking industry to address, both
for societal and for economic reasons. This document has highlighted
a number of the technical challenges and opportunities in that
regard.

Of those, perhaps the key challenge to address right away concerns
the ability to expose at a fine granularity the energy impact of any
networking actions. Providing visibility into this will enable many
approaches to come towards a solution. It will be key to
implementing optimization via control loops that allow to assess the
energy impact of decisiont taken. It will also help to answer
questions such as: is caching - with the associated storage energy -
better than retransmitting from a different server - with the
associated networking cost? Is compression more energy-efficient
once factoring the computation cost of compression vs transmitting
uncompressed data? Which compression scheme is more energy

efficient? Is energy saving of computing at an efficient hyperscale DC compensated by the networking cost to reach that DC? Is the overhead of gathering and transmitting fine-grained energy telemetry data offset by the total energy gain by ways of better decisions that this data enables? Is transmitting data to a Low Earth Orbit (LEO) satellite constellation compensated by the fact that once in the constellation, the networking is fueled on solar energy? Is the energy cost of sending rockets to place routers in Low Earth Orbit amortized over time?

Determining where the sweet spots are and optimizing networks along those lines will be a key towards making networks "greener". We expect to see significant advances across these areas and believe that IETF has an important role to play in facilitating this.

9. IANA Considerations

This document does not have any IANA requests.

10. Security Considerations

Security considerations may appear to be orthogonal to green networking considerations. However, there are a number of important caveats.

Security vulnerabilities of networks may manifest themselves in compromised energy efficiency. For example, attackers could aim at increasing energy consumption in order to drive up attack victims' energy bill. Specific vulnerabilities will depend on the particular mechanisms. For example, in the case of monitoring energy consumption data, tampering with such data might result in compromised energy optimization control loops. Hence any mechanisms to instrument and monitor the network for such data need to be properly secured to ensure authenticity.

In some cases there are inherent tradeoffs between security and maximal energy efficiency that might otherwise be achieved. An example is encryption, which requires additional computation for encryption and decyption activities and security handshakes, in addition to the need to send more traffic than necessitated by the entropy of the actual data stream. Likewise, mechanisms that allow to turn resources on or off could become a target for attackers.

Energy consumption can be used to create covert channels, which is a security risk for information leakage. For instance, the temperature of an element can be used to create a Thermal Covert Channel[TCC], or the reading/sharing of the measured energy consumption can be abused to create a covert channel (see for instance [DRAM] or [NewClass]). Power information may be used to create side-channel attacks. For instance, [SideChannel] provides a review of 20 years

of study on this topic. Any new parameters to consider in protocol
designs or in measurements is susceptible to create such covert or
side channel and this should be taken into account while designing
energy efficient protocols.

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