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An Overview of Energy-related Effort within the IETF

Abstract

This memo provides an overview of work performed by or proposed within the IETF related to energy and/or green: awareness, management, control or reduction of consumption of energy, and sustainability as it related to the IETF.

This document is written to help those unfamiliar with that work, but interested in it, in the hope to raise more interest in energy-related activities within the IETF, such as identifying gaps and investigating solutions as appropriate.

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1. Introduction

This document summarizes work that has been proposed to or performed within the IETF/IRTF. Particularly, it covers IETF/IRTF RFCs as well as ISE RFCs and IETF/IRTF or individual submission drafts that were abandoned for various reasons (e.g., lack of momentum, broad scope).

There are various aspects how a given work relates to energy that are classified into categories. Such a classification does not attempt to propose a formal taxonomy, but is used for the sake of better readability. Technologies are listed under a category that is specifically significant, for example, by being most narrow.

This memo usually refers to the technologies by significant early RFC or specific draft version, as opposed to the newest. This is contrary to the common practice in IETF documents to refer to the newest version. This approach is meant to allow readers to better understand the historic timeline in which a specific technology was proposed or introduced. Especially successful IETF technologies will have newer RFC that updates such initial work.

2. Energy Saving: An Introduction

Technologies that simply save energy compared to earlier or other alternatives are the broadest and most unspecific category. In this memo such an energy saving simply refers to energy savings in some unit of electricity, such as kWh and does not take other aspects of energy optimization into account. See [Section 4](#) for more details.

2.1. Digitization

Digitization describes the transformation of processes from non- or less digital with networking to more digital with computer-networking. For comparable process results, the digitized option is often, but not always, less energy-consuming. Consider, for example, the energy consumption in the evolution of messaging starting from postal mail and over telegrams and various other historic form to solutions including e-mail utilizing, for example, the IETF "Simple Mail Transport Protocol" (SMTP, [\[RFC822\]](#) obsoleted by [\[RFC2822\]](#), [\[RFC5322\]](#)), group communications utilizing the IETF "Network News Transport Protocol" (NNTP, [\[RFC3977\]](#)) or the almost infinite set of communication options built on top of the IETF "HyperText Transport Protocol" (HTTP, [\[RFC2086\]](#) and successors), and IETF "HyperText Markup Language" (HTML, [\[RFC1866\]](#) superseded by various later version of HTML, see [\[RFC2854\]](#)).

Conventionally, digitization had only "incidental", but not "intentional" relationship to energy consumption: If it saved energy, this was not only not a target benefit, it was not even recognized as one, until probably recently. Instead, the evolution was driven from anything-but-energy benefits, but instead utility benefits such as improved speed, functionality/flexibility, accessibility, usability, scalability, and reduced cost.

In hindsight though, digitization through IETF technologies and specifically the Internet will likely have the largest contribution to energy saving amongst all the possible categories, but it is also the hardest to pinpoint on any specific technology/RFC. Instead, it is often a combination of the whole stack of deployed protocols and operational practices that contributes to energy saving through digitization. It is likely also the biggest overall energy saving impact of all possible categories that relate IETF work to energy:

The Internet as well as all other IP/MPLS networks are likely the biggest energy saving development of the past few decades if only the energy consumption of equivalent services is compared. On the other hand, they are also the cause for the biggest new type of new energy consumption because of all the new services introduced in the past decades with the Internet and the hyper-scaling that the Internet affords them.

2.2. Energy Saving Through Scale

2.2.1. An Iconic Example: Telephony

In most cases, energy saving through the use of IETF protocols compared to earlier (digitized or non digitized) solutions is purely a result of the reduction in the energy cost per bit over the decades in networking. For example, the energy consumption of digital voice telephony through the IETF "Session Initiation Protocol" (SIP, [[RFC2543](#)] superceeded by [[RFC3261](#)] and successors) can easily be assumed to be more energy efficient on a per voice-minute basis than prior voice technologies such as analog or digital "Time Division Multiplex" (TDM) telephony solely because of this evolution in mostly device as well as physical-layer and link-layer networking technologies.

2.2.2. The Packet Multiplexing Principle

Nevertheless, it is at the heart of the packet multiplexing model employed by the IETF networking protocols IP ([[RFC791](#)]) and IPv6 ([[RFC1883](#)] superceeded by [[RFC2460](#)] and [[RFC8200](#)]) to successfully support this scaling that brough down the cost per bit through ever faster links and network nodes, especially for networks larger than building scale networks. While the IETF protocols have not been the first or over their early decades necessarily the most widely deployed packet networking protocols, they where the ones who at least during the 1990s started to break away from other protocols both in scale of deployment, as well as in development of further technologies to support this scaling.

2.2.3. End-to-End Transport

At the core of scalability, even up to now, is the lightweight per-packet-processing enabled through end-to-end congestion loss management architecture as embodied through the IETF "Transmission Control Protocol" (TCP, [[RFC793](#)] and successors, e.g. [[I-D.ietf-tcpm-rfc793bis](#)]). This model eliminated more expensive per-hop, per-packet processing, such as would be required for reliable hop-by-hop forwarding through per-hop ARQ, which was key to scaling routers cost effectively.

2.2.4. Global vs Restricted Connectivity: The Internet Routing Architectures

The meshed peer-to-peer and transitive routing of the Internet enabled through the IETF Border Gateway (Routing) Protocol (BGP, [\[RFC4271\]](#) as well as predecessors) is another key factor to successful scalability, because it enabled competitive market forces to explore markets quickly.

Prior to the Internet, the public often only had access to highly regulated international networking connections through often per-country monopoly regulated data networks.

2.2.5. Freedom to Innovate

(non-IP) networks often also did not allow as much "freedom-to-innovate" (as it is often called in the IETF) for applications running over it. Instead those networks were exploring the coupling of packet transport with higher layer services to allow the network operator some degree of revenue sharing with the services running on top of it. Such approaches resulted not only in higher cost of those services but also (likely) preferential and (often) exclusionary treatment of network traffic not fitting the perceived highest revenue service options.

2.2.6. End-to-End Encryption

When the same business practices were applied to IP network, it was one of the key factors leading to the development of IETF end-to-end encryption though protocols such as "Transport Layer Security" (TLS, [\[RFC2246\]](#) [\[RFC4346\]](#), [\[RFC5246\]](#), [\[RFC8446\]](#)). This further strengthened the ability to scale service/applications at minimum additional cost for the underlying packet transport, arguably driving innovation into ever faster networking technology and likely lower cost per bit.

2.2.7. Converged Networks

Another key factor to support scaling where IETF technologies that allowed to multiplex different types of traffic (e.g., realtime vs. non-realtime) which previously used separate networks with typically incompatible networking technologies.

Eliminating multiple physical networks with separate routing/forwarding nodes and separate links affords significant energy savings even at the same generation of speed and hence energy/bit simply by avoiding the N-fold production and operations of equipment and links. Of course, originally the CAPEX and OPEX of multiple, technology-diverse networks and host-stacks was the core reason for unified networks, and energy saving is in hindsight just incidental (as for all other cases mentioned here).

2.2.7.1. IntServ and DetNet

The first (non-IETF) wider adopted technology promising converged networks was "Asynchronous Transfer Mode" (ATM), which was designed and deployed at the end of the 1980s to support specifically multiplexing of "Data Voice and Video", where both Voice and Video

(at that time) required loss-free deterministic bounded latency and low-jitter and had therefore their own Time-Division-Multiplex (TDM) networks, both separate from so-called Data networks using packet multiplexing. This technology was very expensive on a per-bit basis due to its cell-forwarding nature though.

At the end of the 1980s, it was proven in [[BOUNDED_LATENCY](#)] that variable length packet multiplexing in network can also support non-NP-hard calculations for bounded latency. This led to the IETF "Integrated Services WG" (INTSERV) to support such guaranteed throughput and bounded latency traffic via [[RFC2212](#)] - and to the demise of ATM.

IntServ has so far seen little traction because it too got superseded as explained in the following section - for its original use-cases (voice and video). However this type of services are being revisited for a broader set of use-cases [[RFC8575](#)] in the DetNet WG, which should enable even further network infrastructure convergence for IoT and industrial markets.

2.2.7.2. DiffServ

Due to the much higher per-packet processing overhead of INTSERV versus standard (so-called Best-Effort) Internet traffic, the INTSERV model was already recognized in the 1990s to not support highest-scale at lowest cost, leading to the parallel development of the IETF "Differentiated Services WG" (DIFFSERV) model defined in [[RFC2475](#)]. This has since then become the dominant technology to support multiplexing of applications and services originally not designed for the Internet onto a common TCP/IP network infrastructure, specifically for voice and video over UDP ([[RFC768](#)]) including RTP [[RFC3550](#)] and SIP.

2.2.7.3. SIP

SIP has most notably in the past two decades eliminated additional network infrastructures previously required for (voice) telephony services starting in the early 2000 with commercial/enterprise deployments and today by removing even the option for any (non-IP/SIP) analog or digital (ISDN) telephone service connection, instead delivering those purely as services over adaptation interfaces on home routers (TBD: Any RFC to cite for those tunneling/adaptation services ?).

3. Higher or New Energy Consumption

Digitized, network centric workflows may consume more energy than their non-digitized counterpart, as may new network centric workflows without easy to compare prior workflows.

In one type of instances, the energy consumption on a per-instance basis is lower than in the non-digitized/non-Internet-digitized case, but the total number of instances that are (Internet)-digitized is orders of magnitudes larger than their alternative options, typically because of their higher utility or lower overall cost.

For example, each instance of (simple text) email consumes less energy than sending a letter or postcard. Even streaming a movie or TV series consumes less energy than renting a DVD [DVDvsStreaming](#). Nevertheless, the total amount of instances and in result energy consumption for email and streaming easily outranks their predecessor technologies.

While these instances look beneficial from a simple energy consumption metric, its overall scale and the resulting energy consumption may in itself become an issue, especially when the energy demand it creates risks to outstrip the possible energy production, short term or long term. This concern is nowadays often raised against the "digital economy", where the network energy consumption is typically cited as a small contributor relative to its applications, such as what is running in Data Centers (DC).

In other cases, the energy consumption of digitization requires often significantly more than their pre-digitization alternatives. The most well-known example of this are likely crypto-currencies based on "proof-of-work" computations (mining), which on a per currency value unit can cost 10..30 times or more of the energy consumed by for example gold mining (very much depending on the highly fluctuating price of the crypto-currency). Nevertheless, its overall utility compared to such prior currencies or valuables makes it highly successful in the market.

In general, the digital economy tends to be more energy intensive on a per utility/value unit, for example by replacing a lot of manual labor with computation), and/or it allows for faster growth of its workflows.

The lower the cost of network traffic, and the more easily accessible everywhere network connectivity is, the more competitive and/or successful most of these new workflows of the digital economy can be.

Given how TCP/IP based networks, especially the Internet have excelled through their design principles (and success) in this reduction of network traffic cost and ubiquitous access over the past few decades, as outlined above, one can say that IETF technologies and especially the Internet are the most important enabler of the digital economy, and the energy consumption it produces.

4. Some Notes on Sustainability

Sustainability is the principle to utilize resources in a way that they do not diminish or run out over the long term (e.g., ore depletion required for building hardware). Beyond the above covered energy saving, sustainability relates with respect to the IETF specifically to the use of renewable sources of energy to minimize exhaustion of fossile resources, and the impact of IETF technologies on global warming to avoid worsening living conditions on the planet.

While there seems to be no IETF work specifically intending to target sustainability, the Internet itself can similarly to how it does for digitization play a key role in building sustainable

networked IT infrastructures. The following subsections list three examples areas where global high performance, low-cost Internet networking is a key requirement.

4.1. Follow the Energy Cloud Scheduling

Renewable energy resources (except for water) do commonly have fluctuating energy output. For example, solar energy output correlates to night/day and strength of sunlight. Cloud Data Centers (DC) consume a significant amount of the IT sectors energy. Some workloads may simply be scheduled to consume energy in accordance with the amount of available renewable energy at the time, not requiring the network. Significant workloads are not elastic in time, such as interactive cloud DC interactive work (cloud based applications) or entertainment (gaming, etc.). These workloads may be instantiated or even dynamically (over time) migrate to a DC location with sufficient renewable energy and the Internet (or large TCP/IP OTT backbone networks) will serve as the fabric to access the remote DC and to coordinate the instantiation/migration.

4.2. Optimize Generated Heat

The majority of energy in cloud DCs is normally also wasted as exhaust heat, requiring even more energy for cooling. The warmer the location, the more energy needs to be spent for cooling. For this reason, DCs in cooler climates, such as <https://greenmountain.no/power-and-cooling/>, can help to reduce the overall DC energy consumption significantly (independent of the energy being consumed in the DC to be renewable itself). The Internet again plays the role of providing access to those type of DCs whole location is not optimized for consumption but for sustainable generation of compute and storage.

4.3. Heat Recovery

Exhaust heat, especially from compute in DCs, can be recovered when it is coupled to heating systems ranging in size all the way from individual familys home through larger buildings (hotels, for example) all the way to district heating systems. A provider of such a type of compute-generated heat as a service can sell the compute capacity as long as there is cost efficient network connectivity. "Cloud & Heat" is an example company offering such infrastructures and services https://www.cloudandheat.com/wp-content/uploads/2020/02/2020_CloudHeat-Whitepaper-Cost-saving-Potential.pdf.

4.4. Telecollaboration

Telecollaboration has a long history in the IETF resulting in multiple core technologies over the decades.

If one considers textual communications via email and netnews (using e.g., NNTP) as early forms of Telecollaboration, then telecollaboration history through IETF technology reaches back into the 1980s and earlier.

Around 1990, the IETF work on IP Multicast (e.g. [RFC1112] and later) enabled the first efficient forms of audio/video group collaboration through an overlay network over the Internet called

the Mbone <https://en.wikipedia.org/wiki/Mbone> which was also used by the IETF for more than a decade to provide remote collaboration for its own (in-person + remote participation) meetings.

With the advent of SIP in the early 2000s, commercial telecollaboration started to be built most often on SIP based session and application protocols with multiple IETF working groups contributing to that protocol suite (TBD: how much more example/details should we have here). Using this technology and the Internet, the immersive nature of telecollaboration was brought to life-size video, was/is called Telepresence <https://en.wikipedia.org/wiki/Telepresence> and later to even more immersive forms such as AR/VR telecollaboration.

In 2011, the IETF opened the "Real-Time Communication in Web-browsers" (RTCWEB) WG, that towards the end of that decade became the most widely supported cross-platform standard for hundreds of commercial and free tele-collaboration solutions, including Cisco Webex, which is also used by the IETF itself, Zoom and the new IETF collaboration suite MeetEcho (TBD: good references here ?).

While the various forms of Telecollaboration are mostly instances of digitization, they are discussed under sustainability because of its comparison to in-person travel that is not based on simple comparison of energy, but nowadays by comparing their impact on global warming, a key factor to sustainability.

Telecollaboration was primarily developed because of the utility for the participants - to avoid travel for originally predominantly business communications/collaborations. It saw an extreme increase in use (TBD: references) in the Corona Crisis of 2019, when especially international travel was often prohibited, and often even working from an office. This forced millions of people to work from home and utilizing commercial telecollaboration tools. It equally caused most in-person events that were not cancelled to be moved to a telecollaboration platform over the Internet - most of them likely relying on RTCWEB protocols.

Actual energy consumption related comparison between teleconferencing and in-person travel is complex but since the last decades is commonly based on calculating some form of CO2 emission equivalent of the energy consumed, hence comparing not simply the energy consumption, but weighing it by the impact the energy consumption has on one of the key factors (CO2 emission) known to impact sustainable living conditions.

[[VC2014](#)] is a good example of a comparison between travel and telecollaboration taking various factors into account and using CO2 emission equivalents as its core metric. That paper concludes that carbon/ energy cost of telecollaboration could be as little as 7% of an in-person meeting. Those numbers have various assumptions and change when time-effort of participants is converted to carbon/energy costs. These numbers should even be better today in favor of telecollaboration: cost of Internet traffic/bit goes down while cost of fossil fuel for travel goes up.

Recently, air travel has also come under more scrutiny because the greenhouse gas emissions of air travel at the altitudes used by

commercial aviation has been calculated to have a higher global warming impact than simply the amount of CO₂ used by the air plane if it was exhausted at surface level. One publicly funded organization offering carbon offset services calculates a factor 3 of the CO₂ consumption of an air plane https://www.atmosfair.de/de/fliegen_und_klima/flugverkehr_und_klima/klimawirkung_flugverkehr/.

In summary: Telecollaboration has a higher sustainability benefit compared to travel than just the comparison of energy consumption because of the higher challenge to use renewable energy in transportation than in networking, and this is most extreme in the case of telecollaboration that replaces air travel because of the even higher global warming impact of using fossile fuels in air travel.

5. Energy Optimization in Specific Networks

5.1. Low Power and Lossy Networks (LLN)

Low Power and Lossy Networks (LLNs) are networks in which nodes and/or radio links have constraints. Low power consumption constraints in nodes often originate from the need to operate nodes from as long as possible from battery and/or energy harvesting such as (today most commonly) solar panels associated with the node or ambient energy such as energy harvesting from movement for wearable nodes or piezo cells to generate energy for mechanically operated nodes such as switches.

Several IETF WGs have or are producing work is primarily intended to support LLN through multiple layers of the protocol stack. [RFC8352] gives a good overview of the energy consumption related communication challenges and solutions produced by the IETF for this space.

To minimize the energy needs for such nodes, their network data-processing mechanisms have to be optimized. This includes packet header compression, fragmentation (to avoid latency through large packets at low bitrates, packet bundling to only consume radio energy at short time periods, radio energy tuning to just reach the destination(s), minimization of multicasting to eliminate need of radio receivers to consume energy and so on. [RFC8352] gives a more detailed overview, especially because different L2 technologies such as IEEE 802.15.4 type (low power) wireless networks, Bluetooth Low Energy (BLE), WiFi (IEEE 802.11) and DEC ULE.

In the INT area of the IETF, several LLN specific WGs exist(ed):

5.1.1. 6LOWPAN WG

The "IPv6 over Low power WPAN (Wireless Personal Area Networks)" (6lowpan) WG ran from 2005 to 2014 and produced 6 RFC that adopt IPv6 to IEEE 802.15.4 type (low power) wireless networks by transmission procedures [RFC4949], compression of IPv6 (and transport) packet headers [RFC6282], modifications for neighbor discovery (ND) [RFC6775], as well as 3 informational RFCs about the WPAN space and applying IPv6 to it. "Transmission of IPv6 Packets over IEEE 802.15.4 Networks" [RFC4944], "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks" [RFC6282], "Neighbor

Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)" [[RFC6775](#)] (6LOWPAN-ND).

5.1.2. LPWAN WG

Since 2014, the "IPv6 over Low Power Wide-Area Networks" (LPWAN) WG has produced 4 RFC for low-power wide area networks, such as LoRaWAN <https://en.wikipedia.org/wiki/LoRa>, with three standards, [[RFC8724](#)], [[RFC8824](#)], [[RFC9011](#)].

5.1.3. 6TISCH WG

Since 2013, the "IPv6 over the TSCH mode of IEEE 802.15.4e" (6tisch) WG has produced 7 RFC for a version of 802.15.4 called the "Time-Slotted Channel Hopping Mode" (TSCH), which supports deterministic latency and lower energy consumption through the use of scheduling traffic into well defined time slots, thereby also optimizing/minimizing energy consumption when compared to 802.15.4 without TSCH.

5.1.4. 6LO WG

Since 2013, the "IPv6 over Networks of Resource-constrained Nodes" (6lo) WG has generalized the work of 6lowpan for LLN in general, producing 17 RFC for IPv6-over-12foo adaptation layer specifications, information models, cross-adaptation layer specification (such as header specifications) and maintenance and informational documents for other pre-existing IETF work in this space.

5.1.5. ROLL WG

In the RouTinG (RTG) area of the IETF, the "Routing Over Low power and Lossy networks" (ROLL) WG has produced since 2008 23 RFC. Initially it produced requirement RFCs of different type of "Low-power and Lossy Networks": urban: [[RFC5548](#)], industrial [[RFC5673](#)], home automation [[RFC5826](#)] and building automation [[RFC5867](#)].

Since then its work is mostly focused on the "IPv6 Routing Protocol for Low-Power and Lossy Networks" (RPL) [[RFC6550](#)], which is used in a wide variety of the above described IPv6 instances of LLN networks and which are discussed in two ROLL applicability statement RFCs, "Applicability Statement: The Use of the Routing Protocol for Low-Power and Lossy Networks (RPL) Protocol Suite in Home Automation and Building Control" [[RFC7733](#)] and "Applicability Statement for the Routing Protocol for Low-Power and Lossy Networks (RPL) in Advanced Metering Infrastructure (AMI) Networks" [[RFC8036](#)].

The ROLL WG also wrote a more generic RFC for LLN, "Terms Used in Routing for Low-Power and Lossy Networks" [[RFC7102](#)]. RPL has a highly configurable set of functions to support (energy) constrained networks. Unconstrained root node(s), typically edge routers between the RPL network and a backbone network calculate "Destination-Oriented Directed Acyclic Graphs" (DODAG) and can use strict hop-by-hop source routing with dedicated IPv6 routing headers [[RFC9008](#)] to minimize constrained nodes routing related compute and memory requirements. "The Trickle Algorithm" [[RFC6206](#)] allows to minimize routing related packets through automatic lazy updates. While RPL is

naturally a mesh network routing protocol, where all nodes are usually expected to be able to participate in it, RPL also supports even more lightweight leave nodes [[RFC9010](#)].

The 2013 [[I-D.ajunior-energy-awareness-00](#)] proposes the introducing of energy related parameters into RPL to support calculation/selection of most energy efficient paths. The 2017 "An energy optimization routing scheme for LLNs", [[I-D.wang-roll-energy-optimization-scheme](#)] observed that DODAGs in RPL tend to require more energy in nodes closer to the root and proposed specific optimizations to reduce this problem. Neither of these drafts proceeded in the IETF.

While original use-cases for RPL where energy and size limited networks, its design is to a large extent not scale limited. Because of this, and due to its reduced compute/memory requirements for the same size networks compared to other routing protocols, especially the so-called link-state "Interior Gateway routing Protocols" (IGP), such as most commonly used protocols ISIS ([RFC1142](#) superceeded by [ISO10589-Second-Edition](#)) and OSPF [[RFC2328](#)], RPL has also proliferated into use-cases for non-constrained networks, for example to support the largest possible networks automatically, such as in [[RFC8994](#)].

5.2. Constrained Nodes and Networks

(Power) constrained nodes and/or networks exist in a much broader variety than coupled with low-power and lossy networks. For example WiFi and mobile network connections are not considered to be lossy networks, and personal mobile nodes with either connections are order of magnitude less constrained than nodes typically attached to LLN network. Therefore, broader work in the IETF than focused primarily on LLN typically uses just the term lightweight or constrained (nodes and networks).

5.2.1. LWIG WG

Since 2013, the "Light-Weight Implementation Guidance" (lwig) WG is has produced 6 informational RFC on the groups subject, much of which indirectly supports implementing power efficient network implementations via lightweight nodes/links, but it also addressed the topic explicitly including via the aforementioned [[RFC8352](#)] and [[RFC9178](#)], "Building Power-Efficient Constrained Application Protocol (CoAP) Devices for Cellular Networks".

5.2.2. CoRE and CoAP

In the Application (APP) area of the IETF, the "Constrained RESTful Environments" (core) WG has produced since 2010 21 RFC, most of them for or related to "The Constrained Application Protocol" (CoAP) [[RFC6690](#)], which can best be described as a replacement for HTTP for constrained environment, using UDP instead of TCP and DTLS instead of TLS, compact binary message formats instead of human readable textual formats, RESTful message exchange semantic instead of a broader set of options (in HTTP), but also more functionality such as (multicast) discovery and directory services, therefore providing a more comprehensive set of common application functions with more compact on-the-wire/radio encoding than its unconstrained

alternatives. "Object Security for Constrained RESTful Environments" (OSCORE), [\[RFC8613\]](#) is a further product of the CoRE WG providing a more message layer based, more lightweight security alternative to DTLS.

While originally designed for LLN, CoAP is transcending LLN and equally becoming standards in unconstrained environments such as wired/ethernet industrial Machine 2 Machine (M2M) communications, because of simplicity, flexibility and relying on the single set of protocols supporting the widest range of deployment scenarios.

In the SECurity (SEC) area of the IETF, the "Authentication and Authorization for Constrained Environments" (ace) working group has since 2014 produced 4 RFC for security functions in constrained environments, for example CoAP based variations of prior HTTPS protocols such as EST-coaps [\[RFC9148\]](#) for HTTPS based EST [\[RFC7030\]](#). Constrained node support in cryptography especially entails support for Elliptic Curve (EC) public keys due to their shorter key sizes and lower compute requirements compared to RSA public keys with same cryptographic strength. While the benefits of EC over RSA where making them preferred, this "additional market space" (constrained node) benefit helped in their faster market proliferation even beyond constrained networks.

5.2.3. Satellite Constellations

Emerging communication infrastructures may have specific requirements on power consumption. Such requirements should be taken into account when designing/customizing techniques (e.g., routing) to be enabled in such networks. For example, [\[I-D.lhan-problems-requirements-satellite-net\]](#) identifies a set of requirements (including power) for satellite constellations.

5.2.4. Devices with Batteries

Many IETF protocols (e.g., [\[RFC3948\]](#)) were designed to accommodate the presence of middleboxes mainly by encouraging clients to issue frequent keepalives. Such strategy has implication on battery-supplied devices. In order to optimize battery consumption for such devices, [\[RFC6887\]](#) specifies a deterministic method so that client can control state in the network, including their lifetime. Keepalive alive messages may this be optimized as a function of the network policies.

A_REC#2 of [\[RFC7849\]](#) further insist on the importance of saving battery exacerbated by keep-alive messages and recommends the support of collaborative means to control state in the network rather than relying on heuristics.

5.3. Sample Technical Enablers

5.3.1. (IP) Multicast

5.3.1.1. Power Saving with Multicast

IP Multicast was introduced with [\[RFC1112\]](#) and today also called "Any Source Multicast" (ASM) has various protocols standardized in the IETF across multiple working groups. There are also MPLS and

BIER multicast protocols from the IETF developed in the equally named WGs.

These three, network layer multicast technologies can be a power saving technologies when used to distribute data because they reduce the number of packets that need to be sent across the network (through in-network-replication where needed). Because most current link and router technologies do not allow to actually save significant amounts of energy on lower than maximum utilization, these benefits are often only theoretical though. Software routers are the ones most likely to expose energy consumption somewhat proportional to their throughput for just the forwarding (CPU) chip.

Likewise, in large backbone networks, IP multicast can free up bandwidth to be used for other traffic, such as unicast traffic, which may allow to avoid upgrades to faster and potentially more power consuming routers/links. Today, these benefits too are most often overcompensated for by lower per-bit energy consumption of newer generations of routers and links though.

Multicasting can also save energy on the transmitting station across radio links, compared to replicated unicast traffic, but this is rarely significant, because except for fully battery powered mesh network, there are typically non-energy-constrained nodes, such as (commonly) the wired access-points in WiFi networks.

In result, today multicasting has typically no significant power saving benefits with available network technologies. Instead it is used (for data distribution) when the amount of traffic that a unicast solution alternative (with so-called ingress replication) is not possible due to the total amount of traffic generated. This includes wireless/radio networks, where equally airtime is the limiting factor.

5.3.1.2. Power Waste Through Multicast-based Service Coordination

(IP) multicast is often not used to distribute data requested by receivers, but also coordination type functions such as service or resource announcement, discovery or selection. These multicast messages may not carry a lot of data, but they cause recurring, often periodic packets to be sent across a domain and waste energy because of various ill-advised designs, including, but not limited to the following issues:

(a) The receivers of such packets may not even need to receive them, but the protocol shares a multicast group with another protocol that the client does need to receive.

(b) The receiver should not need to receive the packet as far as multicast is concerned, but the underlying link-layer technology still makes the receiver consume the packet at link-layer.

(c) The information received is not new, but just periodically refreshed.

(d) The packet was originated for a service selection by a client, and the receiving device is even responding, but the client then chooses to select another device for the service/resource.

These problems are specifically problematic in the presence of so-called "sleepy" nodes [Section 5.3.2](#) that need to wake up to receive such packets (unnecessarily). It is worse, when the network itself is an LLN network where the forwarders themselves are power constrained and for example periodic multicasting of such coordination packets wastes energy on those forwarders as well - compared to better alternatives.

In 2006, the IETF standardized "Source Specific Multicast" (SSM) [[RFC4607](#)], a variation of IP Multicast that does not allow to perform these type of coordination functions but is only meant for (and useable for) actual data distribution. SSM was introduced for other reasons than the above-described power related issues though, but deprecating the use of ASM is one way to avoid/minimize its ill-advised use with these type of coordination functions, when energy efficiency is an issue. [[RFC8815](#)] is an example for deprecating ASM for other reasons in Service Provider networks.

5.3.1.3. Multicast Problems in Wireless Networks

[[RFC9119](#)] covers multicast challenges and solutions (proposals) for IP Multicast over Wi-Fi. With respect to power consumption, it discusses the following aspects:

- (a) Unnecessary wake-up of power constrained Wi-Fi Stations (STA) nodes can be minimized by wireless Access Points (APs) that buffer multicast packets so they are sent only periodically when those nodes wake up.
- (b) WiFi access points with "Multiple Input Multiple Output" (MIMO) antenna diversity focus sent packets in a way that they are not "broadcast" to all receivers within a particular maximum distance from the AP, making WiFi multicast transmission even less desirable.
- (c) It lists the most widely deployed protocols using aforementioned coordination via IP multicast and describes their specific challenges and possible improvements.
- (d) Existing proprietary conversion of WiFi multicast to Wi-Fi unicast packets.

[[I-D.desmouceaux-ipv6-mcast-wifi-power-usage](#)] focuses on IPv6-related concerns of multicast traffic in large wireless network. This document provides as set of statistics and the induced device power consumption of such flows.

5.3.2. Sleepy Nodes

Sleepy nodes are one of the most common design solutions in support of power saving. This includes LLN level constrained nodes, but also nodes with significant battery capacity, such as mobile phones, tablets and notebooks, because battery lifetime has long since been a key selling factor. In result, vendors do attempt to optimize power consumption across all hardware and software components of such nodes, including the interface hardware and protocols used across the nodes WiFi and mobile radios.

Restating from [\[I-D.bormann-core-roadmap-05\]](#): CoAP has basic support for sleepy nodes by allowing caching of resource information in (non-sleepy) proxy nodes. [\[RFC7641\]](#) enhances this support by enabling sleepy nodes to update caching intermediaries on their own schedule. Around 2012/2013, there was significant review of further review of further support for sleepy nodes in CoAP, resulting in a long list of drafts, whose sleepy nodes benefits are discussed in [\[I-D.bormann-core-roadmap-05\]](#): [\[I-D.vial-core-mirror-server\]](#), [\[I-D.vial-core-mirror-proxy\]](#), [\[I-D.fossati-core-publish-option\]](#), [\[I-D.giacomin-core-sleepy-option\]](#), [\[I-D.castellani-core-alive\]](#), [\[I-D.rahman-core-sleepy-problem-statement\]](#), [\[I-D.rahman-core-sleepy\]](#), [\[I-D.rahman-core-sleepy-nodes-do-we-need\]](#), [\[I-D.fossati-core-monitor-option\]](#). None of these drafts proceeded though.

One partial solution to some sleepy node issues related to their energy consumption, especially the ones caused by the use of multicast [Section 5.3.1.2](#), [Section 5.3.1.3](#) is the use of the "Constrained RESTful Environments (CoRE) Resource Directory" (CoRE-RD) [\[RFC9176\]](#). It allows for sleepy nodes to register discover and register resources via unicast and avoids waking up sleepy nodes when they are not selected by a resource consumer.

An partial alternative to CoRE-RD is the "DNS-Based Service Discovery" {DNS-SD} [\[RFC6763\]](#) combined with for example "Service Registration Protocol for DNS-Based Service Discovery" [\[I-D.ietf-dnssd-srp\]](#). Services can be seen as a subset of resources, and in networks where DNS has to be supported anyhow for other reasons, DNS-SD may be a sufficient alternative to CoRE-RD. It is used for example in Thread [https://en.wikipedia.org/wiki/Thread_\(network_protocol\)](https://en.wikipedia.org/wiki/Thread_(network_protocol)) for this purpose and the only multicast based coordination is the one to establish network wide parameters, such as the address(es) of DNS-SD server(s).

"Building Power-Efficient Constrained Application Protocol (CoAP) Devices for Cellular Networks" [\[RFC9178\]](#) discusses sleepy devices, especially the use of CoAP PubSub [\[I-D.ietf-core-coap-pubsub\]](#) as a mechanism to build proxies for sleepy devices. "Sensor Measurement Lists (SenML)", Standardized proxy infrastructures are best built with standard data models, such as "Sensor Measurement Lists" (SenML) [\[RFC8428\]](#) for sensors, likely the largest number of sleepy devices, especially in LLN.

"Reducing Energy Consumption of Router Advertisements", [\[RFC7772\]](#) eliminates/reduces the energy impact for sleepy nodes of the ubiquitous IPv6 "Neighbor Discovery" (ND) protocol by giving recommends for replacing multicast "Router Advertisement" (RA) messages with so-called directed unicast versions, therefore not waking up sleepy nodes (with an IP multicast RA message). This was already allowed in ND [\[RFC4861\]](#), but not recommended as the default. Note that [\[RFC7772\]](#) does not provide all the energy related optimizations of ND as developed by 6LoWPAN through [\[RFC6775\]](#). [\[I-D.chakrabarti-nordmark-energy-aware-nd\]](#) proposes generalizations for those applications for to all IPv6 links, but was not further pursued by the IETF so far.

5.4. (Lack of) Power Benchmarking Proposals

[[I-D.petrescu-v6ops-ipv6-power-ipv4](#)] presented some measurement results of the power consumption when using IPv6 vs IPv4 with a focus on mobile devices. Such measurements are not backed with formal benchmarking methodologies so that solid and reliable references are set to compare and interpret data.

<https://www.ietf.org/proceedings/103/slides/slides-103-saag-iot-benchmarking-00> presented a benchmark example but with a focus on power cost of encryption.

6. Energy Management Networks

Use of IETF protocol networks in networks that operate power consumption and production is another broad area of digitization.

6.1. Smart Grid

"Smart Grid" is the most well-known instance of such energy management networks. According to https://en.wikipedia.org/wiki/Smart_grid, the term covers aspects mostly centered around intelligent measured and controlled consumption of energy. This includes "Advanced Metering Infrastructure" / "Smart Meters", remote controllable "distribution boards", "circuit breakers", "load control" and "smart appliances". Use cases for the "Smart Grid" include for example timed and measured operations of home devices such as washers or charging cars, when energy consumption is below average.

The 2011 "Internet Protocols for the Smart Grid" [[RFC6272](#)] is a quite comprehensive (66 page) overview of all IETF protocols considered to be necessary or beneficial for Smart Grid networks. This document was written in response to interest by the (not-yet-smart grid) community in utilizing the IETF TCP/IP technologies to evolve previously non-TCP/IP network, and the risk that unnecessary reinvention of the wheel/protocols would be done by that community instead of reusing what was already well specified by the IETF.

Most of the overview in this document is not specific to networks used for Smart Grid applications but just summarized in the document for the above described outreach and education to the community. The aspects most specific to Smart Grids is the back in 2011 still somewhat in its infancy adaptation of IPv6 network technologies to LLN networks (see [Section 5.1](#)): smart meters, circuit breakers, load measurement devices, car chargers and so on - all those devices would most likely be connected to the network via a low-power radio networks, which ideally would utilize IPv6 directly. Support for LLN networks with IPv6 has well improved in IETF specifications in the past decade.

6.2. Syncro Phasor Networks

Power output of multiple power plants/generators into the same power grid needs to be synchronized by power levels based on consumption and power phase (50/60Hz depending on continent) to avoid that energy created out-of-phase is not only wasted, but would actually burn out power lines or create permanent damage in power generators.

When generators go out-of-sync, they have to be emergency switched off, resulting in (rolling-)blackouts, worsening the conditions beyond its likely root-cause such as a single overloaded limited region.

Syncro Phasor Networks are networks whose goal it is to support synchronization of power generators across a power grid, ultimately also permitting to build larger and more resilient power grids. "Power Measurement Units" (PMU) are their core sensing elements. Since about 2012? these networks have started to move from traditional SCADA towards more TCP/IP based networking and application technologies "to improve power system reliability and visibility through wide area measurement and control, by fostering the use and capabilities of synchrophasor technology" (www.naspi.org).

With their fast control loop reaction time and measurement requirements, they also benefit from reliable, fast propagation of PMU data as well as stricter clock synchronization than most Smart Grid applications. For example, transmission lines expand under heat that s caused by electrical load and/or environmental temperature by as much as 30% (between coldest and hottest or highest-load times), impacting the necessary phase relationship of power generation on either end (speed of light propagation speed based on effective length of contracted/expanded wire).

The length of transmission wires can be measured from data sent across the transmission lines and measuring their propagation latency with the help of accurate clock synchronization between sender and receiver(s), using for example network-based clock synchronization protocols. The IETF "Network Time Protocol version 4" (NTPv4), [[RFC5905](#)] is one option for this. The IEEE PTP protocol is often preferred though because it specifies better how measurements can be integrated at the hardware level of Ethernet interfaces, thus allowing easier to achieve higher accuracy, such as Maximum Time Interval (MTIE) errors of less than 1 msec. See for example [[NASPICLOCK](#)].

The "North American Syncro Phasor Initiative" (NASPI), <https://www.naspi.org> is an example organization in support of syncro phasor networking. It is an ongoing project by the USA "Department of Energy" (DoE).

7. (Limited) Energy Management for Networks

7.1. Some Metrics

A 2010-2013 draft [[I-D.manral-bmwg-power-usage](#)], which was not adopted discussed and proposed metrics for power consumption that where intended to be used for benchmarking.

The later work in [Section 7.2](#) referred instead to other metrics for measuring power consumption from other SDOs.

A 2011-2012 draft [[I-D.jennings-energy-pricing](#)], which was not adopted, discusses and proposes a data model to communicate time-varying cost of energy in support of enabling time-shifting of network attached or managed equipment consumption of power.

7.2. EMAN WG

While the IETF did specify a few MIBs with aspects related to of power management, it was only with the formation of the "Energy Management" (EMAN) WG which ran from 2010 to 2015 and released 7 RFC, that the IETF produced a comprehensive set of MIB based standards for managing energy/power for network equipment and associated devices and integrated prior scattered power management related work in the IETF.

EMAN produced (solely) a set of data/information models (MIBs). It does not introduce any new protocol/stacks nor does it address "questions regarding Smart Grid, electricity producers, and distributors" (from [\[RFC7603\]](#)).

[\[I-D.claise-power-management-arch\]](#) describes the initial EMAN architecture as envisioned by some of the core contributors to the WG. It was rewritten in EMAN as the "Energy Management Framework" [\[RFC7326\]](#). "Requirements for Energy Management" are defined in [\[RFC6988\]](#).

According to [\[RFC7326\]](#), "the (EMAN) framework presents a physical reference model and information model. The information model consists of an Energy Management Domain as a set of Energy Objects. Each Energy Object can be attributed with identity, classification, and context. Energy Objects can be monitored and controlled with respect to power, Power State, energy, demand, Power Attributes, and battery. Additionally, the framework models relationships and capabilities between Energy Objects."

One category of use-cases of particular interest to network equipment vendors was and is the management of "Power over Ethernet" via the EMAN framework, measuring and controlling ethernet connected devices through their PoE supplied power. Besides industrial, surveillance cameras and office equipment, such as WiFi access points and phones, PoE is also positioned as a new approach for replacing most in-building automation components including security control for doors/windows, as well as environmental controls and lighting through the use of an in-ceiling, PoE enabled IP/ethernet infrastructure.

EMAN produced version 4 of the "Entity MIB" (ENTITY-MIB) [\[RFC6933\]](#), primarily to introduce globally unique UUIDs for physical entities that allows to better link across different entities, such as a PoE port on an ethernet switch and the device connected to that switch port.

The "Monitoring and Control MIB for Power and Energy" [\[RFC7460\]](#) specifies a MIB for monitoring for Power State and energy consumption of networked. The document discusses the link with other MIBs such as the ENTITY-MIB, the ENTITY-SENSOR-MIB [\[RFC3433\]](#) for which it is amending missing accuracy information to meet IEC power monitoring requirements, the "Power Ethernet MIB" (POWER-ETHERNET-MIB) [\[RFC3621\]](#) to manage PoE, and the pre-existing IETF MIB for Uninterruptable Power Supplies (UPS) (UPS-MIB) [\[RFC1628\]](#), allowing for example to build control systems that manage shutdowns of devices in case of power failure based on UPS battery capacity and device consumptions/priorities. Similarly, the EMAN "Definition of

Managed Objects for Battery Monitoring" [[RFC7577](#)] defines objects to support battery monitoring in managed devices.

The pre-existing IETF "Entity State MIB" (ENTITY-STATE-MIB) [[RFC4268](#)] allows to specify the operational state of entities specified via the ENTITY-MIB respective to their power consumption and operational capabilities (e.g.: "coldStandby", "hotStandby", "ready" etc.). Devices can also act as proxies to provide a MIB interfaces for monitoring and control of power for other devices, that may use other protocols, such as in case of a home gateway interfacing with various vendor specific protocols of home equipment.

The EMAN "Energy Object Context MIB" [[RFC7461](#)] defines the ENERGY-OBJECT-CONTEXT-MIB and IANA-ENERGY-RELATION-MIB, both of which serve to "address device identification, context information, and the energy relationships between devices" according to [[RFC7461](#)].

To automatically discover and negotiate PoE power consumption between switch and client, non-IETF technologies, such as IEEE "Link Layer Discovery Protocol" (LLDP) and proprietary MIBs for it, such as LLDP-EXT-MED-MIB can be used.

Finally, the "Energy Management (EMAN) Applicability Statement" [[RFC7603](#)] provides an overview of EMAN with a user/operator perspective, also reviewing a range of typical scenarios it can support as well as how it could/can link to a variety of pre-existing, non-IETF standards relevant for power management. Such intended applicability includes home, core, and DC networks.

There are currently no YANG equivalent modules. Such modules would not only be designed to echo the EMAN MIBs but would also allow to control dedicated power optimization engines instead of relying upon static and frozen vendor-specific optimization.

8. Power-Awareness in Forwarding and Routing Protocols

8.1. Power Aware Networks (PANET)

In 2013/2014, some drafts proposed how networks themselves, specifically those of Internet Service Providers (ISP) could dynamically regulate their power consumption based on the required performance, for example by switching off or low-powering non-needed components (links, nodes, linecards) or changing speeds on links, or reducing clock-rates of processing elements, and/or routing traffic to utilize as few components as will support the required performance. The authors called this "Power Aware Networks" (PANET), even though no awareness of actual power consumption is required in this approach.

The 2013 "Power-Aware Networks (PANET): Problem Statement" [[I-D.zhang-panet-problem-statement](#)] gives an overview of this concept, and so does "Power-aware Routing and Traffic Engineering: Requirements, Approaches, and Issues", [[I-D.zhang-greenet](#)] from the same year.

The 2014 [[I-D.retana-rtgwg-eacp](#)] exemplifies the concept and discusses key challenges such as the reduced resilience against

errors when redundant components are switched off, the risk of increased stretch (path length) and therefore latency under partial network component shutdown or downspeeding, as well as the idea of saving energy through (periodic) microsleeps such as possible with "Energy Efficient Ethernet" https://en.wikipedia.org/wiki/Energy-Efficient_Ethernet links. The 2013 draft "Reducing Power Consumption using BGP with power source data", [\[I-D.mjsraman-panet-inter-as-power-source\]](#) proposed BGP attributes to allow calculation of power efficient (or for example green) paths.

One core market driver for this work where rolling blackouts that especially affected India at the time of these drafts, raising the desire to be for example reducing the total power consumption of a network in times of such energy emergencies.

While there was technical interest in the IETF, the market significance for the vendors mostly present in the IETF was considered as not to be important enough. Likewise, traditional routers, unlike for example today's standard PC hardware designs do exhibit little power savings upon shutdown of components such as line-cards or interfaces.

In addition, an SDN / controller-based solution where relatively in their infancy back in 2013/2014, and technologies that would allow for SDN controller to have resilient (self-healing) connectivity such as described in [\[RFC8368\]](#)/[\[RFC8994\]](#) was also not available, making the risk of severely impacting network reliability one of the key factors for this PANET work to not proceed so far.

8.2. SDN-based Semantic Forwarding

Recently, [\[I-D.boucadair-irtf-sdn-and-semantic-routing\]](#) provided the following feature as an examples of capabilities that can be offered by appropriate control of forwarding elements:

Energy-efficient Forwarding: An important effort was made in the past to optimize the energy consumption of network elements. However, such optimization is node-specific and no standard means to optimize the energy consumption at the scale of the network have been defined. For example, many nodes (also, service cards) are deployed as backups.

A controller-based approach can be implemented so that the route selection process optimizes the overall energy consumption of a path. Such a process takes into account the current load, avoids waking nodes/cards for handling "sparse" traffic (i.e., a minor portion of the total traffic), considers node-specific data (e.g., [\[RFC7460\]](#)), etc. This off-line Semantic Routing approach will transition specific cards/nodes to "idle" and wake them as appropriate, etc., without breaking service objectives. Moreover, such an approach will have to maintain an up-to-date topology even if a node is in an "idle" state (such nodes may be removed from adjacency tables if they don't participate in routing advertisements).

8.3. Misc

The non-adopted, expired 2013 draft [[I-D.okamoto-ccamp-midori-gmpls-extension-reqs](#)] discusses power awareness in routing in conjunction with Traffic Engineering (tunnels), specifically in the context of Generalized MPLS (GMPLS), e.g.: various L2 technologies such as switched optical fiber networks. It primarily claims the issue that the existing management objects are not sufficient to express energy management related aspects, and thus do not allow to build energy conscious policies into PCE for such GMPLS networks.

The non-adopted 2013 "Requirements for an Energy-Efficient Network System", [[I-D.suzuki-eens-requirements](#)] proposes a signaling of network capacity towards DC, for example based on load or network energy management in support of appropriate performance control (such as VM migration) the DC - or vice versa (DC load-based traffic engineering in the network to support that DC load).

The non-adopted 2013 "Building power optimal Multicast Trees" [[I-D.mjsraman-rtgwg-pim-power](#)] proposes that (PIM based) IP Multicast routing could perform local routing choices in the case of "Equal Cost MultiPath" (ECMP) "Reverse Path Forwarding" (RPF) alternatives based on the energy that would be consumed in the router, such as when one ECMP alternative would use a more power efficient linecard or when one ECMP choice was on the same linecard as the interfaces to which the packets would need to be routed (and therefore avoiding to forward the packet across separate ingress and egress linecards).

9. Gaps

The 2013 "Towards an Energy-Efficient Internet" [[I-D.winter-energy-efficient-internet](#)] summarizes some of the same work items as this document (as written back in 2013) and lists additional more non-adopted drafts. It also identifies three areas of gaps, that it suggests the IETF to work on: "Load-adaptive Resource Management", "Energy-efficient Protocol Design" and "Energy-efficiency Metrics and Standard Benchmarking Methodologies".

Some aspects for those areas of gaps were partially tackled by later work in the IETF, but broadly speaking, most of those areas remain open to a wide range of possible further IETF/IRTF work.

10. Acknowledgments

Thanks for Fred Baker for his review and suggestions.

11. Changelog

[RFC-Editor: this section to be removed in final document.]

The master for this document is hosted at <http://github.com/toerless/energy>. Please submit Issues and/or Pull-requests for proposed changes or join the team of authors and edit yourself.

00: Initial version

01: Added Co-author (Mohamed Boucadair) - long list of typo fixes, editorial improvements in abstract, introduction and other chapters. Added section on satellite networks, devices with batteries, power benchmarking and SDN-based forwarding semantics.

02: Minor text edits (med), add pointer to additional draft (med), Added co-author pascal (tte),

03: Added Jeff Tentsura as co-author

04: Various textual fixups, added new versions of RFC for references using obsoleted RFCs, so that both original and latest are referenced.

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