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Energy Efficient Implementation of IETF Constrained Protocol Suite
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Abstract

   This document summarizes the problems and current practices of energy
   efficient protocol implementation on constrained devices, mostly
   about how to make the protocols within IETF scope behave energy
   friendly. This document also summarizes the impact of link layer
   protocol power saving behaviors to the upper layer protocols, so that
   they can coordinately make the system energy efficient.

Status of this Memo

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1. Introduction

   In many scenarios, the network systems comprises many battery-powered
   or energy-harvesting devices. For example, in an environmental
   monitoring system or a temperature and humidity monitoring system in
   the data center, there are no always-on and handy sustained power
   supplies for the large number of small devices. In such deployment
   environments, it is necessary to optimize the energy consumption of
   the entire system, including computing, application layer behavior,
   and lower layer communication.

   Various research efforts have been spent on this "energy efficiency"
   problem. Most of this research has focused on how to optimize the
   system's power consumption regarding a certain deployment scenario or
   how could an existing network function such as routing or security be
   more energy-efficient. Only few efforts were spent on energy-
   efficient designs for IETF protocols and standardized network stacks
   for such constrained devices [I-D.kovatsch-lwig-class1-coap].

   The IETF has developed a suite of Internet protocols suitable for
   such small devices, including 6LoWPAN ([RFC6282],[RFC6775],[RFC4944]
   ), RPL[RFC6550], and CoAP[I-D.ietf-core-coap]. This document tries
   to summarize the design considerations of making the IETF protocol
   suite as energy-efficient as possible. While this document does not
   provide detailed and systematic solutions to the energy efficiency
   problem, it summarizes the design efforts and analyzes the design
   space of this problem.

   After reviewing the energy-efficient design of each layer, an overall
   conclusion is summarized. Though the lower layer communication
   optimization is the key part of energy efficient design, the protocol
   design at the network and application layers is also important to
   make the device energy-efficient.

1.1. Conventions used in this document

   The key words "MUST", "MUST NOT", "REQUIRED", "SHALL","SHALL NOT",
   "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this
   document are to be interpreted as described in [RFC2119]

1.2. Terminology

   The terminologies used in this document can be referred to [RFC7228].

2. Overview

The IETF has developed multiple protocols to enable end-to-end IP communication between constrained nodes and fully capable nodes. This work has witnessed the evolution of the traditional Internet protocol stack to a light-weight Internet protocol stack. As show in Figure 1 below, the IETF has developed CoAP as the application layer and 6LoWPAN as the adaption layer to run IPv6 over IEEE 802.15.4 and Bluetooth Low-Energy, with the support of routing by RPL and efficient neighbor discovery by 6LoWPAN-ND. 6LoWPAN is currently being adapted by the 6lo working group to support IPv6 over various other technologies, such as ITU-T G.9959, DECT ULE and MS/TP-BACnet.

```
+-----+   +-----+    +-----+                  +------+
|http |   | ftp |    |SNMP |                  | COAP |
+-----+   +-----+    +-----+                  +------+
    \    /          /                      /        \
    +-----+      +-----+              +-----+      +-----+
    | tcp |      | udp |              | tcp |      | udp |
    +-----+      +-----+     ===>     +-----+      +-----+
         \     /                           \        /
 +-----+ +------+  +-------+              +------+   +-----+
 | RTG |--| ipv6 |--|ICMP/ND|              | ipv6 |---| rpl |
 +-----+ +------+  +-------+              +------+   +-----+
           |                                 |
        +-------+                         +-------+  +----------+
        |MAC/PHY|                         |6lowpan|--|6lowpan-nd|
        +-------+                         +-------+  +----------+
                                             |
                                          +-------+
                                          |MAC/PHY|
                                          +-------+
```
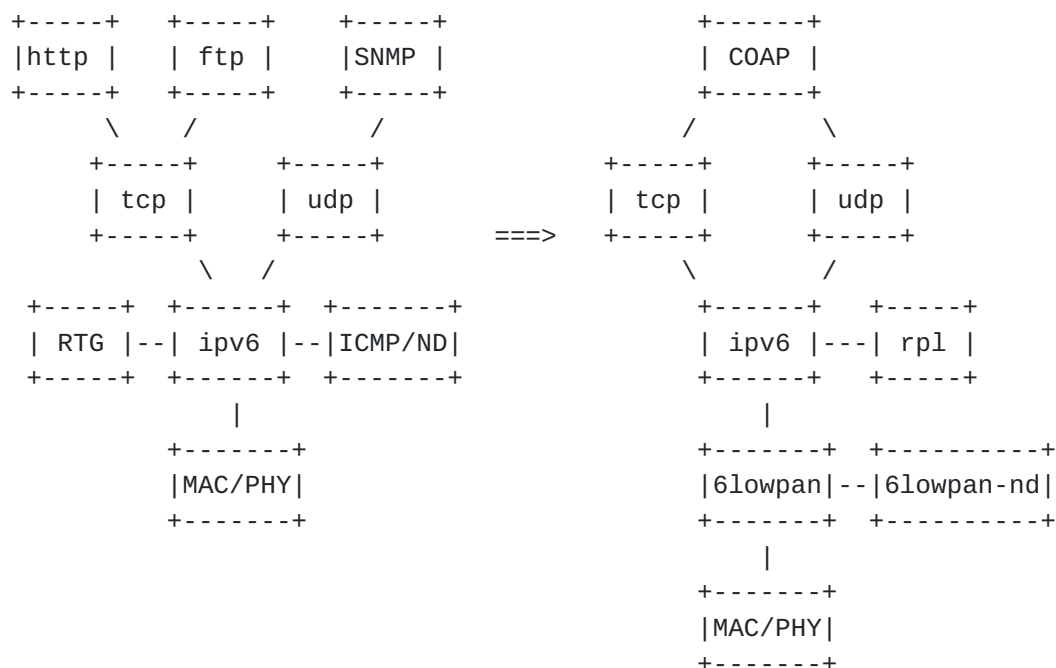
Figure 1: Traditional and Light-weight Internet Protocol Stack

There are numerous published studies reporting comprehensive measurements of wireless communication platforms[Powertrace]. Below we list the energy consumption profile of the most common atom operations on a prevalent sensor node platform. The measurement was based on the Tmote Sky with ContikiMAC as the radio duty cycling algorithm. From the measurement, we can see that optimized transmissions and reception consume almost the same amount of energy. For IEEE 802.15.4 and UWB radios, transmitting may actually be even cheaper than receiving. Only for broadcast and non-synchronized communication transmissions become costly in terms of energy because they need to flood the medium for a long time.

+---------------------------------------+---------------+
| Activity | Energy (uJ) |
+---------------------------------------+---------------+
| Broadcast reception | 178 |
+---------------------------------------+---------------+
| Unicast reception | 222 |
+---------------------------------------+---------------+
| Broadcast transmission | 1790 |
+---------------------------------------+---------------+
| Non-synchronized unicast transmission | 1090 |
+---------------------------------------+---------------+
| Synchronized unicast transmission | 120 |
+---------------------------------------+---------------+
| Unicast TX to awake receiver | 96 |
+---------------------------------------+---------------+

       Figure 2: Power consumption of atom operations on the Tmote Sky with
                              ContikiMAC

3. MAC and Radio Duty Cycling

   In low-power wireless networks, communication and power consumption
   are intertwined. The communication device is typically the most
   power-consuming component, but merely refraining from transmissions
   is not enough to attain a low power consumption: the radio may
   consume as much power in listen mode as when actively transmitting.
   This augments the key problem known as idle listening, whereby the
   radio of a device may be in receive mode (ready to receive any
   message), even if no message is being transmitted to that device.
   Idle listening consumes a huge amount of energy unnecessarily. To
   reduce power consumption, the radio must be switched completely off
   -- duty-cycled -- as much as possible. By applying duty-cycling, the
   lifetime of a device operating on a common button battery may be in
   the order of years, whereas otherwise the battery may be exhausted in
   a few days or even hours. Duty-cycling is a technique generally
   exploited by devices that use the P1 strategy [RFC7228], which need
   to be able to communicate on a relatively frequent basis. Note that
   a more aggressive approach to save energy relies on the P0, Normally-
   off strategy, whereby devices sleep for very long periods and
   communicate infrequently, even though they spend energy in network
   reattachment procedures. ContikiMAC is an example of a very typical
   Radio Duty Cycling (RDC) protocol [ContikiMAC].

   From the perspective of MAC&RDC, all upper layer protocols, such as
   routing, RESTful communication, adaptation, and management flows, are
   all applications. Since the duty cycling algorithm is the key to
   energy-efficiency of the wireless medium, it synchronizes the TX/RX
   request from the higher layer.

   The MAC&RDC are not in the scope of the IETF, yet lower layer
   designers and chipset manufactures take great care of the problem.
   For the IETF protocol designers, however, it is good to know the
   behaviors of lower layers so that the designed protocols can work
   perfectly with them.

   Once again, the IETF protocols we are going to talk about in the
   following sections are the customers of the lower layer. If they
   want to get better service in a cooperative way, they should be
   considerate and understand each other.

3.1. Radio Duty Cycling techniques

   This subsection describes the main three RDC techniques. Note that
   more than one of the presented techniques may be available or can
   even be combined in a specific radio technology:

   a) Channel sampling. In this solution, the radio interface of a

device periodically monitors the channel for very short time
intervals (i.e. with a low duty cycle) with the aim of detecting
incoming transmissions. In order to make sure that a receiver can
correctly receive a transmitted data unit, the sender may prepend a
preamble of a duration at least the sampling period to the data unit
to be sent. Another option for the sender is to repeatedly transmit
the data unit, instead of sending a preamble before the data unit.
Once a transmission is detected by a receiver, the receiver may stay
awake until the complete reception of the data unit. Examples of
radio technologies that use preamble sampling include ContikiMAC, the
Coordinated Sampled Listening (CSL) mode of IEEE 802.15.4e, and the
Frequently Listening (FL) mode of ITU-T G.9959.

b) Scheduled transmissions. This approach allows a device to know
the instants in which it should be awake (during some time interval)
in order to receive data units. Otherwise, the device may remain in
sleep mode. The decision on the instants that will be used for
communication is reached by means of some form of negotation between
the involved devices. Such negotation may be performed per
transmission or per session/connection. Bluetooth Low Energy is an
example of a radio technology based on this mechanism.

c) Listen after send. This technique allows a node to remain in
sleep mode by default, wake up and poll a sender (which must be ready
to receive a poll message) for pending transmissions. After sending
the poll message, the node remains in receive mode, ready for a
potential incoming transmission. After a certain time interval, the
node may go back to sleep. The Receiver Initated Transmission (RIT)
mode of 802.15.4e, and the transmission of data between a coordinator
and a device in IEEE 802.15.4-2003 use this technique.

3.2. Latency and buffering

The latency of a data unit transmission to a duty-cycled device is
equal to or greater than the latency of transmitting to an always-on
device. Therefore, duty-cycling leads to a trade-off between energy
consumption and latency. Note that in addition to a latency
increase, RDC may introduce latency variance, since the latency
increase is a random variable (which is uniformly distributed if
duty-cycling follows a periodical behavior).

On the other hand, due to the latency increase of duty-cycling, a
sender waiting for a transmission opportunity may need to store
subsequent outgoing packets in a buffer, increasing memory
requirements and potentially incurring queuing waiting time that
contributes to the packet overall delay and increases the probability
of buffer overflow, leading to losses.

The parameters controlling the radio duty cycle have to be carefully
tuned to achieve the intended application and/or network
requirements. On the other hand, upper layers should take into
account the expected latency behavior due to RDC.

3.3. Power save services available in example low-power radios

This subsection presents power save services and techniques used in a
few relevant examples of wireless low-power radios: IEEE 802.11v,
Bluetooth Low Energy and IEEE 802.15.4. For a more detailed overview
of each technology, the reader may refer to the literature or to the
corresponding specifications.

3.3.1. Power Save Services Provided by IEEE 802.11v

IEEE 802.11v [IEEE80211v] defines mechanisms and services for power
save of stations/nodes that include flexible multicast service (FMS),
proxy ARP advertisement, extended sleep modes, traffic filtering. It
would be useful if upper layer protocols knows such capabilities
provided by the lower layer, so that they can coordinate with each
other.

These services include:

Proxy ARP: The Proxy ARP capability enables an Access Point (AP) to
indicate that the non-AP station (STA) will not receive ARP frames.
The Proxy ARP capability enables the non-AP STA to remain in power-
save for longer periods of time.

Basic Service Set (BSS) Max Idle Period management enables an AP to
indicate a time period during which the AP does not disassociate a
STA due to non-receipt of frames from the STA. This supports
improved STA power saving and AP resource management.

FMS: A service in which a non-access point (non-AP) station (STA) can
request a multicast delivery interval longer than the delivery
traffic indication message (DTIM) interval for the purposes of
lengthening the period of time a STA may be in a power save state.

Traffic Filtering Service (TFS): A service provided by an access
point (AP) to a non-AP station (STA) that can reduce the number of
frames sent to the non-AP STA by not forwarding individually
addressed frames addressed to the non-AP STA that do not match
traffic filters specified by the non-AP STA.

Using the above services provided by the lower layer, the constrained
nodes can achieve either client initiated power save (via TFS) or
network assisted power save (Proxy-ARP, BSS Max Idel Period and FMS).

Upper layer protocols would better synchronize with the parameters
such as FMS interval and BSS MAX Idle Period, so that the wireless
transmissions are not triggered periodically.

3.3.2. Power Save Services Provided by Bluetooth Low Energy

Bluetooth Low Energy (Bluetooth LE) is a wireless low-power
communications technology that is the hallmark component of the
Bluetooth 4.0 and Bluetooth 4.1 specifications [Bluetooth41]"/>.
BT-LE has been designed for the goal of ultra-low-power consumption.
Currently, it is possible to run IPv6 over BT-LE networks by using a
6LoWPAN variant adapted to BT-LE [I-D.ietf-6lowpan-btle].

Bluetooth LE networks comprise a master and one or more slaves which
are connected to the master. The Bluetooth LE master is assumed to
be a relatively powerful device, whereas a slave is typically a
constrained device (e.g. a class 1 device).

Medium access in Bluetooth LE is based on a TDMA scheme which is
coordinated by the master. This device determines the start of
connection events, in which communication between the master and a
slave takes place. At the beginning of a connection event, the
master sends a poll message, which may encapsulate data, to the
slave. The latter must send a response, which may also contain data.
The master and the slave may continue exchanging data until the end
of the connection event. The next opportunity for communication
between the master and the slave will be in the next connection event
scheduled for the slave.

The time between consecutive connection events is defined by the
connInterval parameter, which may range between 7.5 ms and 4 s. The
slave may remain in sleep mode since the end of its last connection
event until the beginning of its next connection event. Therefore,
Bluetooth LE is duty-cycled by nature. Furthermore, after having
replied to the master, a slave is not required to listen to the
master (and thus may keep the radio in sleep mode) for
connSlaveLatency consecutive connection events. connSlaveLatency is
an integer parameter between 0 and 499 which should not cause link
inactivity for more than connSupervisionTimeout time. The
connSupervisionTimeout parameter is in the range between 100 ms and
32 s.

Upper layer protocols should take into account the medium access and
duty-cycling behavior of Bluetooth LE. In particular, connInterval,
connSlaveLatency and connSupervisionTimeout determine the time
between two consecutive connection events for a given slave. The
upper layer packet generation pattern and rate should be consistent
with the settings of the aforementioned parameters (and vice versa).

3.3.3. Power Save Services in IEEE 802.15.4

   IEEE 802.15.4 is a family of standard radio interfaces for low-rate,
   low-power wireless networking [fifteendotfour]. Since the
   publication of its first version in 2003, IEEE 802.15.4 has become
   the de-facto choice for a wide range of constrained node network
   application domains and has been a primary target technology of
   various IETF working groups such as 6LoWPAN
   [RFC6282],[RFC6775],[RFC4944] and 6TiSCH
   [I-D.ietf-6tisch-architecture]. IEEE 802.15.4 specifies PHY and MAC
   layer functionality.

   IEEE 802.15.4 defines three roles called device, coordinator and PAN
   coordinator. The device role is adequate for nodes that do not
   implement the complete IEEE 802.15.4 functionality, and is mainly
   targeted for constrained nodes with a limited energy source. The
   coordinator role includes synchronization capabilities and is
   suitable for nodes that do not suffer severe constraints (e.g. a
   mains-powered node). The PAN coordinator is a special type of
   coordinator that acts as a principal controller in an IEEE 802.15.4
   network.

   IEEE 802.15.4 has mainly defined two types of networks depending on
   their configuration: beacon-enabled and nonbeacon-enabled networks.
   In the first network type, coordinators periodically transmit
   beacons. The time between beacons is divided in three main parts:
   the Contention Access Period (CAP), the Contention Free Period (CFP)
   and an inactive period. In the first period, nodes use slotted
   CSMA/CA for data communication. In the second one, a TDMA scheme
   controls medium access. During the idle period, communication does
   not take place, thus the inactive period is a good opportunity for
   nodes to turn the radio off and save energy. The coordinator
   announces in each beacon the list of nodes for which data will be
   sent in the subsequent period. Therefore, devices may remain in
   sleep mode by default and wake up periodically to listen to the
   beacons sent by their coordinator. If a device wants to transmit
   data, or learns from a beacon that it is an intended destination,
   then it will exchange messages with the coordinator and will thus
   consume energy. An underlying assumption is that when a message is
   sent to a coordinator, the radio of the latter will be ready to
   receive the message.

   The beacon interval and the duration of the beacon interval active
   portion (i.e. the CAP and the CFP), and thus the duty cycle, can be
   configured. The parameters that control these times are called
   macBeaconOrder and macSuperframeOrder, respectively. As an example,
   when IEEE 802.15.4 operates in the 2.4 GHz PHY, both times can be
   (independently) set to values in the range between 15.36 ms and 251.6

s.

In the beaconless mode, nodes use unslotted CSMA/CA for data
transmission. The device may be in sleep mode by default and may
activate its radio to either i) request to the coordinator whether
there is pending data for the device, or ii) to transmit data to the
coordinator. The wake-up pattern of the device, if any, is out of
the scope of IEEE 802.15.4.

Communication between the two ends of an IEEE 802.15.4 link may also
take place in a peer-to-peer configuration, whereby both link ends
assume the same role. In this case, data transmission can happen at
any moment. Nodes must have their radio in receive mode, and be
ready to listen to the medium by default (which for battery-enabled
nodes may lead to a quick battery depletion), or apply
synchronization techniques. The latter are out of the scope of IEEE
802.15.4.

The main MAC layer IEEE 802.15.4 amendment to date is IEEE 802.15.4e.
This amendment includes various new MAC layer modes, some of which
include mechanisms for low energy consumption. Among these, the
Time-Slotted Channel Hopping (TSCH) is an outstanding mode which
offers robust features for industrial environments, among others. In
order to provide the functionality needed to enable IPv6 over TSCH,
the 6TiSCH working group has been recently created. TSCH is based on
a TDMA schedule whereby a set of time slots are used for frame
transmission and reception, and other time slots are unscheduled.
The latter time slots may be used by a dynamic scheduling mechanism,
otherwise nodes may keep the radio off during the unscheduled time
slots, thus saving energy. The minimal schedule configuration
specified in [I-D.ietf-6tisch-minimal] comprises 101 time slots,
whereby 95 of these time slots are unscheduled and the time slot
duration is 15 ms.

Other 802.15.4e modes, which are in fact designed for low energy, are
the previously mentioned CSL and RIT.

4. IP Adaptation and Transport Layer

6LoWPAN is the adaption layer to run IPv6 over IEEE 802.15.4 MAC&PHY.
It was born to fill the gap that the IPv6 layer does not support
fragmentation and assembly of <1280-byte packets while IEEE 802.15.4
only supports a MTU of 127 bytes.

IPv6 is the basis for the higher layer protocols, including both TCP/
UDP transport and applications. So they are quite ignorant of the
lower layers, and are almost neutral to the energy-efficiency
problem.

What the network stack can optimize is to save the computing power.
For example the Contiki implementation has multiple cross layer
optimizations for buffers and energy management, e.g., the computing
and validation of UDP/TCP checksums without the need of reading IP
headers from a different layer. These optimizations are software
implementation techniques, and out of the scope of IETF and the LWIG
working group.

The 6LoWPAN contributes to the energy-efficiency problem in two ways.
First of all, it swaps computing with communication. 6LoWPAN applies
compression of the IPv6 header. This means less amount of data will
be handled by the lower layer, but both the sender and receiver
should spend more computing power on the compression and
decompression of the packets over the air. Secondly, the 6LoWPAN
working group developed the energy-efficient Neighbor Discovery
called 6LoWPAN-ND, which is an energy efficient replacement of the
IPv6 ND in constrained environments. IPv6 Neighbor Discovery was not
designed for non-transitive wireless links, as its heavy use of
multicast makes it inefficient and sometimes impractical in a low-
power and lossy network. 6LoWPAN-ND describes simple optimizations to
IPv6 Neighbor Discovery, its addressing mechanisms, and duplicate
address detection for Low-power Wireless Personal Area Networks and
similar networks. However, 6LoWPAN ND does not modify Neighbor
Unreachability Detection (NUD) timeouts, which are very short (by
default three transmissions spaced one second apart). NUD timeout
settings should be tuned taking into account the latency that may be
introduced by duty-cycled mechanisms at the link layer, or
alternative, less impatient NUD algorithms should be considered
[I-D.ietf-6man-impatient-nud].

5. Routing Protocols

   The routing protocol designed by the IETF for constrained
   environments is called RPL [RFC6550]. As a routing protocol, RPL has
   to exchange messages periodically and keep routing states for each
   destination. RPL is optimized for the many-to-one communication
   pattern, where network nodes primarily send data towards the border
   router, but has provisions for any-to-any routing as well.

   The authors of the Powertrace tool [Powertrace] studied the power
   profile of RPL. It divides the routing protocol into control and
   data traffic. The control channel uses ICMP messages to establish
   and maintain the routing states. The data channel is any application
   that uses RPL for routing packets. The study has shown that the
   power consumption of the control traffic goes down over time and data
   traffic stays relatively constant. The study also reflects that the
   routing protocol should keep the control traffic as low as possible
   to make it energy-friendly. The amount of RPL control traffic can be
   tuned by setting the Trickle algorithm parameters (i.e. Imin, Imax
   and k) to adequate values. However, there exists a trade-off between
   energy consumption and other performance parameters such as network
   convergence time and robustness.

   RFC 6551 [RFC6551] defines routing metrics and constraints to be used
   by RPL in route computation. Among others, RFC 6551 specifies a Node
   Energy object that allows to provide information related to node
   energy, such as the energy source type or the estimated percentage of
   remaining energy. Appropriate use of energy-based routing metrics
   may help to balance energy consumption of network nodes, minimize
   network partitioning and increase network lifetime.

6. Application Layer

CoAP [RFC7252] was designed as a RESTful application protocol,
connecting the services of smart devices to the World Wide Web. CoAP
is not a chatty protocol, it provides basic communication services
such as service discovery and GET/POST/PUT/DELETE methods with a
binary header.

The energy-efficient design is implicitly included in the CoAP
protocol design. CoAP uses a fixed-length binary header of only four
bytes that may be followed by binary options. To reduce regular and
frequent queries of the resources, CoAP provides an observe mode, in
which the requester registers its interest of a certain resource and
the responder will report the value whenever it was updated. This
reduces the request response roundtrip while keeping information
exchange a ubiquitous service and, most importantly, it allows an
energy-constrained server to remain in sleep mode during the period
between observe notification transmissions.

Furthermore, [RFC7252] defines CoAP proxies which can cache resource
representations previously provided by sleepy CoAP servers. The
proxies themselves may respond to client requests if the
corresponding server is sleeping and the resource representation is
recent enough. Otherwise, a proxy may attempt to obtain the resource
from the sleepy server.

Beyond these features of CoAP, there have been a number of proposals
to further support sleepy nodes at the application layer by
leveraging CoAP mechanisms. A good summary of such proposals can be
found in [I-D.rahman-core-sleepy-nodes-do-we-need]. The different
approaches include exploiting the use of proxies, leveraging the
Resource Directory [I-D.ietf-core-resource-directory] or signaling
when a node is awake to the interested nodes. As of the writing,
none of these proposals has been adopted by the CoRE working group.

CoAP offers mechanisms for reliable communication between two CoAP
endpoints. A CoAP message may be signaled as a confirmable (CON)
message, and an acknowledgment (ACK) is issued by the receiver if the
CON message is correctly received. The sender starts a
Retransmission TimeOut (RTO) for every CON message sent. The initial
RTO value is chosen randomly between 2 and 3 s. If an RTO expires,
the new RTO value is doubled (unless a limit on the number of
retransmissions has been reached). Since duty-cycling at the link
layer may lead to long latency (i.e. even greater than the initial
RTO value), CoAP RTO parameters should be tuned accordingly in order
to avoid spurious RTOs which would unnecessarily waste node energy
and other resources.

7. Cross Layer Optimization

   The cross layer optimization is a technique used in many
   scenarios.There are some technologies for power efficient
   optimization via PHY to Routing cross layer design
   [Cross-layer-Optimization]. In this research, cross-layer
   optimization frameworks have been developed to minimize the total
   power consumption or to maximize the utility-power trade-off using
   cooperative diversity.

   Also a cross-layer design in multihop wireless networks is proposed
   for congestion control, routing and scheduling - in transport,
   network and link layers into a coherent framework
   [Cross-layer-design]. This method and thinking could be applied to
   the implementation of energy effective cross layer design.

   Todo: more discussion of Cross layer issues.

8. Summary

We find a summary section necessary although most IETF documents do
not contain it. The points we would like to summarize are as
follows.

a. All Internet protocols, which are in the scope of the IETF, are
    customers of the lower layers (PHY, MAC, and Duty-cycling). In
    order to get a better service, the designers of higher layers
    should know them better.

b. The IETF has developed multiple protocols for constrained
    networked devices. A lot of implicit energy efficient design
    principles have been used in these protocols.

c. The power trace analysis of different protocol operations showed
    that for radio-duty-cycled networks broadcasts should be avoided.
    Saving unnecessary states maintenance is also an effective method
    to be energy-friendly.

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initiate this facilities.

10. IANA Considerations

   This document has no IANA requests.

11. Security Considerations

This document discusses the energy efficient protocol design, and
does not incur any changes or challenges on security issues besides
what the protocol specifications have analyzed.

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