Networking Working Group D. Culler
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Routing Requirements for Low Power And Lossy Networks
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Abstract

The need for high quality routing for Low power and Lossy Network (L2N) such as sensor networks comprised of highly constrained devices (CPU, memory, ...) in sometimes unstable wireless environments is critical now and will continue to increase. Interest in this class of applications has grown dramatically in recent years and a routing solution addressing the specific environments of such networks is highly required considering the numerous, incompatible open-source

and proprietary routing protocols as well as several industrial forums. The aim of this document is to define the routing requirements for Sensor Networks at the IP layer. Such routing protocol(s) would need to address several unique aspects of this class of embedded devices and would operate in networks comprising links of various nature.

Requirements Language

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 RFC 2119 [RFC2119].

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1. Terminology

CMOS: Complementary metal-oxide-semiconductor. DRAM: Dynamic Random Access Memory. L2N: Low power and Lossy Network.

MAC: Medium Access control. PAN: Personal Area Network. RAM: Random Access Memory. RF Links: Radio Frequency Links. RL2N: Routing in Low power and Lossy Networks.

SNR: Signal Noise Ratio. SRAM: Static Random Access Memory.

2. Introduction

The need for high quality routing for wireless networks comprised of highly constrained (memory, power, bandwidth, CPU ...) and typically embedded devices in a potentially variable environment (thus the therm "Lossy") is critical now and will continue to increase. Interest in this class of applications, including sensor networks, device networks, environmental monitoring, home automation, building automation, process control, automated meter readings, condition-based maintenanace, security, and others, has grown dramatically in recent years; a routing solution addressing the specific environments of such networks is highly required considering the numerous, incompatible open-source and proprietary routing protocols that have emerged, as well as several industrial forums that have emerged over the IEEE 802.15.4 link and various proprietary links.

Such routing protocol(s) would need to address several unique requirements of this class of embedded devices and would operate in networks comprising links of various nature. Considering the variety of Sensor and Controller-based applications, there may not be a single routing protocol satisfying the entire list of requirements, in which case it may be decided to define a limited set of routing protocols that could be combined to satify the overall objective. It is also envisioned that the designed solution will not address very specific requirements of some more "exotic" networks.

3. "Route over" versus "Mesh under"

Within the IETF, working groups are attending to aspects of this issue with, for example, 6LoWPAN considering layer 2 "mesh-under" for IEEE 802.15.4 links and MANET considering layer 3 and higher layer routing in mobile environments with relatively high powered nodes and links. Meanwhile, industry forums, including Zigbee, Zwave, Wireless HART, and ISA SP100.11a, and numerous proprietary offerings address the combination of low-power and wireless, but only within the

equivalent of a single IP link and only within the context of stacks vertically integrated from the physical layer to the application with no provisions for routing to other kinds of links.

It is clearly envisioned that Low Power and Lossy Networks (L2Ns) will comprise a variety of nodes interconnected by links of different nature including IEEE 802.15.4, IEEE 802.11, IEEE 802.16 and so on.

The IETF 6LoWPAN working group has defined a format for IPv6 over 802.15.4 with extensive header compression, fragmentation for very small link frames, and support for mesh routing under the IP link (see [I-D.ietf-6lowpan-format]).

Clearly routing techniques can be defined at the link layer (also referred as to the "Mesh Under" approach). By contrast, the "Route over" approach exclusively relies on IP routing over a network made of a variety of nodes interconnected by links of various nature. The aim of this document is to define the routing requirements L2Ns at the IP layer. As such, it pertains to collections of IEEE 802.15.4 devices, but is not limited to communication within a single IP link. It pertains to IP level routing among multiple such PANs, routing among IEEE 802.15.4 PANs and other links, and routing in other low power (wireless) networks.

4. Unique Routing Requirements of Low Power Wireless Networkson

L2Ns present a variety of unique routing requirements driven partly by implementation technology constraints, partly by the domain of usage, and partly by application characteristics. These issues are listed roughly in order of criticality. [I-D.levis-rl2n-overview-protocols]provides an overview of existing protocols in light of L2Ns' specific requirements. Of course, none of these protocols were designed with all these considerations in mind, and so it is not surprising that some of the issues remain unsolved.

Whereas this document lists the set of generic requirement for RL2N other documents lists application specific routing requirements. The routing requirements for home control and automation are discussed in [I-D.brandt-rl2n-home-routing-reqs].

4.1. Spatially-Driven Multihop

The low transmission power of PAN (Personal Area Network) radios (e.g. collection of IEEE 802.15 links, implies that the range is relatively short; multiple hops are required to achieve communication over greater distances. Variously referred to as mesh or multihop

routing, such multihop routing communication is important from a basic energy viewpoint. The energy cost to traverse a given distance with multiple fixed-power hops grows only linearly with distance, whereas the energy of a single RF "hop" grows as a cubic or higher power of the distance, depending on elevation and other factors.

It is also essential from a reliability viewpoint. Lower transmission power generally means lower SNR, relatively high per-hop loss rates and greater sensitivity to fading, interference, attenuation, and occlusion. Mutihop communication permits routing around obstacles and provides temporal diversity through retransmission as well as spatial diversity through multiple receivers, i.e., multipath routing. In addition, with multihop routing use to cover distance, route formation and reliability are intimately linked. Taking a longer hop will typically incur a larger loss rate, while a more reliable hop incurs more transmissions to reach the destination. These issues occur potentially both at layer 2, with IP routing over mesh-routed links, and, of course, at layer 3, with IP routing over similar or dissimilar links.

Furthermore, with multiple points of egress between low-power wireless networks and conventional powered networks, route selection over on type of link may be influenced by factors in the low-power links.

4.2. Light footprint

Integrated CMOS radios typically have sophisticated physical layer and MAC support integrated with the transceiver. However, the network layer over this MAC (or sub-MAC) is generally implemented on a microcontroller device with the capabilities and resources historically associated with serial links (e.g., RS-232 and RS-485). In particular, as of today, these devices have only a few kilobytes of RAM and a few to several tens of kilobytes of program ROM. The memory capacity of these device has been growing, but at much slower rate than the SRAM and DRAM storage found in microprocessor-based systems. The marginal cost of memory in embedded devices is much greater than in conventional computers and standby power consumption increases with RAM capacity due to leakage, so memory capacity impacts the lifetime of battery powered, low-duty cycle devices.

Thus, the small memory capacity of these units is fundamental and constrains routing table size, buffer capacity, and all routing states, including neighbor tables, link estimators, sequence number and other caches. For example, link state algorithms, distance vector algorithms, and various intermediates and hybrids may have quite different relative merits when footprint is at premium, as compared to convergence rate, information exchange rate, and so on.

Existing routing protocols generally attend to constraints imposed by the links more than to constraints imposed by the nodes that connect those links. The prime exception to this is scalability concerns of very large networks given fixed, albeit powerful, routers. Here we are concerned with how routing protocols scale down to less capable nodes, even a fixed network scale. We are also concerned with how routing protocols can allow more capable nodes to relieve less capable ones, even with common link characteristics. Compression techniques, such as that in 6LoWPAN, enable the opportunity to perform routing on low-power devices (and permit the use of small MTUs and modest forwarding buffers), but do not address the resource requirements of the routing protocols that guide the exchange of such compressed packets.

4.3. Small MTU

Potentially high bit error rates, limited buffer capacity, limited channel capacity shared among numerous devices, and pervasive hidden-terminal occurrences due to the presence of many devices spread over physical regions all lead to the use of relatively small frames. Thus, per packet routing and header information comes at a premium. These issues, as well as limited energy, storage and bandwidth resources, imply that routing needs to be more aware of underlying physical factors than in traditional, even wireless, networks. For example, protocols involving the exchange of lists of all 1-hop or all 2-hop neighbors may be forced to reckon with longs lists (if the physical density is high compared to the communication range).

Alternatively, efforts to limit the degree of the network by adjusting transmission range bring additional physical factors into the purvue of routing. Moreover, such measures to optimize route formation may be at odds with optimizing forwarding cost.

4.4. Deep Power Management

In most L2Ns, average transmission rates are very low, relative to channel capacity and powering on the radio to be ready receive costs power consumption that is roughly equal to that of actual transmission or reception.

Thus, power budgets tend to be dominated by idle listening costs, unless the receivers are heavily duty cycled. Thus, routing protocols MUST permit deep power management in the underlying link layers. Currently, these link level techniques fall into three general categories: variants of TDMA either local or global, variants of cluster-based beaconing, and variants of preamble sample. While power management is typically viewed as a layer 2 responsibility, few routing protocols anticipate that the devices responsible for

forwarding (and for route maintenance) have their network link off most (often over 99%) of the time. Alternatively, certain link-level power management strategies may introduce extreme constraints on routing protocols.

4.5. Heterogeneous Capabilities

While the majority of devices are highly constrained, in many settings they operate in conjunction with more capable devices, including microprocessors hosting the same RF link but with greater RAM capacity, devices on mains power with either large or small storage, devices with directional to high-gain antennas, and devices that bridge or route to higher bandwidth links. The existence of such a wide scope of device types within L2N (e.g Sensor Networks must be taken into account by the routing protocol to increase the lifetime and robustness of the most constrained devices. In some cases, it may be advantageous to decrease the routing optimality at the benefit of energy saving for the most constrained (set of) devices. Thus the routing protocol must not only be capable of supporting such a wide variety a devices but should consider the device capability as a key element of the routing decision, domain scope for the exchange of routing control plane messages.

The routing protocol MUST support the ability to perform constrained based routing taking into account a variety of static or dynamic node metrics.

4.6. Highly Variable Connectivity

In many use cases for low power wireless devices, mobility is a central element. However, even where all the devices are stationary, changes in environmental conditions gives rise to substantial changes in the connectivity relationships. Moving objects, opening and closing of doors, background interference due to machinery, electronic equipment, radios, or other wireless networks, even atmospheric changes which increase or decrease absorption all alter the connection topology over which routing takes place. Thus, routing protocols MUST be adaptive to a changing underlying topology and able to utilize connectivity and related information, such as link quality or signal strength, to maintain viable paths.

The routing protocol MUST be particularly robust to topology changes in the network due to frequent change of link states. For many embedded networks with substantial, often the mobility is structured, rather than ad hoc, such as items moving through a manufacturing process, shipping exchanges, mobile devices moving through a stationary network of similar devices, or collections of devices moving together as a network. The most extreme variations in

connectivity, including mobility over large distances and enclosure into RF-opaque settings, give rise to intermittent connectivity (DTN: Delay Tolerant Networks). Many use cases involve logging over long periods of disconnected operation and dispersion of logged data upon arrival and detection of a point of connectivity. Such topology changing environments are usually challenging for routing protocols and may lead to frequent rerouting decisions: careful consideration must be given to bound the number of rerouting decisions for the most constrained devices so as to save energy.

4.7. Structured Workload and Traffic Pattern

The above characteristics suggest that effective general-purpose RL2N can be very hard - multiple hops are required over spontaneously varying connections where bandwidth is precious, packets are small and little state can be expended at each router. However, the same observations suggests that routing protocols can take advantage of the constrained setting to simplify the general problem. The workload or traffic pattern of use cases for these networks tend to be highly structured (Point-to-Multipoint or Multipoint-to-point due to the specific role of one or more sinks), unlike the any-to-any data transfers and interactive key-strokes that dominate typical client and server workloads. Instrumentation and monitoring typically involve regular, periodic, or alarm-based collection from a large collection of devices. Configuration, tasking, and management typically involve dissemination of commands to an aggregate of devices. Automation, such as lighting control, involve numerous long-lived aggregates of actuation points and control points. Uses in transportation and shipping involve opportunistic communication bursts upon arrival at suitable way points. General-purpose any-to-any connectivity arises in situations such as management, diagnosis, and field access. In many cases, exploiting such structure may simplify difficult problems arising from resource constraints or variation in connectivity. Thus the routing protocols MUST support Point to Point, Point to Multipoint and Multipoint to Point routing. However, the highly correlated, repetitive use of particular traffic patterns will typically allow routing protocols to optimize for very common simple cases.

4.8. Partial Information

The density of connectivity varies dramatically from long nearly-linear structures (e.g., over a transect of land, a bridge or a road) to extremely dense collections in a single RF 'cell' (e.g., parcels on a dock or containers in transport). Thus, routing protocols and addressing SHOULD avoid placing arbitrary limits on the underlying connection topology. Conversely, routing with partial information is an important property in L2Ns as it facilitates scaling down of the

node or scaling up of the network to points where algorithmic concepts such "all 1-hop neighbors", "all 2-hop neighbors", all nodes, or all pairs may not be representable with the resources available per node.

4.9. Multi-topology Routing

Multi-topology Routing (MTR) is also important to consider both with the goal of improving service where it is desirable, but in reducing effort where service requirements are lax. Although many L2Ns use initially provide fairly latency in-sensitive monitoring, many applications have emerged that require timely delivery of the vast majority of the readings, eventual delivery of the remainder, time-sensitive delivery of alarms, and/or increasing predictability for soft and moderately real-time.

These issues impact path selection and path quality optimization, as well as the impact of protocol and route maintenance traffic on data traffic, especially during times of critical physical change. Thus, the mix of applications with a wide range of requirements in term of path quality leads to the requirements for MTR.

4.10. Data Aware routing

Ultimately, scalability may benefit from the ability to perform computations for data reduction or fusion within the network, not just at the data processing sink level. The most common case being aggregation along a dynamically computed path to a sink.

Thus the routing protocol MUST take points of aggregation (another node capability) into account when calculating routes.

5. Relationship with other Routing Protocols

This family of unique characteristics pose unique routing challenges. At the same time, these challenges have deep similarities (and substantial points of difference) with several other IETF routing protocols. Like MANET, the interconnection topology over which routing is performed must, in general, be deduced from observed communication events, in addition to physical wiring or explicit configuration. This topology may be static or dynamic, depending on physical conditions. However, the routing state, neighbor table size, and cache state per node will in many cases be highly constrained. Devices themselves have important structure and characteristics, as many are stationary and some are unconstrained.

In general, the average bandwidth and power demand per node should

stay bounded and not grow unreasonably with the size of a network. Thus, it may be unacceptable to generate unscoped floods, unless the frequency of floods per node diminishes with the size of the network. In these respects, light footprint routing has much in common with IGP. Effective routing must be carried out in the presence of partial (space limited) and somewhat imperfect information. Note that mixed routing protocol may be considered (Distance Vector and Link state). That said, none of the currently available routing protocol fulfills the requirement of L2Ns network listed above. [I-D.levis-rl2n-overview-protocols]aims at providing an overview survey of existing routing protocols. The aforementioned requirements may be conflicting and defining a new routing protocol fully satisfying those requirements might be challenging. The objective of this work would be to define a routing protocol that will satisfy those requirements as much as possible and that would potentially adapt itself to the particular deployment context.

6. Security Issues

TBD

7. Manageability Issues

TBD

8. IANA Considerations

This document includes no request to IANA.

9. Security Considerations

TBD

10. Acknowledgements

11. References

11.1. Normative References

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Authors' Addresses

D Culler
Arch Rock
657 Mission St. Suite 600
San Francisco, CA 94105
USA

Email: dculler@archrock.com

JP Vasseur
Cisco Systems, Inc
1414 Massachusetts Avenue
Boxborough, MA 01719
USA

Email: jpv@cisco.com

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