

Design Considerations for Low Power Internet Protocols

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ABSTRACT

Over the past 10 years, low-power wireless networks have transitioned to supporting IPv6 connectivity through 6LoWPAN, a set of standards which specify how to aggressively compress IPv6 packets over low-power wireless links such as 802.15.4.

We find that different low-power IPv6 stacks are unable to communicate using 6LoWPAN, and therefore IP, due to design tradeoffs between code size and energy efficiency. We argue that applying traditional protocol design principles to low-power networks is responsible for these failures, in part because receivers must accommodate a wide range of senders.

Based on these findings, we propose three design principles for Internet protocols on low-power networks. These principles are based around the importance of providing flexible tradeoffs between code size and energy efficiency. We apply these principles to 6LoWPAN and show that the resulting design of the protocol provides developers a wide range of tradeoff points while allowing implementations with different choices to seamlessly communicate.

1 INTRODUCTION

Interoperability has been fundamental to the Internet’s success. The Internet Protocol (IP) allows devices with different software and different link layers to communicate, while higher layer protocols allow them to share a rich suite of networked applications. In the decades of the Internet’s evolution, we have accumulated and benefited from a great deal of wisdom and guidance (e.g., Postel’s Law) in how to design, specify, and implement robust, interoperable protocols.

Over the past decade, the Internet has extended to tens of billions of low-power, embedded systems such as sensor networks and the Internet of Things. In particular, hundreds of proprietary protocols have been replaced by 6LoWPAN, a standardized format for IP networking on low-power wireless link layers such as 802.15.4 [17] and Bluetooth Low Energy [27]. Many embedded operating systems have adopted 6LoWPAN [2, 4, 5, 12, 13, 15, 30] and every major protocol suite uses it [3, 26].

The increasing dominance of 6LoWPAN would suggest a future in which tens of billions of connected devices can communicate with each other. In fact, devices today can communicate with the broader Internet. However, in many cases they cannot communicate *with each other*. We find that no pairing of the major implementations fully interoperates (Section 3). 6LoWPAN was created with the express purpose of bringing interoperable IP networking to low power devices, yet two key features of the protocol — range extension via mesh networking of devices, and the convenience

of different vendors being able to share a gateway — are largely impossible over 10 years later.

Each of the openly available 6LoWPAN stacks — most of which are used in production — implements a subset of the protocol. Furthermore, each implementation includes compile-time flags to cut out additional compression/decompression options. As a result, two devices might both use 6LoWPAN, yet be unable to exchange IP packets. This is especially problematic for gateways, which *need* to be able to talk to multiple implementations to enable significant scaling of these devices in real world applications. Because there is no mechanism to discover which protocol features a particular device supports, gateways must either conservatively minimize compression to ensure devices can receive its packets, or somehow determine supported features out-of-band (e.g. only supporting devices from the same vendor).

This paper argues that the failure of 6LoWPAN interoperability stems from applying traditional protocol design principles to low-power networks. Low-power protocols minimize energy consumption by compressing packets. Squeezing every bit out of packet headers, however, requires many different options and operating modes. Principles such as Postel’s Law¹ imply that an implementation must be able to receive all of a protocol’s features, even if it never sends them. However, code space is a tight constraint on most embedded systems. When application-critical code + networking code does not all fit on-device, implementations opt to partially implement network protocols, and break interoperability in the process.

Low-power Internet protocols need different design principles. In particular, low-power devices face a tension between code size and energy efficiency. Because application requirements vary, there is no “one size fits all” choice for this tradeoff. Instead, individual applications must be able to decide how to balance communication efficiency and code size. Currently, when devices pick different points in this design space, they may fail to communicate.

To address this problem, we propose three design principles for low power protocols:

Capability spectrum: a low-power protocol specifies a linear spectrum of capabilities. Simpler implementations have fewer capabilities and save less energy, while fuller implementations have strictly more capabilities and are able save more energy. When two devices differ in capability levels, communication can always fall back to the lower one.

Capability discovery: a low-power protocol provides mechanisms to discover the capability of communicating devices. This discovery

¹“Be liberal in what you accept, and conservative in what you send” [7]

can be proactive (e.g., a device advertises its capability level) or reactive (e.g., a device sends an error when it receives a packet it cannot process).

Explicit, finite bounds: a low-power protocol specifies explicit, finite bounds on how big a decompressed packet can be. Without explicit bounds, receiving every valid packet requires allocating buffers too conservatively. In practice, implementations allocate smaller buffers and silently drop packets they cannot decompress.

We examine how these principles could be applied to a low power protocol and evaluate the code size overhead of capability discovery. We find that applying these principles to 6LoWPAN promises interoperability across a wide range of device capabilities, while imposing a code size cost of less than 10%. In particular, capability discovery requires an order of magnitude less code than the code size difference at the extremes of our capability spectrum.

2 BACKGROUND

In this work, we focus on protocols for applications intended to be very low power and low cost, such as long-life sensor nets or very small form factor IoT devices. Devices in these low-power networks typically use ultra-low power, low-cost microcontrollers. The marginal cost of additional resources, in terms of both price and energy, is significant. At the same time, radio communication usually dominates the energy budget for networked applications: each transmitted bit consumes as much energy as hundreds or thousands of instructions.

2.1 Low Power Protocols

These embedded and low-power networked systems have historically been dominated by a communication model based on ad-hoc custom designs. These systems were vertical application silos: each manufacturer, or even each application, defined its own protocol stack. Even in places where rich application-level standards exist, such as Bluetooth, most devices implement their own APIs and abstractions, precluding interoperability or larger composition.

In recent years, a number of standards have emerged to attempt to break out of these vertical silos. Cellular IoT solutions like LTE-M or Nb-IoT offer broad coverage and high data rates, at the cost of monthly service charges and support limited to more expensive and powerful embedded hardware [34]. As a result, these solutions are outside the scope of this work. Low-power wide-area networks (LPWANs) such as LoRaWAN and SigFox offer long range connectivity for lower power/cost than cellular IoT, but force much lower data rates, and do not support IP addressable nodes [1].

But the Internet always wins. The communication and interoperability IP provides is a goal in and of itself. It allows systems to easily incorporate new services and applications, and allows applications to build on all of the existing Internet systems. Over the past decade, most major embedded operating systems and network stacks have transitioned to using 6LoWPAN [2, 4, 5, 12, 13, 26], a standard protocol to communicate IPv6 over low-power wireless link layers such as IEEE 802.15.4 and Bluetooth [17, 24, 27]. 6LoWPAN primarily specifies two things: compression of IPv6 headers and how to fragment/re-assemble packets on link layers whose MTU is smaller than the minimum 1280 bytes required by IPv6.

Table 1: Flash size varies widely across IoT platforms

IoT Platform	Code (kB)	Year
Tmote Sky	48	2004
Zolertia Z1	92	2013
Atmel RZRaven	128	2007
TI CC2650	128	2015
NXP MKW40Z	160	2015
SAMR21 XPro	256	2014
Nordic NRF52840 DK	512	2018
Arduino Due	512	2012

The core 6LoWPAN specifications are quite succinct: RFC6282 is 22 pages long. However, these 22 pages contain 19 different compression mechanisms, covering only basic IPv6 data frames. There are separate documents for neighbor discovery (ND) and other mechanisms. The savings from these compressions schemes are significant: in the best case, it can compress a 40-byte IPv6 header to two bytes: one which specifies how to derive addresses and other fields, and one containing the hop limit. For small payloads typical in low-power devices, 6LoWPAN can reduce the overhead of IPv6 from 400% to 20%.

2.2 Application Specificity

Even within this low power/low cost space, devices vary significantly in capability and focus — some devices are limited primarily by power, others by cost, others by size, and others by processor resources. Every combination of device and application has a unique set of requirements for each of these parameters. For example, some low-power applications may require the battery last at least a year, while others may require the device used be small enough to attach to a bird or go unnoticed in a piece of clothing. Other applications may need on-device data processing operations that requires large libraries, and still others may require RAM-hungry cryptographic primitives.

Despite this diversity of devices, the difficulties associated with writing custom embedded firmware for an application means that a small set of embedded operating systems are used for most embedded applications. These embedded operating systems are expected to serve a wide set of devices - and are unlikely to become popular if they cannot accomplish this. Ultimately, this leads to a reality in which limiting embedded operating system code size is of paramount importance.

2.3 Hardware Constraints

Table 1 shows a variety of older and more recent low-power platforms. Modern microcontrollers typically have 128-512 kB of code flash. This limited space holds the operating system, networking software, sensor drivers, storage abstractions, and application code. Chips have limited flash because the type of flash used (NOR) is space-intensive: a chip with less flash is smaller and so more can be made on a single silicon die. NOR flash is used because, unlike much denser NAND flash, NOR allows random access, which has better energy properties for instruction streams.

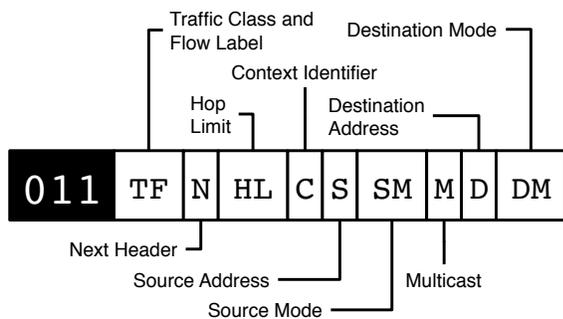


Figure 1: The 6LoWPAN IPHC header compression encoding. In some cases, 6LoWPAN can compress a 40-byte IPv6 header to these two bytes. The address bits denote whether stateful or stateless compression is used, while the address mode bits denote what portion of the address (128, 64, 16, or 0 bits) is included in the header or derived from other information.

Microcontrollers have limited flash and applications struggle with these limits. Given the expectation that these systems will run the same application for years, applications do not leave code space unused. To help accommodate these tight tolerances, embedded operating systems have a wide range of compile-time flags to include or exclude parts of the system or networking stack. [4, 12, 13] Some systems take an even more extreme approach, dynamically generating the minimum code to compile from the application itself. [2] Moreover, chip vendors often allow application developers to select their particular system/application size tradeoff by providing multiple firmware images for the same chip, with different levels of functionality. Nordic Semiconductor, for example, provides three different SoftDevices for their Bluetooth Low Energy microcontrollers, from the minimal S112 that only supports the peripheral role, to the fully featured S132 which supports both peripheral and central roles with up to twenty concurrent connections.

3 LOW-POWER IP TODAY

“The Working Group will generate the necessary documents to ensure interoperable implementations of 6LoWPAN networks”

– 6LoWPAN Working Group Charter [19]

This section gives an overview of 6LoWPAN and its implementations. It finds that no implementation today implements the entire protocol and that these implementation holes are non-uniform: every pair of implementations succeeds to receive packets in some cases but deterministically fails to receive packets in others. Examination of the source code finds that these problems are due to concerns with code size. Experiences with a new, clean implementation verify these concerns.

3.1 6LoWPAN Summary

6LoWPAN is comprised of 3 core documents - RFC 4944 [24], RFC 6282 [17], and RFC 6775 [32]. 6LoWPAN defines new header types to compress and structure IPv6 packets over low-power link layers. Because link layers have different communication models and address

formats, each link layer has its own specification. [8, 17, 22, 23, 27] In this paper we focus on 802.15.4, since it was the original driver for 6LoWPAN and its dominant use case. 6LoWPAN solves three major problems: header compression, stateless address autoconfiguration, and sub-IP fragmentation.

A standard IPv6 header is 40 bytes. Low-power devices, however, have small MTUs (Bluetooth Low Energy, for example is 27 bytes) and often send small data payloads (e.g., 10 bytes). 6LoWPAN therefore provides mechanisms to heavily compress IPv6 packets. Because addresses dominate the header, there are context-based and context-free compression schemes for unicast and multicast IPv6 addresses, as well as cases in which other fields within IP and UDP headers may be compressed.

Figure 1 shows the layout of the two-byte header compression field. For example, the Traffic Class and Flow Label fields can be elided, while the Hop Limit field can be compressed if it is one of several common values and certain UDP ports can be compressed. In the most extreme case, 6LoWPAN can compress the 40 byte header to 2 bytes; for a 10 byte packet, over Bluetooth Low Energy, this is the difference between a 400% overhead and sub-IP fragmentation or a 20% overhead and no fragmentation.

This compression is tightly entwined with the second problem, stateless address autoconfiguration. Each link layer defines how to map unicast and multicast IPv6 addresses from and to its link layer addresses.

The third major problem 6LoWPAN solves is fragmentation. IPv6 requires that a link layer support 1280 byte packets without IP fragmentation. Because low-power link layers often have small MTUs (e.g., 802.15.4 has an MTU of 127 bytes), 6LoWPAN defines how to fragment and reassemble larger-than-MTU packets using a fragmentation header.

In addition to these three core problems, the protocol covers edge cases related to fragmentation and compression, such as restricting header compression to the first fragment of a fragmented packet. Finally, RFC 6775 [32] describes 6LoWPAN optimizations for IPv6 Neighbor Discovery.

3.2 Feature Fail

6LoWPAN gives senders a broad range of compression options to use. For example, a sender can choose to simply not compress a packet at all, e.g. a full 40-byte IPv6 header can follow the 2-byte 6LoWPAN header. A receiver, however, has much less flexibility: it must be able to receive and process any valid compression it receives. Every 6LoWPAN receiver is required to parse multiple 6LoWPAN header types, including the mesh addressing header, broadcast header, fragmentation header, and compression headers.

Table 2 shows the features supported by 6 major open-source 6LoWPAN stacks. Some, such as TinyOS, are mostly developed and used in academia. Others, such as ARM Mbed and Nest’s OpenThread, are developed and supported commercially. Contiki and Contiki-NG sit somewhere in the middle, having both significant academic and commercial use. Riot is an open-source operating

²Contiki-NG and OpenThread do not support compression of the mobility header

³TinyOS can receive packets which use the mesh header, but will never forward such packets or send packets using this header, effectively preventing TinyOS devices from participating in route-under networks

⁴TinyOS supports only some of RFC 4861

Table 2: 6LoWPAN Interoperability Matrix. No implementation can receive all viable messages in the 6LoWPAN specification, and no stack chooses to elide the same features, with each instead opting for a combination that works best for its particular resource requirements.

Feature	Stack					
	Contiki	Contiki-NG	OpenThread	Riot	Arm Mbed	TinyOS
Uncompressed IPv6	✓	✓		✓	✓	✓
6LoWPAN Fragmentation	✓	✓	✓	✓	✓	✓
1280 byte packets	✓	✓	✓	✓	✓	✓
Dispatch_IPHC header prefix	✓	✓	✓	✓	✓	✓
IPv6 Stateless Address Compression	✓	✓	✓	✓	✓	✓
Stateless multicast address compression	✓	✓	✓	✓	✓	✓
802.15.4 16 bit short address support		✓	✓	✓	✓	✓
IPv6 Address Autoconfiguration	✓	✓	✓	✓	✓	✓
IPv6 Stateful Address Compression	✓	✓	✓	✓	✓	✓
IPv6 Stateful multicast address compression			✓	✓	✓	
IPv6 Traffic Class and Flow label compression	✓	✓	✓	✓	✓	✓
IPv6 NH Compression: Ipv6 (tunneled)			✓		✓	✓
IPv6 NH Compression: UDP	✓	✓	✓	✓	✓	✓
UDP port compression	✓	✓	✓	✓	✓	✓
UDP checksum elision						✓
Compression + headers past first fragment				✓	✓	
Compression of IPv6 Extension Headers		~	~ ²		✓	✓
Mesh Header			✓		✓	~ ³
Broadcast Header						✓
Regular IPv6 ND	✓	✓		✓	✓	~ ⁴
RFC 6775 6LoWPAN ND				✓	✓	
RFC 7400 Generic Header Compression						

~ = Partial Support

Table 3: Hardware/Software used for code size measurements and IPv6 communication tests

Stack	Commit Hash	Device
Contiki	bc2e445817aa546c	CC2650 LaunchXL
Contiki-NG	7b076e4af14b2259	CC2650 LaunchXL
OpenThread	4e92a737201b2001	Nordic NRF52840
Riot	3cce9e7bd292d264	SAM R21 X-Pro
Arm Mbed	4e92a737201b2001	N/A
TinyOS	4d347c10e9006a92	Atmel SAM4L

system with hundreds of contributors for industrial, academic, and hobbyist use.

There are significant mismatches in feature support between stacks. These mismatches lead to deterministic cases when IP communication fails. We verified these failures by modifying existing network applications and testing them on hardware, using Wireshark to verify packets were compressed and formatted as we expected and that receivers would fail to receive packets. Every implementation pair fails in some fashion:

- **Contiki** → **OpenThread**: Contiki generated message using uncompressed IPv6
- **Contiki-NG** → **Contiki**: Contiki-NG generated message with compressed IPv6 extension headers

- **Riot** → **Contiki**: Riot generated message using stateful multicast address compression
- **Mbed** → **Contiki**: Mbed generated message using compressed, tunneled IPv6
- **TinyOS** → **Contiki**: TinyOS generates messages containing a compressed IPv6 mobility header
- **OpenThread** → **Riot**: OpenThread generates messages containing any of the IPv6 extension headers, which the OpenThread stack automatically compresses
- **Mbed** → **OpenThread**: Mbed generates IPv6 packet containing the IPv6 mobility header
- **OpenThread** → **TinyOS**: OpenThread generates message for which the destination address is compressed using stateful multicast compression
- **Mbed** → **Riot**: Mbed generates IPv6 message containing any compressed next header other than the UDP header
- **Riot** → **TinyOS**: Riot generates message for which the destination address is compressed using stateful multicast compression
- **Mbed** → **TinyOS**: Mbed generates Neighbor Discovery message using the 6LoWPAN context option as specified in RFC 6775.

This is a non-exhaustive listing – in most pairings there are many packet formats which would cause IP to fail. Table 3 lists

the exact software/hardware combinations we used for our code analysis and hardware tests.

In addition to the IPv6 header itself, 6LoWPAN receivers are expected to decompress some next headers as well as destination options. The ability to compress next headers is critical for low-power routing protocols such as RPL [36], which often tunnel IPv6 inside IPv6 to manage ICMP errors.⁵ Every stack, however, fails to decompress tunneled IPv6 packets, while Contiki and OpenThread fail to decompress any extension headers.

3.3 Constant Disagreement

In addition to the feature mismatches in Table 2, IP communication between different stacks can fail due to disagreement on certain constants. These disagreements generally arise out of concerns for RAM use by one of the participants. One example where this can lead to problems is when stacks make assumptions about the maximum amount of decompression which is possible from a single link layer frame. 6LoWPAN’s extensive compression means that a decompressed packet can be much larger than what is received over the air. Further, because of 6LoWPAN fragmentation, fragments of a packet can arrive out of order. To maintain layering, and prevent interleaved or stray packets from starving the single MSS size receive buffer present on most devices, most stacks decompress initial 6LoWPAN fragments into a slightly extended link layer size buffer. One implementation decision a stack must make is how much RAM to allocate for each of these extended frame buffers. Given that most devices in this space do not have the option of dynamic allocation, this can be an impactful decision.

As a result, every stack we analyzed imposes a limit on the amount of header decompression possible in a received packet. The maximum amount of header decompression allowed by the 6LoWPAN specification is about 1200 bytes, basically, if an entire Maximum Segment Size (MSS) IPv6 packet was sent containing only compressed headers. Stacks place much lower limits to avoid a requirement for multiple IPv6 size buffers which would mostly sit empty. For example, Contiki’s 38 byte limit is exceeded by any packet with a maximally compressed IP header and any UDP compression. Contiki merely seems to have chosen a 38 byte limit because the limited Contiki stack will not compress frames by more than that amount. We verified that some stacks send packets with more header compression than this limit, causing IP communication to fail.

3.4 Why?

IP communication routinely fails in low-power networks, despite the presence of succinct standards (RFC6282 is 22 pages) explicitly designed for low-power embedded devices. Furthermore, this failure is silent. For example, if a Contiki device tries to forward an uncompressed IPv6 packet to an OpenThread device, the OpenThread device will drop the packet.

Examining the stacks and their implementations, we find a single, common cause: concerns about code (and to a lesser degree, RAM) size.

⁵If a gateway adds source routing headers and these cause ICMP errors later, the errors should go to the gateway, not the source host. So gateways tunnel IPv6 packets inside IPv6 packets they source.

The tensions between RAM and code size has always been a delicate dance on low power embedded platforms. For example, designing for the particular RAM/code size split of one architecture can be problematic for others: TinyOS service APIs had to change dramatically over time to accommodate devices with different ROM/RAM splits than the mica platform for which it was originally developed [20].

In low power networking, another important “slider” exists—the tradeoff between code size and network protocol efficiency. Techniques such as advanced MAC and physical layers, and tracking the state of a network can reduce packet sizes and, thus, radio energy consumption. However, these techniques require more complex implementations. Increased code size, however, requires more expensive and power hungry microcontrollers.

6LoWPAN takes great efforts to save energy through IPv6 header compression. The result, however, is that implementations take up a large fraction of the code space on small devices. Analyzing the comments and documentation of each stack, we found that code size concerns motivated features elision. Mbed, Riot, and Contiki take this one step further, including compile-time flags to remove features.

Figure 2 shows the code size of each of the six implementations broken into independent compression, fragmentation, mesh and broadcast headers, the rest of 6LoWPAN and the rest of the IPv6 networking stack (physical layer drivers, IPv6, UDP, and ICMP). Compression dominates the code size of 6LoWPAN implementations, and in several cases 6LoWPAN’s size is comparable to the whole rest of the IPv6 stack. Contiki, and Contiki NG implementations are significantly smaller than the others in part because they elide significant and complex features. The ARM Mbed IPv6 stack, for example, uses 45kB of flash. This is nearly 1/3 of the available space on a CC2650, just for IPv6: it does not include storage, sensors, the operating system kernel, cryptography, higher layer protocols, signal processing, or applications.

3.5 Investigating Ourselves

Can a careful developer avoid these pitfalls and implement a lean, fully-featured stack? To answer this question, we implemented our own full 6LoWPAN stack. Our 6LoWPAN stack is written in Rust, for Tock, a secure embedded operating system that provides a safe multiprogramming environment for microcontrollers. [21]

Our experiences support the comments and documentation of the other stacks. Furthermore, we discovered parts of it that require particularly surprisingly complex and large code to properly handle. For example, tunneling IPv6 inside a compressed packet requires the interior headers be compressed as well. This requires the decompression library to support recursive invocation, which increases minimum stack sizes and makes tracking buffer offsets during decompression more difficult. Refusing to support tunneled IPv6 packets (e.g., Contiki) greatly simplifies the code. Another example is the fact that headers in the first 6LoWPAN sub-IP fragment must be compressed, while headers in subsequent fragments must not be compressed. Given that low-power link layer have variable length headers, correctly determining exactly where to fragment and what should be compressed requires complex interactions between layers of the stack. The exercise of implementing

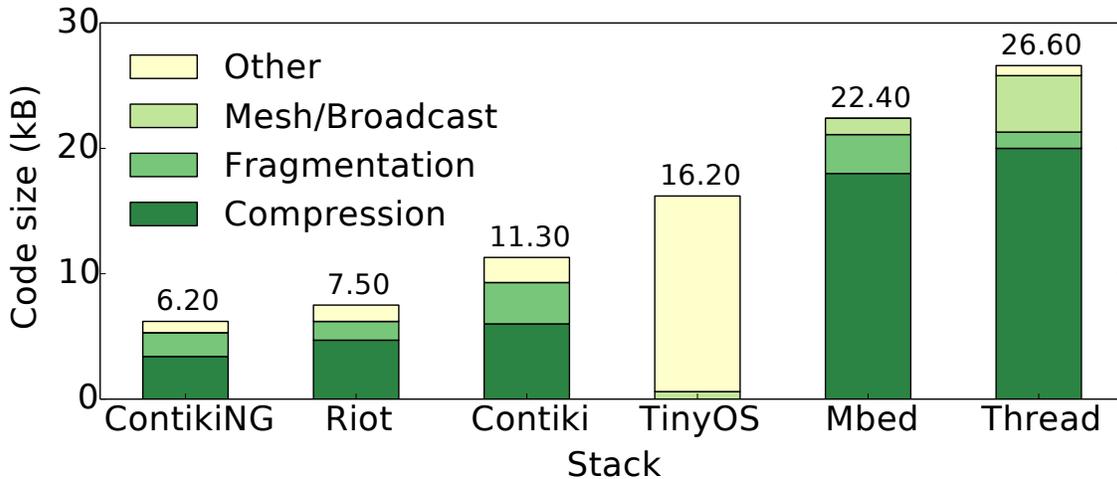


Figure 2: 6LoWPAN Stack Code Size for 6 open source stacks. The code size varies by over a factor of 4, in part due to different feature sets. In all cases, compression dominated the code requirements of each stack. In some cases, the size of the 6LoWPAN implementation is larger than the rest of the IPv6 stack. TinyOS’s whole-program optimization model precluded separating out subcomponents of its implementation.

a 6LoWPAN stack from the ground up affirmed the observation that there is a tension between code size and energy efficiency in low power protocol design.

3.6 Why Does This Matter?

For each unique 6LoWPAN implementation, there is presumably an accompanying border router implementation that always successfully interoperates with this device, and pairing the two will make that device available to the broader Internet. But this status-quo model of connectivity forces vertical integration and fails to meet the original design goals of 6LoWPAN, for two reasons.

First, the current situation is such that a 6LoWPAN gateway cannot know how much compression is allowable for IP packets intended for different nodes, unless that gateway communicates only with devices produced by the same vendor. As a result, for a coverage area containing devices produced by 5 disparate vendors, 5 6LoWPAN gateways are required. Each device can communicate only with the gateway produced by its vendor, or directly with other devices by the same vendor. If not for the feature mismatch we have demonstrated, a single gateway would suffice, an approach which has substantial benefits from the perspectives of usability, cost, and wireless efficiency. Secondly, the current situation significantly limits the potential range extension made possible via mesh topologies. Most existing 6LoWPAN meshes rely on route-over mesh routing at the network layer, which requires that each node can at least partially decompress and recompress IP headers when forwarding frames sent by other nodes. Even mesh-under routing is not a reliable option, as implementation of the mesh header is not ubiquitous as shown in table 2. Ubiquitous direct connectivity between 6LoWPAN nodes is crucial in realizing the range extension and cost/power savings promised by 6LoWPAN mesh topologies.

4 TRADITIONAL PRINCIPLES IN THE LOW-POWER DOMAIN

Connectivity through interoperability is a key premise of the Internet: Following this premise has enabled its tremendous success in connecting a diverse and varied collection of different networks and software stacks into a single, cohesive whole. Over the past 45 years, we have coalesced on a small number of principles that lead to protocols which are simultaneously well-defined enough to support many implementations yet flexible enough to evolve and improve as networks change. Principles such as layering and encapsulation support composing protocols in new ways (e.g., tunneling), while the end-to-end principle [31] allows us to build a robust network out of an enormous and complex collection of unreliable parts. The simplicity principle [9] discourages complexity in protocols, and is used to support claims like “optimization can also be considered harmful. In particular, optimization introduces complexity, and as well as introducing tighter coupling between components and layers” [11]. There are great reasons for traditional Internet principles, and they have generally served us well.

The robustness principle is one such principle. The robustness principle asserts that implementations should make no assumptions on packets they receive: bugs, transmission errors, and even memory corruption can cause a device to receive arbitrarily formatted packets. An implementation must also be ready to receive and properly discard packets that are arbitrarily malformed. As one RFC puts it, “In general, it is best to assume that the network is filled with malevolent entities that will send in packets designed to have the worst possible effect.” [7]

The robustness principle also asserts that an implementation must be ready to receive any and all properly formatted packets. This aspect of the principle is often attributed to John Postel as Postel’s Law, first written down in the initial specification of IPv4:

“In general, an implementation should be conservative in its sending behavior, and liberal in its receiving behavior.” While some have recently argued that instead protocols should be maximally strict [35], even this restriction of Postel’s Law assumes that an implementation properly handles the full protocol.

Protocols often have optional features (“MAY, SHOULD, and OPTIONAL” in RFC language). These features are often accompanied by explicit instructions for how receivers should act in the presence of these optional features, or lack thereof. For example, RFC6282 says that interface identifier bits may be elided if they match the link layer address (effectively deriving part of the IPv6 address from the link layer address); this means that a sender can but does not have to elide in this way. Implicitly, due to Postel’s Law, however, a receiver needs to be able to handle either case. This scenario creates an interesting asymmetry, where it can be easy to write sender code with reduced complexity but difficult to write receiver code that does the same. This asymmetry leads to a situation in which meaningful reductions in complexity/code size are difficult to realize while maintaining interoperability and following the robustness principle.

A similar example is UDP checksum elision, one of the least supported features in Table 2. At the 6lo working group meeting at IETF 102, one of the authors of RFC 6282 noted that UDP checksum elision was including at the request of a vendor who wanted to use 6LoWPAN and had applications that required this feature [14]. Unfortunately, without capability discovery or error signaling, the existence of this feature in the specification implicitly adds a requirement that all receivers support decompression of packets formatted in this manner. This is an undesirable situation.

In low power networks, following the principle that receivers should accommodate every sender is expensive. Senders have the choice of what features to implement, but receivers have to implement every one and handle every combination. Following the simplicity principle is hard when writing low-power protocols, as optimizations are crucial in the low-power space. But protocols need to make it possible for individual vendors to use optimizations without breaking interoperability by imposing code size costs on all implementations.

We need to think about low-power protocols differently. They need new principles to help guide their design. These principles need to embrace the fact that there is no “one size fits all” design, while defining how devices choosing different design points interoperate. Flexibility needs to exist not only for senders, but also for receivers, without harming interoperability. The next section describes three principles that achieve this goal, and following sections describe an application of them to the 6LoWPAN protocol suite.

5 THREE PRINCIPLES

“A good analogy for the development of the Internet is that of constantly renewing the individual streets and buildings of a city, rather than razing the city and rebuilding it.”

— RFC 1958, *Architectural Principles of the Internet* [10]

In light of the conflicts between traditional Internet principles and interoperability on low power devices, this section describes

three protocol design principles which, when working on low-power protocols, should be closely observed. These principles are of a different nature than many traditional Internet principles, but in this space are absolutely necessary in ensuring interoperable implementations. In the next section, we show how to apply each to 6LoWPAN.

5.1 Principle 1: Capability Spectrum

A low power protocol should be implementable on devices which are at the low end of code and RAM resources. Rather than require every device pay the potential energy costs of fewer optimizations, a protocol should support a linear spectrum of device capabilities.

At first glance, this principle may seem to suggest an approach already applied by traditional Internet protocols — the IP [28] and TCP [29] specifications provide optional fields which can be used by endpoints at their leisure; many non-standard HTTP headers will be ignored unless both client and server support them; TLS ciphersuite support is often asymmetrical. In reality, the capability spectrum necessary for a low power Internet protocol is distinctly different from any of these examples. For each of these examples, no linear spectrum exists — support, or lack thereof, for any particular capability in each of those examples is generally unrelated to support for other options in the set. Checking for support of any of these options requires explicit enumeration of each. Such a design generally precludes the possibility of effective compression of such options, as the options themselves would become difficult to parse without additional information. Further, a non-linear spectrum means that storing capability information for neighbors requires storing details about every single optional aspect of the protocol for each neighbor, or requires re-discovering capabilities on every exchange.

Low power protocols, on the other hand, require simple spectrums, such that the spectrum truly enables simpler implementations from the perspective of both RAM and code size. A low power protocol should define a capability spectrum with a clear ordering via which especially resource constrained devices can reduce code size or RAM use by eliding features. Such a spectrum makes a protocol usable by extremely low resource devices without forcing more resourceful devices to communicate inefficiently.

This capability spectrum should be a linear scale. For a device to support capability level N , it must also support all lower capability levels. More complex configuration approaches (e.g., a set of independent options) would allow for a particular application or implementation to be more efficient, picking the features that give the most benefit at the least complexity cost. However, this sort of optimization then makes interoperability more difficult, as two devices must negotiate which features to use.

5.2 Principle 2: Capability Discovery

The second principle follows immediately from the first: if two implementations may have different capability levels, there should be an explicit mechanism by which two devices can efficiently determine what level to use when they communicate.

Once again, we would like to emphasize that the capability negotiation we propose as appropriate for this space is different from capability discovery mechanisms built for traditional systems, such

as IP Path MTU discovery or the Link Layer Discovery Protocol (LLDP). Though the MTU of a given path is by definition a linear scale, IP Path MTU discovery relies on continual probing until an acceptable value is discovered. The energy overhead of such network probing is unacceptable in most low power environments. Given this, *capability discovery in low power networks should require no more than one failure between any two neighbors*, even if this slightly increases the overhead of handling a single error. Further, assumptions for traditional systems that prohibit storing per-endpoint state do not hold for these systems. On low power networks, it is feasible to store state for a small number of neighbors — most low power nodes communicate with only a few neighbors at a time, so storing state can significantly reduce the amount of radio energy needed for communication. Further, the code size cost of storing state is small compared to the cost of complex compression mechanisms.

Similarly, LLDP requires regular capability advertisements at a fixed interval which contain detailed capability information. This regular, unique, and proactive capability discovery is impractical in low power networks, where radio energy is at a premium. Instead, low power networks should incorporate any proactive capability discovery mechanisms into other baseline communication required for tasks such as neighbor discovery or route maintenance. Beyond that, these networks should rely on reactive discovery and small amounts of stored state.

In a low power network with capability discovery, if two devices wish to communicate, they default to the lower of their supported capability levels. For example, suppose a TinyOS device supports level 2 and a Contiki device supports level 4; Contiki must operate at level 2 when communicating with the TinyOS device. This requires keeping only a few bits of state for each neighbor a node may want to communicate with. Also, note that this state is per-hop; for a layer 3 protocol like IP, it is stored for link-layer neighbors (not IP endpoints) and so does not require knowledge of the whole network. This is the case because route-over topologies commonly used in low power IP networks frequently involve decompression and re-compression at each hop to enable forwarding. One offshoot of this principle is that it requires implementations have symmetric capabilities for send and receive — if the two nodes will always default to the lower of their support capability levels, no benefits can be realized from an asymmetric implementation.

5.3 Principle 3: Explicit and Finite Bounds

Protocols should specify explicit and reasonable bounds on recursive or variable features so implementations can bound RAM use. These bounds have two benefits. First, they allow implementations to safely limit their RAM use without silent interoperability failures. E.g., today, if an mbed device sends a 6lowpan packet whose compression is greater than 38 bytes to a Contiki device, Contiki will silently drop the packet. Second, it ensures that capability discovery is sufficient for interoperability.

The idea of imposing bounds is, on its own, not unique to this space. TCP enforces a finite limit of 40 bytes for TCP options which may be appended to the TCP header, as does IPv4. DHCP allows for the communication of maximum DHCP message sizes. In the space of low power Internet protocols, however, this idea *must be pervasive*. What is unique to space of low power embedded networking

is the importance of compression at all layers of the stack, which leads to scenarios in which, without reasonable, finite bounds, it can be difficult for implementations to impose appropriate maximum buffer sizes. Many low power systems lack dynamic allocation, but do allow for the storage of multiple datagrams of various types. The ability to precisely set the buffer sizes required to hold these packets is an important concern, and undefined bounds on decompression or variable options can lead to significant RAM waste summed across protocols. Rather than forcing implementers to make difficult decisions between interoperability and processor resources, low power protocols must recognize that the energy gains of unbounded option sets are useful in a tiny set of cases. Further, while recursive compression mechanisms can be tempting to allow for maximal packet size reductions, implementing these recursive mechanisms can require tail recursion on the stack, which is problematic for low resource devices, and these recursive mechanisms are rarely used in practice. RAM resources, on the other hand, are an omnipresent concern.

Reasonable, finite bounds must exist in every scenario for low power Internet protocols. Notably, the original designers of a specification may not know exactly what these values should be. This is not a new problem: TCP congestion control, for example, had to specify initial congestion window values. In this space, bounds should initially be very conservative. Over time, if increasing resources or knowledge suggests they should grow, then future devices will have the onus of using fewer resources to interoperate with earlier ones. The capability spectrum defined in the previous two principles can be helpful in this regard.

6 A PRINCIPLED 6LOWPAN

This section proposes how to apply the three principles in the previous section to 6LoWPAN through specific modifications to the protocol. These modifications ensure that two 6LoWPAN devices can communicate even if they choose different code size/energy efficiency tradeoffs. We refer to this modified protocol as Principled 6LoWPAN (P6LoWPAN).

This application of our principles is not intended as a suggestion that these changes should be made immediately to 6LoWPAN, as modifying an established protocol is a complex task very different from constructing new protocols. Rather, this application is a means by which we can evaluate how these principles are useful toward developing other Internet protocols in this space.

6.1 Principle 1: Capability Spectrum

We propose replacing the large collection of “MUST” requirements — the features in Table 2—into 6 levels of functionality. These “Capability Levels” are depicted in Table 4

These levels prioritize features which provide the greatest energy savings per byte of added code size, based off of our measurements of code size, the number of bits saved by each additional compression mechanism, and our observations of existing implementations. They allow for a wide range of code size/efficiency tradeoffs.

For example, addresses dominate an uncompressed IPv6 header. Level 0 devices only support compressed source addresses, while level 1 devices support all stateless address compression. In one early design of this spectrum, Level 0 supported only uncompressed

Table 4: Capability Spectrum

Capability	Basic Description	Added Features
Level 0	Uncompressed IPv6 + ability to send ICMP errors	<ul style="list-style-type: none"> • Uncompressed IPv6 • 6LoWPAN Fragmentation and the Fragment Header • 1280 Byte Packets • Stateless decompression of source addresses
Level 1	IPv6 Compression Basics + Stateless Address Compression	<ul style="list-style-type: none"> • Support for the Dispatch_IPHC Header Prefix • Correctly handle elision of IPv6 length and version • Stateless compression of all unicast addresses • Stateless compression of multicast addresses • Compression even when 16 bit addresses are used at the link layer • IPv6 address autoconfiguration
Level 2	Stateful IPv6 Address Compression	<ul style="list-style-type: none"> • Stateful compression of unicast addresses • Stateful compression of multicast addresses
Level 3	IPv6 Traffic Class and Flow Label Compression	<ul style="list-style-type: none"> • Traffic Class compression • Flow Label Compression • Hop Limit Compression
Level 4	IPv6 and UDP Next Header Compression + UDP Port Compression	<ul style="list-style-type: none"> • Handle Tunneled IPv6 correctly • Handle the compression of the UDP Next Header • Correctly handle elision of the UDP length field • Correctly handle the compression of UDP ports • Correctly handle messages for which headers go on longer than the first fragment, and the headers in the first fragment are compressed.
Level 5	Entire Specification	<ul style="list-style-type: none"> • Support the broadcast header and the mesh header as described in RFC 4944 • Support compression of all IPv6 Extension headers

packets. However, this raises a problem with ICMP error generation. If a node cannot decompress the source address of a received packet, it cannot send ICMP errors. ICMP errors are required for capability discovery. Stateful compression depends on an out-of-band signal to set up state, such that nodes only send statefully compressed packets to nodes who also support it. Therefore Level 0 has the minimal requirement that it can decompress stateless source addresses.

The classes in this scale do not precisely reflect the current feature support of the implementations described in Section 3. For example, Contiki supports UDP port compression (level 5) but does not support 802.15.4 short addresses (level 2) or tunneled IPv6 (level 5): following this formulation, Contiki only provides level 1 support. If Contiki supported 16-bit addresses, it would provide level 4 support.

A concrete spectrum such as the one above gives stack designers a structure and set of guidelines on which features to implement. Based on our experiences developing a 6LoWPAN stack, we believe that if this scale existed as part of the initial specification, implementations would have made an effort to adhere to it. It provides a clear order with which to incorporate features.

One additional advantage of this spectrum is that it allows for some future modifications to the P6LoWPAN specification without breaking interoperability between new and old implementations. For example, our scale does not include support for Generic Header Compression [6] because none of the open-source stacks we analyzed implement it. Despite this, support for this RFC could easily be added as a new class on this linear scale (as Class 6), and all lower class implementations would know they were unable to interoperate with this new, higher order interoperability class.

This spectrum requires that a node store 3 bits of state for each neighbor. Given that low-power nodes often store ten or more bytes for each entry in their link table (link quality estimates, addresses, etc.), this cost is small.

6.2 Principle 2: Capability Discovery

We propose two mechanisms by which P6LoWPAN performs capability discovery: neighbor discovery (ND) and ICMP. Neighbor discovery [25] is analogous to ARP in IPv4: it allows IPv6 devices to discover the link layer addresses of neighboring addresses as well as local gateways. Devices use neighbor discovery to proactively discover capability levels and ICMP to detect when incompatible features are used. Of the two, only ICMP is required; neighbor discovery simply allows a pair of nodes to avoid an initial ICMP error if they have different capability levels.

ICMP: We propose adding a new ICMPv6 message type—P6LoWPAN Class Unsupported—which a device sends in response to receiving a packet compression modes or 6LoWPAN features it does not understand. This error encodes the device’s capability level. A node receiving such an error updates its link table entry with the capability level. In the future, any packets sent to that address use at most the supported level.

Neighbor discovery: We propose adding a IPv6 ND option that allows a device to communicate its capability class during network association. The inclusion of a few extra bits in ND messages would allow all devices that learn neighbor addresses via ND to also know how to send packets which that neighbor can receive. When a node uses ND to resolve an IP address to a link layer address, it learns the supported capability level as well as the link layer address. This option minimizes the energy cost of communicating capabilities. It is worth noting that RFC 7400 already employs a similar method for communicating whether devices implement General Header Compression: adding such an option is clearly viable. [6]

6.3 Principle 3: Provide Reasonable Bounds

Section 3 discussed two unreasonable bounds which affect 6LoWPAN interoperability: the full-MTU (1280 byte) bound on header decompression and unbounded recursion when decompressing tunneled IPv6.

For P6LoWPAN, we propose that header decompression be bounded to 50 bytes. This bound allows for significant RAM savings in implementations that decompress first fragments into the same buffer in which the fragment was originally held. 50 bytes is a good trade-off between RAM savings and how frequently we expect such a bound would force packets to be sent uncompressed. A 50 byte limit allows for transmission of a packet containing a maximally compressed IP header, a maximally compressed UDP header, and still leaves room for some IPv6 extension headers. Constructing a packets which could require more decompression than this would require extremely rare and unusual circumstances. This extremely rare cost, however, buys the hundreds of bytes of RAM that can be saved, and the increased ease of creating implementations that will always interoperate.

Second, we propose that headers for tunneled IPv6 should not be compressed. The primary motivation for this feature was from

the RPL protocol [36], as discussed in Section 3.2. However, the fact that RPL must tunnel IPv6 in this way is generally agreed to be a problem and a wart in its design that should be avoided when possible [16]. This change allows implementations to avoid recursive functions to decompress these headers, and instead use simple if/else statements.

7 EVALUATION

This section evaluates the costs of applying our three principles to 6LoWPAN. First, can a reasonable set of capability levels provide a good range of implementation complexity from which a developer can choose? Second, what is the overhead of the proposed mechanisms? If the mechanisms themselves increase code size significantly on their own they are not viable. Third, are the savings afforded by a linear capability spectrum worth the associated limitations? Ultimately, we find that the incremental costs of these mechanisms is small, in the worst case requiring 172-388 bytes of additional code. We also find that the linear spectrum presents noticeable savings in code size, memory usage, and the size of capability discovery messages.

7.1 Implementation

We implemented the proposed P6LoWPAN on the Contiki-NG 6LoWPAN stack. We selected Contiki-NG for this purpose because it already has the smallest 6LoWPAN stack of those tested, so represents the case where any overheads the mechanisms introduce would be the most pronounced. Furthermore, Contiki-NG offers compile-time options for eliding portions of its 6LoWPAN implementation, indicating it needs to provide flexible code size/energy tradeoffs to its users. The changes required modifying 500 lines of code relative to the head of the 4.2 release of Contiki-NG. Throughout this section, all code sizes provided are the binary sizes of Contiki-NG compiled with the Texas Instruments CC2650 as the target.

We modified the Contiki-NG stack so it can be compiled to support any of the 6 capability levels. We did not add additional 6LoWPAN features which were absent from the original Contiki-NG 6LoWPAN stack. Our code size numbers therefore represent a conservative lower bound of the total possible savings. A compile-time option — `CAPABILITY_LEVEL` — determines exactly which features of the 6LoWPAN specification are compiled.

We also added ICMP and ND support for capability discovery. The updated stack responds to incompatible 6LoWPAN messages with an ICMP error, and communicates its capability level in Router Solicitation messages using the 6CIO prefix originally defined in RFC 7400 [6]. It stores the capability class of each node in its link table, and automatically compresses IPv6 packets by the maximum amount supported by the destination.

Finally, we implemented a second modified 6LoWPAN stack in Contiki-NG, which does not follow the recommendation of using a linear capability spectrum. In this modified implementation, each node can select any of the 6LoWPAN features it chooses. We refer to this implementation as FLEX-6LoWPAN. For this alternative policy, we isolated 26 features of 6LoWPAN as single bit flags in a 32 bit bitfield. Thus, FLEX-6LoWPAN stores and communicates capabilities using 4 byte objects. FLEX-6LoWPAN also supports

Table 5: Code size of different capabilities levels in Contiki-NG. Each capability adds between 0.3 and 1.1 kB, with the spectrum spanning a nearly 100% increase in code size from the lowest capability.

Capability	Code Size (kB)	Increase (kB)
Level 0	3.4	-
Level 1	4.4	1.1
Level 2	5.2	0.7
Level 3	5.4	0.3
Level 4	5.9	0.4
Level 5	6.3	0.5

Table 6: Cost of implementing capability discovery in Contiki-NG. On average, the cost of discovery is less than 5% of the total 6LoWPAN size, and capability levels offset the overhead of capability discovery by a factor of 10.

Capability	6LoWPAN Code Size (kB)		
	Base	w/Discovery	Increase
Level 0	3.2	3.4	188 bytes
Level 1	4.2	4.4	260 bytes
Level 2	4.8	5.2	388 bytes
Level 3	5.1	5.4	340 bytes
Level 4	5.6	5.9	296 bytes
Level 5	6.2	6.3	172 bytes

the added granularity required to maximally compress outgoing messages intended for a device supporting any specific combination of features. Once again, we did not add back in any 6LoWPAN features which the Contiki-NG stack did not originally support. This second implementation required modifying about 300 additional lines of code from the P6LoWPAN implementation.

The code for both of the aforementioned implementations can be found at *removed for anonymity*.

7.2 Savings and Costs

Table 5 shows the size of the original Contiki-NG 6LoWPAN stack compiled at each possible capability level. Each capability level adds between 0.25 and 1.05 kB of code, and the spectrum enables implementations to cut the size of the 6LoWPAN stack by up to 45%.

The code size cost of capability discovery, using the P6LoWPAN implementation with the linear capability spectrum, is shown in 6. Capability discovery adds 178-388 bytes, a fraction of the size which implementations can save by supporting lower capability levels. The code added for communication varies across capability levels because the number of code paths for ICMP error generation and compression changes depending on the supported level.

Finally, we evaluated the importance of using a linear capability spectrum by comparing our P6LoWPAN implementation with our bitfield-based FLEX-6LoWPAN implementation. While FLEX-6LoWPAN allows for a completely tailored 6LoWPAN on each node, it has several immediately obvious drawbacks. This approach requires communicating 32 bits of state to convey or store a nodes

Table 7: Resource requirements for a 6LoWPAN stack in Contiki-NG using a linear capability spectrum vs. using a capability bitfield that allows nodes to pick and choose arbitrary features from the original specification. These numbers are for a node configured with capabilities equivalent to a level 4 device. The capability field approach adds over 0.5 kB of code size, increases ND router solicitations by 4 bytes, and increases RAM used for capability storage.

	Linear Spectrum	Arbitrary Bitfield
6LoWPAN Code Size	5.9 kB	6.5 kB
Size of ND Option	4 Bytes	8 Bytes
RAM per neighbour	19 Bytes	22 Bytes

capability, instead of 3 bits as in the case of a linear spectrum. This represents a relatively small increase in RAM usage by 6LoWPAN, but a significant increase in communication cost - 4 bytes is a substantial added length, and makes capability communication using short ND options like the 6CIO option impossible, forcing the use of some longer, currently unspecified ND option. It also makes the process of determining the maximum allowable compression between two nodes significantly more complex, as demonstrated in Table 7. One important takeaway from this table is that opting for a less restrictive set of allowable capabilities mitigates much of the savings provided by implementing these capabilities. For example, a FLEX-6LoWPAN device with the equivalent of level 4 capabilities requires more code space than a level 5 P6LoWPAN device - the linear capability spectrum makes a difference. Once again, the code size addition for FLEX-6LoWPAN represents a conservative lower bound, as we did not need to add checks for handling the compression features of 6LoWPAN that Contiki-NG does not support.

8 DISCUSSION AND CONCLUSION

A new generation of low-power devices face a connectivity dilemma: Internet protocols are not designed for energy efficiency, but compression and other energy saving adaptations takes up precious code space. Device deployments specialized for single-vendor local networks make trade-offs specific to their application requirements. As a result, IP communication between IP enabled devices fails.

These trade-offs are fundamental to low-power networked devices. Popular and heavily used 6LoWPAN stacks today implement different subsets of the protocol. Some of them even include compile-time configuration options to elide additional required features in order to further conserve code space and fit the stack into a particular application. Arguing that every device should always implement everything will relegate many devices and applications to the brittle, proprietary protocols they have been historically so problematic.

Part of the challenge is that some traditional protocol design principles do not apply well to the low-power setting. While senders are given flexibility in how to format a message, receivers are expected to be able to process any particular sender's decision. This asymmetry in expectations forces implementations to cover every case which is more complex than is feasible for many low-power devices.

We propose three new design principles for low-power Internet protocols. These principles explicitly acknowledge the unique code space/energy tradeoffs of low-power devices by allowing individual devices to choose their own point in the tradeoff space while simultaneously allowing devices with different tradeoffs to find common ground:

- (1) **Capability spectrum:** acknowledge that low power devices will have varying abilities to implement complex protocols and define a linear spectrum of levels such that the costs of complex techniques are only borne by more resourceful devices.
- (2) **Capability discovery:** include a mechanism for determining which level each endpoint supports. Ensure that such a mechanism is primarily reactive, but that discovery requires no more than one failure.
- (3) **Explicit and finite bounds:** static bounds should exist to establish the maximum resources a packet may consume. Bounds should be conservative, finite, and, above all else, pervasive.

While traditional network principles such as layering and end-to-end still have their place in low power networks, these three principles are also paramount. Without them, traditional network principles can fail to provide devices with the effortless connectivity that is the hallmark of the Internet's success. We evaluate these principles through an example application to the 6LoWPAN protocol suite, where we find they prevent communication failures with at most a few hundred bytes of overhead.

Looking forward, considering the tension between energy efficiency and code size is critical for protocol designers in this ecosystem of diverse hardware capabilities and application tradeoffs. 6LoWPAN is not the only low power Internet protocol — the low power space uses its own routing protocols, address discovery protocols, and application layer protocols [33, 36]. Additional protocols will follow as the space matures. Many of these protocols will be initially developed outside the IETF — Jonathan Hui was a graduate student when he presented the first complete IPv6-based network architecture for sensor nets [18]. We have presented a roadmap for how these principles can reframe the discussion of how to connect the next hundred billion devices to the Internet.

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