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Connected Lighting System Interoperability Study

Part 1: Application Programming Interfaces

Prepared for the U.S. Department of Energy
Solid-State Lighting Program

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Prepared by Pacific Northwest National Laboratory

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Executive Summary

Lighting systems are increasingly incorporating network interfaces and sensors, and metamorphosing into data collection platforms that can implement advanced adaptive lighting strategies, enabling data-driven lighting energy management in buildings and cities, and can deliver other potentially high-value services, ranging from space utilization and office scheduling to asset or inventory management and many other functions. Although such connected lighting systems (CLS) might enable dramatic improvements in the energy performance of lighting and other energy-intensive systems or services, at this early stage in their development, that potential is limited by significant fragmentation of the underlying technologies and interfaces. As a result, today's CLS are generally not natively interoperable, meaning they cannot be assumed to work well together or be capable of exchanging the data that they collect with one another or other systems.

As the lighting industry brings connectivity to more products, their interoperability becomes key to leveraging that capability – specifically, the data that might be exchanged between devices and systems – towards better energy efficiency, lighting quality, user experiences, and perhaps other non-energy or non-lighting value propositions. Without sufficient interoperability, connected lighting systems may see limited market adoption. Devices need to use common communication protocols and information models in order for the number of valuable applications to grow and reach the critical mass that will drive adoption. Although owners of devices and systems that produce information are generally understood to own that information, the utility of that ownership is limited if the information is locked up in a proprietary data model. Interoperability unlocks the data in a system by allowing it to be communicated to and used by other systems, analyzed by other applications, and managed or archived in other ways, thereby enabling true ownership.

The main goal of this series of studies is to discern and document the state of CLS interoperability in this early stage, multi-vendor, multi-technology, and multi-business-model landscape. Although a number of industry consortia are developing frameworks or technologies that facilitate more native interoperability, at present these efforts are either incomplete or immature, do not support lighting applications sufficiently, or are not adopted by a significant number of lighting manufacturers. At present, interoperability between CLS offered by different vendors – or, in some cases, even between different solutions from the same vendor – is facilitated primarily through application programming interfaces (APIs), or not at all.

This initial study, which focuses on interoperability as realized by the use of APIs, explores the diversity of such interfaces in several CLS; characterizes the extent of interoperability that they provide; and illustrates challenges, limitations, and tradeoffs that were encountered during this exploration. More specifically, the system architectures and API structure, nomenclature, and information models were characterized; the development of a common integration platform was investigated; and two real-life use-cases were simulated to illustrate the relative effort required to use APIs to enable new features and capabilities facilitated by information exchange. Commonly observed issues, such as the challenge of integrating heterogeneous and asynchronous data and resources from multiple origins, are discussed in detail in this report, and suggestions are made for how API architectures and information models might be more coordinated, and thereby lower barriers to interoperability and enable increased CLS adoption.

Key Findings and Lessons Learned, Recommendations, and Next Steps

Although APIs and web services enable a certain level of interaction between heterogeneous systems on the Internet, they require some effort and skill to use effectively and efficiently, and they do not serve all interoperability goals. Integrating multiple CLS through APIs does not result in a homogenous system; at best it yields a common user interface and experience. However, effectively abstracting any underlying heterogeneous characteristics that do not serve the end user in some tangible way can require a significant amount of integration work. Managing what functionally remains a distributed system at one or more interoperability layers can be challenging and can require substantial effort. Differences among network protocols, device representations, and access policies that affect performance must be understood, addressed (if possible), and managed – not only initially, but over the course of hardware, firmware, and software upgrades. Asynchronous data flow can lead to latency issues and bandwidth bottlenecks. Integrated system failures and performance issues can be very difficult to debug and subsequently isolate and mitigate, without taking down the entire system. Implementing mechanisms and policies that maximize reliability and quality of service while still allowing the integrated system to scale and simultaneously continue to deliver end-use functionality requires advanced developer skills. Further, at present, system integrators may have to navigate API implementations that are poorly or insufficiently documented, or have not been well-exercised, rendering them immature or, in some cases, unusable.

APIs are becoming increasingly available for connected lighting systems. The APIs provided by current market-available CLS vendors can be utilized to facilitate enough interoperability between lighting systems to enable lighting-system owners and operators to implement some level of multi-vendor integration and some remote configuration and management services, as well as some adaptive lighting strategies. However, in many instances, API inconsistency and immaturity unnecessarily increase the effort required to implement these services and strategies, and reduce the value and performance that they deliver. API developers are encouraged to provide up-to-date and comprehensive API documentation and to support the efficient identification of bugs. Further, they should explore and attempt to implement common approaches to naming and organizing resources, as well as common information and data models – which are key to both minimizing the effort required to integrate heterogeneous systems and enabling functional, high-value use-cases.

The U.S. Department of Energy (DOE) intends to support improved interoperability by continuing to investigate approaches to realizing interoperability between CLS from different providers, as well as between connected lighting and non-lighting systems. Without more effective, efficient, and, ultimately, native interoperability, connected lighting technologies may see limited deployment, unable to go beyond simple connectivity and to fulfill their energy efficiency and transformative potential. Lighting industry stakeholders and system integrators are encouraged to provide DOE with investigation recommendations and to propose collaborations that might best contribute to realizing these goals.

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Symbols and Abbreviations

6LoWPAN	Internet Protocol IPv6 and Low-power Wireless Personal Area Networks
API	application programming interface
CLS	connected lighting systems
CLTB	Connected Lighting Test Bed
CoAP	Constrained Application Protocol
CORS	cross-origin resource sharing
CPU	central processing unit
DHCP	Dynamic Host Configuration Protocol
DOE	U.S. Department of Energy
GUI	graphical user interface
HTML	HyperText Markup Language
HTTP	HyperText Transfer Protocol
IETF	Internet Engineering Task Force
IoT	Internet of Things
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
LAN	local area network
LED	light-emitting diode
MD5	Message Digest 5
MQTT	Message Queue Telemetry Transport
OCF	Open Connectivity Foundation
PNNL	Pacific Northwest National Laboratory
REST	representational state transfer
RPC	remote procedure call
RSSI	received signal strength indication
SHA	Secure Hash Algorithm
SOAP	Simple Object Access Protocol
TCP	Transmission Control Protocol
URL	Uniform Resource Locator
UDP	User Datagram Protocol
W3C	World Wide Web Consortium
XML	eXtensible Markup Language
XMPP	Extensible Messaging and Presence Protocol
XSS	cross site scripting

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1 Introduction

The intersection of still-evolving solid-state lighting technology and the emerging Internet of Things (IoT) is giving rise to a new breed of lighting system. Connected lighting systems (CLS) – composed of intelligent light-emitting diode (LED) luminaires with one or more modern network interfaces and one or more sensors – hold the potential to deliver improved energy performance and to become platforms for the collection of data relevant to their surrounding environment. Although the ability to control lighting and implement energy-saving strategies is not new, many of today's lighting systems and their underlying technologies are rooted in outdated command-and-control architectures that require significant configuration effort, and that centralize information and intelligence. In contrast, IoT systems are being built on the most modern and mature communication technologies, with architectures that allow for information and intelligence to be more distributed and extensible. Improved connectivity and the ability to collect and use more and new types of data could reduce historical cost and complexity barriers to the implementation of energy-saving adaptive lighting strategies. Because data are also the fuel powering emerging IoT capabilities (e.g., space utilization, location-based services), delivering data can add significant value to lighting systems.

The IoT is not a new concept, and is more or less consistent with the ongoing pursuits of networking, automation, machine-to-machine communication, and cloud computing. However, the IoT is receiving increasing attention and business focus, and is being described and marketed by many different industry stakeholders, resulting in myriad definitions in a wide range of contexts, from research publications to marketing material. The following examples of definitions show the diversity in focus[1]:

The Internet of Things is…	*…the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment.*
	…the internetworking of physical devices … embedded with electronics, software, sensors, actuators and network connectivity that enable these objects to collect and exchange data.
	…an infrastructure of interconnected objects, people, systems and information resources together with intelligent services to allow them to process information of the physical and the virtual world and react.
	…a network that connects uniquely identifiable things to the internet. The things have sensing/actuation and potential programmability capabilities. … Information about the thing can be collected and the state of the thing can be changed ….

Many industry forecasters are predicting exponential growth in IoT devices over the next few years, resulting from rapidly falling economic and technological barriers, improved autonomous and self-learning technologies, and more mature and interoperable communication protocols. The development and success of new innovative business models are seen as a key catalyst to this growth; if the value of a network grows with the square of the number of connected nodes,[2] the IoT has a lot of business potential to unlock. Such opportunities are expected to heavily leverage data

[1] ISO/IEC JTC-1. 2015. *Internet of Things (IoT): Preliminary Report 2015*. International Organization for Standardization, Geneva. https://www.iso.org/files/live/sites/isoorg/files/developing_standards/docs/%20en/internet_of_things_report-jtc1.pdf.

[2] Wikipedia, Metcalfe's law: wikipedia.org/wiki/Metcalfe's_law.

collection and analytics towards high-value knowledge that might not only result in improved energy performance, but also give rise to automation or service optimization in any number of traditionally vertical industries (e.g., consumer, municipal infrastructure, building, transportation, healthcare).

Connected lighting systems are uniquely positioned to be a backbone of the IoT and change the way people interact with their surroundings. Lighting is ubiquitous – it exists everywhere that people gather – and often has a near-ideal viewpoint from which to monitor surrounding conditions, making it perhaps the most attractive infrastructure for developing sensing platforms. Further, the same electronics that regulate the delivery of low-voltage power to LEDs can easily be modified to provide power to embedded sensors, microcontrollers, and network interfaces. In addition to occupancy and daylight sensors that have traditionally been used to implement energy-saving lighting-control strategies, other sensors that might be integrated into lighting devices include, for example, those to measure carbon dioxide, vibration, and sound – resulting in such "smart building" or "smart city" benefits as air quality monitoring, theft detection, and guidance to available spaces (e.g., office, parking). CLS are already being used as a platform for monitoring occupant position and movement in retail environments and other heavy-traffic buildings (e.g., shopping malls, airports, universities, healthcare facilities, and warehouses) by using Bluetooth beacon and/or visible-light communication technologies. This data is then analyzed to provide personalized location-based services to help occupants navigate in the building, and space-utilization and occupant-flow services to help building owners improve operational efficiencies, enhance safety, and increase revenues. A comparison of LED conversion forecasts (progressing from 424 million devices installed in the U.S. in 2015 to 2,740 million devices in 2020[3]) and predictions of how many IoT devices might be deployed over the next few years (increasing from 4,902 million devices worldwide in 2015 to 20,797 million in 2020[4]) suggests strong alignment between the race to convert lighting devices and the forecasted deployment of IoT devices.

Many industry experts believe that interoperability is the pivotal enabler of and catalyst for IoT deployment[5,6] and, thus, CLS adoption and associated energy savings. One analysis[7] predicts that interoperability will be key to accessing 40% of the potential future economic value enabled by the IoT, accounting for more than an estimated $4 trillion per year starting 2025. However, the decision of whether, when, and how to pursue interoperability is not trivial for technology developers, who must juggle the technical challenges of developing and implementing the scalable communication protocols and inclusive data models that can deliver interoperability with many other needs and concerns, including cybersecurity risks, privacy, data ownership, and, of course, the viability and sustainability of their business model.

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[3] DOE. 2016. *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications*, U.S. Department of Energy, Washington, D.C. energy.gov/sites/prod/files/2016/10/f33/energysavingsforecast16_0.pdf.

[4] Gartner. 2015. "Gartner Says 6.4 Billion Connected 'Things' Will Be in Use in 2016, Up 30 Percent From 2015." Press Release, November 10, 2015. gartner.com/newsroom/id/3165317.

[5] OCF. 2017. *New Survey Highlights Importance of Interoperability in the Internet of Things*, Open Connectivity Foundation, Beaverton, OR. https://openconnectivity.org/announcements/new-survey-highlights-importance-interoperability-internet-things

[6] AHA. 2015. *Why Interoperability Matters*, American Hospital Association, Chicago, IL www.aha.org/content/15/interoperabilitymatters.pdf

[7] McKinzey & Company. 2015. *Unlocking the Potential of the Internet of Things*. mckinsey.com/business-functions/digital-mckinsey/our-insights/the-internet-of-things-the-value-of-digitizing-the-physical-world.

In the early development days of other technology ecosystems (e.g., personal computing, Internet access, mobile phones), many technology providers initially attempted to chart their own course and win a competitive advantage by becoming the *de facto* standard. Although this approach can be successful, it is the exception rather than the rule. Many technology providers overestimate the value of their in-house solution[8] and are unsuccessful in establishing it as a *de facto* standard. CLS, and especially the IoT in its fully imagined form, are arguably more complex technology ecosystems than any developed previously – spanning dozens if not hundreds of applications, and significantly more use-cases and device and data types. This suggests that the pursuit of proprietary systems and "walled-garden" strategies will only limit the potential of connected lighting and the IoT, if not prevent them from getting off the ground. However, because the IoT market is still relatively young, highly competitive, and at least perceived as being driven by both cost and time-to-market, market forces are currently working against interoperability. Many manufacturers are pursuing proprietary approaches in hopes of becoming a *de facto* standard and achieving a significant competitive advantage over other solutions,[9] and open specifications and standards have thus far seen a slow adoption rate.

At present, CLS vendors are addressing interoperability in myriad ways, often pursuing multiple paths simultaneously. Although some are implementing open specifications or standards, others are continuing to implement or develop proprietary ones. Some are waiting for specific standards to develop market momentum, or for competing efforts to converge. In the meantime, end users who want to install CLS from multiple vendors or integrate their CLS with non-lighting systems must, in general, develop their own interoperability strategy. Technology providers are primarily supporting such needs by providing technical assistance for specific integrations, developing and releasing interfaces for legacy protocols (e.g., DALI, BACnet), and developing and releasing one or more APIs, by which a CLS can interact with the Internet and, in doing so, communicate and exchange data with other devices and systems or cloud applications. APIs can come in many flavors, but effectively they spell out what can be communicated and how communication requests should be made. More specifically, they comprise a set of data structure and protocol specifications that enable software applications to expose and share resources.

Consistent with its longstanding mission to accelerate the development of energy-saving technologies, the U.S. Department of Energy (DOE) is undertaking a series of research studies focused on CLS interoperability. These studies will characterize the interoperable performance of emerging systems and highlight the benefits of an interoperable approach and increasing levels of interoperability. The studies will focus on qualitatively evaluating the interoperability enabled by consensus industry efforts (e.g., frameworks, specifications, standards), and not on whether, or how well, specific devices and/or systems comply with said frameworks or platforms, specifications, or standards. In the early days of LED general lighting technology, immature performance claims were often misunderstood or, even worse, misleading. Such issues inhibited adoption and slowed the realization of energy savings, and DOE efforts played a role in identifying and addressing them. DOE aims, through its research, to play a similar role in studying early interoperability claims. While these studies may identify interoperability issues that contradict, or are otherwise inconsistent with, the claims made for a specific framework or platform, specification, or standard, they will not

[8] Wikipedia, Not invented here, en.wikipedia.org/wiki/Not_invented_here; people.hbs.edu/mnorton/norton%20ariely.pdf.

[9] Fältström P. 2016. *Market-driven Challenges to Open Internet Standards*. Paper Series: No. 33 - May 2016, Global Commission on Internet Governance, Waterloo, Ontario, Canada. cigionline.org/sites/default/files/gcig_no33web.pdf.

determine whether a device or system complies with a given framework or platform, specification, or standard – that is the role of certification testing and programs.

This first study is focused on the development and use of APIs to achieve interoperability between CLS. The anticipated impacts of this study include the following:

1. Provide feedback to technology developers on the capabilities and limitations of currently available APIs.

2. Educate potential CLS owners and operators on what type of data exchange is enabled by currently available APIs, and the relative effort required to use APIs to realize new features and capabilities facilitated by such information exchange.

3. Accelerate the development of interoperability frameworks or platforms, specifications, and standards.

4. Educate (non-lighting) IoT stakeholders about the needs of and opportunities offered by CLS.

2 Interoperability Background

One of the defining attributes of the Internet is the interoperability of devices that comprise it. Internet hardware and software evolve without requiring a revision of the basic Internet architecture, and information crosses technology boundaries (e.g., from Ethernet to Wi-Fi) seamlessly. In many ways, today's IoT is comparable to the early years of the Internet, when there were several types of computers and networks, and custom hardware was required to bridge otherwise isolated islands. Although interoperability has been defined many ways by many authorities, perhaps the most elegant definition was put forward the European Research Cluster on the Internet of Things, which defines interoperability simply as the ability of two or more systems or components to exchange data and use information.[10] Regardless of the exact definition, it is important to differentiate interoperability from the ability to physically exchange systems or components and maintain a defined level of identical operation (sometimes referred to as interchangeability) and the ability to merely coexist in the same physical environment (sometimes referred to as compatibility).

Interoperability implies communication in a form and format that can be understood and processed across heterogeneous software, operating systems, network communication hardware, and protocols. As shown in Figure 2.1, when viewed at different depths, it can be broken down into at least three categories.

[10] IERC. 2016. *Internet of Things. IoT Semantic Interoperability: Research Challenges, Best Practices, Recommendations and Next Steps*. M Serrano, P Barnaghi, F Carrez, P Cousin, O Vermesan, and P Friess (eds). European Research Cluster on the Internet of Things, Oslo, Norway. internet-of-things-research.eu/pdf/IERC_Position_Paper_IoT_Semantic_Interoperability_Final.pdf.

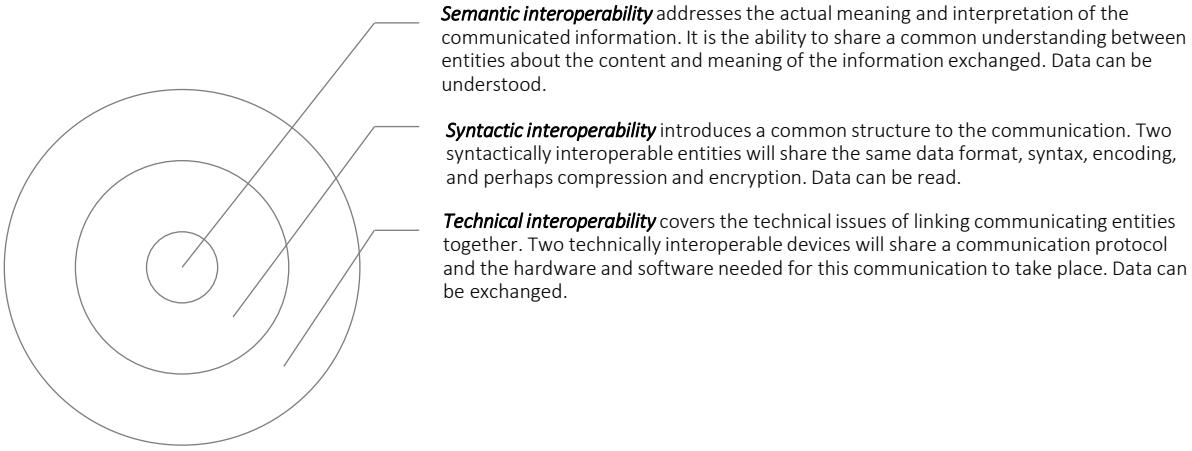


Figure 2.1. Three conceptual layers of communication-system interoperability

Limited interoperability can manifest itself in many different ways:

- reliability, scalability, and latency issues
- difficulty developing cross-platform applications
- difficulty maintaining a functioning communication network
- slower identification of failure modes and cybersecurity issues
- limited reusability of technical solutions
- higher costs, lower adoption rates, and higher user dissatisfaction

On the other hand, deeper and more mature interoperability can reduce integration/operation costs; accelerate competition and innovation; and facilitate more robust security, privacy, and data management.

2.1 Interoperability Frameworks and Specifications

Many industry associations and standards development bodies are working on interoperability frameworks and specifications for the IoT. A comprehensive comparison or detailed description of the technical details that comprise any of them is beyond the scope of this study, as many useful references exist elsewhere. For example, a high-level overview of many of these efforts can be found on the website of the Internet Architecture Board committee of the Internet Engineering Task Force (IETF).[11] As a prelude to this exploration of APIs, however, it is useful for understanding some of the different approaches taken towards harmonization of application layer protocols, and the definition of common information and data models.

Although some interoperability frameworks and specifications for connected systems have been under development for years (e.g., Wi-Fi Alliance, ZigBee Alliance), new contenders more focused on IoT devices are emerging. Historically, adoption and success come to those frameworks and

[11] Groves C, L Yan, and Y Weiwei. 2016. *Overview of IoT semantics landscape*. Huawei Technologies, Plano, TX. iab.org/wp-content/IAB-uploads/2016/03/IoTSemanticLandscape_HW_v2.pdf.

specifications that best meet true market needs and are most efficiently validated by user experience and real-life applications. Products and standards typically evolve in parallel and require efficient cross-cutting feedback loops, whereby new learning in the development of either informs the other. The following examples of industry associations working on interoperability illustrate a diversity in approaches being pursued, as well as in market adoption status.

The Open Connectivity Foundation (OCF), a cross-industry consortium with over 300 members (including Intel, Qualcomm, Broadcom, Cisco, and Microsoft[12]), is one of the most active. It is promoting IoT interoperability around the Constrained Application Protocol (CoAP) by providing specifications,[13,14,15] open-source reference implementations (IoTivity), a collaborative tool for crowd-sourcing the design of data models (oneIoTa), and a certification program.
Project Haystack,[16] a partnership of several industry leaders created to streamline the integration of IoT data, is focusing on the development of semantic data models and web services specifications for building systems and intelligent devices.
The FIWARE platform, driven by the European Union with a focus on smart cities, sustainable transport, and renewable energy, strives "to build an open sustainable ecosystem around public, royalty-free and implementation-driven software platform standards that will ease the development of new smart applications in multiple sectors."[17]
Google is pursuing an approach that relies on the Android developer community and the widespread deployment of Google services. They have released a stripped-down embedded operating system for IoT devices (Android Things) and a communication platform (Weave[18]), along with developer tools and device schemas, including provisions for lighting devices.

Application layers in interoperability frameworks essentially define how data should be represented, structured, and understood. They are often further broken down into (1) information models, which define schemas for conceptual objects separately from any underlying architecture, interface, or protocol; and (2) data models, which define those objects at a lower level of abstraction and can include implementation-specific details.[19] There are many different application layer protocols that could conceivably be used for IoT device communication, and most industry experts do not believe that a single Internet application layer protocol will be well-suited for all conceivable IoT use-cases. Although there is some overlap, the fundamental goals, architectures, and capabilities behind each protocol differ in important ways. The following list briefly describes some of the ones that are currently most popular:

[12] Open Connectivity Foundation: Membership List, openconnectivity.org/about/membership-list.
[13] Open Connectivity Foundation: Specifications, openconnectivity.org/resources/specifications.
[14] Linux Foundation Collaborative Projects: IoTivity: About, iotivity.org/about.
[15] Open Connectivity Foundation: oneIoTA Data Model Tool, openconnectivity.org/resources/oneiota-data-model-tool.
[16] Project Haystack, project-haystack.org.
[17] FIWARE: About Us, fiware.org/about-us.
[18] Nest Developers: Weave, https://developers.nest.com/weave/?nav=true&hl=zh-CN.
[19] Internet Engineering Task Force: On the Difference between Information Models and Data Models, tools.ietf.org/html/rfc3444.

HTTP (Hypertext Transfer Protocol, developed by the IETF and the World Wide Web Consortium [W3C]) underpins client/server interactions on the Internet. Each resource is identified by a Uniform Resource Locator (URL) and is accessed and manipulated through request/response methods (e.g., GET, PUT, POST) over the Transmission Control Protocol (TCP) transport layer.[20]
MQTT (Message Queue Telemetry Transport) is an International Organization for Standardization (ISO) standard asynchronous publish/subscribe protocol that runs over TCP. It was initially developed by IBM for satellite monitoring of oil pipelines and is commonly used in today's building-automation and online messaging services. Specifications are available via ISO and OASIS.[21]
XMPP (Extensible Messaging and Presence Protocol) is another mature IETF development,[22] *initially designed for online messaging (originally known as Jabber) and later extended to social networking, Voice over Internet Protocol (VoIP), and IoT applications. It provides both request/response and publish/subscribe methods over TCP using eXtensive Markup Language (XML) payloads.*
Websocket is a real-time full-duplex (pub/sub-ish) communication protocol that runs over TCP and was standardized by the IETF[23] *and W3C as part of the HTML5 specifications, with the goal of achieving very low-latency connections and real-time web applications.*
CoAP was also developed by the IETF[24] *for use with constrained devices and networks. It is a lightweight request/response protocol with built-in discovery and multicast support over the UDP (User Datagram Protocol) transport layer.*

Application layers often have dependencies on lower-layer protocols or assumptions regarding their nature. The underlying dependency on how data is communicated – specifically the transport layer – is particularly relevant. As noted in the given examples, this is typically a choice between TCP and UDP. With three-way handshake and error checking, TCP is used when an emphasis is placed on reliability; in contrast, UDP, which is connectionless and uses smaller headers, is more appropriate when speed and network efficiency are priorities. Another important distinction is the choice between request/response and publish/subscribe architectures. Request/response is valued for its simplicity, but may not be well-suited for IoT use-cases where ecosystems need to scale, not all messages need to be responded to, or constant polling to request updates might overburden available central processing unit (CPU) time and network bandwidth. For example, although HTTP might work well for devices that exchange considerable amounts of data, require a web interface, and are connected to a reliable source of power, a large constellation of small, limited-CPU, battery-powered devices might require more lightweight and scalable solutions.

2.2 RESTful APIs

Although there are many ways to implement an API, perhaps the most common technique is to utilize a Representational State Transfer (REST) architecture that implements resource-oriented

[20] Internet Engineering Task Force: Hypertext Transfer Protocol - HTTP/1.1, tools.ietf.org/html/rfc2616.
[21] Oasis: MQTT Version 3.1.1 Plus Errata 01, https://docs.oasis-open.org/mqtt/mqtt/v3.1.1/mqtt-v3.1.1.html.
[22] Internet Engineering Task Force: Extensible Messaging and Presence Protocol (XMPP): Core, tools.ietf.org/html/rfc6120.
[23] Internet Engineering Task Force: The WebSocket Protocol, tools.ietf.org/html/rfc6455.
[24] Internet Engineering Task Force: The Constrained Application Protocol (CoAP), tools.ietf.org/html/rfc7252.

client-server interactions. Such RESTful approaches are commonly used to implement the web services that allow, for example, one website to access information from another website. REST is not a standard or even a contained specification in and of itself; rather, it comprises a fundamental set of architectural principles and best practices. Although not all self-proclaimed REST services are created equal, in general, RESTful practices adhere to two defining implementation constraints[25]:

- Addressability: Each resource or representation of it should be identifiable and accessible. Uniform Resource Identifiers should define a global namespace and use consistent nomenclature. Resources can comprise individual items or collections of items, virtual or physical objects, or computation results.
- Statelessness: Each communication should always contain all information and metadata needed to perform the request. Messages should be self-descriptive and cacheable. Clients should not need prior context or knowledge of the service to execute the request, and should be able to dynamically discover available resources and possible actions.

Although REST is not a perfect solution for every real or imagined web service, it is valued for its flexibility and simplicity. REST is considered lightweight in terms of bandwidth usage, relative to other web service architectures like SOAP (Simple Object Access Protocol) and RPC (Remote Procedure Call), and it makes full use of the underlying HTTP transport layer, methods, and responses. An example of a RESTful request to and response from the Wikipedia public API[26] is shown in Table 2.1 to illustrate the underlying mechanism.

In this example, the API request performs a Wikipedia search for the term "json" and asks for the results of the search in the JavaScript Object Notation (JSON) data format. JSON is an open, programming-language-independent data format that uses text that is human-readable and simultaneously easy for machines to parse to generate data objects. It is based around two structures: (1) unordered sets of key and value pairs separated by a colon and between braces; and (2) ordered arrays of values, separated by a colon and between brackets (for example {'key': 'value', 'key': ['value', 'value']}). JSON is commonly supported by CLS and other IoT systems, because it is less verbose than many other data formats, such as XML.

GET is the HTTP method used to retrieve a representation of a given resource. Notably, this method is characterized as safe (will not change the state of the server), idempotent (multiple identical requests will generate the same response), and cacheable (allowed to be stored for future use). A characterization of all methods defined by the HTTP/1.1[27] specification is provided in Table 2.2.

[25] Wikipedia: Representational state transfer, wikipedia.org/wiki/Representational_state_transfer.
[26] MediaWiki: API:Opensearch, mediawiki.org/wiki/API:Opensearch.
[27] Internet Engineering Task Force: Hypertext Transfer Protocol (HTTP/1.1): Semantics and Content, tools.ietf.org/html/rfc7231.

Table 2.1. Example of an RESTful API, showing a HTTPS GET request and 200 (OK) response from the Wikipedia API. Note that in some instances, text that is not essential to the example has been removed and replaced with [….] to improve readability.

Request

Method	Base URL	Parameters	Headers
GET	https://en.wikipedia.org/w/api.php	({'action': 'opensearch', 'search': 'json'})	{ 'Content-Type': 'application/json', 'Connection': 'keep-alive', 'Accept-Encoding': 'gzip, deflate', 'Accept': '*/*', 'User-Agent': 'python-requests/2.11.1' }

Response

Status Code	Body	Headers
200 (OK)	{ ..., ["In computing, JSON [...] is an open-standard format that uses human-readable text to transmit data objects consisting of attribute-value pairs.","","JsonML, the JSON Markup Language is a lightweight markup language used to map between XML (Extensible Markup Language) and JSON (JavaScript Object Notation).","JSON Web Token (JWT) is a JSON-based open standard (RFC 7519) for creating access tokens that assert some number of claims.","JSON-RPC is a remote procedure call protocol encoded in JSON. It is a very simple protocol, ..."], ... }	{ 'Content-Type': 'application/json;charset=utf-8', 'Content-Length': '1023', 'Date': 'Mon, 06 Feb 2017 23:14:42 GMT', 'Age': '6029', 'Server': 'mw1189.eqiad.wmnet', 'Connection': 'keep-alive', ... }

Table 2.2. Definitions and characteristics of HTTP/1.1 request methods

HTTP Method	Description	Request has body	Response has body	Safe	Idempotent	Cacheable
GET	Requests the representation of a resource. The primary information retrieval mechanism.	no	yes	yes	yes	yes
HEAD	Retrieves only metadata without the actual content associated with the resource. Can be used for testing for accessibility or recent modifications.	no	no	yes	yes	yes
POST	Requests server processing of an attached payload according to its own semantics. Can be used to submit a form, post a message, or add items to a database…	yes	yes	no	no	yes
PUT	Replaces (or creates) the representation of a resource. Mostly used to update data or change the status/value of a resource.	yes	yes	no	yes	no
DELETE	Requests server removal of a specified resource. It is up to the server to archive or actually delete information.	no	yes	no	yes	no
OPTIONS	Learn server capabilities and allowed methods and options for a given resource. Can be used to test and discover what the server allows.	yes/no	yes	yes	yes	no
CONNECT	Requests that the recipient (proxy) initiates a tunnel to the destination server. Used to establish virtual connections and secure/encrypt communications.	yes	yes	no	no	no
TRACE	Remote loop-back echo of the request received by the server. Used for testing/diagnostic/debug purposes.	no	yes	yes	yes	no

Status codes are included in the response to an HTTP request, to indicate whether the request has been successfully completed or what kind of exception occurred. The first digit specifies the class of the response: 1xx is informational, 2xx is success, 3xx is redirection, 4xx is client error, and 5xx is server error. Among the most common response codes, "200 OK" indicates that the request was successful; "400 Bad Request" occurs when the server cannot process the request because of, for example, a syntax error; "401 Unauthorized" is the response when the required authentication is missing or has failed; and "404 Not Found" indicates that the server was unable to find the requested resource. A detailed list of standard and common HTTP status codes is available elsewhere.[28]

Headers are used to communicate metadata and operating parameters. In a request, "Content-Type" specifies – as already noted in the Table 2.1 example – the response data format, "Accept-Encoding" enumerates the acceptable character encoding schemes, "Accept" defines the acceptable Content-Types for the response, and "Authorization" is used to transmit authentication credentials or API tokens. In a response, "Content-Type" specifies the format of the response body, "Age" denotes how long (in seconds) the object has been in cache, and "Server" spells out the actual server name. Some headers are automatically added by, for example, the web browser or an associated HTTP library. A detailed list of common request and response headers is available elsewhere.[29]

The Wikipedia web service API can be defined as "open," because it is free to use (i.e., it is not subject to restrictive terms of service and licensing agreements, without copyright or patent constraints) and is based on open standards and specifications, such as JSON. Open APIs allow, if not encourage, more developers to explore ideas for combining different web services and creating new applications, potentially leading to more innovation and increasing the value of the web service. However, the physical devices and systems accessed by APIs in the IoT ecosystem are often, if not typically, more exposed to the world than, for example, the servers that power the web, and thus are more susceptible to real-world cybersecurity risks. Opening backend resources to the public can increase these cybersecurity risks. Further, devices on low-bandwidth networks might be overwhelmed with network traffic if API requests are not secure and well-managed. Fortunately, closing programming interfaces is not the only tool that developers have for protecting data and resources. A variety of authentication and authorization schemes have been developed to manage cybersecurity risks, including the following:

[28] Internet Engineering Task Force: Hypertext Transfer Protocol (HTTP) Status Code Registry, ietf.org/assignments/http-status-codes/http-status-codes.xml.
[29] Wikipedia: List of HTTP header fields, wikipedia.org/wiki/List_of_HTTP_header_fields.

HTTP basic authentication[30] uses the "Authorization" field within the header of each request to transmit cleartext Base64-encoded username and password credentials to confirm the identity of the user and enforce access control and permission rules. Transmitted credentials can easily be decoded, which is why basic authentication has to be secured using HTTPS encryption. As an alternative to sending cleartext credentials, some implementations use API tokens[31] that are generated and revoked server-side in order to identify users. Typically, these tokens are also just a cleartext string, and thus do not offer additional security unless a unique, difficult-to-discern protocol (such as timestamp concatenation or encryption hash calculation) is implemented.

HTTP digest authentication[32] uses Message Digest 5 (MD5), a 128-bit cryptographic function, to transmit a hash of username and password credentials, as well as additional mechanisms to avoid collision and replay attacks. Although this scheme is not considered secure, it does allow the server to confirm the user identity without having a cleartext password being transmitted or stored server-side.

Form or session authentications require the client to send its credentials in the payload of a POST request – as is sent when filling out an online form – in exchange for a session ID that can then be stored in a cookie client-side and attached to every subsequent request. However, this scheme somewhat violates the REST principle of statelessness, as it requires the server to store and manage session information.

OAuth, an IETF-developed scheme for authorization and API access delegation,[33] specifies a method for issuing tokens that can be used by third-party applications to access protected resources, with the approval of the resource owner. Two very different and incompatible versions coexist – OAuth1.0a and OAuth2.0. Where OAuth1.0a specifies a full protocol that relies on Secure Hash Algorithm (SHA1), a cryptographic signature that can be safely used over unsecured HTTP, OAuth2.0 provides a framework that offers different scenarios and relies exclusively on HTTPS for encryption.

Whether hosted locally or in the cloud, APIs are run on servers that must be configured and administered. Server administrators must carefully balance access with security. Server administration involves the establishment of policies that, ideally, facilitate efficient access to server resources to support legitimate uses while protecting the confidentiality and integrity of server data. The development of applications that access data from multiple servers through APIs, as might be done when integrating multiple CLS with a control interface or data dashboard, are often challenged by needs or desires to support various user interfaces, network architectures, and software platforms. Restrictive server policies can limit application compatibility to specific integration approaches. However, as recommended by the Mozilla Developer Network,[34] "data requested from a remote website should be treated as untrusted. Executing JavaScript code retrieved from a third-party site without first determining its validity is not recommended. Server administrators should be careful

[30] Internet Engineering Task Force: The 'Basic' HTTP Authentication Scheme, tools.ietf.org/html/rfc7617.
[31] World Wide Web Consortium: Token Based Authentication -- Implementation Demonstration, w3.org/2001/sw/Europe/events/foaf-galway/papers/fp/token_based_authentication.
[32] Internet Engineering Task Force: An Extension to HTTP: Digest Access Authentication, tools.ietf.org/html/rfc2069 , tools.ietf.org/html/rfc2617.
[33] Internet Engineering Task Force: The OAuth 1.0 Protocol, tools.ietf.org/html/rfc5849 , tools.ietf.org/html/rfc6749.
[34] Ranganathan A. 2009. "Cross-site xmlhttprequest with CORS." *Mozilla Hacks*, July 6, 2009. hacks.mozilla.org/2009/07/cross-site-xmlhttprequest-with-cors/.

about leaking private data and should judiciously determine that resources can be called in a cross-site manner."

One of the simplest and most common policies that might be implemented is known as a same-origin policy, under which a web browser permits scripts contained in a first web page to access data in a second web page, but only if both web pages have the same origin. Same-origin policies, which are generally enforced by web browsers on the client side rather than on the server that hosts the data, help prevent malicious code on one website from accessing restricted content on another website. This behavior, often referred to as cross-site scripting (XSS), is arguably the most common cybersecurity attack vector. However, rich web experiences commonly require and rely on simultaneous access to data from multiple origins, making the same-origin policy sometimes too restrictive. An alternative to the same-origin policy recommended by the W3C is known as Cross-Origin Resource Sharing (CORS), which defines a method by which clients and servers can interact to determine whether or not a web page in a given domain is allowed to request data from another domain. It extends the HTTP specifications with an "Origin" request header and a set of "Access-Control-Allow" response headers, with which servers can whitelist origins, methods, and headers that are permitted to access data. CORS is not considered secure, however. Although it is honored by common web browsers, it can be bypassed by attackers who instead use specialty tools.

In summary, RESTful APIs provide a flexible means for connected lighting and IoT system developers to facilitate varying levels of interoperability with other systems. This flexibility is primarily responsible for both its current adoption and its limitations. System developers are free to expose whatever system data or control points they wish, while leaving others inaccessible, and the REST approach leverages simple HTTP methods that are well known and used by software developers. Performance and cybersecurity, however, are primarily a function of the underlying HTTP implementation, which is subject to many choices. Despite the use of common methods, each API is generally unique, and there is no requirement for them to be self-explanatory or user-friendly, nor is there a well-adopted framework for facilitating that. Successful and efficient use of a given API is often subject to a learning curve, especially in the absence of accurate and up-to-date documentation or vendor or community-based technical support.

2.3 DOE Connected Lighting Test Bed

Central to DOE's connected lighting systems efforts is a testing facility, referred to henceforth as the Connected Lighting Test Bed (CLTB), that was designed and is operated by the Pacific Northwest National Laboratory (PNNL) to characterize the capabilities of CLS and conduct technology research and evaluations. These activities aim to increase the visibility and transparency of newly developed technologies and to create feedback loops to inform technology developers and standards bodies of needed improvements related not only to interoperability, but also to energy reporting, configuration complexity, and other new features. More details about the CLTB (Figure 2.2) are available on the DOE Solid-State Lighting program website.[35]

[35] DOE Office of Energy Efficiency and Renewable Energy: Connected Lighting Test Bed, energy.gov/eere/ssl/connected-lighting-test-bed.

Figure 2.2. Infrastructure for characterizing CLS in the DOE Connected Lighting Test Bed

2.4 Web-Based Interoperability Platform

To enable the testing of multiple devices and systems in the CLTB, a software interoperability platform was developed to allow installed lighting devices and systems that were not natively capable of exchanging data with one another to communicate through a defined middleware interface. The vision for this first version (v1) CLTB interoperability platform was something akin to If-This-Then-That (IFTTT),[36] a popular web-based tool that is simple enough for anyone to use and was developed primarily to support the integration of residential devices to support simple use-cases. An attempt was made to develop a similarly easy-to-use tool, with a bit more flexibility, that would enable interoperability demonstrations and use-case explorations. The basic building blocks include connected lighting systems' APIs as well as other web services and online data sources (e.g., real-time weather or traffic data) that might be combined and used within algorithms and chains of conditional statements to demonstrate and explore new use-cases.

The developed web application is hosted remotely in the Microsoft Azure cloud, which requires locally hosted CLS API server requests and responses to be forwarded through the firewall, representing the first of many tradeoffs inherent in this approach to realizing interoperability. Such forwarding of server communication exposes the servers to the entire web, thereby increasing their cybersecurity risks and magnifying any vulnerabilities associated with, for example, their chosen authentication scheme. A user who desires to implement a given use-case is invited, through the graphical user interface (GUI), to connect to and authenticate available CLS APIs and third-party web services (Figure 2.3). APIs that facilitate resource discovery automatically populate the appropriate field after successful authentication. The user then selects from available inputs (e.g., CLS sensors, online data sources) and outputs (e.g., CLS light-source output level) that are essential to the implementation of the targeted use-case.

[36] IFTTT, https://ifttt.com/.

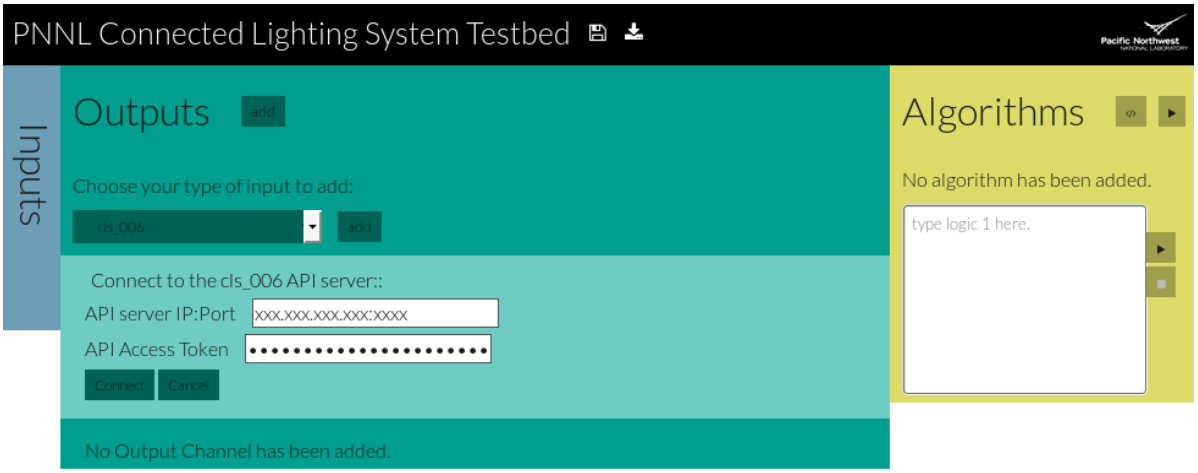


Figure 2.3. Web-based interoperability platform user interface

The user can then directly enter JavaScript code into a GUI "Algorithms" window that defines how selected outputs should respond to changes in one or more selected inputs, thereby enabling the intended use-case. Algorithms can be executed either individually or simultaneously. In the example illustrated by Figure 2.4, a CLS light source is instructed to blink when the temperature sensor from another CLS fixture exceeds a specified threshold.

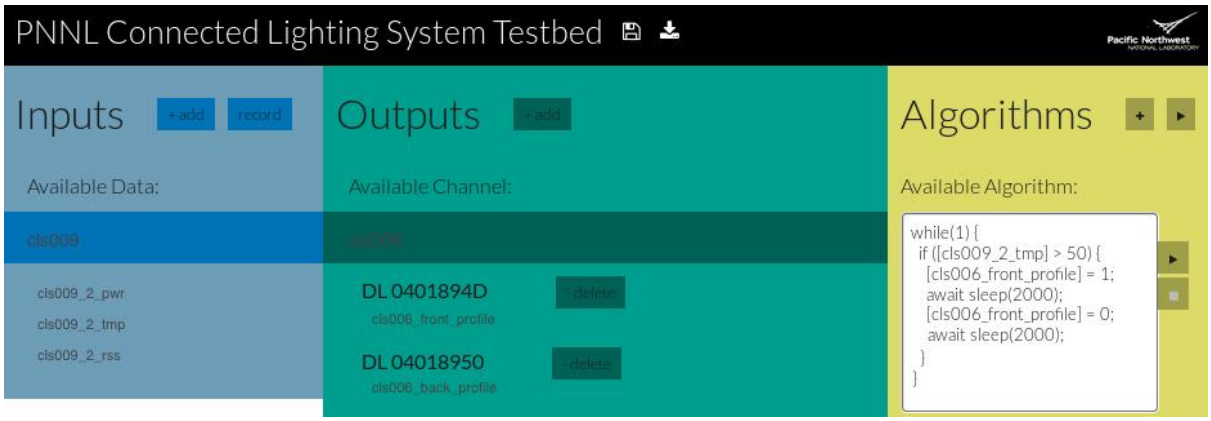


Figure 2.4. Web-based interoperability platform use-case example

Multiple commercially available indoor and outdoor CLS were installed in the CLTB and integrated via their APIs into this web-based interoperability platform. Integrating multiple APIs into a single user interface while maintaining the intended functionality of the web-based platform proved to be an increasingly difficult proposition, as incompatibilities among, for example, different API data models limited the level of integration that could be achieved. Keeping this platform and its connected CLS secure and the user experience simple and straightforward were equally challenging. The development and use of this platform towards abstracting the differences and complexities of the underlying systems brought valuable insight into what level of interoperability can be enabled by APIs, and how much effort is required to exchange information between different devices and systems via APIs. This integration effort exposed how differences in API architectures, data models, features, and capabilities limited the interoperability between heterogeneous and asynchronous systems.

3 Connected Lighting System API Comparison

At present, very few commercially available CLS are fully and natively interoperable. Rather, interoperability is facilitated by using APIs, which, rather than defining a common method for interacting with a device or system, define how to interact with a given device or system. Although APIs can facilitate the exchange of information between different systems, they do not deliver native interoperability. They do, however, enable system integrators to write software that enables systems to exchange data with one another through some form of software interoperability platform, which effectively implements a level of interoperability that is a function of the platform architecture and characteristics.

3.1 CLS APIs

This study focused on the exploration of six CLS, three developed primarily for indoor applications (Enlighted, Digital Lumens, Xicato) and three developed for outdoor use (Current, powered by GE; Silver Spring Networks; Telematics Wireless). All CLS were procured or donated prior to June of 2016, and all exploration and characterization was completed prior to June of 2017. These CLS communicated using a variety of radio (i.e., physical and transport layer) protocols, including Bluetooth Low Energy, IEEE 802.15.4, ZigBee, and 6LoWPAN, and exhibited significant differences in system architecture. Some were cloud-centric, while others used a more distributed intelligence architecture, processing some data at the device level or in gateways at network edges, an approach sometimes referred to as "fog computing."[37] Data collection and data analytics solutions were also diverse, as user and application interface servers were remote in some cases and ran on an onsite device in others. However, the common denominator and basis for this study was that they all served an HTTP RESTful API to facilitate interoperability.

3.2 CLS API Authentication Schemes

Three of the six API servers were installed and managed on site in the CLTB, and not necessarily designed to be brought outside of the local area network (LAN). Each of these systems used a different authentication scheme:

- One implemented HTTP basic authentication over unencrypted HTTP with a simple cleartext 32-character API key token.
- One implemented HTTP basic authentication over encrypted HTTP Secure (HTTPS) with a proprietary security measure on top, using a SHA1 cryptographic hash of the user ID, API token, and millisecond Unix timestamp (to avoid replay attacks) as an authentication key.
- One CLS did not offer a commercial gateway server over the period of this study. To facilitate inclusion in this study, an ad-hoc gateway was built for the sole purpose of serving a RESTful API that did not require authentication

The three remaining API servers were remote and managed by the vendor. All implemented a form/session authentication scheme, one over unsecured HTTP and the other two over HTTPS.

[37] Wikipedia: Fog Computing, wikipedia.org/wiki/Fog_computing.

3.3 CLS API Origin Policies

The CLTB web-based interoperability platform was used to explore whether CORS could be enabled for each of the six CLS. The platform was installed on both a cloud server to enable testing with onsite API servers, and an onsite server to enable testing with offsite API servers. Only one of the six API servers was natively capable of supporting CORS, and responded with a descriptive "Access-Control-Allow" header when presented with a properly configured "Origin header." An example API response from this CLS is shown in Table 3.1. The API server for a second CLS was able to be modified by the manufacturer to support CORS following a request. Attempts to enable CORS with the other four systems over the course of this study were unsuccessful.

3.4 CLS API Resource Organization

Although the REST architecture specifies that URLs should uniquely identify system resources, it does not require or even suggest any particular way to name resources or organize them. One approach might arguably be no better than another if organization and naming were just used by devices and systems behind the scenes, as is the case when they are natively interoperable. However, achieving interoperability with APIs requires integration, involving software written by humans, for whom readability and logic matter. Resource trees are often used to graphically depict how resources are named and organized. Although some of the APIs that were explored here have a logically consistent resource tree structure, others were clearly developed incrementally over multiple version releases, as more features were added over time. Figure 3.1 through Figure 3.3 show examples of partial API resource trees that were encountered in this study, illustrating significant variation in structure, nomenclature, and complexity.

Table 3.1. Example of a Connected Lighting System API response allowing Cross-Origin Resource Sharing

Request

Method	Base URL	Headers
GET	/ems/api/org/sensor/v3/details/3	{ 'Hostname': [...], 'ApiKey': [...], 'Authorization': [...], 'ts': '1493240606352', 'Accept': 'Application/JSON', 'Content-Type': 'Application/JSON' }

Response

Status Code	Body	Headers
200 (OK)	{ 'name': 'Sensor37a117', 'id': '3', 'power': '0.59', 'lightLevel': '0', 'temperature': '62.52' }	{ 'Date': 'Wed, 26 Apr 2017 21:02:43 GMT', 'Server': 'Apache-Coyote/1.1', 'Connection': 'Keep-Alive',, 'Set-Cookie': [...], 'Content-Length': '96', 'Access-Control-Allow-Origin': '*', 'Access-Control-Allow-Methods': 'POST, GET, OPTIONS, DELETE, PUT', 'Access-Control-Allow-Headers': 'Hostname, ApiKey, Authorization, ts, Accept, Content-Type', 'Access-Control-Max-Age': '1000', 'Content-Type': 'application/json' }

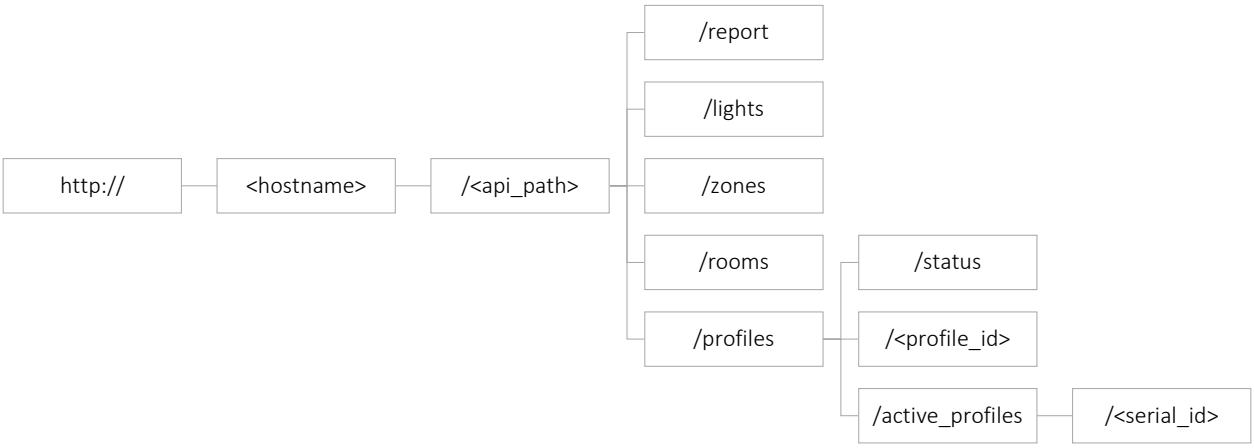


Figure 3.1. Connected lighting system API resource tree, example 1

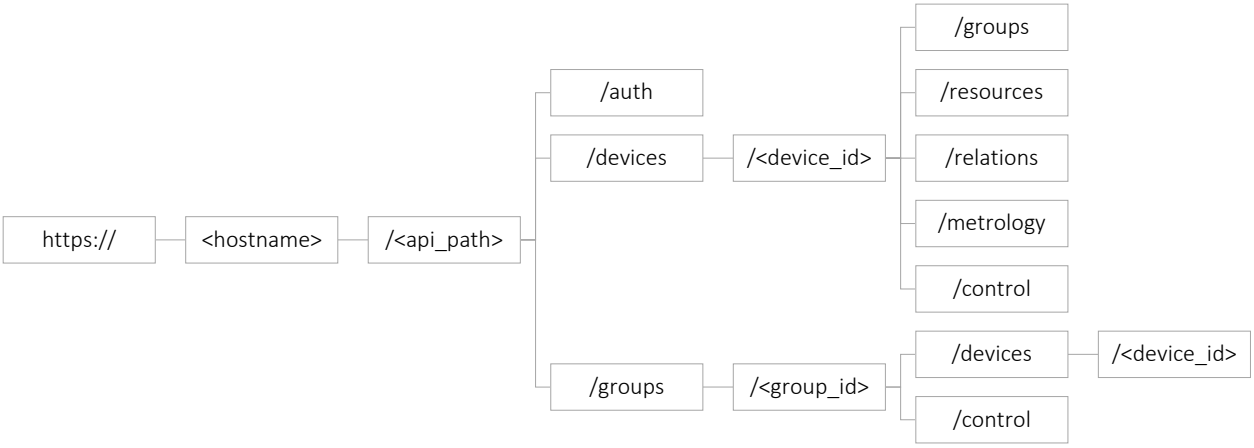


Figure 3.2. Connected lighting system API resource tree, example 2

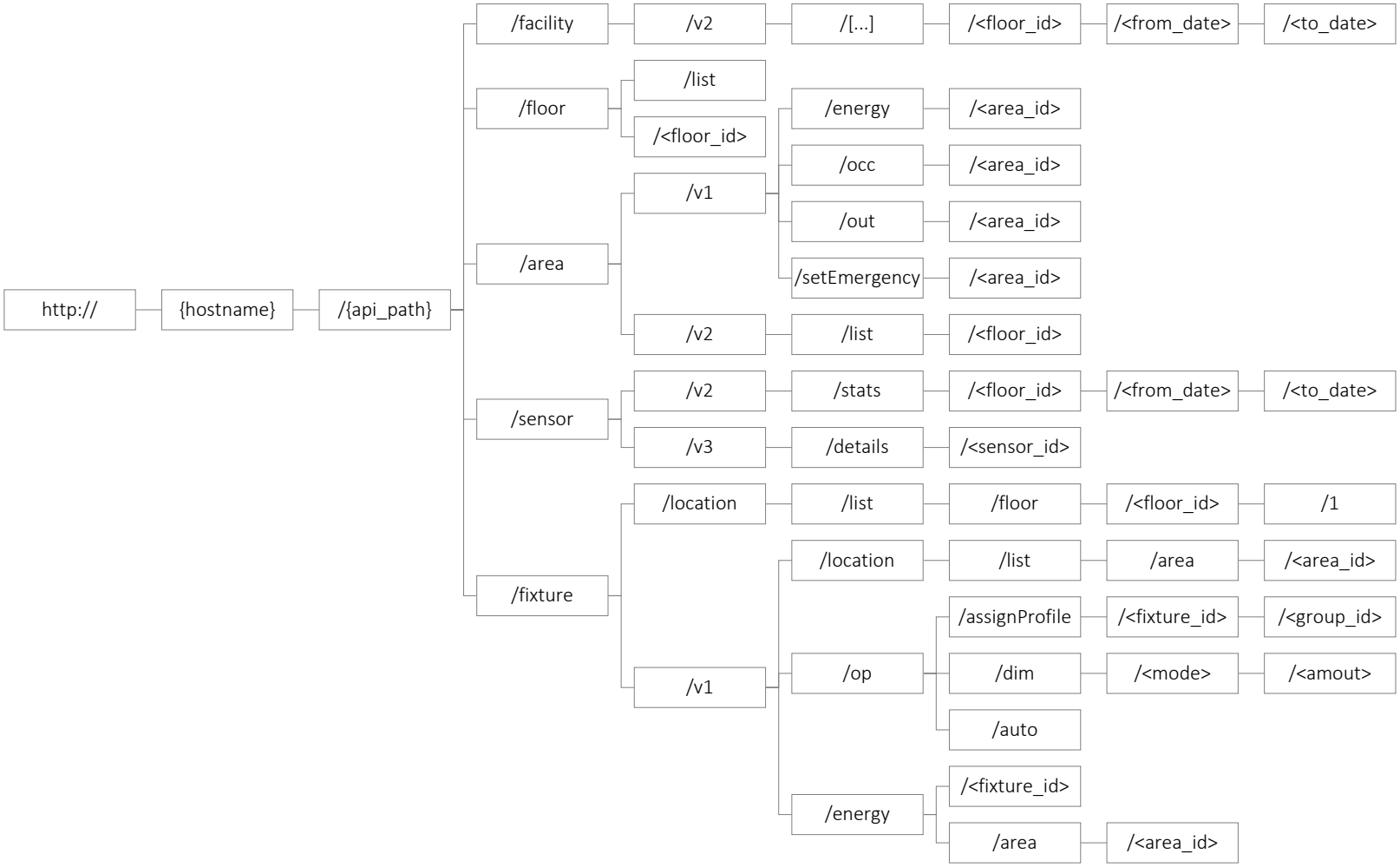


Figure 3.3. Connected lighting system API resource tree, example 3

One example of an attempt to define a common resource structure is shown in Figure 3.4. IoTivity uses the /oic namespace prefix to define a mechanism that results in the consistent organization of resources in the OCF ecosystem. Among core resources, /oic/res is used for resource discovery, /oic/p allows for platform-specific information to be discovered, and /oic/d exposes device properties. For device management, /oic/con allows for device-specific information to be configured, /oic/mnt can be used for maintenance and diagnostic purposes, and /oic/sec is used for security.

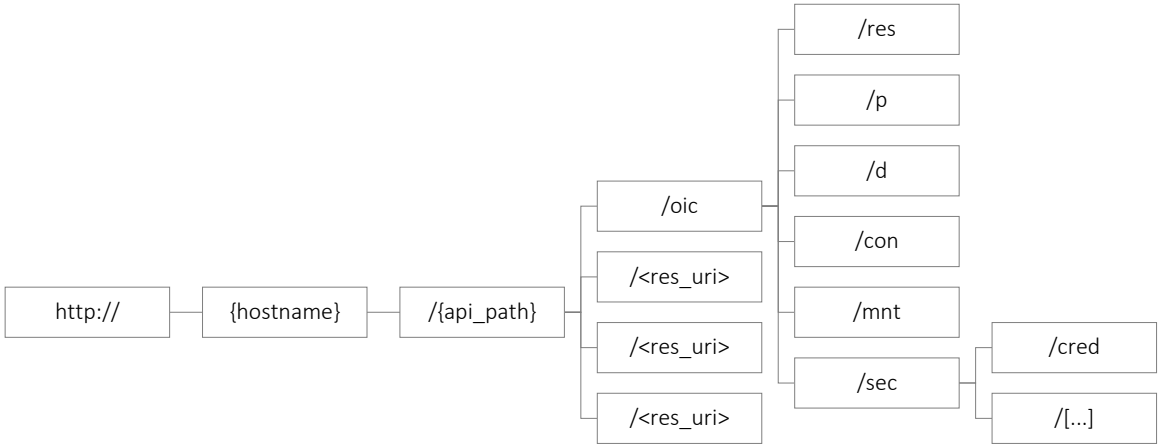


Figure 3.4. The IoTivity resource tree structure developed by the OCF

3.5 CLS API Data Models

As noted by the IETF, information models can, and generally should, specify relationships between objects; in turn, the contents of an information model should be used to delimit the functionality that can be included in a data model. Data models provide a structure for communicating information between devices and systems. They include rules that explain how to map managed objects onto lower-level protocol constructs. Well-defined and formatted models are essential to interoperability, as poor mappings can lead to misinterpretation of information and possibly to duplication (i.e., multiple models for essentially the same information). For developers, an ideal data model is human-readable, consistent, and intuitive. Although there is likely no perfect data model - "All models are wrong, but some are useful"[38] - and there is no well-honed approach or framework for evaluating the viability of a data model, it can be illustrative to examine some use-cases. A system integrator who desires to achieve some degree of interoperability between systems with heterogeneous APIs must infer an information model that suitably encompasses the myriad data models to be integrated, in order to effectively aggregate measurements or broadcast commands. Some of the challenges that this effort entails are revealed by examining Table 3.2 and Table 3.3, which show the results of API requests to two different outdoor CLS that expose parts of the data models for street lighting resources.

[38] Wikipedia: All models are wrong, wikipedia.org/wiki/All_models_are_wrong.

Table 3.2. Exposed CLS API resources, example 2. Note that in some instances, text that is not essential to the example has been removed and replaced with [….] to improve readability.

Request

Method	Resource URL	Parameters

GET	/reports/api/monitoring
	
	/* Returns an array of metering value descriptors for a given device.
	(not a comprehensive list of resources) */
		{
		“methodName”: “getDeviceMeteringValueDescriptors”,
		“controllerStrId”: “<controller_id>”,
		“idOnController”: “<device_id>”,
		“ser”: “json”
		}

Response

Status Code	Body
200 (OK)	[{'name': 'MainVoltage' , 'label': 'Mains voltage (V)' , 'type': 'float' , 'unit': 'V' , 'labelKey': 'db.meaning.mainvoltage.label' , [...] }, {'name': 'VoltageMax' , 'label': 'Voltage Max' , 'type': 'float' , 'unit': None , 'labelKey': 'db.meaning.voltagemax.label' , [...] }, {'name': 'VoltageMin' , 'label': 'Voltage Min' , 'type': 'float' , 'unit': None , 'labelKey': 'db.meaning.voltagemin.label' , [...] }, {'name': 'Current' , 'label': 'Mains current' , 'type': 'float' , 'unit': 'A' , 'labelKey': 'db.meaning.current.label' , [...] }, {'name': 'MeteredPower' , 'label': 'Metered power (W)' , 'type': 'float' , 'unit': 'W' , 'labelKey': 'db.meaning.meteredpower.label' , [...] }, {'name': 'Energy' , 'label': 'Lamp energy (kWH)' , 'type': 'float' , 'unit': 'kWh' , 'labelKey': 'db.meaning.energy.label' , [...] }, {'name': 'PowerFactor' , 'label': 'Power factor' , 'type': 'float' , 'unit': '' , 'labelKey': 'db.meaning.powerfactor.label' , [...] }, {'name': 'Frequency' , 'label': 'Frequency (Hz)' , 'type': 'float' , 'unit': 'Hz' , 'labelKey': 'db.meaning.frequency.label' , [...] }, {'name': 'Temperature' , 'label': 'Temperature' , 'type': 'float' , 'unit': '' , 'labelKey': 'db.meaning.temperature.label' , [...] }, {'name': 'LuxLevel' , 'label': 'Lux level (Lux)' , 'type': 'float' , 'unit': '' , 'labelKey': 'db.meaning.luxlevel.label' , [...] }, {'name': 'RunningHoursLamp' , 'label': 'Lamp burning hours' , 'type': 'float' , 'unit': 'h' , 'labelKey': 'db.meaning.runninghourslamp.label' , [...] }, {'name': 'UpTimeInSeconds' , 'label': 'Up time (sec)' , 'type': 'integer' , 'unit': None , 'labelKey': 'db.meaning.uptimeinseconds.label' , [...] }, {'name': 'supplyLossCount' , 'label': 'Supply losses' , 'type': 'int' , 'unit': None , 'labelKey': 'db.meaning.supplylosscount.label' , [...] }, {'name': 'PhotocellMode' , 'label': 'Photocell mode' , 'type': 'boolean' , 'unit': None , 'labelKey': 'db.meaning.photocellmode.label' , [...] }]

Table 3.3. Exposed connected lighting system API resources, example 1. Note that in some instances, text that is not essential to the example has been removed and replaced with [….] to improve readability.

Request

Method	Resource URL	Parameters

GET	/papi/v1.1/devices/<device_id>/resources
	/* Lists the latest resources of a given light fixture, mostly undocumented.
	Some values are ASCII strings and some base64 encoded. */
		{
		'Accept': '*/*',
		'Cookie: 'JSESSIONID=[...]'
		}

Response

Status Code	Body
200 (OK)	[{'timeMeasured': '2016-11-30 09:19:36.971', 'name': '/bin/address', 'value': '[...]'}, {'timeMeasured': '2016-11-30 09:16:06.0', 'name': '/bin/fw_info', 'value': '[...]'}, {'timeMeasured': '2016-10-13 18:27:19.0', 'name': '/bin/fw_ota_progress', 'value': '[...]'}, {'timeMeasured': '2016-11-30 13:51:14.0', 'name': '/bin/gps', 'value': '[...]'}, {'timeMeasured': '2016-11-30 13:51:14.0', 'name': '/bin/metrology', 'value': '[...]'}, {'timeMeasured': '2016-11-30 08:48:44.0', 'name': '/bin/net_stats', 'value': '[...]'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/I', 'value': '0.5887'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/I/inst', 'value': '0.5901'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/I/max', 'value': '0.6138'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/I/min', 'value': '0.034'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/P', 'value': '72.87'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/P/inst', 'value': '72.81'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/P/max', 'value': '75.88'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/P/min', 'value': '1.6'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/V', 'value': '124.51'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/V/inst', 'value': '124.29'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/V/max', 'value': '125.5'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/V/min', 'value': '122.91'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/ontime', 'value': '3060.46'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/pfact', 'value': '0.994'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/pfact/inst', 'value': '0.994'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/pfact/max', 'value': '0.995'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/pfact/min', 'value': '0.375'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/dev/totKwh', 'value': '235.942'}, {'timeMeasured': '2017-03-08 18:54:22.0', 'name': '/fw/curr/NanoLightingApplication/ver', 'value': '06.05.08.00043'}, {'timeMeasured': '2017-03-08 18:54:22.0', 'name': '/fw/curr/pwloss', 'value': '[...]'}, {'timeMeasured': '2017-03-08 18:54:22.0', 'name': '/fw/new/NanoLightingApplication/ver', 'value': '06.05.08.00043'}, {'timeMeasured': '2017-02-08 20:37:37.924', 'name': '/fw_ota_progress/download_status', 'value': '0'}, {'timeMeasured': '2017-02-08 20:37:37.924', 'name': '/fw_ota_progress/image_crc', 'value': '0'}, {'timeMeasured': '2017-02-08 20:37:37.924', 'name': '/fw_ota_progress/ota_progress', 'value': '0'}, {'timeMeasured': '2017-02-08 20:37:37.924', 'name': '/fw_ota_progress/ota_status', 'value': '0'}, {'timeMeasured': '2017-02-08 20:37:37.924', 'name': '/fw_ota_progress/upload_status', 'value': '0'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/gps/fix', 'value': '1'}, {'timeMeasured': '2016-10-13 17:29:22.0', 'name': '/gps/lat', 'value': '[...]'}, {'timeMeasured': '2016-10-13 17:29:22.0', 'name': '/gps/lng', 'value': '[...]'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/lt/0/ctr', 'value': '1'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/lt/0/dim', 'value': '100'}, {'timeMeasured': '2017-03-08 19:49:24.0', 'name': '/lt/ontime', 'value': '2323.44'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/frag_rx_errors', 'value': '0'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/frag_tx_errors', 'value': '0'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/ip_routed_up', 'value': '9142'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/ip_rx_bytes', 'value': '14513'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/ip_rx_count', 'value': '177'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/ip_rx_drop', 'value': '0'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/ip_tx_bytes', 'value': '28173'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/ip_tx_count', 'value': '256'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/mac_rx_bytes', 'value': '32042'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/mac_rx_count', 'value': '410'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/mac_rx_drop', 'value': '0'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/mac_security_drop', 'value': '0'}, {'timeMeasured': '2016-11-30 08:48:44.0', 'name': '/net_stats/mac_tx_buf_overflow', 'value': '0'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/mac_tx_buf_overflow', 'value': '0'}, {'timeMeasured': '2017-03-08 14:48:58.0', 'name': '/net_stats/mac_tx_bytes', 'value': '57985'},

```
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/mac_tx_cca_cnt'          , 'value': '562'          },
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/mac_tx_count'            , 'value': '613'          },
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/mac_tx_failed'           , 'value': '0'            },
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/mac_tx_failed_cca'       , 'value': '3'            },
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/mac_tx_retry'            , 'value': '60'           },
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/prssi'                   , 'value': '-69'          },
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/rpl_no_route'            , 'value': '0'            },
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/rpl_route_ld'            , 'value': '0'            },
  {'timeMeasured': '2017-03-08 14:48:58.0'  , 'name': '/net_stats/rpl_route_rcbc'          , 'value': '0'            },
  {'timeMeasured': '2017-03-07 22:49:40.0'  , 'name': '/nw/eripaddr'                       , 'value': '[...]'        },
  {'timeMeasured': '2017-03-07 22:49:40.0'  , 'name': '/nw/ipaddr'                        , 'value': '[...]'        },
  {'timeMeasured': '2017-03-07 22:49:40.0'  , 'name': '/nw/macaddr'                       , 'value': '[...]'        },
  {'timeMeasured': '2017-03-07 22:49:40.0'  , 'name': '/nw/pipaddr'                       , 'value': '[...]'        },
  {'timeMeasured': '2017-03-07 22:49:40.0'  , 'name': '/nw/sipaddr'                       , 'value': '[...]'        }
]
```

The highlighted rows in Table 3.2 and Table 3.3 show the data model for the light-output setting of a lighting device. Note that in the first example, although the parameter label "LuxLevel" suggests that light output is specified in lux, and the data type specifies a floating-point representation for the light-output setting, no parameter unit is actually shown. In the second example, no data type representation or unit is revealed. Further, the default parameter value of "100" leaves open the possibility that the data representation is absolute (e.g., in lux or foot-candles) or relative (e.g., percent of maximum). The parameter label "dim" suggests the latter.

Although API calls only expose a fragment of the underlying data models, these examples reveal perhaps the most significant IoT challenge: the coexistence of multiple, often incompatible, data models. Custom data models are not always thoughtfully designed from a user perspective, or self-consistent, or even well documented. Consequently, it is often incumbent on the system integrator to figure out what a resource represents, and what its data model defines (e.g., measurement units, data type). Although inconsistencies might be resolved by algorithms that, for example, convert lux to foot-candles or translate from a relative representation of light output to an absolute representation, these converters and translators must be checked and possibly modified each time an API is updated, and the approach for implementing and managing them must be capable of scaling as necessary if/as the size of an integrated CLS grows and/or more CLS are integrated.

As noted in the previous discussion of resource tree organization, some industry consortia are developing and publishing open-source approaches to and resources for interoperability challenges.

Table 3.4 and Table 3.5 show examples of data models published by two such consortia. The OCF manages an open-source library of data models that are made available via a web-based tool it refers to as oneIoTa.[39] Developers are encouraged to use existing, and share newly created, data models for IoT devices and device resources. The tool allows for complex devices and systems to be defined as collections of simpler devices and resources.

Table 3.4 shows a few of the lighting-related contributions that had been made at the time of this publication. Notably, they include lighting-device resources but not any specific lighting devices (e.g., street lighting device, office lighting device).

FIWARE also manages a library of data models that are open-sourced[40] under a Creative Commons license and made available via a web interface. FIWARE is open to library contributions that meet its guidelines.[41] Table 3.5 shows portions (not including optional fields) of the data models for all four available (street) lighting resources.[42]

[39] oneIoTa, oneiota.org.
[40] GitHub: Fiware/dataModels, github.com/Fiware/dataModels.
[41] FIWARE Datamodels: Data Models Guidelines, fiware-datamodels.readthedocs.io/en/latest/guidelines/.
[42] FIWARE Datamodels: Street Lighting Data Models, fiware-datamodels.readthedocs.io/en/latest/StreetLighting/doc/introduction.

Table 3.4. oneIoTa data model definitions for light resources, as available in June 2017

oic.r.light.brightness

```
{
  "id": "http://openinterconnect.org/iotdatamodels/schemas/oic.r.light.brightness.json#",
  "$schema": "http://json-schema.org/draft-04/schema#",
  "description" : "Copyright (c) 2016 Open Connectivity Foundation, Inc. All rights reserved.",
  "title": "Brightness",
  "definitions": {
    "oic.r.light.brightness": {
      "type": "object",
      "properties": {
        "brightness": {
          "type": "integer",
          "description": "Quantized representation in the range 0-100 of the current sensed or set value for Brightness",
          "minimum": 0,
          "maximum": 100
        }
      }
    }
  },
  "type": "object",
  "allOf": [
    {"$ref": "oic.core.json#/definitions/oic.core"},
    {"$ref": "oic.baseResource.json#/definitions/oic.r.baseresource"},
    {"$ref": "#/definitions/oic.r.light.brightness"}
  ],
  "required": [ "brightness" ]
}
```

oic.r.light.dimming

```
{
  "id": "http://openinterconnect.org/iotdatamodels/schemas/oic.r.light.dimming.json#",
  "$schema": "http://json-schema.org/draft-04/schema#",
  "description" : "Copyright (c) 2016 Open Connectivity Foundation, Inc. All rights reserved.",
  "title": "Dimming",
  "definitions": {
    "oic.r.light.dimming": {
      "type": "object",
      "properties": {
        "dimmingSetting":  {
          "type": "integer",
          "description": "Current dimming value"
        }
      }
    }
  },
  "type": "object",
  "allOf": [
    {"$ref": "oic.core.json#/definitions/oic.core"},
    {"$ref": "oic.baseResource.json#/definitions/oic.r.baseresource"},
    {"$ref": "#/definitions/oic.r.light.dimming"}
  ],
  "required": ["dimmingSetting"]
}
```

oic.r.light.rampTime

```
{
  "id": "http://openinterconnect.org/iotdatamodels/schemas/oic.r.light.rampTime.json#",
  "$schema": "http://json-schema.org/draft-04/schema#",
  "description" : "Copyright (c) 2016 Open Connectivity Foundation, Inc. All rights reserved.",
  "title": "Ramp Time",
  "definitions": {
    "oic.r.light.ramptime": {
      "type": "object",
      "properties": {
```

```
        "rampTime": {
          "type": "integer",
          "description": "Actual speed of changing between 2 dimming values"
        }
      }
    }
  },
  "type": "object",
  "allOf": [
    {"$ref": "oic.core.json#/definitions/oic.core"},
    {"$ref": "oic.baseResource.json#/definitions/oic.r.baseresource"},
    {"$ref": "#/definitions/oic.r.light.ramptime"}
  ],
  "required": ["rampTime"]
}
```

Table 3.5. FIWARE data model definitions for street lighting resources

StreetlightModel

```
{
  "id": "streetlightmodel:TubularNumana:ASR42CG:HPS:100",          // Entity's unique identifier
  "type": "StreetlightModel",                                      // Must be equal to StreetlightModel
  "name": "Tubular Numana 6M - ASR42CG - Son-T 100",               // Name of the streetlight model
  "columnModelName": "01 TUBULAR P/T 6M NUMANA",                   // Name of the column's model
  "columnColor": "green",                                          // Column's painting color (according to the W3C std color keywords)
  "lanternModelName": "ASR42CG",                                   // Name of the lantern's model
  "lanternManufacturerName": "Indal WRTL",                         // Name of the lantern's manufacturer
  "lampModelName": "SON-T",                                        // Name of the lamp's model
  "lampBrandName": "Philips",                                      // Name of the lamp's brand
  "lampTechnology": "HPS",                                         // Technology used by the lamp (allowed values: [LED,LPS,HPS])
  "powerConsumption": 100,                                         // Nominal power consumption by the lamp (W)
  "colorTemperature": 3000,                                        // Correlated color temperature of the lamp (K)
  "colorRenderingIndex": 25,                                       // Color rendering index of the lamp
  "luminousFlux": 2300,                                            // Maximum light output which can be provided by the lamp
  "category": ["postTop"]                                          // Type of asset (allowed values:
[postTop,bollard,lamppost,lightTower,flashingBeacon,sideEntry,...])
}
```

Streetlight

```
{
  "id": "streetlight:guadalajara:4567",                            // Entity's unique identifier
  "type": "Streetlight",                                           // Must be equal to Streetlight
  "location": {                                                    // Streetlight location represented using the GeoJSON[43] point format
    "type": "Point",
    "coordinates": [  -3.164485591715449, 40.62785133667262 ]
  },
  "areaServed": "Roundabouts city entrance",                       // High level area to which this streetlight belongs to
  "status": "ok",                                                  // Overall status of this streetlight (allowed values:
[ok,defectiveLamp,columnIssue,brokenLatern])
  "refStreetlightGroup": "streetlightgroup:G345",                  // Reference to a StreetlightGroup entity, if belongs to any
  "refStreetlightModel": "streetlightmodel:STEEL_Tubular_10m",     // Reference to a StreetlightModel entity
  "circuit": "C-456-A467",                                         // Identifier of the circuit to which this streetlight connects and gets power from
  "lanternHeight": 10,                                             // Lantern's height (m)
  "locationCategory" : "centralIsland",                            // Allowed values: [facade,sidewalk,pedestrianPath, road,playground,park,garden,bridge,...]
  "powerState": "off",                                             // Streetlight's power state (allowed values: [on,off,low,bootingUp])
  "controllingMethod": "individual",                               // Method used to control this streetlight (allowed values: [group,individual])
  "dateLastLampChange": "2016-07-08T08:02:21.753Z"                 // Timestamp of the last change of lamp made (datetime type)
}
```

StreetlightGroup

```
{
  "id": "streetlightgroup:mycity:A12",                             // Entity's unique identifier
  "type": "StreetlightGroup",                                      // Must be equal to StreetlightGroup
  "location": {                                                    // Locations of the streetlights in the group, represented using the GeoJSON multigeometry
format
    "type": "MultiLineString",
    "coordinates": [
      [ [100.0, 0.0], [101.0, 1.0] ],
      [ [102.0, 2.0], [103.0, 3.0] ]
    ]
  },
  "powerStatus": "on",                                             // StreetlightGroup power state (allowed values: [on,off,low,bootingUp])
  "areaServed": "Calle Comercial Centro",                          // High level area to which this streetlight group belongs to
  "circuitId": "C-456-A467",                                       // Identifier of the circuit to which these streetlights connect and get power from
  "dateLastSwitchingOn":  "2016-07-07T19:59:06.618Z",              // Timestamp of the last switching on
  "dateLastSwitchingOff": "2016-07-07T07:59:06.618Z",              // Timestamp of the last switching off
  "refStreetlightCabinetController": "cabinetcontroller:CC45A34",  // Reference to StreetlightCabinetController(s) entity(ies)
  "switchingOnHours": [                                            // Switching on hours, structure used to set special schedules for certain dates
```

[43] Internet Engineering Task Force: The GeoJSON Format draft-ietf-geojson-03, tools.ietf.org/html/draft-ietf-geojson-03.

```
    {
      "from" :  "--11-30",
      "to" :    "--01-07",
      "hours" : "Mo,Su 16:00-02:00",
      "description": "Christmas"
    }
  ]
}
```

StreetlightControlCabinet

```
{
  "id": "streetlightcontrolcabinet:A45HGJK",                    // Entity's unique identifier
  "type": "StreetlightControlCabinet",                          // Must be equal to StreetlightControlCabinet
  "location": {                                                 // Control cabinet location represented using the GeoJSON point format
    "type": "Point",
    "coordinates": [  -3.164485591715449, 40.62785133667262 ]
  },
  "cupboardMadeOf": "plastic",                                  // Material the cabinet's cupboard is made of (allowed values: [plastic,metal,concrete,other])
  "brandName": "Siemens",                                       // Name of the cabinet's brand
  "modelName": "Simatic S7 1200",                               // Name of the cabinet's model
  "refStreetlightGroup": ["streetlightgroup:BG678",             // Reference to StreetlightGroup entities controlled
                          "streetlightgroup:789"  ],
  "compliantWith": ["IP54"],                                    // List of standards to which the cabinet controlle is compliant with
  "dateLastProgramming": "2016-07-08",                          // Date at which there was a programming operation over the cabinet
  "maximumPowerAvailable": 10,                                  // The maximum power available for the circuits controlled by this cabinet (kW)
  "energyConsumed": 162456,                                     // Energy consumed by the circuits controlled since metering started (kWh)
  "dateMeteringStarted": "2013-07-07",                          // Timestamp of the starting date for metering energy consumed
  "lastMeterReading": 161237,                                   // Value of the last reading obtained from the energy metering system (kWh)
  "meterReadingPeriod": 60,                                     // The periodicity of the energy meter reporting (days)
  "intensity": {                                                // Electric intensity per alterning current phase (Europe: R,S,T) (A)
     "R": 20.1,
     "S": 14.4,
     "T": 22
  },
  "reactivePower": {                                            // Reactive power per alternating current phases (kVArh)
    "R": 45,
    "S": 43.5,
    "T": 42
  }
}
```

The highlighted rows in Table 3.4 and Table 3.5 show, once again, the data model for either (1) a lighting resource that allows the light output to be set, or (2) the light-output setting of a lighting device. Note that in the first example, both "brightness" and "dimming" appear to specify parameters with an integer data representation and a 0-to-100 relative scale. The "brightness" parameter specifies a 0-to-100 scale, and although no scale is specified for "dimming," the parameter name itself typically refers to a relative data representation. This presumption, further substantiated by the lack of a specified unit, seemingly leaves no means for differentiating between the two parameters. In the second example, the "luminous flux" parameter does not specify a scale, unit, or data representation. The parameter is described as representing "maximum light output," perhaps in units of lumens, which suggests that it defines the maximum rated light output, rather than the current or targeted light output state. The "powerState" parameter specifies four allowed states: on, off, low, and booting up. Together, these parameters suggest that the FIWARE data models can only be used to represent and control bi-level streetlights, and not fully dimmable streetlights, which are now common with LED technology.

Although an API provides a defined mechanism for integrating a given system with other systems, it doesn't solve all issues associated with the heterogeneity of devices, resources, and services. As highlighted in the above examples, APIs can and do use arbitrary data models. In lieu of a common programming abstraction layer, the work of reconciling how multiple systems represent data via their APIs is the responsibility of the system integrator, who may then need to juggle varying formats, structures, syntaxes, and semantics in an attempt to pursue integration use-cases and other needs.

4 Interoperability Use-Cases

This study initially intended to compare CLS APIs based on the lessons learned from integrating multiple CLS into the CLTB web-based interoperability platform, and then use the platform as a means for characterizing the CLS APIs through the implementation of one or more use-cases. As the study became further defined and various options for use-cases were identified, it was decided that the v1 interoperability platform was not suitable for exploring the intended use-cases fairly and efficiently. Modifications that might improve its feasibility for interoperability testing were identified, including a complete update of the backend architecture and the addition of a structured database based on a common information model to facilitate low-level manipulation of the data and improve the experience for both the system integrator and the user. A project was initiated to develop a v2 interoperability platform that implemented these modifications. However, in the interests of not delaying further investigation into CLS APIs and the publication of this study, a strategy to develop Python integration code to implement illustrative use-cases was identified and pursued. Two use-cases were explored, as described below.

4.1 Use-Case 1: Energy Data Reporting

The first use-case consisted of polling and aggregating energy data from all six CLS in real time, something a user could be interested in doing for data logging, analysis, and visualization purposes as well as subsequent human review and consideration. This example showcases two hurdles directly associated with limited interoperability. First, even in the case of seemingly simple attributes such as energy consumption, data models can be different. Energy data can be and, in practice, are delivered in many different ways (e.g., measurement unit, accumulation period) and with different accuracy and resolution − which are often unspecified or undocumented. Second, because not all systems provide access through the API to historical data, this use-case requires the system integrator to

query the system in real time and log energy data, which requires some dedicated computing and storage resources.

Table 4.1 and Table 4.2 show examples of API requests for historical and most recent energy data, respectively. In the first example, a full day of data is returned, upon request, in watt-hours - aggregated across the whole facility and presented in timestamped intervals. The second example shows the response of the most recent accumulation of kilowatt-hours consumed by a single lighting device from day one up to the associated timestamp.

Overcoming these barriers requires an adaptation to the architecture of each API. In the absence of publish/subscribe solutions or historical data access, propagating updates to the user requires actively pulling data at some frequency that may or may not be aligned with the data rate of the system − which is, once again, often unspecified or undocumented. Once all data are pulled and aggregated, using them requires some data mapping; in the absence of a common data model, system integrators need to define their own internal data model or otherwise normalize the data in a way that allows them to integrate data from the multiple sources and present aggregated information. For this use-case, it makes sense to normalize to watt-hours consumed per 15-minute intervals, to minimize the amount of data manipulation while keeping a maximum time resolution. Figure 4.1 shows the data aggregated from each individual CLS over a period of 200 hours. Each API request was scheduled using simple crontab[44] jobs.

[44] Wikipedia: Cron, wikipedia.org/wiki/Cron.

Table 4.1. Connected lighting system API request for historical energy data

Request

Method	Resource URL	Headers	Payload

GET	/api/v1/report.json
	
	/* The report command allows third-party systems to easily query for aggregated data at any level, and for a specified range of dates. All usage data is presented in 15m intervals, energy in Wh. */
		{
		'Authorization': '<api_token>'
		}
			{
			'start': '2017-04-07',
			'end': '2017-04-08'
			}

Response

Status Code	Body

200 (OK)	{
	'header': {'timestamp': '2017-04-07T15:24:49-07:00', 'end': '2017-04-08', 'start': '2017-04-07'},
	'usage_facts': [
	{'sensor1_sec': 0, 'wh_merged': 1.0 , 'remote_sec': 0, 'interval_start': 1491550200, 'total_sec': 1800, 'active_sec': 0, 'sensor0_sec': 0},
	{'sensor1_sec': 0, 'wh_merged': 5.0 , 'remote_sec': 0, 'interval_start': 1491554700, 'total_sec': 1800, 'active_sec': 378, 'sensor0_sec': 183},
	{'sensor1_sec': 0, 'wh_merged': 0.0 , 'remote_sec': 0, 'interval_start': 1491555600, 'total_sec': 1800, 'active_sec': 0, 'sensor0_sec': 0},
	{'sensor1_sec': 0, 'wh_merged': 2.0 , 'remote_sec': 0, 'interval_start': 1491556500, 'total_sec': 1800, 'active_sec': 0, 'sensor0_sec': 0},
	{'sensor1_sec': 0, 'wh_merged': 4.0 , 'remote_sec': 0, 'interval_start': 1491558300, 'total_sec': 1800, 'active_sec': 314, 'sensor0_sec': 139},
	{'sensor1_sec': 0, 'wh_merged': 0.0 , 'remote_sec': 0, 'interval_start': 1491560100, 'total_sec': 1800, 'active_sec': 0, 'sensor0_sec': 0},
	{'sensor1_sec': 0, 'wh_merged': 3.0 , 'remote_sec': 0, 'interval_start': 1491561000, 'total_sec': 1800, 'active_sec': 228, 'sensor0_sec': 60},
	{'sensor1_sec': 0, 'wh_merged': 2.0 , 'remote_sec': 0, 'interval_start': 1491561900, 'total_sec': 1800, 'active_sec': 0, 'sensor0_sec': 0},
	{'sensor1_sec': 0, 'wh_merged': 1.166667, 'remote_sec': 0, 'interval_start': 1491566400, 'total_sec': 1800, 'active_sec': 112, 'sensor0_sec': 89},
	{'sensor1_sec': 0, 'wh_merged': 3.833333, 'remote_sec': 0, 'interval_start': 1491567300, 'total_sec': 1800, 'active_sec': 216, 'sensor0_sec': 66},
	{'sensor1_sec': 0, 'wh_merged': 4.0 , 'remote_sec': 0, 'interval_start': 1491571800, 'total_sec': 1800, 'active_sec': 186, 'sensor0_sec': 113},
	[...]
	{'sensor1_sec': 0, 'wh_merged': 1.0 , 'remote_sec': 0, 'interval_start': 1491603300, 'total_sec': 1800, 'active_sec': 0, 'sensor0_sec': 0}
	]
	}

Table 4.2. Connected lighting system API request for most recent energy data

Request

Method	Resource URL	Headers	Payload

GET	/papi/v1.1/devices/<device_id>/metrology
	/* Returns device latest metrology values. All values are base64 encoded. Energy is reported as total cumulative energy consummed by the device in kWh. */
		{
		'Content-Type': 'application/json'
		}	

Response

Status Code	Body

200 (OK)	{
	'status': 'SUCCESS',
	'transactionId': '1018102',
	'deviceId': '<device_id>'
	'attributes': [
	{'timeMeasured': '1491605872820', 'name': 'averageVoltage', 'value': 'MTI0LjY1' },
	{'timeMeasured': '1491605872820', 'name': 'minVoltage', 'value': 'MTIwLjQ2' },
	{'timeMeasured': '1491605872820', 'name': 'minPowerFactor', 'value': 'MC4w' },
	{'timeMeasured': '1491605872820', 'name': 'instantaneousCurrent', 'value': 'MC4wMzUz' },
	{'timeMeasured': '1491605872820', 'name': 'maxVoltage', 'value': 'MTI3LjM3' },
	{'timeMeasured': '1491605872820', 'name': 'maxPower', 'value': 'NzYuMDQ=' },
	{'timeMeasured': '1491605872820', 'name': 'lightOnTime', 'value': 'Mjc3MS42OQ==' },
	{'timeMeasured': '1491605872820', 'name': 'minPower', 'value': 'MS41OQ==' },
	{'timeMeasured': '1491605872820', 'name': 'lampDimLevel', 'value': 'MTAw' },
	{'timeMeasured': '1491605872820', 'name': 'averagePower', 'value': 'MS42NA==' },
	{'timeMeasured': '1491605872820', 'name': 'averageCurrent', 'value': 'MC4wMzQx' },
	{'timeMeasured': '1491605872820', 'name': 'maxPowerFactor', 'value': 'MC45OTU=' },
	{'timeMeasured': '1491605872820', 'name': 'averagePowerFactor', 'value': 'MC4zODQ=' },
	{'timeMeasured': '1491605872820', 'name': 'lampOnOffStatus', 'value': 'MA==' },
	{'timeMeasured': '1491605872820', 'name': 'instantaneousPower', 'value': 'MS42Mg==' },
	{'timeMeasured': '1491605872820', 'name': 'cumulativeEnergyReading', 'value': 'MjQ4Ljc4MjQ=' }, // 'MjQ4Ljc4MjQ' --base64decoding-> '248.7824'
	{'timeMeasured': '1491605872820', 'name': 'instantaneousPowerFactor', 'value': 'MC4zODM=' },
	{'timeMeasured': '1491605872820', 'name': 'deviceOnTime', 'value': 'Mzc4OC41Ng==' },
	{'timeMeasured': '1491605872820', 'name': 'minCurrent', 'value': 'MC4wMjg4' },
	{'timeMeasured': '1491605872820', 'name': 'instantaneousVoltage', 'value': 'MTI0LjY=' },
	{'timeMeasured': '1491605872820', 'name': 'maxCurrent', 'value': 'MC42MTM4' }
	],
	}

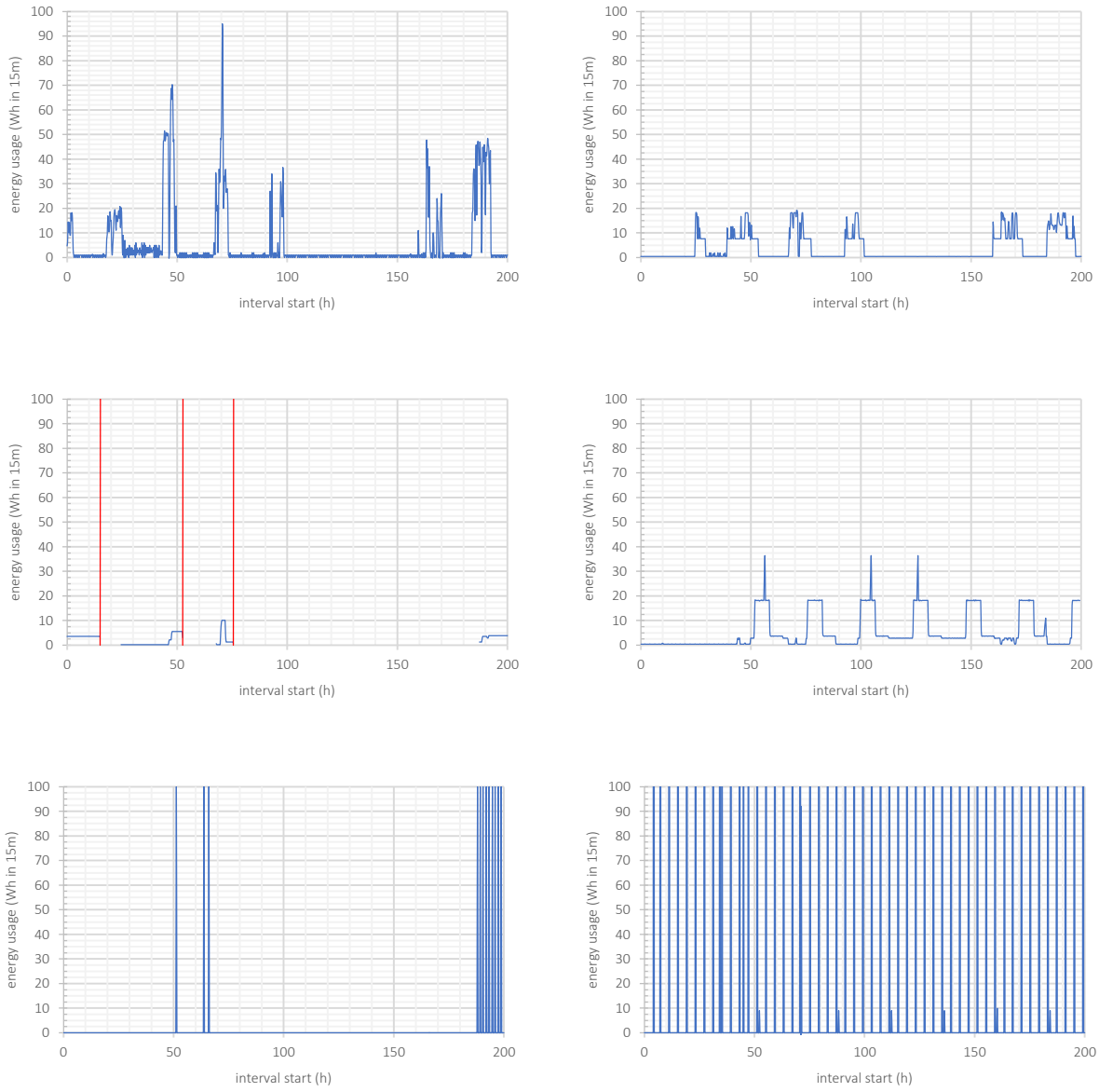


Figure 4.1. Energy usage per 15-minute interval for each of the six CLS over a period of 200 hours. Red vertical lines indicate a 15-minute-interval data point that was not reported due to network or other issues.

As mentioned, a certain amount of data conversion and post-processing, involving conservative interpolation and resampling, was done in order to implement the common 15-minute interval watt-hour energy-usage data model, and to align those intervals with one another. The CLS system whose performance is shown in the upper left of Figure 4.1 consisted of two luminaires with an occupancy-sensing control strategy implemented. The upper-right graph shows the performance of three luminaires implementing a combination of schedule-based control, occupancy sensing, and daylight compensation. The middle left graph shows the performance of a CLS consisting of three luminaires with only manual control and an early development gateway with limited error handling, which resulted in random disconnects of the API server (red lines) that required a manual reboot. Further,

this CLS only reports its current power status, so to log energy data in 15-minute intervals, a power reading was requested for each fixture every 10 seconds, and power was integrated every 15 minutes using the composite trapezoidal rule with linear interpolation. The middle right plot shows the energy consumption of a single-fixture system under the control of varying schedules across the duration of the test. And finally, the bottom two graphs show the energy consumption of two single-fixture systems, manually controlled (on and off on the left, and always-on on the right). Their API only reports energy usage in cumulated kilowatt-hours since commissioning, and the graphs were obtained by subtracting each reading from the previous one, and aligning and summing the results within the proper interval period. These two plots do not appear to represent the actual behavior of the two CLS, because of limited reporting resolution and a low power draw relative to the 15-minute interval. Rather than depicting a constant level of energy consumption that is consistent with being on at a steady power level, they show zero consumption until a new minimum resolution increment is reached, which then results in a spike. Using additional post-processing, such as a moving average or low-pass filter, provides a more realistic representation, shown by the green lines.

Figure 4.2 shows the aggregation of energy data for all CLS. All resampling and post-processing calculations were done conservatively and in a manner that could be fully automated. The total energy consumed over the 200-hour period is 36.4 kWh (ca. 182 W average power draw), with a peak of 152.4 Wh/15 min (ca. 610 W average power draw) and a low of 19.4 Wh/15 min (ca. 78 W average power draw).

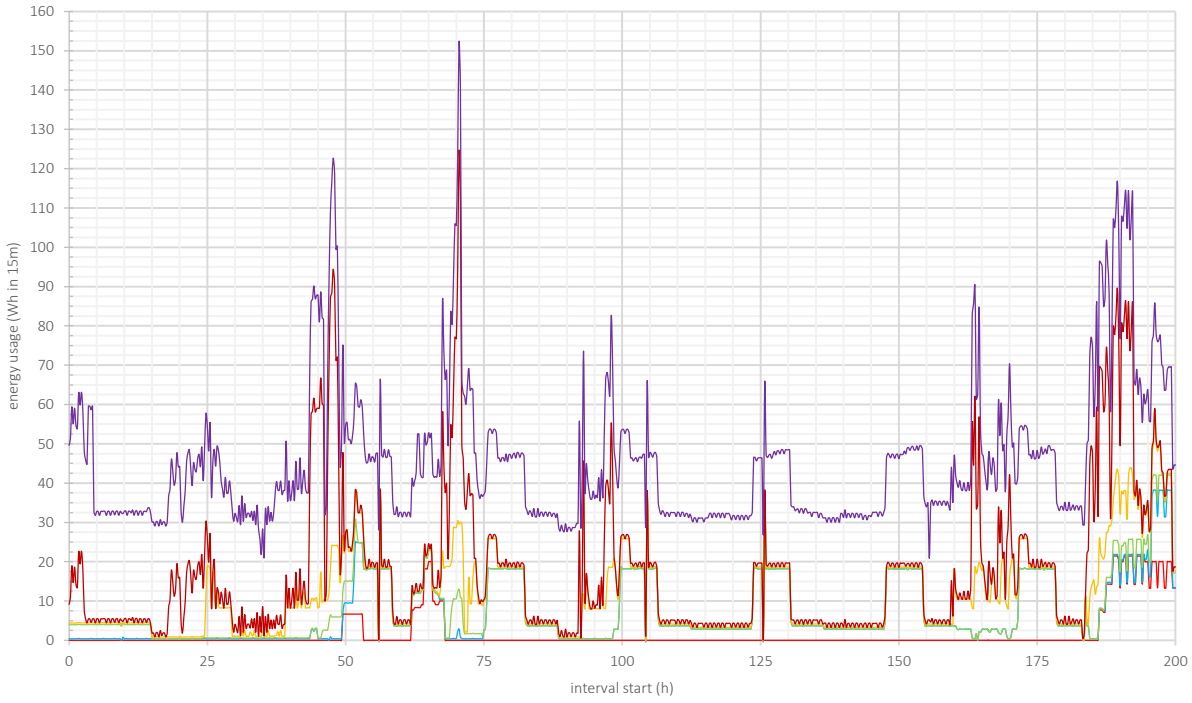


Figure 4.2. Energy usage per 15-minute interval for each of the six CLS over a period of 200 hours, aggregated and presented in a stacked format to show the cumulative consumption.

Although energy data aggregation through APIs is clearly possible, merging heterogeneous data with different levels of accuracy and resolution − both of which were unspecified in the API

documentation of every CLS in this study − clearly shows the limitations of interoperability as facilitated by APIs. First, the diversity of API architectures and energy data models required a significant amount of system integration work that required human, computing, and network bandwidth resources. Secondly, aggregating reported energy data with different overlapping and unsynchronized accumulation periods can mask actual behavior and result in misconceptions, as the energy performance of systems with the higher accuracy and resolution is lost in the noise of the lower-quality data.

4.2 Use-Case 2: Broadcasting a Lighting Command

The second use-case consisted of broadcasting a uniform lighting control command to every luminaire in all six CLS, as might be done in emergency and/or manual override scenarios. A variety of API features were used to simultaneously turn all luminaires on to their maximum output level in a minimum amount of time, including group commands, dynamic discovery, emergency modes, manual override, and software tools such as coroutine[45] networking libraries that enabled the creation of parallel HTTP requests.

Only one out of the six CLS implemented a dedicated API call for emergency situations that allowed setting the relative light output of all luminaires to 100% via a single request. For the others, the best action was to define an "emergency" group containing all luminaires. However, not all systems implemented the option to group fixtures together, and some had limitations on the creation of those groups; in some CLS, luminaires could only be assigned to a single group; in others, groups could not partially overlap (i.e., some luminaires that were in one group could also belong to a fully overlapped subgroup, but the subgroup could not contain luminaires from outside the main group). Hence, the creation of an emergency group can limit the ability to implement other control strategies in specific areas during normal operation. Among CLS investigated in this study, three out of six enabled the user to define a group that contained all luminaires, as well as smaller subgroups, and control both through the API. For the remaining systems, implementing this feature required dynamic discovery and broadcast commands or multiple individual commands, thereby requiring several HTTP requests to turn all lights on. One of the six CLS did not at the time have any broadcast capability, or the ability to group luminaires and change the light output for all luminaires in the group; rather, it required one API call per luminaire to change the light output of the entire CLS.

Table 4.3, Table 4.4, and Table 4.5 show examples of requests and responses for the API methods used to implement this use-case.

[45] Wikipedia: Coroutine, wikipedia.org/wiki/Coroutine.

Table 4.3. Connected lighting system API, emergency mode example

Request

Method	Resource URL	Headers	Payload

POST	/ems/api/org/area/v1/setEmergency/<area_id>
	/* During an emergency, this command automatically sets the lighting level of all fixtures in the area to the maximum level of 100%, so the area is entirely lit up. The response is success or failure. */
		{
		'Hostname': '<host_ip>',
		'ApiKey': <usr>,
		'Authorization': 'sha1(<usr><token><ts>)',
		'ts': '<ts>',
		'Accept': 'Application/JSON',
		'Content-Type': 'Application/JSON'
		}
			{
			'time': '<emergency_timeout>'
			}

Response

Status Code	Body

200 (OK)	{
	'status': '0'
	}

Table 4.4. Connected lighting system API, group command (via profile activation) example

Request

Method	Resource URL	Headers	Payload

POST	/api/v1/profiles/active_profiles.json
	/* Push a specified profile. */
		{
		'Authorization': '<api_token>'
		}
			{
			'profile: '<emergency_profile_id>',
			'expiry': 'fixed' or 'permanent',
			'duration': '<minutes>' (if fixed expiry)
			}

Response

Status Code	Body
200 (OK)	None

Table 4.5. Connected lighting system API, dynamic discovery and manual override example

Request

Method	Resource URL	Headers	Payload

GET	/reports/api/servlet/SLVAssetAPI
	/*
	Return an array of devices for the given geozone.
	*/
			{
			'methodName':'getGeoZoneDevices',
			'geoZoneId':'<zone_id>',
			'recurse':'True',
			'ser':'json'
			}

Response

Status Code	Body

200 (OK)	[
	{
	'categoryStrId': 'controllerdevice',
	'name': 'PNNL Lab Controller',
	'geoZoneNamesPath': 'PNNL Lab Portland',
	'id': [...],
	'controllerStrId': 'AP_PNNL',
	'geoZoneId': [...],
	[...]
	},
	{
	'categoryStrId': 'streetlight',
	'name': 'SELC-1D2F06',
	'geoZoneNamesPath': 'PNNL Lab Portland',
	'idOnController': 'SELC-1D2F06',
	'id': [...],
	'controllerStrId': 'AP_PNNL',
	'geoZoneId': [...],
	[...]
	},
	{
	'categoryStrId': 'streetlight',
	'name': 'SELC-1D2EFC',
	'geoZoneNamesPath': 'PNNL Lab Portland',
	'idOnController': 'SELC-1D2EFC',
	'id': [...],
	'controllerStrId': 'AP_PNNL',
	'geoZoneId': [...],
	[...]
	}
	]

Request

Method	Resource URL	Headers	Payload

POST	/reports/api/servlet/SLVDimmingAPI
	/*
	Update the dimming levels for the given
	streetlights.
	*/
			{
			'methodName':'setDimmingLevels',
			'controllerStrId": <controller_array>,
			'idOnController": <streetlight_array>,
			'dimmingLevel': <dimminglevel_array>,
			'ser': 'json'
			}

Response

Status Code	Body

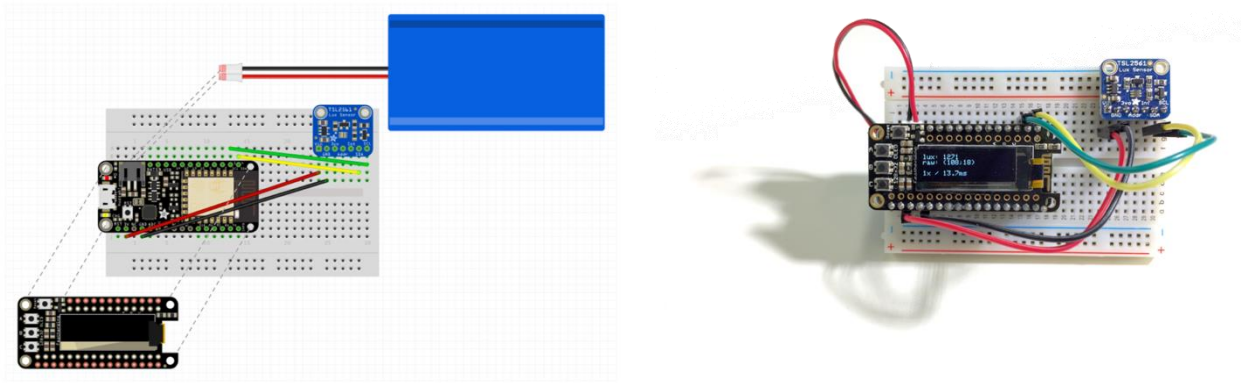
200 (OK)	{
	‘errorCode’: 0,
	‘status’: null,
	‘value’: [‘OK’,‘OK’],
	[...]
	}

One challenge a system integrator might encounter when implementing this use-case is the need to send multiple HTTP requests to several CLS servers in a minimum amount of time. Although the simplest approach is to send them sequentially and wait for each response before moving to the next one, doing so might not be compatible with the use-case latency needs. To minimize the time (and cost) required to send multiple HTTP requests, one can implement a protocol that allows those requests that can execute concurrently to do so. This can be accomplished by using requests that are non-blocking and asynchronous (i.e., that return and let work happen in the background before the response triggers some future action in the program). The ability to launch new requests while waiting for previous requests to respond can result in a significant reduction in overall latency. The protocol described and used in this study was developed using Python 2.7 and the grequests[46] library; other Python options include tornado and asyncio HTTP clients.[47]

A sub-100ms latency illuminance meter was designed and built to measure how quickly CLS react to commands through their application programing interfaces. The prototype was built using open-hardware development boards and open-source libraries from Adafruit[48,49,50,51] with the Platformio[52] cross-platform build system for embedded development. The illuminance meter and its prototype construction are shown in Figure 4.3, along with its key components. A breadboard schematic as well as the firmware source code can be found on GitHub.[53]

The data-rate limitation for this meter comes from the light-sensor analog-to-digital converter that integrates photodiode current; the fastest setting enables a minimum resolution reading for a 13.7ms integration time. A small improvement that might be considered for future development would use the programmable interrupt instead of continuously polling the sensor data registers. The firmware includes manual control of the sensor gain (1x or 16x) and integration time (13.7ms, 101ms, or 402ms), as well as a deep-sleep mode to minimize battery drain when not in use. The light sensor provided three outputs per integration period: a) the raw digitized measurement from a broadband (visible + infrared) photodiode, b) the raw digitized measurement from an infrared photodiode, and c) an illuminance calculation based on the empirical formula generated from the manufacturer's optical testing with fluorescent and incandescent light sources. A Wi-Fi connection is implemented through Dynamic Host Configuration Protocol (DHCP), the Websocket data is served on port 88, and a human-readable HTML page is presented on port 80.

[46] GitHub: kennethreitz/grequests, github.com/kennethreitz/grequests.
[47] tornadoweb.org , docs.python.org/3/library/asyncio
[48] Adafruit: Adafruit Feather HUZZAH with ESP8266 WiFi, adafruit.com/products/2821.
[49] Adafruit: FeatherWing OLED - 128x32 OLED Add-on For All Feather Boards, adafruit.com/products/2900.
[50] Adafruit: Adafruit TSL2561 Digital Luminosity/Lux/Light Sensor Breakout, adafruit.com/products/439.
[51] GitHub: Adafruit Industries, github.com/adafruit.
[52] PlatformIO, platformio.org.
[53] GitHub: clem-g/luxinterior, github.com/clem-g/luxinterior.



Key components:
ESP8266[54] Wi-Fi microcontroller from Espressif Systems with full TCP/IP stack
TSL2561[55] I²C light sensor from AMS
Univision UG-2832HSWEG02[56] OLED display
WebSocket[57] (a low-overhead protocol for real-time web applications)

Figure 4.3. Low-latency illuminance meter and prototype construction

Figure 4.4 shows the results of latency measurement tests performed for each of the six CLS explored in this study. Testing consisted of sending a single command to change the power state or light output of a luminaire or group of luminaires through the API, and measuring the time between this request and the actual change of illuminance below a specific luminaire. An estimated 20ms maximum additional latency is introduced by the illuminance sensor measurement. For API servers hosted locally, the request was sent from the LAN and under normal network load conditions. One hundred latency measurements were collected per CLS in order to characterize the reliability and statistical performance of each system and its API. Each blue dot in Figure 4.4 plots represents one measure; each red line represents an API request that either did not get through or timed out. The statistics below each graph describe the reliability, or percentage of requests that were successfully executed (ρ); the response time average (μ); and the response time standard deviation (σ) of the CLS.

[54] Espressif. 2017. *ESP8266EX Datasheet*, Version 5.4. Pudong, Shanghai, China. espressif.com/sites/default/files/documentation/0a-esp8266ex_datasheet_en.pdf.
[55] ams AG. 2005. *TSL2560, TSL2561 Light-to-Digital Converters*. Unterpremstätten, Austria. ams.com/eng/content/download/250094/975485/file/TSL2560-61_DS000110_2-00.pdf.
[56] Univision Technology Inc. 2010. *UG-2832HSWEG02 OEL Display Module* Doc No.: SAS1-B026-B. Taiwan 350, R.O.C. cdn-shop.adafruit.com/datasheets/UG-2832HSWEG02.pdf
[57] Internet Engineering Task Force: The WebSocket Protocol, tools.ietf.org/html/rfc6455.

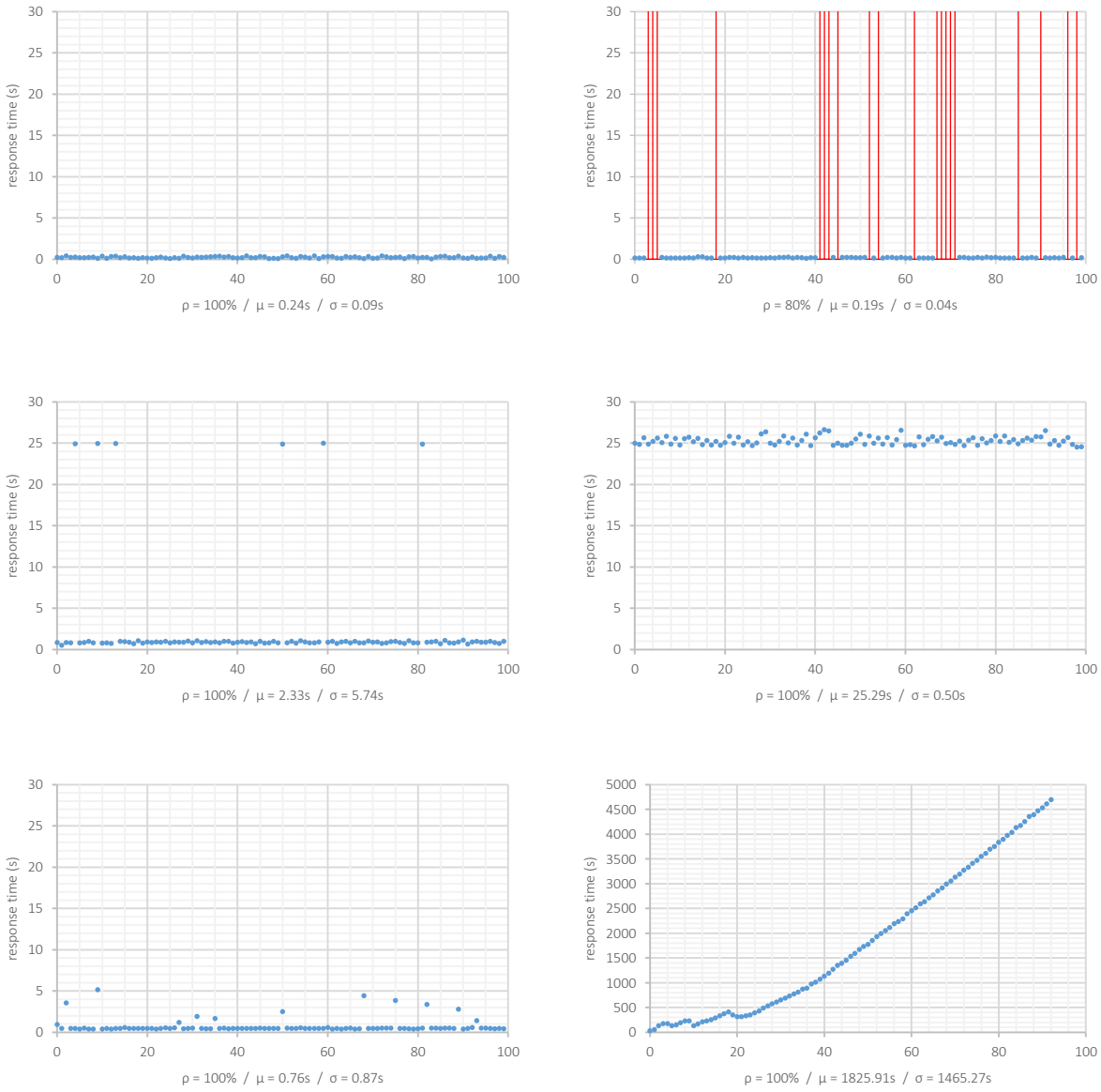


Figure 4.4. Response time for each of the six CLS, measured and plotted sequentially 100 times for statistical analysis

Notably, there was significant variation among the six CLS in the both the average response time and latency behavior. Half of the CLS demonstrated an average latency of less than one second. Among these three, however, one (upper left) was both very reliable (ρ=100%) and consistent (σ=0.09s); one (lower left) was very reliable but noticeably less consistent, due to occasionally slower response times; while the third (upper right) was significantly less reliable (ρ=80%), but very consistent when it did respond (σ=0.04s). The remaining three CLS were all very reliable, but varied in other ways. One (middle left) demonstrated a latency that was more than three times as long as than the fastest three (μ=2.33s), and also suffered from some occasionally long response times. One (middle right) was very consistent, but consistently slow (μ=25.29s). One (lower right) exhibited particularly odd behavior, whereby each subsequent test resulted in a longer response time than the one before it. At

the time of this publication, the vendor had not yet resolved whatever oddity was causing this clearly unintended behavior. Long response times, even if they only occur occasionally, can be explained in different ways: Some systems are designed to administer a significant number of nodes and are not designed for real-time control; some systems have more complicated network architectures, with several middleware layers and software stacks; and some APIs are hosted on a remote server and can therefore be susceptible to sporadic routing delays, reordered or repeated packet delays, overloaded switches, network timeouts, or connection losses. The reliability issues observed with one CLS (upper-right plot) were likely due to the gateway being a pre-commercial prototype, for which connection quality of service was simply determined based on the received-signal-strength indicator (RSSI) between the gateway and the end nodes, and no handshake had yet been implemented; as a result, commands were not always received by the luminaires.

5 Summary and Recommendations

The full potential of connected lighting systems will only be realized if they can be easily and efficiently interconnected to and exchange data with one another and with other (non-lighting) systems. Although APIs provide a means to bridge islands of data and create coherent ecosystems, the integration work is not trivial. Beyond the learning curve of each individual interface, API integration presents new challenges, including data mapping, translation or normalization, workflow orchestration, and development of a single user interface – all in a secure, scalable, and maintainable way. Making hardware resources, information, and services accessible in a distributed system is not easy. They are hosted on different platforms in different networks, using different communication technologies, information representations, and data models, and are managed by different administrators. In order to hide the inherent complexity and appear to the users as a single coherent system, a significant amount of backend integration work is required.

APIs enable the implementation of many use-cases. However, use-case performance may be hampered by one or more issues. Asynchronicity is a significant hurdle to the creation of an interoperability platform via APIs. When a number of processes are running in parallel on different machines in several locations, and the network between them is not always perfectly reliable or immune to latency issues and bandwidth limitations, synchronization of commands or readings may be difficult. Further, partial failures of a subsystem or an interface, as well as performance issues, are difficult to control, debug, and handle in a system stitched together using APIs. Implementing mechanisms and policies that maximize reliability and quality of service, while still allowing the integrated system to scale and remain effective and perform when the number of managed resources or the number of users increases, requires advanced developer skills. Finally, providing a user experience that reduces the inherent complexity of multiple systems and interfaces requires the navigation of data residing in multiple heterogeneous locations, potentially presented in different formats and conveying different information, and also requires an ability to mend structural and semantic gaps.

This study is the first of a multipart effort to explore the interoperability of commercially available (or in some cases, pre-commercial) CLS. This exploration was aimed at answering the following key questions, which might then facilitate the identification of industry needs and the development of recommendations for meeting those needs:

1 Question

- How do API implementation and information models currently found in commercially available CLS vary?

Answer

- Availability: Not all APIs were readily available (e.g., described in an unrestricted webpage or downloadable document). Some required contacting the CLS developer, who in some instances provided the API readily, and in others required an explanation of why the API was being requested and how it would be used. Some required a signed nondisclosure agreement in order to obtain API access or documentation.
- Authentication schemes: APIs used a wide variety of authentication schemes – some over unencrypted HTTP, others over secured HTTPS; some with a simple cleartext key, and others with a cryptographic hash authentication key. Integration required support of multiple schemes, subjecting the integrated environment to different cybersecurity vulnerabilities.
- Resource structure: System resources described in APIs were named and organized in myriad – and, in some cases, inconsistent – ways, with significant variation in structure, nomenclature, and complexity. Although some APIs had a logically consistent resource-tree structure, others were apparently developed incrementally over multiple version releases, as more features were added over time; incremental extensions were not always implemented consistently or logically.
- Data models: APIs used a wide variety of data models, each apparently custom-developed. Custom data models are not always well designed or documented, or even self-consistent. Data might exist in very different locations within API resource trees (e.g., /devices/<device_id>/resources, /reports/api/monitoring), and very different naming conventions or labels (e.g., /lt/dim, LuxLevel, brightness, dimming), units (e.g., absolute lux, relative % illuminance), and data types (e.g., integer, floating point) are used for seemingly similar or at least related parameters. In some cases, models from different systems may be functionally incompatible.
- CORS support: Some API developers supported CORS, while others either did not, or did not do so readily (i.e., it was difficult to find the vendor staff who could whitelist access from specific domains).
- Historical data access: Some CLS did not provide API access to historical data outside a certain time window, or only provided real-time data. In some cases, the real-time update rate was unspecified, seemingly inconsistent, or asynchronous, and was dependent on how frequently the CLS could be queried through the API.

Recommendations

- CLS developers should make their APIs readily available and ensure that documentation is synchronized with software updates. Further, they should facilitate easy, efficient bug reporting.
- The lighting industry, and perhaps the IoT industry as well, should consider developing and adopting a common approach to authentication, with some minimum level of resistance to cybersecurity vulnerabilities.

- CLS developers should enable CORS, secured by the use of HTTPS together with authentication and authorization schemes.
- CLS developers should name and organize API resources in readable, logical, and consistent ways.
- CLS developers should fully document API data models, including reporting unit (when applicable), data type, resolution, and accuracy.
- The lighting industry, and perhaps the IoT industry as well, should consider developing and adopting a well-thought-out, modern, and evolving common resource organization.
- The industry should consider developing and adopting well-thought-out, maintained common information and/or data models. These models should be created by entities with application expertise specific to the information or data model.

2 Question

- What type of effort is required to exchange information between – or, more fundamentally, to integrate – heterogeneous and asynchronous resources residing in different CLS, via their APIs, into a single interoperable platform?

Answer

- Software coding: Such integration requires some degree of software coding. Although the type and amount of coding required can vary by the approach pursued, integration via APIs requires more than configuration and validation. Integration via an existing "platform" might require less development time – in particular, if the platform was designed for, or has been previously used to implement, intended use-cases. However, the use of such "platforms" typically comes with tradeoffs between user-friendliness, functionality, and flexibility. Further, they must be maintained to address hardware, firmware, and software updates, and ideally support new systems as they enter the market.
- Harmonization: In lieu of sufficient documentation, system integrators may have to ascertain, sometimes through crude trial-and-error experimentation, what an available API resource represents and what information and data model it uses. Converters or translators may need to be developed to handle inconsistent data models. Further, an information model that suitably encompasses the myriad data models to be integrated may need to be inferred, in order to effectively aggregate data or broadcast commands, for example.
- Maintenance: Integrating multiple CLS through APIs does not result in a homogenous system; at best, it yields a common user interface and experience. However, effectively hiding the underlying complexity can require a significant amount of backend integration work. Managing what functionally remains a distributed system at one or more layers can be challenging and effortful. Differences between network protocols, device representations, and access policies that affect performance must be understood, addressed (if possible), and managed – not only initially, but over the course of hardware, firmware, and software upgrades.

Recommendations

- API developers should explore approaches to reducing system integrator effort – for example, by providing support for multiple measurement units and time aggregations for reported data, and support for controls schemes beyond switching between or pushing out

of new device profiles.

- API developers should consider the implementation of publish-subscribe models for reported data.
- API developers should consider the implementation of override or prioritization schemes that support adaptive control of configurable system devices.
- DOE intends to continue to identify and explore viable interoperability approaches. System integrators, industry consortia, and CLS developers should inform DOE when existing or new interoperability approaches reach new levels of functionality, viability, or market adoption.

3 Question

- How might the implementation of real-life use-cases effectively characterize the level of interoperability found in CLS?

Answer

- The implementation of real-life use-cases can expose previously unseen or unanticipated issues. Often, this occurs when a design constraint, boundary condition, or tradeoff is challenged by the functional or performance requirements of the use-case. Implementation can also lead to the identification of new or additional API functionality or features that might support, or better support, both the use-case under investigation as and other use-cases.
- In this study, implementation of an energy data aggregation use-case exposed issues beyond the impact of working with different data models. Energy measurement accuracy and resolution were generally unspecified in marketing literature and API documentation, raising concern as to how to statistically treat data from different sources. Further, the lack of API access, in some cases, to historical energy data required the system integrator to query the CLS in real time and log energy or power data, thereby requiring dedicated storage and computing resources.
- In this study, the implementation of a broadcast lighting command use-case exposed latency differences between systems that might arguably compromise both the functionality and performance needs of the use-case.

Recommendations

- CLS developers should support user exploration of new and previously unproven use-cases and facilitate easy, efficient bug reporting.
- DOE intends to continue to identify potentially high-value use-cases, and explore how well they can be implemented by integrated heterogeneous CLS using available interoperability approaches, as well how they might be enabled by interoperability between CLS and other systems. Lighting-industry stakeholders should provide DOE with suggestions for use-cases to explore, and estimates of their relative value.