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A Survey on the IETF Protocol Suite for the Internet of Things: Standards, Challenges, and Opportunities

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Abstract

Technologies to support the Internet of Things are becoming more important as the need to better understand our environments and make them smart increases. As a result it is predicted that intelligent devices and networks, such as WSNs, will not be isolated, but connected and integrated, composing computer networks. So far, the IP-based Internet is the largest network in the world; therefore, there are great strides to connect WSNs with the Internet. To this end, the IETF has developed a suite of protocols and open standards for accessing applications and services for wireless resource constrained networks. However, many open challenges remain, mostly due to the complex deployment characteristics of such systems and the stringent requirements imposed by various services wishing to make use of such complex systems. Thus, it becomes critically important to study how the current approaches to standardization in this area can be improved, and at the same time better understand the opportunities for the research community to contribute to the IoT field. To this end, this article presents an overview of current standards and research activities in both industry and academia.

Introduction

In recent years, the Internet of Things (IoT) has become the new research focus for both industry and academia. The concept of IoT can be traced back to the pioneering work done by Kevin Ashton in 1999 and was initially linked to the new idea of using radio frequency identification (RFID) in the supply chain. Soon after, this term became popular and is well known as a new communication system where the Internet is connected to the physical world via ubiquitous wireless sensor networks (WSNs). With the development of IoT technologies in the past few years, a wide range of intelligent and tiny sensing devices have been massively deployed in a variety of vertical applications and several major standardization alliances have formed based on the interests of technology selections and commercial markets, such as ZigBee and WAVE2M [1]. Generally, sensing devices share common features, such as constrained energy resources, limited processing capability, vulnerable radio conditions, the real-time nature of applications, and minimal direct human interaction. By interconnecting these devices using low-cost wireless communication technologies, usually WSNs, a new ecosystem with a large deployment of smart applications has been formed.

Motivated by the fact that TCP/IP is the de facto standard for computer communications in today's networked world, many believe that IP offers a more flexible architecture and could be the future for IoT networks. However, the biggest challenges in the deployment of IPv6 sensor devices are to efficiently use the low power and low bandwidth. In order to tackle these challenges, such as extensive protocol overheads against memory and computational limitations of sensor devices, the Internet Engineering Task Force (IETF) has taken the lead in standardizing communication protocols for resource constrained devices and develop a number of Internet protocols, including the Routing Protocol for Low Power and Lossy Networks (RPL) and Constrained Application Protocol (CoAP) [2], among others. Figure 1 illustrates the IoT system architecture where a normal IP device (e.g., PC or smart phone) remotely accesses wireless sensor devices via the HTTP-CoAP gateway. Although it is still in too early a stage to be commercialized, there are already a signifi-

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Because of its designated nature of low power and low complexity, an increasing number of IoT devices have been built as IEEE 802.15.4-compliant devices. Moreover, many well-known standardization organizations are also active in developing low-power protocol stacks based on IEEE 802.15.4.

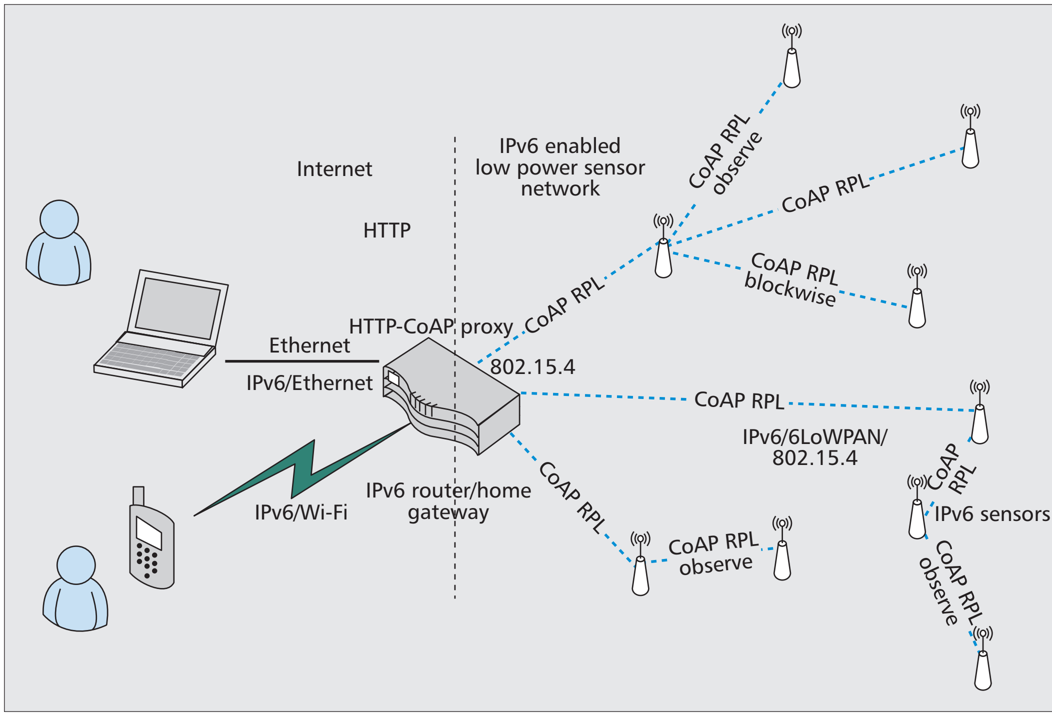

Figure 1. *IoT system architecture.*

cant number of IP-based WSN solutions as demonstrated by a growing number of research institutes.

To develop IoT communications on a large scale, there is a considerable need to understand its practical benefits and limitations, and its interdependence with application functions. There are still open challenges across layers to date in deploying IP-based solutions because of technical difficulties and the stringent requirements imposed by various services. To be specific, it is of fundamental importance to understand:

- What are the IETF solutions for the IoT? We provide an introduction to the communication standards on a layer basis, ranging from the physical and medium access control (MAC) layers up to the application layer.
- What are technical challenges to the implementation of the proposed standards on a large scale with the stringent service requirements imposed by applications? It becomes critically important to understand how the current solutions can be improved and what the opportunities are for research community to contribute to IoT development. We therefore analyze the technical challenges across layers and identify possible solutions for further improvement, which could fundamentally contribute to the field to further understanding and open the doors to better IoT practices.

The remainder of this article is organized as follows. We introduce the physical and MAC layers as well as 6LowPAN layer protocols in IoT and discuss their technical challenges and opportunities. The routing and application layers are reviewed and discussed, respectively. Future perspectives and conclusionS are then given.

Communication Standards for Lower Layers

De Facto Standards

IEEE 802.15.4 — IEEE 802.15.4 [3] is a radio technology standard for low-power and low-data-rate applications with a radio coverage of only a few meters. The standard has been developed within the IEEE 802.15 Personal Area Network (PAN) Working Group. Because of its designated nature as low power and low complexity, an increasing number of IoT devices have been built as IEEE 802.15.4-compliant devices. Moreover, many well-known standardization organizations are also active in developing low-power protocol stacks based on IEEE 802.15.4, such as WirelessHART [4] and ZigBee.

IEEE 802.15.4 specifics both physical and MAC layers. However, depending on application requirements in different vertical scenarios, both radio and MAC mechanisms could be altered to guarantee certain requirements. For example, by considering the sophisticated radio environment and deployment challenges in dense building space, IEEE 802.15.4c is developed for the newly opened 314–316 MHz, 430–434 MHz, and 779–787 MHz bands in China. Also, WirelessHART adopts part of the MAC header and integrates its own logic on top of the MAC format.

IEEE 802.15.4 typically has a maximum data rate of 250 kb/s and a maximum output power of 1 mW. The maximum packet size is 127 bytes. Besides the physical and MAC layer headers, the available space for an upper layer protocol is between 86 and 116 bytes. The power consumption is also critical for IEEE 802.15.4, which shows that the idle power consumption of CC2420, an IEEE 802.15.4 transceiver, is significantly lower than both the listen and transmit power consumption. In order to achieve energy savings, radio power management (e.g., duty cycling) is an essential part of MAC layer mechanisms. The radio transceiver must be managed so that it can be switched off when there is no traffic but switched on when nearby communication is engaged.

6LoWPAN — Since the beginning of the IETF research on IoT related technologies, IPv6 has been selected as the only choice to enable wireless communication. Its key features, such as universality, extensibility, and stability, have attracted a lot of attention and may become the de facto solution for future Internet technology. In order to enable IP connectivity in resource constrained sensor networks, the IPv6 over Low-Power WPAN (6LowPAN) Working Group has been established and works on protocol optimization of IPv6 over networks using IEEE 802.15.4. Specifically, the 6LoWPAN protocol discusses how to apply IPv6 to the MAC and PHY layers of IEEE 802.15.4.

In fact, there are two key challenges to applying IPv6 over the IEEE 802.15.4 network. On one hand, consider that the maximum frame size supported by IEEE 802.15.4 is only 127 bytes and significant header overheads occupied by layered protocols (e.g., MAC layer header, IPv6 header, security header and transmission layer); the payload size available for the application layer is very limited. On the other hand, since the minimum value of maximum transmission unit (MTU) specified by IPv6 is 1280 bytes (RFC 2460), if MTU supported by the lower layer (i.e., IEEE 802.15.4) is smaller than this value, the data link layer must fragment and reassemble data packets. In order to address these issues, 6LoWPAN designs an adaptation layer right above the data link layer to segment the IPv6 packet into the small pieces required by the lower layer. Moreover, 6LoWPAN specifies stateless compression, that is, LOWPAN_HC1 (RFC 4944) and LOWPAN_IPHC (RFC 6282), for the IP header in order to reduce the overhead of IPv6. The position of 6LoWPAN in the IPv6 protocol stack is shown in Fig. 2.

In addition to stateless IPv6 header compression, 6LoWPAN also develops other relevant standards, including the scheme supporting mesh routing, simplified IPv6 neighbour discovery protocol, use cases, and routing requirements. In summary, the 6LoWPAN Working Group is fundamental to IETF IoT communications, its contributions significantly promoting the establishment and research work of other working groups.

Open Questions and Opportunities

The state of the art shows that IoT working groups mainly aim to build the wireless subnetworks of the future IoT on top of the IEEE 802.15.4 MAC as well as other carrier sense multiple access (CSMA)-based lower-power wireless MACs such as IEEE 802.15.4 e/g and low-power Wi-Fi. However, extensive studies have shown that there is great opportunity to improve the practical performance of IEEE 802.15.4 MAC, and many promising solutions have been proposed. Current efforts on IoT communication have not paid enough attention to these fruitful results. In this subsection, we summarize the key issues of implementing IEEE 802.15.4 MAC for future IoTs and discuss possible solutions to these issues.

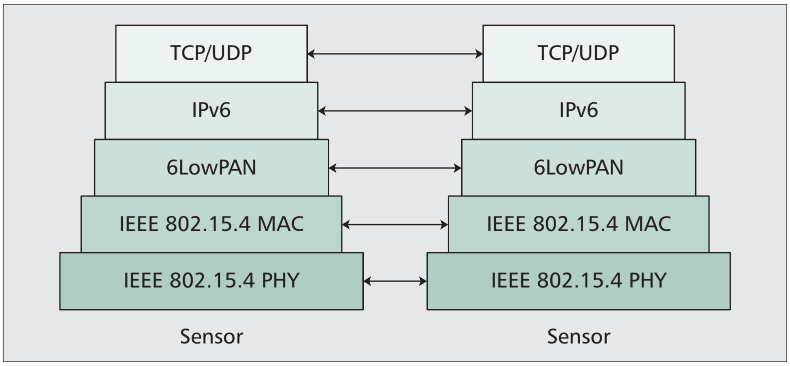

Figure 2. *The position of 6LowPAN in the IPv6 protocol stack.*

Limited Channel Capacity — The channel rate of IEEE 802.15.4 is only 250 kb/s in the 2.4 GHz band, which limits the scalability and application traffic load of the IoT. For instance, experiment results show that the CC2420 radio can only support around 100 40-byte packets/s [5], which implies that serious congestion would occur at the nodes close to the gateway when sensing applications produce heavy traffic (e.g., traffic burstiness for target tracking applications or use of many sensors to monitor a large geographic area). Furthermore, although 6LoWPAN has already compressed the IPv6 packet header, the residual overhead still aggravates congestion, which significantly impedes the ambitious IoT objective of connecting billions of things in the future.

On the MAC layer, one approach to solving the limited capacity issue is to exploit the multiple communication channels provided by IEEE 802.15.4 (e.g., up to 16 channels in the 2.4 GHz band), such as the time slotted channel hopping (TSCH) MAC proposed by the IEEE 802.15.4e group. In addition, max-weight scheduling is also a promising solution, as it has been proven to be throughput optimal in theory. Recent practical studies also show that it is easy to implement max-weight scheduling schemes on top of CSMA, which is used in the IEEE 802.15.4 MAC.

Energy Scarcity — The energy scarcity of the low-cost and low-powered sensor node has been a key issue for WSNs and for future IoT [6]. To prolong its lifetime, the sensor node operates in a duty-cycled mode. The recent development of energy harvesting technologies mitigates the energy scarcity issue, but the sensor node still has to operate in duty-cycled mode due to limited energy collection from the environment (e.g., light, RF, and vibration), and has to dynamically adjust its duty cycles to adapt to the availability of environmental energy. Such dynamic duty cycles pose challenges for networks with IEEE 802.15.4 MAC in terms of synchronization, packet loss, waste of channel resource and energy, and so on. Therefore, standards of duty-cycling-

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aware middleware between MAC and power management are highly desired.

Traffic Diversity — Similar to today's Internet, future IoT will also provide numerous types of applications. Such applications will produce data traffic with highly different patterns and quality of service (QoS) requirements. For instance, data traffic produced by target tracking and information query applications would have much harsher QoS requirements than regular environment monitoring applications. In order to reuse resources and reduce implementation costs, more and more multi-purpose sensor networks will be implemented and connected to the Internet by using IoT standards. However, several studies such as [7] show that IEEE 802.15.4 performs poorly in QoS support for networks with heterogeneous coexisting traffic. As proposed in [7], this problem could be solved by adopting multiple transmission queues in 802.15.4 as in IEEE 802.11e, which maintains four transport queues to separately deal with different traffic classes based on their level of urgency.

Network Layer Protocol

De Facto Standard

The IETF Routing over Lossy and Low-Power Networks (RoLL) working group was established in February 2008. It focuses on routing protocol design and is committed to the standardization of the IPv6 routing protocol for lossy and low-power networks (LLNs). Its tasks began with the routing requirements of various application scenarios. So far, the routing requirements of four application scenarios have been standardized: home automation (RFC 5826), industrial control (RFC 5673), urban environment (RFC 5548), and building automation (RFC 5867).

In order to develop suitable standards for LLNs, RoLL first provided an overview of existing routing protocols for WSNs. The literature [8] analyzes the characteristics and shortcomings of the relevant standards and then discusses the quantitative metrics for constructing routes in the routing protocol. RFC 6551 introduces two kinds of quantitative metrics: node metrics, including node state, node energy, and hop count, and link metrics, including throughput, latency, link reliability, expected transmission count (ETC), and link color object. In order to assist dynamic routing, nodes can select path(s) based on the quantitative metrics to achieve the defined objective.

Based on the results of routing requirements and quantitative static link metrics, RoLL developed a routing protocol for LLN (RPL) [9]. RPL supports three kinds of traffic flow: point-to-point (between devices inside the LLN), point-to-multipoint (from a central control point to a subset of devices inside the LLN), and multipoint-to-point (from devices inside the LLN toward a central control point). RPL is a distance-vector routing protocol, in which nodes construct a destination-oriented acyclic graph (DODAG) by exchanging distance vectors and root with a controller, illustrated in Fig. 3. Through broadcasting routing constraints, the root node (i.e., central control point) filters out the nodes that do not meet the constraints and selects the optimum path according to the metrics. In the stable state, each sensor node has identified a stable set of parents and forwarded packets along the path toward the root of the DODAG.

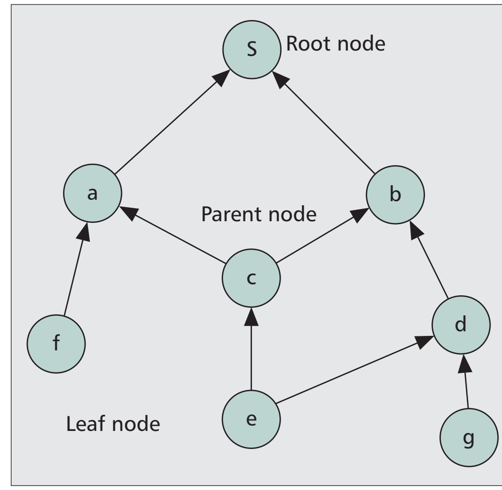

Figure 3. *RPL routing tree: DODAG.*

Open Questions and Opportunities

Routing plays an important role in providing efficient end-to-end networking services in communication networks. The emerging IETF routing standard, RPL, aims to support ubiquitous sensing applications in future large-scale low-power IoTs. Although the current RPL has provided many nice features such as supporting multiple link and node metrics, it still needs to be improved to achieve this ambitious goal. In this subsection, we summarize the potential issues of the current RPL and propose possible solutions.

End-to-End Throughput — Similar to the IEEE 802.15.4 MAC in data link layer, RPL in the network layer also meets the throughput challenges because of multiple coexisting applications in one physical network and the potential large network size. Different from the DAG routing topology used by RPL, the queue-aware back-pressure routing algorithm sends packets to the gateway(s) by exploiting all possible end-to-end paths, which has been proved to be throughput optimal in theory and successfully implemented in real-world sensor networks [10]. To improve the potential throughput, RPL could define the queue backlog as a node metric and combine this with link quality metrics (e.g., data rate) for data forwarding. Besides the back-pressure approach, integrating the ideas of opportunistic routing and network coding are also promising and practical solutions.

Packet Reordering — Different from traditional tree-based WSN routing, RPL provides multi-path routing solutions (i.e., the DAG routing topology; a node can have multiple parents). The multi-path routing structure would result in packet reordering; that is, earlier generated packets may be received by the gateway later. Therefore, this fundamental issue of multi-path routing should be addressed when RPL is used to provide networking services for jitter-sensitive applications such as target tracking.

Impact of Duty Cycling — Besides the MAC layer, dynamic duty cycling also has a non-trivial impact on the end-to-end performance of the network layer (e.g., [11]), including end-to-end latency, throughput, delivery radio, and other factors. In energy-harvesting networks, for instance, every sensor node should adapt to the time-varying environment energy by adjusting its duty cycle (i.e., energy consumption) dynamically, in order to achieve sustainable operation (i.e., no node should run out of battery). Our previous work [12] also demonstrates that such dynamic duty cycling significantly affects end-to-end throughput of routing, as shown in Fig. 4.

However, the current RPL design has paid very little attention to duty cycling. Therefore, how to seamlessly integrate duty-cycle awareness into the multi-path routing RPL remains an open question.

Multi-Topology Routing vs. Traffic Diversity — In a network carrying multiple traffic types, different routes should be constructed to support different types of application traffic, according to their requirements of physical resources, such as bandwidth-aware routing and delay-aware routing. To support different applications (e.g., information query and data collection) in one wireless network, RPL adopts the multi-topology routing (MTR) approach to construct and identify a routing graph (e.g., a DAG) over one physical mesh network for each application. MTR should work well in LLNs with small numbers of light traffic applications. However, the cost of DAG construction and maintenance increases as the number of applications increases. Furthermore, since routing traffic over each DAG coexists and competes for resources of the same physical network (e.g., link rate, energy, and node memory), the priority and fairness for every DAG become nontrivial issues. Therefore, separately optimizing each DAG cannot result in an efficient routing policy as a whole. Recently developed network optimization approaches such as [13] could be useful to solve such problems, but it is a challenge to minimize the modification of RPL when adopting these theoretical optimization ideas.

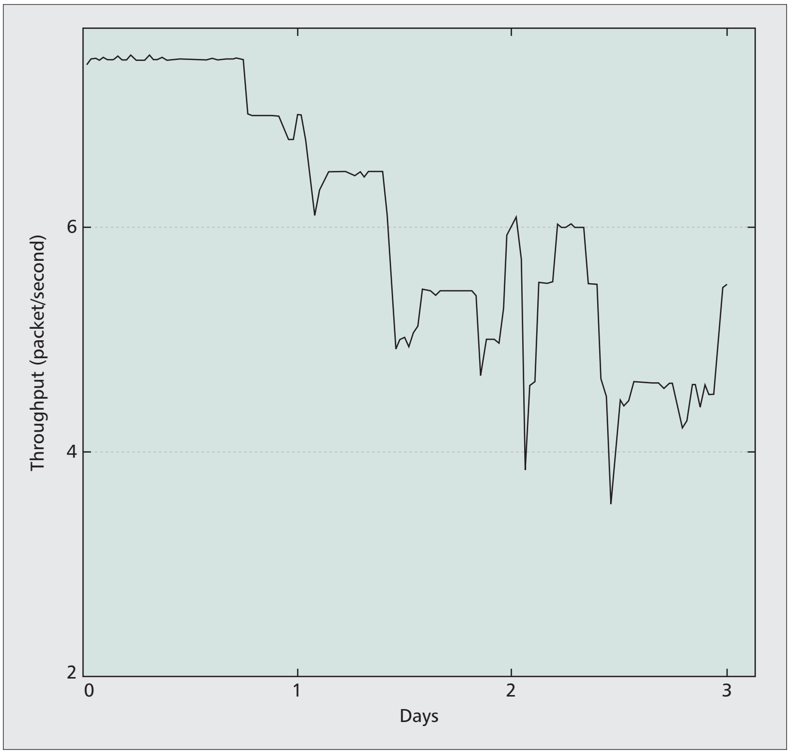

Figure 4. *Experiment results to show the impact of dynamic duty cycling on end-to-end network throughput of a backpressure routing algorithm in a 16-node solar powered WSN for three days.*

APPLICATION LAYER PROTOCOL

DE FACTO STANDARD

The Constrained Application Protocol (CoAP) specified by the IETF CoRE Working Group, is a specialized web transfer protocol for resource constrained nodes and networks. CoAP conforms to the REST style. It abstracts all the objects in the network as resources. Each resource corresponds to a unique universal resource identifier (URI) from which the resources can be operated stateless, including GET, PUT, POST, DELETE, and so on.

Strictly speaking, CoAP is not an HTTP compression protocol. On one hand, CoAP realizes a subset of HTTP functions and is optimized for constrained environments. On the other hand, it offers features such as built-in resource discovery, multicast support, and asynchronous message exchange.

Unlike HTTP, CoAP adopts datagram-oriented transport protocols, such as UDP. In order to ensure reliable transmission over UDP, CoAP introduces a two-layer structure, which is shown in Fig. 5. The messaging layer is used to deal with asynchronous interactions with UDP, such as confirmable (CON), non-confirmable (NON), acknowledgment (ACK), and reset (RST) messages.

The request/response interaction layer is used to transmit resource operation requests and the request/response data. As a summary, CoAP has the following features:

- Constrained Web protocol fulfilling M2M requirements
- Asynchronous message exchanges
- Low header overhead and parsing complexity
- URI and Content-type support
- Simple proxy and caching capabilities
- Built-in resource discovery
- UDP binding with optional reliability supporting unicast and multicast requests
- A stateless HTTP-CoAP mapping, allowing proxy to provide access to CoAP resources via HTTP in a uniform way and vice versa

OPEN QUESTIONS AND OPPORTUNITIES

Although CoAP is extensively developed in IETF to act as the core application layer protocol in resource constrained networks, it is still

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confronted with challenges in application deployment scalability, network robustness, device cost and power efficiency.

Application Deployment Scalability — The CoAP is normally coupled with the 6LoWPAN and IP protocol suite to provide application layer services. The successful delivery of a CoAP message requires the reachability of the device with an IP address. However, the application provided by the device with 6LoWPAN cannot have a constant IP address and is usually associated with the MAC address of the network interface. Once the device is replaced, the destination IP address assigned by previous applications should be modified to ensure routability of new CoAP messages. Such update procedures will increase the operational complexity, especially in situations where lots of external clients need to be served. Existing solutions, for instance, the Dynamic Domain Name System (DDNS), can successfully track dynamic IP address. However, it is difficult for a constrained device to allocate more resources for DNS client implementation.

Network Robustness — It is highly possible that some constrained devices (e.g., a temperature sensor for public access) will have to cope with a vast amount of requests from clients. They may collapse due to extremely high processing loads, which is similar to the situation in the presence of distributed denial of service (DDoS) attacks. It is unfortunate that the CoAP fails to provide any solutions to deal with massive access. The caching mechanism in CoAP can merely reduce the access traffic from the users that have already issued the requests within a limited duration of time, but is unable to alleviate the processing loads caused by new clients.

Device Cost — Reference [14] evaluates the memory consumption of the IETF protocol suite including CoAP in Contiki.[1] The whole operating system, including the IPv6 protocol stack, takes up 6 kbytes RAM and 35 kbytes ROM, which means that the IETF suite cannot be realized in a single-chip solution with an inexpensive microcontroller such as 89C51X2, whose built-in ROM and RAM are only 4 kbytes and 128 bytes, respectively. Therefore, without mass production of a mature IP-based solution, the unit price of a sensor device with a simple service (e.g., a light sensor) is relatively higher than customer expectation, given that it is implemented with the IETF protocols. For instance, the price of a plug switch with IP-based remote control capability is about 10 times that of an ordinary one.

Power Efficiency — Different from the network layer protocols to improve energy efficiency [15], the application layer protocol can also improve the power efficiency of constrained devices. CoAP introduces the observer/subject mechanism, where a client can subscribe to a resource, and the server only responds once the resource changes. It helps the server process multiple requests in a more efficient way and accordingly reduce power consumption. However, the CoAP server must be kept alive to listen to possible requests from clients. It turns out that devices with CoAP still have to face relatively large power consumption even if CoAP has been optimized for the power issues.

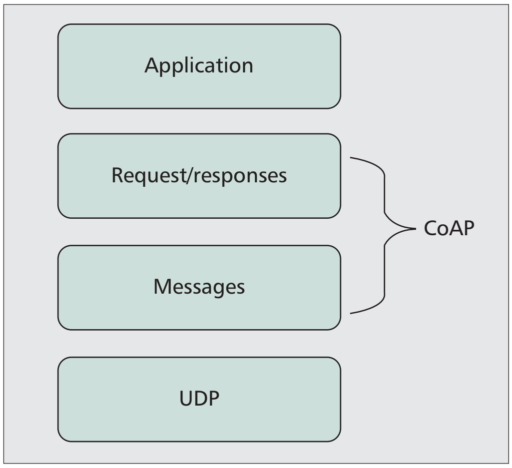

Figure 5. *CoAP protocol stack.*

Content-centric networking (CCN) [16] provides a promising way to overcome the above concerns for resource constrained networks. The communication in CCN is driven by a data consumer who sends out a request message carrying a URI-like name that identifies the desired data. The router in the network maintains a data structure to remember the interface where the request arrives and then forwards it by looking up the data name in another data structure where the list of interfaces that can serve the request is recorded. Once the request reaches a node with the target data in its local storage, a data packet containing the requested content with the data name will be sent back via the reverse path created by the request message.

Figure 6 illustrates the comparison of the IP protocol stack and CCN stack. It is worth noting that the content layer of CCN is the crucial component for the application request/response processing, which is equivalent to the request/response exchange in CoAP except that the intermediate device may also interpret RESTful messages besides the server and client. To further improve the transport performance, we propose in [17] a content identifier compression method. Specifically, the method defines a series of message exchanges between sensor devices and upward devices such as routers or gateways to generate a 2-byte code representing the content identifier.

In essence, there is great convenience in building IoT systems with the CCN architecture. As for the application deployment scalability, the named-based routing can enable the CCN-based IoT to implement the addressing scheme, which is independent of the IP address and tightly coupled with the hardware with no DNS required. In addition, the CCN-based IoT is superior to the CoAP in dealing with massive access, because CCN is primarily designed for content dissemination. The routers may identify multiple requests destined to the same resource object and make the destination respond to a single request even in the presence of many requests. Furthermore, there is a significant advantage in

[1] Contiki is an open source operating system for the IoT. Contiki allows tiny battery-operated low-power systems to communicate with the Internet.

reducing the device cost for CCN-based IoT solutions as well. In particular, a device using the protocol stack in Fig. 6b can further eliminate the IP address management procedure. Power saving can easily be achieved in the CCN architecture. Given the request arrival, the router can respond with the cached data without waiting for the activation of the target. Moreover, by introducing resource subscription, the IoT device can only keep the subscription message from the router serving the request with the cached data to enable timely reaction to the access request even if it is in sleep mode for power saving.

Future Research Challenges

So far, we have introduced the IETF effort on developing the global communication solution for WSN and summarized some of the critical opportunities and challenges of bringing the current IoT standards into reality. From the technical perspective, the Internet of Things relies not only on industry efforts to promote network convergency, but also academic innovations at a fundamental level to improve engineering designs. For a long-term vision, we identify some interesting research opportunities and challenges for future IoTs:

1. Convergent networks: Future IoT infrastructures may exist everywhere, in home, industry, cities, and so on. Considering that the emerging number of IoT standards (e.g., ZigBee) and different communication technologies (e.g., power line communications [PLC], WiFi) coexist, it is necessary to develop heterogeneous technologies to enable convergent networks. For instance, ZigBee has officially released its ZigBee IPv6 specification to consider its compatibility with the IETF standards. By taking advantage of possible radio resources nearby, different communication technologies can cooperate together to deliver highly efficient and green communications.
2. Hybrid communication paradigm: Current IoT solutions focus on a multihop short-range communication paradigm, which is limited by poor end-to-end throughput and the high cost of large-scale deployment. Alternatively, sensor data can also be forwarded to the Internet using opportunistic (i.e., carry-and-forward) [18] or one-hop long-range (e.g., third/fourth generation [3/4G] cellular) communications. Seamlessly combining these communication paradigms could result in more cost-effective IoT solutions.
3. Joint data processing and networking: It is expensive to transmit huge volumes of raw data produced by numerous smart things to the Internet. Fortunately, sensor data processing techniques such as compressive sensing and data fusion can significantly reduce the sensor data volume. Consequently, designing a communication paradigm with data processing awareness for future IoTs is highly desired.
4. Social and economic awareness: As sensors or smart things are owned by the public, organizations, or individuals, social and economic behaviors of users, network service providers, and sensor data providers should be considered in the IoT design [19], such as incentive, resource pricing, and social-aware privacy.

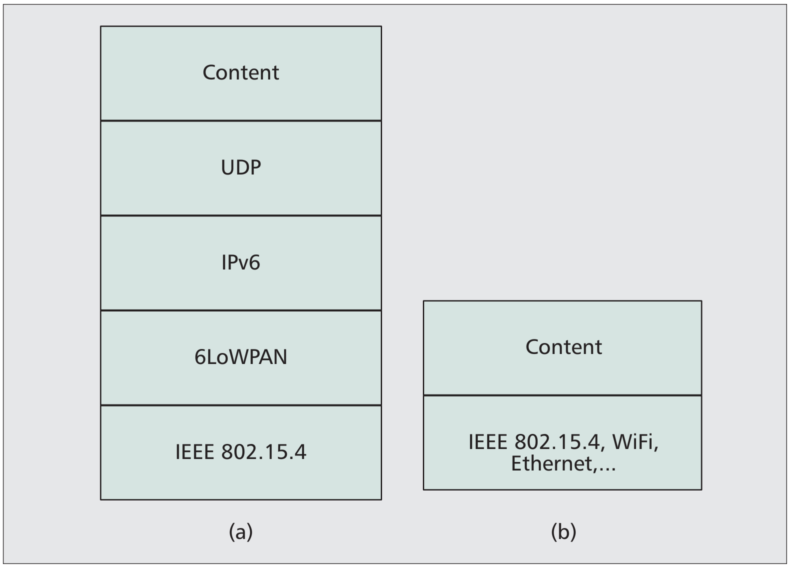

Figure 6. *Comparison of IP protocol stack and the proposed solution: a) IP-based stack; b) non-IP-based stack.*

Conclusion

This survey provides a brief overview of the IETF protocol suite proposed to support the Internet of Things. Taking each layer in the protocol in turn, we have presented the technical challenges and opportunities that exist. That is, the physical layer, MAC layer, 6LowPAN, RPL protocols, and CoAP standards have been reviewed and critiqued. It is our view that these standards are a good start, but there are many open issues remaining. However, based on the current trajectory of research combined with more forward thinking, better solutions capable of combating radio unreliability and meeting future application requirements of high-speed and high-quality services with high energy efficiency can be developed. New insights regarding protocol analysis could also provide precise guidelines that will result in efficient designs of practical and reliable communications systems. The resulting ideas have the potential to have a broad impact across a range of areas, including wireless communications, network protocols, and radio transceiver design.

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