CIP over 6LoWPAN -
Expand CIP to IPv6-based Field Wireless Network

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Abstract:

In this paper, we examine the expansion of Industrial IP network architectures into field wireless networks and investigate the technical feasibility of adapting the Common Industrial Protocol (CIP™) over 6LoWPAN networks (IPv6 over Low-power Wireless Personal Area Network). Fundamental business and technology problems are introduced, and the critical challenges for running CIP over 6LoWPAN are identified. The paper describes a prototype of CIP over 6LoWPAN protocol stack to validate the concepts of how CIP could execute in a very low-end, energy-limited wireless node. Based on the stack concepts, a wireless demo platform using Wi-Fi as the control network and 6LoWPAN as the field wireless sensor/actuator network is presented.

Keywords:

CIP, EtherNet/IP, 6LoWPAN, CIP over 6LoWPAN, IPv6, IoT

Definition of terms:

CIP: Common Industrial Protocol
6LoWPAN: IPv6 over Low-power Personal Wireless Network
FWN: Field Wireless Network, Wireless HART is an example of FWN
ICN: Industrial Control Network
IoT: Internet of Things

1 Background

Since its introduction in 2001, EtherNet/IP™ has become the most developed, proven and popular industrial Ethernet network, well accepted by the automation industry. Hundreds of vendors provide thousands of EtherNet/IP product lines and millions of Ethernet ports have been installed into automation systems around the world. Besides basic control functions, the EtherNet/IP network also supports the CIP Sync™, CIP Safety™, CIP Motion™, and CIP Energy extensions. This leads to diverse EtherNet/IP applications varying from machine control, process control, drive control, motion control and safety control. Because EtherNet/IP is built on a standard unmodified Ethernet network and TCP/IP protocol suite, it is possible to reuse the technologies, tools, people skills, and knowledge that are well developed and established in the IT field. Furthermore, it also prepares EtherNet/IP devices, such as PACs, drives, I/O modules, etc., as a part of the Internet of Things.

In the Internet of Things (IoT) movement, the Field Wireless Network (FWN) is one important driving force. In the domain of automation, 6LoWPAN[2][3] (IPv6 over Low power Wireless Personal Area Networks) is a significant and promising standard for building field wireless networks. In a narrow sense, 6LoWPAN is just a protocol adapter layer between IPv6 (Network Layer) and IEEE802.15.4[1] (MAC/PHY Layer). From the technical perspective, the 6LoWPAN protocol defines encapsulation and header compression mechanisms that allow IPv6 packets to be sent to and received over IEEE 802.15.4 networks with high efficiency and low cost. The protocol also promises a seamless integration of 6LoWPAN networks with the existing IP network while maintaining interoperability and scalability.

Seamless integration of field wireless devices into industrial IP networks will create larger volumes of data that enable more timely business decisions for the manufacturing processes. For example, by transforming sensor data into actionable information, online monitoring and diagnostics become obvious and attainable. This paper investigates the applicability of CIP to low power wireless personal area networks (using 6LoWPAN as an example), and presents a proof of concept demonstrating one aspect of IoT in manufacturing using ODVA technologies - thus enabling ODVA and its members to continue to lead the introduction and adoption of IoT techniques into manufacturing.

2 CIP over IP Network Architecture

Traditionally, EtherNet/IP is deployed in a private IPv4-only network. This network architecture is poised to change.

2.1 IPv6 Transition in Industrial Networks

The transition of IP networks from IPv4 to IPv6 is ongoing, driven by the exhaustion of available IPv4 public addresses, government policies, mobile devices and the IoT movement. IPv6 resolves numerous IPv4 issues by re-architecting the IP protocol. New or improved features, such as transparent end-to-end communication, large addressing space, an auto-addressing method, more efficient routing protocol, enhanced mobile capability, and self-network forming and configuration are very attractive and useful for the plant control network. This transition will not occur in automation in the short term because there is no significant driving force inside the plant control network which is typically a private network. The expected pattern would be that the internet and then the enterprise intranet will first complete this transition and then the plant control network will migrate to IPv6 in order to integrate with the enterprise intranet and the internet.

2.2 Convergence of Industrial and Enterprise Networks

The convergence of plant control and enterprise networks is being driven by manufacturers and manufacturing applications. The manufacturers want a connected enterprise where the information can flow timely and freely from the field devices to controllers, MES and enterprise analytic software. The wide deployment of EtherNet/IP technology for manufacturing networks acts as the technology enabler for this convergence. EtherNet/IP's open architecture makes this convergence easy. Business decision-makers can take advantage of real time information by accessing key performance indicators and data analytics at the manufacturing application level. The industrial process can be monitored and adjusted in real time to improve production flexibility. The assets can be utilized in an optimized manner to improve productivity. Maintenance events can be predicted and remediation can be scheduled in a proactive way to avoid unnecessary or unplanned down time.

2.3 IP Penetration into the Field Wireless Network

Besides the IPv6 transition and enterprise network convergence, the emergence of the IP-enabled Field Wireless Network (FWN) is another important trend. Years ago, the belief was that it was not feasible to run the TCP/IP stack in a computing resource constrained wireless sensor node. In recent years, technology advancements in FWNs, such as low cost, increased microprocessor control unit (MCU) performance, lightweight TCP/IP stacks, and the 6LoWPAN communication protocol, make IP communication in FWN devices possible.

2.4 Expanded CIP over IP Network Architecture

With the convergence of industrial and enterprise networks and the emergence of IP-enabled FWNs, the IP-based CIP network architecture has a new opportunity to break the boundary between the field and enterprise networks.

Figure 1 shows a logical representation of a mixed IP-based CIP network architecture - presenting three levels of networks: Field Wireless Network (FWN, e.g., 6LoWPAN), Industrial Control Network (ICN, e.g., EtherNet/IP), and enterprise network. It does not illustrate the non-automation devices which would typically be present in a converged network architecture.

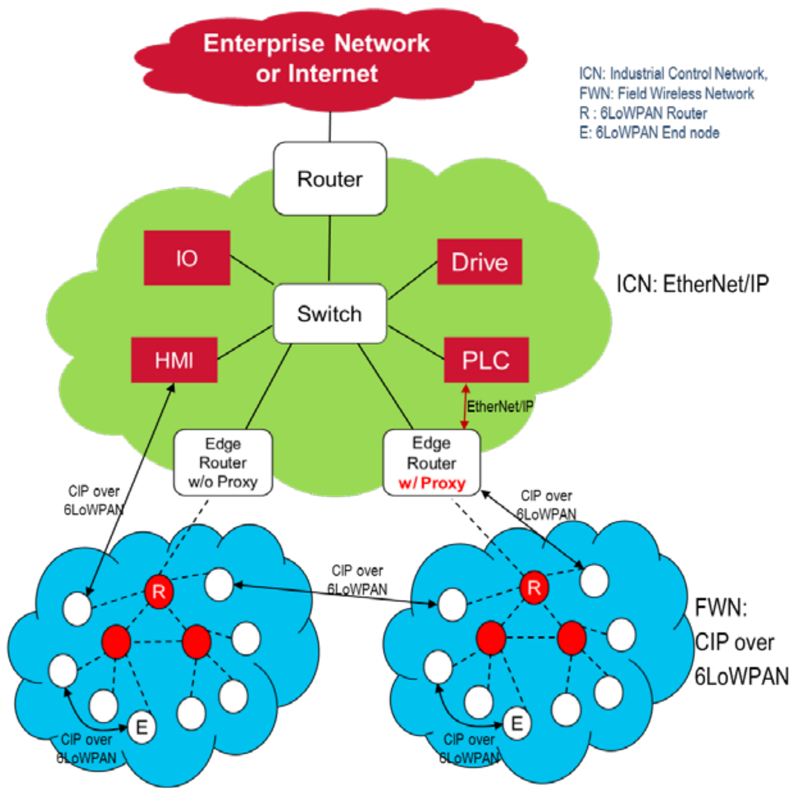

Figure 1 Future CIP over IP Network Architecture

The 6LoWPAN networks (blue clouds) connect 6LoWPAN end nodes (e.g., 6LoWPAN sensors or actuators) in a mesh, tree, or star topology. 6LoWPAN end nodes (white bubbles) are addressed by IPv6 addresses, and are typically battery-powered and sleep most of the time to save battery energy. The end nodes usually have very limited processing and memory resources. The 6LoWPAN routers (red bubbles) form a mesh to convey 6LoWPAN packets across the FWN for the 6LoWPAN end nodes. The physical communication path between two 6LoWPAN devices is a 6LoWPAN link. The 6LoWPAN link has 250 Kbps bandwidth, and 127 bytes of frame size which is standardized in IEEE802.15.4 (assuming the 2.4 GHz band is used). The nodes and links comprise a network. A typical 6LoWPAN network may operate with update rates measured in seconds (to preserve battery life) and contain hundreds of nodes.

The EtherNet/IP network connects automation devices such as HMIs, PACs, drives, and I/O modules into an automation system. The EtherNet/IP network is commonly connected to the enterprise network or internet through a secure router.

6LoWPAN networks are connected to the EtherNet/IP network through edge routers. Assuming the EtherNet/IP network is an IPv6 network (a future CIP enhancement); the edge router compresses or decompresses the IPv6 packets between the Ethernet and 6LoWPAN networks to provide IP routing while not requiring any translation at the network layer. The edge router also provides network management and security functions for the 6LoWPAN network to interface with the IPv6 network.

With this expanded CIP network architecture, there are several new communication scenarios to be considered:

- Peer-peer communication between CIP over 6LoWPAN nodes within one CIP over 6LoWPAN network
- Peer-peer communication between CIP over 6LoWPAN nodes in different CIP over 6LoWPAN networks (For example, the CIP over 6LoWPAN sensors in one site can communicate with the CIP over 6LoWPAN actuators in another site by utilizing the IP network infrastructure.)
- End-to-end communication between CIP over 6LoWPAN nodes in a CIP over 6LoWPAN network and EtherNet/IP nodes in an EtherNet/IP network that supports the function of CIP over 6LoWPAN
- CIP over 6LoWPAN nodes communicating with EtherNet/IP nodes through a proxy that may be in the edge router or in the EtherNet/IP node itself. The proxy does the protocol translation between EtherNet/IP and CIP over 6LoWPAN networks
- CIP over 6LoWPAN sensors delivering IP packets of sensing data to the intranet/internet over IP network infrastructures, not requiring any gateway in between

In the situation of the IP network transitioning to IPv6 and penetrating into the field wireless network in the automation domain, ODVA's EtherNet/IP technology has advantages (use of standard Ethernet and IP) for achieving a seamless integrated IP network throughout the plant floor, the enterprise, and the internet. However, many field wireless devices on the plant floor are not suitable for running the existing EtherNet/IP protocol due to the relatively large overhead. The 6LoWPAN network is a highly competitive candidate for implementing a suitably lightweight IPv6-enabled field wireless network for the plant floor.

The following sections investigate the technical feasibility of implementing CIPover a 6LoWPAN network.

3 CIP over 6LoWPAN Network Stack Concept

A conceptual architecture for a CIP over 6LoWPAN network stack for the field wireless network is presented in the OSI 7-layer network model, as shown in Figure 2.

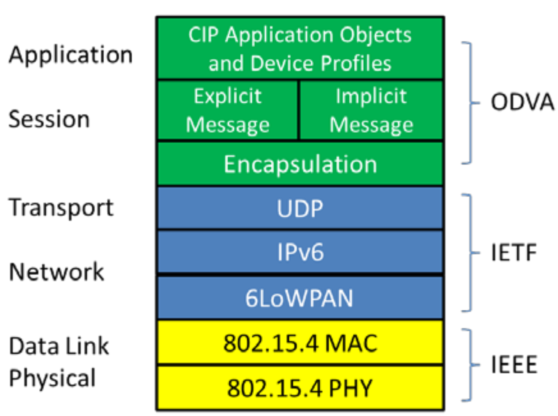

Figure 2 CIP over 6LoWPAN Network Stack

A key element of EtherNet/IP is the encapsulation layer between CIP and TCP/UDP/IP. This is where the majority of changes are considered. CIP over 6LoWPAN requires encapsulation, but, practically speaking, does not support TCP and only supports IPv6 addressing – thus a new encapsulation approach is required. This paper will next discuss in detail how CIP can be adapted to support resource constrained end nodes.

4 Technical Requirements, Challenges, and Proposals for CIP over 6LoWPAN

This section investigates the challenges in the application protocol space in order to address the differences between the 6LoWPAN node/link/network and the Ethernet node/link/network. Table 1 provides a summary of the requirements and challenges in running CIP over a 6LoWPAN network. The corresponding possible solutions to these challenges are also proposed. The following subsections detail each item in Table 1.

Table 1 Requirements, Challenges, and Proposals

6LoWPAN Requirements	EtherNet/IP and CIP's Challenges	Proposed Solutions
IPv6	Not IPv6 ready	Migrate to IPv6
UDP-only	TCP for explicit messages	Enhance EtherNet/IP and CIP to transport explicit messages over UDP
Small packet size (127 bytes PHY payload)	EtherNet/IP assumes larger packet size (1,500 bytes PHY payload)	Simplify the packet format of EtherNet/IP and CIP to improve the protocol efficiency
Limited resources (e.g., second-level update rates, 128 Kbytes Flash and 32 Kbytes RAM)	CIP and EtherNet/IP assumes there are enough resources (e.g., ms-level update rates, 256 Kbytes Flash and 128 Kbytes RAM)	Simplify and optimize EtherNet/IP and CIP to reduce memory and performance requirements (remove session, Class 3 connection, and simplify Class 1 connection)
Sleep and battery-power	Doesn't consider sleep mode; always mains-powered	Enhance EtherNet/IP and CIP to consider sleep mode and battery-power requirements (active report, aggregation, etc.)
Peer-to-peer communication among field devices	Difficult to support peer-to-peer communication for field devices due to their limited resources	Simplify and enhance EtherNet/IP and CIP to support peer-to-peer communication (i.e., every device can originate the communication not requiring much resources)
Security	EtherNet/IP and CIP rely on external security services but do not integrate them	Define security mechanism for EtherNet/IP and CIP
Backward compatibility	How to operate with old CIP devices	Define protocol coexistence/translation functions
Wireless network management (large scale, dynamic topology)	Doesn't consider 6LoWPAN wireless network management	Define the link and network management function for 6LoWPAN

4.1 IPv6

Requirement: The 6LoWPAN network is IPv6 based and the addressing space is very large. The CIP over 6LoWPAN protocol shall support IPv6.

Challenge: EtherNet/IP is not IPv6-ready. Many places in the EtherNet/IP protocol use IPv4 addressing.

Solution: EtherNet/IP and CIP need to be migrated to IPv6 to be able to operate over 6LoWPAN networks. ODVA EtherNet/IP system architecture SIG is working on the IPv6 migration for EtherNet/IP.

4.2 UDP-only

Requirement: The 6LoWPAN network stack is UDP-only. The CIP over 6LoWPAN protocol shall transport explicit messages over the UDP protocol.

Challenge: EtherNet/IP depends on both TCP and UDP transport protocols. Explicit messages (UCMM and Class 3) use the TCP transport protocol, while Implicit messages (Class 0/1) use the UDP transport protocol.

Solution Options:

a) Add the TCP transport protocol into the 6LoWPAN network stack so that the transport method for explicit messages is not changed.
b) Change the transport method for explicit message delivery over the UDP transport protocol.

Recommendation:
Although the TCP transport protocol can be supported over 6LoWPAN networks (in theory), it is not practical because the TCP packet is difficult to compress due to the protocol complexity. TCP's flow control function and reliable transfer mechanism through packet acknowledgment and retransmission cause trouble for the adapted protocols to run over the unreliable large scale personal area wireless network. With the above concerns, the commercial 6LoWPAN stack only supports UDP. Solution b) is recommended.

The challenge for solution b) is to remove the TCP dependency for explicit messages. The major difference between TCP and UDP is that TCP can detect communication errors, such as packet repetition, out of order, and packet loss, with its reliable data transfer mechanism. Therefore we first need to analyze whether explicit messages (UCMM and Class 2/3) must rely on TCP for a reliable transfer.

UCMM uses a Transaction ID to match the response to the request for multiple outstanding transactions. Out of order packets do not cause an issue for UCMM. Packet repetition can be detected with the Transaction ID.

In most implementations, the Class 2/3 connection only allows one outstanding transaction, the out of order error will never happen. Assuming the intermediate network does not make mistakes to repeat the packet, the packet repetition error caused by end points can be detected according to the strict Request/Response pair rule, thus the repeated packet can be dropped.

Because both UCMM and Class 2/3 transports use the client/server model, the client's application can detect the packet loss error and then retry.

Based on the above analysis, CIP has its own mechanism to ensure the communication is reliable, not relying on TCP's reliable transfer mechanism. So there is no issue in running CIP over UDP. UDP-only CIP is one key factor to significantly reduce the complexity and memory consumption of the CIP stack in order to ensure the feasibility of implementing CIP on low end 6LoWPAN wireless nodes.

4.3 Small Packet Size

Requirement: The 6LoWPAN network only allows a 127 byte PHY payload (a 102 byte IP packet after subtracting a maximum 25 byte MAC header). The 6LoWPAN protocol itself compresses IPv6 and UDP headers from greater than 40 bytes down to several bytes. The CIP over 6LoWPAN protocol packet length shall be short enough so that the whole packet fits within 127 bytes.

Challenge: The PHY payload of 6LoWPAN networks is much smaller than Ethernet which assumes a larger packet size (1500 bytes). In EtherNet/IP, the Class 0/1 connection allows 511 bytes of data. Although the fragmentation and reassembly function is defined to transfer larger packets, it is desirable to avoid using it to improve the protocol efficiency and reliability. It is also worth noting that the majority of simple end node devices implemented in EtherNet/IP today do not exceed a 64 byte CIP payload and simple field wireless devices may just transfer an analog in or output value which is less than 5 bytes with status included.

Solution options:

a) Compress the EtherNet/IP encapsulation layer protocol to reduce the overhead for 6LoWPAN and keep all functions unchanged.
b) Redesign a new high efficient encapsulation protocol for 6LoWPAN by simplifying the EtherNet/IP encapsulation protocol and optimizing CIP functions.

Recommendation: The EtherNet/IP design is based on the Ethernet network. The EtherNet/IP protocol is not very efficient for constrained networks like 6LoWPAN. Many fields and functions in the EtherNet/IP encapsulation protocol are not necessary and can be taken away or optimized for 6LoWPAN networks. Encapsulation protocol header compression does not solve the problem well because it does not reduce complexity, but only reduces the payload size. Hence solution b) is recommended.

4.4 Limited Resources (Memory and Performance)

Requirement: Most 6LoWPAN nodes (e.g., wireless sensors) have very limited processing power and limited memory (e.g., 128 Kbytes Flash, 32 Kbytes RAM). The CIP over 6LoWPAN protocol shall be simple enough to be implemented in constrained 6LoWPAN nodes with limited resources.

Challenge: CIP and EtherNet/IP assume the device has enough processing and memory resources to run a complex communication stack (e.g., 256 Kbytes Flash, 128 Kbytes RAM). A 6LoWPAN device's timing performance is in the order of seconds or minutes, while EtherNet/IP's is in the order of milliseconds.

Solution: It is impractical and unnecessary to run a full function EtherNet/IP stack in a constrained 6LoWPAN node. The possible simplification of EtherNet/IP and CIP function includes:

- Remove the session management mechanism in the encapsulation layer and all TCP-related artifacts.
- Remove connection based Class 3 explicit messages; only keep UDP-only UCMM explicit messages.
- Simplify the Produce/Consume connection mechanism. Allow only unidirectional connections. Allow only the symbolic application path to address application data (e.g., continuous process data).
- Remove the CIP routing function for the 6LoWPAN network.

Once the session management mechanism is removed, the revision check function embedded in the session mechanism must be done in an alternative way. The proposed method is to place the revision information into the encapsulation header so that every packet will carry the revision information by itself. Another way is to define a dedicated revision check mechanism, for example, adding new revision check commands in the encapsulation protocol.

4.5 Sleep and Battery-power

Requirement: Constrained 6LoWPAN nodes are typically battery-powered. A default sleep mode is briefly exited for communication, I/O and other housekeeping functions based on a periodic timer or external interrupts in order to conserve energy. The CIP over 6LoWPAN protocol shall be energy-efficient to preserve the energy of the battery.

Challenge: EtherNet/IP devices are typically mains-powered. The protocol itself does not contain an appropriate energy-efficiency and sleep mode methodology. In addition, communication draws much more power than sleeping and the typical periodic communication is inefficient.

Solution:

- Reduce the protocol overhead as mentioned in 4.3 Small Size Packet, thus decreasing network traffic.
- Provide data aggregation and packet aggregation functions between devices to reduce the communication overhead (within the small packet limits).
- Enhance the communication model: use "Change of State" connection as default.
- Add an active data reporting mechanism so that devices can actively report the information rather than being passively polled.

4.6 Peer-to-Peer Communication among Field Devices

Requirement: The CIP over 6LoWPAN protocol should have a light-weight peer-to-peer communication capability for the resource constrained device-to-device communication (e.g., two constrained 6LoWPAN nodes).

Challenge: EtherNet/IP assumes a central control architecture for field devices. It can support peer-to-peer communication among high end devices (e.g., two PACs). However, supporting peer-to-peer communication is difficult for a field device because its limited resources cannot afford the EtherNet/IP originator functions.

Solution:

- Enhance and simplify the CIP protocol so that each field device can originate communication with minimal resources.
- Define resource/service discovery functions in the CIP protocol where devices carrying self-description information can be discovered by the other devices while on-line.

4.7 Protocol Conversion and Backward Compatibility

Requirement: The optimized/enhanced CIP protocol for 6LoWPAN shall cooperate and integrate with today's EtherNet/IP protocol. Similar functions in both protocols shall be easy to convert between the two protocols.

Challenge: The challenge is how to distinguish the optimized/enhanced CIP protocol for 6LoWPAN and the EtherNet/IP protocol and how to make the translation easy between them.

Solution Options:

a) EtherNet/IP is identified with an Internet Assigned Numbers Authority (IANA) assigned port (0xAF12). One obvious idea is to get another static port number assigned for the optimized/enhanced CIP protocol for 6LoWPAN to distinguish it from EtherNet/IP.
b) Another idea is to add a "protocol type" field in the encapsulation header to distinguish the optimized/enhanced CIP protocol for 6LoWPAN from the EtherNet/IP protocol.

In either case, to integrate EtherNet/IP networks and 6LoWPAN networks together, a proxy function should be implemented in between. The proxy function should include a transport protocol conversion between TCP and UDP, and an encapsulation protocol translation between the optimized/enhanced CIP protocol for 6LoWPAN and the EtherNet/IP protocol. It is easy to do UCMM explicit message translation because it just needs translation in the encapsulation layer. However, it may be a little more complex to do CIP Produce/Consume connection translation because it requires both the encapsulation and CIP protocol translation.

The optimized/enhanced CIP protocol for 6LoWPAN can still work over Ethernet, so if devices on Ethernet networks implement the function of the CIP protocol for 6LoWPAN, no proxy function is required in between for the communication between these types of Ethernet devices and 6LoWPAN nodes.

4.8 Security

Requirement: Security is very important for industrial field wireless sensor actuator networks. The CIP over 6LoWPAN protocol should have security functions.

Challenge: The EtherNet/IP and CIP protocol rely on external security services but do not integrate them.

Solution: There are a number of security options for a 6LoWPAN network: Link-level AES-128 which is implemented in the IEEE802.15.4 hardware, IP Security which is thought to be too heavy for 6LoWPAN nodes, DTLS (Datagram Transport Layer Security) which is an end-to-end security for applications, and a firewall which is typically located in an edge router to isolate the 6LoWPAN network from the other IP networks physically. ODVA EtherNet/IP system architecture SIG is working on CIP Security and CIP over 6LoWPAN should be introduced into that work to ensure a complete and holistic solution for CIP.

4.9 Network Management

Requirement: The 6LoWPAN network is commonly large scale and dynamic. The CIP over 6LoWPAN protocol should have network management functions.

Challenge: 6LoWPAN is a new type of physical link network for CIP.

Solution: Define the link and network management function for 6LoWPAN. There are many unknown details for this topic at the time of writing this paper, so a recommendation for a solution is premature.

5 CIP over 6LoWPAN Stack Prototype

Based on the Chapter 4 analysis, some of the requirements and corresponding proposed solutions, such as 4.1, 4.2, 4.3, 4.4, and 4.7, were implemented in a CIP over 6LoWPAN stack prototype which will be described in this section. This CIP over 6LoWPAN stack prototype was built to validate the concept of executing CIP in a low end, energy-challenged wireless node.

5.1 New Usage of UDP Ports

EtherNet/IP distinguishes explicit messages from implicit messages using the transport layer protocol. Explicit messages are transferred over TCP while implicit messages are transferred over UDP. In adapting CIP to 6LoWPAN networks, this mechanism does not work because TCP is not supported in the 6LoWPAN protocol.

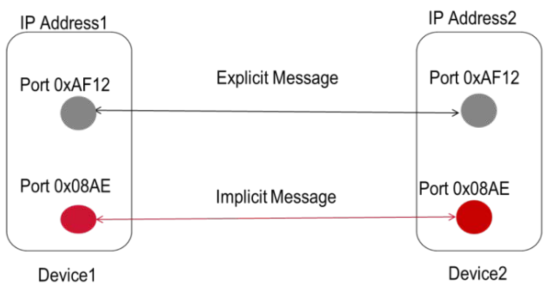

Figure 3 UDP Ports for Explicit and Implicit Messages

To solve this issue, two IANA assigned port numbers for EtherNet/IP are used to distinguish explicit messages from implicit messages. The port number (0xAF12) is used for the explicit message while the port number (0x08AE) is used for the implicit message. The usage of these two port numbers is mandatory. The server always opens a UDP socket with the port number 0xAF12 for receiving the explicit UCMM request.

5.2 CIP over 6LoWPAN Stack Features

Table 2 highlights the major differences between EtherNet/IP and the CIP over 6LoWPAN prototype. All these differences reflect the simplification efforts on today's EtherNet/IP protocol to make it feasible to be executed on the resource constrained 6LoWPAN wireless sensors and actuators.

Table 2 Comparison between EtherNet/IP and CIP over 6LoWPAN

EtherNet/IP	CIP over 6LoWPAN
IPv4	IPv6
TCP and UDP	UDP only
Session-based encapsulation protocol	Simplified session-less encapsulation protocol
Class3 and UCMM	UCMM only
Bi-direction Class 0/1 Produce/Consume connection	Simplified single direction Produce/Consume connection

A simplified encapsulation layer protocol is proposed for the 6LoWPAN network. Most of the unused fields in today's EtherNet/IP encapsulation layer protocol are removed, and the session management mechanism is removed as well.

Only UCMM is allowed for the explicit message while the connection-based explicit message is taken away. Only a unidirectional produce/consume connection is allowed for the 6LoWPAN network to reduce the connection management complexity.

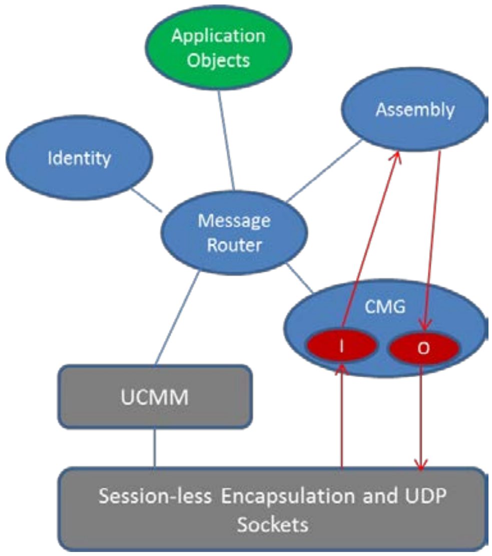

Figure 4 CIP Object Model for CIP over 6LoWPAN Stack

Only basic common CIP objects, such as Identity, Message Router, Assembly, and Connection Manager are implemented in the prototype. The CIP object model for the current CIP over 6LoWPAN stack implementation is shown in Figure 4. The Connection Manager object is optimized and simplified to support unidirectional input or output connections. The I/O connections are still transported over UDP, but based on a simplified encapsulation layer. The object specific services for the Connection Manager object used to create connections are only transported over UDP with UCMM. The object attributes are only accessible through UDP-based UCMM.

5.3 CIP over 6LoWPAN Stack Memory Consumption

The memory consumption of the stack was analyzed because the memory resource is very constrained in the low end 6LoWPAN node. The memory consumption is broken down into subsystems in Flash and RAM, as shown in Table 3.

Table 3 CIP over 6LoWPAN Stack Memory Consumption

Subsystem	Flash (Byte)		RAM (Byte)	
CIP	12,153	9.27%	1,444	4.41%
6LoWPAN	20,083	15.32%	358	1.09%
JNET[1]	29,549	22.54%	1,216	3.71%
Others (Debug, Storage, etc.)	11,400	8.70%	166	0.51%
Heap	N/A	N/A	10,352	31.59%
Stack	N/A	N/A	4,096	12.5%
Total	**73,185 (71.45K[2])**	**55.83%**	**17,632 (17.22K)**	**53.81%**
Available	**131,072 (128K)**	**100%**	**32,768 (32K)**	**100%**
Left for Application	**57,877 (56.55K)**	**44.17%**	**15.136 (14.78K)**	**46.19%**

1 JNET is a commercial personal area wireless networking and management protocol
2 1 Kbytes is 1024 bytes

The CIP stack prototype only occupies 12,153 bytes Flash and 1,444 bytes RAM under conditions: 2 UCMM request, 2 simplified Produce/Consume connections, one 2 byte input assembly, and one 2 byte output assembly.

The 6LoWPAN stack needs 20,083 bytes Flash and 358 bytes RAM with the configuration of 3 UDP sockets and 3 IP packet buffers of 1,496 bytes. Additional RAM required for the 6LoWPAN stack operation is dynamically allocated in the heap.

The JNET protocol (6LoWPAN wireless network management and layer-2 routing protocol) occupies 29,549 bytes Flash and 1,216 bytes RAM, which is the biggest portion of the total. Additional RAM required for the JNET protocol operation is dynamically allocated in the heap.

The heap for 6LoWPAN and JNET consumes 10,352 bytes RAM under the current configuration. This size depends greatly on the 6LoWPAN and JNET protocol configurations. For example, adding one IP packet in the message buffer requires an additional 1,496 bytes of RAM.

Based on the above analysis, 128 Kbytes Flash and 32 Kbytes RAM are big enough for most simple applications, allowing 56.5 Kbytes Flash and 14.78 Kbytes RAM for CIP application code (note 1 Kbyte is 1024 bytes).

6 CIP over 6LoWPAN Proof of Concept

A CIP over 6LoWPAN proof of concept demo platform, as shown in Figure 5, is constructed with two 6LoWPAN wireless nodes, one edge router, and one PC scanner. The 6LoWPAN wireless nodes and the edge router form one 6LoWPAN IPv6 sub network (fd04:bd3:80e8:2/64) while the PC scanner and the edge router connected through Ethernet or Wi-Fi form another IPv6 sub network (fd04:bd3:80e8:1/64). The edger router provides the IPv6 routing functions between these two IPv6 sub-networks, and connects the Ethernet/Wi-Fi, and the 6LoWPAN networks together. The edge router also compresses and depresses the IPv6 packets to and from the 6LoWPAN network.

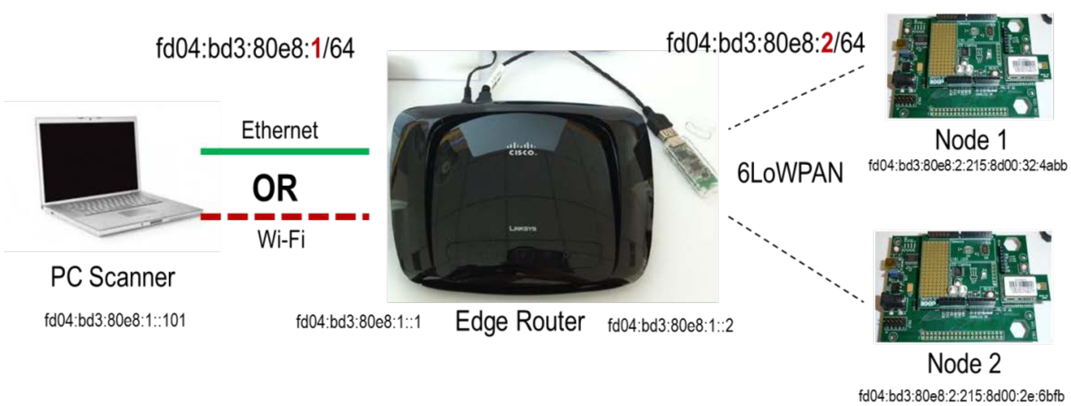

Figure 5 CIP over 6LoWPAN Proof of Concept Demo Platform

The PC Scanner and the 6LoWPAN wireless nodes work together to show light control functions. The graphical user interface in the PC scanner can be used to turn on or turn off the lights and adjust the brightness of the lights on the two 6LoWPAN wireless nodes. Specifically, the proof of concept demonstrates the following functions:

- Operate the devices (e.g., adjust the brightness of the light and turn on/off the light on two 6LoWPAN wireless nodes) by reading and writing the attributes in a Bulb object using UDP UCMM messages
- Operate the devices (e.g., adjust the brightness of the light and turn on/off the light on two 6LoWPAN wireless nodes) through a simplified Produce/Consume connection
- Communicate seamlessly between 6LoWPAN and Ethernet using the IPv6 and CIP protocol (There is no protocol translation in between.)

6.1 Operate Devices through UCMM

An application specific Bulb object is modeled and implemented using the CIP over 6LoWPAN stack in the 6LoWPAN wireless node. The Bulb object's attributes are defined as shown in Table 4. By accessing these attributes through the UCMM message, the lights on the 6LoWPAN wireless node can be turned on/off, and the brightness of lights can be adjusted with a preconfigured step value or be set with an absolute value. The UCMM message is the same as in EtherNet/IP, but the message is transported over the UDP protocol instead of the TCP protocol.

Table 4 Bulb Object Definition

Bulb Object, CLASS Code: 0x66, Instance:1			
Attributes			
ID	Name	Access	Description
1	Mode	SET	Turn On/Off Light
2	State	GET	Light current state
3	Lum_Current	GET/SET	Set bulb brightness
4	Lum_Up	SET	Increase brightness
5	Lum_Down	SET	Decrease brightness
6	Lum_ChangeStep	GET/SET	Set the step for UP and DOWN
7	Op_Cnt	GET	Record the operation count

A UCMM Client prototype was developed within the Pyramid Solutions environment, as shown in Figure 6, to control the lights on 6LoWPAN wireless nodes via the UCMM message. The 6LoWPAN wireless nodes are browsed and displayed in the right panel of the user graphical interface. For a selected 6LoWPAN wireless node, a UCMM request is initiated with the configurable CIP parameters as highlighted in the red box in the left panel of the user graphical interface; then a UCMM response should be received from the target 6LoWPAN wireless node. The response data, if any, will be displayed in the response box in the left panel.

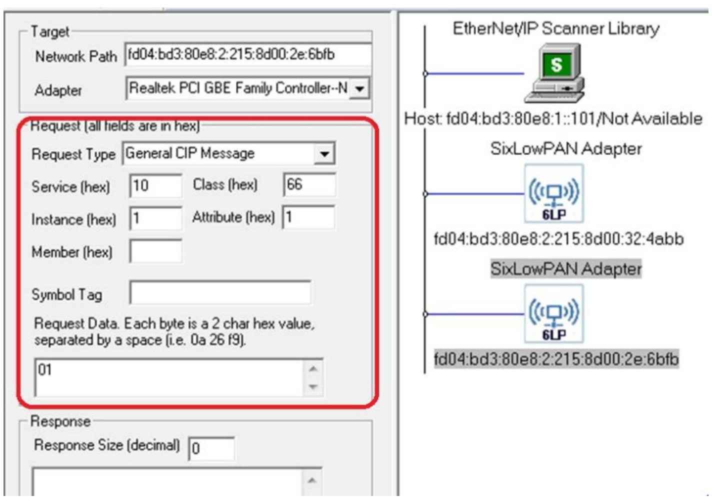

Figure 6 UCMM Client

As an example of the CIP parameter configurations in Figure 6, the target 6LoWPAN wireless node acts on the light control command (UCMM request) to turn on the light.

6.2 Operate Devices through the Simplified Produce/Consume Connection

The lights can also be controlled through the simplified unidirectional Produce/Consume connection. A connection originator, as shown in Figure 7, is prototyped to intuitively control the lights on the CIP over 6LoWPAN wireless nodes. This connection originator can originate a unidirectional Produce/Consume output connection to a target CIP over 6LoWPAN wireless node. The output data over this output connection includes one digital command bit (i.e., turn on/off the light), and one analog command data of the light brightness. The output data comes from the user operations on the graphical user interface shown in Figure 7. The output data will be consumed by the CIP over

6LoWPAN wireless node to update the light state and brightness. The user can easily click the operation buttons to turn on/off the lights and slide the slider bar to adjust the brightness of the lights to experience the effect of this demonstration.

Figure 7 Light Control Output Connection Originator

In summary, an integrated Wi-Fi and 6LoWPAN CIP system is demonstrated. The feasibility of executing CIP over the very low end 6LoWPAN wireless node and the feasibility of integrating the 6LoWPAN device into an EtherNet/IP system are validated.

7 Conclusion

IoT is going through an inflection point, with its technology being applied into more real time highly distributed applications. During the explosive growth of IoT deployment, the FWN is emerging as one of the major building blocks. In the domain of automation, the 6LoWPAN network is emerging as a potential standard for FWN, especially with its IP network support. In this paper we reviewed the 6LoWPAN network features, and analyzed the impacts of its integration into the EtherNet/IP plant control network architecture. The technical requirements and problems were discussed, and the corresponding possible solutions were proposed. A prototype CIP over 6LoWPAN stack was designed based on a commercial 6LoWPAN toolkit. The results show the feasibility of running CIP on a resource constrained 6LoWPAN node. An integrated demonstration was constructed with mixed 6LoWPAN, Ethernet and Wi-Fi networks. The demonstration validated the concept that the 6LoWPAN FWN can be seamlessly monitored and controlled in the EtherNet/IP plant control network without requiring a gateway in between. In the next steps, there are still open CIP topics to work on, including the peer-to-peer communication function, and the active data report function within the 6LoWPAN wireless nodes. In addition, the backward compatibility with the existing IPv4 EtherNet/IP plant network control system and the 6LoWPAN network management function need more study.

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