Assessing Open Interfaces and Protocols of PLCs for Computation Offloading at Field Level

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Abstract—Programmable logic controllers (PLCs) are the core element of industrial plants in todays deployments. They read sensor values, execute control algorithms, and write output values. Furthermore, industrial plants have lifetimes of one or more decades. Thus, in a realistic Industry 4.0 scenario, these devices have to be integrated in novel systems. In order to apply advanced concepts and technologies, such as computation offloading, which requires data exchange between PLCs and edge cloud, we investigate open communication interfaces of two typical PLCs of Siemens S7 series. Hence, each of the interfaces is analyzed based on plug & play capability, if metadata is provided, protocol efficiency, and performance. For the latter, the smallest possible update time for each of the interfaces will be measured.

Index Terms—PLC, smart manufacturing, Industry 4.0, industrial communication, communication protocols

I. Introduction

The convergence of information technology (IT) and operational technology (OT) is one important enabler for realizing Industry 4.0 use cases [1], whereby 5th generation wireless communication system (5G) is seen as key technology for realizing mobile use cases [2]. In addition, mobile devices, such as automated guided vehicles (AGVs) or drones, can profit by the so-called computation offloading, e.g., to save energy [3]. Thus, if these devices provide a high mobility, e.g. movement between factory halls, the offloaded algorithms also have to be mobile [4], [5]. However, there are reasons for not only using computation offloading for mobile devices. Since algorithms are getting more and more complex, the computational power of resource constrained devices, such as PLCs may be exceeded. Furthermore, Industry 4.0 describes "lot size one" what requires a reconfiguration of process controllers at very short time intervals. Since legacy devices do not provide this flexibility but are required as interface to sensors and actuators due to life-cycle-times of industrial plants of ten years or more [6], offloading of algorithms to edge clouds is a suitable approach.

In order to realize data exchange between PLCs and devices that are located in the area of the OT and applying novel

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technologies, such as virtualization [7], open interfaces and protocols are required. Therefore, we investigate communication protocols of PLCs that are natively compatible with OT hardware and thus using standard Ethernet and Internet Protocol (IP) layer.

II. ACCESSING DATA FROM PLCS

In this section the possibilities for accessing data of two PLCs are examined, which are part of the S7 series. Therefore, the individual interfaces are described in detail and a comparison is carried out (see Tab. I). Besides the specification of the protocol, qualitative aspects, such as plug & play capability and the availability of metadata is investigated. In addition, the protocol efficiency, which can be expressed by the payload divided by the total number of bytes sent, is determined for 1, 10, and 100 data values, where each data value is assumed to be 4 bytes. Furthermore, the update time plays a major role as it indicates the frequency with which data packets can be sent. It is defined as the "[...] time interval between any two consecutive messages delivered to the application." [8]. Therefore, we examine the minimum update time that the device can use to send a new data packet for 1, 10, and 100 data values. This value is characteristic for the investigated PLC and network independent.

A. Open User Communication (OUC)

The OUC was originally developed with the intention to allow multiple PLCs to exchange data using the following IP-based protocols:

- User Datagram Protocol (UDP) (RFC 768),
- Transmission Control Protocol (TCP) (RFC 793), and
- ISO-on-TCP (RFC 1006).

Since it cannot exclusively used by PLCs, this interface is well suited for offloading data to edge devices. As ISO-on-TCP, which is also referred to as "S7 Protocol", does not bring an advantage compared to standard TCP, it is not discussed in the OUC section.

1) UDP: For sending data from the PLC to a mini PC using UDP-based OUC, two function blocks (FBs) (TCON, TUSEND) must be configured in the PLC. Among other things, the IP address and the port number must be specified there. For this reason the PLC must be stopped to be able to use the new software module. Therefore, the OUC does not allow plug & play mechanisms to avoid downtime of the PLC. Also, the

Table I

COMPARISON OF THE INTERFACES OF THE INVESTIGATED PLCs USING STANDARD ETHERNET.

Interface		Protocol	Plug &	Meta-	Protocol Efficiency & Min. Update Time								
Configuration			Play	data	1			10			100		
					Data Value		ue	Data Values			Data Values		
						314	1512	ĺ	314	1512		314	1512
					[%] [ms]		[%]	[ms]		[%]	[ms]		
Oper	ı User	UDP	-	-	5.6	1.00	3.61	42.6	1.00	3.60	88.1	1.00	3.63
Communication		TCP	-	-	2.8	1.01	3.77	22.5	1.04	3.78	74.4	1.02	3.83
LIBNODAVE		ISO on TCP	+	-	1.2	2.00	1.32	10.8	2.00	1.32	54.6 ²	4.00	1.40
OPC	Write	UATCP	-	+	0.9	n/a	6.83	6.3	n/a	7.36	14.5	n/a	16.56
UA	Service												
Server	Read	UATCP	+	+	0.8	n/a	9.11	3.7	n/a	30.35	5.4	n/a	246.1
Client	Service												
OPC UA PubSub		UADP	-	0	5.5	n/a	1.02	33.9	n/a	1.26	70.4^{1}	n/a	2.30^{1}

¹As the current firmware of the PLC allows a maximum of 20 data values to be transferred, but it can be assumed that this restriction will be removed in a newer version, the value was estimated.

Table II OVERVIEW ABOUT NAME AND SIZE OF THE DIFFERENT DATA MESSAGES.

Message S	Message Size [byte] Data Values				
Interface	Name	1	10	100	
Open User	UDP_Data	72	94	454	
Communication	TCP_Data	144	178	538	
LIBNODAVE	Job	169	169	169	
	Ack_Data	167	203	563	
OPC	WriteRequest	234	396	2154	
UA	WriteResponse	202	238	598	
Server	ReadRequest	270	756	5778	
Cient	ReadResponse	212	338	1598	
OPC UA	DataSetMessage	73	118	568	
PubSub					

data to be sent is packed directly into the payload of the UDP packet, without any additional information. This means that no metadata is provided and the receiver must know exactly how the data is structured, such as the byte order and data type. Due to this fact, the payload is very heterogeneous, but a very efficient data transmission can be realized, since only the UDP, IP and Ethernet II headers of 8, 20, and 26 bytes have to be added. This results in a protocol efficiency of 5.6% for 1 data value, 42.6% for 10 data values, and 88.1% for 100 data values. One of the drawbacks is that the PLCs is not able to send a packet in each cycle. This results in a update time of \approx 3.6 ms for S7-1512 PLC. However, the udpate time for the S7-314 PLC is significantly lower, compared to S7-1512 PLC. Here, update times of 1 ms are possible. Furthermore, the update times of both PLCs are almost independent of the payload size.

2) TCP: The use of TCP in OUC is comparable to UDP. Besides the configuration of a different FB (TSEND), the only difference lies in the transport protocol, as the name implies.

Here the characteristic is that each of the packets is acknowledged and thus no packet loss can occur, since lost packets are automatically retransmitted. This results in a higher reliability, but also a higher overhead, compared to UDP. Thus, in addition to the larger header of TCP, which is 20 bytes, the 72 bytes per acknowledge reduce the protocol efficiency, which is almost half for 1 and 10 data values and about 15% lower for 100 data values compared to UDP. In addition, the larger header and acknowledgment generation increases the minimum update time slightly.

B. LIBNODAVE

LIBNODAVE is a free and open source library for using the ISO-on-TCP protocol communicating on TCP/IP port 102 for data exchange with Siemens S7 PLCs [9]. If the RJ-45 port where the cable is connected is not explicitly disabled, any device supporting the S7 protocol can communicate directly with the PLC. This enables plug & play capability, but is also the reason why this protocol has already been used for cyber attacks such as Stuxnet [10]. This means that appropriate security measures must be taken if there is a connection to the Internet or if there is a possibility that malware can be placed on a device that communicates with the PLC, because on some series not only can data values be read and written, but the complete PLC can also be stopped. This is especially true for older models like the 300 and 400 series. In the 1500 series, the function has been severely restricted so that critical functions such as start and stop can no longer be executed by any device. However, read and write access is still possible. This makes it a suitable protocol for accessing data of the PLCs studied in this paper.

Since in this communication method the S7 protocol is built on top of TCP, the protocol overhead is larger compared to OUC. In addition, the data exchange must be triggered by the edge device. Since all network traffic required for the data exchange should be considered, the messages required to query the data and its acknowledgements must also be considered. To request data, the so-called *Job* message is sent. As shown in Tab. II,

²For the S7-314 series this value is halved, because two requests have to be sent.

this remains the same size for both 1, 10, and 100 data values. This is because the data is requested over its memory area and the length of the data chunk. The response of the PLCs, called Ack_Data message, contains the data and consequently becomes larger, with increasing the number of data values. Considering both messages results in low protocol efficiencies of 1.2%, 10.8% and 54.6% without any meta information about the sent data. In addition, the protocol data unit (PDU) size of the S7-314 PLC is limited to 240 bytes. Therefore, only \approx 50 data values can be read within one request. In order to obtain 100 data values, two requests have to be send. This results in twice the update time, protocol overhead, and thus, in a halved protocol efficiency. However, until a maximum of polling 50 data values, the update time of the S7-314 PLC is constantly 2 ms. Regarding the S7-1512 PLC, the aforementioned restriction is not given. Furthermore, it is able to send a new data packet every 1.2, 1.32, and 1.4 ms.

C. Open Platform Communications Unified Architecture (OPC UA)

To close the gap between IT and OT, OPC UA [11] was introduced. It aims at a secure, simple and platform-independent exchange of information between industrial applications [12]. For this purpose, it provides both a self-describing information model and various communication protocols. Even though the information model in conjunction with the data exchange is a major milestone in industrial automation, we will focus on the communication protocols in the following. Since OPC UA is not supported for the S7-300 series, no values can be measured for this interface for the S7-314 PLC. If computation offloading using OPC UA server client or Publish/Subscribe (PubSub) is explicitly required, a gateway has to be connected next to the PLC, as proposed in [13]. To offload data from the S7-314 PLC to the gateway, the investigated interfaces can also be used. Then the data can be offloaded to an edge device.

1) OPC UA Server Client: The OPC UA server client pattern supports the binary TCP-based communication protocol (UATCP) as well as a solution that is well suited for web services based on Simple Object Access Protocol (SOAP)/Hypertext Transfer Protocol (HTTP). Due to lower resource consumption and less overhead, which is important for embedded devices like PLCs, we focus on the UATCP protocol running on port 4840.

Two different services are possible for data exchange between PLC and the edge node, depending on the role of each device in the specific scenario, since the client and server roles are strictly defined. The client sends requests to the server that are answered with a response. Thus, if the PLC is the client and wants to send data to the mini PC, it must send so-called *WriteRequests* containing the data values to be written to the server's address space. Then, this message is replied with the *WriteResponse* to give the client a response with some information, such as a status code. Also, both messages contain a lot of metadata, such as the timestamp of the device, the unique identifier of the variable in the address space, and the data type, just to name some of the information. This makes the protocol very powerful, but comes with a larger overhead. Therefore, the *WriteRequests* have the sizes of 234 bytes, 396 bytes, and 2154 bytes for 1, 10, and 100

data values, respectively. In addition, the *WriteResponses* add another 202 bytes, 238 bytes, and 598 bytes. This results in a low protocol efficiency that is, for example, < 1% for 1 data value.

If the roles are swapped, so the PLC being the server and the remote application running on the edge node being the client, the data must be exchanged via the ReadService. This means that the edge node is the client and must poll the data from the server. To do this, a *ReadRequest* containing the variables to be read is sent to the server running on the PLC. The message is then responded with the *ReadResponse*, which contains the current data values. Similar to the WriteService, the data also contains a lot of metadata. Therefore, the protocol efficiency is also low for 1, 10, and 100 data values. Due to the protocol overhead and meta information, the efficiency for 100 data values does not improve much compared to 1 or 10 data values because the message must be split into multiple TCP segments and thus multiple Ethernet packets. These issues are also responsible for the low performance in terms of update times. However, what is an advantage for this interface is the direct access to the data without reconfiguration of the PLC.

2) OPC UA PubSub: Due to the drawbacks of the server client model concerning protocol overhead and the descresed protocol efficiency of exchanging requests and responses, part 14 of the OPC UA specifications adds the PubSub pattern. This allows many subscribes to register for a specific content [14]. For the message distribution both broker-based protocols, in particular message queuing telemetry transport (MQTT) and advanced message queuing protocol (AMQP), and UADP, a custom UDP-based distribution based on the IP standard for multicasting has been defined. Due to the advantages to send real-time messages on the field level directly on the data link layer, part 14 defines the transport of PubSub messages based on Ethernet frames. Until now, the PLCs of the S7 family only support the data exchange with UADP. Therefore, only this protocol is discussed. As shown in Fig. 1, there are several possibilites regarding structure of the packet. Since this

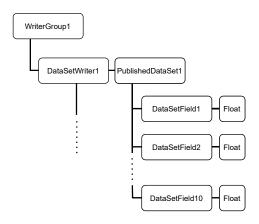


Figure 1. Structure of OPC UA PubSub network messages.

interface requires reconfiguration of the PLC, it is not plug & play capable. First a *WriterGroup* must be defined. Under the *WriterGroup* are logically grouped the so-called *DataSetWriters*, which are associated with a *PublishedDataSet*. Furthermore, the *PublishedDataSet* contains the *DataSetFields* where the specific data value is placed. Additionally, the OPC UA data type of

the data is added as meta information so that the subscriber can interpret the data correctly. We decided to configure only one DataSetWriter and one PublishedDataSet containing 1 to 10 data values for our measurements. So far, it is only possible to use 10 DataSetFields per PublishedDataSet and two DataSetWriters per WriterGroup. Therefore, the maximum data values that can be sent per WriterGroup is 20. For this reason, we can only estimate the protocol efficiency and update time for 100 data values. Independently, OPC UA PubSub performs best in terms of update times for 1 and 10 data values of ≈ 1 ms and 1.26 ms, respectively. Moreover, the achievable protocol efficiency is comparable to that of OUC. This is the result of the low overhead given by the metadata. If this is even better for 1 and 10 data values, the additional overhead of 1 byte per data value for 100 data values compared to the TCP-based OUC is slightly higher than the TCP protocol overhead including acknowledgements.

D. Summary

Looking deeper into the different interfaces, it can be seen that each of the interfaces has strengths in one of the categories. If a low overhead is the most important requirement, OUC is best suited. If the focus is on plug & play functionality to integrate brownfield devices without having to reconfigure the PLC, LIBNODAVE or the ReadService of the OPC UA server client model can be used. Here, a decision must be made between good performance and the need of meta information. Last but not least, UDP-based OPC UA PubSub provides a very good trade-off in terms of update time, protocol efficiency, and the presence of at least some meta information of the data values plus a standardized communication protocol. This is very important for the required interoperability of devices and applications on the way to Industry 4.0. Here also the combination of time-sensitive networking (TSN) and the Ethernet-based OPC UA PubSub has already been discussed [15]. The use of raw Ethernet frames can save both the overhead and processing of the UDP/IP protocol headers. Therefore, increased performance of this interface can be assumed.

III. CONCLUSION

In this paper, we investigated open interfaces of two PLCs of Siemens S7 series. Therefore, we assessed all available interfaces using standard Ethernet according to qualitative aspects such as the protocol used, plug & play capability, and the availability of metadata. Furthermore, quantitative criteria, such as protocol efficiency and update time, were evaluated for each of the interfaces of both PLCs. It turned out, that all of the interfaces, that were taken into account have their strengths and weaknesses. Concluding, the interface and protocol used must be carefully selected according to the requirements of the particular application.

IV. FUTURE WORK

Even though our research mainly focused on the best performance in terms of lowest overhead, least update time, most metadata, and plug & play capability, other protocols may be attractive for various industrial Internet of Things (IIoT) applications. Examples include application layer protocols such as

MQTT, Constrained Application Protocol (CoAP), and HTTP. Especially when dealing with 1-to-n relationships and latency or minimal update time are not the main concern, these protocols can be a good solution.

In addition, it would be interesting to examine break-even points for a realistic computing offloading scenario, based on the chosen interface, network design, and complexity of the algorithm. For the latter, different levels of complexity are possible, such as classical proportional-integral-derivative (PID) controllers, more complex ones, such as linear-quadratic regulators (LQRs) in combination with Kalman filters or state observers for multiple states, or ones that solve nonlinear equations.

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