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An overview of DLMS/COSEM and g3-plc for smart metering applications

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Abstract

A crucial part of the smart grid communication network is the Advanced Metering Infrastructure (AMI), connecting a utility company to end-users to support telemetry and remote-control applications. Although different technologies and standards for smart metering systems exist, Power-Line Communication is the preferred technology for AMI networks in dense urban areas, and the G3-PLC, which uses DLMS/COSEM to support data exchange, is the most used standard in PLC-based AMI networks. This paper provides a holistic view of G3-PLC in smart metering systems, including its interaction with the DLMS/COSEM. It also covers the challenges and research opportunities in G3-PLC smart metering systems.

Keywords

Advanced metering infrastructure, HDR NB-PLC, Narrowband power-line communication standard, Smart grid communication, Smart metering data exchange standard.

Introduction

Constant monitoring and control of the grid are the essential parts of the Smart Grid (SG) operation. To achieve this, having a widespread sensor network for monitoring the grid's status and an effective communication infrastructure for transferring data between different grid entities are required. In fact, it is not far from reality to claim that the SG's success depends on the reliability of its deployed communication network (Khurana et al., 2010). The smart metering system is a major part of the SG's monitoring and communication network, and its establishment is considered as an early step in the realization of the SG (Wu et al., 2018).

A smart metering system, which is also known as the Advanced Metering Infrastructure (AMI), is a telemetry and control network connecting SG's end-users to utility companies' data and control centres. The AMI employs information and communication technology to establish bi-directional communication links between Smart Meters (SMs) and Utility Companies (UCs) for transferring measurement data from SMs to UCs and notifications and control commands from UCs to SMs (Uribe-Pérez et al., 2016).

Both wireline and wireless technologies have been used in AMI networks. While wireless technologies are more suitable for geographically dispersed and versatile networks, Power-Line Communication (PLC) technologies are the preferred and cost-effective choice for dense urban areas, as no additional media installation is required (Deblasio and Tom, 2008; Erlinghagen et al., 2015). Power line intelligent metering evolution (PRIME), supported by the PRIME Alliance, and G3-PLC, supported by the G3-PLC Alliance, are the most widely used PLC-based standards in AMI networks. PRIME has been deployed on more than 20 million SMs across 15 different countries in the world "Prime Alliance Home Page", (2022), and G3-PLC, which has a larger market, is currently used by over 80 million products in more than 30 countries "G3-PLC Alliance Home Page" (2022). The G3-PLC penetration has faster growth, and the number of G3-PLC-enabled devices in the past two years has grown by 60%.

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Since the G3-PLC standard release in 2009, field experiments and research on G3-PLC-based AMI networks have begun (Razazian et al., 2011, 2013), and it continues to this date (Llano et al., 2020; Kumar et al., 2021; Lavenu et al., 2021). G3-PLC benefits from various communication techniques, such as channel estimation, frequency selectivity, extensive channel coding schemes, mesh routing protocol and the support for IPv6, which have made it a suitable choice for a variety of applications. However, the increase in G3-PLC penetration into more devices and applications has brought up new challenges and research opportunities to overcome its existing limitations.

To the authors' best knowledge, all research done on the G3-PLC focuses on improving the performance of the standard on a specific layer, mostly the physical layer. However, smart metering systems, regardless of their employed communication technologies, should operate in accordance with data exchange standards. This allows seamless interoperability between different smart metering elements from different vendors (Gungor et al., 2012). Such interoperability reduces costs and opens doors to a larger market. Although in some wireless smart metering systems, the data modelling has been influenced by the concept of wireless sensor networks and Machine-to-Machine communications (Wu et al., 2011), such as the OneM2M data exchange standard, the Device Language Message Specification/Companion Specification for Energy Metering (DLMS/COSEM) has been considered as the most popular data exchange standard in smart metering applications around the globe (Commission, 2002; Feuerhahn et al., 2011; DLMS User Association, 2022). PRIME and G3-PLC both use DLMS/COSEM as their data exchange standard. Figure 1 shows an overview of the protocols used in different layers of G3-PLC metering applications. The upper three layers are part of the DLMS/COSEM suite, and the four lower layers belong to the G3-PLC.

This paper provides a holistic view of G3-PLC in smart metering systems, including its interaction with the DLMS/COSEM. The rest of the paper is organized as follows: First, in the section "smart metering systems", an overview of smart metering systems and the most used technologies and standards in such systems have been covered. The section "An overview of DLMS/COSEM" covers the DLMS/COSEM standard used for data exchange in the G3-PLC. This follows by covering the G3-PLC protocol layers in the section "An overview of G3-PLC". The recent challenges and research opportunities for G3-PLC-based AMI network are discussed in the section "Challenges and Research opportunities for G3-PLC", and, finally, the paper is summarized in the section "Conclusion".

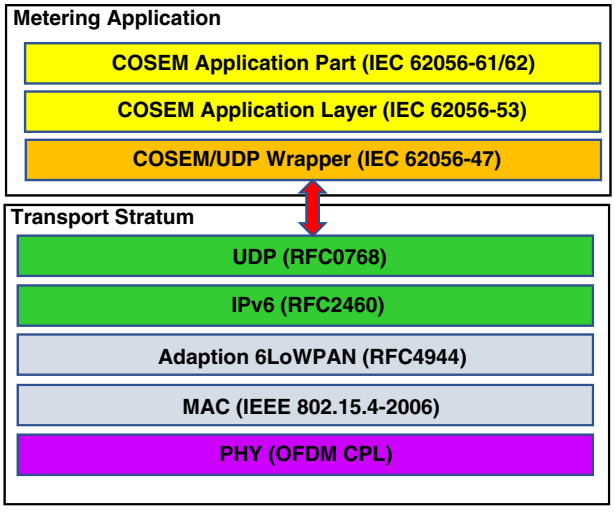


Figure 1: OSI layer mapping for metering application of G3-PLC.

Smart metering systems

The first generation of communicating meters is the automated meter reading (AMR) system. AMR systems operate based on one-way communication links, which connect multiple meters to a data centre and can only be used for remote data collection (Khalifa et al., 2010). The collected data is used for billing, consumption analysis and troubleshooting purposes. Although employing AMR systems reduces labour costs and provides more accurate and up-to-date billing, it cannot be used in more advanced applications, such as demand response and load control applications.

The AMI is a developed version of AMR systems that benefits from SMs' capabilities. SMs, which are more than just data collectors (Yan et al., 2012), make the AMI a sophisticated metering system capable of supporting data exchange between consumers and the UCs for supporting advanced applications, such as load management and controlling distributed generation and storage units (Wu et al., 2016a, 2016b; Wang et al., 2018). As a result, establishing the AMI opens up many new opportunities to increase the efficiency, reliability, and safety of the grid. Figure 2 depicts an overview of the AMI system. The AMI comprises SMs, Data Concentrators (DCs) and meter data management systems (MDMS). A DC collects measurement data from SMs at a set time interval and forward it to MDMS for further processing and storage. Also, a DC conveys

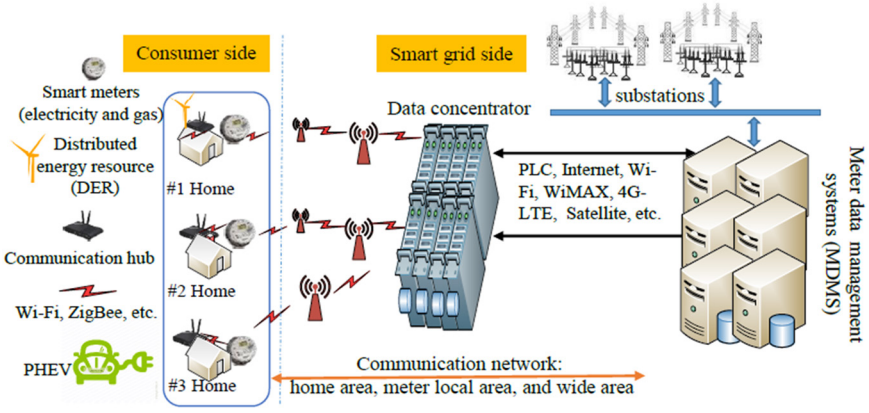


Figure 2: An AMI network and its components (Fan and Gong, 2013).

the control commands and notifications from the UC's control centres to its connected SMs.

According to the IEEE2030-2011 standard, the AMI communication network is divided into three sub-networks: home-area network (HAN), neighbourhood-area network (NAN) and wide-area network (WAN) (Zhou et al., 2012). HAN links SMs to in-home smart appliances. NAN covers communications between SMs and DCs, and WAN consists of communication links between DCs and MDMS.

Wireless smart metering technologies and standards

Wireless standards such as IEEE 802.15.4 (Zigbee and Zwave) and IEEE 802.11 have a great potential to be used in an AMI's HAN (Kumar et al., 2017). IEEE 802.15.4 can establish low-cost, energy-efficient communication networks with data rates of up to 250 kbps over a range of 100 m. However, IEEE 802.15.4 does not contain a sufficient level of security (He et al., 2014). IEEE 802.11, on the other hand, supports secure communication with data rates of up to 54 Mbps over a range of 300 m. Nevertheless, it is prone to interference and suffers from high power consumption (Erol-Kantarci and Mouftah, 2014).

Among cellular standards, GSM/GPRS, UMTS and LTE are more popular to be used in wireless AMI systems. Cellular technologies can offer high data-rate communication over long ranges; however, establishing cellular infrastructure owned by a UC is very costly. The required infrastructure can, alternatively, be hired from a cellular communications service provider. Nevertheless, this can bring in other concerns, such as the reliability and security of the network. IEEE 802.16 (WiMAX) (Mao and Julka, 2012) and IEEE 802.20 (MobileFi) have also been proposed for the AMI's WAN. Although in many countries, wired technologies, such as fibre optic communications, are more preferred for this part of the network (Yaacoub and Abu-Dayya, 2014). The standards and technologies used for WAN should be capable of supporting high data-rate communication over a range of a few tens of kilometres.

The other group of wireless standards used in the AMI network is based on Radio Frequency (RF) mesh technologies and are mostly deployed in the NAN. RF links use unlicensed radio frequencies of up to 900 MHz, which makes them vulnerable to interference caused by other transmitters operating in this band. Nevertheless, an RF-based NAN has the advantage of being self-formed and self-healed. This is because the collected information by an SM is routed to a DC by hopping through other SMs, and if a meter becomes unavailable, a different route can be established to get information across. KamstrupRF, MeshNet3 and Flexnet are examples of RF mesh metering standards. KamstrupRF and MeshNet3 can achieve data rates of up to 9.6 kbps over a range of 10 km in rural areas. Flexnet, on the other hand, supports data rates of up to 172 kbps over a range of 30 km (Gungor et al., 2011).

PLC smart metering technologies and standards

PLC technologies use frequency modulation techniques for data transmission and are categorized, according to their operational bandwidths, into three major groups: Ultra-narrowband PLC (UNB-PLC), narrowband PLC (NB-PLC) and broadband PLC (BPL). UNB-PLC systems, which utilize frequencies below

3 kHz, can transmit information over long distances without a need for repeaters. However, UNB-PLCs are only useful for low data-rate transmissions. NB-PLCs, on the other hand, operate at the frequency range of 3 to 500 kHz. This frequency range includes the US Federal Communication Commission (FCC) band (10–490 kHz), the Japanese Association of Radio Industries and Business (ARIB) band (10–450 kHz), the Chinese band (3–500 kHz), and the European CENELEC bands: CENELEC-A (35.9–90.6 kHz), CENELEC-B (98.4–120.3 kHz), CENELEC-C (125–140 kHz) and CENELEC-D (140–143.7 kHz). NB-PLCs can only support transmissions of up to 500 kbps. Lastly, BPLs operate at the frequency ranges of 1 to 250 MHz with data rates of up to 500 Mbps.

The data rate in PLC technologies reduces by the increase in transmission range. As a result, BPL systems have a limited transmission range of a few hundred meters. Moreover, BPL standards are not interoperable, which makes them a less favourable technology to be used in smart metering applications. NB-PLCs, on the other hand, are useful for smart grid's supervisory, control and telemetry applications. NB-PLCs can cover a range of 2 km, and in many countries, including China, Russia, France, Spain and Italy, are the preferred technology to be used in the AMI's NAN. NB-PLC technologies are categorized into two groups as low data rate (LDR) and high data rate (HDR).

LDR NB-PLCs operate based on single carrier modulation and have a transmission rate of a few tens of kbps. Open Smart Grid Protocol (OSGP), Meters&More, Power Line Automation Network (PLAN) and Automated Measuring and Information System (AMIS) are the most popular LDR NB-PLC standards. OSGP was initially promoted by Echelon and partially standardized by the International Electrotechnical Commission (IEC) under ISO/IEC 14908–3. OSGP has the highest penetration in Russia and Nordic countries. Another well-known LDR NB-PLC standard is Meters&More, which is widely used in Spain and Italy's AMI network. Meters&More is led by the ENEL group. Both OSGP and Meters&More standards use Binary Phase Shift Keying (B-PSK) modulation and can achieve data rates of up to 57 kbps. The other European LDR NB-PLC standard is PLAN, which is standardized by the IEC under IEC 61334. As a requirement by the European standards body CENELEC, PLAN should operate over the CENELEC-A band, and so it can co-exist with other compatible standards on the same AMI network. AMIS is an LDR NB-PLC standard developed by Siemens and uses Differential Code Shift Keying (DCSK) to transmit data rates of up to 3 kbps. AMIS is mainly deployed in Austria.

HDR NB-PLC standards can offer higher throughputs (up to 1Gbps) by employing Orthogonal Frequency-Division Multiplexing (OFDM) modulation over a frequency range of 9 to 500 kHz. PRIME which is later standardized as ITU G.9904, G3-PLC (ITU G.9903), ITU G.9902 and IEEE 1901.2 are the most popular HDR NB-PLC standards for smart metering applications (Atayero et al., 2012). PRIME is proposed by Iberdrola, a Spanish distribution system operator, and has two versions. The European version, PRIME v1.3.6, operates over the CENELEC-A frequency band, and the American version, PRIME V1.4, which is designed for frequencies of up to 500 kHz. PRIME v1.3.6 can transmit data rates in the range of 21.4 to 128.6 kbps and uses convolutional codes for error correction. PRIME can only support iPv4. G3-PLC, which is developed by ERDF (a French distribution system operator), has a transmission rate in the range of 2.4 to 33.4 kbps over the CENELEC-A frequency band and can support up to 150 kbps over 150 to 500 kHz (FCC) band. It also supports iPv6. G3-PLC standard uses extensive channel coding techniques to increase data transmission robustness at lower data rate transmissions.

Interoperability is an issue among different NB-PLC standards. For example, the PRIME standard cannot co-exist with PLAN on the same network segment. There have been attempts by both ITU-T and IEEE to homogenize NB-PLC metering standards. ITU G.9902 (ITU-T G.hnem) is an attempt taken by ITU-T in this regard, which contains the recommendation for NB-PLC technologies over both CENELEC and FCC frequency bands. The focus of the ITU G.9902 is on robustness, which even outperforms G3-PLC. IEEE 1901.2 is an attempt by the IEEE to standardize NB-PLC technologies. It includes both PRIME and G3-PLC specifications providing mechanisms that both standards can co-exist on the same network. Table 1 summarizes the technical characteristic of the abovementioned NB-PLC standards.

An overview of DLMS/COSEM

During the European standardization process, it became clear that there is a need for a single application data model to help improve interoperability between devices and databases in an AMI network. Data exchange standards have been developed to serve such a need. DLMS/COSEM is a suite of standards covering data exchange and interface modelling of metering devices. DLMS/COSEM has been amended by the IEC TC13 WG14 as IEC 62056 series of standards, specifically for electricity metering applications (S. G. S. Group, 2010). Nevertheless, there

Table 1. An overview of the technical characteristic of the NB-PLC standards.

Standard	Modulation	Data rates	Frequency Band	IP	Other features
PLAN	S-FSK	0.2–2.4 kbps	CENELEC-A		
AMIS	DCSK	0.6–3 kbps	CENELEC-A		
OSGP	B-PSK	3.6–57.6 kbps	CENELEC-A		
Meters&More	B-PSK	4.8–57.6 kbps	CENELEC-A, ARIB, FCC		
PRIME	OFDM	21.4–128.6 kbps	CENELEC-A	iPv4	Tree
G3-PLC	OFDM	2.4–33.4 kbps	CENELEC-A, ARIB, FCC	iPv6	Robust mode, mesh routing
1901.2	OFDM	Approximately 80 kbps	CENELEC-A, ARIB, FCC	iPv6	Coherent modulation
G.9902	OFDM	Approximately 80 kbps	CENELEC-A, FCC	iPv6	Coherent modulation

are minor differences between the communication specifications of DLMS/COSEM and IEC 62056.

COSEM provides objective models for describing the functionalities of metering devices, and DLMS (IEC 62056-5-3) is a stack of open standards developed by the DLMS User Association (DLMS UA) for supporting data exchange for telemetry and remote control of different energy sources, including water, electricity, gas and heat. In other words, COSEM is the data model, which describes a meter's functionality, and DLMS specifies the rules to access and modify (i.e., get/set) such data. DLMS/COSEM has been described by a set of colour-coded books (blue, green, yellow and white). Blue book describes the COSEM meter classes and interface object models. Green book covers DLMS's architecture and protocol. Yellow book pertains to questions concerning conformance testing, and white book contains a glossary of terms.

G3-PLC employs COSEM interface classes (IEC 62056-6-2) and object identification system (IEC 62056-6-1) standards for interface modelling and data identification of AMI devices. According to IEC 62056-6-2, each physical metering device consists of a set of logical devices (LDs), where each LD supports one or more applications. For instance, in a multi-meter device, one LD can be allocated for the electricity metering, another for the gas metering and a third one for the water metering. Physical metering devices may have multiple LDs, but it is mandatory for every meter to contain a management LD. DCs, on the other hand, are modelled by a set of client application processes (APs) for representing metering functionalities. Similarly, a DC may have multiple APs, but it is mandatory for every DC to contain a public client AP. There are specific applications for the management LD and public client in establishing connections between meters and DCs, which will be explained later in this section.

The functionalities of LDs are defined through COSEM interface objects. A COSEM interface object is an instantiation of an interface class (IC). An IC is identified by a "class_id" and generalizes COSEM interface objects that share common characteristics. A COSEM interface object comprises a set of attributes and methods for describing an LD's functionalities. An LD may have one or more objects, but all LDs must have an "Association" object. This object has an attribute called "object list" containing the list of all available objects on an LD with their names, addresses and access rights. "Association" object would also be used in establishing communications between a DC and an LD.

COSEM interface objects are named with logical names (LNs). LNs are generated based on Object Identification System (OBIS), which is an octet-string of length 6 as 

... The value of "A" identifies the energy type (A = 1 for electricity-related objects). The value of "B" is related to the channel number. The value of "C" depends on the value of "A" (Some of "C" values are given in Table 2 for A = 1). The value of "D" identifies the method of measurements (e.g., instantaneous values, maximum value). The value of "E" refers to further measuring information, such as electricity fees (tariff rates), which is also identified according to the value of "A". Finally, the value of "F" pertains to historical information in a meter related to the parameters from "A" to "E". More on the OBIS code values can be found in the DLMS/COSEM blue book and the IEC 62056-6-1 standard. Using short names (SNs)

Table 2. Values of group C for electricity energy (A = 1).

Code	Physical data
0	General purpose objects
1	Active power+
3	Reactive power+
11	Current: any phase
12	Voltage: any phase
14	Supply frequency
⋮	⋮

mapped to the LNs is also allowed to reduce the complexity.

An example of the COSEM model for an electricity meter capable of measuring active and reactive energy is shown in Figure 3. In this example, the "Register" IC with "class_id=3" is defined for modelling the generic register containing measured information. The "Register" IC has two attributes: "logical_name" and "value" and a method named "reset". Two objects are instantiated from the "Register" IC for capturing the "Total Positive Active Energy" and the "Total Positive Reactive Energy".

The DLMS protocol (IEC 62056-5-3) covers the data exchange between SMs and DCs. The communication follows a client/server model, where a DC acts as a client, and the SM plays the role of a server. DLMS can be implemented on top of different lower layer protocols, including Transmission control protocol (TCP) and User datagram protocol (UDP) at the transport layer, logical link control (LLC), High-Level Data Link Control (HDLC) and Medium access control (MAC) at the data-link layer and different PLC and RF technologies at the physical layer. DLMS is a connection-oriented protocol, which covers the logical connections between a client and a server and also the interconnections to the lower layers' protocols.

To establish a connection and collect data, the public client AP residing in a DC should communicate with the meter's management LD, also known as the server AP. The packet transfer by the DLMS protocol follows a precise sequence. This sequence is classified into three steps: namely, set up data link, data transfer, and disconnect data link. Before data collection can take place, a communication link between client and server APs should be established. This is known as

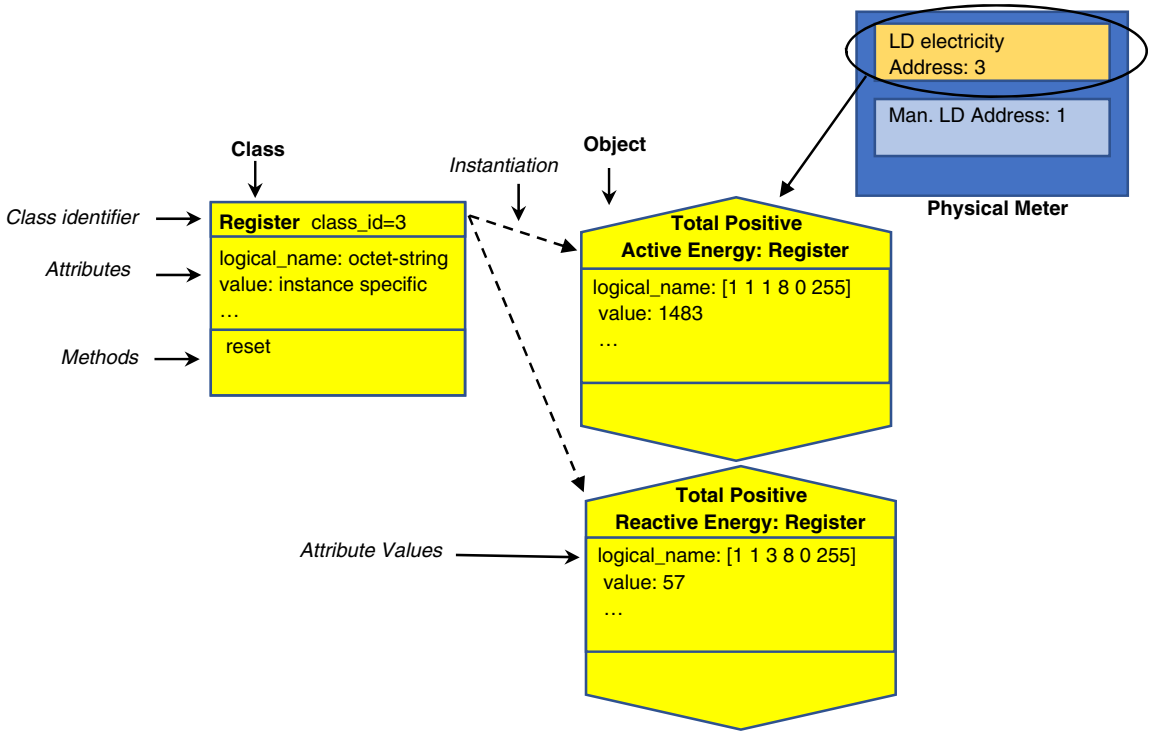


Figure 3: Example of COSEM object models.

Application Association (AA) establishment, which is a logical connection between client and server APs and has to be supported by prior lower layers connections. The association (logical connection) between APs is done by the Application Control Service Element (ACSE), which is an application layer's standard service. ACSE uses AARQ (A-Associate Request) and AARE (A-Associate Response) packets to start a connection. Once the AA is established, data can be exchanged between a client and a server using another application layer standard service, known as the Extended DLMS application service element (xDLMS_ASE). The task of xDLMS_ASE is to access COSEM interface objects' attributes and methods. xDLMS_ASE uses the attributes of an LD's Association object, which are in the form of LNs or SNs, to identify and locate different objects residing in an LD. After the data exchange is complete, the session will be closed by releasing the AA. ACSE uses RLRQ (A-Release Request) and RLRE (A-Release Response) packets to terminate the session. The ACSE's application protocol data units (APDUs) are encoded by the basic encoding rule (BER), while the data transfers, which are done by xDLMS APDUs, are encoded in the Adapted extended data representation (A-XDR).

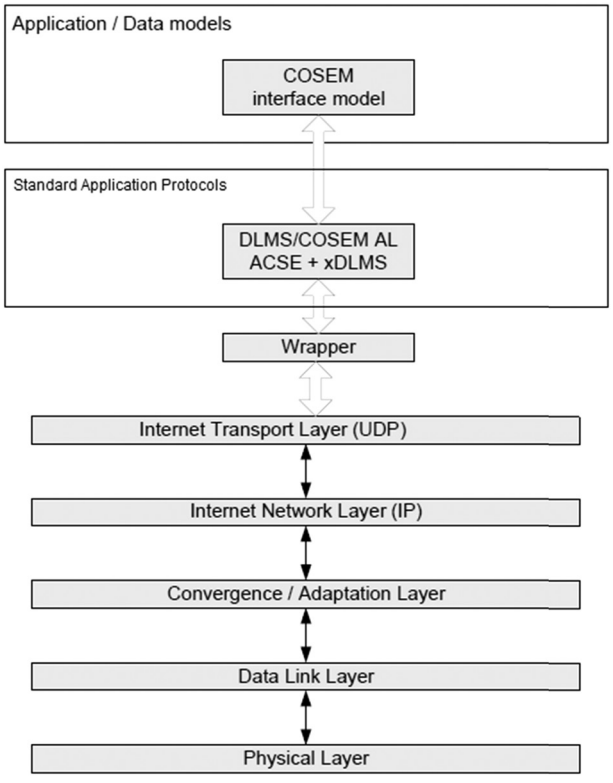


Figure 4: DLMS/COSEM supported by G3-PLC protocols.

An overview of G3-PLC

As was mentioned, the DLMS provides support for COSEM APs connections based on the services received from the lower layers. In G3-PLC, these lower layers are COSEM/UDP wrapper (IEC 62056-4-7), UDP, iPv4 or iPv6, which is implemented in conjunction with 6LoWPAN, MAC layer and finally OFDM PLC at the physical layer. Figure 4 shows an overview of the DLMS/COSEM, which is supported by the G3-PLC protocol.

Addressing is an important part of any communication system. In a G3-PLC AMI network, an IP address is assigned to each physical device during the network registration process. Moreover, all LDs and APs are labelled by two-octets addresses known as Service Access Points (SAPs). While some SAPs are predefined, such as 0x10 for the public client APs and 0x01 for the management LDs, others are open to being assigned to other APs and LDs. Any new meter that is added to the network should first communicate with the DC's public client AP to be registered. Also, a meter's management LD contains SAP addresses for all the LDs residing in that meter.

The UDP wrapper (IEC 62056-4-7) task is to map the SAP values to a UDP port number, which is also known as the Wrapper port. The wrapper is a stateless protocol and only scales down the SAPs values to match the values of the UDP ports. The wrapper also helps with identifying the length of APDUs that are transmitted. The length of the payload will be included in the UDP header. The DLMS's APDUs may consist of ACSE's APDU or xDLMS APDUs, with each having a different length. Therefore, there is a need to identify the length of the packets.

Transport and network layer

The communication model of G3-PLC integrates a transport layer protocol with an IP suite in the network layer. The recommended network layer protocol for the G3-PLC is UDP (RFC 0768). However, UDP offers transport of datagrams in a non-connected mode, which is unreliable. To increase reliability, G3-PLC also allows the TCP protocol to be implemented at the transport layer. Nevertheless, TCP is not considered in the G3-PLC documentation, as sufficient reliability for data transmission has already been provided by subjacent layers.

For the network layer, both iPv4 and iPv6 have been considered by the standard. However, G3-PLC standard documentation considers iPv6 protocol (RFC 2460), which is preferred for supporting applications over the

long term. The header size of UDP/iPv6 is originally 48 bytes. However, this amount of overhead would compromise the transmission speed. To overcome this problem, instead, G3-PLC uses compressed headers for the UDP and iPv6. The compression is done at the upper sublayer of the data-link layer using an adaption sublayer, which will be covered in the next section.

Data-link layer

The data-link layer in G3-PLC consists of two sublayers: An adaption sublayer based on RFC 4944 and a MAC sublayer based on IEEE 802.15.4-2006. The adaption sublayer compresses the UDP/iPv6 headers. The compression is done by using the 6LoWPAN (RFC 4944) specification. 6LoWPAN was originally developed for supporting iPv6 on low-power devices with limited processing power, and it compresses the UDP/iPv6 headers from 48 bytes to 5 bytes.

Figure 5 shows the Adaption 6LoWPAN frame format. The number of bytes for each frame segment has been shown above that frame segment. The HC1, HC2 and UDP sections form the 5 bytes representing the UDP/iPv6 header. HC1 and HC2 bytes are used to compress iPv6 and UDP headers, respectively. HC1 provides information on the compression format of iPv6, and HC2 byte holds information on the UDP-header compression format. The byte that is shown as the iPv6 segment contains the Hop Limit value. The UDP component includes information about the UDP source port, UDP destination port, length of the UDP payload and a checksum byte. The port numbers are compressed into 4-bit from their original 16-bit values. The actual 16-bit values are calculated by adding the 0xF0B0 value to the compressed port number.

The routing function that the G3-PLC uses in the Mesh mode is the Lightweight On-demand Ad hoc Distance-vector (LOAD) protocol-next generation. LOAD is a simplified version of the Ad hoc On-demand Distance Vector (AODV) routing protocol that is drafted for 6LoWPAN. It is a reactive on-demand protocol, which means it is only triggered by the request of a source node, and no periodic signalling is required. LOAD enables identifying the optimized route between any two nodes in a network. Optimization is done based on minimizing the route cost. The LOAD's messaging diagram is shown in Figure 6.

1	1	1	3	0-n
HC1 (IPv6)	HC2 (UDP)	IPv6 NC fields	UDP NC fields	Frame Body

Figure 5: The 6LoWPAN frame format for the G3-PLC.

When no valid route is available between a source and a destination node, the source node first broadcasts a route request signal (RREQ) to all its neighbouring nodes. RREQ carries route cost information based on the used metric. Each intermediate node on the path then adjusts the route cost information and forwards the signal to its neighbouring nodes till it reaches the destination. The destination can then select the optimized route according to the route cost information. The destination node will then unicast back a route replies (RREP) signal to the source node. The source and intermediate nodes will be able to identify their neighbours and the optimal route through the RREP signal. LOAD has originally been developed for the wireless network and has shown a few shortcomings in the PLC networks. As a result, an enhanced version of LOAD for PLC networks has been developed. This enhanced version is known as the LOAD-next generation (LOADng) protocol.

To access the medium, the G3-PLC uses the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism with a random back-off time. As a result of this random back-off mechanism, the collision probability will be reduced as the channel access time by a node is randomly spread over a period of time. After the back-off time is over, a node will try to access the medium. If the channel is found to be idle, the node starts transmitting. Alternatively, if the channel is found to be busy, the node shall wait for the next contention period based on the packet's priority. Then the process will start all over again by waiting for the back-off time to be expired before trying to access the channel.

A typical MAC layer data frame is shown in Figure 7. As is seen, it encapsulates the 6LoWPAN fame by 13 bytes of header and 6 bytes of trailer. All segments except the security header and Message Integrity Check (MIC) are compulsory segments in every frame.

The Frame Control (FC) segment, which consists of 2 bytes, identifies the type of a frame and its format. This segment is followed by a byte of information on the sequence number, which is used to eliminate duplicate transmitted frames. The addressing is done by 4 bytes: Two bytes are considered for the PAN number to allow several networks co-existing on the same given infrastructure and two bytes for the destination address. The Security Header is optional and contains information related to the security methods and their information. The trailer has two

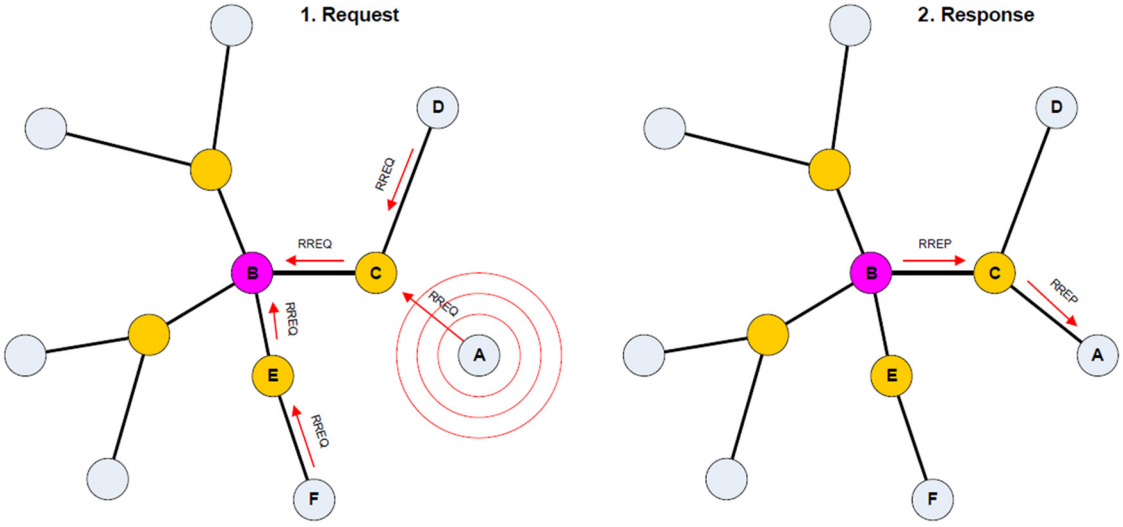


Figure 6: The messaging in LOAD protocol.

Bytes: 2	1	2	2	6	1	1	1	3	0-n	4	2
Frame Control	Seq Nbr	Dest PAN	Dest Addr (RA)	Security Header	HC1 (IPv6)	HC2 (UDP)	IPv6 NC fields	UDP NC fields	Frame Body	MIC	FCS

Figure 7: A typical MAC layer data frame.

segments: MIC and Frame Check Sequence (FCS). MIC is optional, but FCS is a compulsory segment. MIC length is four bytes and is used to verify whether the frame has been maliciously modified or truncated. FCS length is two bytes and is used to identify transmission disturbances during the frame transmission.

Physical layer

G3-PLC has been defined over CENELEC, FCC, and ARIB bands. In this section, we look at the G3-PLC physical layer specifications defined over the CENELEC-A band, which has been mostly used. The frame structure of the G3-PLC at the physical layer is given in Figure 8. Each physical frame starts with a preamble sequence used for synchronization and detection in addition to automatic gain control adaptation. This sequence follows by a 5 bytes frame control header (FCH) block. The FCH contains important information that is required for demodulating the data frame. Figure 9 shows the overall block diagram of the transmitter in a G3-PLC system. The G3-PLC uses OFDM, Differential Phase Shift-Keying (DPSK) modulation and multiple FEC coding schemes to overcome harsh impairments in PLC channels.

There are three modes of transmission in G3-PLC: Normal mode, Robust mode and Super Robust mode. Normal mode and robust mode are used for data transmission, and super robust mode is only used for transmission of the FCH. DBPSK is the modulation scheme for the robust and super robust modes, while the normal mode can use either DBPSK, DQPSK or D8PSK modulation schemes.

To transmit data across a PLC channel, the collected data from the upper layers, together with the

	Bytes: 5	Bytes: 2	1	2	2	6	1	1	1	3	0-n	4	2
Preamble	Frame Control Header	Frame Control	Seq Nbr	Dest PAN	Dest Addr (RA)	Security Header	HC1 (IPv6)	HC2 (UDP)	IPv6 NC fields	UDP NC fields	Frame Body	MIC	FCS

Figure 8: A typical physical layer frame format.

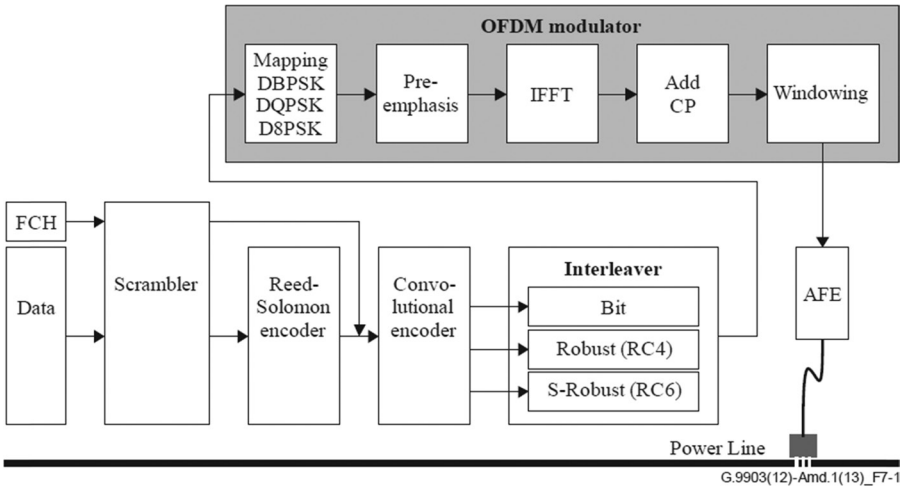


Figure 9: Block diagram of the G3-PLC transmitter at the physical layer.

33 bits belonging to the FCH, should, first, go through a data scrambler block, which gives them a random-like distribution. The data bits are then encoded by shortened Reed-Solomon (RS) codes. The RS codes are either shortened from RS(255,247,8) or from RS(255,239,16). Shortening is done by making a certain number of data symbols equal to zero at the encoder and then re-inserting them at the decoder to be able to decode the codewords. The RS code rates used in the CENELEC-A band are given in Table 3. The code rate selection is based on the chosen number of transmitted symbols per frame and the modulation scheme.

The encoded data and the FCH bits are then passed through two consecutive channel coding blocks: a convolutional code and a repetitive code (RC). The convolutional code has a rate of ½ and a constraint length of 7. The encoder is shown in Figure 10. The RC block code for super robust, robust and normal modes are RC(6,1), RC(4,1) and RC(1,1), respectively.

The G3-PLC uses a 256 points fast Fourier transform (FFT). In the CENELEC-A, only 36 sub-carriers are active, and the rest are masked. Each subcarrier carries a DPSK modulated signal. DBPSK, DQPSK and D8PSK are the considered constellation sizes.

For preventing channel group delays, a 30-sample cyclic prefix (CP) is added to the beginning and again repeated at the end of each sequence. The generated

Table 3. RS encoders based on modulation.

CENELEC-A Number of symbols	Reed-Solomon blocks (bytes) D8PSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) DQPSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) DBPSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) Robust (Out/In) (Note 2)
12	(80/64)	(53/37)	(26/10)	N/A
20	(134/118)	(89/73)	(44/28)	N/A
32	(215/199)	(143/127)	(71/55)	N/A
40	N/A	(179/163)	(89/73)	(21/13)
52	N/A	(233/217)	(116/100)	(28/20)
56	N/A	(251/235)	(125/109)	(30/22)
112	N/A	N/A	(251/235)	(62/54)
252	N/A	N/A	N/A	(141/133)
NOTE 1 – Reed-Solomon with 16 bytes parity. NOTE 2 – Reed-Solomon with 8 bytes parity.				

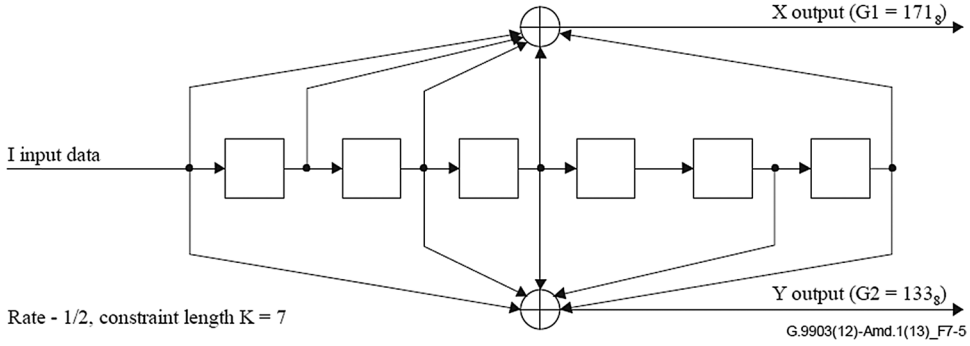


Figure 10: Convolutional encoder used in the G3-PLC.

sequence will then pass through a windowing block to reduce the out-of-band leakage of the transmit signals. Finally, the signal will be sent to the PLC medium through an analogue front-end (AFE).

To calculate the number of FCH symbols, we begin by considering n_{FCH_bits} = 33, which occupies 5 bytes. The output of the convolutional encoder contains:

$$n_{FCH_bits_conv_encoded} = 2 \times (n_{FCH_bits} + 6) = 2 \times 39 = 78\, bits$$

The encoder adds six zeros tail bits at the end of the input sequence to return the convolutional encoder to the "zero state". Since FCHs are transmitted in super robust mode, RC(6,1) will be used, and so the encoded sequence length of the RC block encoder is:

$$n_{FCH_bits_RC_encoded} = 6 \times n_{FCH_bits_conv_encoded} = 6 \times 78 = 468\, bits$$

and the number of OFDM symbols by considering that super robust mode uses DBPSK is equal to:

$$n_{FCH_symbols} = \frac{n_{FCH_bits_RC_encoded}}{N_{carr}} = \frac{468}{36} = 13\, symbols$$

Therefore, in each physical frame, 13 OFDM symbols should be transmitted for the FCH. Also, the preamble length is 9.5 symbols.

Table 4 shows the achievable data rate for different modulation schemes. The maximum data rate that can be achieved is by using the RS (215,199) encoder. However, as is seen in Figure 8, 25 bytes

Table 4. Data rate for various G3-PLC modulation and coding schemes.

CENELEC-A	Data rate per modulation type, bit/s			
Number of symbols	D8PSK, P16 (Note 1)	DQPSK, P16 (Note 1)	DBPSK, P16 (Note 1)	Robust, P8 (Note 2)
12	21 829	12 619	3 410	N/A
20	32 534	20 127	7 720	N/A
32	42 619	27 198	11 778	N/A
40	N/A	30 385	13 608	2 423
52	N/A	33 869	15 608	3 121
56	N/A	34 792	16 137	3 257
112	N/A	N/A	20 224	4 647
252	N/A	N/A	N/A	5 592

NOTE 1 – Reed-Solomon with a 16 byte parity.
NOTE 2 – Reed-Solomon with an 8 byte parity.
NOTE – N/A means not applicable and the reason for this is that the corresponding number of symbols specified results in an RS encoder block length that exceeds the maximum allowable limit of 255.

of the header and trailer bytes should be transmitted in addition to the DLMS/COSEM payload. Therefore, the DLMS/COSEM payload transmission per physical frame is only 199–25 = 174 bytes, which makes its data rate equal to 37 kbit/s, considering sampling frequency of 0.4 MHz.

Challenges and research opportunities for G3-PLC

Two approaches have been considered for studying the G3-PLC AMI networks. The first approach benefits from field tests on the existing infrastructures (Razazian et al., 2011, 2013), while the other uses simulations and analytical methods for studying a network (Di Bert et al., 2014). Analytical approaches can be useful in the sense that they can provide a fair network performance approximation prior to installing physical equipment. This helps to avoid any unnecessary costs due to the network alteration.

Traditionally, the focus of much research in PLC-based AMI networks was to, first, model the physical layer of a standard and then attempt to improve its performance (Kim et al., 2010; Mengi and Vinck, 2010; Razazian et al., 2010). The work presented in Banwell and Galli (2001) has attracted more attention among different studies that have been done on modelling the physical layer. In this work, the transmission line theory was used to model PLC channels with transfer functions. The obtained transfer function was then used to identify the frequency response of a PLC channel. The transmission line and the graph theories have been combined in González-Sotres et al. (2017) to propose an analytical approach for computing the signal attenuation in a PLC-based AMI network. In addition to the frequency-selectivity of a PLC medium, noise is also an important factor in PLC communications. Background noise (Hooijen, 1998) and impulsive noise (Nassar et al., 2012) are the two major impairments in PLC channels. The model of the G3-PLC standard's physical layer is given in Sanz et al. (2017). Also, the source of the noise in the G3-PLC network in the United States powerlines has been studied in Razazian et al. (2011). Recently, the focus of the research on the physical layer has been shifted towards meeting the required Electromagnetic compatibility (EMC) of the G3-PLC (Beshir et al., 2021; El Sayed et al., 2021a, 2021b; Sayed et al., 2021a; Sayed et al., 2021b), as more power electronic devices have been connected to the PLC channel causing electromagnetic interference (EMI) in the 9 to 150 kHz band.

The performance of the MAC protocols in a PLC-based AMI network has been studied in Korki et al. (2011). It was shown that the MAC layer protocols are required to be carefully adjusted to be suitable for being effectively used in the PLC-based networks (Razazian et al., 2013). A dynamic trust evaluation method is designed in Weiqiang et al. (2020) to improve the performance of the G3-PLC standard's MAC layer. Moreover, the obtained information from the G3-PLC node's neighbour table (NT) has been used for the power outage and phase detections (Lavenu et al., 2021).

Network layer protocols also play an important role in the overall performance of AMI networks. The effectiveness of wireless network protocols for being used in the PLC-based AMI network has been studied in Ikpehai and Adebisi (2015) and Peng and Fei (2016). Data transmission latency and communication outage can significantly affect the Quality-of-Service (QoS) required for fulfilling AMI applications. As a result, QoS-aware routing protocols have to be employed in AMI communication networks. For this purpose, first, the required QoS for an AMI application has to be identified, and then the focus should be on the routing methodologies to achieve such targets. Examples of QoS requirements can be as an acceptable delay, jitter and connection outage probabilities. There are many challenges in selecting efficient routing protocols for an AMI network. Firstly, routing for SG applications should be based on multiple QoS-aware routing that holds multiple constraints. The probabilistic dynamics of a grid is another factor that should be considered in developing QoS requirements (Ferreira et al., 2011). Through analyzing field measurement data, the routing anomalies in the G3-PLC network have been studied (Marcuzzi et al., 2020). Therefore, routing protocol enhancement to avoid unstable routes in dense networks is required. This topic can specifically be studied considering that data transmission and routing in G3-PLC is based on the flooding method, which is not an efficient method in dense networks.

Multi-hop message routing is a challenge in PLC-based AMI networks. In such systems, each SM also acts as a repeater for the other SMs to extend the network coverage (Bumiller, 2009). As a result, the topology of a network has a significant effect on the routing reliability in a PLC network. In Bumiller (2009), Bumiller et al. (2010), Ngcobo and Ghayoor (2019), the effects of unforeseen changes of topology on the reliability of PLC networks have been studied, and the concept of single-frequency network transmission is presented for flooding of messages. The recent shift in improving routing in the G3-PLC is towards employing artificial intelligence methods (Cui et al., 2018; Marcuzzi and Tonello, 2019).

Similar to any other communication network, topology should have an effect on the performance

of an AMI network. The locations of SMs in PLC-based AMI networks have been considered in Biagi et al. (2016) to obtain optimum routing algorithms. The optimization problems were constrained by energy consumption and transmission delays. The optimized location of SMs in PLC-based AMI networks was found in Atat et al. (2019). They proposed a stochastic geometry-based method. The AMI network considered in this research has a dynamic nature, and the optimization is done by forecasting the topology in the future.

Recently researchers have considered hybrid PLC-RF AMI networks to take advantage of both technologies (Sanz et al., 2021a). studied the performance of such systems and showed improvement in the AMI network coverage. The field measurement for a hybrid PLC-RF network has been performed in Sanz et al. (2021b) to validate the simulation results. This recent development opens up new opportunities for developing applications beyond smart metering over the same AMI network.

Conclusion

After covering a summary on smart metering systems and different wireless and wireline technologies employed in various sections of the AMI network, it was discussed that the PLC is the preferred technology for smart metering applications in dense urban areas. Among all PLC-based standards deployed in AMI networks, the G3-PLC is the most widely used standard and has the fastest growth. This is a result of various communication techniques considered in the G3-PLC design, which has been made it a suitable choice for a variety of applications. However, the increase in G3-PLC penetration into more devices and applications has brought up new challenges and research opportunities to overcome its existing limitations. Therefore, this paper first provided a holistic view of G3-PLC in smart metering systems, including its interaction with its data exchange standard, the DLMS/COSEM. This was followed by the still-existing challenges in different layers of the G3-PLC and recent advances that have been made to alleviate such challenges. Finally, it was concluded that the future AMI system would benefit from a hybrid of wireless and PLC-based technologies to efficiently exploit rare spectral resources.

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