G3-Alliance

User Guidelines

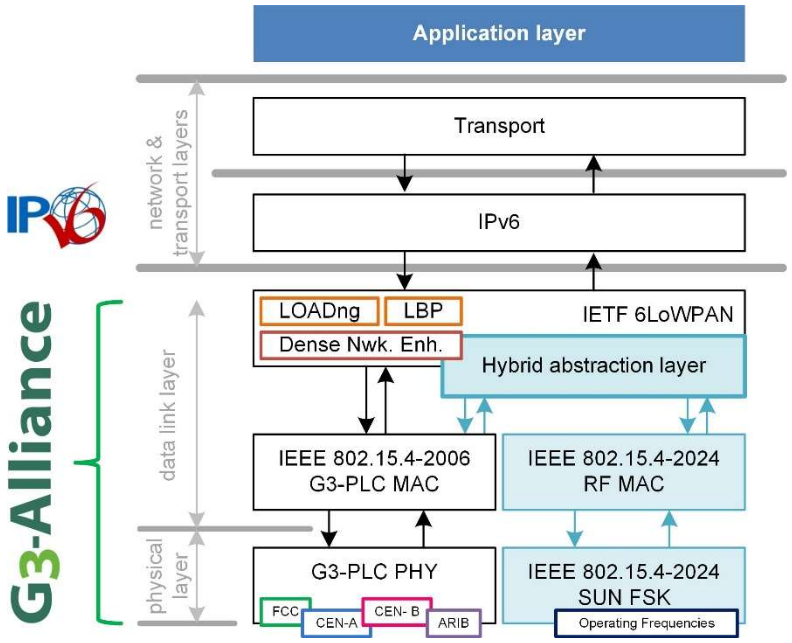
Introduction to G3-PLC and G3-Hybrid (version 3.0, 10/2025)

Executive Summary

This paper is an introductory document to the G3 technology and precedes a series of user guidelines published by the G3-Alliance, intended to help end-users and manufacturers in implementing and deploying G3-PLC and G3-Hybrid products.

In this document, the G3-PLC protocol stacks and its main characteristics will be briefly presented, as well as the G3-Hybrid profile which comes as an extension to the existing G3-PLC protocol stack.

In addition, this paper also introduces the G3-Alliance and its certification program.



About G3-Alliance Solutions

G3-Alliance solutions facilitate high-speed, highly reliable and long-range communication over the existing power grid (G3-PLC), possibly using additional radio communications (G3-Hybrid). These solutions' features and capabilities have been developed to address the difficult challenges of powerline communications. While earlier approaches were a step in the right direction, they fall short of meeting the technical and reliability requirements necessary in the hostile environment of the power grid.

G3-PLC meets these requirements because of its unique features such as a mesh routing protocol to determine the best path between remote network nodes, a "robust" mode to improve communication under noisy channel conditions and channel estimation to select the optimal modulation scheme between neighbouring nodes.

G3-Hybrid complements G3-PLC with an additional radio communication medium, enabling unprecedented levels of coverage and resilience. G3-Hybrid also paves the way for new interconnection possibilities by extending hybrid network connectivity to other radio communication devices and infrastructures.

Furthermore, the support of IPv6 enables easy integration of various application profiles, adds high versatility and carries G3-PLC and G3-Hybrid well into the future.

G3-PLC and G3-Hybrid are open international standards published by ITU: https://www.itu.int/rec/T-

REC-G.9903

To help adopters properly integrate the G3-Alliance protocol stacks in products and systems we have developed a set of user guidelines. All user guidelines can be found on the G3-Alliance website: https://g3-alliance.com/technologies/specifications-user-guidelines-private/

For more information: visit www.g3-alliance.com

Content

1. Overview of G3 technology

1.1. The G3-PLC protocol stack

1.1.1. Introduction

G3-PLC [1] is a narrowband power line communication (NB-PLC) OFDM technology based on state-of-the-art narrowband PLC standards (the reference published international standard is ITU-T G.9903 [3] while power spectral density is defined in ITU-T G.9901 [2]) operating in several bandplans covering the overall frequency range 3 – 500 kHz to address numerous use cases matching regional regulation, as shown in Figure 1:

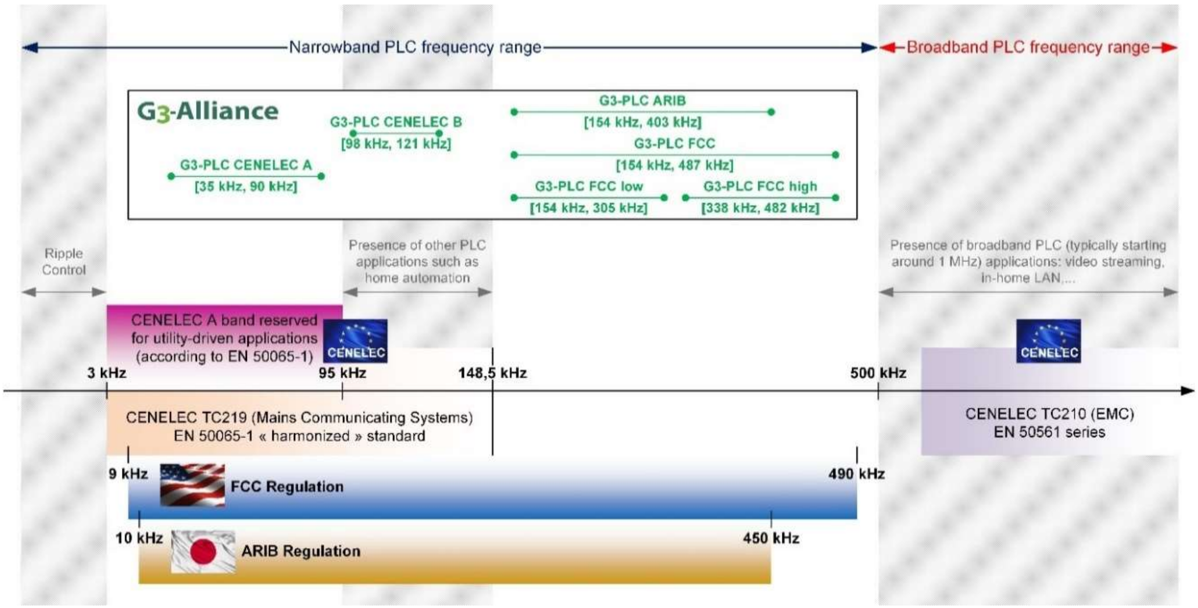


Figure 1: Different bandplans to address different needs and match regional regulation

The G3-PLC communication stack consists of a specific **OFDM physical layer**, an **IEEE 802.15.4-2006 [4] based MAC layer** and an **IETF 6LoWPAN-based adaptation layer** allowing **native support of IPv6.** The ITU-T G.9903 [3] standard is describing the G3-PLC lower layers (physical and data link layers). The G3-PLC communication stack is maintained, promoted and certified by the G3-Alliance.

The modular design of the stack allows the selection of different options at different layers (especially frequency bandplan and routing).

In addition, support of the IPv6 protocol [5] grants end-user flexibility to fulfil business requirements when choosing the appropriate higher layers (transport and application layers). This key feature also secures G3-PLC infrastructures in the long term, thanks to the scalability and future application compatibility provided by IPv6.

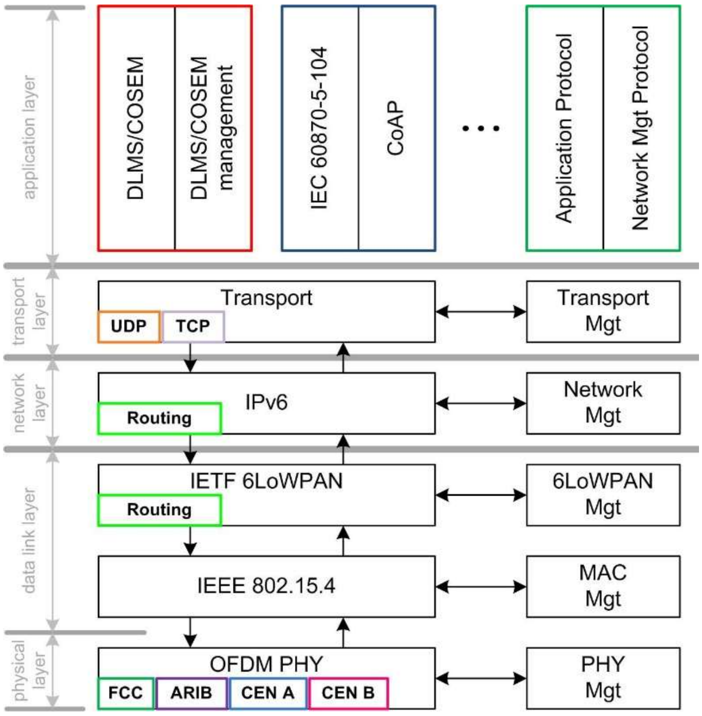


Figure 2: Typical G3-PLC communication stacks

1.1.2. G3-PLC main technical features in a nutshell

As pointed out previously, G3-PLC is an internationally standardized communication protocol stack gathering the advantages of an IPv6 compatible solution and offering high performances at the data link and physical layers.

Indeed, the OFDM physical layer embeds **powerful error correction** mechanisms based on a Reed-Solomon encoder followed by a convolutional encoder and a two-dimensional interleaver introducing time and frequency diversity, as well as an additional redundancy scheme with repetition codes.

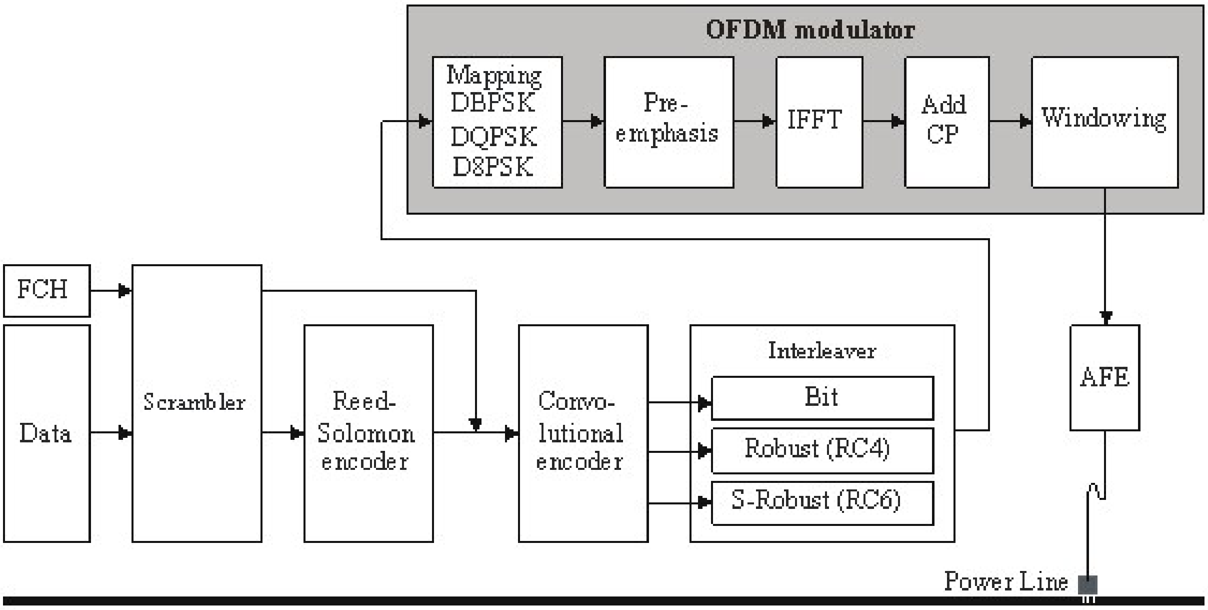


Figure 3: Block diagram of a G3-PLC OFDM transceiver

Each OFDM subcarrier uses one of the following differential modulations: **D8PSK, DQPSK and DBPSK**. Optional coherent modulations offering a higher level of robustness (BPSK, QPSK, 8PSK) may be used. **Robust mode**, consisting of a DBPSK modulation and a repetition code is a unique feature in NB-PLC, making G3-PLC particularly suitable for use in noisy environments. These modulations provide physical theoretical data rates of **up to 44 kbps in the CENELEC-A bandplan** and **up to 280 kbps in the FCC bandplan**.

In addition, **channel estimation allows G3-PLC neighbour nodes to continuously adapt the robustness/data rate compromise** by choosing the appropriate modulation but also to transmit data on the right OFDM subcarriers (“tone mapping”).

The abovementioned physical layer key features position G3-PLC as a technology suitable for harsh noisy environments typically observed on power lines.

From a data link layer perspective, the MAC layer is based on an adapted version of the original IEEE 802.15.4-2006 [4] standard including an **enhanced CSMA/CA access method**, **acknowledgement of unicast frames**, **automatic repeat request (ARQ)** and **different priority levels to carry out QoS**. The IETF 6LoWPAN-based adaptation layer allows **IPv6 header compression** (to limit the impact of the overhead imposed by the IPv6 protocol) and **fragmentation** for optimal IPv6 support but also provides a G3-PLC node with a **routing algorithm optimized for the PLC medium: LOADng**.

Note: LOADng is implemented and enabled by default in all G3-PLC products. However, if required by the end-user, it is possible to disable the LOADng protocol[1]*.*

Security is also present at several layers of the G3-PLC communication stack. **CCM* AES-128 ciphering** is provided by the IEEE 802.15.4-based MAC layer and **EAP-PSK authentication** is provided by the adaptation layer allowing the secure association of G3-PLC nodes to a G3-PLC network.

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[1] Routing may be done at the IP level using LOADng or any other routing protocol.

1.2. The G3-Hybrid (PLC+RF) extension

1.2.1. Rationale for the G3-Hybrid (PLC+RF) extension

Different communication technologies are often seen as competitors by the different industry stakeholders. When selecting a technology, end-users are called upon to make the best achievable compromise taking into account the characteristics of a technology and its appropriateness to the targeted use cases. In the market of low cost and low data rate technologies, **power line communications (PLC) and radio frequency (RF) technologies are systematically opposed, but why not combine their advantages?** The concept of mixing PLC and RF lower layers in the same protocol stack is not new, but market demand has only emerged recently, increasing the potential for development opportunities.

The G3-Alliance has identified this opportunity and acknowledged the need for interoperable solutions which are key for the roll-out of sustainable large-scale systems. The G3-Hybrid profile was developed in the first half of 2020 and released at the end of July 2020. It is the first open standard that guarantees interoperable multi-vendor hybrid implementations.

As a result, the relevance and versatility of G3-PLC are increased on worldwide markets:

- By using both PLC and RF media, the **G3-Hybrid meshed topology maximizes coverage and resilience.**
- The G3-Hybrid profile can provide a more efficient solution for smart metering, smart grid and smart city use cases enhancing the relevance of the G3-PLC technology.
- Connectivity of G3-PLC networks can be extended to RF-only devices.
- G3-PLC is already a multi-purpose technology and the G3-Hybrid profile further leverages its ability to address different application use cases (smart metering, smart grid, smart city, lighting control, building automation, demand response, railway applications, etc.).

What is a PLC+RF hybrid technology?

In a logical network, the PLC+RF hybrid technology features the use of PLC or RF media over each link of a single network topology as depicted in Figure 4. Considering a single link, the use of PLC or RF is dynamically and automatically negotiated over time, depending on real-time channel conditions for the two media.

A hybrid PLC+RF technology should not be confused with a multi-protocol router embedding two or more chips carrying independent PLC and RF communication protocols. In contrast, a hybrid technology consists of a unified protocol stack enabling adaptive PLC or RF transmissions in a transparent manner with respect to the upper layers, which stay agnostic to lower layer characteristics.

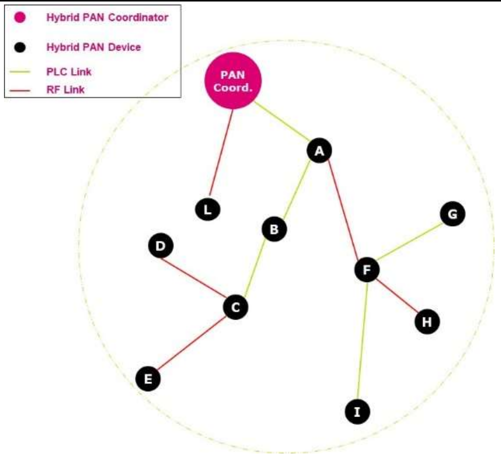

Figure 4: G3-Hybrid PLC+RF network topology

1.2.2. Presentation of the G3-Hybrid protocol stack

The G3-Hybrid profile is specified in [1] (Annex H) and extends the existing G3-PLC protocol stack by **providing a secondary radio frequency (RF) medium.**

The RF physical layer is based on the **SUN (Smart Utility Network) FSK modulation,** as specified in IEEE 802.15.4-2024 [6], which was developed for low power wireless applications characterized by a large number of outdoor devices spread over a wide geographical area typically using multi-hop traffic patterns.

The RF MAC layer uses **unslotted CSMA/CA for non-beacon-enabled networks** (as for G3-PLC) is **based on IEEE 802.15.4-2024 [6]** which differs from a previous version of the standard used by the PLC MAC layer: IEEE 802.15.4-2006 [4]. Keeping the 2006 version for the PLC medium ensures that backwards compatibility is guaranteed with original G3-PLC networks.

The data link layer comprises a **Hybrid Abstraction layer which has the main function to redirect the data flow to/from the appropriate interface** (PLC and RF MAC service primitives, adaptation layer service primitives) **while keeping the 6LoWPAN Adaptation layer mechanisms unchanged** (same frame format, same IPv6 compression rules, use of the LowPAN Bootstrap Protocol, use of the mesh-under LOADng routing protocol). The only exception lies in the definition of a new link cost formula that takes into account the characteristics of RF links (link quality, duty cycles) intended for route cost computation during LOADng route discoveries.

The G3-Hybrid protocol stack is shown in Figure 5:

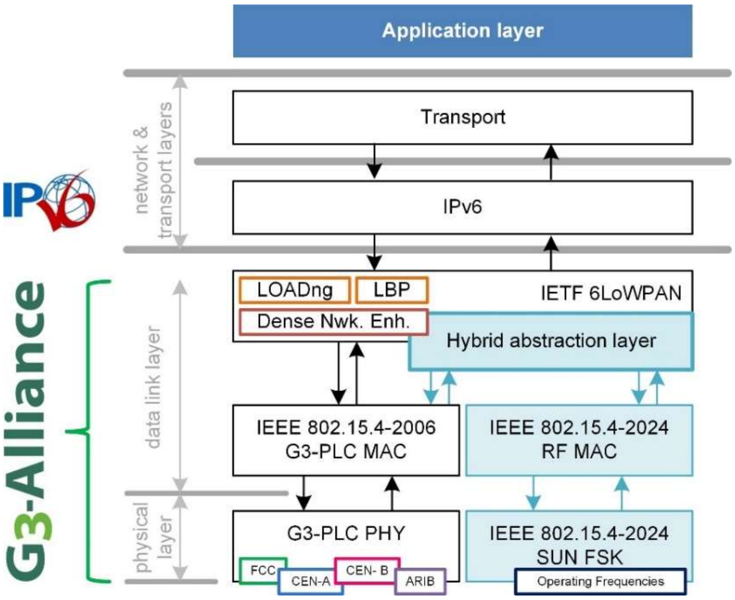

Figure 5: G3-Hybrid protocol stack

1.2.3. Mixing G3-Hybrid devices with G3-PLC devices

The G3-Hybrid profile is fully compatible with the G3-PLC "PLC-only" stack. Hence, G3-Hybrid devices are interoperable with G3-PLC devices: they can be mixed in the field, for example to connect PLC islands as shown in Figure 6:

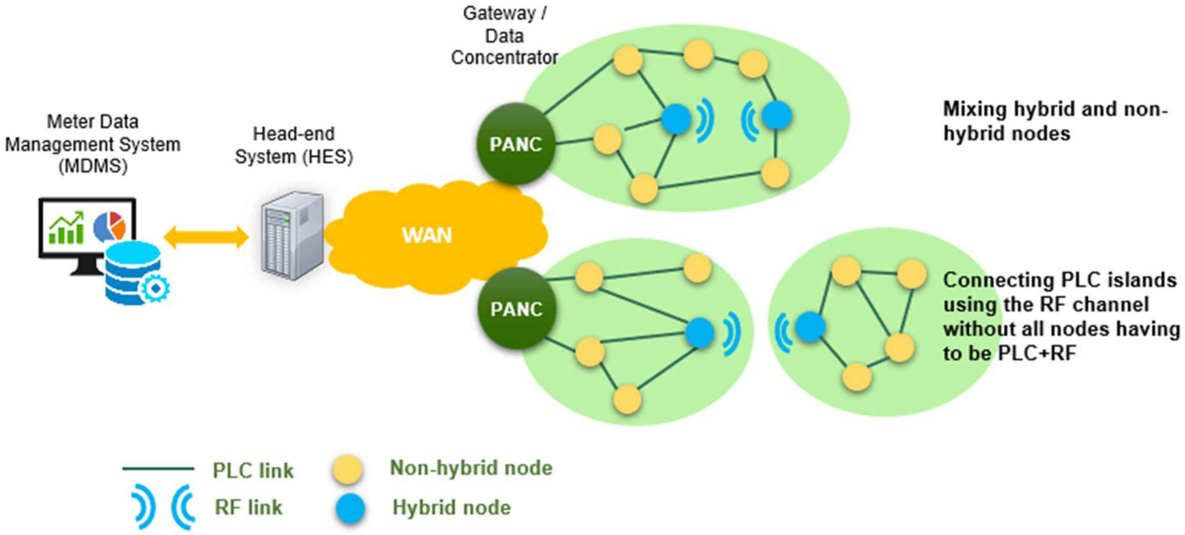

Figure 6: Mixing G3-Hybrid devices with G3-PLC devices

In existing deployments, the data concentrator does not need to be upgraded to a G3-Hybrid device, while it is nevertheless recommended to update its software for better interpretation of bootstrapping messages[2].

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[2] If the PAN coordinator is not ugraded, the LBA always receives LBP messages (from PAN coordinator)

1.3. G3-PLC High Data Rate mode

This extension is designed **for operation of G3-PLC lower layers in clean environments, characterized by high signal-to-noise ratios** (which differ from the challenging AC mains, for example, where PLC devices have to cope with high levels of noise), where short packets are being exchanged between two devices (point-to-point) or one and multiple devices (point-to-multipoint) and low-latency communications are expected.

The G3-PLC High Data Rate mode consists of additional 64-QAM and 256-QAM modulations available for FCC bandplans, enabling **theoretical data rates of up to 737 kbps and 1129 kbps,** respectively.

Note: When High Data Rate mode is enabled, the two lower-rate modulation "(D)BPSK" and "ROBO" shall not be used, according to [1]. The following modulations are available in this operating mode: (D)QPSK, (D)8PSK, 16-QAM, 64-QAM and 256-QAM.

1.4. G3-Hybrid support for battery-powered Leaf Nodes

Since the publication of the latest G3 Specifications in 2025 [1], **connectivity can also be extended to RF-only G3-Hybrid Leaf Nodes which are typically battery-powered.** G3-Hybrid operation had to be adapted to **minimize Leaf Nodes' energy consumption** while **specific mechanisms were defined for efficient communication between one or several Leaf Nodes and a nearby "Parent" G3-Hybrid device** (e.g. a mains-powered G3-Hybrid device supporting "parenting" functionality).

Support for battery-powered Leaf Nodes include:

- **Periodic time synchronization** and **scheduling unicast and broadcast transmission slots** from/to a Leaf Node to/from a Parent device, as Leaf Nodes are sleeping most of the time.
- **Adapted network discovery for Leaf Nodes** to identify nearby G3-Hybrid devices with parenting functionality.
- **Leaf Node and Parent association** using specific messages: Leaf Nodes are registered in Parent G3-Hybrid devices' "Destination Address Set", which is useful to **delegate the routing of data within the local G3 network to/from a Leaf Node to its Parent.**

1.5. Application domains

G3-PLC was originally developed for massive smart meter rollouts and, therefore, it was designed to deal with harsh channel conditions commonly found in the low voltage distribution network, by including features such as automatic adaptive modulation. G3-PLC is being used for smart metering globally, in different bandplans.

Yet, as G3-PLC facilitates high-speed, highly reliable, long-range communication over existing powerlines, there are many more applications areas outside smart metering.

G3-Hybrid complements G3-PLC with an additional radio communication medium, enabling unprecedented levels of coverage and resilience. G3-Hybrid also paves the way for new interconnection possibilities by extending hybrid network connectivity to other radio communication devices and infrastructures.

The main applications of the technology include smart metering, smart grid, street lighting, smart cities, railway control systems, building automation, home automation and further kinds of industrial applications where it makes sense to use the powerline with or without radio as a communication medium. The G3-PLC High Data Rate mode extension introduced in §1.3 also allows envisaging the operation of G3-PLC lower layers on clean wired infrastructures, such as specific DC networks, for HVAC, building automation or Voice-over-PLC. Moreover, support for battery-powered Leaf Nodes, as described in §1.4, also positions G3 technology as a suitable solution for multi-utility solutions (gas, water or heat meters can benefit of connectivity with nearby G3-Hybrid electricity smart meters) or, more generally, to connect RF-only devices to the local existing G3 infrastructure.

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with DisableBackupMedia = 0 (for G3-PLC devices that field is reserved and therefore set to 0). Thus, the LBA will attempt reaching the bootstrapping device (LBD) using PLC first, and possibly using RF as a second option (if the communication attempt using PLC fails).

G3-PLC and G3-Hybrid provide a high level of flexibility regarding network architectures. The protocol stack is modular, allowing for different options at different layers (see §1.1, §1.2, §1.3 and §1.4). G3-PLC and G3-Hybrid may be used in a meshed configuration (typical architecture when deployed over a low voltage distribution network – see §3.6) or in a point-to-point/point-to-multipoint configuration. Connectivity to a remote head-end system may be established in an end-to-end fashion or carried out through an applicative gateway (see §3.7). The location of different components such as the PAN-Coordinator (see §3.5), the authentication server (see §3.9), or the border router (see §3.7) may be located in different physical devices. Finally, native compatibility with the IPv6 protocol offers compatibility with a wide range of application layer protocols.

G3-PLC and G3-Hybrid are constantly evolving to address new applications and challenges, making it successful in different countries!

2. The G3-Alliance: standardization and certification

The G3-Alliance is a non-profit association created in 2011 to standardize and promote G3 technology for smart metering, smart grids, smart appliances and industrial applications on a worldwide scale. The industry members of the G3-Alliance (utilities, equipment manufacturers, chip manufacturers, test houses) are committed to its charter mainly consisting in the maintenance of the G3 Specifications [1] and their support in internationally recognized standards bodies, in facilitating interoperability among G3-PLC and G3-Hybrid adopters and in promoting the G3 technology.

Practically, the G3-Alliance is organized in four workshops under the supervision of the Strategic Steering Committee (SSC):

- WS1: Specification Maintenance
- WS2: Marketing & Promotion
- WS3: Interoperability
- WS4: Regulatory Advisory Group
- CPEC: Certification Program Maintenance

The involvement of the Alliance's members in the different workshops and standardization bodies led to the publication of the ITU-T G.9903 [3] standard. A liaison between ITU-T and the G3-Alliance allows the maintenance work of WS1 to be directly injected into new corrigenda, amendments or revisions of the ITU-T G.9903 [3] standard.

Since 2014, the Alliance has started the operation of the G3-PLC certification program for the CENELEC-A, CENELEC-B, ARIB and FCC bandplans. The publication of converged standards and the availability of a G3-PLC certification program positions G3-PLC as a mature solution for large scale rollouts of smart energy systems:

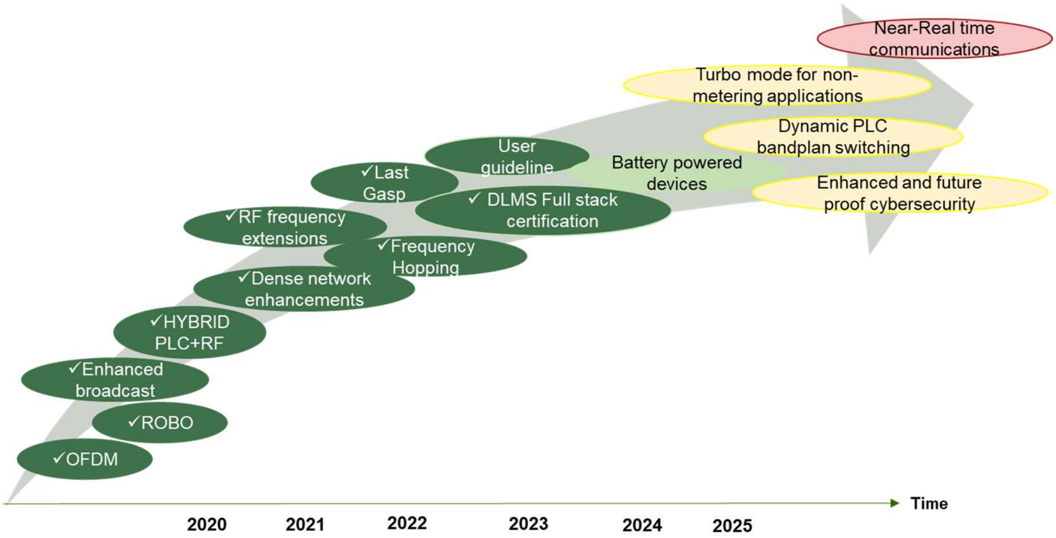

Figure 7: Evolution of G3 technology over time

The certification program of the G3-Alliance is based on the three following fundamental pillars:

- **Conformance assessment**: aims to verify the conformance of the candidate implementation with the different clauses of the G3 Specifications [1].
- **Interoperability assessment**: sole conformance does not guarantee interoperability between different implementations. As a result, a candidate implementation is tested against a set of previously certified implementations.
- **Performance assessment**: performance tests are also necessary to prevent some issues to occur in the field. For instance, a too-long processing time may lead to application timer expiry and failure.

The G3-Alliance certification program is operated by accredited test houses. An updated list of certified devices is available at the following link: https://g3-alliance.com/certification/.

3. Technical basics

3.1. Communication over the electrical network

3.1.1. General principles

Power Line Communication (PLC) consists in using electrical wires as a support for information transfer by adding a low power signal, usually between live and neutral wires. The superimposition of the PLC signal over an AC mains network is depicted in Figure 9:

- Time-domain: addition of low-amplitude high-frequency signal over the 50 Hz sinusoidal wave
- Frequency domain: presence of a group of low-amplitude kHz-range spectral lines in addition to the fundamental frequency of the 230 V / 50 Hz AC mains. Such a group of spectral lines spread over a band up to 350 kHz is typical of OFDM technologies such as G3-PLC.

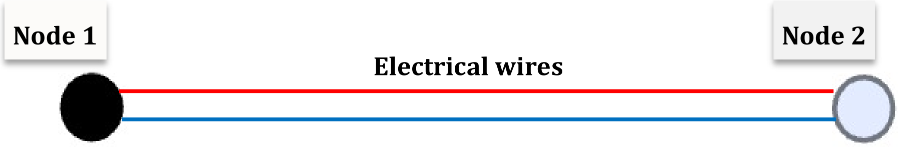

Figure 8: Two PLC nodes communicating over two electrical wires (live and neutral)

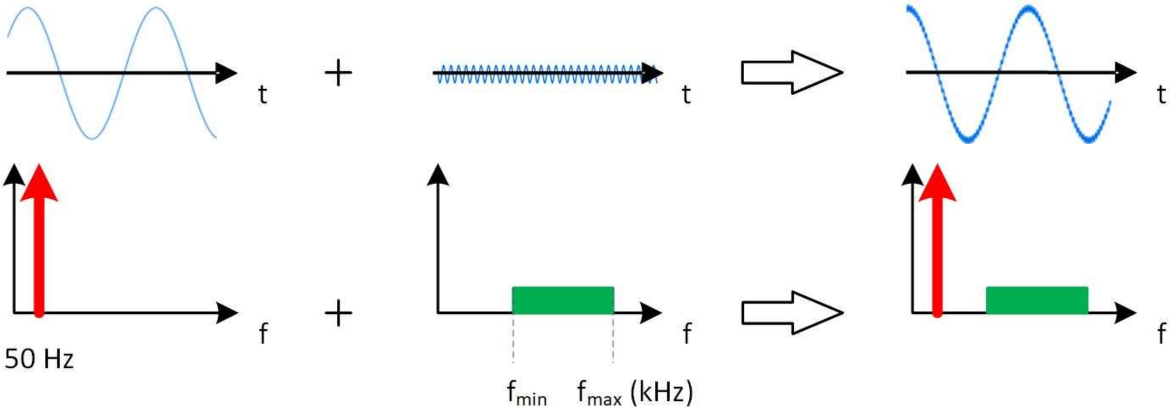

Figure 9: Representation of the superimposition of the G3-PLC signal over a 50 Hz AC mains network

Narrowband PLC devices (operating in the band 3 – 500 kHz according to international regulation as shown in §1.1) can be modelled as voltage generators, delivering a voltage which level has to stay as close as possible to a reference level under varying impedance conditions.

Signal levels are generally quantified as a voltage expressed in dBµV. Typical reference levels are in the range of 134 to 120 dBµV depending on the characteristics of the PLC technology implemented. The relationship between dBµV and Volts is illustrated in the following table:

Signal level in dBµV (logarithmic scale)	**Signal level in Volts** (linear scale)	
134	5	
126	2	
120	1	
114	0,5	
108	0,25	or 250 mV
88	0,025	or 25 mV
68	0,002 5	or 2,5 mV
48	0,000 25	or 250 µV

PLC modems are made of an analog stage (coupling, filtering and signal amplification) and a digital stage typically consisting of a Digital Signal Processor (DSP) and a Micro Controller Unit (MCU).

The coupler is making the interface between the modem and the electrical wires, by ensuring both galvanic insulation and a path for the high-frequency signal between the mains and the PLC device.

When receiving a signal, it is filtered, amplified and processed by the digital stage. Conversely, in transmission mode, these steps are executed in reverse order.

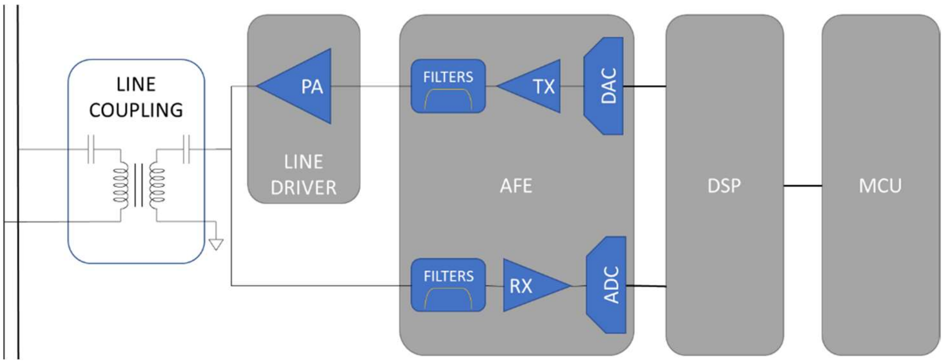

Figure 10: Schematic of a PLC modem

3.1.2. Environmental constraints and mitigation

The electrical network has not been designed for communication. Therefore, it is subject to impedance variations and the presence of noise in the operating frequency band of PLC technologies, which come as additional constraints to PLC signal attenuation along the lines.

Impedance:

Impedance “Z” refers to the opposition a power line presents to the flow of electrical current (here the high-frequency currents of PLC signals), which is composed of resistance (depending on the material electrical conductors are made of) and reactance (i.e. capacitance and inductance, depending on the layout of single or three-phase conductors in power line cables).

As a rule of thumb, network access impedance (i.e. the impedance measured between live and neutral at the location where a PLC device is physically connected) tends to decrease in dense urban areas, where a significant number of customers share the same electricity grid, compared to rural areas where long lines will only serve a few customers.

While the previous statement amounts to saying that, the more electrical branches, the smaller the impedance, impedance is also affected over time and varies with the number of appliances that are connected, switched on or switched off and their characteristics. For example, incandescent lamps modelled as purely resistive steady impedances are replaced by a growing number of LED lamps giving a more capacitive nature to the grid’s impedance. Likewise, as it is observed with lighting equipment, appliances also embed more and more power electronics thus changing the nature of customer impedance.

Impedance cannot be known before the installation of PLC devices and is not constant over time. When impedance conditions become too challenging, power loss may be experienced by PLC devices (low impedances affect transmitters in particular) due to a mismatch between the grid impedance and the modem’s internal impedance.

Attenuation:

Attenuation is described as the loss of signal between the PLC transmitter and the PLC receiver. It is a function of the distance travelled by the PLC signal and the frequency:

- The higher the operating frequency, the higher the attenuation.
- The longer the distance, the higher the attenuation.

Figure 11 shows how the low voltage distribution network (in red) has a low pass effect on the PLC signal resulting in attenuation. The attenuation, expressed in dB, also increases linearly with wire length.

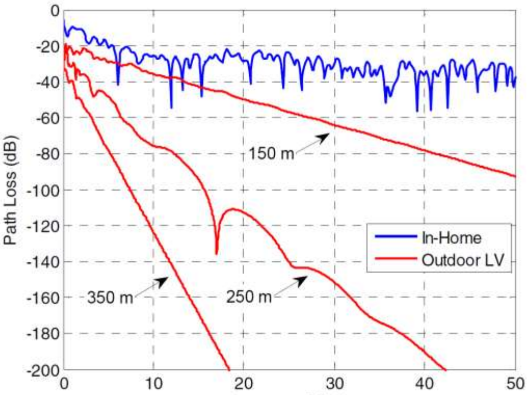

Figure 11: Attenuation in the MHz range for in-home and outdoor low voltage networks

Yet, Figure 11 essentially emphasizes the behaviour in the higher frequency range, up to 50 MHz, essentially used by broadband PLC technologies. If zooming in on the sub-MHz range, only variation of a few dB can be observed. In fact, in the sub-MHz frequency range, attenuation is more influenced by impedance mismatch issues created by the electrical network's topology, as described previously, rather than the losses strictly assignable to the propagation of the PLC signal.

As a conclusion, answering the question "what is the typical range of a narrowband PLC signal?" is almost impossible. It might be 600 meters in a rural area or 50 m in a very dense urban network.

Noise:

Another consequence of the shared nature of the electrical network is the possible presence of noise due to various electrical apparatus in operation. The growing pervasiveness of power electronics is one cause of the noise levels sometimes observed in the operating bands of narrowband PLC.

Practically, in addition to the attenuation effect due to impedance mismatch and signal propagation affecting the PLC signal level, noise is the second component entering in the determination of the signal-to-noise ratio (SNR).

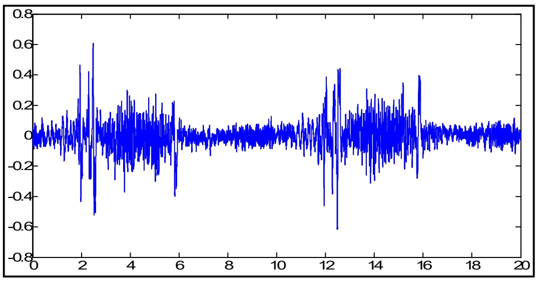

Figure 12: Example of a time-domain noise

The SNR is an essential metric in telecommunications, as it determines whether a receiver implementing a certain telecommunication technology will be able to decode the signal or not.

Mitigation techniques:

The PLC industry has developed hardware techniques and protocol mechanisms to meet the challenges of the electrical network as a propagation channel.

In idle and reception modes, G3-PLC modems are designed to present a high impedance to the grid (> 50 Ω).

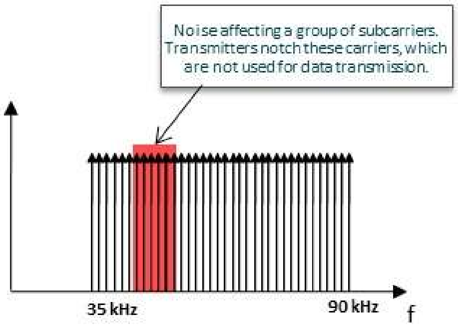

Figure 13: G3-PLC tone mapping

To deal with high attenuation levels, G3-PLC features dynamic adaptation of modulation schemes ranging from the most Robust modulation (DBPSK and repetition code) to modulations offering higher data rates (DBPSK, DQPSK and D8PSK).

G3-PLC may work in noisy environment thanks to the robust design of its physical layer, including a multi-symbol interleaver offering time diversity, and a retransmission scheme upon transmission failure detection.

In addition, G3-PLC takes advantage of frequency diversity offered by the OFDM modulation techniques by tone mapping consisting in avoiding transmitting useful information in the noisy spectral components of the operating band or compensating frequency-selective attenuation by adding a gain in specific frequency sub-bands.

Multi-phase propagation and crosstalk:

While the PLC signal is propagated along the wires to which the modem is connected, a portion of the transmitted signal is also found on the wires of a polyphase system. A signal initially injected between "Neutral" and "Live 1" may also be detected between "Neutral" and "Live 2" or "Neutral" and "Live 3" in a three-phase system. This physical phenomenon due to capacitive and inductive behaviour is called crosstalk.

Multi-phase propagation can be seen as a drawback, as it increases the "collision domain" (more PLC nodes can see each other creating more potential for congestion issues). But in general, multi-phase propagation helps the PLC signal to reach better coverage by offering more link diversity, thus increasing network density.

3.2. G3-Hybrid radio frequency transmissions

3.2.1. Frequency bands, operating modes and data rates

Various RF frequency bands and operating modes (number of available channels, channel centre frequency, channel spacing) are specified in IEEE 802.15.4-2024 [6]. In the current G3-Hybrid profile [1], a selection is made, based on identified market needs.

As a result, G3-Alliance certification is available for any combination between available RF operating frequency bands listed in the table below and CENELEC A, CENELEC B, ARIB and FCC G3-PLC bandplans:

Band designation (MHz)	**Start frequency** (MHz)	**Stop frequency** (MHz)	**Mandatory mode / data rate**	**Optional mode / data rate**
863	863	870	mode #1 / 50 kbps	mode #2 / 100 kbps
866	865	868[3]		
870	870	876		
915	902	928		mode #3 / 200 kbps
915-a	902	928		mode #4 / 200 kbps
915-b[4]	902	907,5		
	915	928		
915-c	915	928		
919	919	923		
920	920	928		mode #6 / 150 kbps
920-b	920	925		mode #4 / 200 kbps

Note: The difference in the data rates available for different operating modes are related to a different choice of modulation index and channel spacing.

Note: 863, 866 and 870 band designations, according to [1] (the "band designation" term and related specification have been established in IEEE 802.15.4-2024 [6]), are referring to different RF bandplans but they may be commonly referred to as 868 MHz bands in the market.

3.2.2. Single-frequency and Frequency Hopping operation

RF operating frequency bands may be used in a single-frequency operation mode or using Frequency Hopping whenever needed and/or required by regulation.

Single-frequency operation is straight forward: the operation of a G3-Hybrid device is chosen amongst the available options (band designation, operation mode) according to §3.2.1 and depending on the local regulatory constraints. Care shall be taken to ensure that all devices of a same G3 network share the same settings.

Frequency Hopping (FH) operation favours enhanced coexistence with other RF systems operated in the neighbourhood within the same ISM bands (which usage is license-free). The G3 Specifications [1] describe the FH mechanisms in §H.6.7 for three main use cases:

(1) Full G3-Hybrid networks where all devices can reach the PAN Coordinator via RF links.

(2) Full G3-Hybrid networks where some links towards the PAN Coordinator are PLC only.

(3) Mixed networks with G3-Hybrid islands.

An accurate time synchronization between G3-Hybrid devices is critical for proper FH operation. Therefore, [1] introduces the time synchronization mechanisms and frequency channel computation mechanisms for the coordination of both unicast and broadcast communications on a time-varying frequency channel. Indeed, the FH mechanisms are designed to ensure that G3-Hybrid devices interacting with each other transmit on or listen to the same frequency channel during the same time slot. This time-frequency coordination is maintained in devices' "listening schedules" (for both unicast and broadcast transmissions).

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[3] The upper bound of the 866 band has changed from 867 MHz to 868 MHz according to IEEE 802.15.4-2024 [6].

[4] The 915-b band designation refers to a discontinuous RF bandplan: from 902 MHz up to 907,5 MHz and from 915 MHz up to 928 MHz.

Note: FH operation, and particularly the computation of the listening schedules, rely on specific signalling between devices using "FHT" and "FHUT" "Information Element": see §3.3.2.

In addition, the G3 Specifications [1] define tolerances in listening schedules by introducing "guard intervals" computed as a function of the RF operating mode and expected G3-Hybrid devices' clock drift (which cause discrepancies between neighbours' listening and transmission schedules in-between time resynchronizations).

It is also worth noting that the unslotted CSMA/CA channel access mechanism used in single-frequency operation is replaced by the CCA (Channel Clear Assessment) channel access mechanism over RF links if FH operation is enabled.

3.2.3. Other transmission parameters

Care shall be taken when operating G3-Hybrid devices, as regional regulation may enforce specific rules such as transmission power limits, duty cycle limits or possible restrictions for operating frequency bands within the frequency range made available for certified devices.

It is to be noted that end-users may decide to operate G3-Hybrid devices such as they adapt their transmission power on channel conditions using the adaptive power control mechanism defined in [1], Annex H.

The choice of transmission parameters according to regulation is further explained in "WS4 – Regulatory Advisory Group – Regional regulations study".

3.3. Frame structure and lower-layer processes

3.3.1. Encapsulation and de-encapsulation process

G3-PLC and G3-Hybrid protocol stacks are designed according to the ISO Open Systems Interconnection (OSI) model.

The specifications under the responsibility of the G3-Alliance addresses the lower OSI layers up to the adaptation layer, generally defined as layer 2,5 (between data link layer 2 and network layer 3). Yet, the higher layer stack, which consists of the use of IPv6 at network layer and UDP as the preferable option for the transport layer, has to be considered with care.

Note: The use of TCP is also possible but sub-optimal with respect to the 6LoWPAN adaptation layer compression features. Therefore, TCP should only be used if required by the application protocol.

In line with the OSI model principles, the encapsulation and de-encapsulation processes, here for the G3-PLC stack operated in the CENELEC-A bandplan (PHY and MAC frame structures are slightly different for G3-PLC in other bandplans or G3-Hybrid), are depicted in Figure 14:

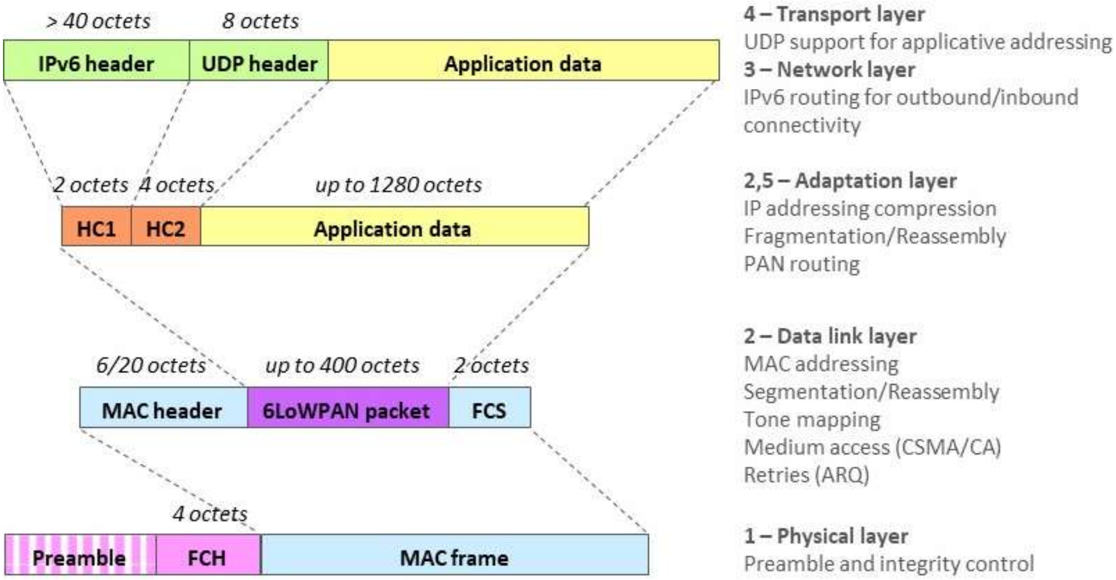
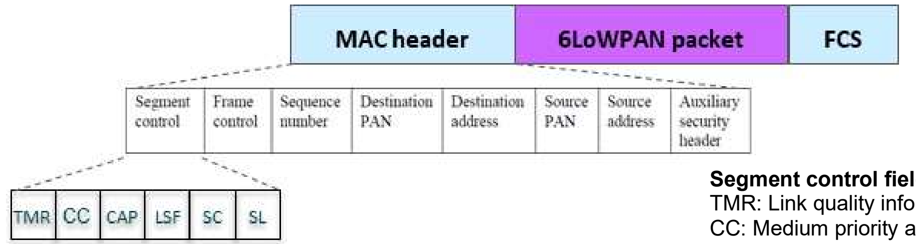


Figure 14: Encapsulation and de-encapsulation process principles (G3-PLC operated in CENELEC-A)

As shown in the right part of Figure 14, different layers perform different actions with respect to their role in the OSI model. For example, the adaptation layer will compress IPv6 and UDP headers and, if applicable fragment the IPv6 packet into multiple 400-Byte 6LoWPAN packets.

In general, layer “n” receives data consisting of a header and a payload and processes this data according to the information carried in the header specific to layer n. For example, as shown in Figure 15, the MAC header of a G3-PLC MAC frame contains information related to the destination address of the node this data is intended to; it may also include a request to re-negotiate the communication parameters (use of the “TMR” flag in the segment control field) with the node having sent this data.



Segment control field:
TMR: Link quality information (for Tone Mapping)
CC: Medium priority access for next message
CAP: Message priority
LSF: Last segment notification
SC: Segment ID
SL: Segment length

Figure 15: MAC header fields

3.3.2. Transmission parameter negotiation between neighbours

Specific information is exchanged and maintained between neighbour nodes using Tone Map Request/Response (TMR) messages populating Neighbour Tables for G3-PLC or G3-Hybrid PLC links, and Information Elements (IE) populating RF POS Tables for G3-Hybrid RF links.

For PLC links, TMR command messages are described as an extension to the IEEE 802.15.4-2006 [4] MAC frame structure and allow neighbours to negotiate various transmission parameters:

- Modulation type (ROBO, (D)BPSK, (D)QPSK, (D)8PSK[5])
- Modulation scheme (differential, coherent)
- Tone Map (groups of OFDM subcarriers to be used or not for data transmission)
- LQI (Linky Quality Indicator, which gives an indicator about the Signal-to-Noise Ratio for a transmission to a given neighbour device)
- Transmission gain (TXRES, TXGAIN) and optional differentiated gain by groups of OFDM subcarriers (TXCOEFF)

For RF links, the Information Element mechanism is defined in IEEE 802.15.4-2024 [6], which avoids the definition of a new mechanism inspired from the TMR message exchange.

Therefore, MAC frame formats are different for both media (IEEE 802.15.4-2024 [6] for RF and IEEE 802.15.4-2006 [4] for PLC), as shown in the following figures for the general MAC frame format:

Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS
		Addressing fields						
MHR							MAC Payload	MFR

Figure 16: PLC medium general MAC frame format (source: IEEE 802.15.4-2006 [4])

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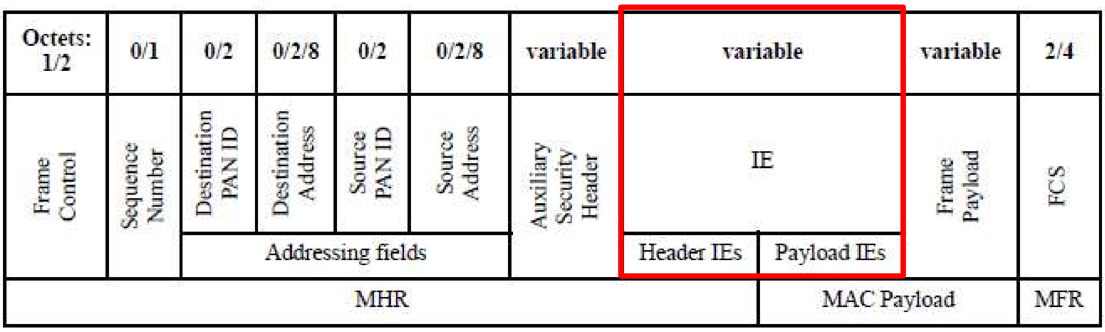
[5] 64-QAM and 256-QAM may be supported in the High Data Rate mode extension, as described in §1.3.



Octets: 1/2	0/1	0/2	0/2/8	0/2	0/2/8	variable	variable		variable	2/4
Frame Control	Sequence Number	Destination PAN ID	Destination Address	Source PAN ID	Source Address	Auxiliary Security Header	IE		Frame Payload	FCS
		Addressing fields					Header IEs	Payload IEs		
MHR								MAC Payload		MFR

Figure 17: RF medium general MAC frame format (source: IEEE 802.15.4-2024 [6])

The G3-Hybrid specification [1] defines different IE types for RF link negotiation, which are piggybacked in different types of MAC frames:

- The Reverse Link Quality “RLQ-IE” carries link quality and background noise information between neighbour nodes (in Enh-ACK – enhanced acknowledgement – MAC frames).
- The Link Information “LI-IE” carries duty cycle consumption and transmission power offset settings between neighbour nodes (in data, enhanced beacon and Enh-ACK MAC frames).
- Frequency Hopping Timing “FHT-IE” and Frequency Hopping Unicast Timing “FHUT-IE” carry timing information for Frequency Hopping operation (see §3.2.2). Shorter FHUTs, related to unicast transmissions only, can easily be transported in “Enh-ACK” acknowledgement frames for enhanced Frequency Hopping schedule synchronization between devices.
- The Beacon Filter “BF-IE” limits which devices may reply when an enhanced beacon request frame carrying this IE is sent (see §3.5). Designed for battery-powered Leaf Nodes (see §1.4).
- Leaf Node Unicast Tming Request “LNUCTR-IE”, Leaf Node Unicast Timing “LNUCT-IE” and Leaf Node Broadcast Timing “LNBCT-IE” enable unicast and broadcast communications between Leaf Nodes and a Parent device (see §1.4).

3.4. G3-Hybrid “Hybrid Abstraction Layer”

3.4.1. Service primitives

The Hybrid Abstraction layer interfaces the 6LoWPAN Adaptation layer (“ADPD-xx” and “ADPM-xx” sets of service primitives) and both PLC and RF MAC layers (“MCPS-xx” and “MLME-xx” sets of service primitives) using newly defined “HyAL-xx” service primitives, as shown in Figure 18.

The following table provides additional information about the interaction between the Hybrid Abstraction layer, higher layers (6LoWPAN Adaptation layer) and lower layers (PLC and RF MAC layers):

ADPD/ADPM service primitives	HyAL service primitives	PLC and RF MCPS/MLME service primitives[6]	Description
ADPD-DATA.request ADPD-DATA.confirm ADPD-DATA.indication ADPM-ROUTE-DISCOVERY.request ADPM-PATH DISCOVERY.request ADPM-NETWORK-JOIN.request ADPM-ROUTE-DISCOVERY.confirm ADPM-PATH DISCOVERY.confirm ADPM-NETWORK-JOIN.confirm ADPM-NETWORK-JOIN.indication ADPM-LBP.request ADPM-LBP.confirm ADPM-LBP.indication	HyAL-DATA.request HyAL-DATA.confirm HyAL-DATA.indication	MCPS-DATA.request MCPS-DATA.confirm MCPS-DATA.indication	Data transmission as well as route discovery, path discovery, joining and LBP procedures triggered by higher layers will invoke HyAL and PLC and/or RF MAC data services. Conversely data received over PLC and/or RF MAC data services will invoke appropriate “indication”

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[6] Both PLC and RF MAC primitives may be invoked.

			primitives.
ADPM-DISCOVERY.request ADPM-DISCOVERY.confirm	HyAL-SCAN.request HyAL-SCAN.confirm	MLME-SCAN.request MLME-SCAN.confirm	Neighbourhood scan and PAN descriptor collection
	HyAL-BEACON-NOTIFY.indication	MLME-BEACON-NOTIFY.indication	
ADPM-NETWORK-STATUS.indication	HyAL-COMM-STATUS.indication	MLME-COMM-STATUS.indication	Alternate PAN detection over PLC or RF MAC to higher layers
ADPM-NETWORK-START.request ADPM-NETWORK-START.confirm	HyAL-START.request HyAL-START.confirm	MLME-START.request MLME-START.confirm	Network start over PLC and RF MACs by the PAN coordinator
ADPM-RESET.request ADPM-RESET.confirm	HyAL-RESET.request HyAL-RESET.confirm	MLME-RESET.request MLME-RESET.confirm	PLC and RF modem reset

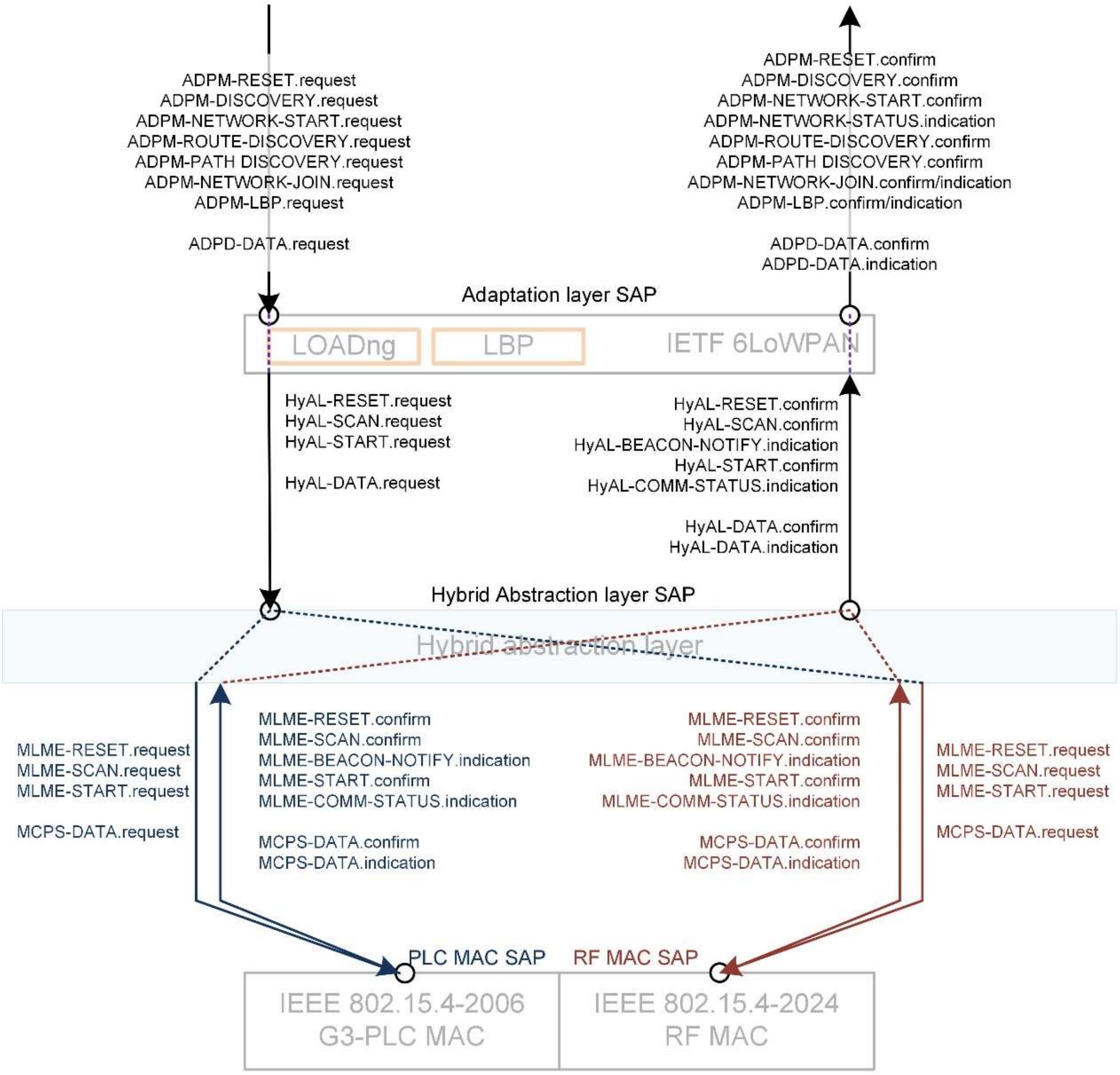

Figure 18: Interaction between the different protocol layers through the service access points (SAP)

3.4.2. Media Types

The Hybrid Abstraction layer defines five media types used together with the service primitives embedding this as a dedicated Media Type parameter. This parameter is used for the transmission of a frame (HyAL-DATA.request), upon confirmation of the transmission of a frame (HyAL-DATA.confirm) or upon reception of a frame (HyAL-DATA.indication, HyAL-COMM-STATUS.indication, HyAL-BEACON-NOTIFY.indication via the HyAL PAN Descriptor structure).

The following table, partly[7] copied from the G3 Specifications [1], Annex H, defines the different valid Media Type values:

Media Type value	**Primitive**		
	.request	**.confirm**	**.indication**
0x00	Power Line interface Backup Radio Frequency interface	Power Line interface used by default	Power Line interface
0x01	Radio Frequency interface Backup Power Line interface	Radio Frequency interface used by default	Radio Frequency interface
0x02	Both Power Line and Radio Frequency interfaces	Both Power Line and Radio Frequency interfaces used for transmission	Not used
0x03	Power Line interface No backup interface	Power Line interface used as backup after failure on Radio Frequency interface	Not used
0x04	Radio Frequency interface No backup interface	Radio Frequency interface used as backup after failure on Power Line interface	Not used

For data transmission, Media Types 0x00 and 0x01 enable a possible retry over the second medium should a transmission error occur over the first medium.

Media Type 0x02 allows simultaneous transmission over both PLC and RF media of 6LoWPAN broadcast frames.

3.4.3. Frame forwarding principles

The G3 Specifications [1] introduce the general principles adopted for frame forwarding, depending on the MAC frame type considered:

Frame type	**MAC destination address**	**Transmission policy**	**Corresponding Media Types**	**Expected receiver MAC behaviour**
Beacon request	0xFFFF	Over **both** RF and PLC media	N/R	Transmit a beacon over the medium the beacon request was received
Beacon	N/R	Over the medium the beacon request was received	N/R	If two subsequent beacons are received over RF and PLC media from the same originator, two PAN Descriptors are forwarded to the upper layers.
Unicast frame	Any unicast address	Over RF **or** PLC media	0x00, 0x01, 0x03, 0x04	Transmit an acknowledgement
MAC acknowledgment	Any unicast address	Over the medium the unicast frame was received	N/R	No action required
Broadcast frame (any 6LoWPAN data frame)	0xFFFF	Over **both** RF and PLC media	0x02	No action required
Broadcast frame (LOADng RREQ message)	0xFFFF	Over **both** RF and PLC media	0x02	If two subsequent RREQ messages are received over RF and PLC media from the same originator, they are both forwarded to the upper layer and will be processed separately by the LOADng routing

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[7] A sixth Media Type value (0x05) was defined to enable the propagation to devices external to the G3 network (managed by the Application layer).

				protocol (as they carry different route costs).

The medium over which the transmission of a unicast frame is carried out is determined by the LOADng routing protocol as described in §3.6.3.

It should be also reminded that if the local RF regulation enforces duty cycles and the maximum time on air is already reached, exclusive usage of the PLC medium may be temporarily forced until the end of the duration over which the duty cycle is established.

3.5. Construction of a G3 network

On a three-phase network, G3 nodes are connected to one or more phases and, most of the time, are transmitting/receiving PLC signals over only one phase. In addition, G3-Hybrid devices will also consider an additional RF signal, received “over the air”.

Using this physical infrastructure, the G3 protocol builds a logical communication network (PAN; Personal Area Network, according to IEEE 802.15.4-2006 [4] terminology), superimposed over the physical electrical network, considering additional radio frequency links between devices embedding G3-Hybrid capabilities (all devices or a selection of devices if the G3 network consists of both G3-PLC and G3-Hybrid devices, as suggested in §1.2.3).

Each PAN is typically identified by a 16-bit identifier (PAN-ID) statically assigned by the end-user. In general, each G3 node is an application-independent device also known as “PAN-Device”. In addition, each PAN is managed by a supervisor node: the “PAN-Coordinator” grants access to the network to PAN-Devices after authentication and allocation of a 16-bit short address (unique in the PAN). The PAN-Coordinator typically provides connectivity to remote hosts through an external telecommunication network for every node.

Note: The use of a PAN-Coordinator is the general use case, but it is possible to build networks using other application layer mechanisms, in particular for simple application scenarios.

One example of a G3 PAN is the electricity metering infrastructure where PAN-Devices are smart meters and the PAN-Coordinator functions are completed by the data concentrator unit (which role mainly consists of collecting metering data).

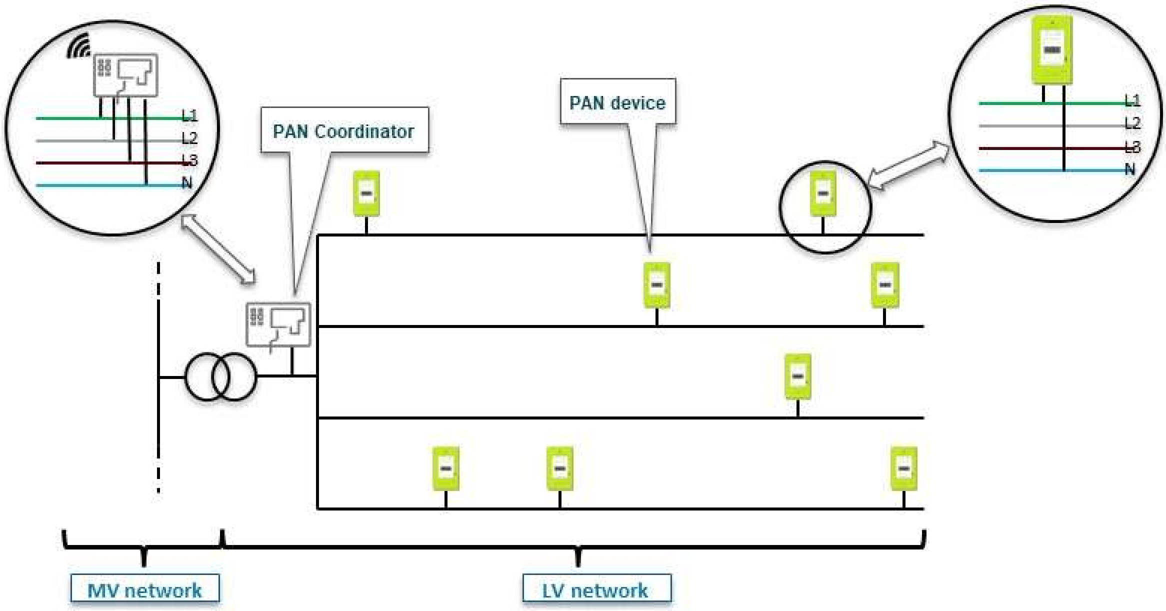


Figure 19: Example of a Linky G3-PLC PAN deployed over a low voltage distribution network

Moreover, the G3-PLC and G3-Hybrid are also designed and deployed to support various applications such as street lighting, smart cities or railway control systems as pointed out in §1.3.

With respect to other technologies with simple topologies (linear or star-shaped), G3 technology allows the deployment of many nodes in complex environments. An optimal meshed, multi-hop network is built using existing link diversity between nodes: remote nodes are reachable using other nodes as relays as to establish end-to-end communications between any originator node and one (unicast communications) or multiple (multicast communications) destination nodes.

The mesh topology obtained is time-variant as links may vanish while others appear during the lifetime of the G3 PAN (for example due to the change of network conditions over time or the addition/removal of specific G3 nodes). The G3 routing protocol deals with these dynamic aspects as further explained in §3.6.

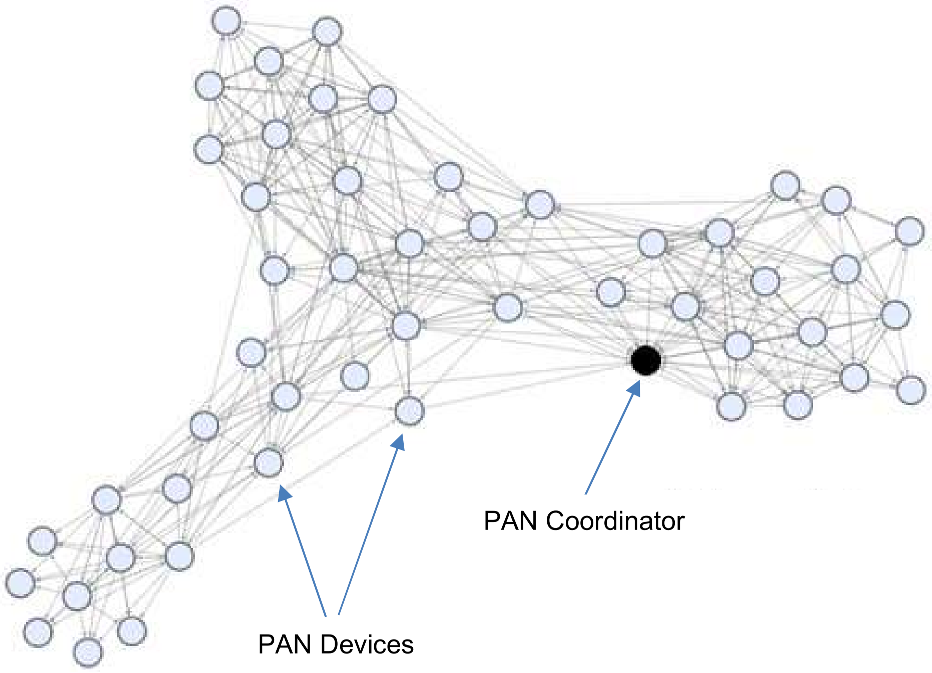


Figure 20: Example of a mesh topology of a G3-PLC PAN (the lines represent "logical" communication links, which may or may not correspond to physical links along the power line)

Yet, before a mesh topology is established, all PAN-Devices typically have to carry out a secured association process following the specifications of the LoWPAN Bootstrap Protocol (LBP) defined in the G3 Specifications [1]. This specification is based on the well-defined EAP-PSK standard.

Before EAP-PSK authentication is carried out, a LoWPAN Bootstrap Device (LBD in LBP terminology) first explores its direct neighbourhood by sending a specific "beacon request" MAC command frame. Neighbours respond to this frame by sending a "beacon" MAC frame allowing the LBD to learn about his environment. If the LBD does not detect a good direct link to the LoWPAN Bootstrap Server (LBS), it selects a relay note also known as LoWPAN Bootstrap Agent (LBA) to which a good connection is found.

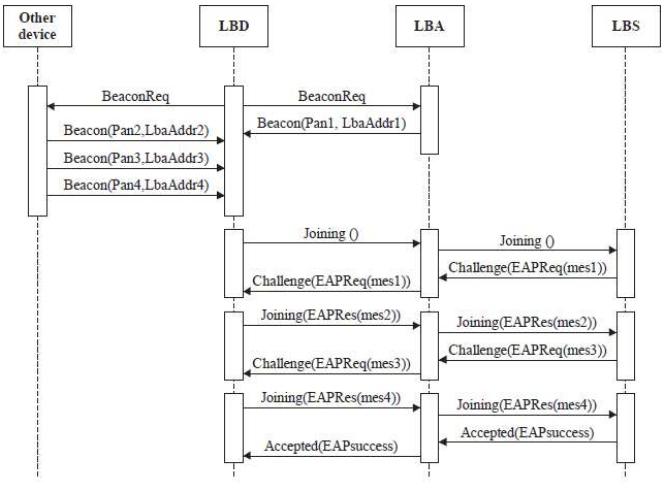


Figure 21: The LoWPAN Bootstrap Protocol (LBP)

The EAP-PSK authentication protocol is then carried out between LBD and LBS, using the selected LBA to forward information to/from the LBS. Both LBD and LBS need to share appropriate credentials before the LBS grants access to the G3 PAN it maintains. Once the bootstrapping process has completed successfully, the LBD becomes an "associated" PAN-Device and is able to exchange information with any other node (PAN-Device or PAN-Coordinator) in the G3 network.

3.6. Routing in a G3 network

3.6.1. The LOADng routing protocol

The size of an electricity grid and its characteristics do not allow all nodes to transmit a message directly to the network coordinator. It is, therefore, necessary to use certain nodes as relays which are chosen to optimize transmission times and the use of available bandwidth. In addition, this choice can be questioned every time disturbances are encountered on the propagation channel (for example changes in impedance, attenuation or noise conditions for PLC links, as explained in §3.1.2).

Therefore, G3-PLC embeds a default reactive routing protocol, LOADng (Lightweight On-demand Ad-hoc Distance-vector routing protocol - Next Generation), responsible for finding the optimal path (according to a given routing metric) between an originator node and a destination node by selecting appropriate intermediate nodes acting as relays. LOADng allows each G3 node to populate its routing table indicating the next hop towards a given destination. Furthermore, when a link breaks, as shown in Figure 22, LOADng allows to find an alternate path to restore connectivity without the involvement of upper layers.

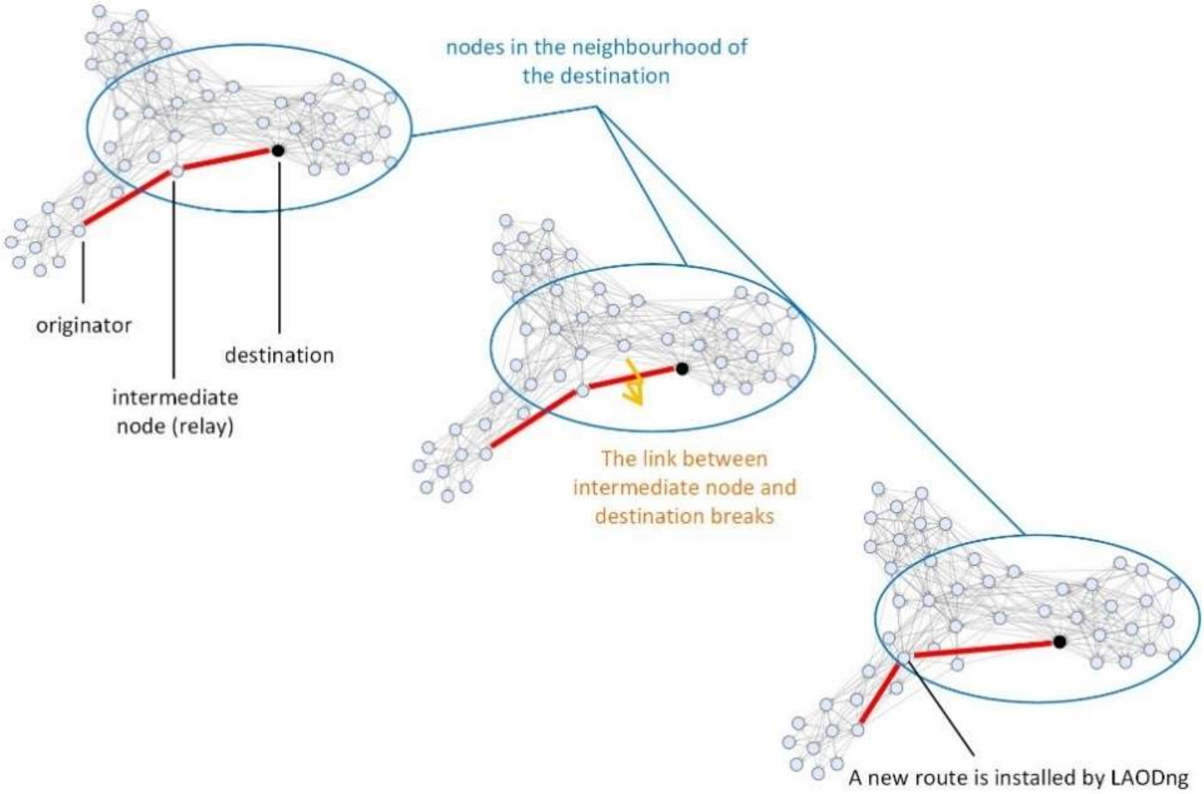


Figure 22: Restoring connectivity

LOADng is of reactive (as opposed to proactive) nature, as route discovery is triggered only if data needs to be transmitted, and if there is no available route to the destination node. In the G3-PLC and G3-Hybrid stacks, LOADng is implemented at data link layer (mesh-under) as it forwards 6LoWPAN frames using MAC addresses.

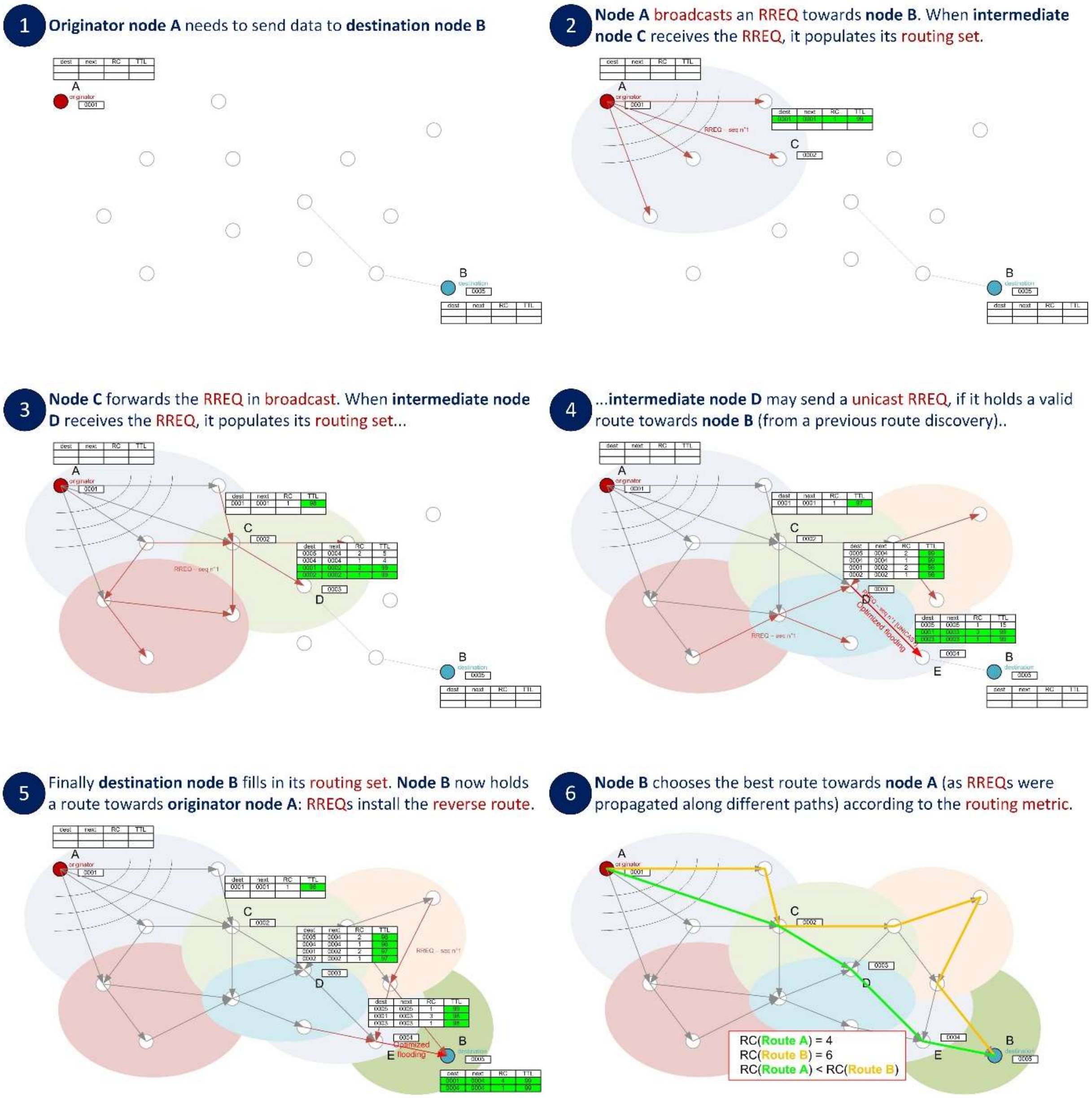
Basic principles are as follows:

- Node A is about to transmit a packet to node B, and node B is not in node A’s routing table.
- Node A initiates a route discovery by sending a Route REQuest (RREQ) message in broadcast, indicating that a route is sought to node B.
- While the RREQ is broadcasted towards the network from node to node, each node updates its routing set (temporary routing table entry), as depicted in Figure 23 (steps 2 to 5). The reverse route is being installed during the propagation of the RREQ message.
- Once node B has received several copies of the initial RREQ message having been propagated

through different paths, it selects the best route according to the routing metric (Figure 23 – step 6) and sends a Route REPly (RREP) back to the originator of the RREQ (node A) in unicast along the selected path (Figure 23 – steps 7 to 10). The forward route is installed during the propagation of the RREP message.

In addition to these basic rules, LOADng allows to:

- Build bidirectional routes as PLC links are often asymmetric (sometimes even unidirectional) in G3 networks (while this characteristic is less common for RF links). The bidirectional nature of a link is assessed by MAC acknowledgements during RREP propagation. The detection of a unidirectional link leads to the blacklisting of the node not having sent an acknowledgement.
- Reduce signalling traffic by allowing optimized flooding when the use of unicast RREQ is enabled (Figure 23 – steps 4 and 5).
- Locally repair broken routes between intermediate nodes (instead of invalidating the whole route between originator and destination nodes).



1 **Originator node A** needs to send data to **destination node B**

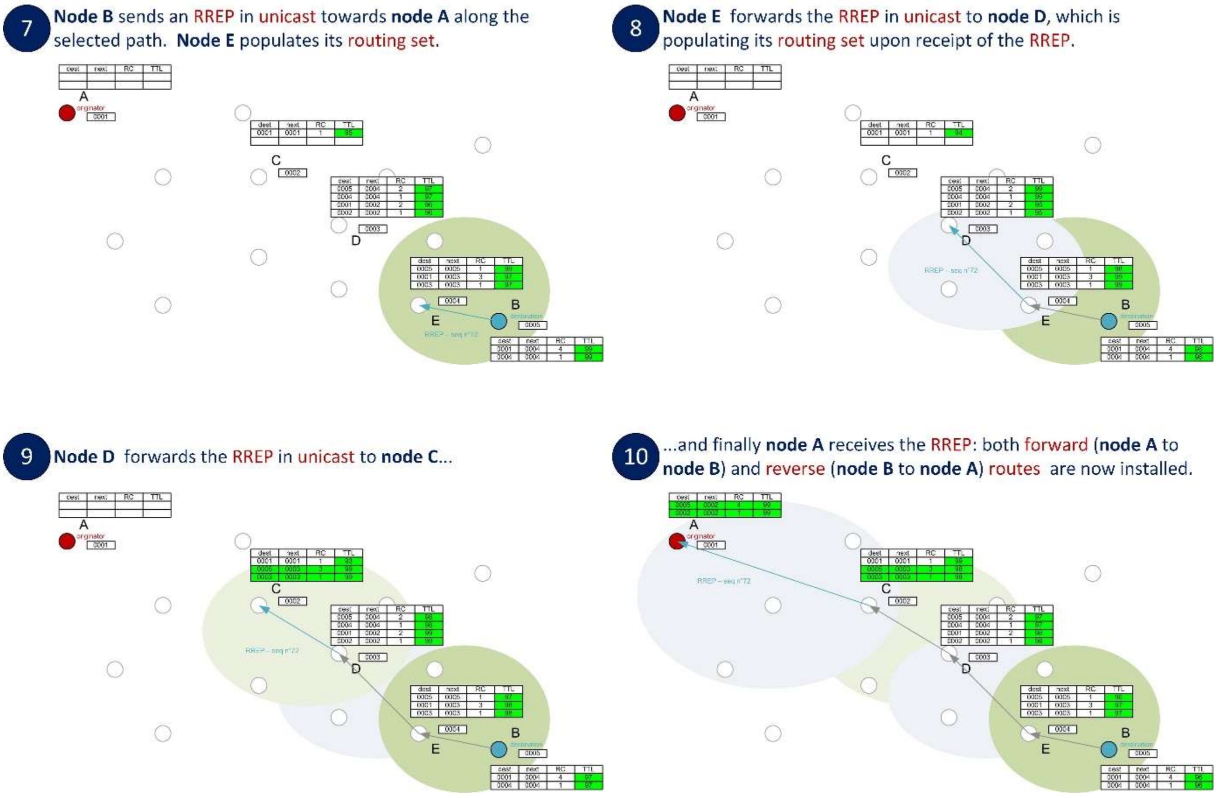
2 **Node A** broadcasts an RREQ towards **node B**. When **intermediate node C** receives the RREQ, it populates its routing set.

3 **Node C** forwards the RREQ in broadcast. When **intermediate node D** receives the RREQ, it populates its routing set…

4 …**intermediate node D** may send a unicast RREQ, if it holds a valid route towards **node B** (from a previous route discovery)..

5 Finally **destination node B** fills in its routing set. **Node B** now holds a route towards **originator node A**: RREQs install the reverse route.

6 **Node B** chooses the best route towards **node A** (as RREQs were propagated along different paths) according to the routing metric.


7 **Node B** sends an RREP in unicast towards **node A** along the selected path. **Node E** populates its routing set.

8 **Node E** forwards the RREP in unicast to **node D**, which is populating its routing set upon receipt of the RREP.

9 **Node D** forwards the RREP in unicast to **node C**...

10 ...and finally **node A** receives the RREP: both forward (**node A** to **node B**) and reverse (**node B** to **node A**) routes are now installed.

Figure 23: LOADng route discovery procedure

Once the LOADng protocol has installed a bidirectional route between an originator node and a destination node, the routing set entries installed by the different nodes along the selected path are converted into routing table entries for a given duration.

The local routing table attribute is maintained locally by each node and contains:

- The short address of the destination node
- The short address of the next hop (intermediate node) to the destination node
- The route cost along the path towards the destination node
- The hop count along the path towards the destination node
- The weak link count along the path towards the destination node
- A valid time

Note: Weak links are links that are considered as fragile, due to a low signal to noise ratio (reflected in a low LQI). LOADng aims at minimizing the number of weak links in installed routes.

The validity of a route depends on the value of the time-to-live parameter (to be chosen according to the use case G3 is addressing) and on the frequency of data traffic being forwarded along this route. Every time a frame is successfully propagated along a route to the destination, valid time is refreshed to its maximum value (time-to-live parameter) thus extending the validity of the route. On the other hand, if no data traffic is forwarded along the route or if a link breaks and local route repair was unsuccessful (a Route ERRor (RERR) is forwarded to the destination and the route valid time is set to 0), the route is no more valid.

Care shall also be taken when choosing a node's routing entry capacity; in a typical smart metering use case, it is recommended that a PAN-Coordinator can manage at least 1500 routing table entries, while 150 entries should suffice for PAN-Devices.

3.6.2. Route Cost for G3-PLC devices

Route cost is a metric that allows the determination of the best route, by adding up the link costs of each link along a path between an originator node and a destination node. LOADng leaves the choice of the best route to the destination node which receives RREQs having been forwarded along different paths, thus carrying different route costs.

In the example depicted in Figure 23, the metric chosen for computing the route cost is hop count, for simplification purposes. Indeed, in step 6, destination node B chooses the green “route A” (route cost = 4 hops) rather than the yellow “route B” (route cost = 6 hops) as it aims at minimizing the route cost.

In G3-PLC, the metric used to compute the route cost is a little more complicated than hop count, as indicators such as link quality or modulation type (a link using Robust mode will not provide any headroom in case a disturbance is encountered; therefore, a link using D8PSK will be preferred) should also be taken into account.

G3 Specifications [1], define the “composite metric” as follows:

$$LinkCost = max\left(C_{i\to j}, C_{j\to i}\right) + AdpKrt \times \frac{NumberOfActiveRoutes}{MaximumNumberOfActiveRoutes} + adpKh$$

where $C_{i\to j}$ and $C_{j\to i}$ are the directional link costs (forward and reverse direction, respectively) between i to j. The directional link cost is computed as follow:

$$\begin{aligned} DirectionalLinkCost &= adpKr \times MOD_{Kr} + adpKm \times MOD_{Km} \\ &+ adpKc \times \frac{(MaximumNumberOfTones - NumberOfActiveTones)}{MaximumNumberOfTones} \\ &+ adpKq \times MAX\left(0, MIN\left(1, \frac{adpHighLQIValue - LQI}{adpHighLQIValue - adpLowLQIValue}\right)\right) \end{aligned}$$

The composite metric consists in taking into account the highest “directional link cost” as links are often of asymmetric nature as well as the number of routes already installed in a node’s routing table (with weighing factor “adpKrt”) and hop count (“adpKh”).

The directional link cost is a function introducing penalty when using Robust mode (weighed by “adpKr”) and depending on modulation type (weighed by “adpKm”), tone map (weighed by “adpKc”) and link quality (weighed by “adpKq”).

Note: Changing the different weighing parameters to values different from the default values recommended in G3 Specifications [1] will change the way routes are established. Yet, if doing so, a thorough validation process has to be carried out before deploying the configuration at large scale.

3.6.3. Route Cost and Media Type selection for G3-Hybrid devices

Media Type selection is carried out in the 6LoWPAN Adaptation layer using the existing LOADng routing protocol: when RREQ messages are propagated through the network in broadcast, which implies simultaneous propagation over both media (using Media Type value 0x02, according to §3.4.2), the destination node ends up in selecting the best route also taking into account the route cost cumulated over different combinations of PLC and RF links.

Therefore, the link cost formula has been updated with a RF Link Quality Indicator (LQI_{RF}) penalty[8] and a duty cycle penalty[9] (which helps to spread routes amongst several neighbours, to avoid too high duty cycle consumption at a same intermediate node) as follows:

$$LinkCost_{RF} = max\left(C_{i\to j}, C_{j\to i}\right) + AdpKrt_{RF} \times \frac{NumberOfActiveRoutes_{RF}}{MaximumNumberOfActiveRoutes} + adpKh_{RF}$$

Where $NumberOfActiveRoutes_{RF}$ is the number of active routes for which the next hop is reachable using the RF medium and $C_{i\to j}$ and $C_{j\to i}$ are the directional link costs (forward and reverse directions, respectively) between i and j. The directional link costs are established as follows:

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[8] Based on POS table information collected through the RLQ-IE Information Element

[9] Based on POS table information collected through the LI-IE Information Element

$$\begin{aligned}
&\mathit{DirectionalLinkCost}_{RF} \\
&\qquad = \mathit{adpKq}_{RF} \times \mathit{MAX}\left(0, \mathit{MIN}\left(1, \frac{\mathit{adpHighLQIValue}_{RF} - \mathit{LQI}_{RF}}{\mathit{adpHighLQIValue}_{RF} - \mathit{adpLowLQIValue}_{RF}}\right)\right) \\
&\qquad + \frac{\mathit{adpKdc}_{RF} \times \mathit{DutyCyclePenalty}}{100} \\
&\qquad + \mathit{adpKn}_{RF} \times \mathit{MAX}\left(0, \mathit{MIN}\left(1, \frac{\mathit{Noise} - \mathit{adpLowNoise}_{RF}}{\mathit{adpHighNoise}_{RF} - \mathit{adpLowNoise}_{RF}}\right)\right)
\end{aligned}$$

“adpKq$_{RF}$”, “adpHighLQIValue$_{RF}$”, “adpLowLQIValue$_{RF}$” and “LQI$_{RF}$” introduce a link quality penalty aiming at optimal route construction.

“adpKdc$_{RF}$” and “DutyCyclePenalty” introduce a duty cycle penalty resulting in the spreading of routes amongst several neighbours. Thus, these parameters avoid too high duty cycle consumption of a same next hop node, entailing possible transmission failure at this neighbour node.

“adpKn$_{RF}$”, “adpHighNoise$_{RF}$”, “adpLowNoise$_{RF}$” and “Noise” introduce an additional penalty for high RF noise levels.

During the propagation of the RREP message, the route is finally installed following LOADng principles. From now on, unicast traffic can be forwarded over PLC or RF thanks to the addition of a dedicated field in the routing table, which indicates the preferred medium for the transmission of a frame to the next hop towards its destination.

3.6.4. Routing message propagation control

During route establishment, nodes propagate received Route REQuest (RREQ) messages in broadcast, if the RREQ route-cost is better than the one carried by the RREQ previously received. As a result, a route establishment procedure will generate at least one RREQ per node or even more, depending on the topology and the path taken by RREQ messages during propagation.

In large networks, the generation of numerous RREQ messages may cause network congestion, increasing the probability of RREQs being afflicted by collisions or transmission failures due to a busy channel. Consequently, some good routes may be lost unexpectedly.

First, RREQ collision risk is reduced by a dedicated CSMA/CA mechanism (controlled by the “macBroadcastMaxCWEnabled” attribute). Second, additional enhancements were finalized in the 2022 release of the G3 Specifications [1]: these new mechanisms help reduce both RREQ collisions and transmission of unnecessary RREQ messages, resulting in better route establishment and reduced network congestion. The impact is particularly visible for large or dense networks, but all types of networks can benefit from these enhancements.

Controlled RREQ jittering:

The first mechanism consists in the addition of a controlled jittering (i.e. transmission delay) when forwarding RREQ messages. This variable delay increases the chances that RREQs carrying better route-cost are the first ones to be transmitted to the destination node, leading to a faster selection of the best route.

Upon reception of an RREQ, intermediate nodes compute the jitter delay based on the measured reception LQI (Link Quality Indicator). Until the duration corresponding to the computed value of "jitter delay” is elapsed, received RREQs are either dropped or selected to replace the buffered RREQ (the one that tiggered the computation of jitter delay), based on a route-cost comparison. This reduces the number of RREQ transmissions and increases the probability of forwarding RREQs with a good route-cost.

Figure 24 shows an example of the calculated jittering delay as a function of the LQI:

- RREQs received with a “bad” LQI have long delays, as they were received through unreliable links and should not be selected if an alternative is possible.
- RREQs received with a “very good” LQI are delayed for a short time, as they are received from a very close neighbour node. Forwarding these RREQ would result in a route with more hops to the destination, which is suboptimal.
- RREQs received with an “intermediate” LQI are delayed the least. In this example an LQI value

of 86 results in no delay.

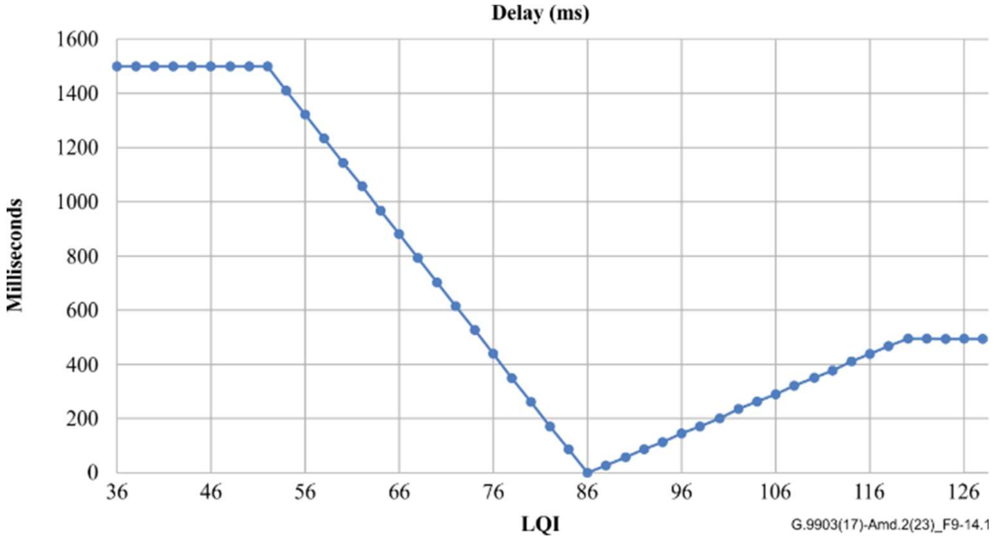

Figure 24: RREQ delay as a function of the LQI

The jitter delay formula is configurable and must be consistent with the LQI addend of the sum corresponding to the route-cost according to the formula given in [1] (see §3.6.2 and §3.6.3).

Topology-aware RREQ forwarding:

The second mechanism consists in a topology-aware RREQ forwarding scheme which enhances route establishment if the physical G3-PLC network is organized in clusters of nodes. This takes advantage of network topologies frequently encountered in field deployments, as shown in Figure 25:

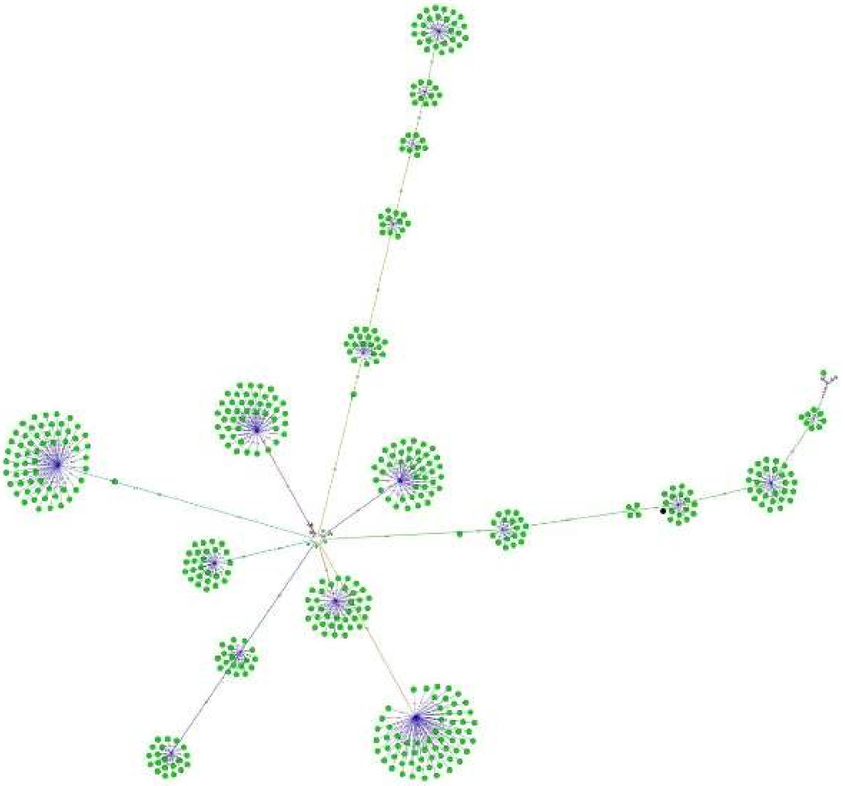

Figure 25: Typical G3-PLC topology organized in clusters

RREQ transmissions can be suppressed for intermediate nodes if other neighbouring intermediate nodes from the same cluster (identified using hop count and LQI information) already forwarded an RREQ carrying a similar route-cost. This is implemented based on the Trickle algorithm [11] and allows to reduce the number of transmitted RREQs for a same route establishment procedure.

3.7. Broadcast transmission for data distribution

Broadcast transmission for data distribution is supported, based on the 6LoWPAN broadcast mechanism [12].

This basic mechanism defines a dedicated “BC0” header that uniquely identifies each broadcast message. Hence, each node in the network will retransmit the same broadcast message exactly once. This high level of redundancy ensures broadcast messages to reach every single node, but at the cost of a high bandwidth consumption, which may cause congestion, especially in large or dense networks.

Enhancements were introduced in the G3 Specifications [1] in 2022, by adding a mechanism to control the amount of broadcast message retransmissions as well as the desired level of redundancy, using the Trickle algorithm [11].

The Trickle algorithm is used to limit retransmissions of broadcast messages, by first counting the number of received messages during a small observation period. If enough messages have been received (i.e. the number of messages received are above a configurable threshold) from other nodes in the neighbourhood at the end of the observation period, the node will not retransmit the message.

The duration of the observation period is automatically selected based on the usefulness of a node for broadcast propagation (considering its role as LOADng router and link quality with neighbours), so that better nodes are given a smaller observation period and are more likely to retransmit broadcast messages.

Trickle can greatly reduce the number of broadcast transmissions, especially in dense networks (> 90% reduction in some cases). The algorithm is configurable, allowing to select the amount of message redundancy required by a given application.

3.8. Native support of IPv6

By design, the G3-PLC and G3-Hybrid protocol stacks allow native support of the IPv6 protocol, which grants end-user flexibility to fulfil business requirements when choosing the appropriate higher layers (ISO/OSI transport and application layers). This key feature also secures G3 infrastructures in the long term, thanks to the scalability and future application compatibility provided by IPv6.

An IPv6 address is a 128-bit identifier (16 Bytes) that allows to uniquely identify a device in a network. It is made up of two parts:

- The 64-bit subnet prefix, which identifies the network the device belongs to.
- The 64-bit interface identifier, which identifies the device itself.

In a G3 network, interface identifiers are always formatted as follows:

yyyy:00ff:fe00:xxxx (hexadecimal representation)

where **yyyy** corresponds to the PAN identifier (PAN-ID) and **xxxx** to the device’s short address (see §3.5).

Several types of IPv6 subnet prefixes are available for use in an IPv6 network:

- Link-local prefix: the support of this prefix is mandatory for any IPv6 device and is always available without configuration. Yet link-local addresses cannot offer end-to-end IPv6 connectivity from a host located outside of the local network.

  The link local prefix always equals:

  fe80:0000:0000:0000 (hexadecimal representation)

- Globally routable prefix (GUA): this prefix allows end-to-end IPv6 connectivity to/from G3-PLC PAN-Devices from/to hosts outside the local network, possibly on the Internet (these addresses are designed to be unique worldwide and can be used over the Internet).

  A globally routable prefix will be in the **2000::/3** (hexadecimal representation) address space, i.e. the three left-most bits are always equal to “001” (binary representation) while the remaining available 61 bits are allocated by a Regional Internet Registry (RIR) or an Internet Service Provider (ISP).

- ULA (Unique Local Address) prefix: this prefix allows end-to-end IPv6 connectivity to/from G3-PLC PAN-Devices from/to hosts outside the local network within an organisation but not from/to the Internet.

  A ULA prefix is formatted as a concatenation of the following fields:

  fc (7 bits – hexadecimal representation) + **L** (1 bit – equals 1 if locally assigned) + **Global ID** (40 bits, random value) + **Subnet ID** (16 bits, identifies a subnet within the organisation)

  Note: In practice organizations may use Global ID and Subnet ID fields as they wish to match their needs, and according to their internal addressing plans.

G3 nodes hold at least a link-local address and if end-to-end IPv6 connectivity is required outside the PAN, an organization may use GUA or ULA addresses.

To obtain a GUA or ULA address, a G3 PAN-Device must be bootstrapped and already have a link-local address. 6LoWPAN "Neighbour Discovery" features allow the advertisement of the local GUA or ULA prefix of the PAN (PIO option in RFC 4861 [7]) and, ideally, additional context information (6CO in RFC 6775 [8]) as to enable external prefix compression for IPv6 packets originating from hosts located outside the local network.

Typically, the PAN-Coordinator becomes an IPv6 "border router" also known as "edge router" (even if the border router could be a dedicated PAN-device) establishing end-to-end IPV6 connectivity to/from the PAN directly from/to external hosts. Nevertheless, enabling IPv6 border router topologies (see example in Figure 26) goes together with reinforced security not limited to MAC ciphering and authentication as offered by G3: **cybersecurity best practices shall be implemented at system level in addition to what G3 natively offers**.

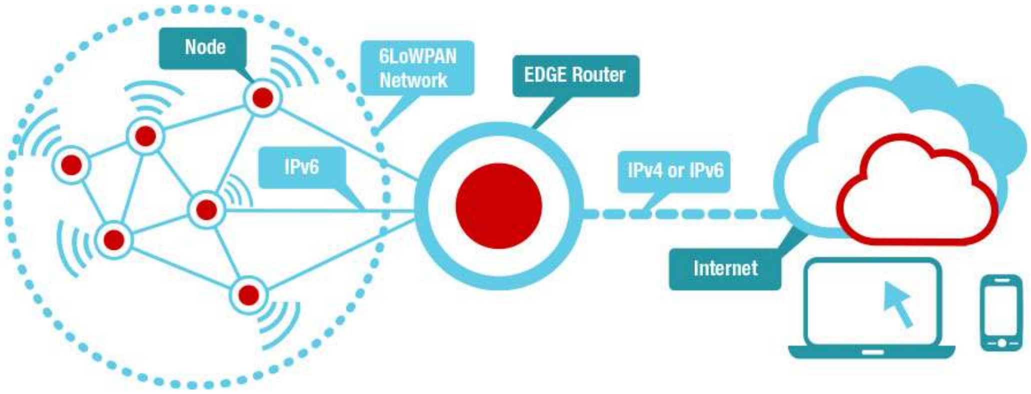

Figure 26: Example of a 6LoWPAN network connected to the Internet through an IPv6 border router

3.9. Cybersecurity aspects

As already introduced previously, cybersecurity is a key aspect to be considered in any network deployment including G3 networks.

The G3-PLC and G3-Hybrid protocol stacks implement state-of-the-art security as they specify mechanisms ensuring mutual authentication and frame encryption at MAC layer (including data, routing or LBP configuration messages) as well as an anti-replay mechanism.

By design, security of G3 PANs is typically managed centrally. The default EAP-PSK (Extensible Authentication Protocol – Pre-Shared Key) authentication method relies on a pre-shared secret: the PSK. Each PSK, specific to each PAN-Device, is known by both the PAN-Device itself and the authentication server either located in the central system or in the PAN-Coordinator.

3.9.1. Overview of the EAP-PSK authentication mechanism

The association of a new PAN-Device (LBD) is done in several steps (see §3.5). The PAN-Coordinator (LBS) is responsible for the authentication of LBDs before granting them access to the PAN by assigning short addresses and providing the shared communication key giving LBDs the ability to decrypt or encrypt data propagated in the PAN.

When a node carries out secured association according to the bootstrapping procedure introduced in

§3.5, mutual authentication between this node and the authentication server is performed according to the EAP-PSK protocol.

The LBP protocol (see §3.5) defines five types of messages:

“**JOINING**”: request for association by any new node, carries embedded EAP-PSK messages during the authentication procedure.

“**CHALLENGE**”: carries embedded EAP-PSK messages during the authentication procedure.

“**ACCEPTED**”: carries embedded EAP-PSK messages in case of successful authentication, it is used to assign configuration parameters to the node (short address, GMK…).

“**DECLINE**”: carries embedded EAP-PSK messages in case of authentication failure.

“**KICK**”: allows the exclusion of an already associated node by the PAN-Coordinator.

At the end of the EAP-PSK procedure, if successful, the node is assigned a short address and is aware of the Group Master Key (GMK) used for MAC encryption: the node is now ready to securely exchange information on the G3 network. The GMK is defined at the start-up by the PAN-Coordinator and is common to all the PAN-Devices of a same PAN.

3.9.2. Overview of MAC layer security: encryption and anti-replay mechanisms

Encryption is based on the use of the GMK previously shared by the PAN-Coordinator (after successful authentication) to all PAN-Devices. All messages sent by PAN-Devices are encrypted using this GMK and AES-128 algorithm with CCM* mode of operation. MAC frame payloads are encrypted, together with security headers used for decryption by recipients.

The CCM* mode requires the definition of an initialization vector to be used as an input parameter for encryption and ensures that encrypted frames are not played back.

MAC encryption generates a slight increase in the size of transmissions:

- The MAC header of an encrypted frame contains a 6-Byte security header consisting of 3 fields:
    - Security level (1 Byte): security level of the frame
    - Key identifier (1 Byte): GMK key identifier
    - Frame counter (4 Bytes): used for the initialization vector and the anti-replay mechanism
- A 4-Byte “Message Integrity Code” (MIC) field is added after the encrypted data. The MIC provides protection against any alteration of the content of the frame or its header.

According to common recommendations, the PAN-Coordinator has the ability to modify the GMK used by all PAN-Devices thanks to a dedicated “re-keying” process.

4. Enabling dense network enhancements

To optimize performances in dense networks, typical of densely populated urban areas, it is recommended to enable the “dense network enhancements” that allow the reduction of broadcast traffic including LOADng routing messages but also for data distribution in case broadcast transmission of application-specific data is envisaged.

The way these mechanisms operate is explained in §3.6.4 (for routing messages) and §3.7 (for data distribution).

To enable the different dense network enhancements (controlled RREQ jittering, topology-aware RREQ forwarding or optimized broadcast transmission for data distribution) in G3-PLC or G3-Hybrid devices, the right attribute values need to be set, as indicated in the following table:

Attribute	Id.	Range	Description	Value
Controlled RREQ jittering				
adpDelayLowLQI	0x25	0-65535	See [1], Table 9-28	1500
adpDelayHighLQI	0x26	0-65535		500
adpRREQJitterLowLQI	0x27	0-254		52
adpRREQJitterHighLQI	0x28	0-254		120
Controlled RREQ jittering, additional parameters for G3-Hybrid (RF links)				
adpDelayLowLQI_RF	0xD9	0-65535	See [1], Table H.8-12	1500
adpDelayHighLQI_RF	0xDA	0-65535		300
adpRREQJitterLowLQI_RF	0xDB	0-254		60
adpRREQJitterHighLQI_RF	0xDC	0-254		180
Topology-aware RREQ forwarding				
adpClusterTrickleEnabled	0x31	FALSE-TRUE	See [1], Table 9-28	TRUE
adpClusterMinLQI	0x32	0-255		90
adpClusterTrickleK	0x33	1-10		3
adpClusterRREQRouteCostDeviation	0x34	0-255		4
adpClusterTrickleI	0x35	0-4096		adpClusterTrickleK * 3 * duration(RREQ)[10]
Topology-aware RREQ forwarding, additional parameters for G3-Hybrid (RF links)				
adpClusterTrickleI_RF	0xDD	0-4096	See [1], Table H.8-12	adpClusterTrickleK_RF * 3 * duration(RREQ)[10]
adpClusterTrickleK_RF	0xDE	1-10		3
adpClusterMinLQI_RF	0xDF	0-254		90
Optimized broadcast transmission for data distribution				
adpTrickleDataEnabled	0x29	FALSE-TRUE	See [1], Table 9-28	TRUE
adpTrickleLQIThresholdLow	0x2A	0-255		60
adpTrickleStep	0x2B	1- 255		1
adpTrickleImin	0x2D	100-5000		1200 for CENELEC bandplans, 600 for FCC bandplans
adpTrickleMaxKi	0x2E	1- 5		3
adpTrickleAdaptiveImin	0x2F	FALSE-TRUE		TRUE
adpTrickleAdaptiveKi	0x30	FALSE-TRUE		FALSE
adpTrickleLQIThresholdHigh	0x36	0-255		90
Optimized broadcast transmission for data distribution, additional parameters for G3-Hybrid (RF links)				
adpTrickleLQIThresholdLow_RF	0xD8	0-255	See [1], Table H.8-12	85
adpTrickleLQIThresholdHigh_RF	0xE2	0-255		95

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[10] Duration(RREQ) equals 50 ms for PLC / CENELEC A, 85 ms for PLC / CENELEC B, 15 ms for PLC / FCC and ARIB bandplans and 5 ms for RF

5. SLA (Service Level Agreement) expectations for PLC

Like many other wired or wireless telecommunication standards, the G3-PLC protocol stack is not designed for deterministic networking and does not provide resource allocation mechanisms. Therefore, performances may vary significantly if higher application layers mechanisms are not appropriately chosen: a G3-PLC channel can obviously not be used the same way as a high throughput medium.

That being said, this section provides reference data on what can be expected in a G3-PLC network composed of devices with correct analog design (parameters such as output level, in particular in low-impedance conditions, shall not be neglected) and possibly embedding additional digital processing such as blanking or clipping techniques, out of scope of the G3 Specifications [1].

Dynamic range:

The dynamic range is defined as the maximum attenuation a PLC signal can undergo before the PLC link between two nodes breaks. In practice, the dynamic range corresponds to the attenuation measured between a transmitter and a receiver (device under test) when the Frame Error Rate (FER) reaches a value of 5%. The dynamic range can be assessed in ideal conditions (no noise, moderate impedance), under low impedance conditions and/or in the presence of noise.

A certified implementation guarantees a dynamic range of at least 60 dB without noise and in moderate impedance conditions (such as those provided by a CISPR 16-1-2 [9] Artificial Mains Network – AMN), and as a rule of thumb a value higher than 80 dB is often measured. It is more difficult to provide reference values in the presence of noise as implementation choices can be differently affected by the same noise waveform.

The dynamic range may be assessed using the methodology described in ETSI TS 103 909 [10] (note that this technical specification uses the term link budget).

Theoretical physical layer data rates, point-to-point UDP throughput and point-to-point latency:

The theoretical physical data rate corresponds to the maximum data rate that can be achieved at physical layer in ideal conditions, and thus, it does not take into account channel access times or possible disturbances observed in the propagation channel. Yet, it is the main data rate indicator used by all telecommunication technologies. G3-PLC can offer data rates up to 44 kbps in CENELEC-A bandplan and up to 280 kbps in FCC bandplan.

Another useful indicator is the UDP throughput which can be achieved between two directly connected G3-PLC nodes, as it reflects the real data rate available for the application layer. The UDP throughput has been established in the laboratory using dedicated well-known tools (iperf or jperf): 13 to 17 kbps have been achieved in CENELEC-A bandplan and 66 to 83 kbps have been reached in the FCC bandplan.

Finally, point-to-point latency has been established in the lab by measuring the ICMP ping roundtrip time between two directly connected G3-PLC nodes. 120 ms have been measured in the CENELEC-A bandplan while a value of 56 ms has been established in the FCC bandplan (64-Byte payload size).

The following table summarizes the abovementioned results:

	Theoretical PHY data rate	**Typical UDP throughput**	**Typical ICMP ping roundtrip time**
CENELEC-A	Up to 44 kbps	13 to 17 kbps	120 ms
CENELEC-B	Up to 19 kbps	5 to 7 kbps	210 ms
FCC	Up to 280 kbps	66 to 83 kbps	56 ms

- **Theoretical PHY data rates of any communication technology should be interpreted with care!**

Theoretical PHY data rates result from a mathematical computation taking into account PHY parameters such as the structure of a PHY frame, the characteristics of the modulation used (OFDM for G3-PLC: number of Fast Fourier Transform points, number of subcarriers, etc.), the sampling frequency, error correction coding, etc. Paragraph 7.3 of the G3 Specifications [1] gives an example of such computation for different bandplans of the G3-PLC technology.

In the field, a communication technology's performance is influenced by many factors. Some, such as noise or interferences, may impair its operation. In addition, intrinsic mechanisms of the protocol stack, such as channel access or routing (for mesh networks) may also impact performance as they influence the timing at which messages are exchanged.

Hence, **the computed PHY data rate is a pure theoretical indication:** some technologies favour higher data rates at the cost of lower robustness (a PHY frame of a given length will include less error correction coding and more payload) while others favour robustness over speed (a PHY frame of a given length will include more error correction coding and less payload). Of course, less robustness increases transmission errors and retries, which will result in loss of time and a reduced data rate (the same quantity of data is sent over a longer period than expected).

In conclusion, an end-user shall always consider typical throughput obtained just below the application layer (for example the UDP throughput in this document) and latency instead of focussing on theoretical PHY data rates. In addition, empirical experience with the technology and performances reported for similar application use cases shall be taken into account when selecting a communication technology.

Empirical high-level SLA for the smart metering use case:

Performances in the field vary according to environmental factors such as the number of nodes in a G3-PLC network, the density of nodes and their geographical distribution, presence of noise, impedances, attenuation and traffic patterns. Due to the meshed nature of G3-PLC PANs, the rollout strategy (massive with saturated PANs or occasional over several years) will also have an impact on the performances during the deployment of the smart metering infrastructure.

Experience shows that G3-PLC allows average daily collection rates of 98% on large scale deployments (more than 1 million units installed over several PANs), thanks to the robustness of the technology as well as appropriate application layer policies.

It is also well-assumed that a medium-sized smart meter network consisting of up to 200 nodes could be read out within 30 minutes. Reaching one individual node (without parallel requests to other nodes) in a multi-hop G3-PLC network could take less than 1 second if there is a valid route to this node and up to a few seconds if a new route has to be built.

6. Abbreviations

6CO	6LoWPAN Context Option
6LoWPAN	IPv6 Low power Wireless Personal Area Network
AC	Alternating Current
AES	Advanced Encryption Standard
ARIB	Association of Radio Industries and Businesses
ARQ	Automatic Repeat request
CENELEC	European Committee for Electrotechnical Standardization
CISPR	International Special Committee on Radio Interference
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
D8PSK	Differential 8 Phase Shift Keying
DBPSK	Differential Binary Phase Shift Keying
DC	Direct Current
DQPSK	Differential Quadrature Phase Shift Keying
DSP	Digital Signal Processor
EAP	Extensible Authentication Protocol
FCC	Federal Communications Commission
FER	Frame Error Rate
FH	Frequency Hopping
FSK	Frequency Shift Keying
GMK	Group Master Key
GUA	Global Unicast Address
HVAC	Heating, Ventilation and Air-Conditioning
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISM	Industrial Scientific and Medical
ISO	International Standards Organization
ITU	International Telecommunication Union
LBA	LoWPAN Bootstrapping Agent
LBD	LoWPAN Bootstrapping Device
LBP	LoWPAN Bootstrapping Protocol
LBS	LoWPAN Bootstrapping Server
LOADng	6LoWPAN Ad-hoc On-demand Distance vector routing – Next Generation
LQI	Link Quality Indicator
MAC	Medium Access Control
MIC	Message Integrity Code
MCU	Micro Controller Unit

NB-PLC	NarrowBand Power Line Communication
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PAN	Personal Area Network
PIO	Prefix Information Option
PLC	Power Line Communications
PSK	Pre-Shared Key
QoS	Quality of Service
RERR	Route ERRor
RF	Radio Frequency
RREP	Route REPly
RREQ	Route REQuest
SLA	Service Level Agreement
SNR	Signal to Noise Ratio
ULA	Unique Local Address
UDP	User Datagram Protocol

7. References

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