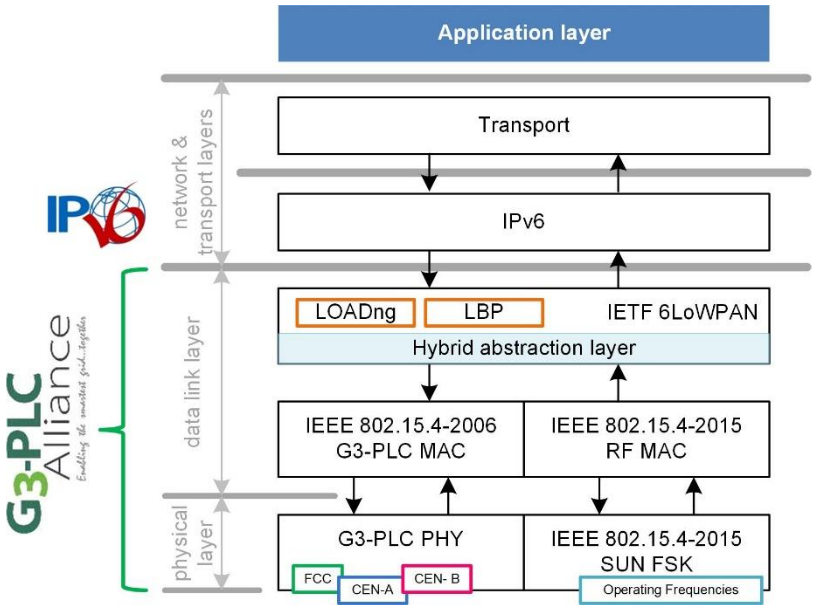
G3-PLC User Guidelines

Introduction to the Hybrid PLC & RF Profile (version 1.0, 06/2021)

Executive Summary

This paper introduces the G3-PLC Hybrid PLC & RF Profile which comes as an extension to the existing G3-PLC protocol stack. In this document, the main features and principles of the hybrid stack will be outlined.



About G3-PLC

G3-PLC facilitates high-speed, highly reliable, long-range communication over the existing powerline grid. The features and capabilities of G3-PLC 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 PLC.

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

G3-PLC is an open, international standard published by ITU: https://www.itu.int/rec/T-REC-G.9903.

To help adopters properly integrate the G3-PLC protocol stack in products and systems we have developed a set of user guidelines. All user guidelines can be found on the G3-PLC Alliance website: http://www.g3-plc.com/what-is-g3-plc/userguidelines

For more information: http://www.g3-plc.com

Content

1. Rationale for the G3-PLC Hybrid PLC & RF Profile

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-PLC 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-PLC Hybrid PLC & RF 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-PLC Hybrid PLC & RF meshed topology maximizes coverage and resilience
- The G3-PLC Hybrid PLC & RF 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-PLC Hybrid PLC & RF 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, a PLC & RF hybrid technology features the use of PLC or RF media over each link of a single network topology as depicted in Figure 1. 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 and 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.

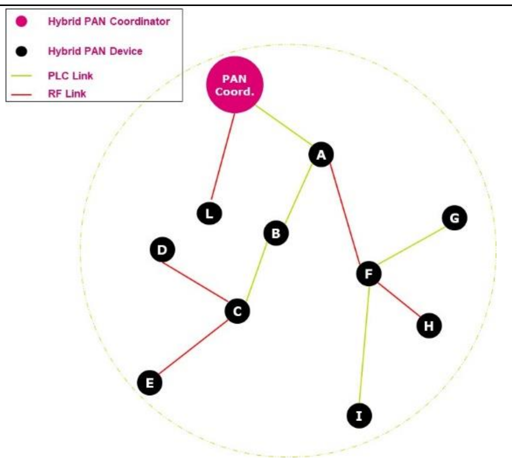


Figure 1: G3-PLC hybrid PLC & RF network topology

2. The hybrid protocol stack

2.1. Presentation of the protocol stack

The G3-PLC Hybrid PLC & RF Profile [1] extends the existing G3-PLC [2] protocol stack by providing a secondary radio frequency (RF) medium.

The RF physical layer is based on SUN (Smart Utility Network) FSK, as specified in IEEE 802.15.4-2015 [3] and amendment IEEE 802.15.4v-2017 [4].

The RF MAC layer is based on IEEE 802.15.4-2015 [3] which differs from the previous version of the standard used by the PLC MAC layer: IEEE 802.15.4-2006 [5]. 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 hybrid protocol stack is shown in Figure 2:

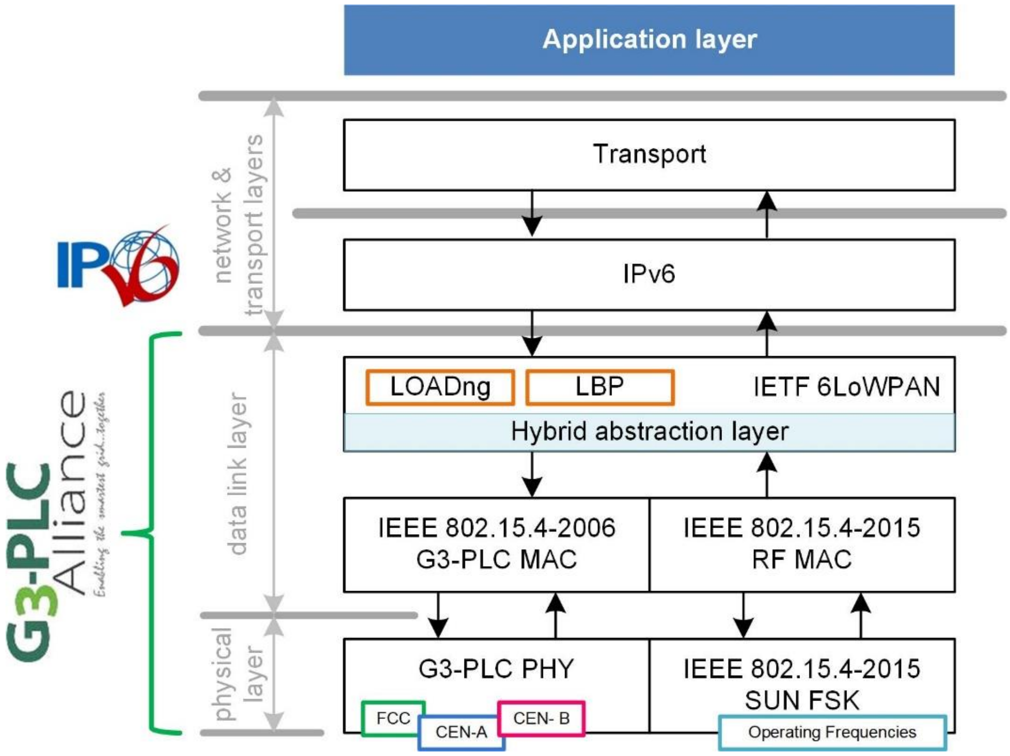


Figure 2: G3-PLC hybrid PLC & RF protocol stack

Further information about the mechanisms common to both G3-PLC and the hybrid protocol stack can be found in the « Introduction of G3-PLC for non-experts » user guidelines [6].

2.2. Mixing hybrid devices with PLC-only devices

The G3-PLC Hybrid PLC & RF Profile is fully compatible with PLC-only G3-PLC stacks. Hence, hybrid devices are interoperable with PLC-only devices: they can be mixed in the field, for example to connect PLC islands as shown in Figure 3:

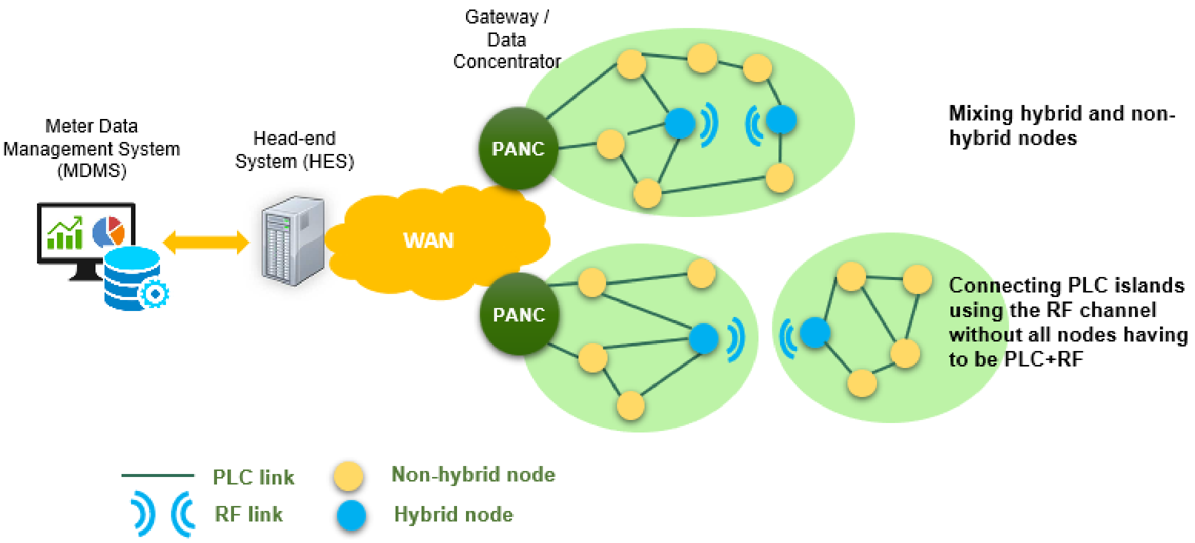


Figure 3: Mixing hybrid devices with PLC-only devices

In existing deployments, the data concentrator does not need to be upgraded to a hybrid device, while it is nevertheless recommended to update its software for better interpretation of bootstrapping messages[1].

3. Frequency bands

Various RF frequency bands and operating modes (number of available channels, channel centre frequency, channel spacing) are specified in IEEE 802.15.4-2015 [3] and amendment IEEE 802.15.4v-2017 [4]. In the current G3-PLC Hybrid PLC & RF Profile [1] a selection is made, based on identified market needs.

As a result, G3-PLC Alliance certification is available for any combination between available RF operating frequency bands (only one at the moment) and CENELEC A, CENELEC B and FCC G3-PLC bandplans:

RF operating frequencies *available for hybrid certification*	**G3-PLC bandplans** *available for hybrid certification*
863–870 MHz (as defined in [1])	CENELEC A
	CENELEC B
	FCC

Care shall be taken when operating 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.

The G3-PLC Alliance is working on the introduction of additional operating frequencies and a frequency hopping mechanism to comply with a broader set of regional regulations.

4. RF Lower layers

4.1. RF physical layer

The RF physical layer is based on the SUN FSK modulation (with or without specific FEC mechanisms), 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 physical layer is also responsible for measuring the LQI specific to the RF medium. Together with the LQI established by the PLC physical layer, the RF LQI is key in the media selection process carried out in upper layers.

4.1. RF MAC layer

As with the PLC medium, unslotted CSMA/CA for non-beacon-enabled networks is used and specific information is exchanged and maintained between neighbour nodes using Information Elements (IE) and a dedicated “POS table”.

The Information Element mechanism is defined in IEEE 802.15.4-2015 [3], which avoids the definition of a new mechanism inspired from G3-PLC Neighbour Tables and Tone Map Response messages (cf. [2] and [6]). Therefore MAC frame formats are different for both media (IEEE 802.15.4-2015 [3] for RF and IEEE 802.15.4-2006 [5] for PLC) as shown in the following figures for the general MAC frame format :

[1] If the PAN coordinator is not ugraded, the LBA always receives LBP messages (from PAN coordinator) with DisableBackupMedia = 0 (for PLC-only 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).

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 4: RF medium general MAC frame format (source: IEEE 802.15.4-2015 [3])

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 5: PLC medium general MAC frame format (source: IEEE 802.15.4-2006 [5])

The hybrid companion specification [1] defines two IE types, which are piggybacked in different types of MAC frames:

- Reverse Link Quality "RLQ-IE", carries link quality information between neighbour nodes (in Enh-ACK – enhanced acknowledgement – MAC frames).
- 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).

5. The Hybrid Abstraction Layer

5.1. 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 the figure below:

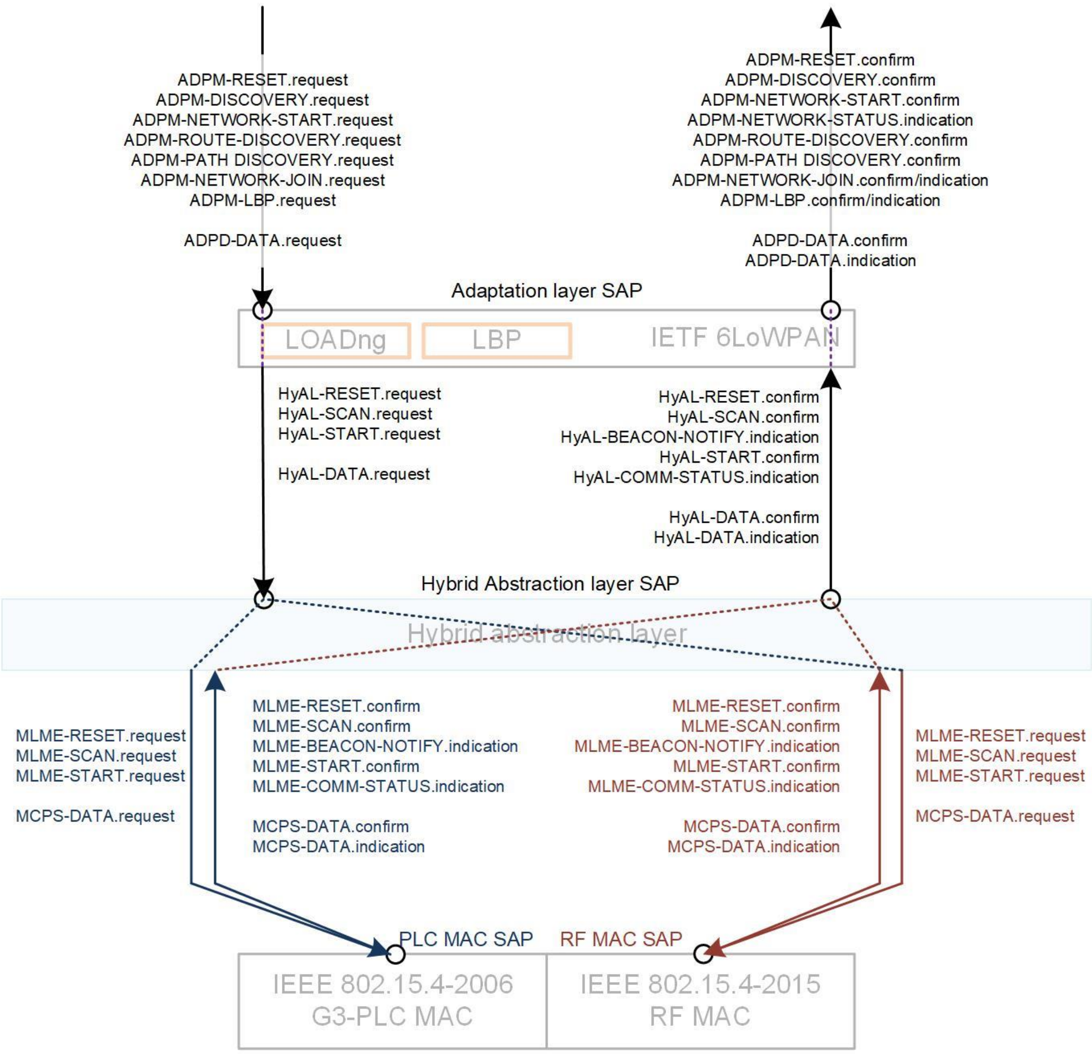


Figure 6: Interaction between the different protocol layers through the service access points (SAP)

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[2]	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" primitives.

[2] Both PLC and RF MAC primitives may be invoked (cf. §5.3)

ADPM-DISCOVERY.request ADPM-DISCOVERY.confirm	HyAL-SCAN.request HyAL-SCAN.confirm HyAL-BEACON-NOTIFY.indication	MLME-SCAN.request MLME-SCAN.confirm MLME-BEACON-NOTIFY.indication	Neighbourhood scan and PAN descriptor collection
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

5.2. 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, copied from the hybrid companion specification [1], 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 as further explained in §5.3.

5.3. Frame forwarding principles

The hybrid companion specification [1] introduces 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 acknowlegement
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 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 §6.

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.

6. Media Type selection

Media Type selection is carried out in the G3-PLC 6LoWPAN Adaptation layer using the existing LOADng routing protocol: when RREQ messages are propagated through the network in broadcast (for more information, see [6]), which implies simultaneous propagation over both media (using Media Type value 0x02, according to §5.2), 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[3] and a duty cycle penalty[4] (which helps to spread routes amongst several neighbours, to avoid too high duty cycle consumption at a same intermediate node) as follows:

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

Where:

- $NumberOfActiveRoutes_{RF}$ is the number of active routes for which the next hop is reachable using the RF medium
- $C_{i\to j}$ 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:

$$DirectionalLinkCost_{RF} = adpKq_{RF} * MAX\left(0, MIN\left(1, \frac{adpHighLQIValue_{RF} - LQI_{RF}}{adpHighLQIValue_{RF} - adpLowLQIValue_{RF}}\right)\right) + \frac{adpKdc_{RF} * DutyCyclePenalty}{100}$$

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

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

Where: • $adpHighLQIValue_{RF}$, $adpLowLQIValue_{RF}$ and LQIRF 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.

During the propagation of the RREP message, the route is finally installed following LOADng principles (cf. [6]). 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.

7. Abbreviations

6LoWPAN	IPv6 Low power Wireless Personal Area Network
CENELEC	European Committee for Electrotechnical Standardization
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
FCC	Federal Communications Commission
FEC	Forward Error Correction
FSK	Frequency Shift Keying
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITU	International Telecommunication Union
LBP	LoWPAN Bootstrapping Protocol
LOADng	6LoWPAN Ad-hoc On-demand Distance vector routing – Next Generation
LQI	Link Quality Indicator
MAC	Medium Access Control
OFDM	Orthogonal Frequency Division Multiplexing
PAN	Personal Area Network
PLC	Power Line Communications
RREP	Route REPly
RREQ	Route REQuest

8. References

[1] HYB_20200731_G3-PLC Alliance - Companion Specification - Hybrid G3-PLC and RF Profile_v0.11 – 2020

[2] G3-PLC Alliance – G3-PLC Specifications – CENELEC – ARIB – FCC – revision (march-2017): Narrowband OFDM PLC Specifications for G3-PLC Networks – 2017

[3] IEEE 802.15.4:2015, IEEE Standard for Low-Rate Wireless Networks – 2015

[4] IEEE 802.15.4v:2017, IEEE Standard for Low-Rate Wireless Networks - Amendment 5: Enabling/Updating the Use of Regional Sub-GHz Bands – 2018

[5] IEEE 802.15.4:2006, IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs) – 2006

[6] G3-PLC User Guidelines, Introduction of G3-PLC for non-experts