White Paper

PLC & Wi-Fi

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Contents

devolo AG and the history of PLC:

devolo AG, the technology company from Aachen, Germany, has focused on PLC technology (**P**ower**L**ine **C**ommunications) since the company's founding in 2002. The company's first products included pure PLC solutions that distributed the Internet signal from the router throughout the entire home over the existing electronic energy supply lines. The current products from the devolo Magic series also rely on a Powerline backbone (PLC) in accordance with ITU-T G.9960 standard (G.hn), which is particularly advantageous in combination with mesh Wi-Fi.

The following pages will explain how PLC technology works and what its advantages are compared to other data transmission options and demonstrate the enormous future potential PLC technology offers as a backbone.

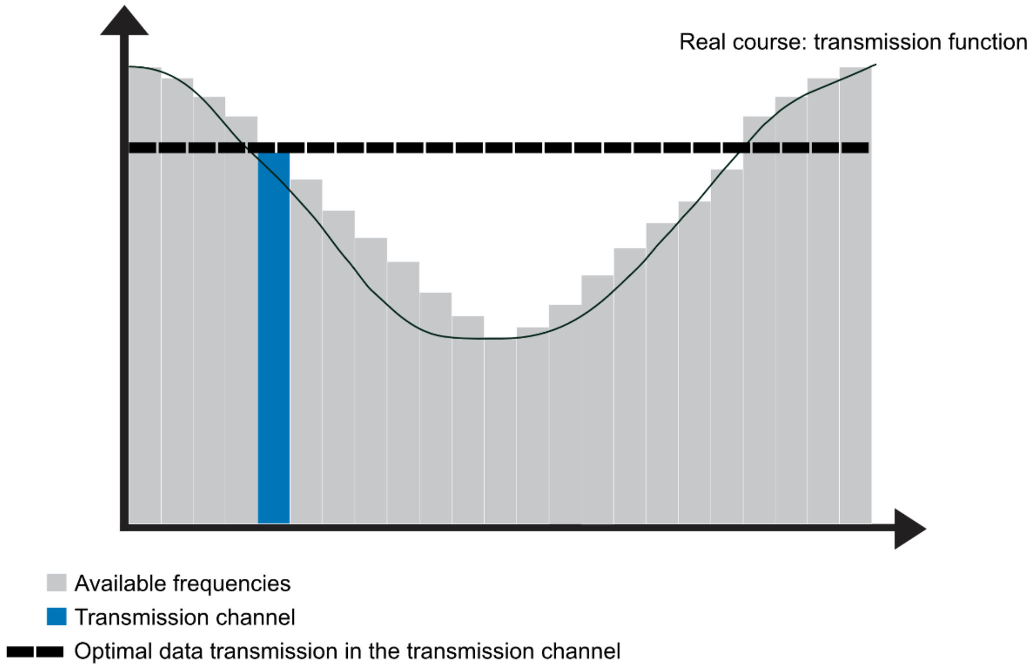
1. Basics of data transmission

To transmit data (information) over a medium (e.g. Ethernet cable, power cable, the air, etc.), the information is converted to electromagnetic signals. These signals are sent on a certain frequency. In turn, the frequency determines the speed of the electromagnetic signals.

The frequency used to transmit the data is called the carrier frequency. This frequency is changed (modulated) when transmitting data in order to represent information with this change. Of course, this only works if a device on the receiver side can revert (demodulate) these changes back to the original information. This combination of actions is called modulation and demodulation.

2. Data transmission over the power grid

The properties that a power cable has for transmitting data on different frequencies can best be depicted graphically. The figure below shows the available frequencies in the bars on the X-axis. The height of the bars represents how well signals can be transmitted on this frequency over the cable and how strongly these signals are attenuated. When the tops of the bars are connected with a line, the result (black curve) is what is known as the transmission function. The higher the value, the better the transmission properties are in the observed frequency band. Conversely, we also refer to these points of good signal transmission as points with low attenuation. A high horizontal path would be ideal, as this would mean that all frequencies are transmitted equally well. In reality, the transfer function may look like it does in the image.



3. OFDM modulation technology

Data transmission in the PLC area is based on **OFDM** modulation (**O**rthogonal **F**requency **D**ivision **M**ultiplex). In this method, the information that is sent is distributed over many different frequencies instead of being transmitted on only one frequency. In the PLC area, data—that is, digital values "1" and "0"—are modulated onto the power line. The power line is therefore the carrier medium for data transmission.

3.1. OFDM modulation occurs in 3 steps:

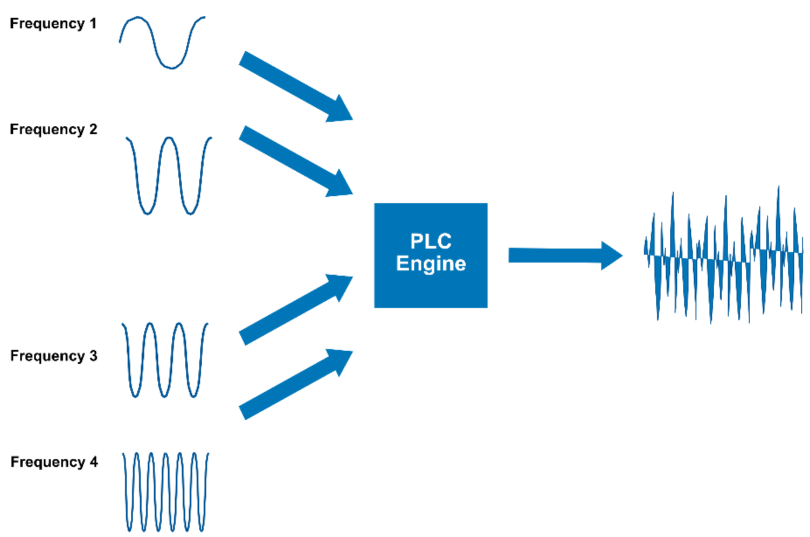
1. Distribution of carrier frequencies

Depending on the standard, different carrier frequencies are used for signal transmission. The number of carrier frequencies used also depends on the standard selected. The following table offers a brief overview of this topic:

Comparison of Powerline standards

Standard	HomePlug 1.0	HomePlug 1.0 Turbo	HomePlug AV	HomePlug AV2	HomePlug AV2 with MIMO	G.hn Wave-2 with MIMO
Introduction	June 2001		August 2005	January 2012	October 2013	January 2013
Frequency band	4.3 to 27 MHz		2 to 30 MHz	2 to 86 MHz	2 to 86 MHz	2 to 86 MHz
Number of carriers*	84	917	1155			
Max. transmission speed (gross)	Up to 14 Mbps	Up to 85 Mbps	Up to 200 Mbps	Up to 600 Mbps	Up to 1200 Mbps	Currently up to 2400 Mbps
Range	Up to 200 m	Up to 300 m	Up to 300 m	Up to 400 m	Up to 400 m	Up to 500 m
Modulation	OFDM	OFDM	OFDM	OFDM	OFDM, combined with MIMO	OFDM, combined with MIMO
Encryption	DES with 56 bits	AES with 128 bits	AES with 128 bits	AES with 128 bits	AES with 128 bits	AES with 128 bits

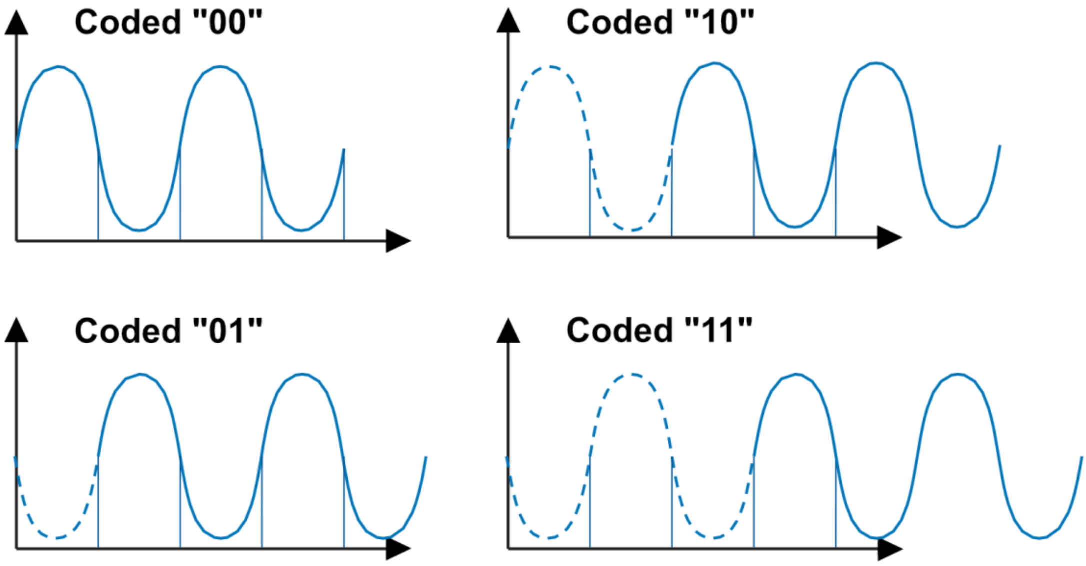
First, the carrier frequencies to be used for signal transmission are determined. For HomePlug 1.0, for example, this is the range from 4.3 MHz to 20.9 MHz in increments of 200 kHz. This results in a total of 84 frequencies which can be used to transmit data. For HomePlug AV, 1155 channels are used in the frequency band from 2 to 30 MHz. Each of these 1155 frequencies is referred to as a channel and can be used to send data independently of other channels. The image below highlights just four different channels as an example. It shows that the frequency in channel 4 performs significantly more oscillations than the frequency in channel 1 within the same time.



2. Encoding

For digital data transmission via PLC, the individual bits are encoded in various processes.

One method of encoding consists of what is called phase shifting. In this process, a signal is defined by the shift of its oscillation compared to the "normal" starting point of the oscillation. The phase shift is evaluated in steps of 90°, allowing four different states (signals) to be differentiated. In this example, a phase shift of 0° stands for a "00", 90° for "01", 180° for "10" and 270° for "11". This kind of encoding not only differentiates a "0" from a "1", but also allows four different numbers to be represented in one wave packet of the oscillation.



In combination with other features of an oscillation, the encoding processes are able to transmit even more information within a unit of time. Simple encoding methods transmit less data per second than more complex methods, but reliability is increased on error-prone lines as a result.

3. Reconstruction

The signals of the various carrier frequencies, encoded using different methods, are sent on the power line in parallel. This way, data is transmitted at the same time across all the carrier frequencies used. While the data in each carrier frequency used is independent of data in other carrier frequencies, only all the data together results in the transmitted data packet. Each encoded data stream occupies its own carrier frequency on the power line.

At the receiver, the entire process is now carried out in reverse order:

- Separating the individual carrier frequencies
- Decoding the data in the individual carrier frequencies
- Reassembling the original data

4. Wi-Fi and wireless solutions

There are many different technologies that bring the Internet into every room of the home. The best known is currently **Wi-Fi** (**W**ireless **L**ocal **A**rea **N**etwork), or wireless data transmission. Wi-Fi is often associated with IEEE 802.11, as the designation **802.11** describes the standard for a technical solution that makes setting up a wireless network (Wi-Fi) possible in the first place. The **IEEE** standard for communication in wireless networks is published by the professional association **I**nstitute of **E**lectrical and **E**lectronics **E**ngineers. Using a new Internet-compatible device over Wi-Fi for the first time is usually very simple. After switching on the Wi-Fi function on the new device, the desired wireless network or network name (**SSID**, **S**ervice **S**et **Id**entifier) of the Wi-Fi network simply needs to be selected and the corresponding password entered.

4.1. Wi-Fi frequency bands

Depending on the Wi-Fi client, the frequency band to be used also plays a major role. In accordance with IEEE 802.11, three frequency bands are available for Wi-Fi networks: **2.4 GHz**, **5 GHz** and **60 GHz**. For home Wi-Fi networks, the 2.4 and 5 GHz frequency bands are used exclusively, since the range with 60 GHz is not sufficient for using Wi-Fi throughout the entire house. The classic frequency band is 2.4 GHz, known as the **ISM** frequency band (**I**ndustrial, **S**cientific, **M**edicine). Its range is significantly greater than in the 5 GHz band, although many common everyday devices use this band, such as wireless input devices, wireless remote controls, smart watches, etc. Since it only offers 13 channels, each spanning 5 MHz, the 2.4 GHz frequency band is heavily overloaded and the Wi-Fi transmission rate is often limited.

The 5 GHz frequency band is used as an alternative. In Europe, it includes a total of 19 channels: 8 in the lower frequency band and 11 in the upper frequency band, starting from 100 MHz. However, due to the growing popularization of the IEEE 802.11ac Wave-2 standard (see the table **Comparison of Wi-Fi standards**), this frequency band is also getting more and more cramped. One problem here is that many Wi-Fi routers in the lower price segment often tout 2.4 and 5 GHz band support, but often only use channels 30, 40, 44 and 48. This is due to the implementation of **DFS** (**D**ynamic **F**requency **S**election), a mechanism of the European regulatory agency **ETSI** (**E**uropean **T**elecommunications **S**tandards **I**nstitute) that is required in Wi-Fi devices in the 5 GHz frequency band. In Germany, dynamic frequency selection has to be used on channels 52 – 64 (5.25 – 5.35 GHz) and 100 – 140 (5.47 – 5.725 GHz).

4.2. Wi-Fi standards and the limitations of wireless connections

Several different Wi-Fi standards are broken down in the table **Comparison of Wi-Fi standards**. In current Wi-Fi routers, all standards are usually implemented for compatibility reasons, but current Wi-Fi clients normally only use the current standards 802.11n (Wi-Fi n) and 802.11ac (including the Wave expansions). The different standards differ in range, frequency band and their modulation methods, as well as in the resulting transmission rate. If both the Wi-Fi-capable device and the router feature the current **802.11ac** Wi-Fi standard, transmission speeds of up to 6936 Mbps are theoretically possible. This is achieved by using wider transmission channels (up to 160 MHz), increased transmitter and receiver units (up to 8x8), more efficient modulation (256QAM) and multi-user MIMO.

4.3. MIMO and modulation

There are various methods for achieving high transmission speeds in the Wi-Fi network. One of those is the use of **MIMO** (**M**ultiple **I**nput **M**ultiple **O**utput), i.e. the implementation of at least two transmitter and receiver antennas in the hardware. In order to ensure optimal utilization of the transmitter and receiver line, the manufacturers of Wi-Fi access points (e.g. routers or Powerline solutions) always construct transmitter and receiver antennas in pairs, i.e. 2x2, 3x3, 4x4, 8x8 etc. This produces an optimal signal-to-noise ratio. However, a higher number of antennas also means higher computing power, which means increased energy consumption as well as increased heat generation for Wi-Fi access points.

The MIMO method makes use of frequency, time and space simultaneously, enabling it to send and receive the data stream over multiple antennas used in parallel thanks to intelligent signal processing. In this process, each receiver antenna receives the wireless signal from all transmitter antennas from the opposite side and calculates the optimal input signal automatically—even if the wireless channel changes. The use of multiple antennas has major advantages. For example, it makes it possible to increase the transmission rate, extend the distance or improve the received signal.

The expansion for **m**ulti-**u**ser **MIMO** (**MU-MIMO**) is also implemented in the Wi-Fi standard IEEE 802.11ac. Multiple antennas are used in this method to send data to various Wi-Fi clients (e.g. smartphones, tablets, laptops, etc.). At least four antennas are suggested for this. For this to work, the Wi-Fi clients also have to be MU-MIMO-capable.

Here is a brief summary of the different types of data stream distribution:

- SISO - **S**ingle **I**nput, **S**ingle **O**utput: Only one antenna is used for sending here. The transmission rate is limited when sending to multiple Wi-Fi-capable devices simultaneously. The capacity on the wireless channel is also wasted.
- MIMO - **M**ultiple **I**nput, **M**ultiple **O**utput: Multiple antennas—at least two—are used for sending and receiving
- MU-MIMO - **M**ulti **U**ser, **M**ultiple **I**nput, **M**ultiple **O**utput: Multiple antennas—at least four—are used for sending to multiple different Wi-Fi-capable devices.

4.4. IEEE 802.11ax – The "high-efficiency Wi-Fi"

While the current Wi-Fi standard IEEE 802.11ac offers high theoretical transmission speeds of up to 6936 Mbps, greater requirements in the future will require even higher transmission speeds. In addition to video-on-demand services such as Netflix, Amazon Video, and the like which stream their content with higher and higher resolutions, PC and console gamers also benefit from significantly increased transmission speeds. After all, in this area, there are more and more providers who want to offer streaming for PC and console games in full HD (1920 x 1080 pixels), Ultra HD (4096 x 2160 pixels) or, in the future, even UHDTV (Ultra High Definition Television, 7680 x 4320 pixels, 8K streaming). The Wi-Fi standard IEEE 802.11ac reveals its performance limitations in these application scenarios, as there is no more room for optimization with the channel bandwidth and modulation method.

Since the physical options for increasing the transmission speed are finite, the goal is to use IEEE 802.11ax to increase efficiency when operating multiple Wi-Fi-capable devices located in the same place—in other words, optimize the efficiency of the protocol in the case of high node density. This is why the IEEE 802.11ax standard is also referred to as "high-efficiency Wi-Fi," since it involves the increase of speed per area, measured in bits per square metre (bps/m2).

To reach this goal, optimizations are made to the Wi-Fi protocol and the transmission speed is controlled individually, depending on the reachability of the Wi-Fi-capable devices. In addition, the 1024QAM modulation method is used (2 symbols or bits) ^10=1024) in order to achieve a gross data rate of 4.8 Gbps with one 160 MHz wireless channel and four antennas used in parallel (MIMO operation). In combination with **OFDMA** (**O**rthogonal **F**requency-**D**ivision **M**ultiple **A**ccess) and the expansion for **M**ulti-**U**ser **MIMO** (**MU-MIMO**) in the uplink, the transmission rate is quadrupled for individual clients compared to 802.11ac. This is possible thanks to the implementation of **spatial reuse**, a function that enables nearby Wi-Fi-capable devices to transmit on the same wireless channel, provided that the signal-to-noise ratio is large enough and there is sufficient signal strength in the respective cells.

However, the use of pure Wi-Fi solutions does not always work optimally and without interference, especially when other Wi-Fi devices are transmitting on the same frequencies. The Wi-Fi standard that was just mentioned, IEEE 802.11ax, is the exception here. Pure Wi-Fi solutions also depend on structural conditions. For example, thick walls which may be made of reinforced concrete, furniture or even closed doors can negatively impact data transmission in the Wi-Fi network. To get optimal Wi-Fi coverage, the placement of the Wi-Fi router is also significant, since all rooms should get a Wi-Fi signal. The incorrect alignment of external rod antennas, if such antennas are present, can be another stumbling block.

UMTS/LTE routers which require a SIM card to be inserted also function wirelessly, and specifically using the mobile phone network. As an alternative, any smartphone and/or tablet can also be converted to a mobile access point. A big disadvantage of this is that, despite the large available data volume, the number of gigabytes is not enough to be able to quickly browse, stream and game.

4.5. Mesh Wi-Fi

The term mesh Wi-Fi describes the intelligent connection of multiple Wi-Fi-capable devices (access points) into a network that is typically connected with each other exclusively via a Wi-Fi backbone. These Wi-Fi-capable devices initially start up completely independently. As soon as the devices are powered on, they are found automatically and independently establish the mesh Wi-Fi network. Thanks to the fully automated and dynamically intermeshed structure of the Wi-Fi-capable devices, the data paths are adjusted automatically when there are changes in the radio field. The Wi-Fi network thus responds intelligently and can optimize itself independently. This is why these are known as **SON** networks. The term **SON** (**S**elf-**O**rganizing **N**etwork) originated in the marketing of chip manufacturer Qualcomm. It describes the functions of a mesh Wi-Fi network as follows:

- **Self-Configuring** → Mesh Wi-Fi devices are found automatically and establish an intermeshed Wi-Fi network independently.
- **Self-Managing** → Mesh Wi-Fi devices automatically detect and respond to performance losses (see the table **Mesh Wi-Fi functions**).
- **Self-Healing** → Mesh Wi-Fi devices find the best connection path in networks where multiple mesh Wi-Fi devices are used. If a device fails at some point, this is detected by the mesh Wi-Fi network and an alternative connection path (different mesh Wi-Fi device) is used.
- **Self-Defending** → The SON framework enables customers to implement additional security technology that is continually learning and can adjust itself to user behaviour automatically. This enables conspicuous behaviour to be detected in the mesh Wi-Fi network and blocked automatically.

4.6. Mesh Wi-Fi functions

Self-Managing	Function	Description
includes	Band steering	Ensures that all Wi-Fi devices automatically switch to the optimum frequency band (2.4 and 5 GHz frequency band) in order to use the best Wi-Fi connection at all times.
	Airtime fair-ness	Fast Wi-Fi devices are given preference. This prevents older devices, which may require more time for a download, from creating bottlenecks in the Wi-Fi network.
	Fast roaming	The **IEEE 802.11r** standard streamlines the registration process for Wi-Fi end devices, such as smartphones or tablets, when switching to another Wi-Fi access point. This is especially important when people move from room to room with their mobile devices.
	Config Sync (devolo function)	Allows settings to be configured uniformly for all devolo Magic WiFi devices in the network. For example, this includes the following settings: • Wi-Fi network • Guest network • Mesh Wi-Fi • Time control and time server settings.
	Wi-Fi Clone	Makes it possible to copy the configuration data (SSID and Wi-Fi password) of any available Wi-Fi access point (e.g. your Wi-Fi router) to all Wi-Fi access points → Single SSID

4.7. EasyMesh – The compatible mesh Wi-Fi

EasyMesh is one of the standards adopted by the Wi-Fi Alliance. It makes it possible to use mesh-capable access points (e.g. routers, repeaters, Powerline solutions) from different manufacturers. Products from the respective manufacturers currently work only with each other, and third-party products cannot be integrated. The new EasyMesh standard aims to fix this problem and is already set to be used in some devices by the end of 2019.

According to the Wi-Fi Alliance, EasyMesh simply regulates communication between the access points, so that important Wi-Fi mesh factors like the number of frequency bands used or the prioritisation (Airtime Fairness) of the existing devices in the Wi-Fi network are still maintained at the respective mesh-capable access point. EasyMesh is not limited just to Wi-Fi compatibility, but also supports various media types, thanks to the use of IEEE protocol 1905.1. For example, this includes classic Ethernet, PLC or coaxial cables.

For end customers, EasyMesh is a major win for convenience, since personal mesh Wi-Fi networks can also be expanded using more affordable products. Furthermore, easy installation of the new standard on existing access points should be possible via software update. However, the question remains of whether EasyMesh will become more widely used. After all, implementation of the standard is not mandatory, meaning that manufacturers can decide independently whether they will offer an update for their solutions.

4.8. Advantages of G.hn Powerline in combination with mesh Wi-Fi

Pure mesh Wi-Fi solutions can only be used in special situations because, despite the 2.4 and 5 GHz frequency bands used, the Wi-Fi radio spectrum is limited—particularly when mesh products acting as dual-band solutions require the 5 GHz band for transmitting payload as well as exchanging information between individual access points within the mesh network. Current devolo devices from the "Magic" series that are also equipped with mesh Wi-Fi therefore use the PLC standard G.hn as the backbone. Compared to classic mesh devices with "Wi-Fi-only" functionality, a PLC backbone has significant advantages, particularly when used in addition to **MIMO** technology. With

MIMO (**M**ultiple **I**nput **M**ultiple **O**utput), all three lines (phase **L**, earth wire **PE** and neutral conductor **N**) are used for data communication in 3-core NYM-J lines, which are used in most households. This makes it possible for data packets to find the fastest path to their destination. If interference signals and attenuations decelerate a path or prevent any transmission, the data communication is maintained through the second channel. The result is a better network saturation and more stable Powerline communication.

4.9. What exactly is G.hn?

G.hn is a technical standard developed by the International Telecommunication Union (ITU) and supported by numerous organisations, including the HomeGrid Forum industrial association. Due to the continuously growing power requirements in the home network, such as those for 8K streaming, devolo has decided that, for its new Magic products, it will no longer rely on the HomePlug AV2 standard used in current dLAN devices (**d**irect **L**ocal **A**rea **N**etwork). Instead, these products will rely on the new and significantly faster G.hn Wave-2 standard.

Differences between G.hn and dLAN (HomePlug AV2)

	G.hn	**dLAN**
PLC transmission speed	currently up to 2400 Mbps (devolo Magic 2)	Up to 1200 Mbps
PLC range	up to 500 metres	up to 400 metres
Automatic pairing (forms an encrypted PLC connection)	Yes	No
PLC encryption	128-bit (AES)	128-bit (AES)
Supported Wi-Fi standards	802.11 a, b, g, n, ac	802.11 a, b, g, n, ac

G.hn means that the speed in the Powerline backbone has been increased enormously (currently as high as 2400 Mbps). The update also features improved stability and a greater PLC range of up to 500 metres. Another advantage is the added convenience, since the new devices based on G-hn are connected with each other automatically after being plugged in and immediately establish an encrypted network in accordance with the AES 128-bit standard (**A**dvanced **E**ncryption **S**tandard).

4.10. G.hn Wave-3 – A peek into the future

There is still plenty of potential in the PLC area. The International Telecommunication Union (ITU) along with countless organizations and chip manufacturers are already working on the next G.hn version, called **G.hn Wave-3**. It will deliver a significantly expanded frequency band of up to 350 MHz in the PLC area and up to 1200 MHz in the coaxial area (baseband/RF) as well as an associated increase in the transmission rate to up to 10,000 Mbps (coaxial, full-duplex). This will also ensure that, in future, the PLC backbone in devices will not reach the limits of its performance—and especially not when the PLC backbone is combined with new Wi-Fi standard 802.11ax, designed to enable a transmission rate of up to 11,000 Mbps over Wi-Fi. The positive performance increase of G.hn Wave-3 will not come at the cost of increased consumption, since neither the dimensions of the chips nor power consumption are intended to be changed compared to the current G.hn Wave-2 standard.

5. Differences between broadband Powerline and narrowband Power-line (G3-PLC)

5.1. In-house PLC, networking within a building via PLC

Like all end customer products in the PLC area, devolo devices use broadband Powerline. On a relatively short line length of up to 500 metres, a high transmission rate of up to 2400 Mbps can currently be attained. This is the ideal solution for end customers who want to supply fast Internet to their entire home.

5.2. Access PLC, forwarding data to a back-end (Home – Street cabinets – Transformer station)

An entirely different application of PLC is its use in the smart grid or smart power grid, i.e. intelligent distribution networks for power supply. Both consumption as well as decentralised generation are controlled here, so that lines or transformers are not overloaded, for example. The transfer protocol **G3-PLC** is used in addition to broadband Powerline in the smart grid. It was created as a standard by the International Telecommunication Union (ITU) for communication in the smart grid area, among other uses, and is also taken into account by well-known standardisation committees (IEEE, IEX and ISO).

G3-PLC is based on OFDM modulation and uses the frequency band between 35 and 487 kHz for data transmission. Two standards must be differentiated here. The standardisation organisation **CENELEC** (**C**omité **E**uropéen de **N**ormalisation **Élec**trotechnique), the European Committee for Electrotechnical Standardization, has defined four frequency bands for specific application scenarios. The transfer protocol G3-PLC uses the CENELEC A band.

- CENELEC A: 9 to 95 kHz
- CENELEC B: 95 to 125 kHz
- CENELEC C: 125 to 140 kHz
- CENELEC D: 140 to 148.5 kHz

The **FCC** (**F**ederal **C**ommunications **C**ommission), an independent American agency that governs communication paths in radio, satellite and cable areas, specifies the frequency band from 10 to 490 kHz. However, G3-PLC only uses the frequency band between 150 and 490 kHz. Products from the devolo Smart Grid business unit use G3-PLC in the FCC band.

The G3-PLC standard enables data communication across long distances. In field tests on medium voltage, devolo and its partners achieved ranges of up to 10 kilometres without repeaters. The possibility of bridging large distances with G3-PLC goes hand-in-hand with a lower bandwidth. The actual transfer properties are always dependent on the local conditions and the network topology.

Access Broadband PLC is used in addition to the G3-PLC standard in the smart grid. The ITU standard G.hn used in the home network area is also used in Access Broadband PLC. Unlike the current implementations of G.hn for the home network area, Access Broadband PLC also uses a relay function (repeaters). Using the repeating function, up to 10 PLC segments can be connected in series, enabling extremely high coverage. A range of up to 400 metres is possible without repeaters connected in series. This function is also part of the G.hn standard. Repeating is also to be included in the G3 standard. In both the G3-PLC as well as in Access Broadband PLC, each node can also be a repeater at the same time.

Difference between Broadband Access PLC and G3-PLC

	Broadband Access PLC	**G3-PLC**
PLC transmission speed	up to 20 Mbps, can be configured on the application level	up to 3 kbps in the CENELEC A band up to 50 kbps in the FCC band
Maximum number of nodes in a network domain	100	300
PLC range	up to 400 metres with low voltage up to 800 metres with medium voltage Can be expanded using repeaters.	up to 1700 metres in low voltage up to 10,000 metres in medium voltage Can be expanded using repeaters.
Automatic integration of nodes in the network	Yes, each node selects the head-end with the best connection properties by default	Yes, each node selects the PAN coordinator with the best connection properties by default **PAN** **P**ersonal **A**rea **N**etwork PAN networks can also communicate with a larger network via uplink.
PLC encryption	128-bit (AES)	128-bit (AES)
Frequency band	2 to 25 MHz	CENELEC A: 35 to 91 kHz FCC: 10 to 490 kHz, but only 150 to 490 kHz is used

6. Appendix

Dynamic Frequency Selection (DFS)

Using **DFS**, a Wi-Fi network automatically switches channels if another, (legally) protected wireless-capable device is detected on the channel used. This is primarily intended to prevent interference with weather radar systems that operate in the same frequency band as Wi-Fi networks. For this purpose, the channel currently being used is listened to periodically. As soon as a third-party transmitter is detected, the device is automatically switched to another channel. Wi-Fi-capable devices that support **DFS** thus use the full bandwidth of the 5 GHz frequency band, allowing them to attain the maximum transmission rate.

Frequency band 2.4 and 5 GHz

Frequency band	5 GHz	2.4 GHz
IEEE standard	802.11 a/h 802.11 n 802.11 ac	802.11b 802.11 g 802.11 n
Indoor frequency range	5150 – 5350 MHz	–
Indoor & outdoor frequency range	5150 – 5725 MHz (802.11 a/h, n) 5150 – 5350 MHz / 5470 – 5725 MHz (802.11 ac)	2399.5 – 2484.5 MHz
Channel bandwidth	20 MHz (802.11 a/h) 20, 40 MHz (802.11 n) 20 MHz, 40 MHz, 80 MHz, 160 MHz (802.11 ac)	20 MHz (802.11 b/g) 20, 40 MHz (802.11 n)
Max. indoor transmission power (EIRP)	200 mW (channel 36 – 64) / 23 dBm	100 mW / 20 dBm
Max. transmitting power	1000 mW (channel 100 – 140) / 30 dBm	100 mW / 20 dBm

Channels and frequencies in the 2.4 GHz frequency band

Channel	Carrier frequency
2	2412 MHz
3	2417 MHz
4	2422 MHz
5	2427 MHz
6	2432 MHz
7	2437 MHz
8	2442 MHz
9	2447 MHz
10	2452 MHz
11	2457 MHz
12	2462 MHz
13	2467 MHz

Channels and frequencies in the 5 GHz frequency band

Channel	Carrier frequency
36	5180 MHz
40	5200 MHz
44	5220 MHz
48	5240 MHz
52	5260 MHz
56	5280 MHz
60	5300 MHz
64	5320 MHz
100	5500 MHz
104	5520 MHz
108	5540 MHz
112	5560 MHz
116	5580 MHz
120	5600 MHz
124	5620 MHz
128	5600 MHz
132	5660 MHz
136	5680 MHz
140	5700 MHz

Comparison of Wi-Fi standards

Standard IEEE	Introduction	Frequency band (GHz)	Channel band-widths (MHz)	Data rate (gross, Mbps)
802.11	1997	2.4	22	< 2
802.11a (Wi-Fi 2)	1999	5	20	up to 54
802.11b (Wi-Fi 1)	1999	2.4	22	up to 11
802.11 g (Wi-Fi 3)	2003	2.4	20	up to 54
802.11 n (Wi-Fi 4)	2009	2.4/5	20, 40	up to 600
802.11 ac (Wi-Fi 5) "Wave-1"	2013	5	20, 40, 80	up to 1333
802.11ac "Wave-2"	2015	5	20, 40, 80, 160	up to 6933 (at 160 MHz)
802.11ax (Wi-Fi 6)	2018	2.4/5	20, 40, 80, 80+80, 160	up to 9607.8 (at 160 MHz)

Comparison of modulation methods

Modulation method	Functional principle
DSSS **D**irect **S**equence **S**pread **S**pectrum	By spreading, the 2.4 GHz frequency band is divided into 22 MHz- to 26 MHz-wide frequency bands. The spreading divides the transmitted signal into high-bit-rate code sequences. The wider the spread, the lower the susceptibility of the transmission to interference.
FHSS **F**requency **H**opping, **S**pread **S**pectrum	Unlike DSSS, the spectrum of the modulated signal remains just as wide as the original signal. The signal is exclusively spread on a chronological basis because the carrier frequency remains constant for only a brief moment. In this process, there is a distinction between fast hopping and slow hopping. The data is first modulated to narrowband and then spread by a frequency synthesizer in a second modulator. A frequency synthesizer is also used on the opposite side to reverse the spread and demodulate the data. **Fast hopping:** A maximum of 1 bit is transmitted per frequency hop. However, 3 frequency hops can take place within one bit. **Slow hopping:** At least 1 bit is transmitted per frequency hop.
QAM **Q**uadrature **A**mplitude **M**odulation	Using QAM, multiple states (of 2, 4, 8 or more bits) are combined and a data word is converted into a symbol of 4, 16, 64 or **more** levels. The QAM is available in 4-QAM, 16-QAM, 64-QAM, etc., currently up to 1024-QAM (802.11ax). The number of the modulation method indicates the number of states.

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