EPoC - THE UPCOMING IEEE P802.3bn STANDARD FOR EPON PROTOCOL OVER COAX OVERVIEW AND IMPACT

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Abstract

Following the interest from both the Chinese and North American cable industries, the IEEE Standards Association approved a project under the IEEE 802.3 Standard For Ethernet Working Group with the scope of extending the EPON protocol over coaxial (EPoC) networks. The P802.3bn EPoC Task Force is in progress, developing a physical layer standard for symmetric and asymmetric operation of up to 10 Gb/s on point-to-multipoint coaxial distribution plants comprising either active or passive media. EPoC objectives, key technical and performance considerations, and resulting architecture are presented. Select comparisons of EPoC with the DOCSIS 3.1 PHY including common component architectures are noted. The resulting PHY standard will enable several deployment models, increasing the number of options available to cable operators as part of their future service growth.

INTRODUCTION

Ethernet Protocol over Passive Networks (EPON) was first standardized in 2004 as part of the IEEE 802.3 Working Group's [1] Ethernet in the First Mile (EFM) initiative. Both 1 Gbit/s and 10 Gbit/s EPON standards are incorporated in the 802.3-2012 - IEEE Standard for Ethernet [2]. The P802.3bn Task Force [3] extends the 10Gbps EPON point-to-multipoint solution over cable operator coax networks via a new physical layer. Initial interest for EPoC developed in China and followed shortly by North America. The motivation in both markets is different. In China, Hybrid Fiber-Coaxial (HFC) solutions are deployed extensively, with a typical architecture of placing the fiber node on the MDU campus. *CableLabs®* DOCSIS® [4] while becoming increasingly more popular, is not as widely deployed as in other parts of the world. Cable operators use government funded optical fiber in the streets and are looking at the opportunity of transparently extending existing EPON services over legacy coaxial cabling present in a large majority of older and new multi-tenant/dwelling units (MxU). In North America, High Speed Data (HSD) residential services are provided using DOCSIS technology. Some cable operators are increasingly deploying EPON to primarily capture business market services and cellular backhaul. Metro Ethernet Forum (MEF) [5]. service performance and contracted Service Level Agreements (SLAs) are pro forma.

Both Chinese nd North American operators appear to have a similar desire for the simplicity of Ethernet at gigabit speeds and for extending the life of existing coax cable networks. Key requirements for EPoC will be maintaining unified management and Quality of Service (QoS). DOCSIS Provisioning of EPON (DPoE™ [6]) is straightforward to extend managed EPoC systems. IEEE P1904.1 Service Interoperability in EPON (SIEPON) is also available for seamless management [7].

Additionally, EPON and EPoC directly support the step-wise migration from back-end legacy MPEG-2 transport to MPEG-4 video distribution via IP over Ethernet. In the future, a large Ethernet-based gigabit pipe to the home and business will be fundamental for cost-effective growth and evolution. When available in the future, a cable operator will then have a choice to deploy IP over

DOCSIS 3.1 or over EPON/EPoC based on their business needs.

Service and Application Architecture

Figure 1 shows an example of the target applications for a mix of EPON and EPoC technologies that leverages fiber-deep access architectures of current networks and the extension to existing coaxial distribution infrastructure.

For EPON, the IEEE Ethernet 802.3-2012 standard [2] defines the MAC and PHY sublayers for a service provider OLT and a subscriber ONU. Two wavelengths are used on the fiber for full-duplex operation, one for continuous downstream channel operation and another for upstream burst mode operation. The OLT MAC controls time-division sharing of the upstream channel for all ONUs via the Multipoint MAC Control Protocol (MPCP).

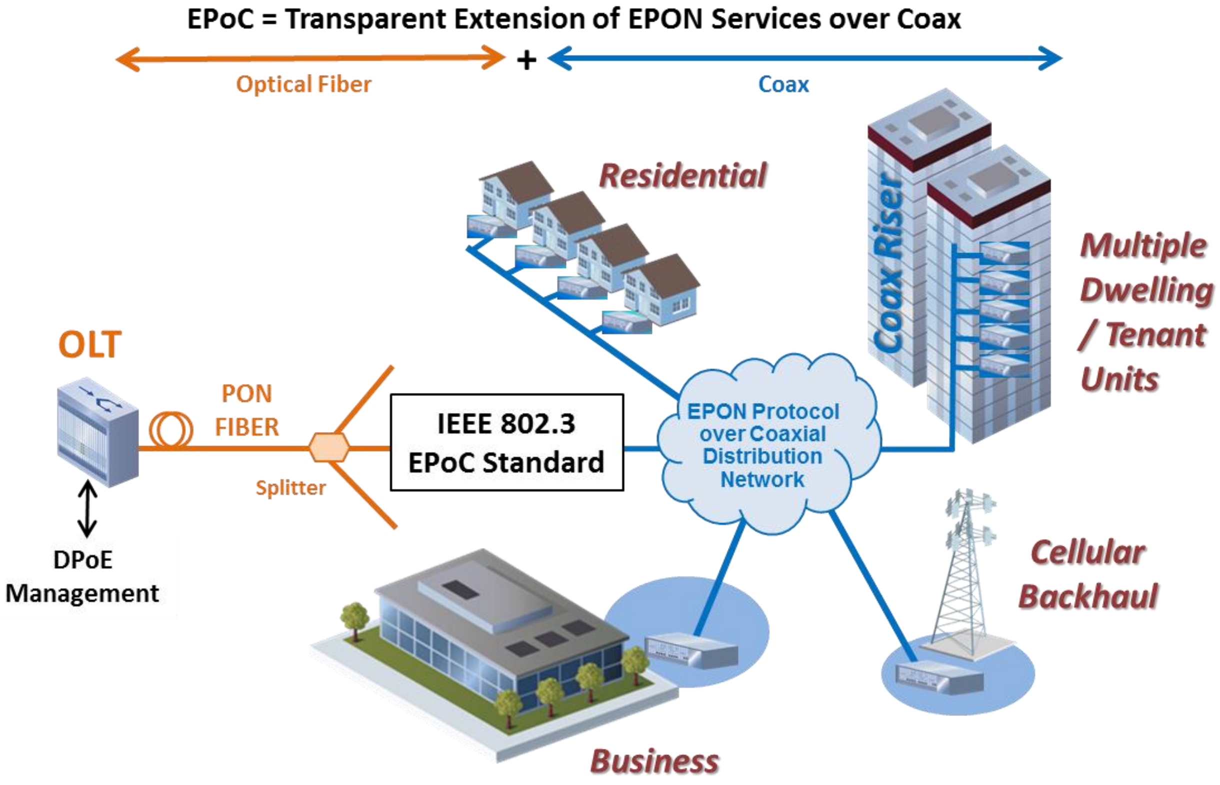

Figure 1. EPoC Applications for Extending EPON Services over Coax

Figure 1 illustrates an existing EPON Optical Line Terminal (OLT) connection through a Passive Optical Network (PON) made up of optical fiber and passive splitters. EPoC services are expected to extend the same range of services as that of EPON: for example, Residential, Business, Multiple Dwelling, and Cellular Backhaul. DPoE Management will be extended to EPoC.

EPoC Architecture

Similarly, the EPoC architecture consists of a service provider Coax Line Terminal (CLT) and a subscriber Coax Network Unit (CNU). The EPoC CLT and CNU MAC sublayers will be substantially similar to respective layers found in the OLT and ONU. Minimal augmentation to MPCP will be necessary to account for new packet burst overheads. Similar to the DOCSIS system, the EPoC PHY employs a full-duplex point-to-multipoint architecture, and the downstream and upstream communication channels will utilize RF spectrum as assigned by a cable operator for their coax network.

EPoC Topology

Figure 2 illustrates the three topology models for EPoC. Each model follows a *Node + N* approach, where N represents the greatest number of amplifiers on a single path between the Coax Line Terminal (CLT) and a Coax Network Unit (CNU). N varies from 0 (e.g., *Node + 0*), and represents a passive network or segment, to a preferred depth of 3. Higher N values are also considered. A traditional HFC architecture is included in the topology.

Similar to DOCSIS 3.1 PHY OFDM, EPoC will require the allocation of dedicated RF spectrum in both downstream and upstream directions. Provisioning of in-band service requires co-existing with other cable operator services in either direction (e.g., video, data, voice) without mutual interference As an operational note on differences in upstream use, EPoC is the sole user of its assigned spectrum, where DOCSIS 3.1 OFDMA may share the same upstream RF channel with legacy DOCSIS via TDMA scheduling of different burst types.

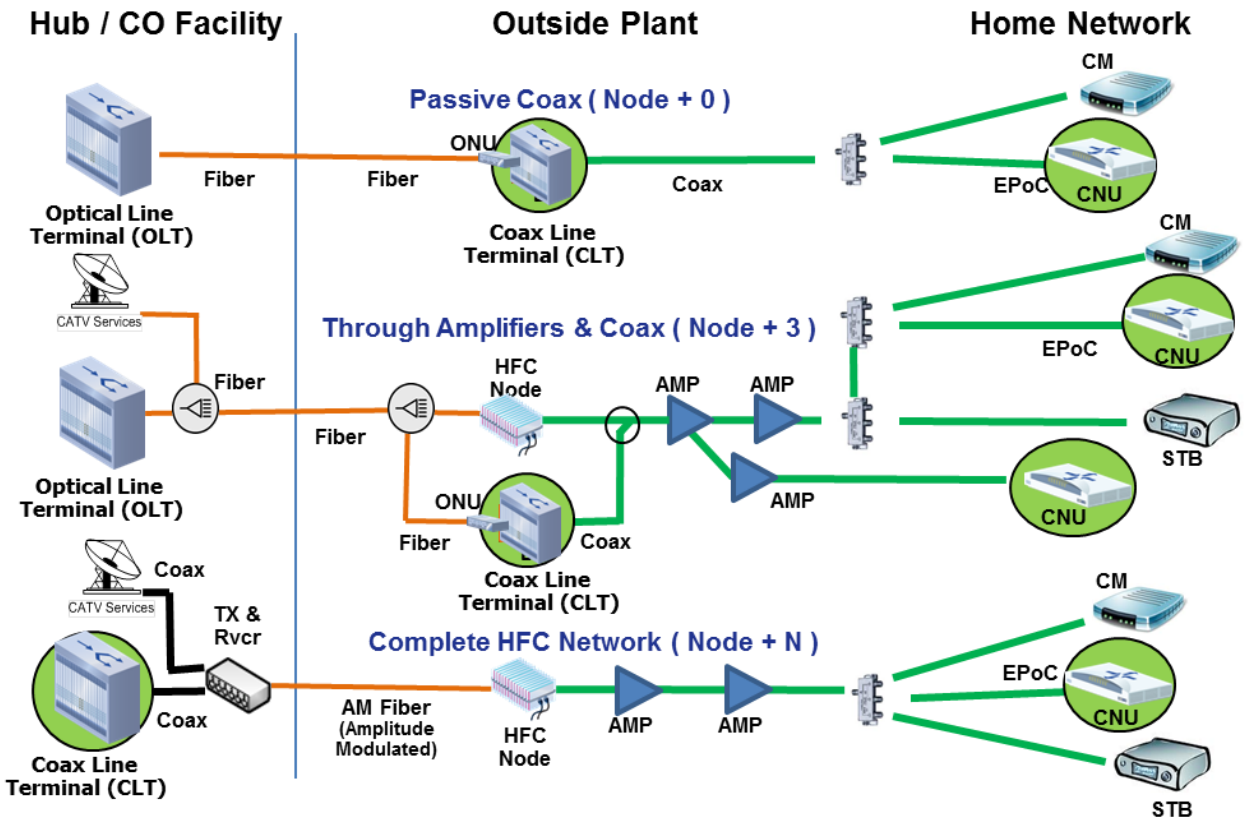

Figure 2. EPoC Topologies

In a practical implementation, the conversion from EPON digital fiber to EPoC coax will be implemented as a single unit device that is placed in the field adjacent to the fiber node. For example, the conversion device in Figure 2 is shown by an ONU coupled with a CLT.

System Models

Two system models have been under discussion in the EPoC Task Force, as shown in Figure 3. The first is a CLT with one more CNUs directly interconnected by a coaxial distribution network. This system model follows the scope of the standard. Product realization would be a CLT that is colocated in a headend as illustrated in the *Complete HFC Network* topology shown in Figure 2.

The second and more preferable system model is enabled by the EPoC standard, but is outside the scope of the IEEE 802.3 Working Group. This model is a traditional EPON with an OLT and multiple ONU devices together with one or more Fiber Coax Unit (FCU) converters that interconnect between PON with a coax distribution network using EPoC. This second model permits CNUs to appear as ONUs to DPoE, and is, therefore, the manageable equivalent to EPON ONUs.

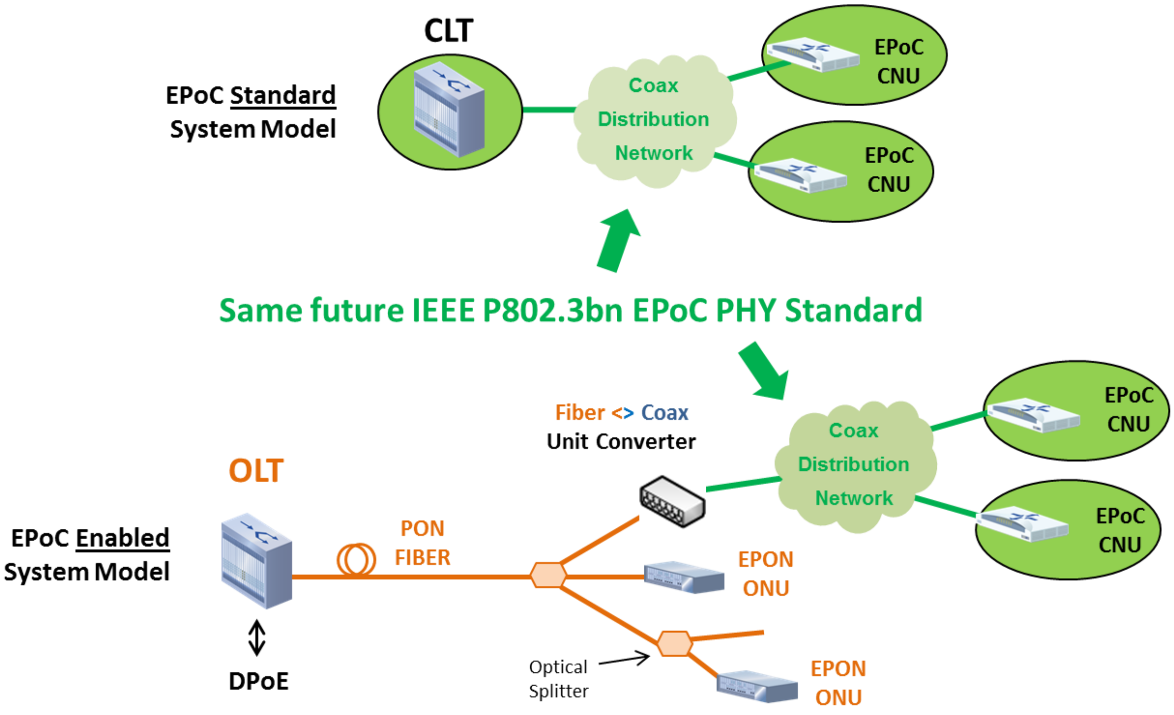

Figure 3. Two EPoC System Models

The FCU has two implementation architectures that can be considered. The first is a repeater FCU, where the OLT MPCP is transparently extended over the coax network. Here, each CNU's MPCP is part of the single MAC domain that includes both CNUs and ONUs. The OLT provides scheduling and MAC control over both the optical media and the coax distribution network. The repeater FCU converts between EPON PHY frames and EPoC PHY frames as the PCS encoding, i.e., the FEC and line encoding, are different. The EPON preamble and LLID are retained, and therefore the same over both media.

The second architecture is a bridge FCU. In this case, the PON port on the FCU and each ONU is a member of the OLT's MPCP domain on the PON with an LLID assigned by the OLT. On the coaxial network port, each CNU is a member of the FCU's MPCP domain with an LLID assigned by the FCU. There would likely be no requirement for LLID values to be retained across the bridge. Rather, the LLID would become part of the internal frame forwarding mechanism. QoS flows may be individually retained; however, it may make sense to aggregate flows in the upstream to support OLT scheduling of traffic from the FCU to the OLT.

The architecture and specifications of both the repeater FCU and bridge FCU are beyond the scope of this paper. It is expected that details would be forthcoming from the cable industry as the IEEE P802.3bn standard work progresses towards finalization.

DETAILS OF IEEE P802.3bn EPoC

The work of the IEEE P802.3bn EPoC PHY Task force is in progress at this time, and the progress of the Task Force can be viewed on the project website located at [3].

The IEEE Standards Association provides an open public process that consists of consensus building and a technical selection process. In IEEE 802 and 802.3, participation is by an individual, and technical consensus is indicated by a 75% or greater vote of Yes versus No on decisions at face-to-face meetings and on ballots. The product of the P802.3bn activity is the Task Force Draft. When complete, this draft is reviewed and subsequently approved through one or more cycles of the 802.3 Working Group Ballot process. Upon approval, this draft is submitted to IEEE 802 as a Sponsor Ballot, and the review ballot cycle is completed again using a larger ballot group. Upon passing the Sponsor Ballet, the result is then reviewed by the IEEE SA New Standards committee. When approved, the work will become the published standard. In terms of prestandard availability, an approved Working Group draft has been shown to be generally stable. However, as with any formal process, a nonapproved draft at any stage is returned to the Task Force for more work, and the process starts again.

P802.3bn maintains a timeline on its website at [3]. The last update from November 2013 anticipates an approved Working Group draft by the end of 2014 with a published standard in Mid 2015

IEEE P802.3bn Project Documents

Each authorized project under the 802.3 Ethernet Working Group has three guiding project documents. The first is the IEEE-SA Project Authorization Request (PAR) which sets the scope, the project area (e.g., amendment to the 802.3 Ethernet standard), and other details. The PAR is the agreement between the IEEE SA, the 802 LMSC, and the 802.3 Working Group. Upon issuance of a PAR, the 802.3 Working Group charters a Task Force. The second document is Criteria for Standards Development (CSD) also known as the *5 Criteria* or *5Cs*. The CSD/5Cs is a requirement the 802 LMSC and the 802.3 Working Group. The third document is the set of Objectives that constitute an agreement between the 802.3 Working Group and the Task Force. Access to past and current project documents for 802.3 is available at [1] and specifically for P802.3bn EPoC at [3].

IEEE P802.3bn Objectives

Developed as an output of the Study Group phase of the EPoC project, the objectives focus the effort within the scope of the PAR. Objectives are developed by the consensus of the participants and then considered and approved by the 802.3 Working Group. Objectives may change over the lifetime of the project as the Task Force develops its understanding and, approach, and after input from the 802.3 Working Group or its members.

The following is the list of current P802.3bn objectives developed by the participants consisting of individuals representing cable operators, equipment and component manufacturers, and others.

1) Specify a PHY to support subscriber access networks capable of supporting burst mode and continuous mode operation using the EPON protocol and operating on point-to-multipoint RF distribution plants made up of either amplified or passive coaxial media.

2) Maintain compatibility with 1G-EPON and 10G-EPON as currently defined in IEEE Std. 802.3 with minimal augmentation to MPCP and/or OAM if needed to support the new PHY.
3) Define required plant configurations and conditions within an overall coaxial network operating model.
4) Provide a physical layer specification that is capable of:
    a. A baseline data rate of 1Gbit/s at the MAC/PLS service interface when transmitting in 120 MHz, or less, of assigned spectrum under defined baseline plant conditions.
    b. A data rate lower than the baseline data rate when transmitting in less than 120 MHz of assigned spectrum or under poorer than defined plant conditions.
    c. A data rate higher than the 1 Gbit/s baseline data rate and up to 10 Gbit/s when transmitting in assigned spectrum and in channel conditions that permit.
5) PHY to support symmetric and asymmetric data rate operation.
6) PHY to support symmetric and asymmetric spectrum assignment for bidirectional transmission.
7) PHY to support independent configuration of upstream and downstream transmission operating parameters.
8) PHY to operate in the cable spectrum assigned for its operation without causing harmful interference to any signals or services carried in the remainder of the cable spectrum.
9) PHY to have:
    a. A downstream frame error ratio better than 10^{-6} at the MAC/PLS service interface.
    b. An upstream frame error ratio better than $5x10^{-5}$ at the MAC/PLS service interface.
10) Define Energy Efficient Ethernet operation for EPON Protocol over Coax PHYs.
11) Mean Time To False Packet Acceptance (MTTFPA) at least equal to $1.4 \text{ x } 10^{10}$ years.

EARLY TASK FORCE DECISIONS

EPoC first met as a Task Force in September 2012 in Geneva, Switzerland. The first technical decisions were: the use of Orthogonal Frequency Division Multiplexing (OFDM) modulation in the downstream channel, OFDM Access (OFDMA[1]) in the upstream channel, the use of Low Density Parity Check Coding (LDPC), up to 4096 QAM in the downstream, up to 1024 QAM in the upstream, an OFDM channel size of 192 MHz with a sample clock of 204.8 MHz, and the ability to combine multiple 192 MHz OFDM/A channels for higher capacity. Later in its progress, the Task Force narrowed for use of a single 8K Fast Fourier Transform (FFT) with a subcarrier spacing of 50 KHz. For the 192 MHz channel, 3800 subcarriers are usable.

Availability of RF Spectrum

The trend in cable will be to convert existing non-IP services running over legacy modulation to IP services running over next-generation modulation: OFDM/A + LDPC. Neglecting overheads, to achieve a 10 Gbit/s data rate using a 12 bit/s/Hz (4096 QAM) modulation rate will require over 830 MHz of spectrum. Transitioning towards this future will be done in steps defined by each cable operator based on their business plans. With protocol overheads, P802.3bn targets a downstream data rate of 1.6 Gbit/s at the MAC/PLS service interface per 192-MHz OFDM channel in baseline channel conditions

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[1] OFDM/A will be used hereafter unless there is a need to differentiate downstream OFDM from upstream OFDMA.

(Refer to Technical Decision #40. See [3].). The minimum downstream RF spectrum allocation for P802.3bn is 24 MHz (the same for DOCSIS 3.1 OFDM). Note that the *baseline channel conditions* are based on an approved channel model [3].

The upstream RF spectrum may use less than 24 MHz initially, and the configuration is intended to be flexible with current split configurations used nationally and internationally (e.g., 5-42 MHz, 5-85 MHz, etc.) and adapt as the cable industry evaluates and implements possible shifts in the split (e.g., 5-120 MHz, 5-234 MHz).

P802.3bn internally will be configured to support frequency and configuration values for up to 5 GHz of RF spectrum. The standard will initially support the frequency ranges as shown in Table 1.

Table 1. EPoC Channel Frequencies

	Frequency Range
Downstream	54 – 1212 MHz
Upstream	5 – 234 MHz

The overlap of the downstream and upstream, diplexer requirement, and the lowest frequency used will be determined by cable operator requirements. P802.3bn will not specify diplexer requirements. The downstream top end to 1212 MHz appears at this time to be a reasonable limit for expansion of existing HFC architecture downstream passband. In the future, upstream and downstream and active and passive topologies beyond 1212 MHz can be accommodated by P802.3bn.

Note that in order to support more than 1.6 Gbit/s, P802.3bn will need to support additional channels. See Section *Up to 10 Gbit/s*.

Challenges of RF Spectrum

The selection of OFDM/A for future modulation has the advantage of being more robust as well as adaptable for creating wide channels that may be flexibly provisioned. Subcarriers may be turned off, meaning no energy is transmitted in that subcarrier. Turned off subcarriers are termed *excluded*. Excluded subcarriers are used for sizing the RF spectrum of the channel, creating notches to work around legacy channels, as well as for well-known interference, such as LTE ingress. A group of adjacent excluded subcarriers is called an *exclusion band* or an *edge band*, depending on location. The minimum size exclusion band is 1 MHz. Allocation of used spectrum versus excluded spectrum can be changed at any time by cable operator provisioning as needed.

Another common challenge for many modulations is resilience to micro-reflections and Inter-Symbol Interference (ISI). An extended OFDM/A modulation symbol includes a cyclic prefix, which essentially is duplicate overhead of an end of the OFDM symbol added to form the transmitted signal. CP size is set during provisioning based on local system conditions and has ranges from 5% to 25% time overhead. There is an additional parameter called windowing that is used to shape the sharpening of the subcarrier edges. There is one CP size and one window size for an OFDM/A channel.

The provisioning of a downstream OFDM/A channel includes the setting of: channel frequency, excluded subcarriers, modulation rate per subcarrier, CP, and window size. In addition, a portion of the non-excluded subcarriers will be allocated for the PHY Link with the remaining non-excluded subcarriers assigned for data. Continuous pilots, as required for OFDM receiver synchronization, will likely be allocated as part of an algorithm based on available subcarriers.

The Need for a PHY Link Channel

OFDM/A is well known in wireless networks and other media, but this is the first time Ethernet[2] has been used for EPoC. In contrast to other Ethernet physical layer (PHY) modulations, OFDM/A has a much higher degree of configuration flexibility and complexity. The permutations on a downstream channel hunt procedure would be significantly higher than the way it is done now, for example, with traditional DOCSIS QAM channels that are located on well-known frequencies.

The EPoC Task Force specifies a PHY Link channel made up of a contiguous subset of the subcarriers available in an OFDM/A channel. A 400 KHz data subchannel is configured and made up of eight (8) adjacent subcarriers. The PHY Link may be placed anywhere within the OFDM/A channel. The modulation rate is 16 QAM. Downstream data is framed on a repeating cycle of 128 symbols, where each cycle begins with a well-known preamble value[3]. Other subcarriers adjacent to the eight main subcarriers are used to convey OFDM/A pilot information. The combination of the above permits a CNU to quickly locate, synchronize with, determine the CP size, and then decode downstream PHY Link messages.In addition, there is a requirement to place the center frequency in increments of 1 MHz permitting a cable operator to provision placement aligned with well-known frequency locations, such as a local channel plan.

The PHY Link cycle of 128 symbols also defines the OFDM frame cycle on the downstream data subchannel. Included in each PHY Link message is a Next Codeword Pointer (NCP) that indicates the starting bit of the first codeword in the next cycle of the data subchannel. The NCP is used for helping to quickly establish frame synchronization after a downstream channel loss event (e.g., burst noise) as well as permitting FEC codewords to straddle cycles; i.e., an FEC codeword is not required to be aligned to the start of the cycle.

CNU Initialization Overview

After locating and decoding the downstream PHY Link messages, a CNU learns of the both the downstream OFDM data subchannel configuration and the upstream OFDMA subchannel configuration, including the upstream PHY Link configuration. At this point, the CNU can participate via the PHY Link with the CLT for the link auto-negotiation process before the CNU is allowed to go *linked,* connecting the CLT and CNU MAC entities. Note that the PHY Link subchannel communications are separate from the main data subchannel communications; i.e., the PHY Link is transparent to the EPON / EPoC MAC.

PHY Link management messages include: PHY Discovery, fine ranging, PHY Link messages, and wideband probes. The first message sent by a CNU is a PHY Discovery in response to a broadcast invitation sent by the CLT. This first response message is used to determine initial range timing as well as CNU MAC address identification. The CLT then assigns a unique PHY identifier and transitions to unicast messaging to direct the new CNU into a fine ranging mode, responding to probes as well as responding to PHY Link messages. Fine ranging permits adjustment of CNU power, symbol timing, and OFDMA frame timing. Wideband probes permit adjustment of pre-equalization coefficients to better match the CNUs signal to the channel response characteristics. When complete, the CLT will transition the CNU to a *linked* status used by Ethernet to signal the link and new station

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[2] In parallel, OFDM/A were selected earlier in 2012 by the CableLabs DOCSIS 3.1 project.

[3] The preamble value is distinguished from that used by the DOCSIS 3.1 OFDM downstream PHY Link.

availability. At this point, the data channels of downstream and upstream are enabled, permitting EPON MAC operation.

Link details such as downstream and upstream PHY rates and CNU capabilities are communicated via station management.

Ongoing PHY Link Operation

After initial station discovery, the PHY Link continues to monitor the PHY operational details of each CNU. Periodic adjustments for power, timing, pre-equalize coefficients, etc. should be a normal and ongoing part of operation.

A given channel configuration is known as a profile. The PHY Link channel will be used to communicate updated channel profiles as well as coordinate switch-over time. It is expected that cable operators will make use of the flexible nature of OFDM to periodically adjust subcarrier configuration to adjust for changes in plant conditions, impairments, spectrum use, etc.

The Downstream Tx PHY Path

Figure 4 presents a high-level block diagram of the P802.3bn downstream CLT physical layer for the data path. The PHY Link processing path is omitted from this description. Following strict 802.3 layering, the MAC is separated from the PHY by the MAC/PLS service interface. This also serves as a reference point for performance measurements. The downstream channel implements point-to-multipoint access in continuous mode; the CLT transmitter is heard by all CNU receivers.

The Physical Layer is composed of three distance sublayers: the Physical Coding Sublayer (PCS), the Physical Media Attachment Sublayer (PMA), and the Physical Media Dependent sublayer (PMD). The PMD connects directly to the Coax Cable Distribution Plant via a Medium Dependent Interface (MDI) commonly known by the cable industry as the standard F Connector. P802.3bn has allocated its functions as described in Figure 4.

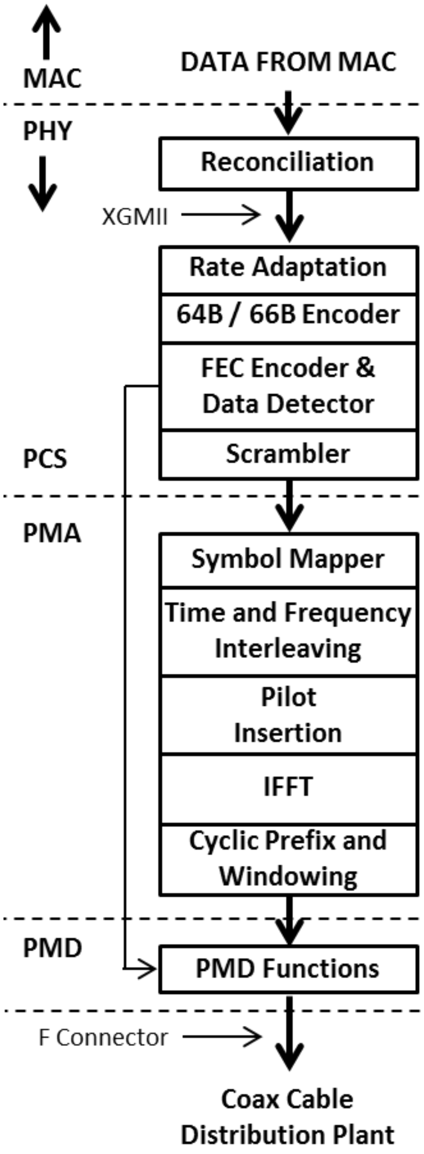

Figure 4. Downstream CLT Tx PHY Block Diagram

User data from the MAC layer is passed as standard Ethernet frames with a traditional length of between 64 and 1500 bytes including the Frame Check Sum (FCS).EPoC will accommodate newer lengths of up to 2000 bytes. Each Ethernet frame includes a 32-bit CRC.

The reconciliation function is the same used by the EPON standard. Its purpose is to prepend an 8 byte EPON preamble containing the assigned Logical Link Identifier (LLID), other information, and a separate CRC. The LLID is required to properly support the virtual MAC entities used by the OLT (CLT) MPCP and each ONU (CNU) MAC entity.

The XGMII is the 10 Gbit/s Media Independent Interface (MII) used by the 10G-EPON standard. It establishes a 10 Gbit/s transfer rate from the MAC to the PHY. In order to accommodate FEC overheads and the required InterFrame Gap (IFG), the EPON MAC layer inserts idles between MAC packets to match the overheads and establish timing. These idles are transferred across the XGMII as part of the constant rate. EPoC will make a minimum augmentation to the EPON MPCP to adjust the idle insertion for both the different EPoC PHY and FEC overheads as well as to effectively lower the overall downstream rate to match the rate of the configured OFDM channel. Cable operators will first deploy EPoC with a minimum of 24 MHz or more, dependent on their cable plant configuration. As the service mix changes and more RF spectrum is allocated to EPoC services, the higher channel rate will be matched by changing the amount of idle insertion by the MAC. The Rate Adaptation removes any idles as required for matching the actual configured line rate.

The 64B/66B encoder is a modified version of the 10G-EPON, where the output is compressed to 65 bits per block rather than 66 bits per block. The line encoder provides a means to multiplex control and data information as well as establish a standard block framing for use by the receiver decoder.

The output of the line encoder is then processed by the downstream FEC encoder. P802.3bn Task Force has selected an LDPC rate 8/9 (14400, 16200) as the single long-sized code for the downstream. The FEC encoder places 220 whole 65-bit line encoded blocks in the information word accompanied by a 40-bit CRC. This CRC is used to meet the 802.3 Working Group Mean Time To False Packet Acceptance (MTTFPA) criteria. There are 36 bits of unused information word that will be removed via shortening.

The output of the FEC encoder is processed by a conventional streaming bit Scrambler. The scrambler is initialized at the beginning of each PHY Link cycle.

The resulting output crosses from the PCA to the PMA and is processed by the Symbol Mapper function. The operation of mapping PCS bits to OFDM symbols and subcarriers relies on configuration information that includes the following: excluded and non-excluded subcarrier status, continuous pilot subcarrier use, bit loading per subcarrier, QAM mapping per subcarrier, scattered pilot repeating placement per cycle, and PHY Link channel subcarriers. Not shown in Figure 4 is the parallel processing of the downstream PHY Link channel via the same (or similar) Symbol Mapper function. The output is a complex I and Q value per subcarrier (IFFT bin).

The Pilot Insertion function places both continuous pilot information and cycle-repeating scattered pilot information into the Symbol Mapper output before being processed by the Inverse Fast Fourier Transform (IFFT) process.

On conversion to digital OFDM symbols, the Cyclic Prefix (CP) and Windowing function adds the necessary CP overhead and symbol shaping. The resulting digital information is then processed by the PMD. Typically, most standards do not specify PMD functionality as specifics of Digital to Analog conversion, and analog processing is left to the vendor. Rather the power and spectral requirement of the electrical output at the F-Connector are very well defined.

The Upstream Tx PHY Data Path

The P802.3bn Task Force has many decisions pending in its upstream PHY path functions and architecture. The material here should be considered as a general overview of topic areas with the details subject to change as the Task Force completes its work.

Figure 5 presents a high-level block diagram of the P802.3bn upstream CNU physical layer for the data path. The PHY Link processing path is omitted from this description. The upstream channel implements multipoint-to-point access based on TDMA scheduling from the CLT MAC. Scheduling is based on time, and each CNU MAC is allocated time on the wire for its next burst. Upstream bursts in EPON frequently contain multiple concatenated MAC packets and EPoC will contain them as well.

To overcome inefficiencies of a single transmitter in an OFDM channel, EPoC uses OFDM/A and introduces a one dimensional (1D) to two dimensional (2D) mapping algorithm together with an upstream framing and timing structure that permits data as well as channel probing with PHY Link Discovery and Ranging. P802.3bn adds a process of employing three upstream FEC codewords and their combination that maximizes burst efficiency.

Overall, upstream PHY processing is very similar to downstream processing. The key differences are:

1) The FEC encoder is replaced with an FEC codeword builder that also includes MAC burst detection,

2) The symbol mapper, interleaver, and OFDM Framer together build a two dimensional framing structure composed of Resource Blocks, and

3) A configuration and timing function controls OFDM/A framing and wideband probes used for per-CNU channel response analysis.

FEC Codeword Builder

The P802.3bn Task Force selected three upstream codewords sizes and rates for the upstream channel: LDPC (14400, 16200), same as the downstream, LDPC (5940, 5040) rate 28/33, and LDPC (1120, 840) rate 3/4.

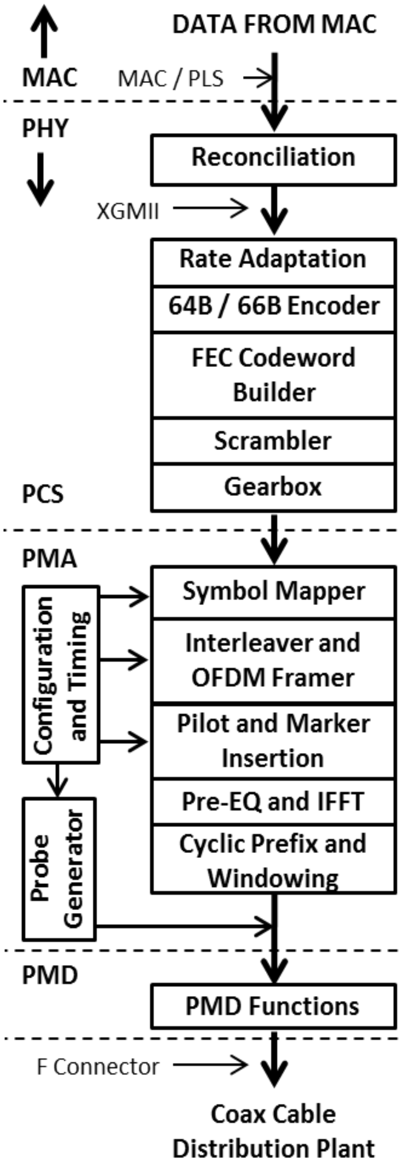

Figure 5. Upstream CLT Tx PHY Block Diagram

These are referred to as long, medium, and short respectively. All codewords support shortening. The Task Force selected a codeword filling approach where the ordering of codewords is concatenated for the upstream burst based on the actual MAC burst length. One of the challenges caused by the 802.3 layering model is that the length of the upstream MAC burst is not known by the PHY. The FEC codeword builder detects the start and stop of a burst and then determines how many and which FEC codewords will be needed for the burst. The basic algorithm is presented in [8] and uses a threshold of 6601 bits to determine the lower limit on long shortened codewords and 1601 bits for medium codewords:

- If there are enough bits to create a full long codeword, do so. Keep doing this until there are not enough bits left.
- If there are now enough bits to create a shortened long codeword (subject to the thresholds above), do so and end the burst.
- Otherwise, if there are enough bits to create a full medium codeword, do so. Keep doing this until there are not enough bits left.
- If there are now enough bits left to create a shortened medium codeword (subject to the thresholds above), do so and end the burst.
- Otherwise, if there are enough bits to create a full short codeword, do so. Keep doing this until there are not enough bits left.
- Use whatever bits remain to create a shortened short codeword and end the burst.

The DOCSIS 3.1 upstream PHY uses a similar upstream codeword building approach. However, EPoC includes a CRC-40 in the information payload and subsequently has different thresholds.

OFDM/A Framing and Resource Blocks

In EPON, each CNU is allocated upstream transmission time via the GATE message. The message specifies both *grantStart* and *stopTime* values[4]. For EPoC, this linear time-on-the-wire sequence of bits is converted to parallel using 1D-to-2D mapping onto Resource Blocks within the OFDM/A frame. A frame is the definition of a matrix of subcarriers by symbols where a repeating sequence is known by both the CLT and each CNU.

A Resource Block (RB) is a frequency and time grouping of Resource Elements (RE) defined by a dedicated set of (N) contiguous subcarriers and a consecutive number of (M) symbols defined by the OFDMA frame length. RBs are nonoverlapping. A CNU may be assigned to transmit in one or more contiguous Resource Blocks in an OFDMA frame. A Resource Element (RE) is a one-subcarrier by one-symbol element that is allocated within a resource block and used to convey a portion of the upstream signal; e.g., data, pilot, or burst marker information.

The P802.3bn Task Force is considering RBs where N may be 1, 4, or 8 subcarriers, and M may be 8, 12, or 16 symbols. M also represents the interleaver depth. For any given OFDM/A frame, the number of RBs and their allocation is static within a cycle and assigned via PHY Link management messages. All RBs in the same frame must have the same value of M. There is no requirement for all RBs in an OFDM/A frame to have the same value of N, simply that the CLT and CNU have the same RB configuration knowledge. As an example, three uses of an N=4, M=8 RB configuration that may be used during a CNU burst are shown in Figure 6. In this figure, the following conventions are used: **B** denotes a

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[4] Refer to [2]: Section 77.3.5 Gate Processing.

begin burst marker, **E** an *end* burst maker, **P** a pilot, **C** a complentary pilot, and **D** is data.

As an example, a MAC burst is transferred from the PCS to the PMA. The Symbol Mapper is aware of the RB timing and starts to use the first RB by inserting a beginning of burst marker into the appropriate RE designated B. Pilot REs for P and C are identified for future insertion in all RBs. As the burst continues, D REs are used to convey data. The bit loading of a D RE is determined by configuration. All D REs have the same bit loading within an RB. The Symbol Mapper continues filling RBs until an end-ofburst is detected in the processing of the PCS data. The RB containing the end-of-PCS burst will be indicated by inserting an end-of-burst maker in the appropriate REs designed E. The first bit of data of the PCS burst should be aligned with the first available D RE in the first RB. The RB containing the end-of-burst will likely have padding in the trailing D REs to account for normal end-of-data burst misalignment with the end of the RB.

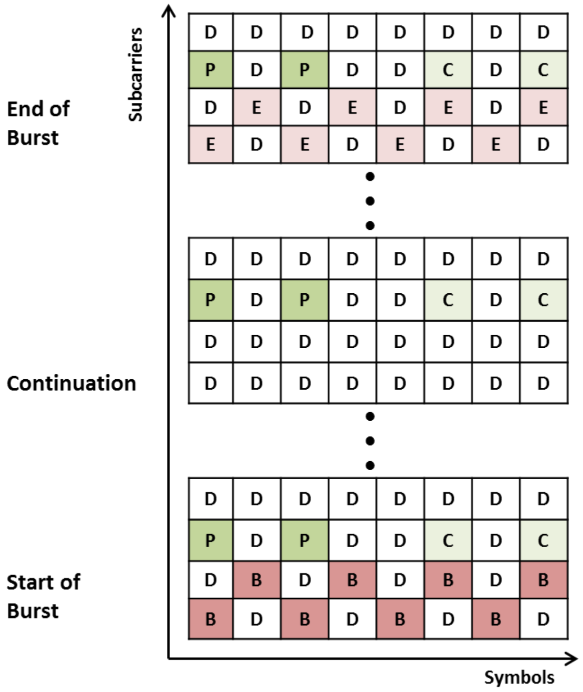

Figure 6. Example Resource Block Use

Bursts from different CNUs will be separated by one or more RBs where zero energy is transmitted. This forms a guard time.

OFDM/A RB framing with interleaving will require buffering as all bits from the PCS that are allocated within the OFDM/A frame must be processed by the Symbol Mapper so that the Interleaver operation is complete before the first OFDM/A symbol is transferred to the IFFT.

<u>Up to 10 Gbit/s</u>

One P802.3bn Task Force objective states: a data rate higher than the 1Gbit/s baseline data rate and up to 10 Gbit/s when transmitting in assigned spectrum and in permitted channel conditions. Another decision of the Task Force is: *the standard shall support the ability for higher capacity by combining multiple 192 MHz OFDM channels* [3]. While one 192 MHz OFDM channel will achieve at least 1.6 Gbits/s MAC/PLS data rate, exploring methods to achieve the 10 Gbits/s objective have been discussed in the Task Force. No technical selections have been made as of this time. One of the methods discussed is presented here as an example.

IEEE 802 standards have different approaches to increasing data rate between stations. Following 802.1 Bridging, multiple MAC/PHY entities can be combined using the 802.1AX Link Aggregation (LAG) standard [9]. For relevance to P802.3bn, this would mean a vendor would combine two or more distinct EPoC MAC and PHY client entities. This approach is already covered under 802 standards and is outside the scope of the 802.3 standard. Within scope, 802.3 standards increase the PHY link data rate by multiplexing PCS data over multiple channels that are referred to as lanes. Up to four lanes are typically combined by a multiplexing function in the PCS, with individual paths through the PMA and PMD. As P802.3bn is already multiplexing bits to subcarriers in the PMA, it makes sense to leverage this architecture and avoid layering another PCS multiplexing layer on top of PMA symbol mapper multiplexing.

Recall that the Symbol Mapper of Figure 4 performs multiplexing bits received from the PCS to a plurality of subcarriers in an OFDM channel under the direction of configuration information that includes bit per subcarrier loading. By extending the number of subcarriers supported and a straightforward approach to mapping subcarriers to individual OFDM Channels, several channels can be run in parallel. Figure 7 shows an example with four OFDM channels.

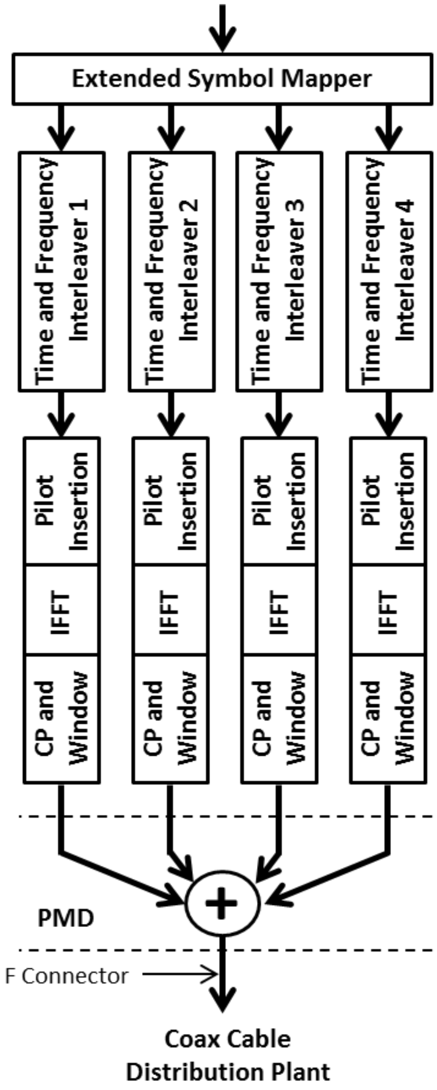

Figure 7. Multiplexed OFDM Channels

There are some assumptions with this approach. There may not be enough available RF spectrum to support all channels remaining operational. As individual subcarriers can be excluded, it would make sense for individual OFDM channels to be set as enabled or disabled until needed by the cable operator. For processing synchronization, all OFDM channels will need to have the same CP and Windowing values so the extended OFDM symbol is of the same size. The outputs of the parallel OFDM channels can be combined in the PMD. Specific combination techniques and the regulation of per channel power, and so forth, can be left up to each individual vendor.

DOCSIS 3.1 Alignment

There has been an ongoing effort to align EPoC and DOCSIS 3.1 OFDM numerology insofar as it is practical. This includes the Task Force consideration of adopting common component architectures for the industry. From an 802 process standpoint, individuals may bring forward alignment proposals, and the Task Force considers these as part of its normal socialization and technical selection process. There has been initial alignment of an OFDM FFT size, 204.8 MHz sample rate, CP and Window sizes, and upstream LDPC FEC coding and rates. In addition, the electrical input and output requirements of the PMD should be well aligned with DOCSIS 3.1 PHY OFDM channels, permitting consistent behavior and expectations when operating on a cable operator’s coaxial network. It is also expected that P802.3bn will add similar sensors and measurements to support Proactive Network Management (PNM).

SUMMARY

An overview and highlights of the IEEE P802.3bn EPoC PHY Task Force have been presented. The EPoC effort is in progress. Final architecture and operational details will be determined by consensus of the Task Force and the ballot approval process. The resulting PHY standard will enable several deployment models, increasing the number of choices for cable operators.

Ethernet is constantly evolving. EPoC is a novel solution for extending Ethernet as found in EPON services to cable operators in support of their multi-gigabit service offerings and for extending the life of the coax network.

REFERENCES

[1] IEEE 802.3 Working Group home page: http://www.ieee802.org/3/

[2] IEEE Standards Association http://standards.ieee.org/findstds/standard/802.3-2012.html

[3] IEEE P802.3bn Task Force home page: http://www.ieee802.org/3/bn

[4] CableLabs®, DOCSIS 3.1 Physical Layer Specification, CM-SP-PHYv3.1-I01-131029, http://www.cablelabs.com/specs/.

[5] Metro Ethernet Forum home page: http://metroethernetforum.org/. For more information on MEF Carrier Class Ethernet *Class of Service* requirements, look under Information Center and then MEF Technical Specifications for document MEF 23.1.

[6] DOCSIS® and DPoE™ are trademarks of CableLabs, Inc. More information DOCSIS and DPoE can be found at the CableLabs specifications web site at: http://www.cablelabs.com/specifications/

[7] IEEE P1904.1 Working Group Standard for Service Interoperability in Ethernet Passive Optical Networks (SIEPON). http://grouper.ieee.org/groups/1904/1/.

[8] Richard Prodan, *FEC Codeword Size Selection Based on Burst Size*, IEEE P802.3bn Task Force, November, 2013.

[9] IEEE Standards Association, http://standards.ieee.org/about/get/802/802.1.html

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