Increasing Cable Bandwidth Through Probabilistic Constellation Shaping

A Technical Paper prepared for SCTE•ISBE by

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Introduction

In the mid 1990s, multiple system operators (MSOs) began replacing coaxial cable trunks with optical links, creating the first hybrid-fiber coaxial (HFC) networks [1]. This new architecture reduced capital and operations costs, but required highly linear optical transceivers capable of transporting a full spectrum of analog RF signals while satisfying stringent electrical signal-to-noise ratio (SNR), composite triple beat (CTB), and composite second order (CSO) requirements. In the ensuing decades, wavelength-division multiplexing (WDM) technology was applied to these linear optical networks to aggregate and route headend-to-hub traffic and to split fiber nodes (FNs) in the access plant, thereby decreasing the number of households served per FN and thus increasing the available bandwidth per subscriber. Nonlinear optical impairments, primarily four-wave mixing (FWM) and cross-phase modulation (CPM), limit WDM channel counts and optical launch powers in linear HFC networks [2], adding further constraints as compared to the digital optical links used for telecom and datacom networking.

The distributed access architecture (DAA) [3], a widely accepted vision for the future evolution of HFC, includes remoting the digital-to-RF interface from the headend to the DAA node. In this scenario, the legacy analog optical links are replaced with digital links, opening a vast array of existing, high-performance, digital optical technologies to MSO network designers. Here, we describe a spectrally efficient and flexible modulation technique that has been recently developed for digital optical transmission links, probabilistic constellation shaping (PCS), that has several potential applications in DAA networks:

- High-speed digital optical links from the headend to the FN (or DAA node);
- Coaxial cable links from the FN (or DAA) to the user (modem);
- Future flexible-rate passive optical network (PON) systems for the next generation evolution.

PCS has been known for decades [4] as an essential element of communications to approach the capacity of a Gaussian channel, known as the Shannon limit [5]. It reached large scale adoption in the mid 90's inside dial-up and fax modems [6], but has been omitted in subsequent higher rate technologies that adopted a paradigm shift from single-carrier to multi-carrier modulation. The invention, in 2015 [7], of an efficient implementation of PCS for optical transmission systems has led to the rapid commercialization of this technology for core optical networks using coherent optics [8].

Although commercial optical coherent systems typically use square quadrature amplitude modulation (QAM) constellations with a uniform probability distribution, optimally performing constellations for a fixed average transmit power should follow a Gaussian probability distribution, yielding a "shaping gain" of up to ~1.5 dB in SNR compared to square QAM. New PCS-based coherent optical networks will benefit from this SNR improvement to increase the aggregate data rate to within a fraction of a dB of the Shannon capacity of optical fiber [9], and enable fully flexible control of transceiver rates, thereby realizing systems with optimized and consistent operating margins in any network configuration.

In this paper, we summarize the basics of PCS for high-speed optical links and describe how PCS-enabled coherent optics may be applied to aggregated digital links in DAA systems. We also report current progress toward transferring this technology to wired copper networks leveraging data over cable service interface specification (DOCSIS) and digital subscriber line (DSL) technologies. In the context of fiber-deeper MSO networks, we explore the potential impact that PCS can have on the optical transport and access networks, including applications to future flexible-rate passive optical network (PON) systems for fiber-deeper architectures.

1. Probabilistic Constellation Shaping

The basic idea of PCS is to transmit a constellation symbol of a smaller energy with a higher probability than that of a larger energy (hence called "probabilistic",) so as to mimic continuous Gaussian signaling that consumes the smallest transmit energy to achieve a desired data rate [5]. In practice, PCS creates a Gaussian distribution not on a continuous symbol set but on a finite and discrete symbol set, as shown in Fig. 1, which is often referred to as the *Maxwell-Boltzmann (MB)* distribution[1]. The variance of the MB distribution determines the *entropy rate*, which is the maximum number of information bits that can be carried by a symbol. For example, as the variance of the MB distribution of the two-dimensional PCS 64-QAMs in Fig. 1 increases, the entropy rate also increases. When a desired entropy rate is given, it is the MB distribution that consumes the smallest average energy among all possible probability distributions for the discrete symbol set [10]. To see the energy efficiency of PCS by an example, the two-dimensional PCS 64-QAM in Fig. 1(b) is projected onto one dimension, such that a PCS 8-ary pulse amplitude modulation (PAM) is produced as shown in Fig. 2(b) with the probability mass function (PMF) of $\mathbf{p} = [p_1, \dots, p_8] = [0.0006, 0.0147, 0.124, 0.3607, 0.3607, 0.124, 0.0147, 0.0006]$. This PCS 8-PAM creates an entropy rate of $H(\mathbf{p}) = -\sum_{i=1}^{8} p_i \log_2 p_i \approx 2$ bit/symbol, by consuming an average energy of $[(-7)^2, (-5)^2, (-3)^2, (-1)^2, 1^2, 3^2, 5^2, 7^2] \times \mathbf{p}^T \approx 3.75$. On the other hand, for the same entropy rate of 2 bit/symbol, and the same minimum distance between constellation points, a uniform 4-PAM shown in Fig. 2(a) uses a much higher average energy of $[(-3)^2, (-1)^2, 1^2, 3^2] \times [0.25, 0.25, 0.25, 0.25]^T = 5$.

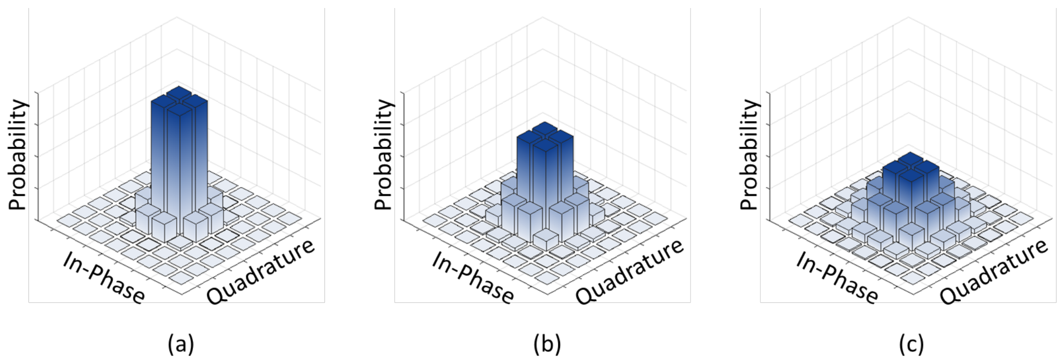

Figure 1 – Examples of the probabilistically shaped square 64-QAM constellation, with entropy rates of (a) 3.2 bit/symbol, (b) 4 bit/symbol, and (c) 4.8 bit/symbol.

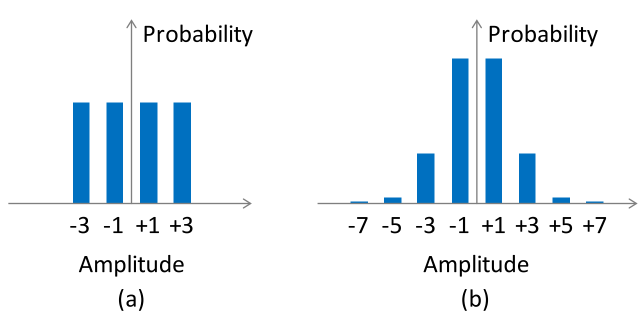

Figure 2 – One-dimensional constellations with the same entropy rate of 2 bit/symbol: (a) uniform 4-PAM, and (b) PCS 8-PAM.

[1] It may more commonly be called the Boltzmann distribution in today's nomenclature, but has historically been called the Maxwell-Boltzmann distribution in the context of PCS.

Although the capacity-achieving performance of PCS has been known since information theory was first established [5], and despite intense effort to advance its practical implementation in the mid 1980s to the early 1990s [4, 10-12], PCS did not initially make it into many applications. One notable exception was the V.34 voice band modem technology over telephone lines standardized by the International Telecommunication Union (ITU) in 1994, that adopted PCS in the form of shell mapping [6]. At the time, V.34 became a popular modem technology for dial-up internet and was also commonly implemented in fax devices. It is only three years ago that PCS began to draw enormous attention again with the focus on optical communications, when an implementation method was reported that is both capacity-approaching and practical [7]. From that time onward, PCS has set numerous new transmission records in optical fiber communications across virtually all transmission distances from 50 km to 11,046 km, with spectral efficiencies ranging from 17.3 b/s/Hz down to 5.7 b/s/Hz [13-17]. This is attributed largely to the flexible rate adaptability, and partly to the optimal energy efficiency. Traditional uniform QAMs permit only a handful of integer-valued entropy rates, hence cause an excessive margin in most optical links where rate adaptation by forward error correction (FEC) codes is limited. On the other hand, PCS can create an arbitrary real-valued entropy rate (cf. Fig. 1) that matches any given optical link, thereby leaving only an intended margin, as illustrated in Fig. 3. With the recent commercialization of PCS for coherent digital optical networks [8], this new technology has gone from the invention of an efficient and near-optimal implementation to a laboratory demonstration to commercialization in a short period of three years. The speed with which PCS has been commercialized is a testament to its potential impact on optical network performance.

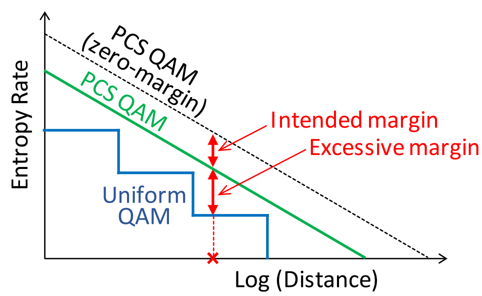

Figure 3 – Rate adaptation via uniform and PCS QAMs.

2. PCS for Digital Optical Links in DAA HFC Networks

Legacy HFC networks, as shown in Fig. 4, include analog RF optical links on a pair of fibers between the head-end (HE) or hub node and the fiber node (FN). The FN is the optical-to-electrical interface between this analog optical link and the coaxial cable distribution plant, that serves several hundred households via cascades of RF amplifiers.

Over the past several years, the cable industry has coalesced around a vision for the evolution of HFC networks that leverages the technical and economic advantages of digital optics to replace the analog optical link with a more robust, higher performance digital link. CableLabs recently released a pair of specifications describing point-to-point (P2P) 100-Gb/s coherent optics [18] and related architectural use cases [19]. The P2P specification is based on coherent transceiver technology using differential quadrature phase shift keyed (DQPSK) modulation, which has been widely deployed in long-haul and metro networks. Since HFC hub-to-FN links are relatively short (typically substantially less than 100 km) and the aggregated data rates are moderate, the specification defines relaxed requirements as compared to commercial dense WDM (DWDM) long-haul transceivers, which should result in reduced costs. These include lower output power, lower optical signal-to-noise ratio (OSNR), relaxed number and spacing of

ITU DWDM channels, and limited chromatic dispersion compensation. Assuming these 100-Gb/s P2P transceivers gain acceptance, PCS-enabled transceivers would be a potential next-generation upgrade capable of providing the maximum data rate allowed by the link given the transceiver's launch power.

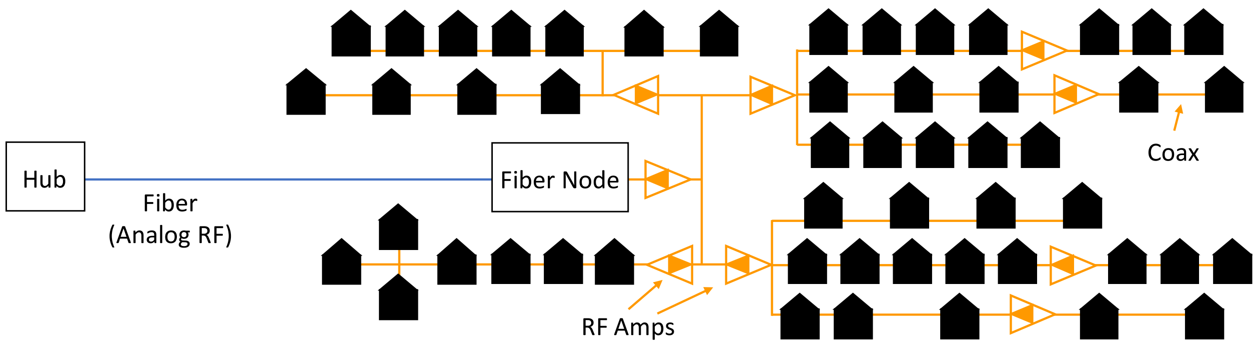

Figure 4 – Legacy HFC access network.

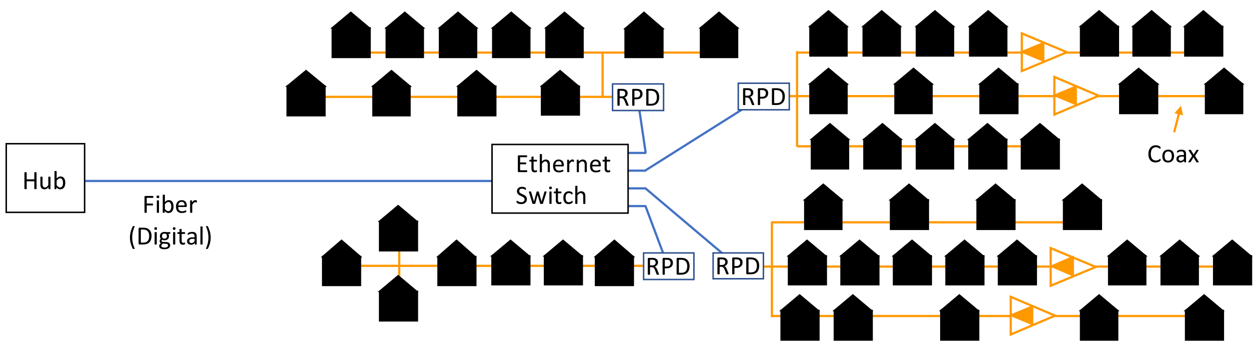

Figure 5 – Fiber deeper Distributed Access Architecture (DAA) with the aggregated digital optical link terminated on an Ethernet switch. Lower rate optical Ethernet links connect the switch to RPDs, located at the sites of legacy RF amplifiers.

The most relevant architectural use cases described in [19] are variations of the distributed access architecture (DAA), for which the analog optical link in a traditional HFC network is replaced with a digital link, and fiber is deployed deeper into the network, significantly reducing the number of households passed per fiber termination and creating new opportunities such as backhauling wireless small cells. One instantiation, shown in Fig. 5, replaces the analog RF optical link with a digital coherent link terminating on an Ethernet switch. The Ethernet switch is in turn connected via lower rate point-to-point optical Gbit or 10-Gbit Ethernet links to remote PHY devices (RPD) or remote MACPHY devices (RMD), that convert these bidirectional digital optical signals to RF signals sent to end users over the coax. Another version of this architecture, shown in Fig. 6, uses multiple DWDM wavelengths passively routed via DWDM optics, or a time division multiplexed (TDM) passive optical network (PON) with a passive splitter, between the hub and the RPDs/RMDs. These options are compatible with PCS-enabled transceivers to optimally adapt the data rate to the particular link. Consider, as an example, an upgrade for the hub-to-switch architecture (Fig. 5) for which a single fixed-rate 100-Gb/s wavelength according to the P2P standard is replaced by PCS-enabled transceivers having a range of finely adjustable data rates from 100 Gb/s up through 600 Gb/s. In this case, the PCS transceivers would automatically optimize the data rate to the link, while maintaining a constant minimum system margin (i.e. separation between the signal SNR and the Shannon capacity), thereby minimizing launch power.

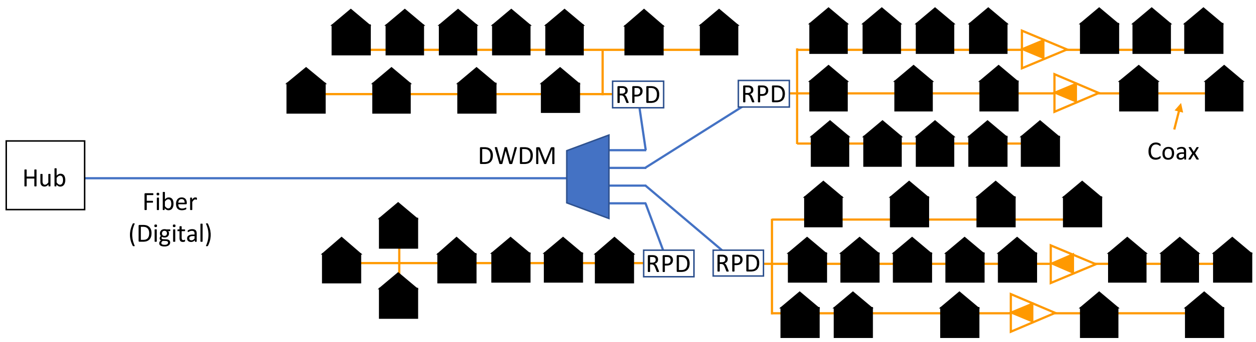

Figure 6 – Fiber deeper Distributed Access Architecture (DAA) using distinct DWDM wavelengths to connect to multiple RPDs. {Note that a PON variant of this architecture is also possible, for which TDM or TWDM optical signals connect the Hub to OLTs (sec. 4).}

3. PCS Over Copper Links

PCS can also be beneficial for transmission over copper access networks, consisting of coaxial cables or telephone wires, but requires several changes to the scheme as reported in [7]. These are explained in detail in [20] and are summarized below.

One major difference with digital optical transmission is that copper access technologies, such as DOCSIS 3.1 for cable and G.fast for DSL, use multi-carrier modulation formats like orthogonal frequency division multiplexing (OFDM), as opposed to single carrier modulation in digital optics. So instead of shaping a single communication channel (or a relatively small number of independent channels in the case of WDM) with a single SNR, thousands of small subchannels have to be shaped simultaneously, each with a potentially different SNR. A solution to this problem consists of using a set of pre-defined shaping codes labeled by so-called "modulation indices", each related with a particular QAM modulation order [20]. Similar to bit-loading in DSL, or modulation profiles in DOCSIS 3.1, one can then assign a modulation index (and the corresponding shaping code) to each subcarrier based on its SNR value. This implies that the algorithms and protocols used for assigning modulation orders in current technologies can be re-used to realize shaping based on modulation indices, and thus that this approach requires minimal standard changes.

Another important difference is that the maximum obtainable SNR on copper networks can be extremely high (40 to 50 dB), which supports very large constellation sizes (e.g., up to 2^{14}-QAM). A characteristic of the PCS scheme as discussed above is that all parity bits from the low-density parity-check (LDPC) code must be transmitted on the sign bits, so as not to alter the occurrence probability of the modulated symbols (i.e., the shaping). This approach introduces a constraint on the modulation orders than can be achieved with a given code rate. For instance, a code rate of 3/4, as used in upstream DOCSIS 3.1, would only allow shaping for constellation sizes up to 2^8-QAM. Hence, the constraints due to this coding approach effectively limit the maximum system performance. To remove this constraint, a set-partitioning coding technique, known as LDPC-coded modulation (LCM) can be exploited [21]. Compared to regular LDPC as used in DOCSIS 3.1, which encodes all bits, LCM only encodes the least significant bits, i.e., a subset of the bitstream. A modified LCM scheme, which maps the parity bits to the sign bits, can be combined with PCS [20]. With this approach, the constraint is shifted from imposing a maximum modulation order to imposing a maximum number of coded bits per symbol (size of the subset). LCM has the additional advantages that it achieves a better net data rate for the same error-correction performance compared to regular LDPC, and a significantly less complex encoder/decoder since only a subset of the bits have to be encoded.

Table 1 – Characteristics of the first five PCS-LCM modulation indices defined in [20].

Modulation Index	QAM modulation order	Information rate [bits/QAM symbol]	SNR [dB]
1	4	2.6	9.06
2	6	3.4	11.81
3	6	4.4	14.86
4	8	5.5	18.17
5	8	6.4	21.17

Table 1 shows as an example the 5 first modulation indices defined in [20], using a rate-28/33 LCM encoding with 6 coded bits. The shaping codes can be designed to obtain any desired distribution of SNR operating points. In the example, the codes have been designed to obtain operating points that lie about 3 dB apart, leading to a uniform coverage of the useful SNR range. As can be seen from the table, modulation indices 2 and 3 both use the same modulation order (2^6-QAM), but realize a different information rate by using a different shaping code. Figures 7(b) and (c), respectively, show histograms of the received frequency-domain IQ samples of modulation indices 2 and 3, i.e. the PCS distribution plus a zero-mean Gaussian noise cloud at the receiver. With this approach, PCS removes the need for odd-bit constellations (i.e., 2^3-, 2^5-, and 2^7-QAM and higher) while still obtaining the same granularity of SNR operating points. Since odd-bit constellations require more complex mapping and demapping than their even counterparts, PCS effectively reduces the QAM mapping/demapping complexity.

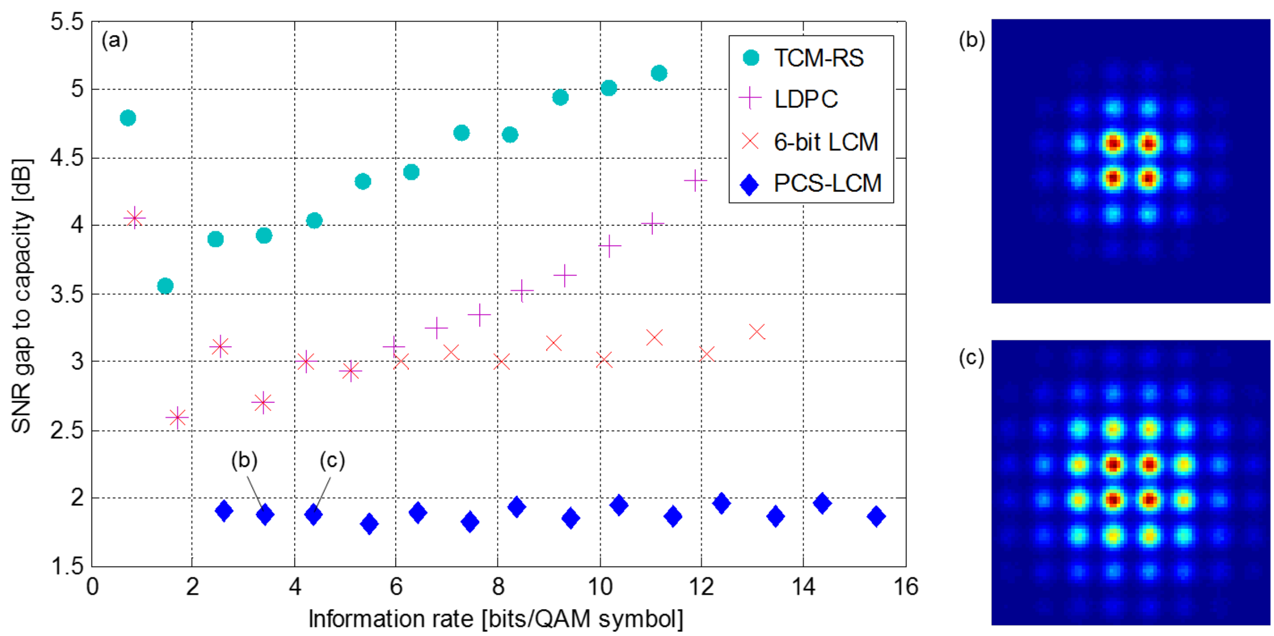

Figure 7 - (a) Comparison of the SNR gap to capacity of different relevant coding schemes as a function of the information rate. The distribution of received samples for PCS-LCM modulation indices 2 and 3 are shown in respectively (b) and (c).

Note that in upstream DOCSIS 3.1 and DSL, the main advantage of using PCS is the shaping gain, and not the matching of capacity and line rate, which can already be done by tailoring the transmit power and/or bit-loading on a per-subcarrier basis. The shaping gain is illustrated in Figure 7(a), where we compare the SNR gap to capacity of the proposed PCS-LCM scheme (blue diamonds) with that of three other schemes:

- inner trellis coded modulation (TCM) with an outer Reed-Solomon (RS) code as used in contemporary DSL systems (cyan circles);
- LDPC encoding with the rate-28/33 code used in upstream DOCSIS 3.1 (purple plus signs);
- LCM encoding with 6 coded bits with the same LDPC code (red crosses).

Here the PCS-LCM scheme also uses 6 coded bits, with the same LDPC code. Compared with the non-shaped LCM, results show that this specific PCS-LCM scheme achieves a shaping gain of 1.1 dB, but even larger shaping gains can be achieved by improved schemes (the theoretical maximum being 1.53 dB). In addition, the SNR gap to capacity of the PCS-LCM scheme is very flat across all the modulation indices, mostly due to the LCM coding scheme.[2] The total gain of the PCS-LCM scheme is roughly 1.5 dB over conventional LDPC as used in DOCSIS, and roughly 2.6 dB over conventional TCM-RS as used in DSL. Using a hardware proof-of-concept platform, we have observed that the PCS-LCM scheme gives a consistent data rate increase of around 9% over TCM-RS in several twisted pair cables (European operator cables and CAT5e) where the entire range of usable SNR values are sampled.

4. Potential Applications of PCS to the PON Segment in Future FTTx Variants

As described above, probabilistic shaping has been shown as an attractive method to introduce flexible data rates and improve spectral efficiency in both coherent optical transport systems [13, 16, 22] and over copper links [20].

Flexibility and optimizing overall throughput are also considered attractive features for future optical access systems. The most commonly used network architecture in Optical Access is a Passive Optical Network (PON) based on time-division-multiplexing (TDM) in downstream and time-division-multiple-access (TDMA) in upstream to share the bandwidth between all users. A PON is a point-to-multipoint (p2mp) architecture which enables higher equipment density in the optical line terminal (OLT), typically located at the central office (CO), and shares fiber among multiple users to reduce cost. A PON also has a stringent optical power budget due to the passive splitting of the signals between the OLT and users. Another specific PON characteristic is the asymmetrical cost sensitivity, where, in the case of fiber to the home (FTTH), the user equipment is more cost-sensitive because it is not shared over the users of the PON.

Even though the OLT equipment is less cost-sensitive relative to the user side, the power consumption requirement is more stringent putting a limit on complexity. Also, signal reception at the OLT is in burst mode to enable TDMA. This often results in further complexity limitations for optimizing data overhead in the upstream due to burst recovery.

Finally, the p2mp nature of PON results in variations of channel quality for each user mainly depending on their distance from the OLT. Modulation flexibility can make advantageous use of this variation to increase overall throughput and thus optimize cost per bit in a PON.

In the literature, techniques have been proposed to achieve a flexible PON. For example, in [23] a flexible PON is implemented by adaptive bit loading in orthogonal frequency division multiplexing (OFDM), whereby an appropriate QAM modulation format is assigned to each OFDM subcarrier based on its SNR.

[2] In case of full LDPC encoding, the number of encoded bits increases with the modulation order. Since, for practical non-ideal codes, the information loss increases per coded bit, implying that the gap-to-capacity increases with the information rate. By using LCM, with or without PCS, the number of coded bits stays limited to for instance 6 bits, and there is no additional loss for higher modulation indices.

Reference [24] proposes the use of so-called non-uniform multilevel pulse amplitude modulation (PAM) to enhance flexibility and the aggregated capacity of a PON. Non-uniform multilevel PAM is a combination of applying PAM with unequally spaced levels and interleaving of PON users using the individual PAM-symbol bits which was earlier proposed in [25] as a method to implement PAM modulation in PON with significantly reduced hardware complexity. Optimizing throughput of a PON based on non-uniform PAM with multilevel interleaved users was demonstrated successfully with an actual PON deployment data in [24].

Although probabilistic constellation shaping has to date mostly been applied in coherent networks [13, 22] to introduce flexible data rates, it has recently also been shown to be advantageous to optimize the capacity of direct-detection links based on PAM for data centers [26]. PCS makes use of existing PAM hardware, so it would not add hardware complexity (and thus cost) relative to a flexible PON based on PAM as described above but does have the potential to further optimize spectral efficiency (throughput) and refine data rate granularity compared to the flexible PAM-based PON. The authors of [26] assume soft-decision FEC in their analysis, but [27] shows that hard-decision FEC, which has much lower complexity can also work outstandingly well with PCS. Moreover, PAM-4 has been shown to be technically feasible and cost-effective for a line rate of 25 Gbps for residential PON (which has the most stringent optical power budget) when optical amplification is applied at the OLT [28].

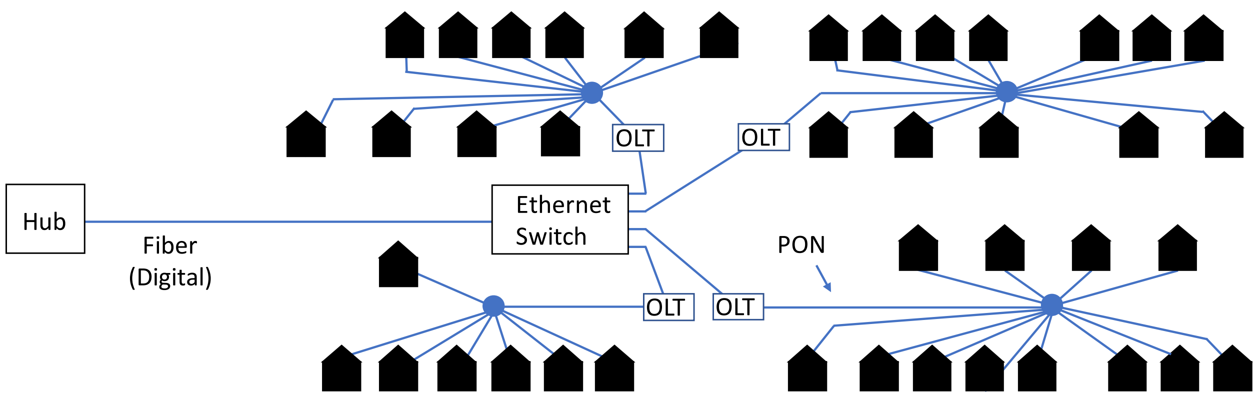

Figure 8 – Fiber deeper Distributed Access Architecture (DAA) with the aggregated digital optical link terminated on an Ethernet switch. Lower rate optical Ethernet links connect the switch to PON OLTs, that are in turn connected to user ONUs (not shown).

Applications beyond FTTH, such as mobile backhaul, mobile fronthaul, and the backhaul of DSL nodes and DOCSIS RPDs (see Figure 6) will benefit from a PON technology that adapts to a range of network topologies, including shorter reach and lower split-ratio and therefore smaller optical budgets. For these shorter and/or smaller PONs, modulation orders beyond PAM-4 will then also become feasible which further enlarges the total achievable data rate [26]. Figure 8 shows an example architecture from the recent CableLabs architectural specification [19], where the coaxial network between the RPDs and users, similar to that shown in Fig. 5, is replaced with PONs.

In summary, flexible PON based on using different modulation orders of PAM, combined with PCS and multi-level user-interleaving with non-uniform PAM, while applying direct-detection and hard-decision FEC, is a valid solution for future flexible PON use cases like high speed residential access and next generation x-haul. It has been shown that these techniques can also optimize overall throughput of the PON, which reduces the cost per bit of this very cost-sensitive network.

Conclusion

In recent years, probabilistic constellation shaping has become a very promising digital signal processing technique thanks to crucial advances in implementation architectures. It allows a reduction of the gap to reach the Shannon capacity limit and the elimination of excess margins (capacity loss) introduced by the coarse granularity of QAM constellations used for signal modulation, increasing the achievable data rates on communication links. We have demonstrated its potential in coherent optics and copper access communication technologies, and see further potential for PCS in PON technologies as used in FTTH networks and/or for backhaul of access technologies.

4. Acknowledgements

The authors gratefully acknowledge Andrew Chraplyvy, Vincent Houtsma, Marty Glapa, Jochen Maes, Laurent Schmalen, and Peter Winzer for helpful contributions.

Abbreviations

CAT5e	Category 5e twisted copper cable
CO	Central office
CPM	Cross phase modulation
CSO	Composite second order
CTB	Composite triple beat
DAA	Distributed access architecture
DOCSIS	Data over cable service interface specification
DQPSK	Differential quadrature phase shift keying
DSL	Digital subscriber line
DWDM	Dense wavelength-division multiplexing
FEC	Forward error correction
FN	Fiber node
FTTH	Fiber-to-the-home
FWM	Four-wave mixing
HE	Head-end
HFC	Hybrid fiber-coaxial
ITU	International Telecommunication Union
LCM	LDPC-coded modulation
LDPC	Low-density parity-check
MB	Maxwell-Boltzmann
MSO	Multiple system operator
OFDM	Orthogonal frequency division multiplexing
OLT	Optical line terminal
ONU	Optical network unit
OSNR	Optical signal-to-noise ratio
P2P	Point-to-point
P2MP	Point-to-multipoint
PAM	Pulse amplitude modulation
PCS	Probabilistic constellation shaping

PMF	Probability mass function
PON	Passive optical network
QAM	Quadrature amplitude modulation
RF	Radio frequency
RMD	Remote MACPHY device
RPD	Remote PHY device
RS	Reed-Solomon
SNR	Signal-to-noise ratio
TCM	Trellis coded modulation
TDM	Time-division multiplexing
TDMA	Time-division multiple access
WDM	Wavelength-division multiplexing

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