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ABSTRACT

Level 3 DSM's vectored VDSL's highest speeds exceed those presently offered, and as well contemplated in the future, on passive optical networks (PONs). This information-only contribution provokes comparison between vectored DSLs and PONs. The suggestion that DSL access architectures using vectored DSLs merit yet stronger consideration appears with justification in terms of attainable data rates, service migration, and management. The objective is to fuel the present expanding investigations into vectored DSLs.

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DSL is Faster than Fiber

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ABSTRACT

Level 3 DSM's vectored VDSL's highest speeds exceed those presently offered, and as well contemplated in the future, on passive optical networks (PONs). This information-only contribution provokes comparison between vectored DSLs and PONs. The suggestion that DSL access architectures using vectored DSLs merit yet stronger consideration appears with justification in terms of attainable data rates, service migration, and management. The objective is to fuel the present expanding investigations into vectored DSLs.

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1. Introduction

High-speed multi-line-dropped vectored VDSL's are introduced in [1] under the name "CuPON" (Copper PON) as a frugal alternative high-speed-access-network architecture to passive optical networks (PONs). Excerpts from that more complete document appear in this contribution with the intent of stimulation of the DSL-knowledgeable NIPP-NAI standards group in the area of Level 3 DSM vectored VDSL. Technologically, current NIPP-NAI readers are nominally aware of vectoring methods (generalizations of what is called "MIMO or self-FEXT cancelling" in various standards bodies [2],[3])[1]. In particular, most know that with cogent vector grouping of mutually crosstalking DSL lines can eliminate downstream FEXT, even without any bonding. Additionally, most NIPP-NAI experts also recall that vectoring eliminates single-line upstream crosstalk of all types (NEXT, FEXT, and even NEXT from other non-vector-group DSLs such as unbundled alternative service-providers), as well as eliminates radio and impulse noise. Vectoring's consequent noise reduction thus enables much higher single-line DSL data rates. Bonding just adds more to vectoring, and indeed vectored bonding can lead to yet more than simple *n* times single-line rates [12] with bonding alone. This contribution pursues vectored bonded

[1] For those that may need a refresher, contribution NIPP-NAI-2006-092 and the references may be of assistance.

concepts into the realm of drop segments to find that per-customer data rates in the 100s of Mbps are possible, and even a Gbps in certain cases, thus exceeding by an order of magnitude the fastest per-customer continuous PON data rates of 20-30 Mbps per customer.

Section 2's CuPON suggests use of DSL drop-segment's extra copper. In particular, customers' multiple drop pairs collaborate in a shared architecture reminiscent of the PON's single-medium dropping with optical splitters. While multi-dropping copper networks are as old as the ages, including party lines [4], early Ethernet "yellow cable"[5], coaxial networks, PONs[6],[7] and some broadcast DSL architectures [8], vectored multi-dropping is fundamentally different: In particular, Section 2's smart management of the line-terminal vectoring unit allows allocation of the various modes of binder transfer to different users, extending well beyond simple frequency- or time-division multiplexing of a single shared-wire/fiber medium. The possible speeds suggest a CuPON to be a very attractive substitute for a PON system, at least within distribution areas of a few thousand feet between line terminal and customers. A PON is an expensive upgrade – at the very least, its implemented bandwidth should greatly exceed the existing copper's best capability or replacement of copper by fiber is of dubious merit.

Section 3 reminds users that vectoring may also exploit the split-pair and common transfers within a binder to effect yet larger data rates. Such exploitation augments the differentially vectored VDSL currently contemplated to yet higher data rates. Ultimately, a binder of 200 pairs (400 wires) can exhibit a total bandwidth approaching 100 Gbps, well beyond the most far-reaching PON projections of today for a similar number of users. No PONs seriously consider such bandwidths for a variety of cost and architectural reasons.

The conclusion of this contribution hopefully evokes honest contemplation of the limits of DSL speeds and motivates chosen elite to pursue them (and certainly before fiber is installed to then lower the customer's data rate)!

2. A CuPON for savings on access-network purchases

Figure 1's PON architecture offers a model for copper systems to exploit, as in this section.

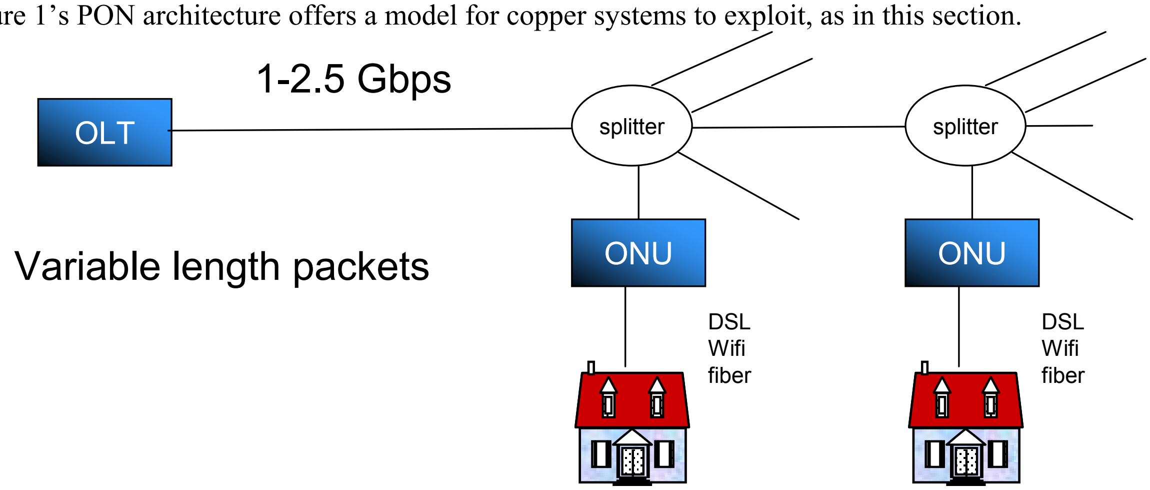


Figure 1 – Basic PON architecture

A single fiber (or coax) emanates from an optical line terminal (OLT) and connects to all subtended customers. The 1 Gbps (EPON, [7]) to 2.448 Gbps (GPON, [6]) data rate is shared among all users. EPONs serve 32 customers, while GPONs serve up to 128 customers, leaving any PON's continuous per-customer bandwidth in the 20-30 Mbps range (deducting overheads, where 20 Mbps = 2.4Gbps/128 for the GPON and 30 Mbps = 1.0 Gbps/32 for the EPON). Increase of these limited PON data rates requires more fibers, PONs, and thus increased deployment cost of an already highly expensive system. A higher peak speed of 100 Mbps is allowed only when other customers are inactive, creating many PON opportunities and protocols for what is called ``dynamic bandwidth allocation'', which is essentially assigning packets to allow sharing among the various sharing users. Optical splitter circuits are inserted into the fiber to drop to customer locations. These passive optical devices are expensive to insert and of course require dispatch of personnel, and digging or aerial dropping to connect to the customer along the same paths presently occupied by the copper-line connections. This is a key point – considerable investment to get 20-30 Mbps to a customer, perhaps 100 Mbps if the other customers are silent. No PONs today (see [6] and [7]) offer higher speeds. While multi-wavelength fiber transmission in the PON might be a research topic, the addition of such wavelengths to an existing PON requires deployment of new OLTs, replacement of optical splitters, and additional optical processing. The single-line PON medium thus means replacement of existing LT equipment before the very first customer can use an additional wavelength. DSL avoids this disadvantage (although clearly multi-ported line cards will replace electronics for all subtended DSLs). NG-PON is being studied, and a 10 Gbps EPON effort was recently initiated, and would provide some improvement, (and again would share this bandwidth over one hundred customers or more), but these are not yet available nor understood.

Figure 2 copies the PON architecture but implements it with the existing 200 copper lines already present in the exact same places where fiber would be placed for a PON. Most North American customer drops have 2-4 pairs (or 4-8 wires). The extra copper occurs only in the last distribution-area or pedestal-drop segment - in other words, the extra wires may not pass all the way back to a LT, but instead would go to an intermediate point or junction box. In Figure 2's Cu-PON architecture, these drop pairs are shared, possibly between two or more homes by connection. Let us suppose that a well-designed vectored VDSL system can allow 50 Mbps symmetric data rate to 3000 feet (see for instance [1],[9]. Thus vectoring performed between groups of differentially vectored VDSL pairs allows the 200 Mbps to a customer or to that customer's neighbor, or to both. Each customer would get 100 Mbps if both were simultaneously active. In effect, this is a mini "PON" shared between two neighbors, or possibly 4. The speeds of the Cu-PON can be higher, not because copper has wider bandwidth than fiber, but because the fibers do not use their extra bandwidth, and again PON upgrade could require changes to use it (possibly replacement of the passive splitters with WDM components, and upgrades to CO equipment, and new ONTs for new subscribers).

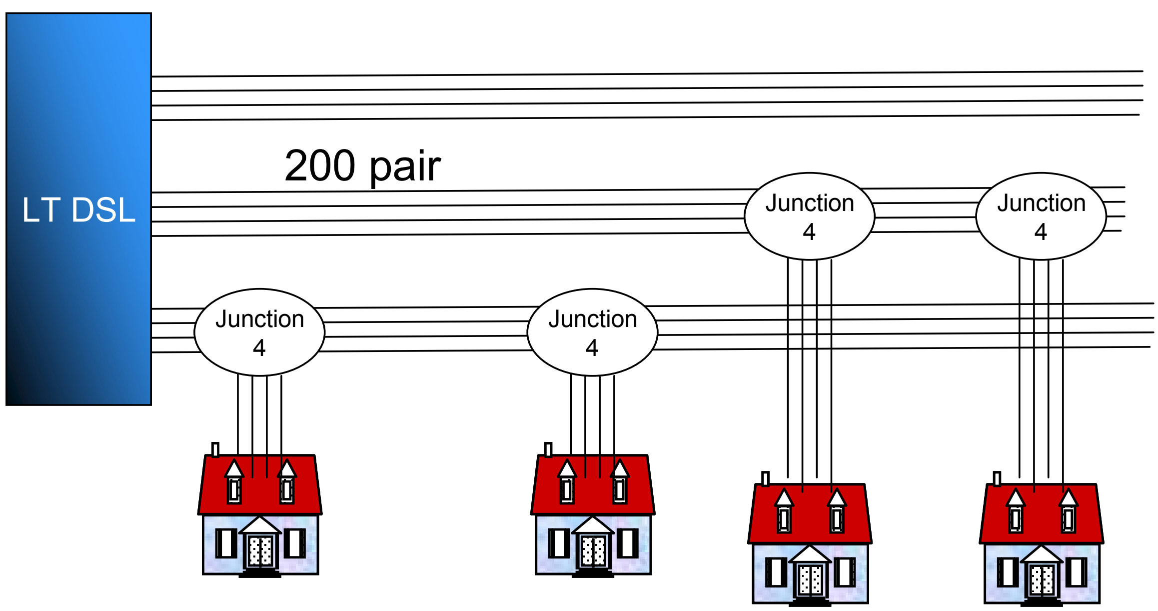


Figure 8 – Basic Cu-PON Architecture

However, we're only beginning with the CuPON. Now that the multiple pairs are used in the drop, simultaneous bonding and vectoring can be used as in Section 3 to implement larger data rates yet.

Figure 2 begs the question of management. Which customer gets priority? What are the various trade-offs. A sophisticated theory [10]-[11] of such management can be summarized in a couple of dual problems that are solved by various convex optimization methods, which incidentally are enormously simplified for digitally duplexed DMT VDSL through what is called "dual decomposition" in the frequency domain.

As with all DSM, there is an achievable rate region of all possibilities customer-rate combinations for the vectored group of customers. One approach to customer priority postulates a group of desired rates across the vectored DMT DSLs. The DSM Center then determines the minimum sum power levels of all users to achieve this data rate vector. If all users' powers are within DSL standardized limits, the rate is achievable and the consequent PSDs and information allocations can be used by the vectored-group users. If some powers are outside limits, a weighting vector (set of positive fractions that adds to one, one fractional value for each user) can be assigned with larger weights to those users exceeding allowed power or power-spectral-density constraints. The optimization is then re-executed. If no such weighting vector exists or can be found, the rates requested are not feasible and thus the DSL-qualification process would consequently prevent those rates from being attempted. The best information and bit assignments do not necessarily correspond to water-filling solutions for all the users in this approach. A dual alternative solution to priority maximizes a weighted sum of user data rates (with users who need more data rate getting higher weighting in the sum) subject to meeting all power and PSDMASK constraints. By varying the weights, different customer rate combinations are possible. See the references [10]-[11] for a more complete description of the underlying mathematics behind such vector spectrum management.

3. The promise of vectored-DSM

3.1 Full vectored and bonded pair groups.

Full binder capacity exploits single-wire transfers and common-mode crosstalk within the vectored group of bonded lines. The key concept in full vectoring is to use all the wires. Full vectored DSLs manage a group of n DSL lines that contains $2n$ wires. Some or all of the n customers may be in service. Even when there are a smaller number of customers, all of the wires can still be helpful to those few active customers. These bonded lines may also be part of a larger vectored group that may contain other single lines or bonded groups of lines, and between which all crosstalk is mutually eliminated. There are possibly as many as $2n$ transfer modes of energy in such a binder of wires, of which n are left dormant in differential vectoring and all previous DSLs. When all these modes are considered, the binder's full-vectored capacity can be computed. The possible exploitation of such modes is clear in MIMO systems (such as in [12],[13] where symmetric Gigabit DSLs are observed on 4 bonded 300-meter-plus telephone lines by using all 8 wires – roughly about double the lengths achieved today by 1G-BT Ethernet systems).

3.1.1 Single-Wire Transfers

Figure 3 illustrates single-wire transfers between two bonded lines or a quad of 4 wires in the downstream direction with three loads. The concept easily generalizes to more than two lines.

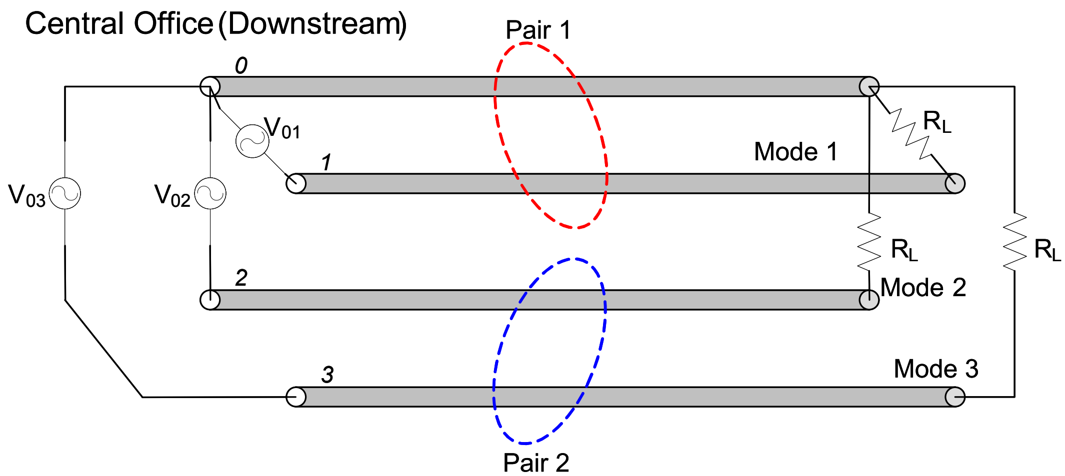
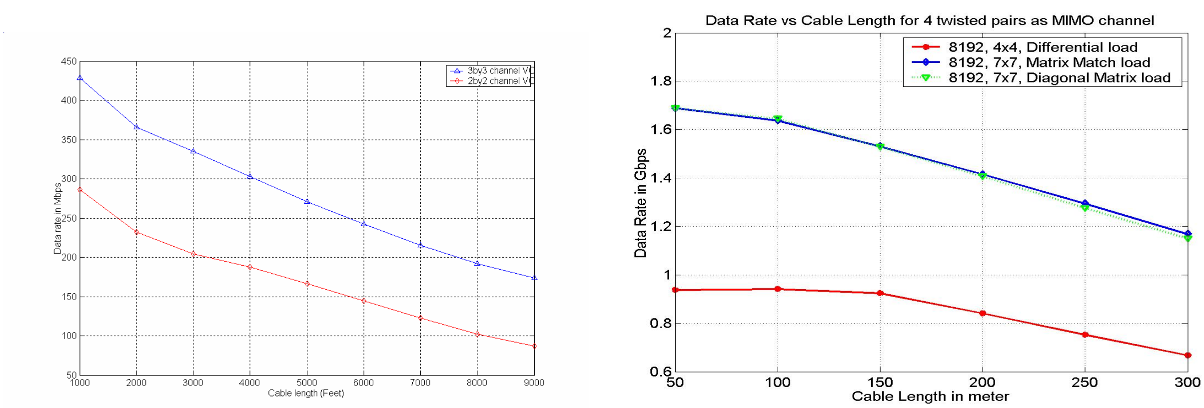


Figure 3: Split-pair excitation of two lines. There are 3 = 2U-1 sources since the ground/shield is not used.

With single-wire (sometimes also called ``split pair") excitation, one wire (0) in one of the pairs is viewed as a reference for 3 sources, V_{01}, V_{02}, and V_{03}. In normal differential operation, the second subscriber's excitation voltage is $V_2 = V_{02} - V_{03}$ and only two excitations appear. However, 3 sources are possible more generally and in fact, can all be assigned to a single subscriber with bonding of the pairs. When the two lines go to different customers, the load resistance placements between wire 0 and wires 2 and 3 is not physically possible. If the pairs go to the same customer, then such termination is possible.

Figure 4 shows the data rates achieved for the situations of 2-pair drops and 4-pair drops. The upper curve in each case corresponds to the use of the extra single-wire modes. The increase is substantial for full vectoring over differential vectoring. In each case though, both vectored curves are beyond the most aggressive data rates per customer of any current fiber system.



(a) (b)

Figure 4: Symmetric upstream and downstream data rates with and without single-wire use for (a) two pair (3 modes) and (b) four pair (7 modes).

Common Crosstalk Modes

There is yet more useful energy in the binder of lines. Figure 5 alternately illustrates the possibility of common-mode transfers within a binder where the sheath has been well-connected to ground at all junctions. Such grounding is the purported practice of all telephone companies. However, the grounds may sometimes not be connected in practice, so such operation is possible only if they are connected. In drop segments with no sheath, one wire in the drop can be used as the ground and the results of Figures 3 and 4 then apply. It is rare to find only one pair in a drop segment, so the full-vectoring common modes can be exploited. The various transfer functions with sheaths can be determined by multi-conductor transmission line and elementary electromagnetic theories [14], and indeed these transfers are significantly larger than those of the differential pairs. The wise old sages of telephone plant engineering will immediately object that the common-mode transfers create large crosstalk noise (and sense large noise also) – that's why Bell originally invented the twisting. They're right – ***without vectoring*** those high-transfer modes annihilate each other in terms of very high noises along with the very high signals. But not with vectoring – recall vectoring cancels that crosstalk effect. The impact on data rate is enormous.

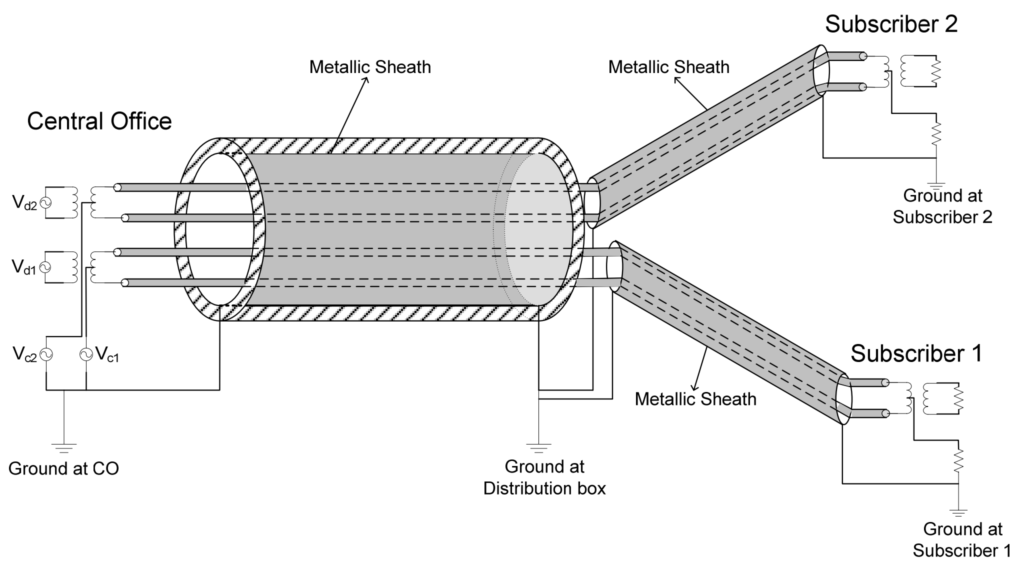


Figure 5: Binder with grounded sheath and full common- and differential-mode excitations.

Figure 6 (see [14]) illustrates with the two upper curves for a single line, the effect of using the common-mode transfers. The rates are compared to differential vectoring alone. This is the limit[2] (these curves are not quite capacity and use a gap of about 11 dB) of practical transmission on the line. It is thus possible to attain almost 250 Mbps symmetric (or up to 500 Mbps asymmetric) on a single pair at distances of 500 meters (or 1500 feet), and 100 Mbps to distances of 1 km (or 3000 feet). These are not what service providers see today from VDSL2 equipment, but are possible with improved vectored systems in development.

[2] It is dangerous to say "this is the limit" as someone will always come along later and find some new effect. However, as we know today, the only possibilities for further data rate increase are "statistical scheduling" of the pairs (which possibly increases the peak rate but not the continuous rate, so we don't count that here) or by using higher order transverse modes of the transmission binder, an area we leave to some enterprising electromagnetics theorist to explore.

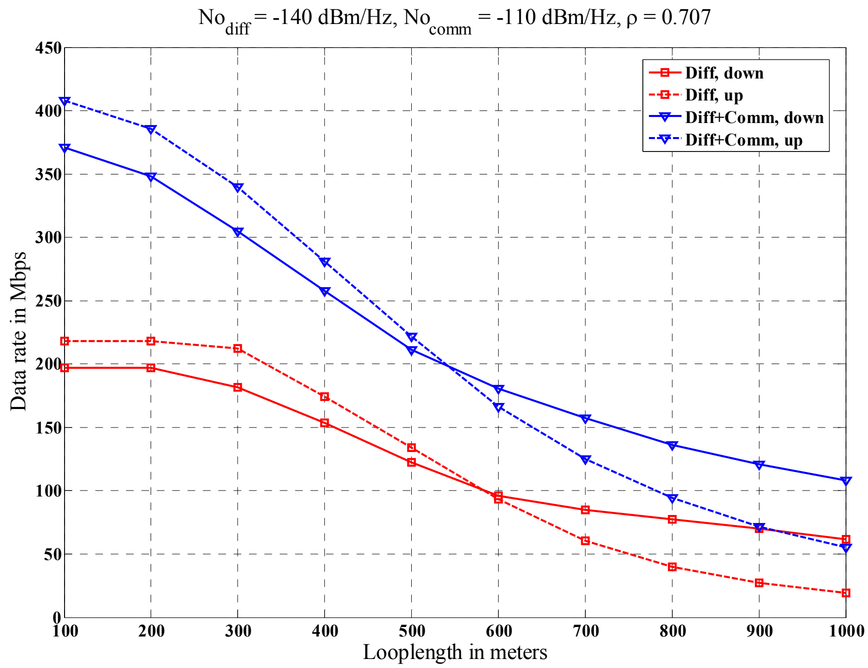


Figure 6: Full binder versus differential vectoring data rates.

Using these more advanced concepts, at 1 km, a bonded group of 4 lines has a bonded capability of any where from 4 times 100 Mbps in Figure 6 that can be multiplied by 7/4 as in Figure 4(b) with all wires used so that 700 Mbps is possible. This might be then shared between 2-4 DSL customers, leading to a few hundred Mbps of continuous unshared bandwidth for each CuPON customer.

Further, Section 2's vectored signal management via weighted rate sums or weighted power sums readily applies to non-square channel matrices that occur with more CPE terminations than LT terminations.

4 A Comparison of DSL and Fiber

Table 1 compares the traditional PONs with the Cu-PON using the best methods from Section 3 to emphasize the potential DSL advantage. The data rates listed are unidirectional (so can be doubled for an aggregate of both directions). The comparison is for 200 pairs (essentially the 192 commonly encountered in distribution areas) in the Cu-PON case; it is these 200 pairs that might be replaced by a PON. The speeds of the Cu-PON are clearly higher, not because copper has wider bandwidth than fiber, but because the fibers do not use their extra bandwidth, and it would require major changes to use it (possibly with replacement of the fiber itself and certainly with all the electronics already there – and unfortunately, likely replacement of all CPE equipment just so the first single customer can get higher bandwidth with some future enhanced PON). The peak binder speed of the Cu-PON could be as high as 10s of Gbps. The peak with 4 drop wires per customer would be 1-2 Gbps in a 300-500m range. The range of the PON is certainly longer but most telephone companies use a distribution-area size of less than 1 km for support of at least 200 hundred customers. The main PON range advantage really translates to the absence of active elements other than at the customer's location or the central office. Thus, electronic failure of the fiber is less likely because the active components are in the nice climate controlled central office (although fiber to the home does require batteries at the home while DSL does not – that is normal phone service works without batteries on copper, but requires batteries with fiber).

The higher-bandwidth copper has the disadvantage that, for most customers, an active line or remote terminal DSLAM is not in the central office. Thus, maintenance of copper needs very sophisticated software running in the telephone company network, notably DSM. Such software is in early stages of deployment at most telephone companies today, but at least one has a full deployment. Such methods have proven to provide significant value, so the advancement of such DSM to include vectoring is very promising.

	(G and E) PON	Copper (Cu-PON)
Aggregate data rate	1- 2.5 Gbps	50 Gbps
User continuous data rate	20-100 Mbps	50-1000 Mbps
User peak data rate	100Mbps-1Gbps	100Mbps – 10s Gbps
Range	10-20 km	1 km
Power	Battery at ONU (no battery if FTTH)	LT needs to be powered
Splitter	Hard	Easy
Maintenance	Expected to be easy	Needs DSM to be cost effective
Deployment cost	high	Much less

Table 1 – Comparison of Cu-PON and G/E PONs

5. Conclusions

Level 3 vectored DSM allows a very favorable comparison for DSL over current and contemplated PON systems. The achievable DSL data rates are an order of magnitude higher than the PON system over comparable ranges for 200 customers. Thus, perhaps DSL merits another strong look in assessing access-network architectures for future broadband-service deployment strategies. Indeed, we might just find that DSL is faster than fiber in terms of what is feasible in the next several years.

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