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CONTRIBUTION

TITLE: **Full Binder Level 3 DSM Capacity and Vectored DSL Reinforcement**

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ABSTRACT

This contribution explores concepts in full-binder capacity and finds data rates to improve upon the "as-if-no-crosstalk-present" results of differential vectoring [1],[2]. Common-mode transfers with respect to the binder sheath, including various antenna-like crossovers, are modeled and exploited for increase of binder capacity. The basic areas needed for further DSM-D and DSM-C interface augmentations are outlined. Some level of data rate reassignment possibility also is that suggests the data rates of different customers may not be as independent as they are with differential vectoring.

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Full Binder Level 3 DSM Capacity and Vectored DSL Reinforcement

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ABSTRACT

This contribution explores concepts in full-binder capacity and finds data rates to improve upon the "as-if-no-crosstalk-present" results of differential vectoring [1],[2]. Common-mode transfers with respect to the binder sheath, including various antenna-like crossovers, are modeled and exploited for increase of binder capacity. The basic areas needed for further DSM-D and DSM-C interface augmentations are outlined. Some level of data rate reassignment possibility also is that suggests the data rates of different customers may not be as independent as they are with differential vectoring.

1. Introduction

Full binder capacity includes the data-carrying capabilities of crosstalk, instead of viewing crosstalk as harmful noise. A binder of *U* DSLs actually contains *2U* wires or conductors that often exist within an enclosed sheath, which can viewed as one more conductor in electromagnetic modeling. Such a binder of wires has an overall achievable rate region that describes the achievable rate combinations for the *U* users. This contribution explores such achievable rates and a number of aspects related to the modeling of the binder and the impact of such modeling upon the rate regions. The upper limits for each user's data rate within a binder are much higher than previously reported for vectored systems when all the possible binder transfers are considered. This contribution finds for customers at 100-300 meters distance from the LT, that a single line can achieve speeds approaching 500 Mbps symmetric data rates using existing VDSL (30 MHz) band plans and best known binder-vectoring methods.

Level 3 vectored DSM systems exploit line-terminal (LT) single-sided coordination of the transmitted downstream and received upstream signals within those DSLs controlled by any single service provider [1]. While bonding is not precluded in Level 3 DSM, this contribution assumes that one a single telephone line connects to each customer, leaving bonded Level 3 (sometimes called "MIMO") to other contributions ([2], [3], see GDSL sections). Level 3 DSM systems have largest gains when all lines are vectored, but also offer significant improvements in either bundled or unbundled environments, in which latter case some Level 2 band preference [4] between groups of vectored lines may also be very helpful.

Previous vectoring studies ([1],[2]) use what is called here "differential" vectoring. A well-known result ([5]) for differential vectoring is that all differentially vectored lines in a binder (whether upstream or downstream) will perform with frequency-division-multiplexing as if no NEXT nor FEXT is present. This contribution goes beyond differential vectoring to explore additional transfer modes within the binder, including the various common-mode transfers (and the consequent increased noise). Such vectoring is called "full" vectoring here.

Section 2 models the full binder by extending some accepted techniques from Section 5 of the DSM Report ([1]) to consider all wire-to-wire intra-binder transfers within a grounded sheath. Sheath grounding[1] is common in well-designed and maintained loop plants with connection points tying adjoining sheath grounds to the same point for integrity all the way to the customer. When such practice is not followed, the results in this paper represent upper bounds on attainable performance. Section 3 progresses to use of the wire-to-wire transfers to calculate capacities. In the first uses, all customers transmit lines carry only their own signals, leading to results on continuous available binder capacity that is always on for all customers. In alternate uses, some wires may carry (downstream) or more importantly collect (upstream) the signals of other users lines to expand the allowable trade-offs by exploiting the absence of full-bandwidth need on another line to its limits. Both types of vectoring are illustrated in Section 3, with the later offering a greater trade-off of upstream user rate capability; downstream data rates for full vectoring remain almost as independent as they are well-known to be in differential vectoring.

2. Full Binder Model

The following configuration was simulated using the same Multi-conductor Transmission Line (MTL) model as in Chapter 5 of the DSM Report [1] with some additions to include the sheath as further detailed in this section. These methods all derive from Clayton Paul's classic text on this subject [5]. The additions allow calculation of the common-mode direct and common-mode FEXT transfer functions with respect to a common surrounding and grounded sheath as in Figure 1. Figure 1 shows two twisted pairs explicitly, but easily generalizes to U twisted pairs. Figure 1 shows the downstream configuration. Common mode excitation downstream would likely be achieved by driving the line-side center tap of the central-office (or line-terminal) transformer with respect to ground. The central office ground is presumed attached to the sheath also (which is the specified practice of most telco's, although such grounding is sometimes accidentally missing). Each subscriber presumably attaches also to the sheath ground of the drop cable and has the connection from the network interface to the receiving modem box (this requires some care in installation and has implication for splitters and micro-filter circuits that are not addressed here). This contribution presumes the integrity of the sheath ground connection and models, then exploits it, leaving debate on viability to future discussion. The intent then is to evaluate the data rate improvements that would occur if the effort were to be (or has been) made to ensure sheath grounding at all junctions as in Figure 1. Note the subscriber side also extracts the signal from the line-side center tap of the subscriber transformer. The upstream configuration is a dual that is easily derived by reversing the source and loads in the diagram and presuming reasonable hybrid coupling circuits to separate up and downstream transmissions in all transfer modes.

[1] Sheath grounding (we hesitate to use the word "bonding" that is used by tele plant personal to refer to "grounding" for fear of confusing the use of the word with inverse multiplexing, because the two uses are very different).

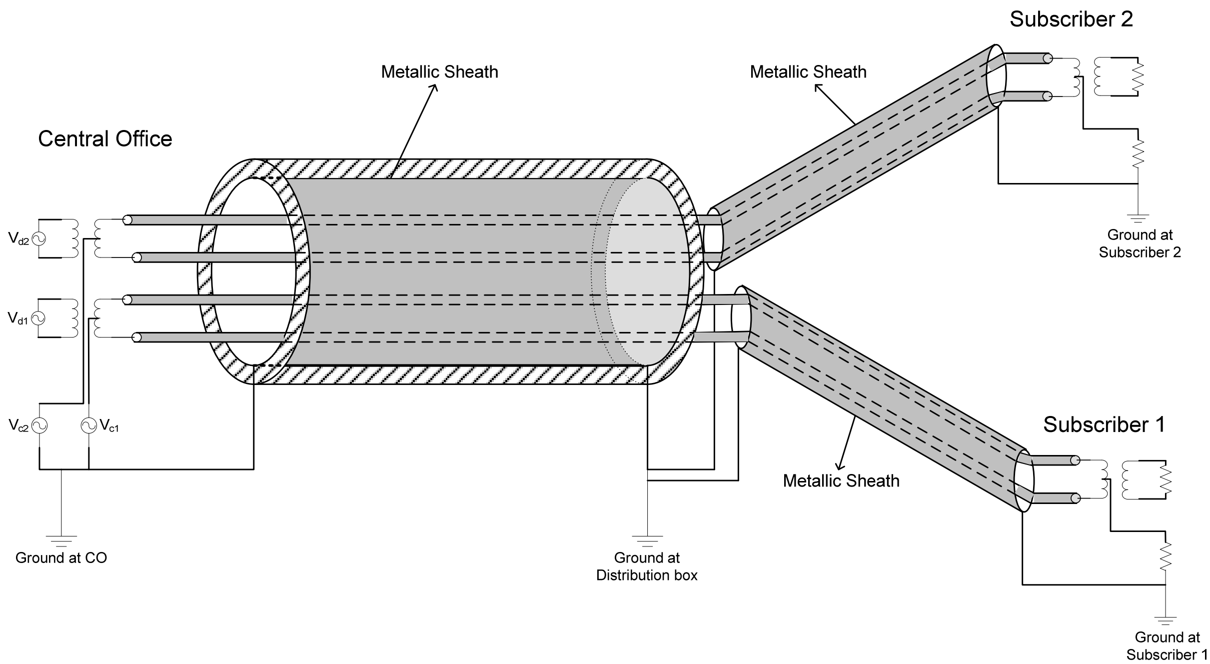

Figure 1 – Binder with grounded sheath and full common- and differential-mode excitation.

Figure 2 continues with a specific configuration of wires that is evaluated for the various transfer functions of interest. The configuration of Figure 2 labels the separation of the wires of twisted pair 1 as *D*. This separation *D* is set equal to $2\times 1.66\times$radius of a wire (it is the total diameter of a wire including the insulation). “AWG 24” wires were used. The twisted pair 0-1 in Figure 2 is assumed to be placed at the center of the sheath. The radius of the sheath is assumed to be *3D*. The second twisted pair 2-3 is assumed to be parallel to 0-1 and the vertical separation is *2D*.

The 4 matrices (**R, L, C** and **G**) of [1] and [5] that are needed to characterize the binder for vector multi-port analysis are calculated as follows (which is similar to the DSM report, Chapter 5):[2]

1. **R matrix**: The per-unit-length resistances of the 4 wires are $r_1= r_2=r_3= r_4= r_0$ and the per-unit-length resistance of the metallic sheath is denoted by r_m. Since, the conductivity value for the metallic sheath was set at $r_m = r_0/10$, because the metallic sheath is expected to be a better conductor than any individual wire (but may simultaneously carry many current flows).
   In the same way as in the DSM report, r_0 is calculated as
   $$\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \mu \cdot \sigma_{cu}}}$$
   $$\begin{cases} r_0 = \dfrac{1}{\sigma_{cu} \cdot \pi \cdot w_r^2} & w_r < 2\cdot\delta \\ r_0 = \dfrac{1}{\sigma_{cu} \cdot 2\pi \cdot w_r \cdot \delta} = \dfrac{\sqrt{\mu \cdot f}}{2 \cdot w_r \sqrt{\sigma_{cu} \cdot \pi}} & w_r \geq 2\cdot\delta \end{cases}$$
   The resulting R matrix is given by:

[2] For 2 pairs of wires, since the metallic sheath is a common ground, and the **R, L, C** and **G** matrices are therefore 4×4 matrices.

$$\mathbf{R} = \begin{bmatrix} r_m + r_1 & r_m & r_m & r_m \\ r_m & r_m + r_2 & r_m & r_m \\ r_m & r_m & r_m + r_3 & r_m \\ r_m & r_m & r_m & r_m + r_4 \end{bmatrix}$$

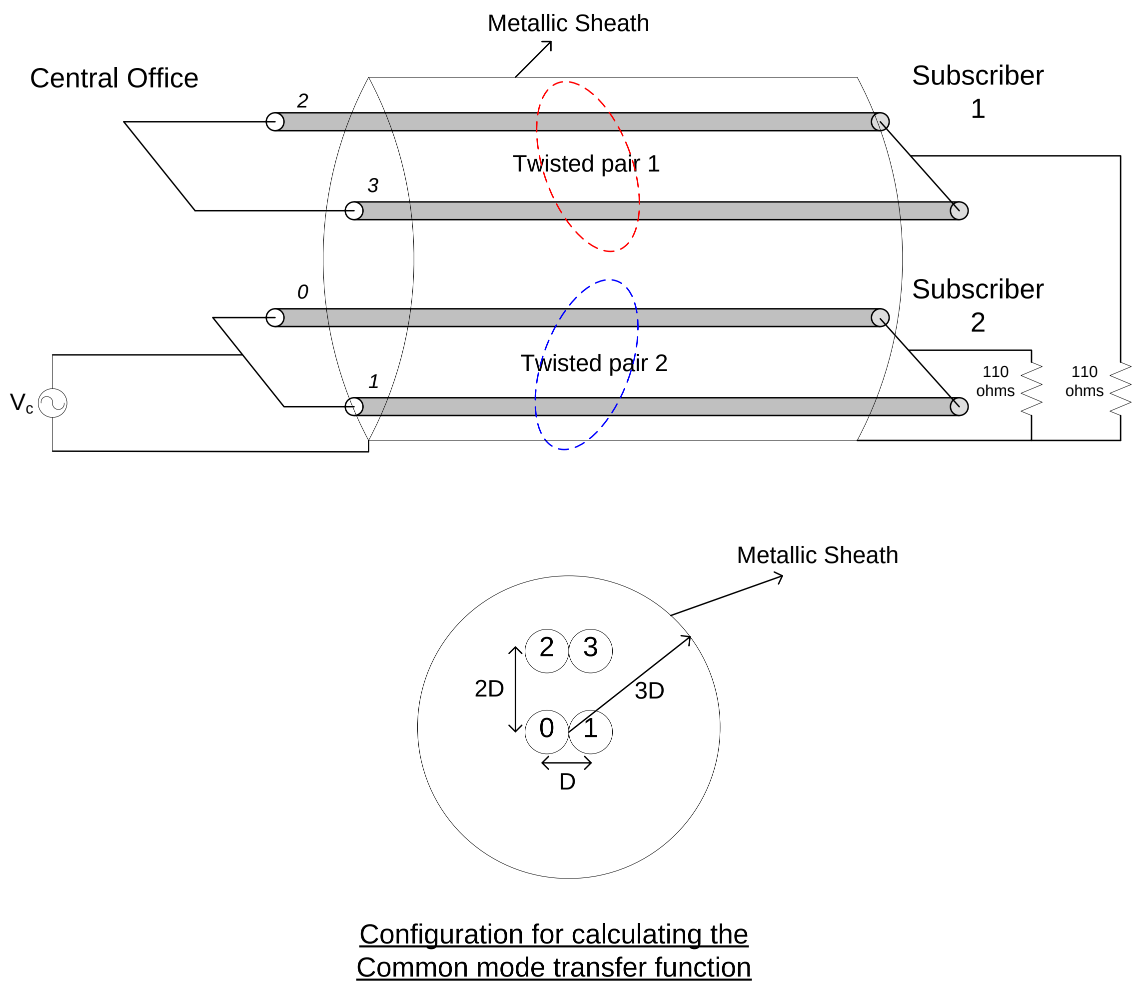

Figure 2 – configuration for calculating the common-mode transfer functions.

2. **L matrix**: In order to calculate the **L** matrix, Figure 3 illustrates the method of images that is employed and is an addition to the material in the DSM Report, but well-known and explained in [5]. The metallic sheath is replaced by image wires of the wires inside the sheath. In order to do this, the metallic sheath is assumed to be a perfectly conducting shield. The currents in these image wires will be in the opposite direction of the currents in the wires inside the sheath.

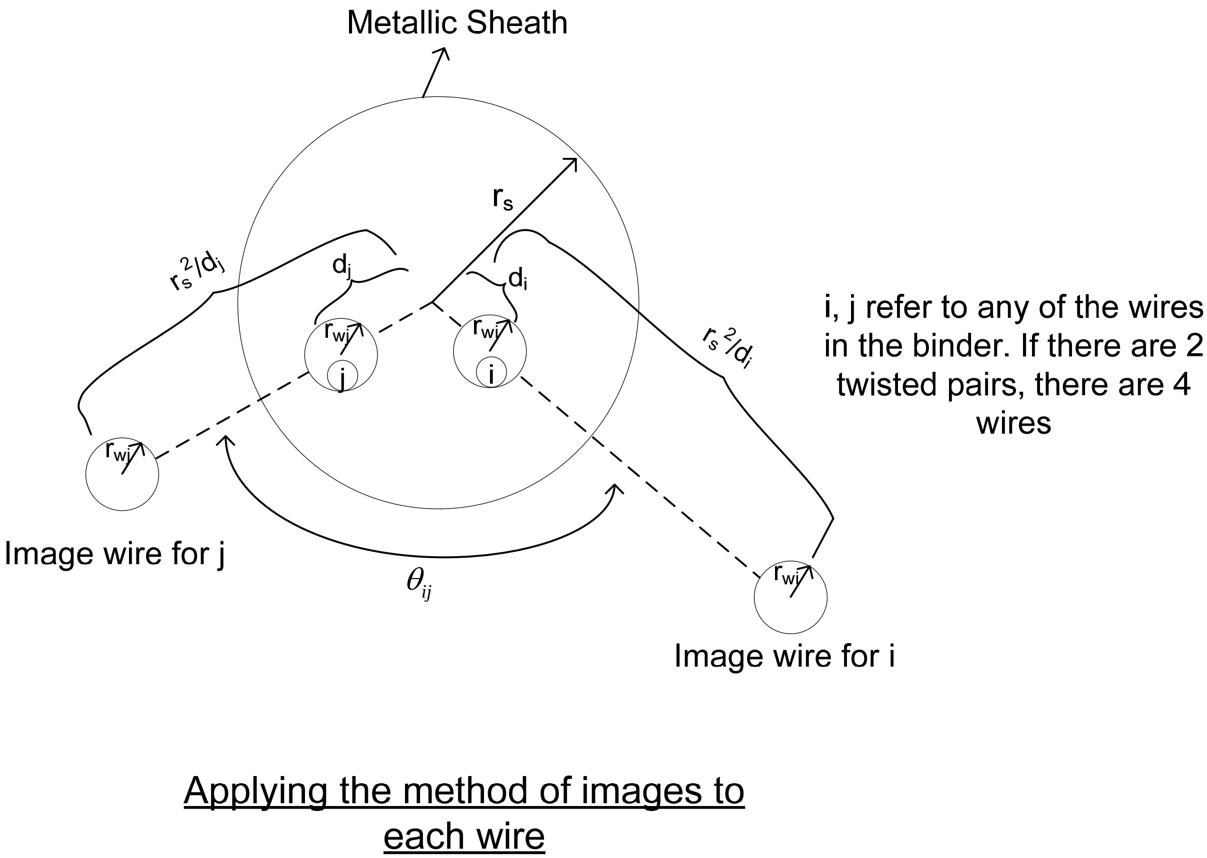

Figure 3 – Method of images use to include the metallic sheath of the binder.

r_S is the radius of the metallic sheath. r_{wi} is the radius of conductor i. d_i is the distance of the center conductor i from the center of the sheath. The image conductor for conductor i is placed outside the sheath with its center aligned with the center of conductor i and the center of the sheath. The distance of the image conductor for conductor i from the center of the sheath is given by r_S^2/d_i (by the method of images). This is repeated for all the conductors inside the sheath and then the sheath can be removed. The equivalent image circuit now has double the number of conductors of the actual circuit (but no sheath) and inductance matrix given by.

$$\mathbf{L} = \begin{bmatrix} l_{11} & l_{12} & l_{13} & l_{14} \\ l_{21} & l_{22} & l_{23} & l_{24} \\ l_{31} & l_{32} & l_{33} & l_{34} \\ l_{41} & l_{42} & l_{43} & l_{44} \end{bmatrix} .$$

Wide separation theory produces the following formulas for the inductance, and consequently the capacitance and conductance.

For i,j=1,2,3 and 4

$$l_{ii} = \left(\frac{\mu}{2\pi}\right) \cdot \ln\left(\frac{r_S^2 - d_i^2}{r_S r_{wi}}\right) \text{ and}$$

$$l_{ij} = \left(\frac{\mu}{2\pi}\right) \cdot \ln\left(\frac{d_j}{r_S}\sqrt{\frac{(d_i d_j)^2 + r_S^4 - 2d_i d_j r_S^2 \cos\theta_{ij}}{(d_i d_j)^2 + d_j^4 - 2d_i d_j^3 \cos\theta_{ij}}}\right)$$

3. **C matrix**:

$$\mathbf{C} = \mu \cdot \varepsilon \cdot \mathbf{L}^{-1}$$ (from homogeneous assumption)

4. **G matrix**:

$$\mathbf{G} = \frac{\sigma}{\varepsilon} \cdot \mathbf{C}$$ (from homogeneous assumption)

Figure 4 illustrates the transfer functions for this case. The common mode if used will have a higher transfer function that is shown over much of the band to 30 MHz. Note also it creates large noise into the common-mode shown as well as into the differential modes of the binder.

Thus, effective use of common-mode requires a vectored solution or noises will overwhelm all gains. Section 3 proceeds to use vectoring prudently to mitigate the noise effects while capturing the bandwith gains.

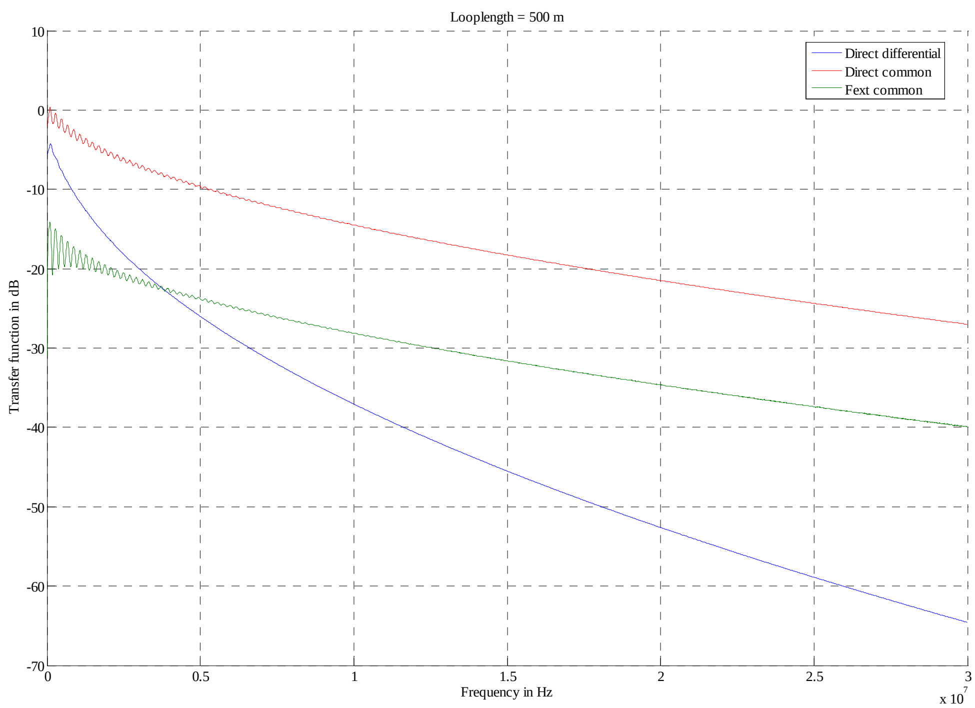

Figure 4 – Illustration of common transfers, direct and crosstalk, as well as nominal transfer.

2.1 Some suggestions for DSM-D and DSM-C interfaces

DSM-D: The DSM report current specifies in Level 3 an Xlog and Xlin capability of specifying differential FEXT measures between differentially excited lines. A $\Delta\mathrm{Xlog}(u,n)$ and corresponding $\Delta\mathrm{Xlin}(u,n)$ could be specified for each transfer from another line u with respect to common-mode excitation with respect to sheath ground (note a low value of Clog would mean that the sheath is not adequately or completely grounded). When $u=0$, the transfer would be the common-to-common transfer function.

DSM-C: The data rates, margins, power levels, and power-spectral density levels as well as coding parameters would be specified as if the line were two lines by the SMC. Thus, no change other than an indication via the DSM-D supplying non-empty values for the $\Delta\mathrm{Xlog}(u,n)$ would imply the assignment of two sets of parameters. It is presumed the SMC would otherwise internally arbitrate rate assignments and the DSM-C interface need not be aware of the assignment.

3. Data-Rate Improvements for Full Binder Level 3

Level 3 DSM or ``vectoring'' enables the highest speeds known for DSLs and can apply to single-line DSLs (where no bonding is necessary). With vectoring, a common DSLAM (more than likely a common multi-line card in the DSLAM or LT) synchronizes downstream DSL transmissions to a common DMT symbol clock (either the 4.3125 kHz clock of ADSL and VDSL or the 8.625 kHz double-width clock option of high-speed VDSLs). Digitally duplexed loop-timed circuits will then provide the same common symbol clock in the upstream direction. The term ``vector'' applies to the co-generation of a synchronized vector of simultaneously transmitted user signals in the downstream direction. These signals can go to different users in different customer locations but are launched in cooperation into the binder. In a dual fashion, a vector of upstream signals is simultaneously sampled and provided to the same common DSLAM/card. Such vectored upstream systems can essentially eliminate all hostile crosstalk and indeed can even exploit friendly reinforcing crosstalk, thus leading to very high speed DSLs. Downstream vectored systems can eliminate all FEXT or can even use FEXT for diversity reinforcement of downstream transmissions. Vectored systems are feasible with DMT because the crosstalk cancellation and processing is independent on each tone, leading to small structures on each tone (as opposed to a much larger cross-coupled time/user-matrix equalizer if the user-synchronized tones were not used).

MIMO (multiple-input-multiple-output, see[6] for more information) is not vectoring. MIMO essentially requires bonding and is used in bonded systems. Vectoring does not require bonding (but of course vectoring can be superimposed for additional gains on multiple bonded systems emanating from the same equipment to different locations). MIMO systems have been shown to improve more than ``N times" the data rates because of mutual crosstalk cancellation when both transmitter and receiver are attached to all the lines. Vectoring can get most of the MIMO gains despite that vectored systems must additionally satisfy the restriction that only one-side (either the transmitter for downstream OR the receiver for upstream) is allowed to subtract (or pre-subtract) crosstalk. Vectoring systems are detailed in [7], and further detailed in [8] and can increase complexity moderately in DSL, leading to a question of the amount of gain versus the cost increase. This contribution only looks at the data rate increase for full binder systems with respect to the differential-vectoring-only systems of a companion contribution [2].

Full binder capacity exploits common-mode crosstalk (and possibly split-pair transfers) within the cable of twisted pairs. Full vectored binder capacity investigates a binder of U DSL lines that contains $2U$ wires inside a sheath as in Section 2. An excitation model could be simply exciting each of the $2U$ wires with respect to the sheath. However, a more realistic model is that *U* common-mode excitations augment the existing *U* differentially excited circuits.

The common modes can be used to improve any individual line by essentially adding a 2nd dimension. This second dimension can sense very large noise (because there is no twisting) that depends on noise sources and the number of sheath grounding points. Such a noise typically has a smaller component in the differential received circuit as is well known in telephony, but exists. Its level of contribution is often measured by the **balance** of the receiving circuit and line. A vectored downstream receiver at the customer location can eliminate most of this noise from its own local common circuit. Furthermore the vector precoder of the transmit-side coordinated vector transmitter can pre-subtract crosstalk contributions from any and all common and differential crosstalkers within the binder. Subsection 3.1 illustrates the improvements from each subscriber using only its own common component. Subsection 3.2 instead explores the concept of using the common crosstalk from another circuit to reinforce.

3.1 Full Vectored Binder Capacity

Figure 5 is a plot of data rate for upstream (dashed curves) and downstream (solid curves) with full vectoring (blue curves) versus the same situation with differential vectoring (red curves)

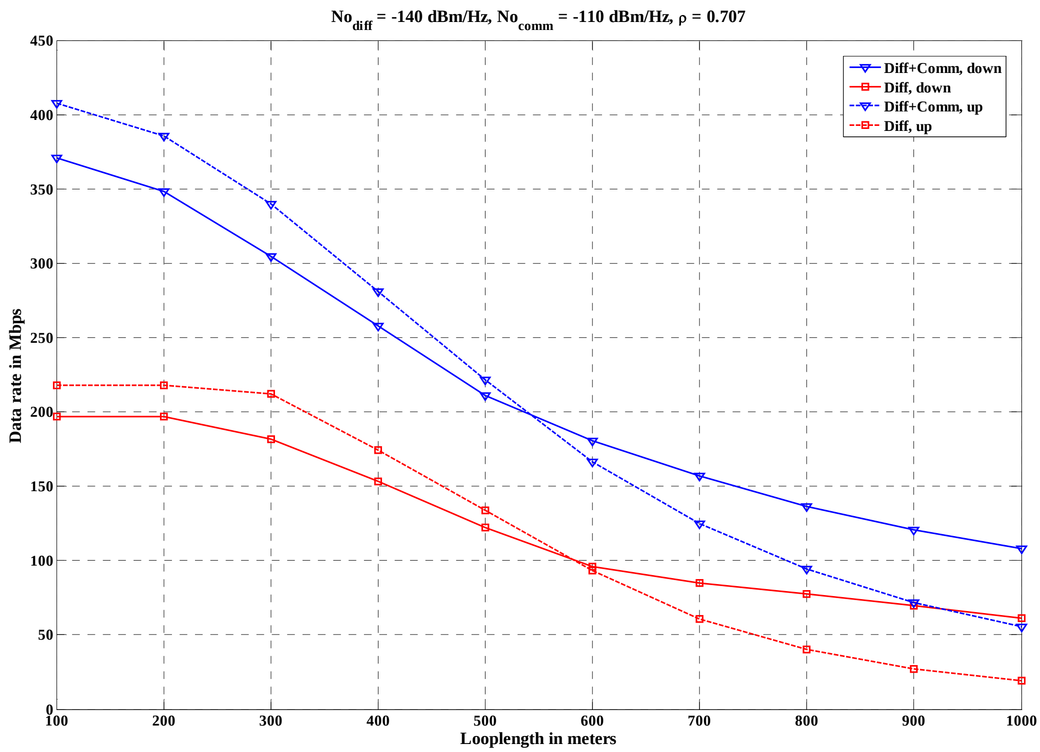

Figure 5 – illustration of the additional data rate available from full binder use.

At shorter line lengths (all lines in the binder are the same length for this simulation, even though they go to different users), upstream actually exceeds downstream data rate because the OSFA band plan [xx] used has significant upstream bandwidth allocated at high frequencies. Note the background noise in the common receivers is set 1000 times larger (at -110 dBm/Hz) than the level of differential noise; nonetheless, the vectoring still significantly increases rates in the presence of the large noise. The reason for setting the common noise so high is that receiver circuits that sense common mode signals will be far more sensitive to environmental noise. Some additional similar simulations show that for lengths greater than 500 meters that additional common noise causes a loss of about 50 Mbps for each 10 dB. The loss is smaller than 50 Mbps for shorter lengths and almost negligible for lengths under 200 meters.

A single subscriber is capable of receiving at 100m of over 700 Mbps simultaneously (almost the bit-cap of DMT over 30 MHz bandwidth on two modes). 100 Mbps symmetric service would easily be achieved at 500 meters of length (or roughly 1600 feet). In fact with some change of band plan (we used the "OFSA" band plan proposed by Infineon in [9]), 100 Mbps symmetric service is possible to 900 meters. Even more interesting perhaps is a continuous service of symmetric 250 Mbps for an FFTC system is available to 400 meters or about 1300 feet.

3.2 Binder Reinforcement

Downstream binder reinforcement allows the crosstalk path from user B's line into user A's line to be excited with user A's data. Such rate-reassignment excitement reduces the maximum achievable data rate on user B's line, but allows reinforcement of the signal power already present on user A's line. Common mode crosstalk is sufficiently large that such crosstalk use can lead to some improvement in downstream data rate of a user A that needs more bandwidth. This is a Level 3 exploitation of the more well-understood Level-1-or-2-DSM concept of user B being polite. Indeed user B is donating while cooperating. Cooperation in Level-3 differentially vectoring leads to each user transmitting as if there were no crosstalk. Donation with full vectoring goes even further, essentially increasing effective received power levels so that the SNR is higher with respect to a situation with no crosstalk.

Upstream binder reinforcement collects the energy from different lines' common and differential signals received. That energy collection from other lines is always present in vectoring, but can be more efficient when the other lines data rates are zeroed or reduced. Specifically, rate reassignment methods can exploit spatially correlated noise[3] entering the LT. Especially in the presence of such correlation, it may be easier for the upstream fully vectored receiver to collect and use aligned energy from other lines' receivers, particularly common mode, if other users are silenced when they don't need to transmit energy. Again, this is a Level 3 donation of bandwidth that exceeds simple politeness at Level 2 or Level 1.

For non-bonded systems, it appears reinforcement has limited gain downstream but has a potential for significant increase of upstream data rates as the plots that follow illustrate. Both downstream and upstream data rates are illustrated for a single user of the length shown. Figure 6 illustrates both upstream and downstream data rates for 3 different common-mode background noise levels of -110, -120, and -130 dBm/Hz (other electronics noise is at -140 dBm/Hz). There are two types of correlation listed. The coefficient ρ (.0995 for weak correlation in Figure 6) reflects that there is a small correlation between the differential component and the common component of any particular line. This correlation is essentially a measure of longitudinal balance for the line (and that balance is good when the correlation is low). A second correlation coefficient of 0.9 reflects the reasonable assumption that the common components between the lines are strongly correlated (that is the same source of common noise dominates the vectored set of lines at any frequency). Strong correlation would be expected since the upstream lines terminate in the same vicinity and equipment. This correlation is not a function of the balance of the lines.

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[3] In this case, spatial correlation refers to the noise collected on different lines, differential received or common-mode received but particularly common-mode-received, is correlated with the same type of noise on a first line. Such correlation is expected and often high between common-mode signals because the noise source is usually the same or focused to appear the same by the effect of a grounded sheath.

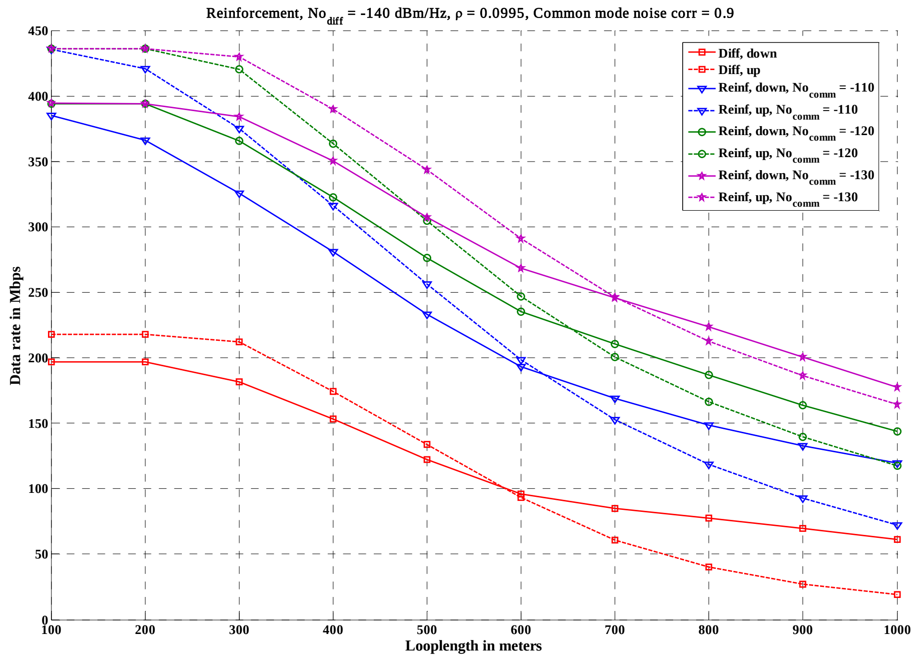

Figure 6 – illustration of reinforcement for a second line into a first line (ρ=.09).

Figure 7 repeats Figure 6 for a different value of $\rho = .707$.

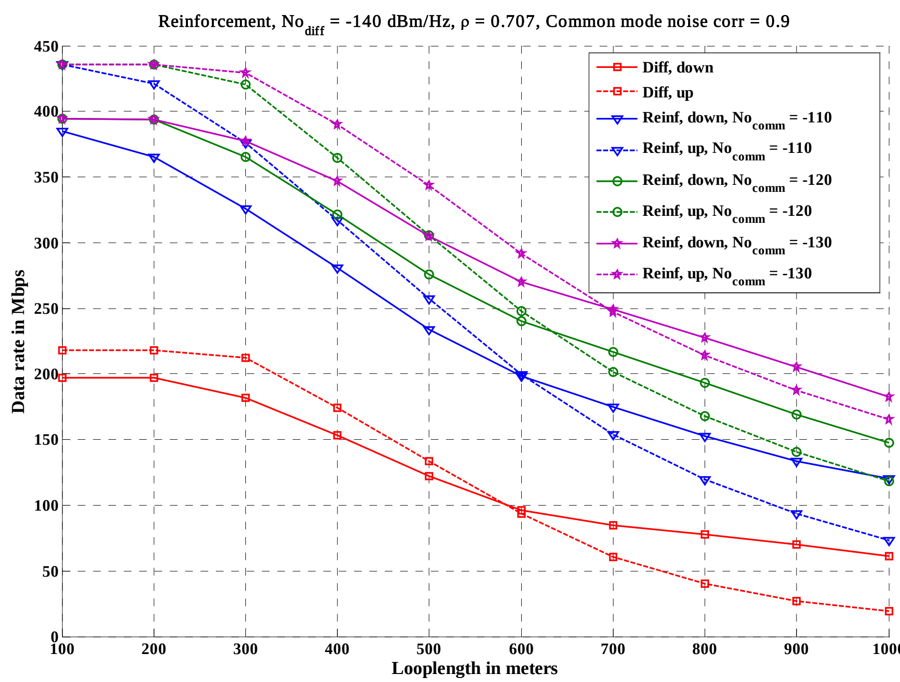

Figure 7 – illustration of reinforcement for a second line into a first line (ρ=.707)

Figure 8 illustrates the data rate for an upstream line as the correlation coefficient changes for the common-to-common correlation. The dependency on such correlation suggests that the fully vectored receiver used is not “simply dependent upon only the line-variance of the non-crosstalk-noise” as is well-known the case for differential vectoring in [1]. The plot strongly suggests that dynamic rate reassignment between upstream users is thus possible even at Level 3 (where it may have been previously not appreciated to be a trade-off).

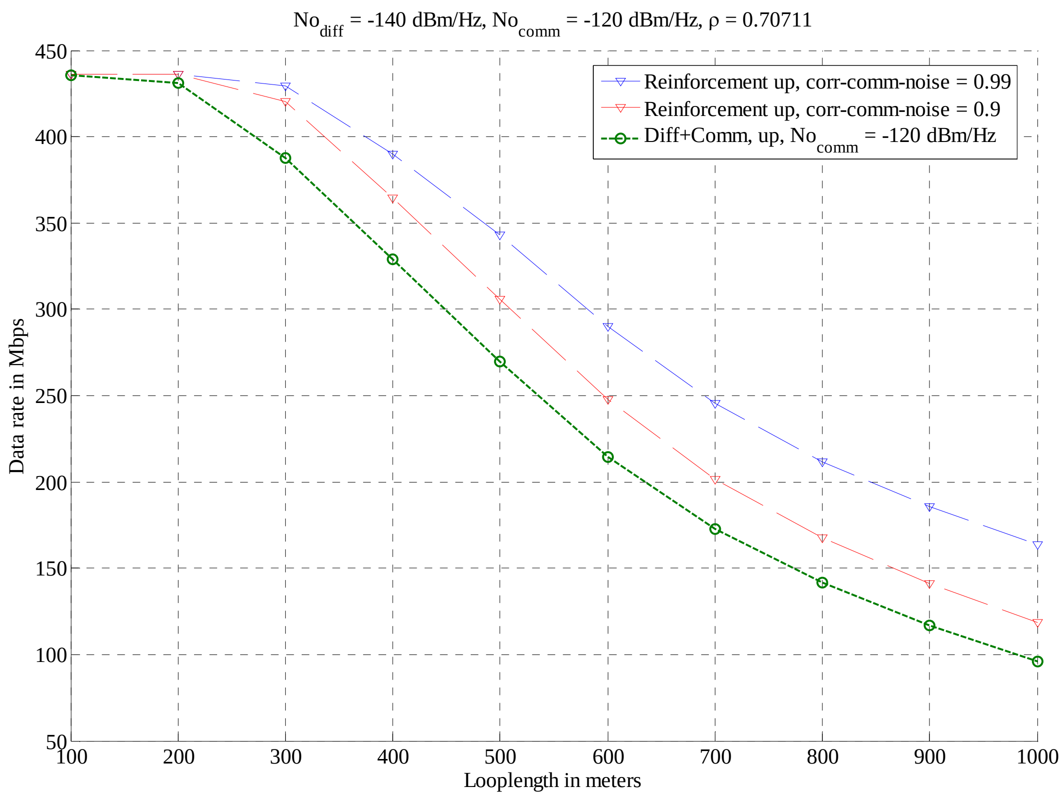

Figure 8 – Illustration of rate gains (up to 75 Mbps additional data rate) available from full exploitation of common-mode noise correlation (here with base level at -120 dBm/Hz).

4. Conclusions

Full binder capacity with the use of Level 3 DSM is much higher than what has heretofore been envisioned for VDSL service. There are many practical issues to be considered including the complexity of sheath integrity maintenance and the vectoring components and Spectrum Maintenance Center (SMC) required in DSM for implementation. Nonetheless, the promise of Gigabit DSLs (perhaps two lines) at several hundred meters leads to a binder of say 200 twisted pair from an LT having 100 Gbps of total bandwidth that can be shared among users. Passive Optical Networks presently at best over 1-2.4 Gbps to be shared over approximately the same number of users. Thus, good vectored DSM use in VDSL may open opportunities for architectural advantages and service advantages without the very difficult placement of fiber to each customer for many decades to come (and maybe longer)!

5. References

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