Assessment of the theoretical limits of copper in the last mile

Final report

SAGENTIA

This document is prepared for Ofcom

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Ref OF013

Executive Summary

This is the final report from our assessment of the theoretical limits of capacity of the approximately 26 million copper pairs which form the 'last mile' of the UK's telephone network. The objective of our work was to look beyond the limitations of current equipment to the fundamental theoretical limits of BT's copper twisted pair network according to communications theory.

Ofcom commissioned this study as part of its technical research programme and makes the following caveats:

- The project was commissioned in order to try to establish a theoretical, rather than practical, limit;
- The degree of which practical implementation can get close to the theoretical limit is not investigated within the project;
- At the time of writing, Ofcom is not aware of any practical implementations of the technology approaches implied in this report that would lead to substantial increases in speed being achieved on BT's copper network;
- Neither is there any indication that the changes in standards implied in this study are being considered by the relevant bodies;
- Ofcom is publishing the report to gain views from interested parties on the possibility that future technologies could exploit, in practice, the theoretical potential described in this report.

BT's copper network has a dendritic structure and typically consists of an exchange building connected by large multi-pair cables to a number of primary cross-connect points (PCPs) or street cabinets (SC). This is called the E-side (exchange).

From these street cabinets smaller multi-pair cables progress to the customer premises equipment (CPE). This is called the D-side (distribution).

Three cases are addressed in this report. The first is a 'pure' case in which all modems are in local exchanges. The second is a pure case in which all modems are in street cabinets. The third case is a combination of the two pure cases, which equates to a broadband service being deployed both from the exchange and a street cabinet at the same time. There are a number of different variants of this final case according to the different migration strategies employed.

Our approach to modelling the maximum capacity is based on the following principles:

1. All lines are driven with a maximum power set by feasible device technology (assumed to be 25dBm)
2. All bandwidth is used up to the frequency at which no further information can be carried for a given total power
3. All crosstalk that is theoretically capable of mitigation through vectoring is 100% mitigated in this way
4. Where crosstalk mitigation is not possible, frequency division multiplexing (FDM) and frequency domain duplexing (FDD) are used to avoid the problems of crosstalk.

Data on the distribution of line lengths was obtained from public domain sources.

The model was implemented in Mathcad.

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For case 3 we looked at five possible scenarios for the gradual rollout of street cabinet modems.

The table below summarises the headline results of our modelling of the theoretical maximum capacities with case 3 being for 25% street cabinet deployment in all cases.

	Percentage of households achieving above 50Mbits/s	**Percentage of households achieving above 100Mbits/s**	**Median data rate Mbits/s**
Case 1: Modems in exchanges	17.7%	6.1%	22
Case 2: Modems in street cabinets	99.1.%	95.5%	492
Case 3: Best is first @25%	24.7%	24.1%	24
Case 3: Worst is first @25%	41.5%	29.0%	42
Case 3: Binder switchover@25%	38.4%	28.8%	35
Case 3: FDM @25%	37.4%	27.3%	34
Case 3: Frequency overlap @25%	36.6%	26.5%	34

Currently achieved capacities are vastly lower than the theoretical maxima we have determined in our modelling. The variants on the mixed deployment (Case 3) scenarios suggest that useful improvements in capacity relative to the base case of having all modems in exchanges could be achieved by moving a relatively small proportion (~25%) to street cabinets.

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1 Introduction

This report presents the progress to date of our assessment of the theoretical limits of capacity of the copper cable ‘last mile’ of the UK’s telephone network.

Our terms of reference were to “Establish the theoretical limit of broadband capacity in the UK using the installed base of copper local loop into subscriber premises”. Ofcom commissioned this study as part of its technical research programme and makes the following caveats:

- The project was commissioned in order to try to establish a theoretical, rather than practical, limit;
- The degree of which practical implementation can get close to the theoretical limit is not investigated within the project;
- At the time of writing, Ofcom is not aware of any practical implementations of the technology approaches implied in this report that would lead to substantial increases in speed being achieved on BT’s copper network;
- Neither is there any indication that the changes in standards implied in this study are being considered by the relevant bodies;
- Ofcom is publishing the report to gain views from interested parties on the possibility that future technologies could exploit, in practice, the theoretical potential described in this report.

Mindful of these important caveats, we were asked to produce *theoretical* results for three cases:

- Case 1: Network providers’ modems deployed in exchange buildings only, as is the case today in the UK.
- Case 2: Network providers’ modems deployed in street cabinets only, with no modems deployed in the exchange buildings.
- Case 3: Network providers’ modems deployed in both street cabinets and exchange buildings.

The majority of local loops are owned by BT. Though involved at the start of the project, data on BT’s infrastructure has been obtained from public domain sources rather than BT itself.

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2 Network topology and line lengths

2.1 Overview of BT's access network

BT's copper twisted pair network has a dendritic structure and typically consists of an exchange building connected by large multi-pair cables to a number of primary cross-connect points (PCPs) or street cabinets. This is called the E-side (exchange). From these street cabinets smaller multi-pair cables progress to the customer premises equipment (CPE) over the D-side (distribution).

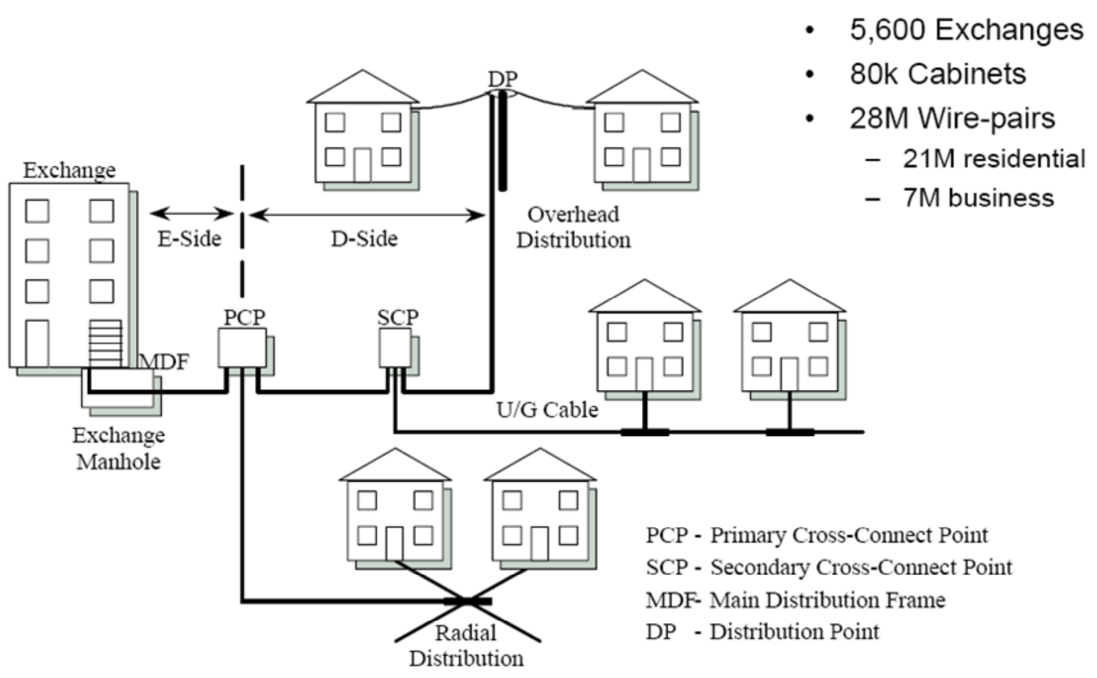

Figure 1 BT's Access network

Figure 1 illustrates BT's Access Network topology[1] and shows that there are 5,600 exchanges and 80,000 street cabinets with 28M pairs serving 21M residences and 7M businesses (2000/1 figures). So on average, there were 14 street cabinets per exchange with each E-side cable carrying approximately 350 pairs. Though the figures will have changed from 2000/1, the ratios and broad architecture will have remained similar. It is important to note that the cables from the exchange to a particular street cabinet are all the same length. So signal emanating from the exchange will be attenuated by the same amount at the street cabinet.

From the street cabinet a number of cables radiate out into the distribution side of the network. These multi-pair cables are therefore isolated from one another.

[1] Kevin Foster "VDSL deployment options & standards"; VDSL and Radio Spectrum Workshop, DTI conference centre, London. 16 January 2001. Reproduced with permission from BT. The numbers of cabinets etc will have changed since the date of the diagram.

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2.2 Data on line lengths

The main data required for this study was the statistical distribution of line lengths and types for the millions of copper loops in the UK. We have obtained this data from public domain sources.

A paper for NICC DSLTG by John Cook[2] presents the cumulative distributions for BT's network of line length for exchange to customer and cabinet to customer in the form of attenuations. The city of Hull is not included as these lines are owned by Kingston Communications

This paper also conveniently gave the BT cable and FEXT models. It has been the basic data used in the present assessment.

2.2.1 Exchange loop data

The data obtained from the NICC DSLTG paper was presented as a cumulative distribution of attenuation at 300kHz from the exchange to the customer. Using their own model (also given in the paper) for a typical cable used in the network (0.5mm DWUG), the attenuation values have been converted into equivalent lengths. This is presented in Figure 2 which shows that all the lines have an equivalent length of less than about 6.5km. Since the DC resistance of this cable is 179Ω per km, the maximum DC loop impedance is about 1.2kΩ. This is consistent with BT's SIN351[3] which gives a maximum DC loop impedance of 1kΩ.

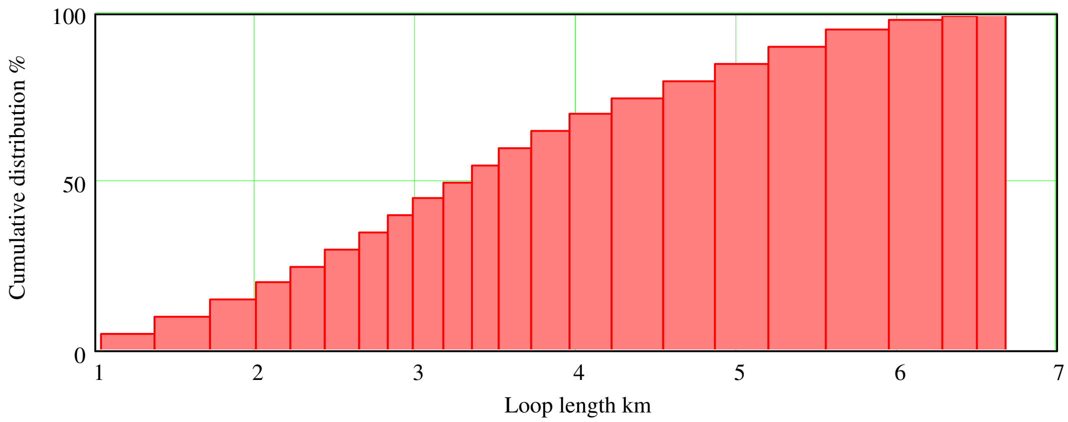

Figure 2 Cumulative line length data (E+D side) from the exchange

Figure 3 presents the data of loop lengths as a simple distribution converted to 0.4km increments. This was calculated from the cumulative distribution by taking its derivative. It has a broad peak around 3km.

[2] PNO-DSTG/CP38(04)2 Simulation parameters for discussion in the NICC-DSLTG
[3] SIN 351 Issue 3.0 section 3.3

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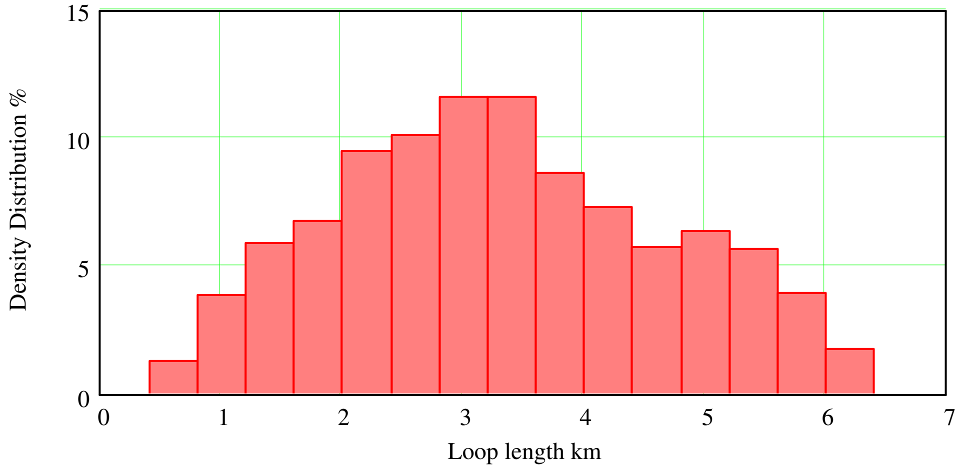

Figure 3 Distribution of exchange (E+D side) loop lengths

2.2.2 Street cabinet loop data

As with the exchange data, the NICC DSLTG paper presented the data as a cumulative distribution of attenuation at 300kHz from the street cabinet to the customer. BT's own model for a typical cable was used to convert the attenuation values into equivalent lengths. This presented is in Figure 4 which shows that all the lines are less than about 3.5km long. Converting the data to an ordinary distribution reveals that there is a strong peak at 0.375km with 25% of the lines.

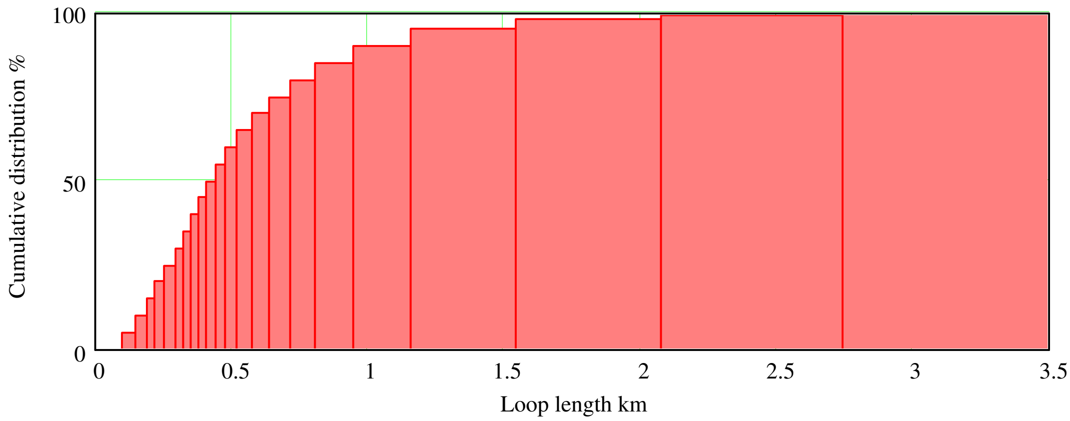

Figure 4 Cumulative distribution of loop lengths (D side) from the street cabinet

Figure 5 shows the distribution for street cabinet lines converted to 0.2km increments. It has a pronounced peak at about 350m with a very long tail of long loops.

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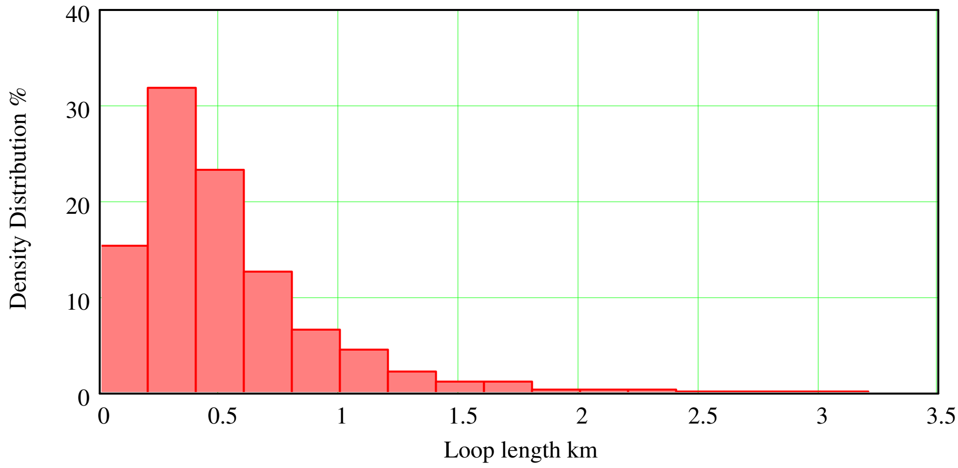

Figure 5 Distribution of street cabinet (D side) loop lengths

2.3 Combining the distributions

The data in Figure 3 and Figure 5 are sufficient to calculate the two ‘pure’ cases, 1 and 2. But in calculating case 3 (mixed deployment) it is necessary to posit the relationship between the two distributions. This is because we need to be able to remove some proportion of exchange lines (E+D) and replace them with a known distribution of street cabinet lines (D).

To do this we would ideally know, for each exchange line, the length of the E side and the length of the D side. Unfortunately, we do not have this data. So we have estimated the data by making two assumptions:

- that the two sets of data are approximately independent of each other
- that D+E is always greater than D (It is clearly impossible to have a street cabinet loop length greater than that for the exchange. An street cabinet length of 1.5km cannot have an exchange length of 1km).

With these two assumptions we have constructed a two dimensional probability density function of D+E side loop lengths against D-side loop lengths. This was calculated by multiplying together the two probability density functions, making the probability of having a D-side greater than an exchange loop length zero, and renormalising. The result is shown in Figure 6.

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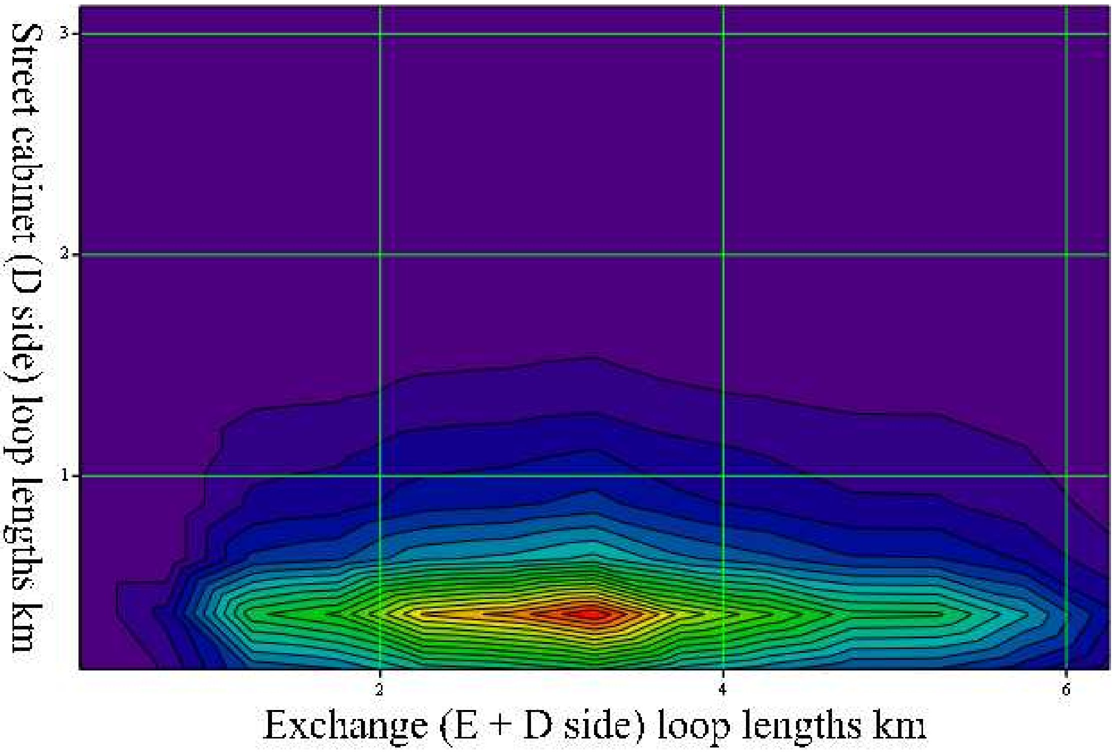

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Figure 6 2D probability distribution of cooper loop lengths

Each contour line corresponds to a change of 0.28%. There is a strong peak around about 3km and 400m with a large plateau above about 1.5km for street cabinet lengths.

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3 Modelling approach

3.1 Discussion of the concept of theoretical maximum capacity

The capacity of an ADSL network is relatively straight forward. It is in essence the application of Shannon's theory. Shannon's formula

$$C = B\log_2(1+SNR)$$

gives the theoretical upper bound for an Additive White Gaussian Noise (AWGN) channel where B is the bandwidth and SNR is the signal to noise ratio.

In practice the capacity is set by three factors:

1 The physical and electrical topology of the network and the noise environment in which it operates;
2 The transmission techniques and equipment used at the exchange (DSLAM) and the customer premises (CP).
3 The access network Frequency Plan (ANFP[4]) which specifies the power spectral density (PSD) upstream and downstream in different circumstances.

In looking at maximum capacity, the first of these factors is considered a 'given' and cannot be changed. The other two factors are open to change and improvement.

The second factor comprises the transmission techniques (such as modulation) and equipment. To calculate the maximum capacity we have had to take a view on the limits to improvement in techniques and in equipment. Pointers to these improvements are given by the research being undertaken in universities and the developments being announced by vendors. They principally concern the use of techniques to cancel crosstalk, one of the main components of noise in Shannon's formula.

The third factor is also open to change. The ANFP is a standard which allows different operators, services and types of equipment to coexist: "to manage the crosstalk interference, particularly between xDSL systems operating over the public access network in the multi-operator environment resulting from local loop unbundling"[5]. It does this by partitioning spectrum between different uses and by limiting the power spectral density (PSD) at each frequency. The ANFP limits PSD in order to limit crosstalk between different lines within the access network, and, in the case of overhead cables, to limit radiated interference from the access network to users of the radio spectrum.

The ANFP currently reserves the very lowest frequencies for voice. Above this, the ANFP specifies a different PSD mask for upstream and downstream use. 25kHz to 138kHz at -36.5 dBm/Hz is allocated to upstream whereas 142kHz to 1.1MHz at -36.5 dBm/Hz is allocated to upstream. No spectrum above 1.1 MHz is used[6].

We have found in our modelling that the useful bandwidth is typically much greater than 1.1MHz.

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[4] http://www.nicc.org.uk/nicc-public/Public/interconnectstandards/dsltg_spec/nd1602_2005_08.pdf
[5] Guidelines on the use of DSL Transmission Systems in the BT Access Network; NICC DSL Task Group
[6] ADSL2+ allows frequencies to 2.2MHz

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3.2 Our approach to defining 'maximum capacity'

The concept of 'maximum capacity' is not unambiguous. Our approach is based on the following principles:

1. All lines are driven with a maximum power set by feasible device technology
2. All bandwidth is used up to the frequency at which no further information can be carried for a given total power
3. All crosstalk that is theoretically capable of mitigation through vectoring is 100% mitigated in this way
4. Where crosstalk mitigation is not possible, frequency division multiplexing (FDM) and frequency domain duplexing (FDD) are used to avoid the problems of crosstalk.

These principles are discussed below.

3.2.1 Principle 1: Power

In principle, increasing power will increase capacity because it raises the signal to noise ratio. However, there are two undesirable consequences:

- Firstly, internal interference, in which increased power increases the level of interference into other pairs in the binder.
- Second, external interference. Increased power will cause interference to other users of the radio spectrum.

For the purposes of this study we assume that all internal interference is mitigated in accordance with principles 3 and 4. We have not explicitly allowed for limiting interference to other users of radio spectrum however specific frequencies could be notched out with little overall impact on capacity.

We have set a limit on total power. There are practical limitations on the analogue front end (AFE) from the line driver and hybrid circuit[7]. In discussions with a DSL chip vendor[8], a sensible upper limit to the transmit power in each direction is 316mW or 25dBm. By contrast, the ANFP corresponds to about 100mW or 20dBm.

3.2.2 Principle 2: Bandwidth

Whereas the ANFP uses a fixed bandwidth regardless of the length of a line, we have allowed the bandwidth to be optimised for the length of a line.

We have assumed a flat PSD mask across a total bandwidth that reduces as the length of a line increases. The principle is illustrated in Figure 7.

[7] The limitations arise from the power rail available in a DSLAM and the peak power required from the driver.
[8] Analog Devices using their AD8016 xDSL Line Driver.

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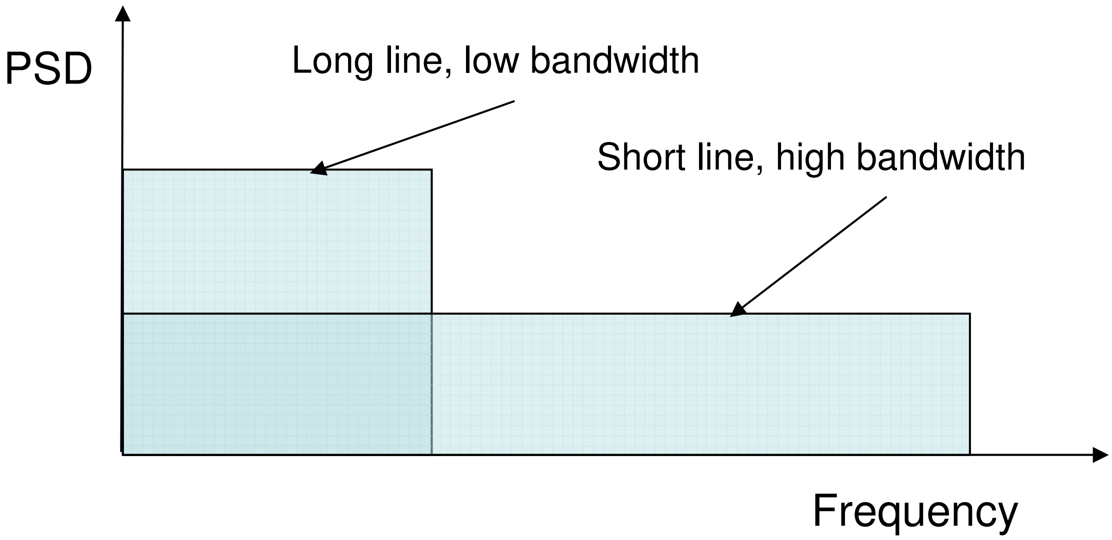

Figure 7 Principle of how PSD mask varies with line length

There are two aspects of this mask that warrant discussion: firstly its shape, secondly the maximum frequency.

On the question of shape we have been able to show mathematically that the optimum PSD mask is not quite flat but tails off towards the highest frequencies (see appendix A). However using a flat mask makes very little difference and is far easier to model.

On the question of maximum bandwidth it can be seen intuitively that, within the constraint of a maximum power, there comes a point at which, as the bandwidth is increased, the increase in bandwidth is compensated for by the reduction in power in each portion of spectrum. The results from our modelling are illustrated in Figure 8.

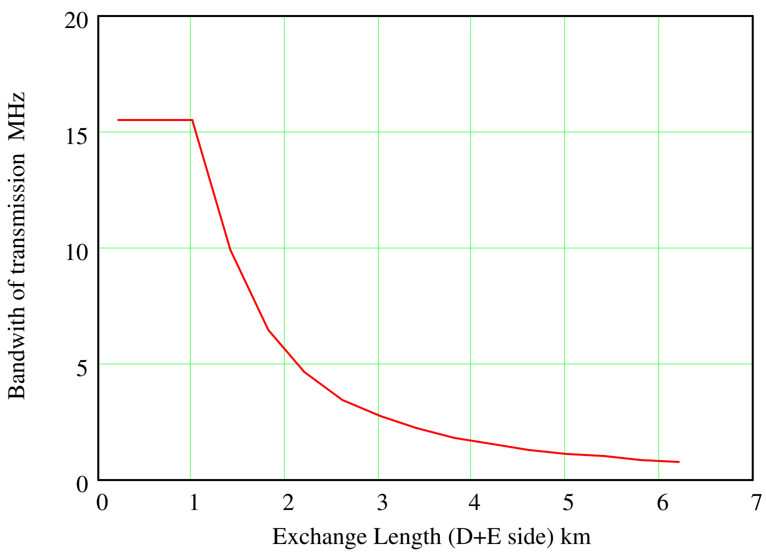

Figure 8 Modelling results showing how PSD mask bandwidth varies with line length

This shows the example for transmission from the exchange and also illustrates the maximum bandwidth allowed (~15.5MHz)

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In the ANFP the split between upstream and downstream traffic is specified such that different portions of the PSD mask are used for the two directions – a form of frequency division duplexing (FDD). In our model we have not specified the split between upstream and downstream traffic, only that the split be managed in practice through FDD. In principle, each subcarrier can be either allocated to upstream or downstream traffic so that the relative capacities upstream and downstream can be set according to requirements.

3.2.3 Principle 3: Crosstalk 100% mitigated through vectoring where theoretically possible

Crosstalk can be present at high levels. Appendix B: explains the different types of crosstalk. The table below shows the currently used measures to mitigate crosstalk.

Table 1: Current measures to mitigate crosstalk

Factor	Current limitation
Upstream NEXT	This form of crosstalk is avoided by partitioning the frequency band (FDD) so that upstream and downstream do not overlap. Capacity is reduced as a result
Downstream NEXT	This form of crosstalk is avoided by partitioning the frequency band so that upstream and downstream do not overlap. Capacity is reduced as a result
Upstream FEXT	Not mitigated
Downstream FEXT	Not mitigated

Because of its impact on capacity, crosstalk reduction is a major area of research. One promising technique is to inject an antiphase signal to compensate for crosstalk; this is known as vectoring. Vectoring is one of a set of technologies which are collectively known as dynamic spectrum management (DSM). The technique is only possible when modems are co-located because it is necessary to calculate the antiphase signal with minimal time delay.

While vectoring is currently a topic of research, there is no theoretical reason why perfect vectoring should not be possible. The limitations as they exist at the moment are concerned with practical techniques and computing power.

Accordingly we have assumed the theoretical measures to mitigate crosstalk are as shown in the table below.

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Table 2: Potential measures to mitigate crosstalk

Factor	Possibility for change
Upstream NEXT	Upstream NEXT cannot be removed because modems at a subscriber's premises cannot know what modems at other subscribers' premises are transmitting.
Downstream NEXT	It would be theoretically possible to cancel upstream NEXT at the DLAM transmitter by vectoring: informing each DSLAM modem what each other DSLAM modem is transmitting, and pre-compensating.
Upstream FEXT	It is theoretically possible to cancel upstream FEXT at the DSLAM receiver by vectoring. This is because the DSLAMs could potentially communicate and the signal be cancelled at the receiver end.
Downstream FEXT	It is theoretically possible to cancel downstream FEXT at the DSLAM transmitter by vectoring.

It can be seen that all crosstalk apart from upstream NEXT can theoretically be cancelled using vectoring. Our concept of maximum theoretical capacity assumes that FEXT is perfectly mitigated using vectoring and uses FDD to avoid NEXT (see Principle 4).

3.2.4 Principle 4: FDM and FDD used where vectoring is not possible

Where vectoring to mitigate crosstalk is not possible, frequency division multiplexing (FDM) and frequency domain duplexing (FDD) are used to avoid crosstalk.

Firstly in respect of duplexing, existing equipment achieves duplexed transmission using frequency domain duplexing (FDD) as agreed in the ANFP. In the future, an alternative approach using echo cancellation may be possible; this would double the capacity. However the practical realisation is dependant on the achievable performance of electronic circuits and is currently not viable. It has proved in practice to be very difficult to cancel out the signal sufficiently and, although the standards accommodate echo-cancelling for the lower part of the spectrum, such systems have not been deployed[9]. It may be viable in 5 years to a certain extent and should steadily improve after that. However, in this model we have adopted the conservative assumption that duplexing is achieved solely through FDD.

In the mixed deployment scenarios there is a need to avoid crosstalk between E side and D side traffic. Because the modems are not co-located (some are at the exchange whereas others are at the street cabinet), vectoring is not even a theoretical possibility. In this case we assume the use of frequency division multiplexing (FDM).

3.3 Other assumptions

3.3.1 Modulation and coding

To transmit digital data over an analogue channel such as a copper loop it is necessary to convert it by some modulation or coding scheme. The capacity given by Shannon's equation is only achievable using infinite complexity[10] in the coding scheme. Practical coding methods are characterised by a defined error rate. Quadrature Amplitude Modulation (QAM) is a commonly used scheme with good spectral efficiency. This is

[9] Private communication with Prof John Cioffi where he stated that FDD is here to stay
[10] Understanding DSL Technology; T. Starr et al

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the modulation scheme used in OFDM transmission systems. Such schemes are modelled by applying a Shannon Gap to the SNR to ensure a given bit error rate (BER). In the case of QAM with BER of 10^{-7} the gap is 9.75dB.

This can be lessened by using clever coding methods. For instance for trellis codes there is a gain of about 5dB. This is the value used for ADSL (3dB for VDSL). However there are codes that can increase the gain[11] to 6.5dB. We have used 6.5 dB for the coding gain.

3.4 Implementation

The approach to modelling was developed for the two pure cases and then extended to cover mixed deployment.

3.4.1 Shannon capacity

Conventional simulation of the capacity of an ADSL network is relatively straight forward. It is in essence the application of Shannon's theory. Shannon's formula

$$C = B\log_2(1+SNR)$$

gives the theoretical upper bound for an Additive White Gaussian Noise (AWGN) channel where B is the bandwidth and SNR is the signal to noise ratio.

The basic formula assumes a frequency independent SNR. However for transmission over telephone cable both the signal *S(f)* and noise *N(f)* are frequency dependent. The frequency dependent version of Shannon's formula is.

$$C = \int_0^B \log_2\left(1+\frac{S(f)}{N(f)}\right)df$$

In practice, there is no integrable function for the SNR in most real situations so a numerical integration is conducted. This requires partitioning the frequency space into discrete steps or bins. The discrete frequency version of Shannon's formula is

$$C = f_s \sum_{bins} \log_2(1+SNR(bin))$$

where f_s is the symbol rate and the summation is over the frequency bins used.

The use of discrete frequency bins is the technique used in Orthogonal Frequency Division Modulation (OFDM) schemes such as the Digital MultiTone (DMT) method used in DSL. So that the assessment results can be compared with those of current deployment, our simulations use the same frequency bin size of DMT, namely 4.3125kHz.

3.4.2 Methodology

Calculations were performed in Mathcad. The following is a summary of the methodology adopted for the current investigation.

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[11] Private communication with Prof John Cioffi

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- The BT cable model for DWUG (0.5mm) is used to calculate the insertion loss of a cable as a function of length and frequency.
- An appropriate total power transmitted onto the line is chosen based on what might be technologically possible. A nominal 25dBm has been chosen to be the total power.
- The frequency bin separation is 4.3125 kHz.
- Power is assigned to every useful frequency bin
- An additional maximum of 16MHz for the exchange and 32MHz for the street cabinet is imposed to allow for slew rate limits
- For all the loop lengths being simulated, the attenuation at each of the frequency bins is calculated
- The receive power is calculated for each bin.
- The noise contribution is calculated at the receiver for each bin. AWGN at -140dBm/Hz is unavoidable. NEXT is ignored since a non-overlapping frequency plan is assumed. Self FEXT is also ignored since vectoring is assumed. However alien FEXT between exchange and street cabinet traffic has to be considered.
- The SNR for each bin is calculated and a coding gain, noise margin and Shannon gap for BER 10^{-7} is included
- The number of bits that can be allocated to each bin is calculated and the integer value taken.

The total capacity is calculated by summing the bits allocated to each frequency bin and multiplying by the symbol rate of 4kHz to get bits/sec.

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4 Case 1: Exchange modems

4.1 ADSL results

We started off by creating a base case simulation of ADSL.

The standard applied to this simulation is ADSL (G.992.1) using a nominal -40dBm/Hz and 256 carriers up to 1.104MHz. It is assumed that all the lines carry the same ADSL so that the FEXT model will use 49[12] as the number of disturbers. It is also assumed that each cable will have this number of interfering adjacent pairs along its whole length. This is a worst case. Normally a given loop will not be adjacent to the same loops along its length since this will change with the many joints along its length. A possibly more realistic scenario would be to reduce the number of adjacent pairs for the longer loops.

Figure 9 presents the cumulative distribution of the capacity achievable from the exchange for the UK population. This shows that if every one was using ADSL then 50% should get a bandwidth of 6.5Mbits/s or more.

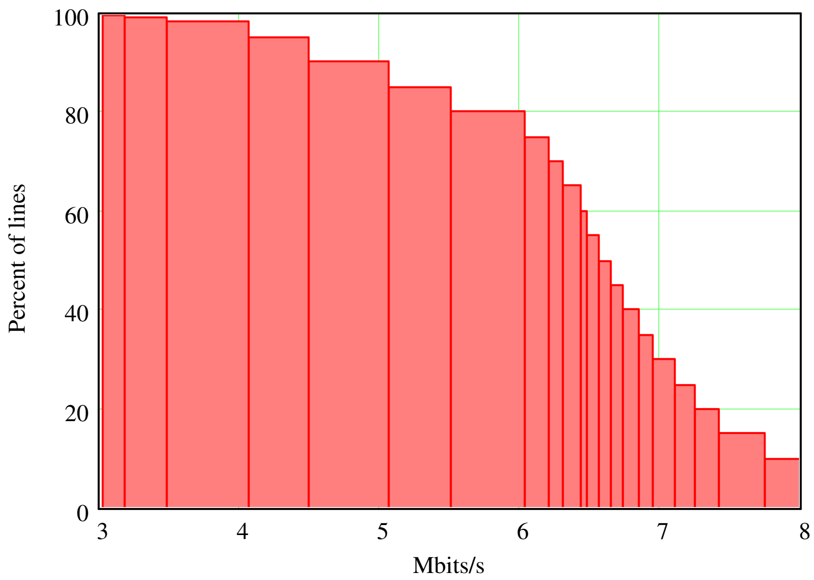

Figure 9 Cumulative distribution of ADSL capacity from the exchange

4.2 Theoretical results

To assess the theoretical capacity of BT's copper loop network according to our model the frequency was opened up to the maximum usable frequency in each case since there was available capacity on the shorter lines, and a total power of 25dBm (316mW) was applied to all the usable bins.

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[12] The FEXT model is based on the crosstalk only occurring within a binder of 50 loops. Larger cables will contain multiple binders.

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Figure 10 shows the basic results in terms of capacity versus line length.

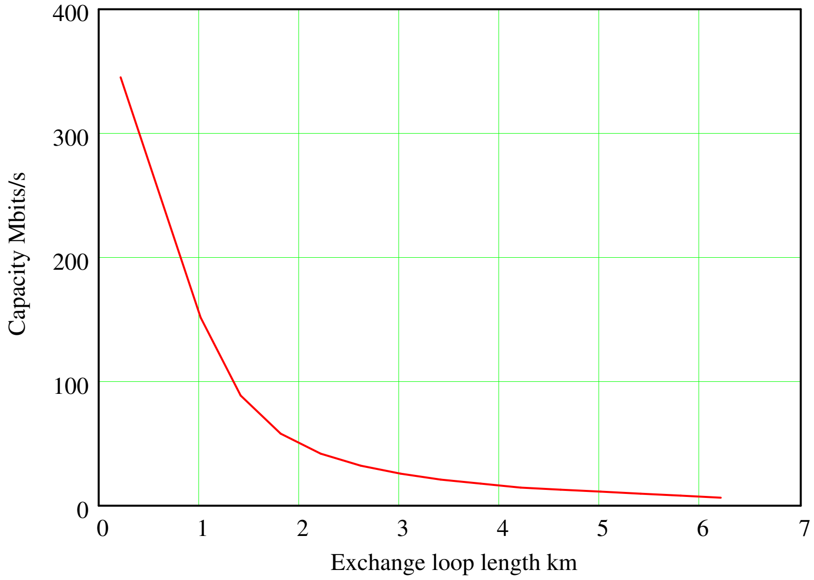

Figure 10 Capacity as a function of exchange line length

Figure 11 then presents the cumulative distribution of the capacity achievable, given the distribution of line lengths in the UK. This shows that 50% should get a bandwidth greater than 22Mbits/s.

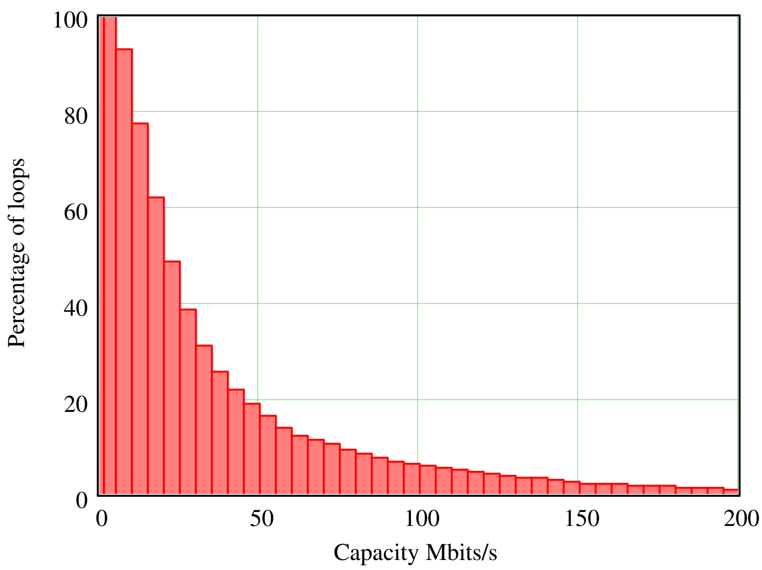

Figure 11 Theoretical cumulative distribution of capacity from the exchange

Figure 12 shows the data rates of the theoretical simulation with both ADSL and ADSL2. For the latter, the upper limit for the carriers was doubled to 2.2MHz, this being the major change that impacts the capacity. For the theoretical results, most of the extra capacity came from eliminating FEXT. Only the shortest lines benefited from increasing the number of carriers. With FEXT eliminated the shortest lines could

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achieve over 25Mbits/s. In like manner, the use of ADSL2 only benefited the shorter lines.

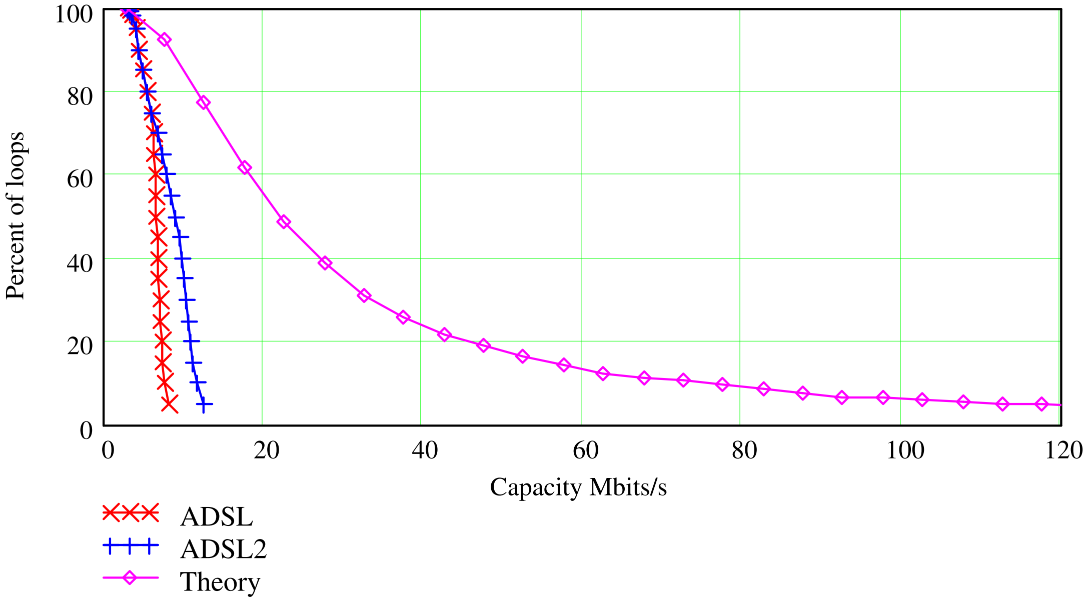

Figure 12 Comparison of data rates

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5 Case 2: Street cabinet modems

5.1 VDSL results

The standard applied to this simulation is VDSL profile 17a using a nominal -58dBm/Hz and 4096 carriers up to 17MHz. It is assumed that all the lines carry the same VDSL so that the FEXT model will use 49[13] as the number of disturbers. It is also assumed that each cable will have this number of interfering adjacent pairs along its whole length. This is a worst case.

Figure 13 presents the cumulative distribution of the capacity achievable from street cabinets. This shows that 50% should get a bandwidth of 29Mbits/s. Currently more than half UK homes have broadband so if only 50% of the loops are carrying VDSL then the capacity increases to 36Mbits/s for 50% of the population.

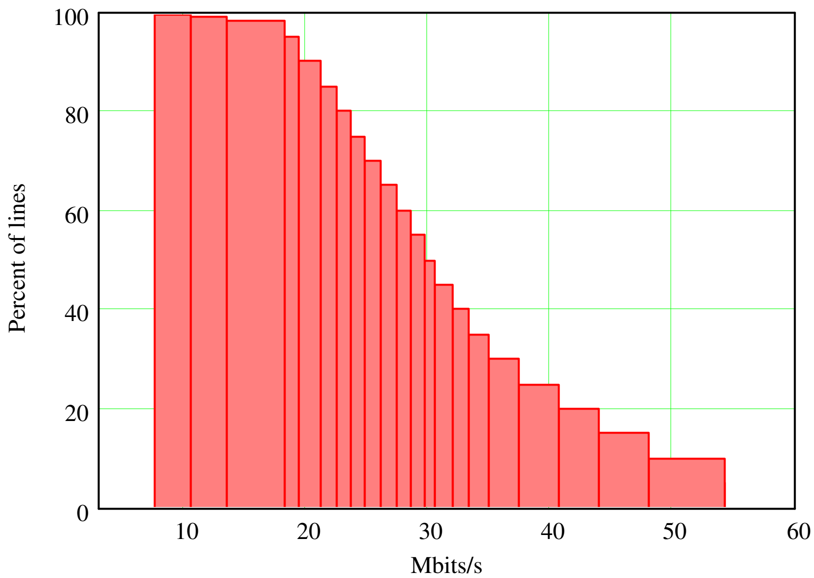

Figure 13 Cumulative distribution of capacity of VDSL profile 17a from a street cabinet

5.2 Theoretical results

For this simulation, the bandwidth was increased to 35MHz and a total power of 25dBm (316mW) was applied to all the usable bins.

Figure 14 shows the basic results in terms of capacity versus line length.

[13] The FEXT model is based on the crosstalk only occurring within a binder of 50 loops. Larger cables will contain multiple binders.

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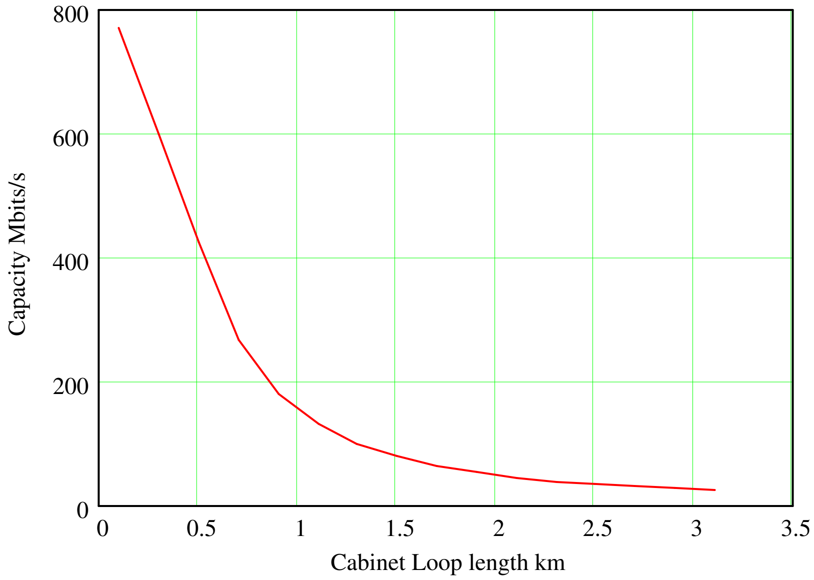

Figure 14 Capacity as a function of street cabinet line length

Figure 15 then presents the cumulative distribution of the capacity achievable, given the distribution of line lengths from a street cabinet in the UK. 50% of customers could receive 500Mbits/s.

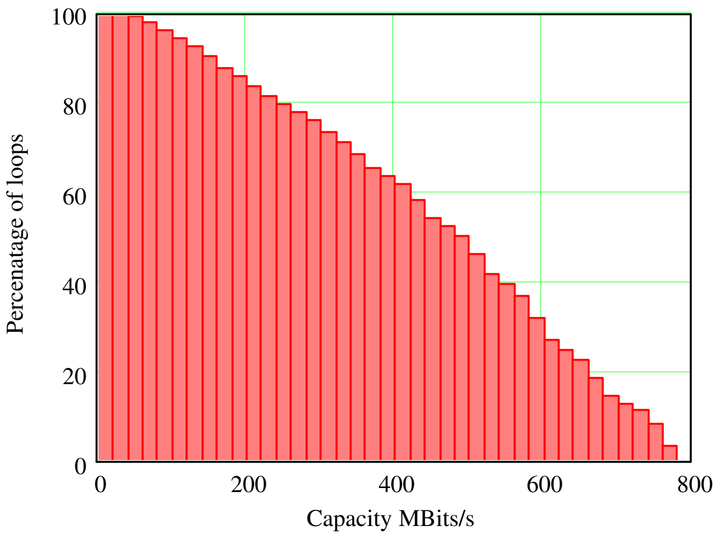

Figure 15 Theoretical cumulative distribution for Street cabinet

Figure 16 Shows the theoretical results plotted with those for VDSL profile 17a. The difference is almost entirely from the effects of FEXT. Increasing the power in the Standards simulation had no effect since the capacity was FEXT limited. Increasing the bandwidth also had marginal effect.

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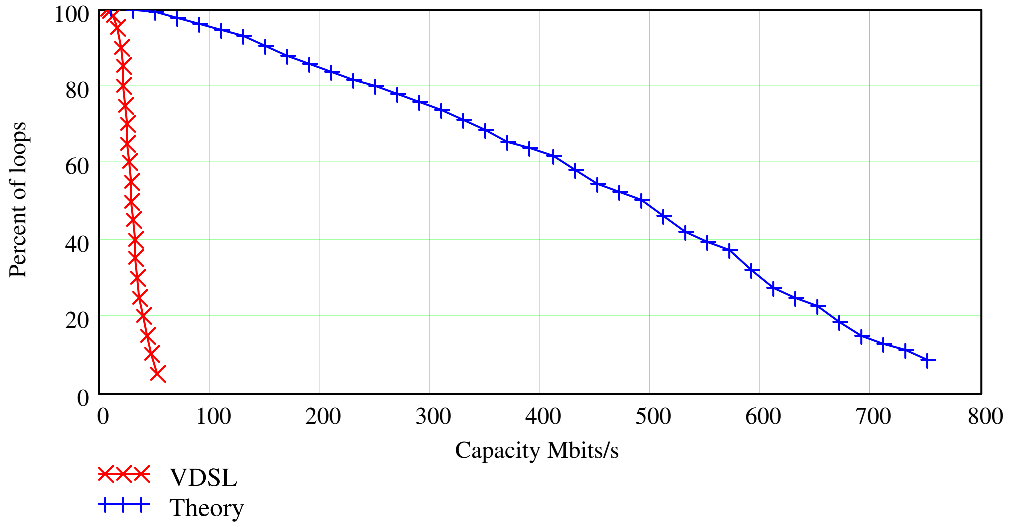

Figure 16 Comparison between VDSL and Theoretical capacity from the Street Cabinet

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6 Case 3: Mixed deployment

6.1 Deployment scenarios

The capacities achieved for the two pure cases are shown in Figure 17. The space between the two curves represents the potential options for case 3.

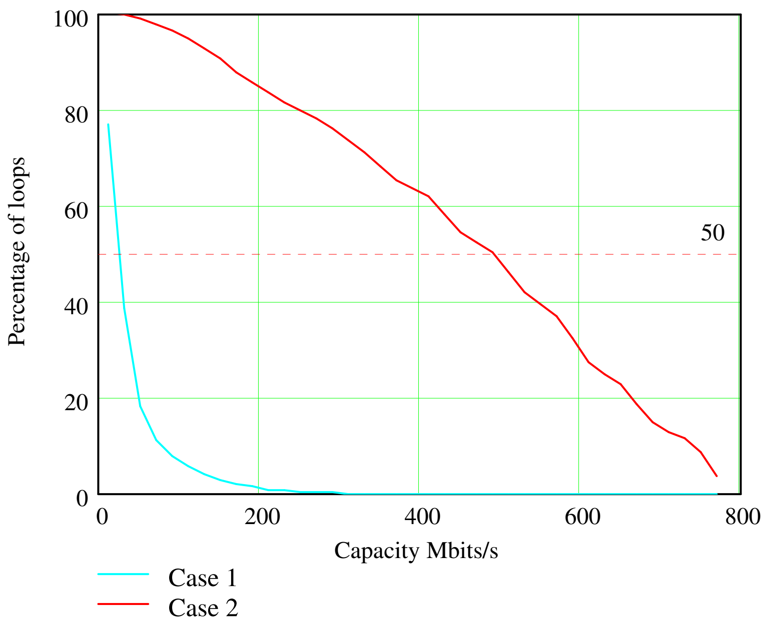

Figure 17 Capacity profiles for the two pure cases

There are a number of deployment scenarios for rolling out broadband from a street cabinet in an environment of existing exchange based broadband that can be implemented. Each will have its own mix of advantages and disadvantages from the perspectives of costs, convenience and performance. The main issues with deployment are as follows:

- The cost of laying fibres to the dozen or so street cabinets in an exchange serving area. As the incumbent, BT has the significant advantage of owning the ducts from the exchange to the street cabinet. However, in some instances these can be very full, making it difficult to pull fibre
- The cost of installing a DSLAM next to a street cabinet
- The cost of installing a source of electrical power for the DSLAM
- The cost of moving the D-side loop over to the DSLAM. In the current theoretical assessment, telephony will be carried by the broadband so there is no requirement for POTS splitters
- The cost of any installation at the CPE. For ADSL this has been self install with in-house wiring being used. With VDSL this will no longer be possible because of the high frequencies involved.

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In addition to these access network costs there will be significant core network costs with significant extra bandwidth required.

A number of deployment scenarios can be considered. The simplest scenario with best performance for all subscribers is that of total switchover of all subscribers from an exchange to street cabinet DSLAM at the same time. The performance results for this scenario are presented in the first report. However this would require all street cabinets to have DSLAMS installed prior to the switchover day. Thus investment in the network will be required up-front before the possibility of any revenue. This is unlikely.

6.1.1 Loop length dependent deployment

Loop length dependent deployment is when exchange loops of a particular length are upgraded to operation from a street cabinet. A whole street cabinet would be changed over at once, thus avoiding the coexistence of two types of traffic in a binder. Figure 18 illustrates the principle.

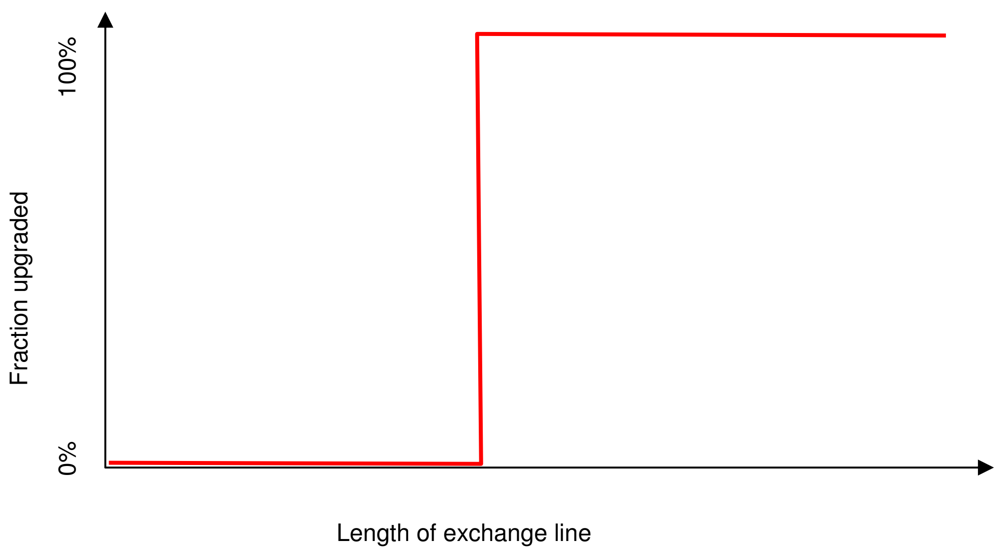

Figure 18 Loop length dependent deployment

There are two versions of this deployment:

Best is First

Because of the costs of laying fibre are proportional to length, from a commercial perspective, the operator is likely to want to deploy short E-side loops first. However this “Best is First” scenario is likely to most benefit those with the best existing broadband. The performance results for this are also available from cases 1 and 2 since each street cabinet is switched over as a whole so no alien crosstalk is present.

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Worst is First

An alternative scenario is "Worst is First" where the furthest street cabinet (longest E-side) get deployed first. This will help to equalise the digital divide caused from loop lengths, and may well be the preference of any regulator. Again the performance results for this are available from cases 1 and 2 since each street cabinet is switched over as a whole so no alien crosstalk is present.

6.1.2 Loop length independent deployment

The most likely scenario is that requests to be upgraded to the faster service will drive the deployment. This was the deployment strategy that applied to ADSL. Such customers will be scattered over all loop lengths so that street cabinets will be installed across the network as required and each one will host a mixture of traffic from the exchange and street cabinet DSLAMs. Figure 19 illustrates the principle of *loop length independent deployment* where a proportion (50%) of all the lines are changed.

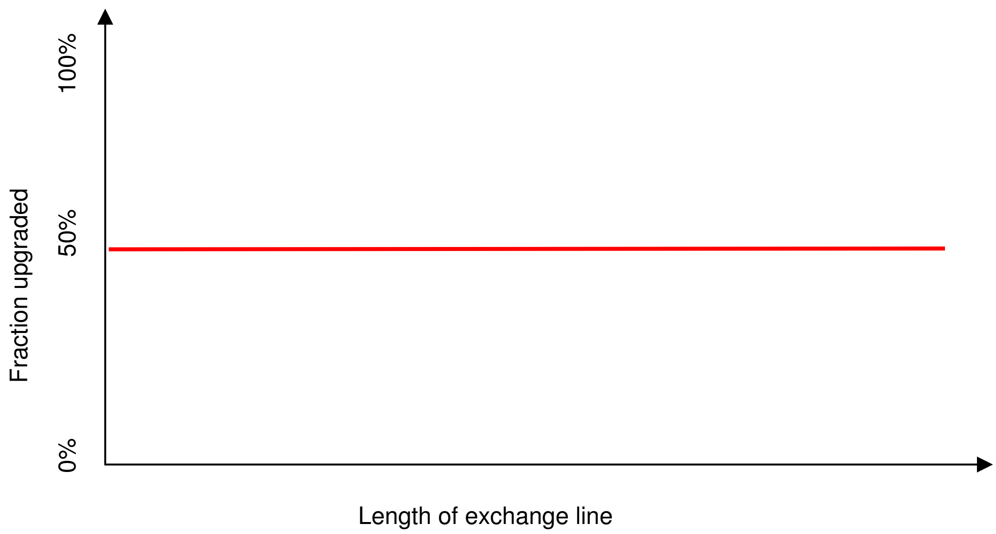

Figure 19 Loop length independent deployment

There are three methods of dealing with this scenario.

Binder switchover

It is being assumed that each multi-pair cable radiating from the street cabinet will split off individual pairs at the same point. In other words, the loss and crosstalk environment for all pairs in one of these cables will be the same. It is thus possible to consider the possibility of switching over all the pairs in such a binder and preventing any crosstalk. As with the threshold upgrades described above, the performance results for this are available from cases 1 and 2.

FDM

This condition is when there is traffic down the pairs from the street cabinet from both the street cabinet and the exchange DSLAMs.

The loops being driven from a DSLAM at the street cabinet are obviously shorter that those from the exchange so will have greater capacity so that they can use higher frequencies. The simplest strategy would therefore be use Frequency Domain

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Multiplexing (FDM) by adopting a frequency plan for the street cabinet which starts above the highest frequency used by the exchange. In this way the limited capacity of the latter would be unaffected by the presence of the former and the capacity calculations for the exchange can be reapplied here. The capacity from the street cabinet must be recalculated using starting frequencies above those used by the exchange transmission. The principle is illustrated in Figure 20.

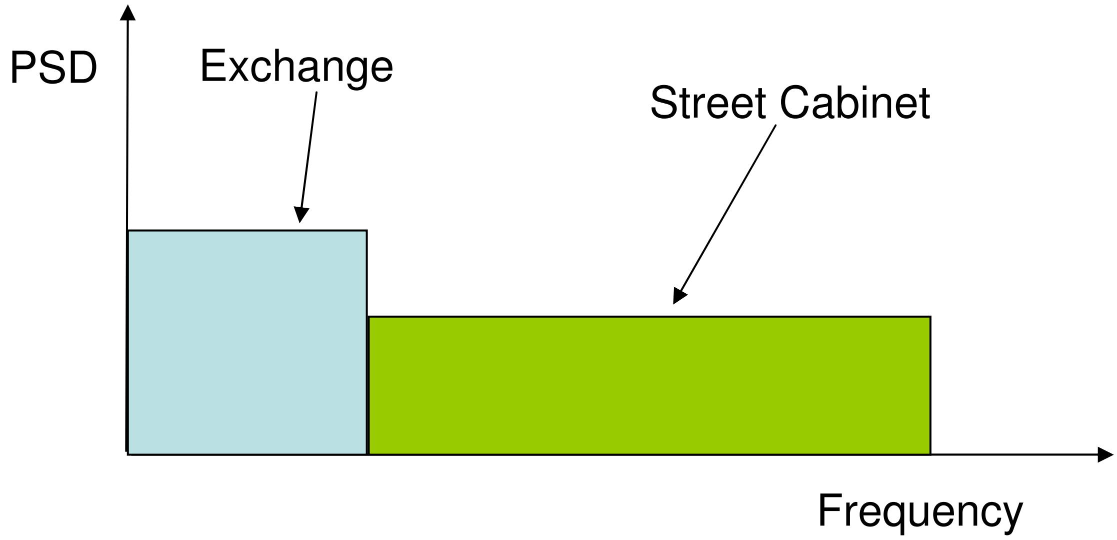

Figure 20 FDM approach to avoiding FEXT

Frequency Overlap

This method is a modification of the FDM method in that the exchange is allowed to configure itself as with FDM using the available frequencies according to the loop length. The street cabinet then uses the frequencies above as before but also uses some lower frequencies. Using an optimiser to maximise the total capacity of the binder, the street cabinet adds lower frequencies, starting from the lowest bin.

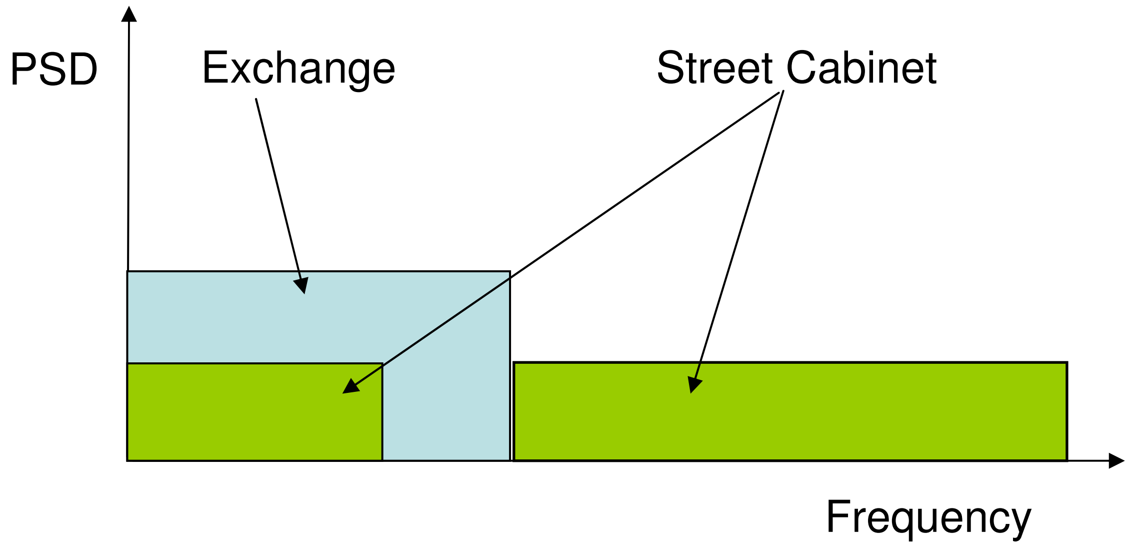

Figure 21 Frequency overlap

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6.2 Results

6.2.1 Loop length dependent deployment

Best is first

This is the method that would be preferred by an operator since it has the least initial investment costs. The least amount of fibre need be laid to service the nearest street cabinet, and these will already have the best service from the exchange. The gradual switchover for this scenario is shown in Figure 22.

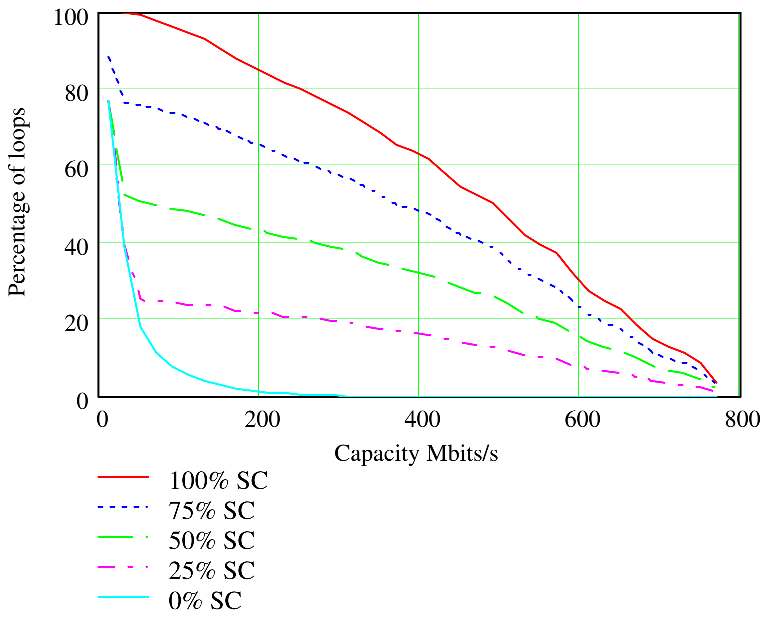

Figure 22 'Best is first' switchover

Table 3 presents the results for 50 and 100Mbits/s and the median capacity. This reveals that the build out to 50Mbits/s occurs very slowly with almost full deployment being required. Because the slope between 50 and 100Mbits/s is fairly shallow, the percentage getting the higher capacity is only slightly less.

The improvement in available capacity at 25% deployment is worst for this scenario because loops with good capacity are being replaced with those with slightly better capacity.

Table 3 'Best is first' switchover

	0% SC	25% SC	50% SC	75% SC	100%SC
50 Mbits/s	17.7%	24.7%	50.1%	77.7%	99.1%
100 Mbits/s	6.1%	24.1%	48.7%	73.1%	95.5%
Median	22 Mbits/s	24 Mbits/s	55 Mbits/s	370 Mbits/s	492 Mbits/s

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Worst is first

This is the method that would be preferred by a regulator since it improves first loops with poor existing service and helps to equalise the "digital divide". However the operator will need to invest most as the longest lengths of fibre will need to be laid. The gradual switchover for this scenario is shown in Figure 23.

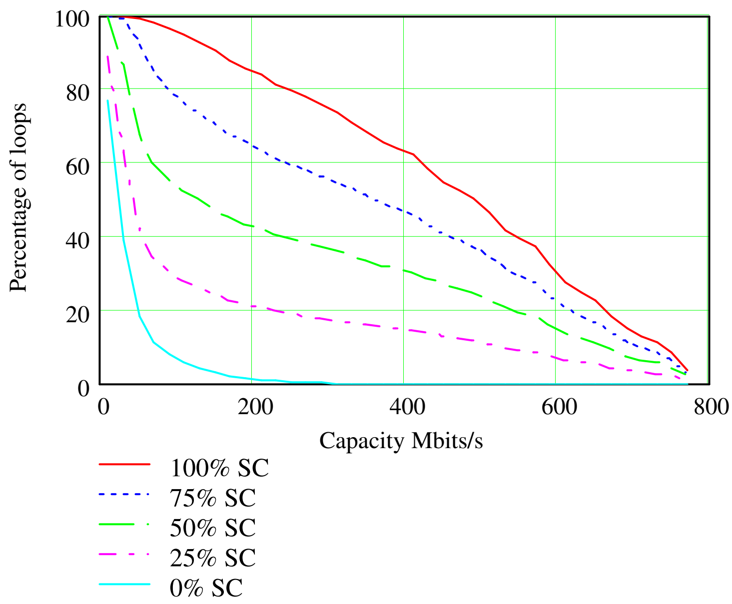

Figure 23 'Worst is first' switchover

Table 4 presents the results for 50 and 100Bits/s and the median capacity. The improvement in available capacity at 25% deployment is greatest for this scenario

Table 4 'Worst is first' switchover

	0% SC	25% SC	50% SC	75% SC	100%SC
50 Mbits/s	17.7%	41.5%	67.1%	92.5%	99.1%
100 Mbits/s	6.1%	29.0%	53.6%	77.9%	95.5%
Median	22 Mbits/s	42 Mbits/s	127 Mbits/s	356 Mbits/s	492 Mbits/s

6.2.2 Loop length independent deployment

Binder switchover

Since alien crosstalk happens within the 50 pairs of a binder, if the whole binder radiating from a street cabinet is switched over together, then there can be no alien crosstalk. The results from this deployment scenario are the best that can be obtained since they are identical to those using an alien FEXT cancellation technology. Figure 24 shows the effects on the cumulative capacity as such binders get converted across the network.

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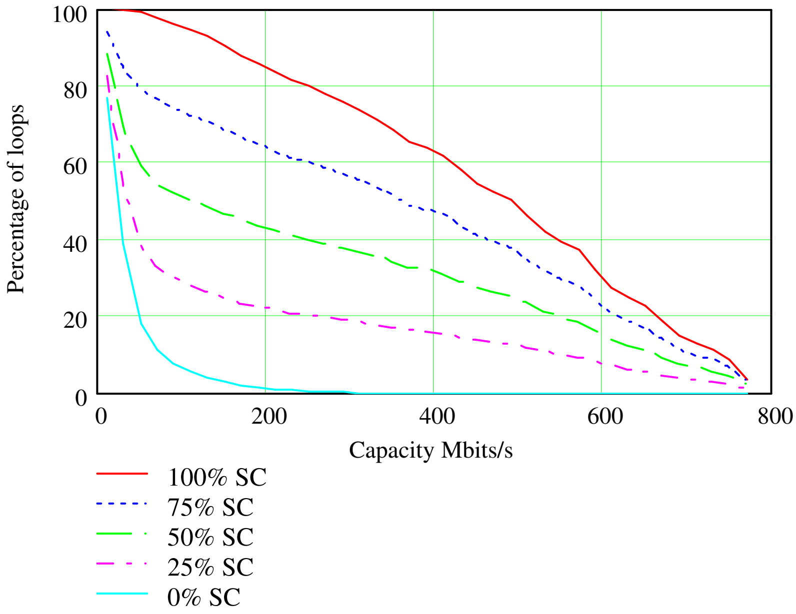

Figure 24 Binder switchover

Table 5 presents the results for 50 and 100Mbits/s and the median capacity. The build up to 50Mbits/s is only slightly faster than for the FDD deployment. The ultimate capacity is also greater since the lower frequencies are being used.

Table 5 Binder switchover

	0% SC	25% SC	50% SC	75% SC	100%SC
50 Mbits/s	17.7%	38.4%	58.6%	78.9%	99.1%
100 Mbits/s	6.1%	28.8%	51.0%	72.3%	95.5%
Median	22 Mbits/s	35 Mbits/s	110 Mbits/s	360 Mbits/s	492 Mbits/s

FDM

The FDM approach is the simplest both from a modelling and deployment perspective. It consists of allowing the exchange traffic to establish its optimum operating condition within the constraint of a maximum allowable total power transmitted onto a loop. This will be a flat PSD mask over the usable bandwidth for that loop length. This maximum frequency is then used as the starting frequency for the traffic from the street cabinet. The PSD mask for this transmission is established in a similar manner to the exchange traffic in that the PSD is constant over the usable bandwidth for that loop length. In both cases there is an upper limit to the frequency used.

The result of this procedure is to prevent any overlap of frequencies used by both exchange and street cabinet systems, thus preventing crosstalk and maximising the capacity from the exchange loops. In practice there may be a requirement for a guard band of a few bins. However simulations have shown that the inclusion of such a band has minimal effect of the overall capacities.

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To understand the effect of FDM and the removal of the lower frequencies from the street cabinet lines we have calculated the total capacities in each case. These are shown in Figure 25. The solid line shows the original case 2 (as applies when whole binders are switched) while the dotted line shows the effect on capacity of restricting transmission to higher frequencies (as applies where FDM is used to segregate traffic in a binder). The difference between the two curves is not large.

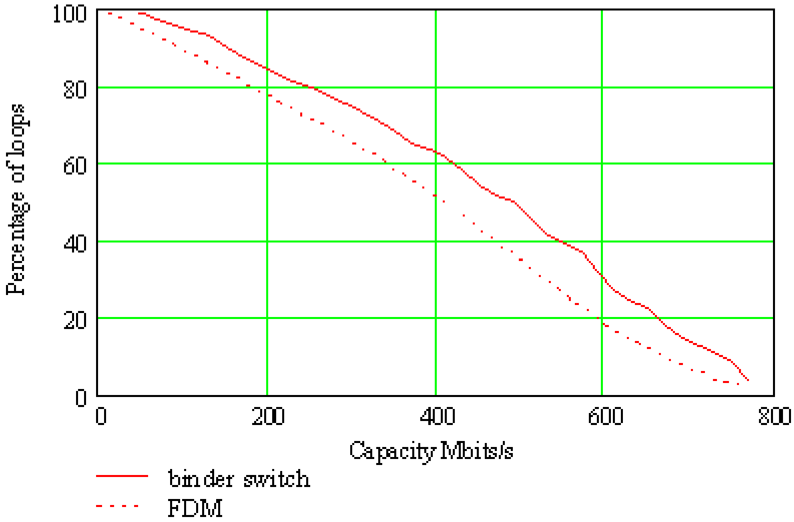

Figure 25 Effect of FDM on Case 2

Using this approach, Figure 26 shows the gradual improvement in the capacity as broadband migrates to the street cabinet using FDM to prevent mutual interference.

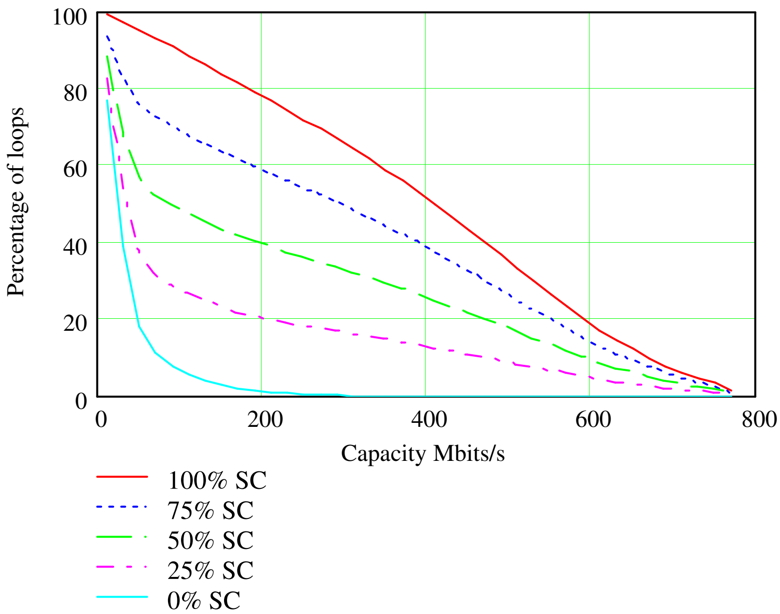

Figure 26 FDM deployment

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The cumulative capacity with no street cabinet deployment is the same as all the other scenarios because the FDM approach to coexistence of broadband in the binder does not affect the exchange capacity. However the capacity at 100% street cabinet deployment is less than for the other scenarios since the lower valuable frequencies have been given exclusively to the exchange. In practice, once 100% street cabinet deployment is accomplished, these frequencies can be reassigned, bringing the capacity back to the other scenarios.

Table 6 presents the results for 50 and 100Mbits/s and the median capacity.

Table 6 FDM deployment

	0% SC	25% SC	50% SC	75% SC	100%SC
50 Mbits/s	17.7%	37.4%	56.7%	76.0%	95.2%
100 Mbits/s	6.1%	27.3%	48.0%	68.8%	89.5%
Median	22 Mbits/s	43 Mbits/s	84 Mbits/s	294 Mbits/s	408 Mbits/s

Figure 27 shows a variant. Here we have restricted the stop frequency available to the exchange transmission. In this case the maximum allowable frequency has been dropped from 15MHz to just over 4MHz. The improvement in the 100% street cabinet deployment is marginal at the expense of the exchange capacity of the short lines.

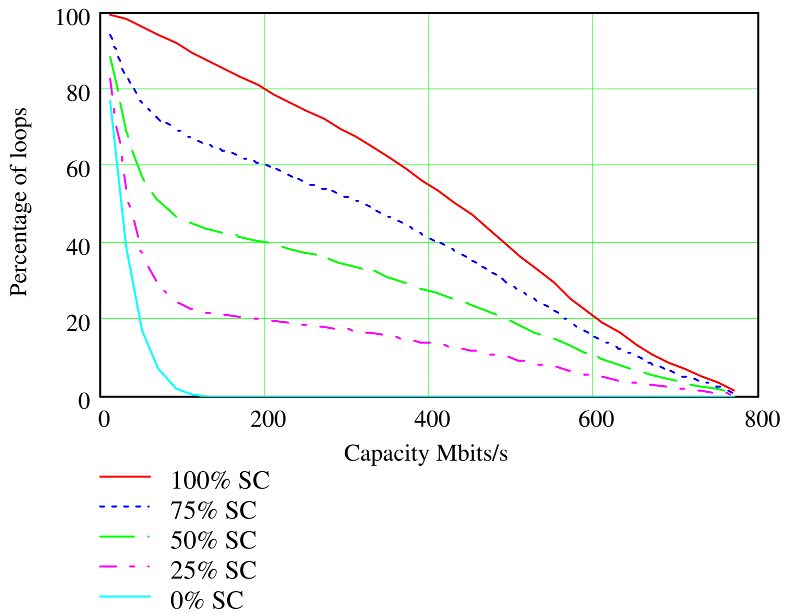

Figure 27 FDM deployment restricting the exchange frequency

Frequency overlap

Figure 28 presents the results from using a frequency overlap approach whereby some of the lower frequencies used for the exchange broadband are also used by the street cabinet broadband. A limited amount of alien FEXT is modelled.

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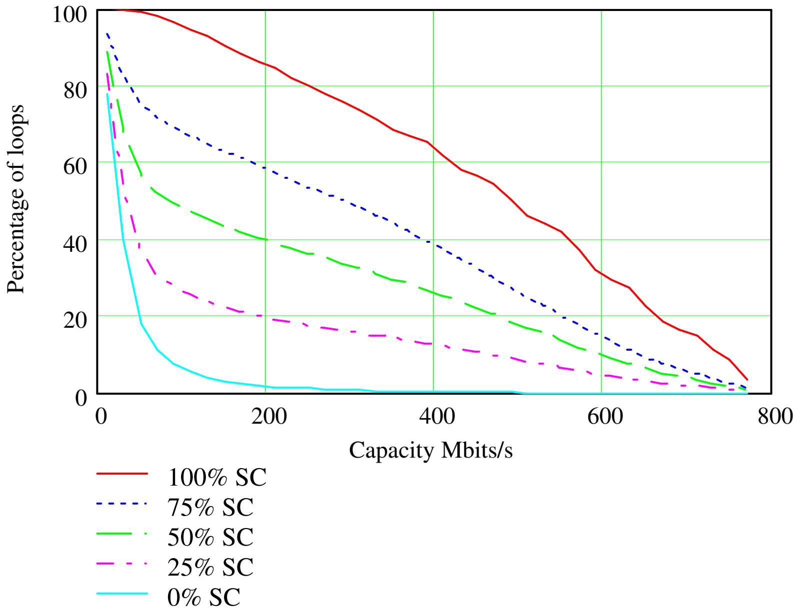

Figure 28 Frequency overlap street cabinet deployment

Table 7 presents the results for 50 and 100Mbits/s and the median capacity.

Table 7 Frequency overlap street cabinet deployment

	0% SC	25% SC	50% SC	75% SC	100%SC
50 Mbits/s	17.7%	36.6%	56.6%	75.2%	99.1%
100 Mbits/s	6.1%	26.5%	48.1%	68.1%	95.5%
Median	22 Mbits/s	34 Mbits/s	84 Mbits/s	290 Mbits/s	492 Mbits/s

The difference between these results and the simple FDD approach is marginal. There is little benefit for this approach until full street cabinet deployment is complete.

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7 Sensitivity analysis for Bit Error Rate (BER)

7.1 Case 1: Exchange

The simulations were conducted using a bit error rate (BER) of 10^{-7}. This is the figure commonly used for such simulations. Increasing the BER to 10^{-10} was investigated to find out how it would alter the capacity distribution. Figure 29 presents the results.

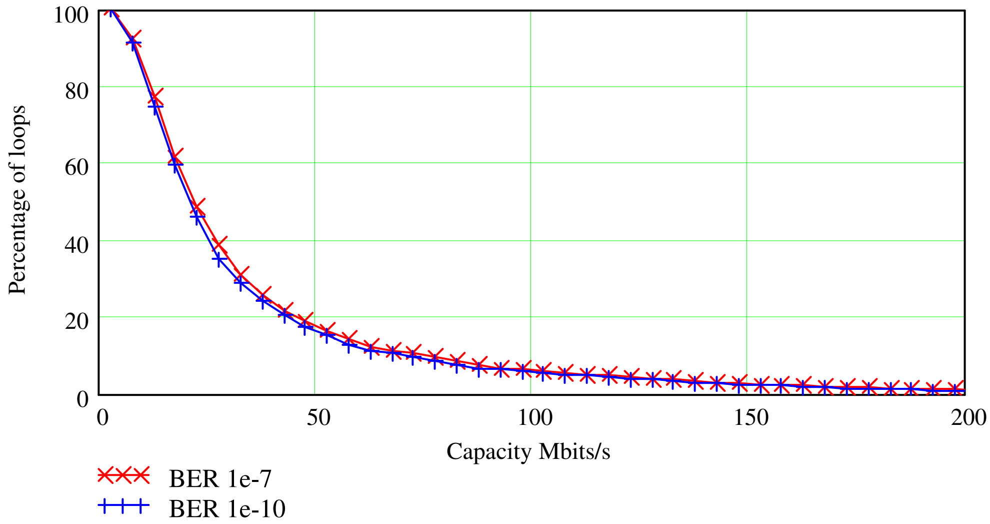

Figure 29 Change in capacity with BER

The change in capacity is marginal for exchange loops. The reason for this is that increasing the BER to 10^{-10} reduces the number of bins available so therefore increases the power in the useful ones.

7.2 Case 2: Street cabinets

The simulations were conducted using a bit error rate (BER) of 10^{-7}. This is the figure commonly used for such simulations. Increasing the BER to 10^{-10} was investigated to find out how it would alter the capacity distribution. Figure 30 presents the results.

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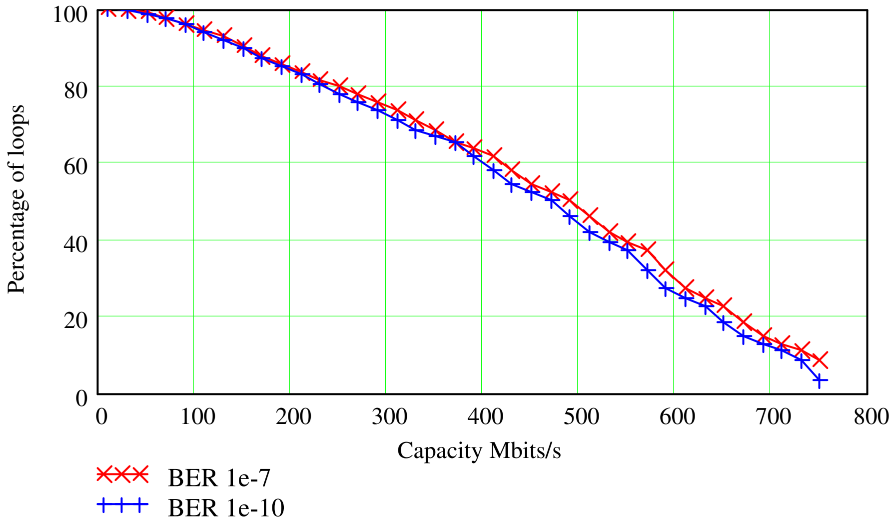

Figure 30 Change in capacity with Bit Error Rate

This shows that improving the BER reduces the capacity only marginally for the longest loops rising to about 5Mbits/s for the shortest loops. As with the exchange case, increasing of the BER to 10^{-10} reduces the number of bins available so therefore increases the power in the useful ones.

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8 Discussion and conclusions

The table below summarises the headline results of our modelling of the theoretical maximum capacities. Case 3 is for 25% street cabinet deployment.

	Percentage of households achieving above 50Mbits/s	**Percentage of households achieving above 100Mbits/s**	**Median data rate Mbits/s**
Case 1: Modems in exchanges	17.7%	6.1%	22
Case 2: Modems in street cabinets	99.1.%	95.5%	492
Case 3: Best is first @25%	24.7%	24.1%	24
Case 3: Worst is first @25%	41.5%	29.0%	42
Case 3: Binder switchover@25%	38.4%	28.8%	35
Case 3: FDM @25%	37.4%	27.3%	34
Case 3: Frequency overlap @25%	36.6%	26.5%	34

The indicated capacity is the total for both upstream and downstream combined. The results are agnostic as to the asymmetry required from the system. This will depend on the types of services required. Businesses have usually required symmetry whilst domestic applications have required asymmetry. If the streaming of video is to be a major application then that requirement is likely to remain. However increasing numbers are requiring symmetry with peer to peer networks.

The theoretical results for the exchange deployment show that even removing FEXT cannot compensate for the SNR of the longest loops being ultimately limited by the AWGN. The PSD could be increased for these loops, however there is a limit to the total power that can be transmitted and impossible levels would be required (tens of watts) to have any worthwhile effect.

For cabinet deployment, the theoretical results show that broadband capable of delivering 100BASE-T becomes possible for the majority of loops. However the longest loops get only 15Mbits/s. Boosting the PSD by 10dB only increases their capacity to 22Mbits/s. Therefore 100BASE-T is theoretically not possible for all users even from the cabinet. For these loops, deployment would need to move to the Drop Point (DP). According to BT the maximum length of lines from the DP is 80m with the minimum being about 5m. Thus the lengths for the DP are within the shortest length from the street cabinet data of 118m. The capacities from the DP will therefore be better than those for the shortest street cabinet. Furthermore, they are unlikely to have many neighbouring pairs.

The overall implication of this modelling is that the capacities currently achieved are vastly lower than theoretically possible. Ofcom commissioned this study as part of its technical research programme and makes the following caveats:

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- The project was commissioned in order to try to establish a theoretical, rather than practical, limit;
- The degree of which practical implementation can get close to the theoretical limit is not investigated within the project;
- At the time of writing, Ofcom is not aware of any practical implementations of the technology approaches implied in this report that would lead to substantial increases in speed being achieved on BT's copper network;
- Neither is there any indication that the changes in standards implied in this study are being considered by the relevant bodies;
- Ofcom is publishing the report to gain views from interested parties on the possibility that future technologies could exploit, in practice, the theoretical potential described in this report.

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Appendix A: Optimisation of PSD mask

We have performed an optimisation of the PSD mask in the absence of NEXT or FEXT. This procedure is described below.

The data capacity (in bits) of one bin can be written as

$$B = floor\left[\log_2\left(1+\alpha\frac{P.L}{N}\right)\right]$$

where *P* is the transmit power in that bin (in watts), *L* is the power loss factor (dependent on frequency and line length), *N* is the noise power in that bin (in watts) and α is a dimensionless number comprising the coding gain, margin and bit error rate. The *floor* function rounds the argument down to the nearest integer.

All the factors above can be combined into a competing power term, *R*:

$$B = floor\left[\log_2\left(1+\frac{P}{R}\right)\right].$$

For a given line, the PSD mask defines a transmit power in each bin, P_i, and there is a competing power in each bin, R_i. The objective of the optimisation is to find that PSD mask that maximises the line capacity

$$B = \sum_{i=1}^{N} floor\left[\log_2\left(1+\frac{P_i}{R_i}\right)\right]$$

subject to a constraints on the total transmitted power and the requirement that the power in each bin be positive:

$$\sum_{i=1}^{N} P_i = Ptot, \quad P_i \geq 0.$$

The only mathematical complication is the *floor* function. This can be handled by requiring $P_i \geq R_i$ or $P_i = 0$, so that each bin contributes at least one bit or is not used at all. The *floor* function can then be dropped, as it affects the end result little. The optimisation method then involves:

- Choosing a maximum bin number, *n*, such that $P_i = 0$ for all $i > n$
- Optimising the PSD mask P_i, $i = 1 \ldots n$, using the method of Lagrange multipliers to handle the constraints. This gives the maximum capacity for a fixed value of *n*.
- Then finding the value of *n* that maximises the capacity.

The end result is that:

- $P_i + R_i$ is constant in each bin

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- *n* is chosen so that $P_n = R_n$ (assuming that the R_i increase monotonically with *i)*

This means that the optimum throughput is achieved when the sum of the transmit power and the transmit equivalent noise power in each frequency bin is a constant. 'Transmit equivalent noise' consists of the insertion loss and the noise. This algorithm has the effect of putting more power into the lower frequency bins than the higher frequency bins.

A series of PSD masks for different line lengths obtained from this optimisation method is shown in Figure 31. The masks are predominantly flat with a tail off at the high frequency end.

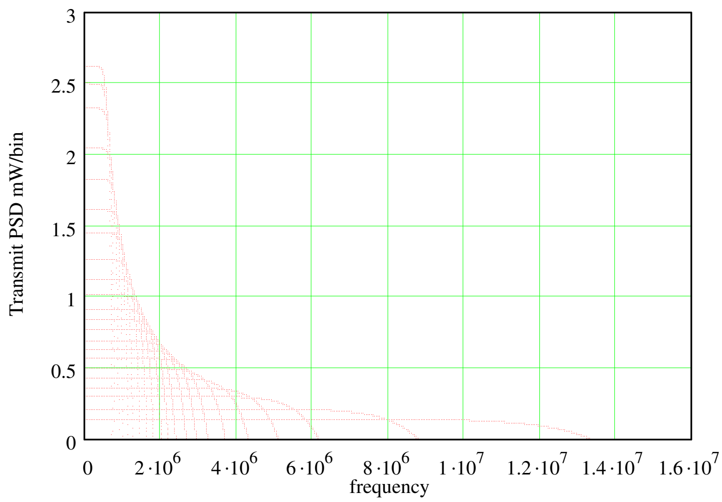

Figure 31 PSD mask for different line lengths

In our model we used a flat PSD mask. It turns out that both methods of shaping the PSD spectrum produce almost identical results as shown in Figure 32.

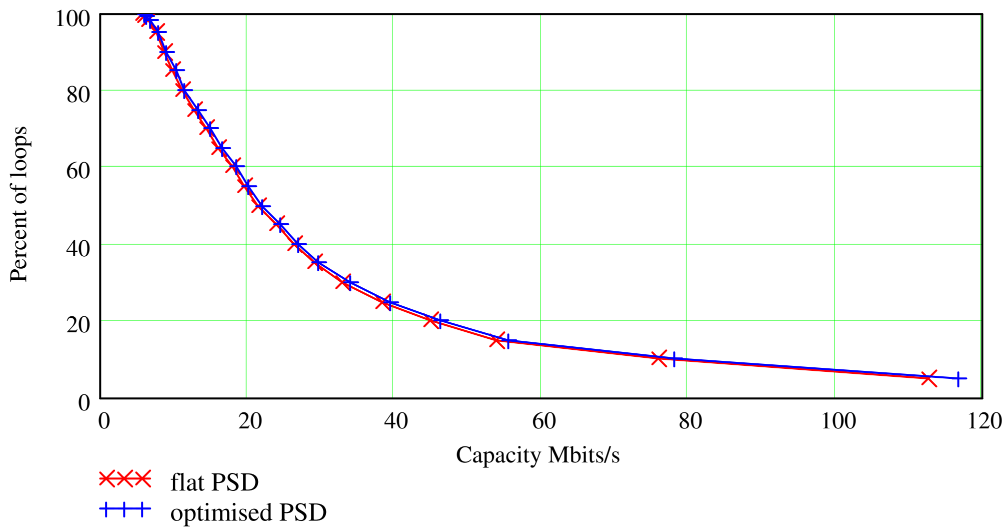

Figure 32 Effect of PSD optimisation (Case 1)

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Appendix B: Crosstalk

Crosstalk refers to the signals from one pair coupling into another pair. There are two types of crosstalk – NEXT and FEXT – and these are further split into upstream and downstream variants, as illustrated in Figure 33.

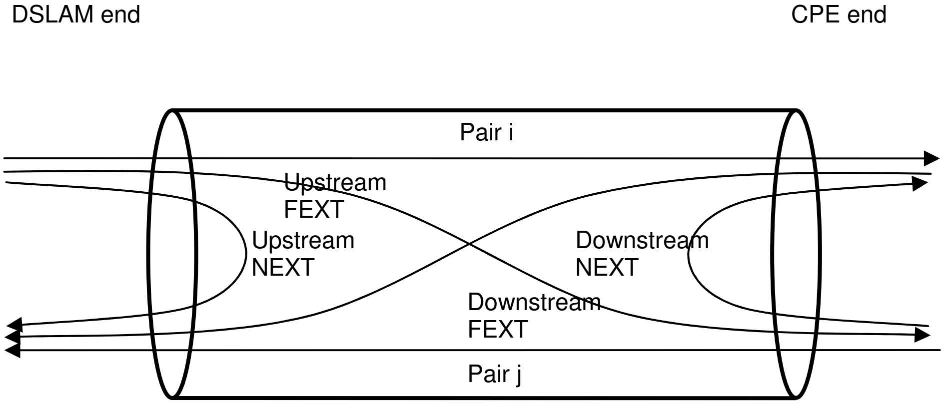

Figure 33 NEXT and FEXT

B.1 NEXT

Near End crosstalk (NEXT) is the leakage of signals from transmitters on other pairs in the same cable back to the input of a receiver at the same end. It is not an issue so long as the frequency plan does not allow overlapping. This is normal practice and, as with the previous assessment, the assumption of a non-overlapping frequency plan is implicit in the current assessment.

B.2 FEXT

Far End Crosstalk (FEXT) is the leakage of signals from transmitters on other pairs in the same cable to the input of the receiver at the other end. It causes the “near far” effect when there is a remote modem feeding to a cable already carrying long reach DSL from the exchange. The power leaking into the long reach pair can overpower its own, much attenuated signal. This is the situation in the mixed deployment of the current investigation so it must be considered.

FEXT can theoretically be eliminated by DSM level 3 - a process known as vectoring. This method of crosstalk cancellation uses techniques very similar to those of an echo canceller. The crosstalk coupling channel varies only slowly with time so it can be modelled as a digital filter. As long as the other modems using that binder are co-located, their signals are known, it is possible to predict the induced crosstalk on all the other lines. This predicted value can then be subtracted from the actual received signal to reduce the amount of crosstalk. All the lines in a binder must be processed as an entity. This requires either all the processing being on one chip or there being very fast communications between the individual chips.

Vectoring is used for the pure exchange and street cabinet situations. It is also be applied in the mixed deployment. However, because of the requirement for co-location, it can only apply to the self FEXT crosstalk. The alien crosstalk from the exchange capacity will impact that from the street cabinet and vice versa.

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