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NICC Document

Operation of G.fast below 17.7 MHz in VDSL spectrum

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Foreword

This NICC document has been produced by the NICC DSL Task Group (DSLTG). It summarises the options that the DSL TG considered as part of work item #321. This work item began by investigating the technical options to extend the spectrum associated with the use of G.fast DSL technology in the UK to lower frequencies.

Introduction

G.fast is the latest DSL technology in use in the UK access network. It is specified by the ITU-T and is standardised in G.9700 [3] and G.9701 [2]. It is currently specified by the ITU-T to be able to use spectrum in the range 2.2-212 MHz.

The spectrum that G.fast is permitted to use in the UK access network is specified in NICC ND1602 [1], the Access Network Frequency Plan (ANFP).

The rationale for lowering the start frequency is to allow G.fast to use a lower loss part of the spectrum to increase the rate and reach of the technology. Currently when reach is required VDSL must be considered, which is currently permitted to use frequencies up to 17.7 MHz in the BT UK access network [1, 5]. The technical challenge addressed in this report is to increase the rate and reach of G.fast whilst minimising the harm to VDSL deployments, present and future. There are two potential magnitudes of "harm" in this sense. The first is due to any changes to existing power spectral density (PSD) definitions allowed for VDSL, such as reducing the maximum used frequency, which might adversely impact the capability of the technology and hence the capability of existing systems where this is due to a mandated change in the existing allowed PSDs (Section B and Section C of the ANFP). The second type of harm is less predictable crosstalk derived impacts from G.fast that overlaps spectra with VDSL which causes unexpected changes in the capability of the system or even individual circuits (if systems are managed at individual service level.)

G.fast technology has been designed so that it can co-exist with VDSL systems such as FTTC via frequency separation. Work on the co-existence of G.fast and VDSL suggests that G.fast speeds may by improved without significant impairment of the VDSL speeds, by allowing G.fast to use the spectrum down to 2.2 MHz and managing the use of that spectrum to limit crosstalk impact to VDSL. Studies show potential for 100 Mbit/s improvements for G.fast in some cases. Two cases of impacts are considered:

- No or insignificant impairment to VDSL.
- Allowing some degradation in ideal VDSL speeds to boost G.fast performance. This involves commercial considerations and agreements.

Work item #321 proposed that one or more options for overlapping G.fast and VDSL spectra could be incorporated in a future issue of the BT ANFP (ND1602), if such options

- can provide sufficient performance improvement to justify any associated complexity increase,
- are verified to cause no unusual degradation in practice and
- are limited to cases where there is sufficient information to ensure spectral compatibility.

The PSDs that can be used and hence performance of spectrum management solutions are affected by the control method chosen. Control methods vary in complexity and affect the gains from spectrum management and so when trying to maximise the gains while lowering the start frequency of G.fast they must be considered as an integral part of the solutions.

1 Scope

This document summarises the most practical options to enable the use of a lower start frequency for G.fast, below the 19MHz currently specified in V6 of the ANFP [1] and how those options meet the caveats from the work item on the implementation of such options. Each option includes PSDs and control methods. The scope includes those frequencies where there is currently exclusive use by VDSL systems. Frequencies below 2.2MHz are not used by G.fast and are out of scope.

2 References

2.1 Informative references

[1] NICC ND1602, V6.1.1 (2016-03): "Specification of the Access Network Frequency Plan applicable to transmission systems connected to the BT Access Network" (ANFP)

[2] ITU-T Recommendation G.9701, "Fast Access to Subscriber Terminals (G.fast) – Physical layer specification

[3] ITU-T Recommendation G.9700, "Fast access to subscriber terminals (FAST) – Power spectral density specification"

[4] Broadband Forum document TR-114 i3, "VDSL Performance Test Plan"

[5] ITU-T Recommendation G.993.2, "Very high speed digital subscriber line transceivers 2 (VDSL2)"

[6] NICC ND1513, Report on Dynamic Spectrum Management (DSM) Methods in the UK Access Network, 2010

[7] ATIS-0000007, Dynamic Spectrum Management Technical Report, issue 2, 2012

[8] NICC ND1518, Data Sharing for DSM, 2015

[9] Broadband Forum TR-349, DSL Data Sharing, 2016

[10] Broadband Forum TR-355, YANG modules for FTTdp Management, 2017

[11] ITU-T Recommendation G.997.1, "Physical layer management for digital subscriber line (DSL) transceivers"

[12] Rainer Strobel and Wolfgang Utschick. "Coexistence of G. fast and VDSL in FTTdp and FTTC deployments." 23rd European Signal Processing Conference (EUSIPCO). IEEE, 2015.

[13] ETSI TS 101 270-1. Transmission and Multiplexing (TM); Access transmission systems on metallic access cables; Very high speed Digital Subscriber Line (VDSL); Part 1: Functional requirements, 2003

[14] Sagentia, prepared for Ofcom, Assessment of the theoretical limits of copper in the last mile, 16-06-2008. https://www.ofcom.org.uk/research-and-data/technology/general/emerging-tech/limits-of-copper

[15] Ofcom, Communications Market Report. 03/08/17, https://www.ofcom.org.uk/__data/assets/pdf_file/0017/105074/cmr-2017-uk.pdf, page 6

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3 Definitions and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

Communications Provider

A Communications Provider (also known as Service Provider), supply phone and internet services to their customers, either businesses or individuals.

fcut — The cut-off frequency, fcut, is the lowest passband frequency allowed to be used by G.fast. VDSL may or may not be restricted to operating below fcut. In static or semi-static cases fcut may be a fixed value across all lines in an area. With DSM fcut may be different for each cable, binder or vector group.

G.fast — DSL technology as specified in ITU-T G.9700 [3] and G.9701 [2].

G.fast DSLAM — G.fast DSLAM is used to refer to either G.fast DSLAM or DPU deployed at the PCP or DP.

mid span — The middle (not at either end) of the cable run, not at existing flexibility points such as the PCP or DP

overlapping — Both VDSL and G.fast con-currently use the same frequencies in a single geographic area.

per-line target rate

The physical layer data rate that a VDSL line should support, based on the expected impact of existing services. Typically used for DSM.

re-farming — Re-farming re-assigns some high frequencies of VDSL over to G.fast. Re-farming increases G.fast performance and reach, while reducing the maximum attainable VDSL data rate, thereby performing a trade-off between G.fast and VDSL.

re-use — G.fast reuses frequencies below 17.7 MHz that are not expected to be used by VDSL. For example, frequencies not used due to long VDSL line lengths.

service rate — The physical layer data rate offered to a consumer of the broadband service.

VDSL — Very high speed Digital Subscriber Line, used to refer to technology operating according to the VDSL2 [5] recommendation or older versions of the technology.

3.2 Abbreviations

ADSL — Asymmetric Digital Subscriber Line

ANFP — Access Network Frequency Plan

ANO — Access Node Operator

CAL — Cabinet Assigned Loss, a parameter that describes the electrical length of the cables between an MDF site (e.g. an exchange) and a connected SLCP (e.g. a PCP).

CGAL	Co-ordinated Group Assigned Loss, a parameter that describes the electrical length of the cables between a cabinet and a connected G.fast DSLAM.
CP	Communications Provider
dB	Decibel
dBm	Power ratio in dB referenced to one milliwatt
DP	Distribution Point – the final flexibility point in the BT access network before the line reaches its customer.
DPBO	Downstream Power Back-off
DPU	DP Unit
DS	Downstream
d-side	Distribution Side – the section of the access network extending from cabinet (PCP) to distribution point (DP).
DSL	Digital Subscriber Line, any of the modem technologies that send high speed data over metallic telephone pairs. A DSL line has a dedicated modem at each end of the physical wire pair; typically one of these is in the exchange or at a cabinet.
DSL TG	Digital Subscriber Line Task Group, a Task Group under NICC
DSLAM	DSL Access Multiplexer, the equipment responsible for supplying DSL services at the exchange or cabinet.
DSM	Dynamic Spectrum Management
FANS	Fixed Access Network Sharing
FDD	Frequency Division Duplex
FEXT	Far-end Crosstalk
FTTC	Fibre to the Cabinet
G.fast	DSL technology defined in ITU recommendations [2] and [3]
INP	Infrastructure network Provider
IWF	Iterative Water-Filling
MUF	Maximum Useable Frequency
NEXT	Near-end Crosstalk
NICC	Network Interoperability Consultative Committee, a committee of UK industry; http://www.nicc.org.uk
NTE	Network Termination Equipment, equipment containing the NTP, often a white socket on the wall of a customer's premises.
NTP	Network Termination Point. The legal demarcation between the network providers' cabling and the customer's in-house wiring. On a telephone line this point often has a master socket or NTE.
PCP	Primary Cross-connection Point (also known as the "cabinet")
PSD	Power Spectral Density

SMC	Spectrum Management Centre
SSM	Static Spectrum Management
SSSM	Semi-Static Spectrum Management
SLCP	Sub-loop connection point
TDD	Time Division Duplex
TX PSD	Transmit PSD
UPBO	Upstream Power Back-Off
US	Upstream
VDSL2	Second generation VDSL, defined in ITU-T Recommendation G.993.2 [5]

4 Options

The high level options considered broadly relate to the use of spectrum overlap or reuse and should be considered relative to the baseline provision for G.fast already allowed in the ANFP. These options further decompose based on whether the VDSL deployed from the Primary Cross-connection Point (PCP) is vectored or not and whether G.fast equipment is co-located at PCP locations.

NOTE: Vectoring of VDSL is optional in the ITU-T G.993.2 standard and improves rate and reach through the use of real time crosstalk cancellation.

The levels of impact or benefit to VDSL and G.fast are a key parameters which influence the options available and these are affected by whether the existing VDSL is vectored or not. The target impact on VDSL is either minimal or large. Larger impact could either be in rate or a need to vector to maintain existing rates and could only be enabled with agreement between operators.

Minimal impact on VDSL is typically made possible by making use of currently spectrum un-useable by VDSL today or by using VDSL frequencies while limiting impact to non-vectored VDSL to that of VDSL self-FEXT. The larger impact on VDSL and additional benefit to G.fast typically comes from re-farming and re-assigned higher VDSL frequencies to G.fast.

The high-level PSD options are broadly:

- **Frequency separation** – where the G.fast spectrum start frequency is lowered whilst maintaining frequency separation from VDSL.
- **Overlapping** – where G.fast is allowed to overlap spectrum with actively used VDSL spectrum.
- **No change**

One or more options for allowing G.fast to use lower frequencies might be considered to take forward if there is sufficient performance improvement to justify any associated complexity increase and they cause no unusual degradation.

The scope doesn’t prevent modification of existing VDSL PSDs and indeed the work described in this document considers cases where G.fast is allowed to use lower frequencies. A range of control (or management) methods can manage interactions between G.fast and VDSL, from frequency reuse when VDSL does not use the frequencies, through to complex co-existence methods.

Control mechanisms are necessary to define and control allowed PSDs. The more flexibility allowed for and the more this tends to “line by line” control, the greater the complexity of the management system (and possibly commercial agreements) that are necessary to facilitate operation of the method in some cases. Ultimately control methods must be considered because they affect the PSDs chosen and the gains that can be achieved.

For this reason, it is important that the control methods are also considered alongside the benefits and disadvantages of any particular option. The control methods considered are static, semi-static and dynamic and are described in detail in section 4.2.

The number of different equipment operators in a PCP area affects the trade-offs that can be made between technology deployments and the complexity of the implementation of some of the options, particularly the difference between the case where there is a single operator versus multiple operators. Some of the options require changes to both VDSL and G.fast configuration and others only to the G.fast configuration. Some of the options also require changes to management system interfaces.

4.1 Background on challenges

There are many challenges from G.fast systems making use of VDSL spectrum because the model changes from one where G.fast cannot interact with VDSL and vice-versa to one where there is interaction and the possibility of significant interaction if the design or implementation isn't properly considered.

Beyond the more obvious considerations embedded in the options, the following must also be accounted for:

- Time versus frequency domain duplex technology and the impact of time varying noise powers on other systems.
- Any limitations on the capabilities of G.fast to specify transmit PSDs. The standards [2] and [3] include definitions of controls and some limits on flexibility.
- Particularly in non-co-located cases the complexity of near end and far end crosstalk modelling must be included.
- Although the actual network may be modelled by a number of approximately "typical" scenarios the network topologies in a real world deployment are much more complex.
- The concept of "harm" is in practice variable and has a statistical basis. The levels of harm that are acceptable depend on which and how many parties are involved.

4.1.1 Duplex Operation

The difference in duplexing operation between technologies, can have an influence on the impact from one system to the other.

Most DSL systems operate either Frequency Division Duplexing (FDD) versus Time Division Duplexing (TDD).

- ADSL and VDSL (all profiles, vectored and non-vectored) use FDD
- G.fast uses TDD

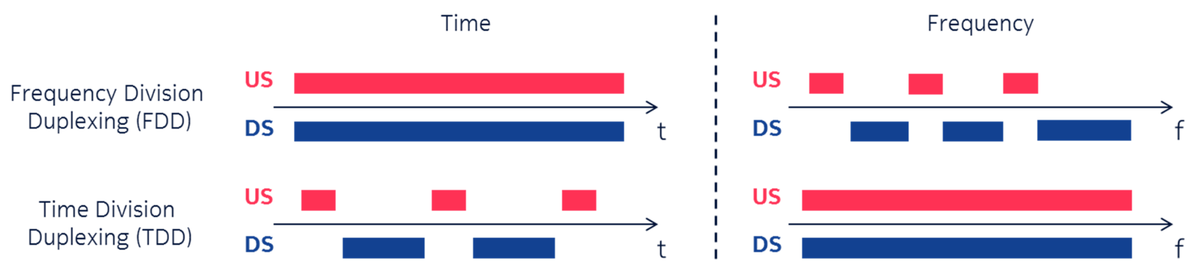


Figure 4-1 FDD versus TDD

G.fast operates in TDD, which could result in non-stationary crosstalk into VDSL (in case of overlapping frequencies).

For a G.fast downstream/upstream split of 80%/20%, this non-stationary aspect is especially important for the impact on upstream VDSL direction.

- For the VDSL downstream direction, most victim lines will hardly notice the difference between crosstalk present 80% or 100% of the time; when the noise is averaged, this average will just be slightly smaller than the real peak level (10 log10 (100 / 80) = 0.97 dB). This difference can easily be taken care of by the noise margin.

For the VDSL upstream direction however, the difference between measured (=averaged) noise and the real peak level can be as high as 7dB (10 log10 (100 / 20) = 6.99 dB). Therefore, to be "safe", either the noise from G.fast upstream transmission should not be a dominant noise source for a VDSL victim line, or the difference between measured and peak noise should be accounted for.

4.2 Control Methods

PSD shapes can be managed using a number of control methods including SSM, SSSM and DSM. The following definitions and assumptions are used. All three methods are already needed to control PSD limits defined in different parts of the existing ANFP [1].

SSM (Static spectrum management)

- One fixed PSD configuration applied across all DSLAMs,
    - or at most a few PSDs.
- Not parameterised through external parameters,
    - although it could include UPBO.
- Examples include ANFP Part A.

SSSM (Semi-static spectrum management)

- Likely to be single configuration per DSLAM,
    - or per group of lines
- Parameterised PSD configuration.
    - External parameters, e.g. CGAL and VDSL vectored state.
    - Typically parameters are based on network topology, state and capability rather than actual individual line performance.
- Changes infrequently for a DSLAM.
    - Perhaps due to network rearrangement, new DSLAM enabled, etc.
- Examples include ANFP Part B and Part C Static PSD.

DSM (Dynamic spectrum management)

- Likely to be configuration per-line, per vector group or per DSLAM.
- Parameterised PSD configuration.
    - Parameter selection driven by performance targets and actual line performance.
- Changes moderately often. Typically less frequently than daily.
    - For example, when new lines are initially brought up, the network is rearranged or new DSLAMs are deployed.
- Examples include ANFP Part C Dynamic PSD.

5 Use cases

There are a large set of possible use cases based on combinations of topology, PSD, control methods and other parameters. Those parameters are described and limited to the most useful values either for deployment or to allow practical comparison of a limited set of cases.

5.1 Topology

The UK access network was built organically over many years and is still being extended and modified today. In many areas downstream of a PCP there are a number of potential locations where G.fast units could be installed. The choice of locations from this set of locations depends on the target service offering. This means there is no single typical physical case to consider, rather a large set of more typical cases, which have been generalised into the following framework for simulations.

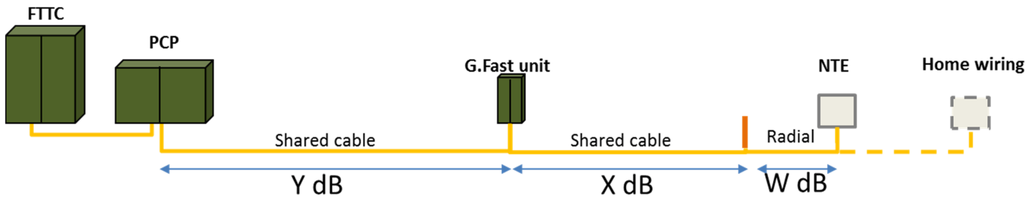


Figure 5-1 Generalised use case diagram

If G.fast is deployed at the cabinet, Y = 0, X represents the distribution side cabinet to distribution point (d-side) loss and, W the final radial drop from the distribution point. The DP is represented by the vertical orange line in Figure 5-1.

If G.fast is deployed at mid-point or DP locations Y is greater than zero and less than the maximum d-side length (W + X + Y). W can be zero for scenarios with no radial or single pair in use cables.

Given the wide distribution of d-side cable lengths, one customer connection from a DP could be longer than another customer from the cabinet.

The following assumptions were agreed for simulations.

- Maximum reach of G.fast = 500m
- All cable is assumed to be multi-pair 0.5mm copper with a loss of 11.47 dB/km at 300 kHz.
- Maximum d-side length is 2km based on VDSL reach from PCP, median length is ~350m
- “Final drop” beyond the DP, W, is up to 100m, median length ~35m

Note: Currently practical G.fast implementations may not reach 500m.

Three G.fast installation location use cases are defined for cabinet, mid-point d-side and DP deployment with loss ranges defined in Table 5-1.

Table 5-1 Loss ranges for use cases, in dB at 300 kHz

G.fast Location	Y	X	W
Cabinet	0	0 – 3.4 (0-300m)	0 – 1.1 (0-100m)
Mid span	3.4 - 23 (300 – 2000m)	0 - 3.4 (0-300m)	0 – 1.1 (0-100m)
DP	0 – 23 (0 - 2000m)	0(0m)	0 – 1.1 (0-100m)

Note: Loss ranges are approximate.

Note: The numbers in brackets are length in metres.

In addition to the loss in network location cases an in-home network as defined in Annex F.1.1 of BBF TR-114 [4] may be added.

Sagentia's report for Ofcom [14], includes the following figures which it quotes as representing the BT cabinet D-side length distribution and has been used by Sagentia and others as a reasonable representation of the situation. There are reproduced in Figure 5-2 and Figure 5-3, and used here.

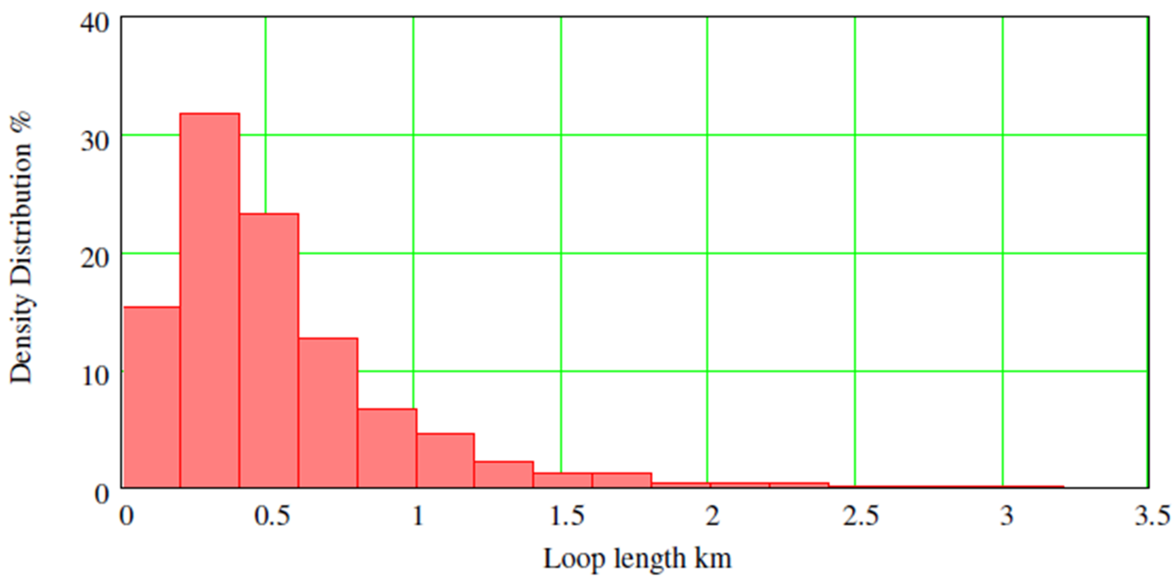


Figure 5-2 Distribution of street cabinet (D side) loop lengths

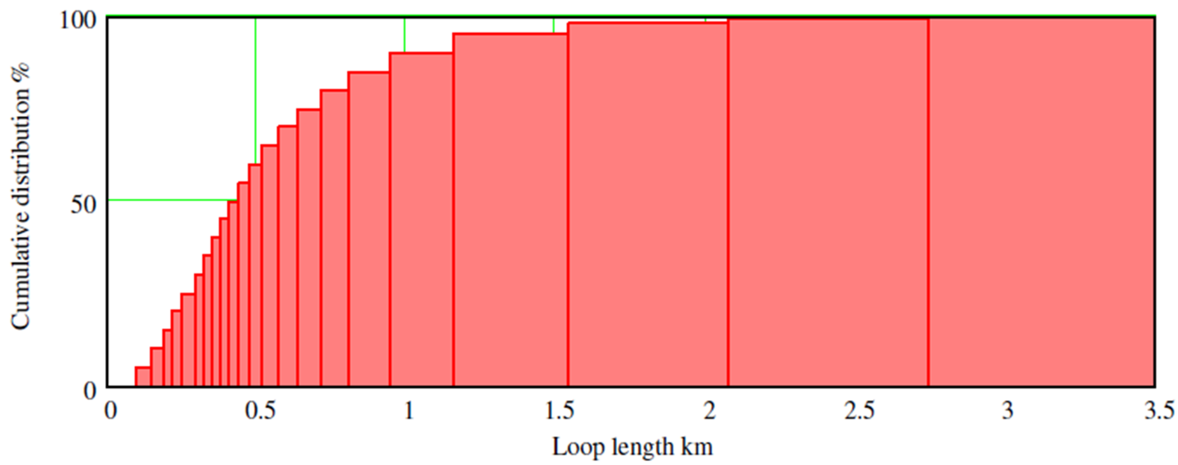


Figure 5-3 Cumulative distribution of street cabinet (D side) loop lengths

The median 'd-side' length, from the PCP to DP, is around 400m. G.fast DSLAMs could be installed in any one of a number of locations between the PCP and the end user equipment (CPE). The options considered in ND1520 have different effects depending on their design and the distance Y. The available spectrum for G.fast tends to increase as Y increases and the higher spectrum becomes less usable for VDSL. However, there will be a limited number of cases where G.fast can be deployed 1km or more from the existing VDSL location, only about 10% of lines exceed this distance and the majority of the lines connected to such a DSLAM would be shorter rather than longer. In general, the fraction of the network covered by cases with high Y is smaller than those covered with lower values of Y as shown in Figure 5-2.

5.2 Cable Fill

5.2.1 Simulation

There are two different approaches and sets of assumptions about cable fill used in the simulations presented in this document: a Monte Carlo approach and a fixed crosstalk approach. The two sets of assumptions result in significantly different levels of crosstalk.

Monte Carlo

This approach, selecting randomly from a distribution of crosstalk couplings, is used in for simulations in sections 7.1, 7.2, 7.5 and 7.6 covering cases for overlapping, re-farming, semi static re-use and dynamic re-use.

These simulations include the following assumptions.

- 12 G.fast lines and 8 VDSLs in a cable binder which are distributed and uniformly spaced
  - There is also a case with double the number of disturbers.
- Crosstalk couplings are randomly selected from a distribution, so the results are 'real' given the number of disturbers and in the average case will lead to a typical rather than worst case noise level.
- Maximum VDSL loop length 2400m
  - This is 1200m in the re-farming simulations, section 7.5.
- Maximum G.fast loop length 500m.

The uniform distribution across 2.4km leads to a VDSL circuit at approximately 300, 600, 900, 1200, 1500, 1800, 2100 and 2400m. Only the first two distances will use the full 17MHz of spectrum so between 12 and 17MHz, the highest VDSL downstream band, there are effectively 2 active VDSL disturbers.

The Monte Carlo approach produces data for minimum, 1% worst case, average, 99% best case and maximum rates, given the noise assumptions.

Fixed crosstalk

This approach, using a fixed crosstalk level, is used for simulations in sections 7.3 and 7.4 covering overlap and frequency re-use.

These simulations include the following assumptions.

- 1 G.fast line and 23 VDSL lines in a cable binder
- The CPE are co-located
- The maximum VDSL loop length is 2000m
- The maximum G.fast loop length is 300m

When considering the G.fast at a given loop length, the VDSL disturbers are all at that same length, so there are 23 disturbers across the whole VDSL frequency range.

This approach only presents the near worst case rates.

5.2.2 UK Access Network 2017

It isn't in the scope of this document to provide a detailed review of broadband use in the UK. However, the following discussion is provided to aid the reader in understanding the implications of the simulations presented in this document with respect to the Openreach access network.

The take-up of different broadband services in the UK is changing all the time, with a general trend in the telephony network of increasing take-up of cabinet based services and a reduction in exchange based services.

Total household broadband take-up is around 88% [15], with in the order of 30% take-up of VDSL, i.e. 8.6m subscribers out of 27.1m passed [16]. This suggests that 58% of household broadband is served from the exchange or by other services such as cable or fibre to the premise.

According to Figure 5-3 roughly 75% of d-side loops are less than 600m in length. Although the distributions vary, the shorter lines dominate most PCPs. The maximum usable frequency of un-vectored VDSL is 17.6MHz up to around 600m and up to 700m for vectored VDSL, therefore the majority of VDSL lines will be transmitting on all frequencies.

30% take-up of VDSL would mean that on average there are slightly fewer than 30 pairs of VDSL in a 100 pair cable leaving the PCP and slightly fewer than 15 pairs of VDSL in a 50 pair cable leaving the PCP.

5.2.3 Crosstalk variability

Options that overlap G.fast and VDSL in the region below 17MHz are highly dependent on the number of VDSL disturbers and the particular strength of the disturbers in each case. Most VDSL circuits in the UK access network are relatively short and use the full VDSL spectrum up to 17.7MHz. Such circuits will crosstalk into G.fast lines using spectrum below 17MHz. This will lead to variable G.fast performance.

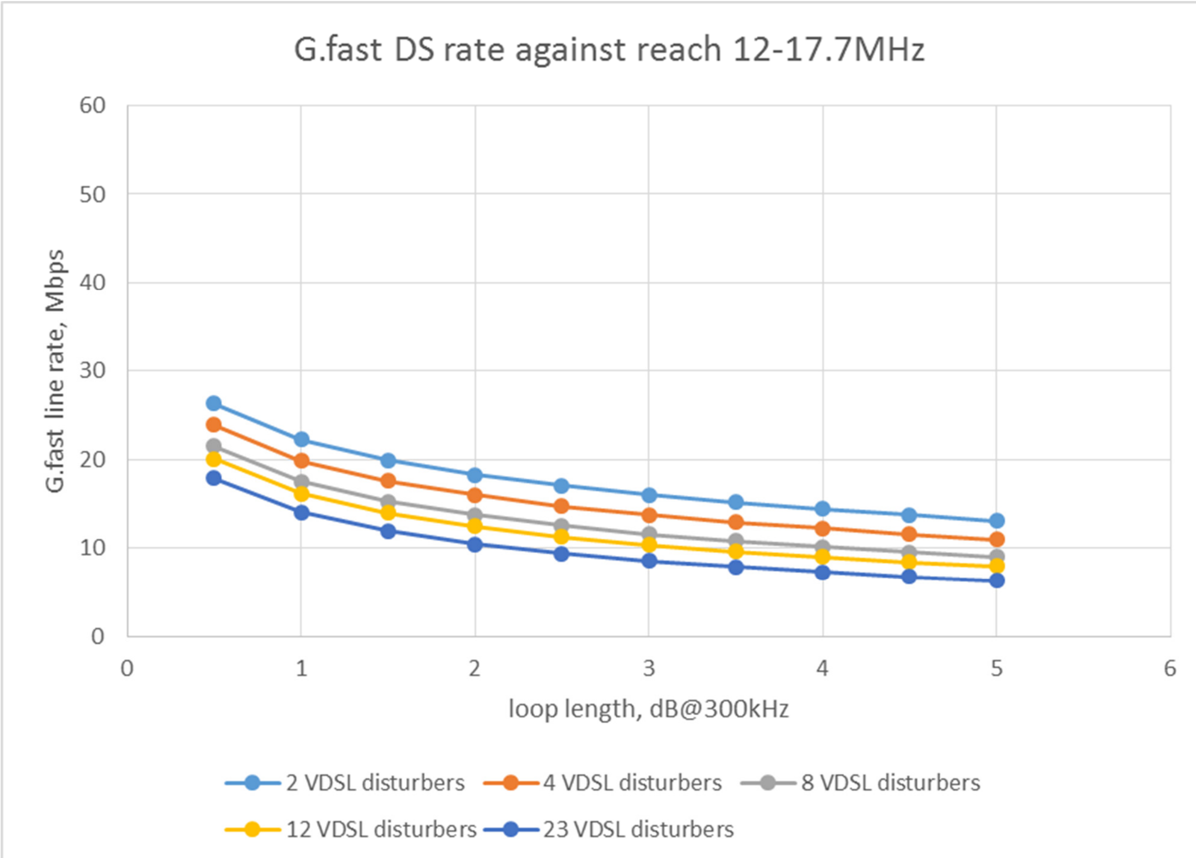


Figure 5-4 G.fast capacity with overlap in spectrum 12 -17.7MHz

The figure is illustrative of cross talk variability and uses co-located disturbers which could be overly pessimistic. The crosstalk is 9dB below the 99% worse case level which is closer to average cross talk severity.

5.3 Control Parameters and Method Details

5.3.1 Cut-off frequency, fcut

The cut-off frequency, fcut, defines the lowest passband frequency allowed to be used by G.fast. The values of fcut range between 2.2 MHz and 17.7 MHz. In static or semi-static cases fcut may be a fixed value across all lines in a given area, PCP or smaller area. In a DSM case fcut may be different for each cable, binder or vector group. In non-overlapping cases VDSL is restricted to operating in a passband below fcut. In overlapping cases VDSL is allowed to use frequencies above fcut.

In practice fcut would most likely be implemented by applying a profile to G.fast that sets a particular subcarrier mask (CARMASK) and/or or PSD mask (MIBPSDMASK). The profile is applied to the equipment by a management system. A profile may similarly be applied to VDSL, setting VDSL-CARMASK and/or PSDMASK.

5.3.2 Static Spectrum Management (SSM)

Description of method

This method uses fixed PSD limits applied across all DSLAMs. The externally applied configuration is the same for all lines, and the transceivers may adjust the PSD based on standardised control methods without external input. In practice the actual PSD used on each line may vary below the fixed PSD limits due to adaptation to the line by the transceivers themselves, for example due to politeness back-off or UPBO.

This may be extended to a limited number of PSDs, for example different PSDs for DP and PCP DSLAMs defined in Part E of the ANFP [1]. The DSLAMs used at the PCP and DP are likely to be different models, due to number of ports and physical location, and so two PSDs could be embedded in the DSLAM configuration without needing to consider which PSD to use on per DSLAM basis. If extended beyond two PSDs or if there is more than simple transceiver adaptation to the line, more control becomes necessary and this should be considered SSSM.

The key feature of SSM is that no variable parameters are externally configured for each DSLAM.

Architecture

There is no architecture applicable to SSM based PSD management.

Advantages

This is the simplest configuration to deploy and configure with no additional systems required to manage the DSLAMs beyond the minimum required setup.

Disadvantages

Often achieves lower bit rates than possible with SSSM or DSM based options.

Additional systems, functions, and interfaces

None. This is the reference control method with no additional system, functions and interfaces.

Transition

None required.

Commercial/regulatory implications beyond ANFP

None.

5.3.3 Semi-Static Spectrum Management (SSSM)

Description of method

This method uses a fixed PSD limit applied to each DSLAM or group of lines. The externally applied configuration is the same for each DSLAM or group of lines, and the transceivers may adjust the PSD based on standardised control methods without external input. In practice the actual PSD used on each line may vary below the fixed PSD limits due to adaptation to the line by the transceivers themselves, for example due to politeness back-off or UPBO.

There are multiple different PSD limits defined. Selection of a limit for each DSLAM is based on one or more parameters. These parameters may depend on network topology, for example Cabinet Assigned Loss (CAL) used in Part B of the ANFP, Cabinet Group Assigned Loss (CGAL) used in Part E of the ANFP or DP Type defined in Part C of the ANFP, or capability, for example DSLAM vectoring capability. The parameters change infrequently and may need updating if the network is rearranged or modified, or if a new DSLAM is enabled.

A database is needed to store the parameters which could be configured manually as needed or automatically using an algorithm or interface.

Architecture

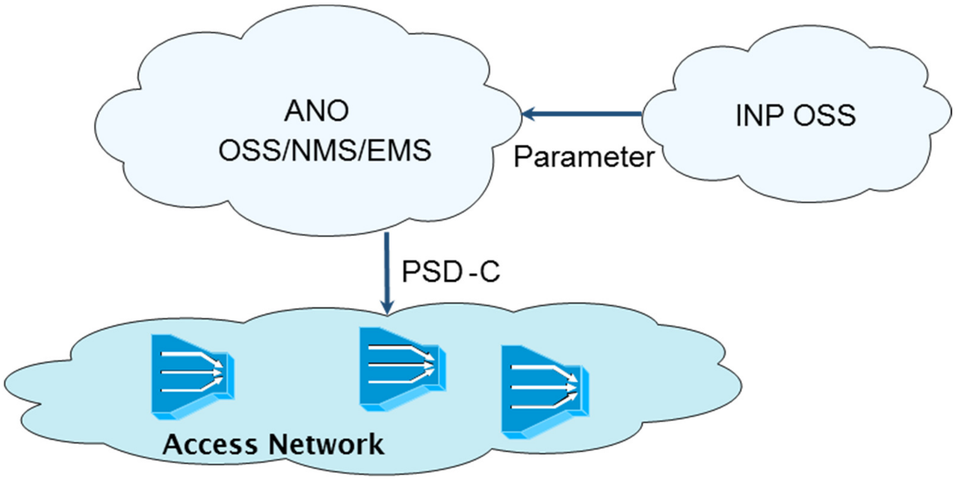


Figure 5-5 SSSM Architecture

Note: The ANO and INP may be the same entity

Advantages

SSSM increases speed relative to the existing ANFP; see Section 7.3 for examples of speed increases over SSM.

Simple configuration to deploy and configure with none real time systems and interfaces.

Performance tends to be stable over time.

Disadvantages

May not deliver as much speed as DSM in a limited number of cases.

Additional systems, functions, and interfaces

- Part B DSLAM/system
    - None, unless re-farming where an assignment of the cut-off frequency between VDSL and G.fast, fcut, would be required.
- Part E/F DSLAM/system
    - Configuration parameter must be sent to ANO (Access Node Operator) systems or DPUs/DSLAMs.
- Physical network operators systems to compute parameter, e.g. CGAL, and extension to existing interfaces to provide information DSLAM operators.

Transition

None required for SSSM control.

If re-farming changes to existing Part B DSLAMs would need to be implemented not after changes to the Part E/F DSLAMS.

Commercial/regulatory implications beyond ANFP

None.

5.3.4 Dynamic Spectrum Management (DSM)

Description of method

This method uses DSM level 2 multi-line spectral optimization. DSM coordinates multiple lines in ways that depend on the transmission environment. The main environment variables are transmission system types (G.fast or VDSL), service levels (e.g., data rate), loop lengths, deployment topology, and crosstalk couplings. DSM level 2 is described in ND1513 [6], and DSM algorithm details are described in ATIS-0000007 [7].

Analyses of DSM in Section 7.1 use the Iterative Water-Filling (IWF) technique, with the addition that G.fast is turned off at frequencies below the cut off frequency, “fcut.” Bit loading is determined by DSL transceivers at start-up, and is a good approximation of water-filling. With DSM, fcut is determined by the Spectrum Management Centre (SMC) depending on the overall environment and per-line target rates. While a conservative estimate of fcut could be made offline, in order to get the full benefits of DSM the parameter fcut should be determined by a SMC that has significant data on the transmission environment. A value of fcut is generally calculated separately for each G.fast DSLAM or vector group. Alternately, the SMC may use a different DSM algorithm [6] to calculate PSDs and then configure the PSDs with parameters such as the G.fast MIBPSDMASK.

In calculating fcut in the simulations, a VDSL per-line target rate can be assumed which makes the impact from a G.fast line on VDSL be no worse than the projected impact if that G.fast line were instead a VDSL. Other data rate targets can be input to the SMC, particularly if DSM is to be used with re-farming VDSL frequencies over to G.fast such that the VDSL per-line target rate may decrease.

The following PSD changes may result from this method:

1. Overlap of G.fast with un-vectored VDSL spectrum, generally matching the VDSL FDD structure, where it causes less impact on VDSL performance than VDSL self-crosstalk due to a lower and shaped transmit PSD.
2. PSD optimisation may reduce the VDSL maximum frequency and/or reduce VDSL PSD levels to improve G.fast capacity in overlapped spectrum while maintaining VDSL target rate. Displacing VDSL circuits with G.fast reduces VDSL self-crosstalk.

Architecture

Terminology here is from the ATIS DSM report [6]. A Spectrum Management Centre (SMC) is used to coordinate multiple VDSL and G.fast lines as shown in Figure 5-6. The SMC outputs DSM-Control (DSM-C) values of fcut, where fcut can be different for each G.fast vector group. The SMC also inputs DSM-Data (DSM-D) data on the transmission environment from the access network. The DSM-Service Provider (DSM-S) interface is optional, it may allow CPs to request delay, speed, and stability trade-offs; and may provide diagnostics and performance data to CPs.

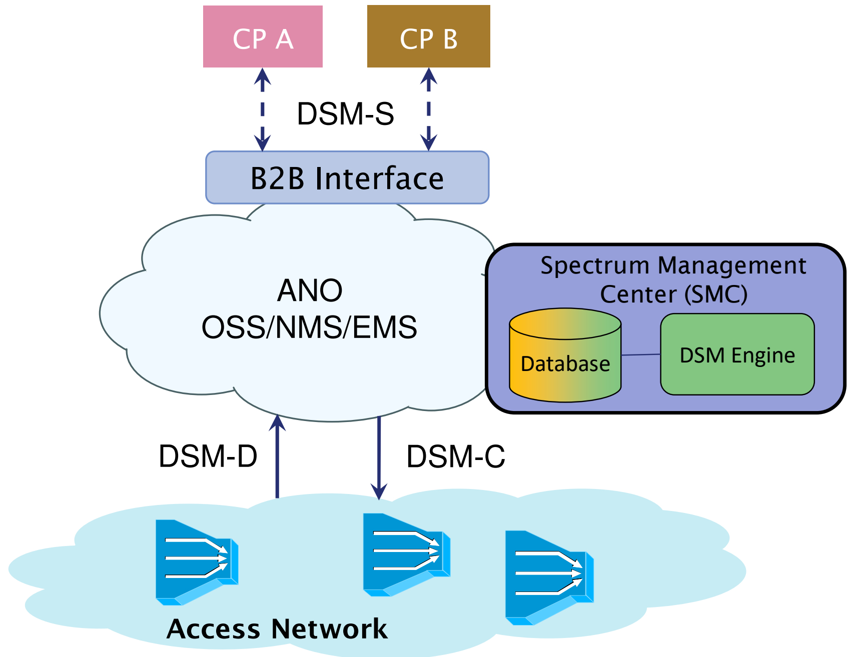


Figure 5-6 DSM Spectrum Management Centre (SMC) Architecture

The ATIS DSM report [7] lists parameters for the DSM-Data and DSM-Control interfaces. The DSM-S interface is as yet undefined. CPs could directly access the SMC, but CP messaging is more likely to pass through a Business-to-Business (B2B) interface before going to and from the SMC.

The DSM function for controlling overlapping VDSL and G.fast is implemented centrally, in the SMC. The configuration output by the SMC in this case is essentially fcut. It is likely that fcut will then be set by an ANO system applying a profile.

In a multi-operator environment, data to and from the SMC can be provided using data sharing as defined in NICC ND1518 *Data Sharing for DSM* [8], and Broadband Forum TR-349 *DSL Data Sharing* [9].

The configuration, particularly the value of fcut should only need to be changed if new lines are brought up or if existing lines are shutdown. In ongoing operation the SMC should oversee the speeds and other data on the VDSL and G.fast lines and make adjustments (e.g., raise or lower fcut) as necessary to ensure that service levels are maintained on all lines. All G.fast and VDSL lines should be grouped into a neighbourhood in which crosstalk between them is expected. After a re-configuration of fcut, neighbouring VDSL lines should be monitored for excessive impact to identify problems. The SMC should also remediate if necessary, for example by rolling back the re-configuration.

The SMC can be located anywhere and can be administered by the Access Node Operator (ANO), Infrastructure Provider (InP), CP / VNO, third party, etc. It can be implemented in server(s) or in part of a Network Functions Virtualization (NFV) system. The SMC may be a simple software system that just calculates fcut, or be part of a larger system that can oversee the impact of overlapping on all the lines.

Advantages

DSM often increases speed compared to SSM or SSSM; see Section 7.1 for examples of speed increases over SSM, and Section 7.7 for examples of speed increases over SSSM.

DSM allows flexibility and can implement various trade-offs between G.fast and VDSL, on a per-line or per vector group basis.

Another advantage of DSM is that there would be no need to change the ANFP once the VDSL2 customers have migrated to G.fast, assuming that the requirements for the algorithm are outside the ANFP

Disadvantages

There is some cost associated with installing and running an SMC. However, a centralized management system for tasks such as DSM level 1 or Fixed Access Network Sharing (FANS) may be installed anyway, which can lower the cost of the SMC itself. The costs of installing and interfacing to an SMC / centralized management system can be offset by using it for multiple functions, such as:

- DSM level 1 / DLM, to improve per-line stability, QoS, etc.
- Automated line diagnostics and monitoring, providing data to CPs on their lines.
- Fault correlation, where the SMC determines if a single root-cause is affecting multiple CPs' lines.
- Enable Fixed Access Network Sharing (FANS) [BBF TR-370]; which can share infrastructure investments, lower operations costs via automated interfaces, enhance VNO operations, and allow retail high-value services (e.g., prioritized business service).

As discussed in the next section, DSM-Data and DSM-Control interfaces are to be implemented, this requires some effort and has an associated cost.

New systems, functions, and interfaces

The SMC is a new system.

DSM-Data and DSM-Control are new interfaces to the SMC. These interfaces are already largely specified, see [8], [9] and [10], however an interface may be desired for passing fcut to an ANO system. However, identities, permissions, logins etc., would need to be configured to connect ANO systems to the SMC.

The DSM-S interface to the CPs is new, optional and not yet specified.

- Part B DSLAM/system
  - VDSL performance data should be supplied from the DSLAMs or ANO systems to the SMC across the DSM-Data interface.
- Part E/F DSLAM/system
  - G.fast performance should be supplied from the DPUs/DSLAMs or ANO systems to the SMC across the DSM-Data interface.
  - DSM-Control data must be sent from the SMC to ANO systems or DPUs/DSLAMs. This can control just one parameter, fcut, or it may also control additional parameters such as MIBPSDMASK.
- Interface to provide information to the SMC identifying interacting lines, such as inventory or topology data.
- (optional) The DSM-S interface between CPs and the SMC through ANO systems
  - CPs to SMC: desired or requested VDSL and G.fast service levels.
  - SMC to CPs: Some level of diagnostics and performance data.

Transition

VDSL operation should not be adversely affected by transitioning to DSM.

G.fast lines can initially use static spectrum management (SSM), overlapping or not overlapping. Some G.fast lines can then incrementally transition to DSM without degradation, however performance would be sub-optimal until most or all lines in a G.fast vector group are transitioned.

Commercial/regulatory implications beyond ANFP

Some agreement among CPs and ANO on a desire to use DSM to improve G.fast speeds is needed.

If DSM is to be used for re-farming VDSL frequencies over to G.fast, then the trade-off between VDSL and G.fast should be agreed between CPs and ANO.

The SMC needs to be installed and administered, so agreements are needed for this.

Permissions need to be enabled for interfaces to and from DSLAMs or ANO systems, and the SMC.

There should be permission for CPs to communicate over the DSM-S interface.

Combination with related uses such as DSM level 1 and FANS could be discussed.

5.3.5 NEXT and static approaches

In order to protect the VDSL lines when designing the G.fast PSD settings, we will first investigate what type of crosstalk from a G.fast line may have an impact, depending on their coupling (FEXT vs NEXT) and their origin (co-located vs non co-located). Considering an SSM or SSSM approach, we assume a worst case scenario for the topology, meaning that we do not look at the actual topology (which would require additional information from the network), but consider the topology for which the impact on the VDSL lines would be highest.

Crosstalk in overlapping bands

- FEXT : Far end crosstalk (= to victim at other side)
- NEXT : Near end crosstalk (= to victim at SAME side)
    - NEXT is much higher than FEXT => Reason for FDD in ADSL and VDSL.

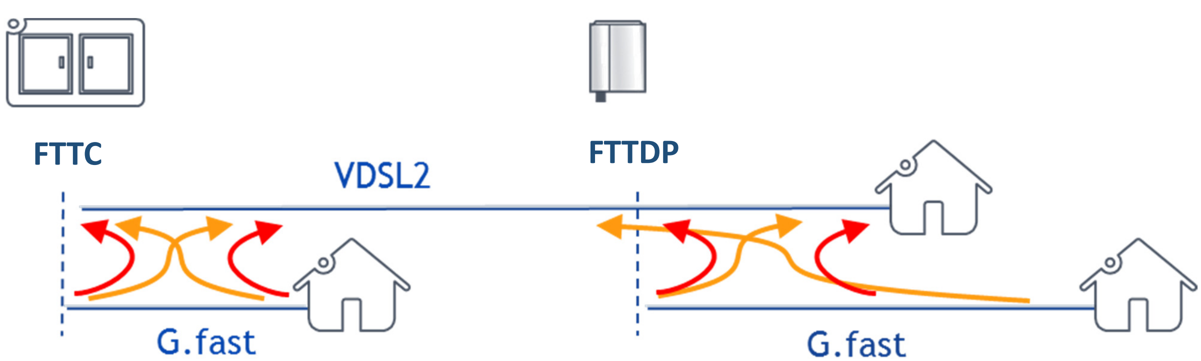


Figure 5-7 Co-located versus non co-located case

In such SSM or SSSM approaches, the following strategies may be adopted

CO-LOCATED CASE	NON CO-LOCATED CASE
NEXT: DS G.fast TX PSD (crosstalk to VDSL US) : avoid such transmit signals, as NEXT could heavily impact **US VDSL**	**NEXT: DS G.fast** TX PSD (crosstalk to VDSL US) : it could be possible to design such transmit signal to co-exist, as it strongly reduced by distance FTTN to FTTB
NEXT: US G.fast TX PSD (crosstalk to VDSL DS) : avoid such transmit signals, as NEXT could heavily impact **DS VDSL**	**NEXT: US G.fast** TX PSD (crosstalk to VDSL DS) : avoid such transmit signals, as it could heavily impact **DS VDSL**
FEXT: DS G.fast TX PSD (crosstalk to VDSL DS) : design such transmit signals to co-exist with the VDSL 17a DS service	**FEXT: DS G.fast** TX PSD (crosstalk to VDSL DS) : design such transmit signals to co-exist with the VDSL 17a DS (DS VDSL 17a attenuated loops, so more vulnerable)
FEXT: US G.fast TX PSD (crosstalk to VDSL US) : design such transmit signals, to co-exist with the VDSL 17a US service	**FEXT: US G.fast** TX PSD (crosstalk to VDSL US) : design such transmit signals to co-exist with the VDSL 17a US service (US G.fast FEXT strongly reduced by distance FTTN to FTTB)

To achieve protection of VDSL from the G.fast crosstalk, for an SSM or SSSM approach, NEXT from G.fast into VDSL should be avoided. This could be achieved either by

1. splitting G.fast and VDSL in frequency (no overlap, means no NEXT), or
2. semi-overlap, which means that in the overlapping spectrum,
    a. Downstream G.fast TX PSD should be limited to the VDSL downstream bands,
    b. Upstream G.fast TX PSD should be limited to the VDSL upstream bands.

5.4 High level control and PSD cases (the options)

There are number of variables and many possible different combinations of options that may be considered to reduce the start frequency for G.fast.

The variables and options include;

- vectored or un-vectored VDSL,
- single or multiple DSLAM operators in a PCP area,
- control by SSM, SSSM or DSM,
- frequency separated PSDs (as today), separate flexible, true overlapping,
- the impact on VDSL either allowing “little or none” or “large” impact, and
- which systems are reconfigured: the VDSL, G.fast or both?

The combinations of these options could lead to 10s of use cases to consider. The cases considered in ND1520 are listed in Table 5-2 and include those most likely to be useful in the UK network.

All options could be implemented with multiple DSLAM operators in a PCP area, although re-farming is most likely to be practical when the VDSL and G.fast DSLAMs are operated by a single operator.

Table 5-2 High level control and PSD cases (the options)

Options	Description	Control	PSDs	VDSL vectored or Not		Target impa existing VDS
1	Existing ANFP	SSM	Separated. Existing fixed split.	Both		None
2	Overlapping	2a SSM 2b SSSM	Overlapped. G.fast follows VDSL PSD. Co-located case only. Non-co-located adds DPBO.	Un-vectored		Little or Nor
3	Re-farming	SSM or SSSM	Separated. New split freq. Variable for SSSM.	Both		Large
4	Variable split freq. per DSLAM	SSSM	Separated. Variable split.	Both		Little or Nor
5	Variable split freq. per line or per vector group	DSM	5a Separated. Variable split. Note 1. 5b Partially overlapping. Variable split.	5a Both 5b Un-vect		Little or Nor
Note 1: Simulations for 5a are not presented in this document.						

5.4.1 Existing ANFP

This option, to continue with the existing ANFP v.6.1.1 specification for G.fast, requires no change to the ANFP or G.fast or VDSL implementations. This option is used as a baseline when considering the other options. The specification was designed to give a high degree of confidence, even though there was no international experience of deployed G.fast, that the introduction of G.fast would have no impact on existing services. It uses frequency separation between G.fast and VDSL, limited by accounting for the weakest known VDSL anti-alias receiver filters.

The two lines in Figure 5-8 show an example of the frequency separation specified in the ANFP v6.1.1 for VDSL CAL52 co-located with a G.fast DSLAM.

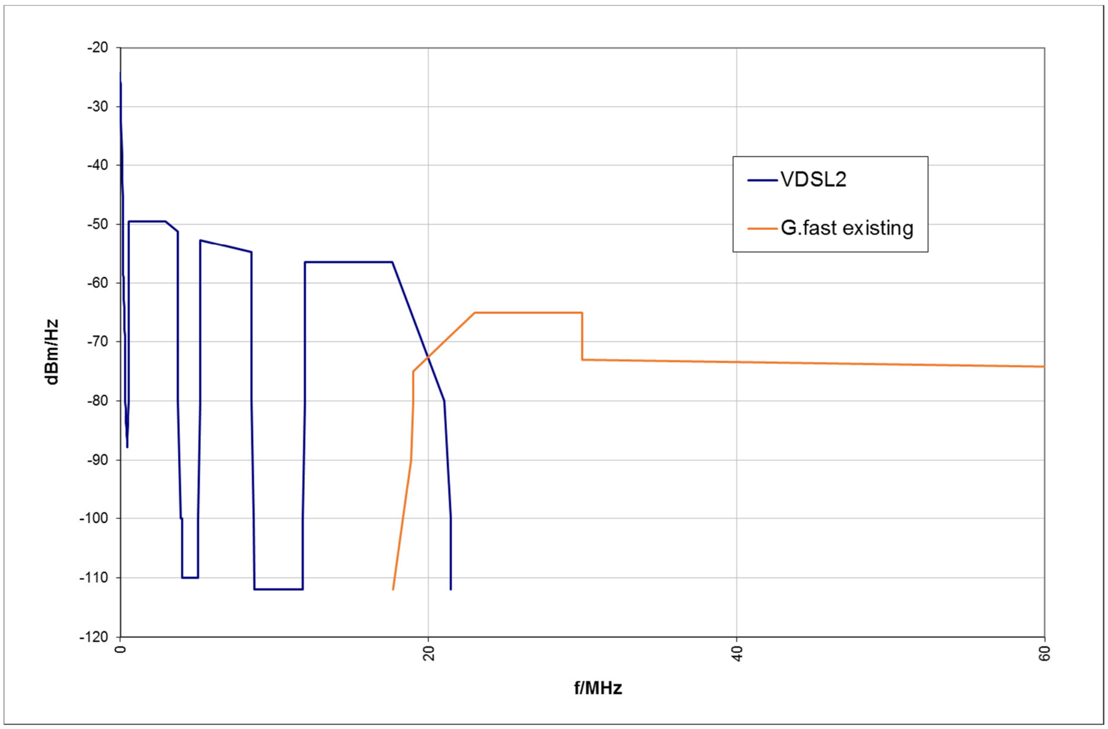


Figure 5-8 Example existing ANFP PSDs

5.4.2 Overlapping

This option is designed to minimise the changes to existing DSLAM implementations, the ANFP and have little or no impact to VDSL performance. It is separated into the co-located and non-co-located cases to demonstrate what is possible with minimum changes or with UPBO. It could increase bit rates of G.fast by changing the existing PSD masks in the ANFP for G.fast. This would not mandate changes to existing G.fast DSLAMs as those implementations would still be compliant. No new functionality would be needed in the ANFP or G.fast DSLAMs, other than changing the PSD. No changes would be needed to VDSL.

The control method is static for the co-located case and semi-static for the non-co-located case. The G.fast start frequency is lowered and would result in actively overlapping frequency use between VDSL and G.fast. Depending on the G.fast start frequency chosen long VDSL lines wouldn't actively overlap with G.fast because they can't use the highest available frequencies. Figure 5-9 illustrates this concept. A number of different static overlapping PSDs will be considered.

To meet the minimal change design requirement DPBO wouldn't be possible for the G.fast PSD; the co-located case (2a) is simple and static. The non-co-located case (2b) would require an additional parameter and SSSM to drive the PSD shape, where the G.fast PSD level below 17.7 MHz is related to the distance between the G.fast and VDSL DSLAM. No new controls are required for the VDSL DSLAMs. Different PSD levels are used by each non-co-located G.fast DSLAM.

The little or no impact to VDSL requirement means that this option is only possible if the VDSL isn't already vectored. Although the aim of the option is little or no harm it should be noted that this option would preclude some of the future gains from vectoring VDSL.

SSM/SSSM overlapping described in this document limits G.fast so that it only transmits in the same direction as VDSL, e.g., downstream G.fast transmits in some of the downstream VDSL frequency bands.

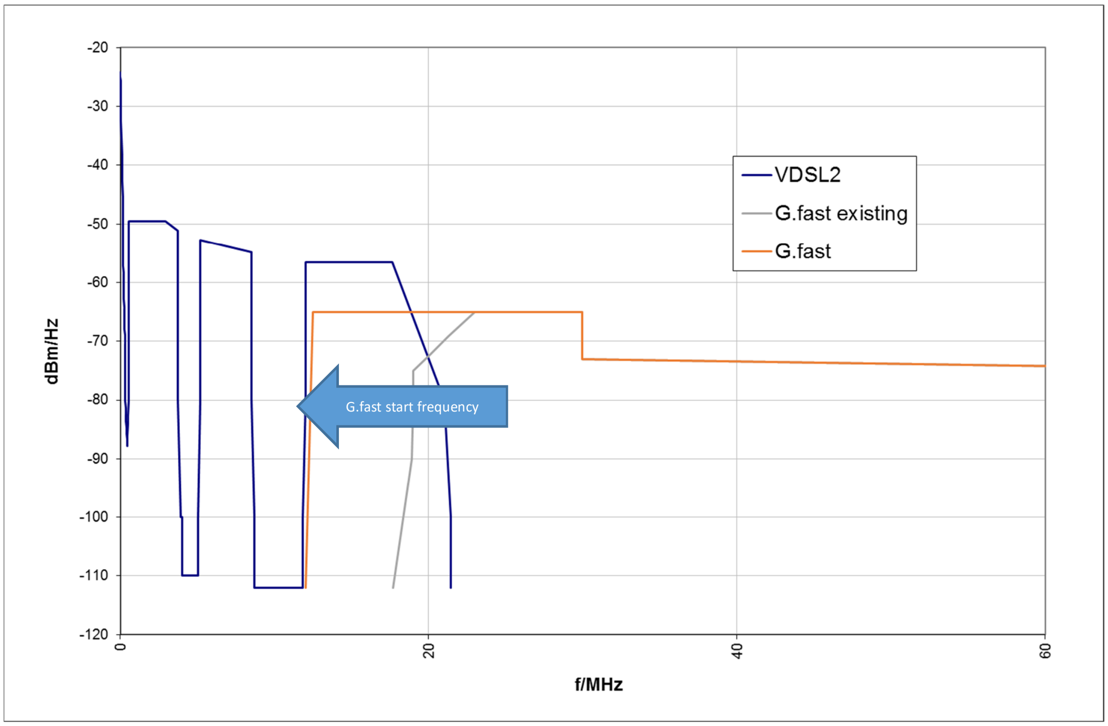


Figure 5-9 Illustration of a simple overlapping PSD for a co-located case

The non-co-located PSD with DPBO is illustrated in Figure 6-3.

5.4.3 Re-farming

This option is designed to show what benefit can be achieved when a large impact is allowed to VDSL. The start frequency for G.fast is lowered and so is the corresponding highest frequency for VDSL. No other changes are required to VDSL or G.fast. This re-allocation of the frequency currently allowed for VDSL to G.fast is what is termed "re-farming", as opposed to re-use.

The control method is static, although it could be combined with either of the following options. A range of possible G.fast start frequencies and their impact on vectored and un-vectored VDSL are considered.

Figure 5-10 illustrates this option.

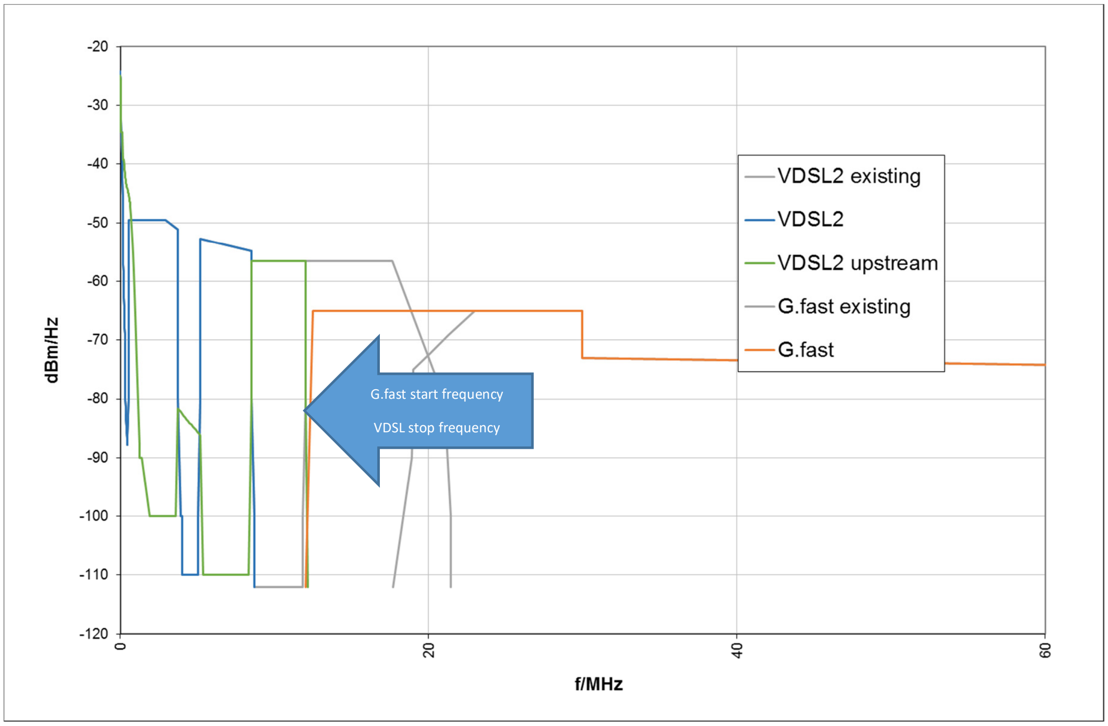


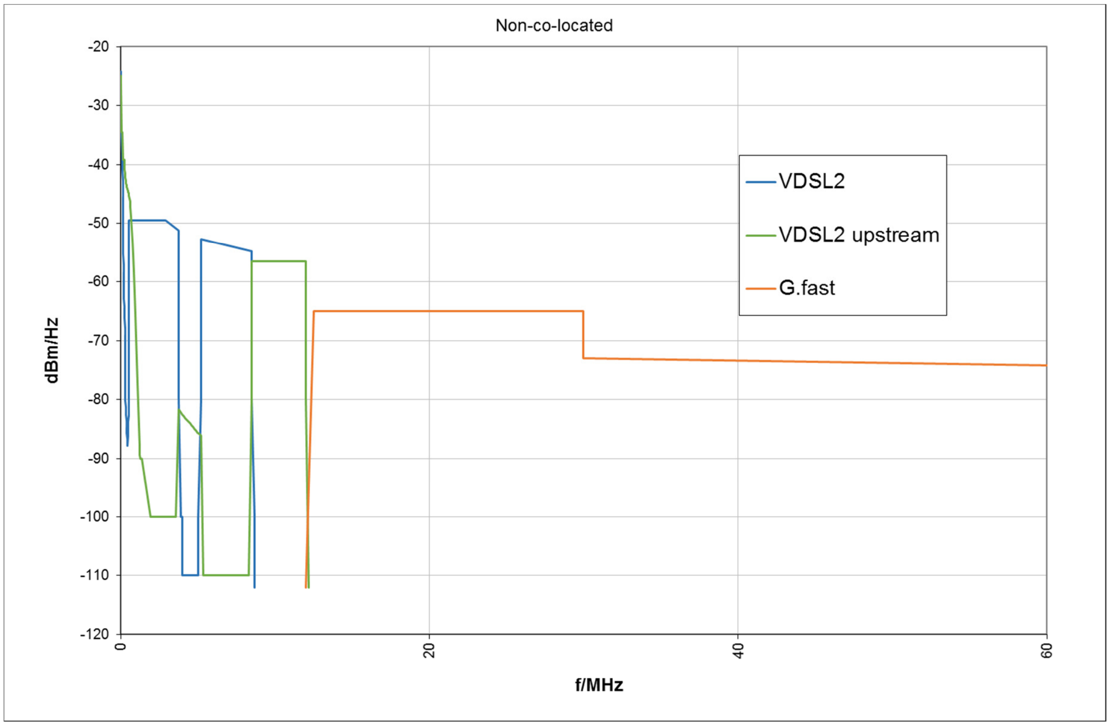
Figure 5-10 Illustration of a re-farming PSD set

5.4.4 Variable split frequency per DSLAM

This option is designed to show the gains from re-using frequencies unused by VDSL when the G.fast DSLAM is deployed closer to the customers than the VDSL DSLAM location. It aims for little or no harm to VDSL services. It requires an additional control of the G.fast PSD shapes through a semi static management approach where the G.fast start frequency is related to the distance between the G.fast and VDSL DSLAM and possibly also whether the VDSL DSLAM is vectored or not. No new controls are required for the VDSL DSLAMs. Different start frequencies are used by each G.fast DSLAM.

The actual start frequencies that could be chosen will be affected by take-up and technology capability. Values will have to be defined for these when calculating the control parameter.

Figure 5-11 shows how the frequency choice could vary given a long distance between the VDSL and G.fast DSLAM or a co-located case.



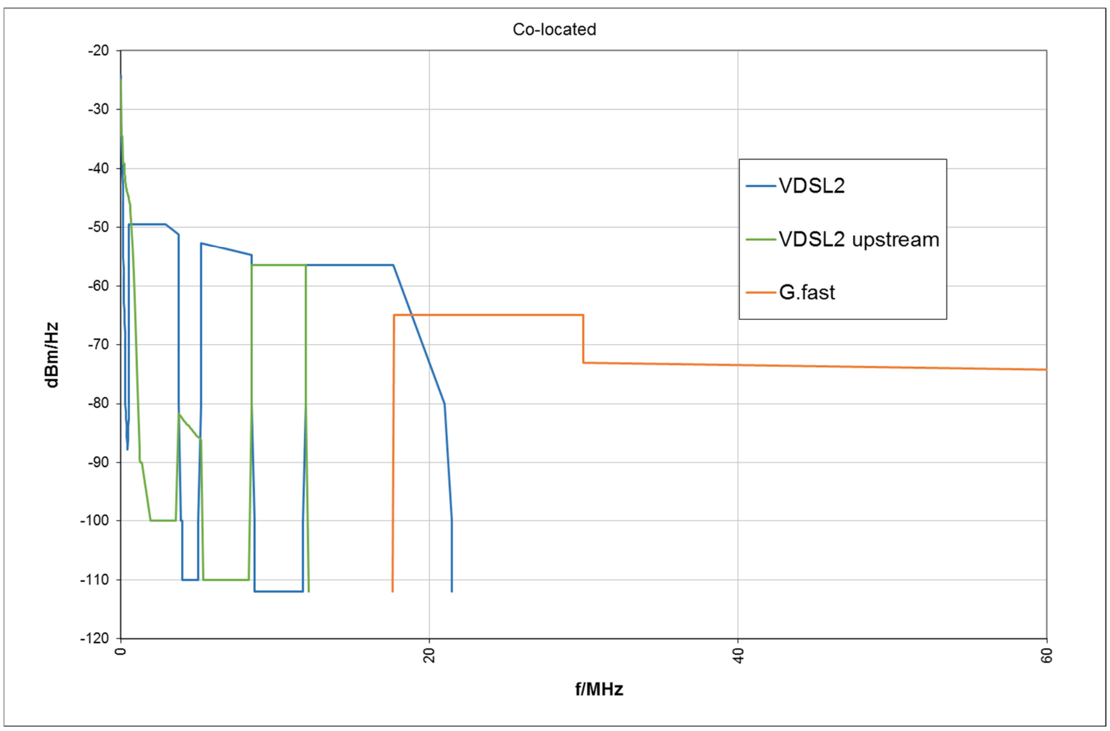


Figure 5-11 Illustrations of PSDs for different G.fast DSLAM locations

5.4.5 Variable split frequency per line or vector group

This option was designed to show what could be achieved with totally dynamic control of individual G.fast and VDSL systems on a line by line basis. This uses Dynamic Spectrum Management (DSM) level 2 [7] multi-line spectral optimization in a situation-dependent manner.

This option optimizes the transmit PSDs of both G.fast and VDSL. Depending on frequency, overlapping transmit PSDs can be reduced in order to reduce crosstalk into other lines, while still transmitting an efficient power level to carry some data. Transmission can be turned off entirely in frequencies with high crosstalk and when the relevant bit cap has been achieved. Similar to option 4, this option reuses frequencies above those actively used by VDSL, but it can also allow G.fast PSDs to overlap with VDSL PSDs. With DSM G.fast usually only transmits in the same direction as VDSL, e.g., downstream G.fast transmits in some of the downstream VDSL frequency bands. However, in some frequencies with low NEXT, downstream G.fast may also overlap with upstream VDSL.

DSM simulations in Section 7.1 determine an adaptive value of fcut and further optimize transmit PSDs of both G.fast and VDSL with Iterative Waterfilling (IWF). Only the un-vectored case is considered in simulations. Other DSM level 2 algorithms could be used.

This option includes control of the start frequency of G.fast and preferably uses VDSL and G.fast equipment that supports waterfilling capability. Control of VDSL and/or G.fast PSD masks is a further possibility, which could be used in lieu of equipment supporting waterfilling.

Examples illustrating PSDs with this option are shown in Figure 7-8 to Figure 7-11.

5.5 Impact between technologies

Historically the ANFP has been based on the principle of “no more harm” when a new technology is deployed compared to the existing ones.

The model has changed with the introduction of vectoring because self and alien crosstalk are no longer equivalent and have a different order of impact on performance. Given the equivalence of disturbers is now broken, we need to consider a new method of trading performance between different systems.

As end customers measure speed and stability, equal capacity (i.e. the combination of rate and margin) is the obvious choice. However, as DSL systems are rarely run at maximum noise free performance, it seems the most obvious use-case would be that of “constrained expected capacity for both downstream and upstream” e.g. a maximum rate of 80Mbps downstream with 9dB SNR margin.

- For non-vectored locations, this is the crosstalk limited performance up to a maximum of the product cap including the desired target margin.
- For vectored locations, this is the vectored crosstalk limited performance up to a maximum of the product cap including the desired target margin.
- For locations where VDSL is vectored at the same time as G.fast is deployed, this could be the initial crosstalk limited performance up to a maximum of the product cap including the desired target margin.

However, in the real world capacity or speed is a time varying parameter, it does not make sense to have the relative mix of ADSL1, ADSL2+, VDSL, vectored VDSL and G.fast implicitly or explicitly defined by the ANFP. The performance of DSL equipment and take-up will vary with equipment and topology.

Therefore, it is proposed that

- a framework rather than an absolute performance level is used for cases that either

  - have high impact on VDSL
  - or exploit variability between locations (DSM), and
- that a performance level is used for cases that
  - aim for low impact and per DSLAM static control

The new impact framework to be considered when designing potential ANFP changes is as follows:

For non-co-located DSLAMs with DSM (part of option 4 from Table 5-2):

- As there is a distance dependency between the cabinet and the G.fast injection point, it is straightforward to use the CGAL to determine the transition frequency without overlapping spectrum and with little or no harm to existing services
- The G.fast could be pushed a small way into the VDSL usable spectrum if it can be shown that G.fast does little or no harm to relative to existing VDSL.

For overlapping spectrum (option 2 from Table 5-2):

- G.fast should not reduce VDSL capacity beyond that of the VDSL disturbers
- For non-co-located scenarios (DSLAM or CPE end) the G.fast power must be shaped to ensure the transmit power in the overlapping region to prevent harm beyond that of the expected level

For re-farming spectrum, large VDSL impact (option 3 from Table 5-2):

- Every sub-loop connection point (SLCP) will be different in terms of technology deployed (VDSL, vectored VDSL and G.fast), network operators of each asset, current take-up of each technology and predicted take-up of each technology
- Network operators should agree on the target performance for each technology in particular the VDSL capacity target and the target technology mix
- Once this is determined, the operators should either:

  a. Uplift a non-vectored VDSL DSLAM to a vectored DSLAM
  b. Migrate customers from VDSL to G.fast to reduce the crosstalk
  c. On a per SLCP basis choose a transition frequency that protects the rates on offer (note: this will significantly reduce the potential level of re-farming)

For DSM (option 5 from Table 5-2)

- Every SLCP will be different in terms of technology deployed (VDSL, vectored VDSL and G.fast), network operators of each asset, current take-up of each technology and predicted take-up of each technology
- Network operators should agree on the target performance for each technology in particular the VDSL capacity target and the target technology mix
- Network operators should agree on data sharing and control architectures, interfaces and systems to support DSM control

The crosstalk coupling between pairs and the loss of the pairs varies between pairs, cables and cable types which means that the exact performance of a DSL on a specific pair is not normally known until it is trained up. SSM and SSSM based control methods tend to include PSD designs based on worst case assumptions of network coupling. In rare cases these assumptions may be broken and the harm be worse than that modelled.

The DSM solutions considered in this document are more flexible and by responding to the actual conditions can avoid unexpected harm in the worst cases.

6 Simulation Assumptions

The follow text provides default assumptions for use in simulations for G.fast performance and impact modelling. Simulations results presented in this document use these assumptions unless otherwise stated. Additional assumptions are presented with simulation results as required.

6.1 Network Parameters

Table 6-1 Network Parameters

Drop wire	0.5mm copper
Distribution cable	0.5mm; 20, 50, or 100 pair
Background noise (baseline)	-140 dBm/Hz below 30 MHz, -150 dBm/Hz above 30 MHz
NEXT model (only validated below about 30 MHz)	**1% worst-case, n disturber model** *"1% probability worst case NEXT coupling will be modelled by:* *NEXT(f , n) = -55 + 15 log10 (f /100kHz) + 6 log10(n /49)* *Where f is frequency in kHz and n is the number of disturbers and the result is expressed as a power coupling factor in dB."* **Stochastic, 24 disturber model** *NEXT(f) = lognormal(mu= -56.8 + 15 * log10 (f /100kHz), sigma 1.04) dB* **Stochastic, pair to pair model** *NEXT(f) = lognormal(mu= -75.2 + 15 * log10 (f /100kHz), sigma = 5.2) dB* Note: These models are based on small cable sizes and hence the stochastic models may be pessimistic for the DSLAM end NEXT coupling.

6.2 Simulation parameters for G.fast

Table 6-2 G.fast Parameters

Physical layer overhead	10%
SNR margin	6 dB
Coding gain	3 dB

Min-Max Bits per tone	1 - 12 or 1 – 14
G.fast nominal transmit PSD	• G.9700 for worst-case crosstalk from G.fast; Maximum PSD from G.9700 [3]. • Or for G.fast performance simulations, G.9700 limit to the aggregate transmit power of 8 dBm. (note that then min value of G.9700 is -76, so a flat PSD of -75.3 dBm/Hz is a good approximation);
Vectoring cancellation depth	Vectoring is assumed to lower the cancellable G.fast FEXT by 40 dB
Frequency limits	2 to 106MHz

6.3 Simulation parameters for VDSL

Table 6-3 VDSL Parameters

SNR margin	6 dB
Coding gain	3 dB
Bits per tone (Min-Max)	1-14
Overhead	10%
VDSL PSD template	All systems transmit the maximum PSD as allowed by the ANFP [1] parts B and C (nominally 3.5 dB below the PSD mask.)
Vectoring cancellation depth	• Vectoring is assumed to lower the cancellable VDSL FEXT by 25 dB. • Non-Vectored systems don't lower the cancellable FEXT

6.4 VDSL anti-alias filter model

A filter roll off is defined in Table 6-4 that should be used to simulate the effect of VDSL anti-aliasing filters. This is the worst case known filter. Linear interpolation in dB should be used between frequencies defined in the table. This filter can be used for the down and upstream receivers.

Table 6-4 VDSL alias filter model

Frequency (MHz)	Filter Loss (dB)
0	0
18.2	0
23.328	-49.5

23.329	-41
25.328	-69
30	-69

6.5 Further Simulation Assumptions

This section provides simulation assumptions that were agreed at the beginning of this study.

1. No exchange based disturbers.
2. VDSL CAL value is 20dB.
3. That that VDSL and G.fast PSDs must be compliant with ITU-T recommendations e.g., number of breakpoints, gradient of slopes etc. These are defined in G.9701 [2] section 7.3.1.1 and G.9700 [3] section 6 for G.fast and in section 7.2 of G.993.2 [5] for VDSL.
4. Assume G.fast is deployed to “most” of the UK. In most cases the route from the PCP will be covered by multiple G.fast units.
    a. When we consider G.fast at the VDSL cabinet there will be other G.fast DSLAMs serving customers beyond the reach of the first DSLAM.
5. That when considering G.fast beyond the VDSL cabinet it is assumed that all subscribers before that point have access to VDSL and G.fast from other DSLAMs.
    a. That we consider cases when there are 2 or 3 G.fast DSLAMs.
    b. The first DSLAM is always located at the PCP.
6. That the maximum reach of G.fast DSLAMs is either 300 or 500m.
    a. And that the next DSLAM is placed between the last customer on the previous DSLAM and the first customer beyond that.
7. That where there is VDSL and G.fast available to customers the take-up is split 40/60 (VDSL/G.fast).
8. Three maximum length cases be considered 1.2km, 2.4km and 4km [for VDSL].
9. There are a low and a high take-up case, and the number of disturbers from the PCP
    a. For simulations that a run using a Monte Carlo approach and take a random selection of coupling paths from a distribution for each simulation, the number of disturbers is either 20 or 40.
    b. For simulations based on worst case crosstalk the numbers of disturbers are defined in the relevant sections.
10. The minimum distance from the PCP to first customer is circa 50m.
    a. The exact minimum length is chosen to fit the detailed scenario.

Simulations in section 7.1, 7.2, 7.5 and 7.6 distribute the VDSL and G.fast NTE. Figure 6-1 illustrates the distribution and losses used in those simulations.

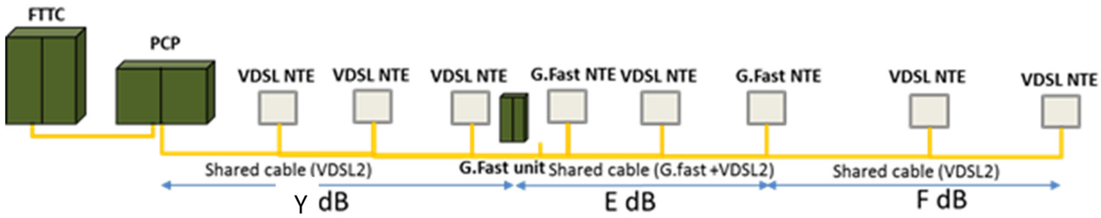


Figure 6-1 Non-co-located DSLAMs with distributed NTE.

6.6 PSD definitions

The PSDs described in this section are used for the simulation of the performance, and not intended as ANFP PSD proposals.

6.6.1 DS3 Only

Can be implemented using current G.fast standards.

The G.fast downstream PSD here is overlapping with some downstream VDSL frequencies.

The G.fast PSD is extended down to around 12MHz as shown in Figure 5-9.

Table 6-5 DS static G.fast PSD mask

freq, MHz	PSD mask, dBm/Hz
0.0001	-100
2	-100
11.825	-100
12	-80
12.28	-65
30	-65

6.6.2 G.fast PSD with “DPBO”, Equal Power

This model is optional and not used by all simulation cases. It modifies downstream G.fast that is not co-located with VDSL to be compatible with downstream VDSL, similar to cabinet VDSL DPBO used to protect exchange based services.

This “DPBO” model is not the same as existing VDSL DPBO models described in ITU G.997.1 [11].

An equal FEXT based model is provided in section 6.6.3.

These PSDs cannot be implemented using current G.fast standards because they do not take into account the ITU-T PSD shaping constraints, nor the PSD side-lobe effects.

To achieve protection of VDSL from the G.fast crosstalk, the NEXT from G.fast into VDSL is avoided.

Semi-overlap is used, which means that in the overlapping spectrum,

- DS G.fast TX PSD should be limited to the VDSL DS bands,
- US G.fast TX PSD should be limited to the VDSL US bands.

G.fast transmission in DS for the co-located scenario:

- In the VDSL DS bands, G.fast can transmit at full power
- Above the VDSL DS bands (as of 17.6 MHz), G.fast can also transmit at full power.

G.fast transmission in DS for the NON co-located scenario:

- In the VDSL DS bands, the PSD of G.fast is attenuated. This is very similar to the DPBO concept in VDSL that is used to protect exchange lines the target: PSD Mask for G.fast in the VDSL DS bands is the minimum of:
    - The G.fast PSD mask as per G.9700
    - The attenuated VDSL PSD mask: this is the PSD mask of the victim VDSL system (deployed from the cabinet) as per G.993.2, reduced by the attenuation per frequency, obtained from the cable attenuation corresponding to the distance from the cabinet to the G.fast injection point.
- To consider the effect of aliasing, some "modification" is done in the transition band.

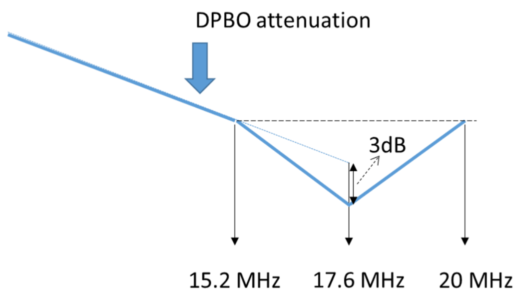


Figure 6-2 Schematic for G.fast DPBO in transition area

    - PSD breakpoint at 20 MHz is the same as at 15.2 MHz
    - PSD breakpoint at 17.6 MHz is reduced by 3 dB
- Above 20 MHz, G.fast can transmit at full power.

G.fast transmission in DS – PSD graphs

Figure 6-3 shows example PSDs for G.fast in DS for both the co-located and non-co-located scenario. For the non-co-located scenario, the DP is assumed to be at 300m away from the VDSL cabinet.

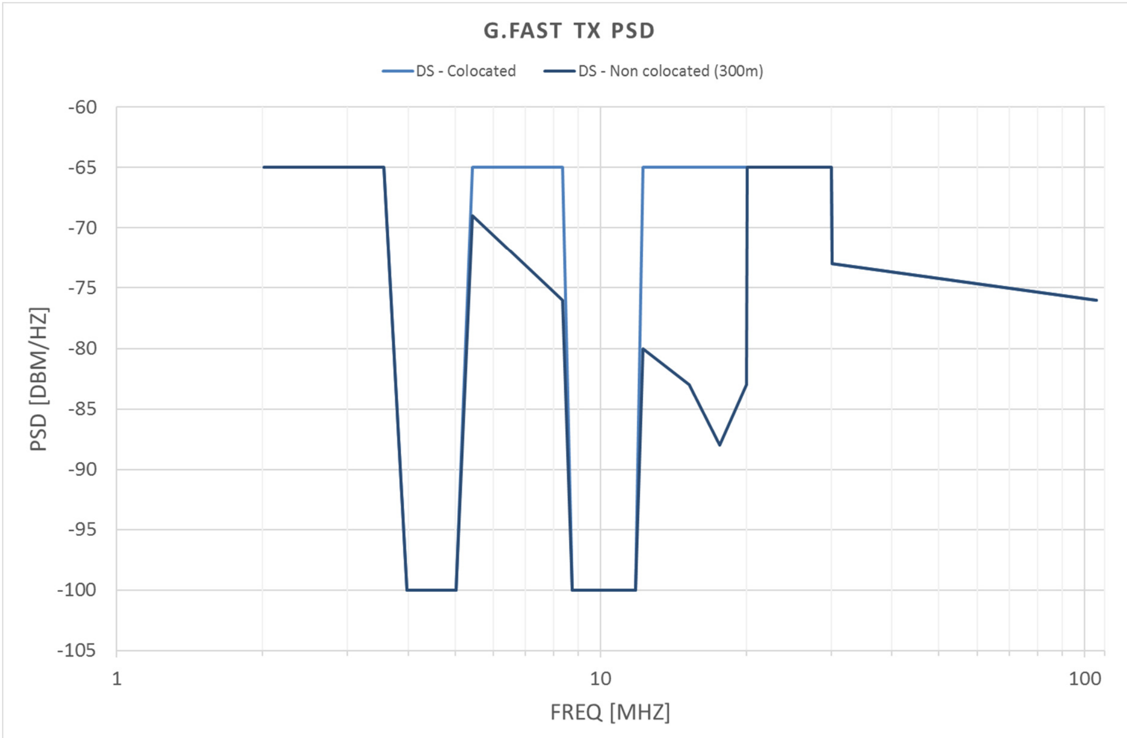


Figure 6-3 G.fast downstream PSDs with DPBO

Note that the PSD above is just an example, used for the simulation of the performance, and is not intended as ANFP PSD proposal, because it doesn't take into account yet the ITU-T PSD shaping constraints, nor the PSD side-lobe effects.

6.6.3 G.fast PSD with "DPBO", Equal FEXT

This model is optional and not used by all simulation cases. It modifies downstream G.fast that is not co-located with VDSL to be compatible with downstream VDSL, similar to cabinet VDSL DPBO used to protect exchange based services.

This "DPBO" model is not the same as existing VDSL DPBO models described in ITU G.997.1 [11].

An approach similar to the ANFP for cabinet-based VDSL FEXT into ADSL for Y > 0 is defined. The overlapping downstream G.fast mask is adjusted such that it generates FEXT commiserate with a PCP-based VDSL.

The well-known FEXT model is

$$FEXT(f) = Klf^2|H(l,f)|^2 TxPSD(f)$$

where *l* is the loop length and $TxPSD(f)$ is the transmit PSD. For the 1-disturber 99% worst-case, with *f* in Hz and *l* in meters, *K* = 2.54E-20.

The FEXT generated from the G.fast unit into an NTE at loop length Z is

$$FEXT_F(f) = KZf^2|H(Z,f)|^2 TxPSD_F(f)$$

The FEXT generated from the VDSL into the same NTE is

$$FEXT_V(f) = K(Y+Z)f^2|H(Y+Z,f)|^2 TxPSD_V(f)$$

The objective is to make the G.fast FEXT, $FEXT_F(f)$, equal the VDSL FEXT, $FEXT_V(f)$.

$$FEXT_F(f) = FEXT_V(f)$$

$$KZf^2|H(Z,f)|^2TxPSD_F(f) = K(Y+Z)f^2|H(Y+Z,f)|^2TxPSD_V(f)$$

$$TxPSD_F(f) = \frac{K(Y+Z)f^2|H(Y+Z,f)|^2TxPSD_V(f)}{KZf^2|H(Z,f)|^2}$$

Approximately, $|H(Y+Z,f)|^2 = |H(Y,f)|^2|H(Z,f)|^2$, so then

$$TxPSD_F(f) = \frac{(Y+Z)}{Z}|H(Y,f)|^2TxPSD_V(f)$$

And so if Y > 0, then the downstream G.fast PSD mask is multiplied by $\frac{(Y+Z)}{Z}|H(Y,f)|^2$ to have impact commensurate with that of VDSL.

An equal PSD method is provided in section 6.6.2. The equal PSD model has

$$TxPSD_F(f) = |H(Y,f)|^2TxPSD_V(f)$$

6.6.4 DSM PSDs

DSM level 2 can vary transmit PSDs depending on the environment: loop topology, crosstalk couplings, noise, systems and services. The ATIS DSM report describes DSM level 2 Algorithms in detail. Iterative Water-Filling (IWF) is a good DSM level 2 algorithm for determining PSDs for overlapping VDSL and G.fast frequencies, and IWF is further discussed in Section 5.3.3 and analysed in Section 7.1. The DSM algorithm use in Section 7.1 combines IWF with an outer loop that optimizes fcut.

DSM PSDs are designed to meet all applicable limit masks as defined in ITU-T standards.

As envisioned here, DSM constructs G.fast PSDs such that the lowest passband frequency of G.fast is fcut, where fcut may be different with each cable, binder or vector group. VDSL may use frequencies above fcut if the DSM PSD optimization supports this. DSM PSDs only slowly vary with time, and the value of fcut should only need to be changed if new lines are brought up or if existing lines are shutdown.

7 Simulations and Analysis

This section includes simulations and analysis that relate to the use cases described in section 5.4. The results aren't exactly aligned between the different simulations because they are assembled from contributions by more than one author.

7.1 DSM, with fcut versus overlapping SSM

This section covers the following high-level use case from Table 5-2:

- Case 5b, variable split frequency per line or per vector group (DSM) for un-vectored VDSL

7.1.1 Description

As described in Section 5.3.4 the Iterative Water-Filling (IWF) DSM level 2 algorithm is used here to adjust PSDs on a case-by-case basis, to maximize G.fast performance while ensuring no more impact on VDSL than there would have been from VDSL self-FEXT.

These simulations also force G.fast to be "off" (transmitting -120 dBm/Hz) in part of the VDSL frequency band, below the cut off frequency "fcut."

Here fcut is dynamic, and is adjusted so that the VDSL data rate on every line in the simulated binder meets or exceeds the per-line target VDSL data rate in all crosstalk cases. The value of fcut is calculated separately for each case of loop lengths and crosstalk couplings. If some VDSL does not meet the per-line target rate, then fcut is adjusted and IWF is performed again until all VDSLs do meet the per-line target rate. Increasing fcut increases VDSL speeds.

7.1.2 Assumptions

These simulations use the assumptions in section 5.1, 6.1, 6.2, 6.3, 6.5 and 6.6.3

UPBO is applied to VDSL upstream as a function of loop length. G.fast has no UPBO.

The SSM model uses the static overlapping G.fast downstream PSD, "DS3 Only" described in section 6.6.1 and the standard upstream G.fast PSD described in the ANFP [1]. The new "DPBO" for VDSL is applied to the SSM model as per 6.6.3.

The DSM G.fast transmit PSD conforms to ITU-T G.9700 [3]. The total power constraint here allows 5.1 dBm G.fast transmit power below 30 MHz, and 4.8 dBm G.fast transmit power above 30 MHz, for a total G.fast transmit power limit of 8 dBm. Background noise is -140 dBm/Hz below 30 MHz, and -150 dBm/Hz above 30 MHz. G.fast uses a linear zero-forcing vector precoder to cancel FEXT, with perfectly calculated precoder coefficients.

The crosstalk coupling phase is random. Simulations account for all NEXT and FEXT between G.fast downstream, G.fast upstream, VDSL downstream, and VDSL upstream. There is no crosstalk between upstream and downstream G.fast. Crosstalk into VDSL is taken to be the worst-case of crosstalk from downstream G.fast and crosstalk from G.fast upstream at each frequency; due to the TDD nature of G.fast this is likely to be the actual impact of G.fast crosstalk into VDSL.

There are usually 12 G.fast and 8 VDSL lines in a cable binder which are distributed and uniformly spaced, except for one case that has 24 G.fast and 16 VDSL lines. For each simulation 10,000 cases of random crosstalk couplings are run, with all lines active including the 12 G.fast lines, thus generating 120,000 G.fast bit rates at each loop length. The minimum, 1% worst, average, 99%

best, and maximum G.fast data rates are recorded across all these cases, with static spectrum management and with DSM using the iterative water filling (IWF) algorithm described below.

The per-line target rates are calculated assuming the VDSL lines are in each G.fast end location, instead of G.fast. The DSM simulations with DSM overlap G.fast with VDSL. Plots assume that G.fast is transmitting either downstream or upstream 100% of the time.

Unless otherwise stated:

- NTEs are uniformly spaced.
- There are 12 G.fast lines and 8 VDSLs.
- The maximum G.fast loop length is 500m (E = 500m).
- The maximum VDSL loop length is 2400m (Y+E+F = 2400m).

G.fast is “off” in part of the VDSL frequency band, below a cut-off frequency “fcut,” and fcut is varied so that all VDSL lines in the simulated binder achieve their per-line target rates.

The minimum used G.fast frequency for static simulations in the upstream direction is 17.7 MHz.

Simulations assume maximum 12 bits per tone for G.fast.

7.1.3 Results

Figure 7-1 to Figure 7-7 show G.fast data rates with DSM and SSM, where SSM uses the overlapping mask with DS3 only.

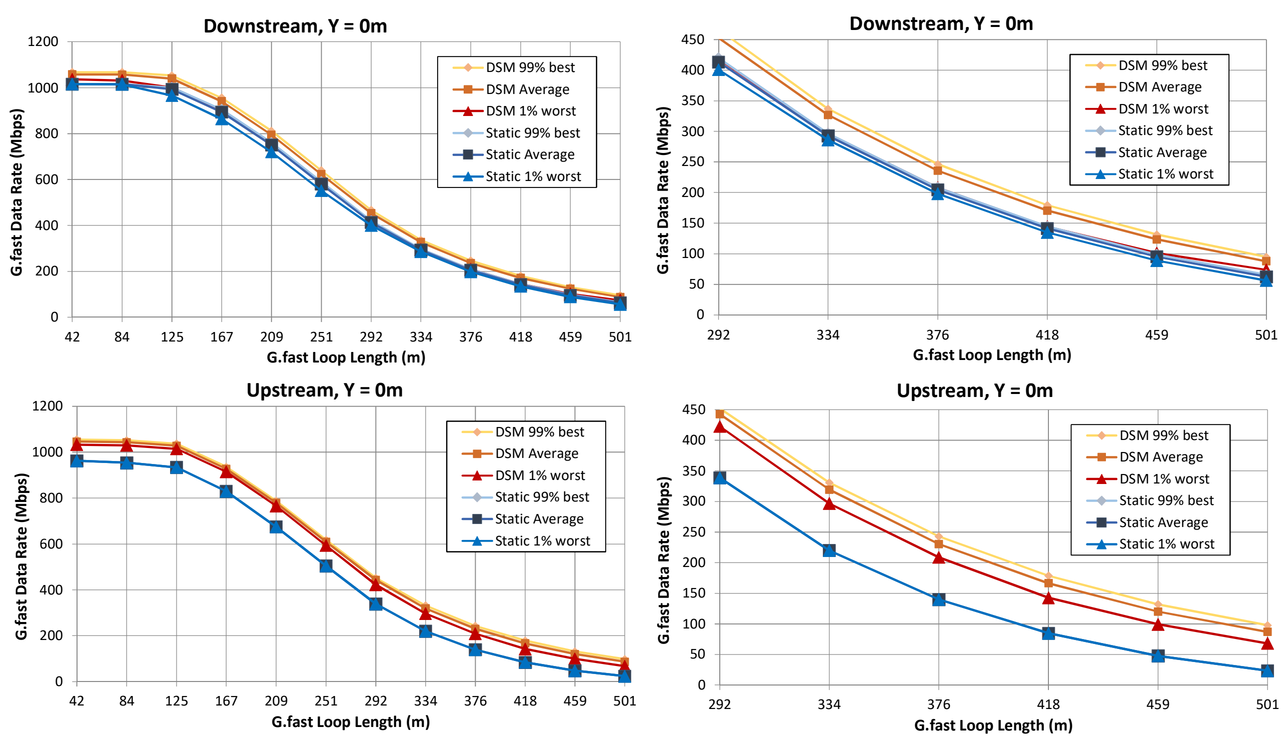


Figure 7-1 G.fast data rates. Y = 0m, Y+E+F = 2400m.

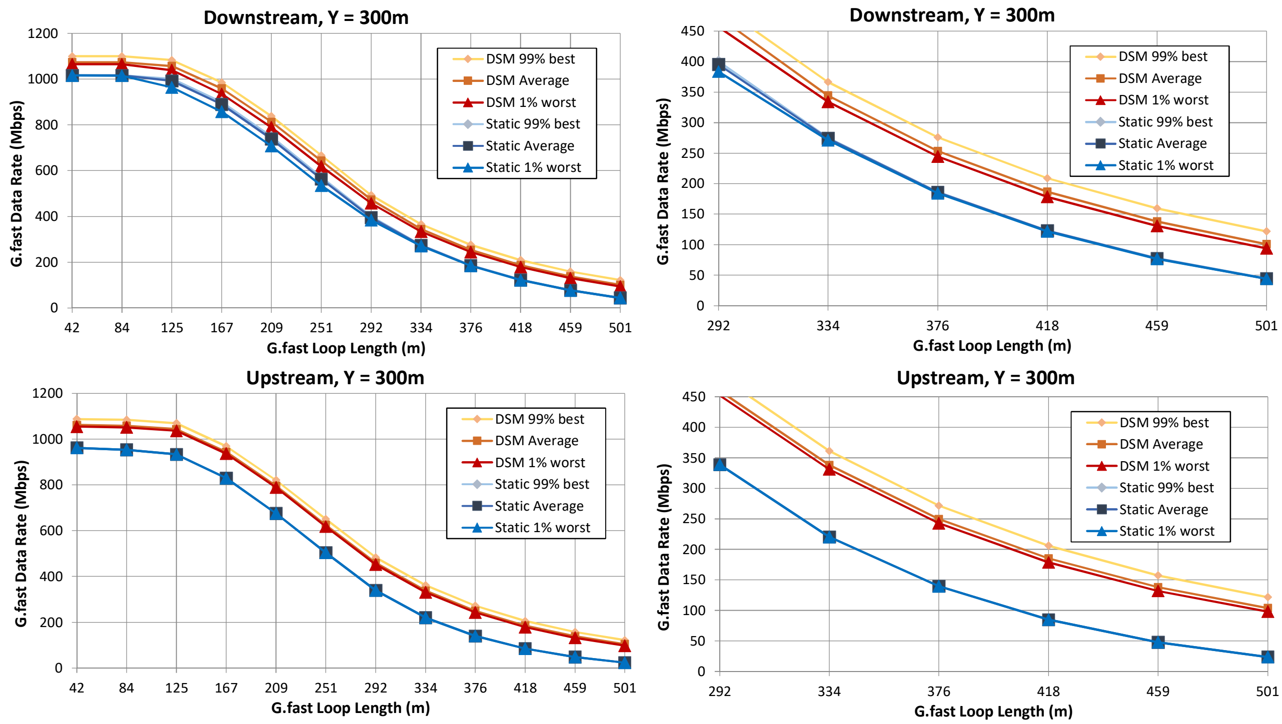


Figure 7-2 G.fast data rates. Y = 300m, Y+E+F = 2400m

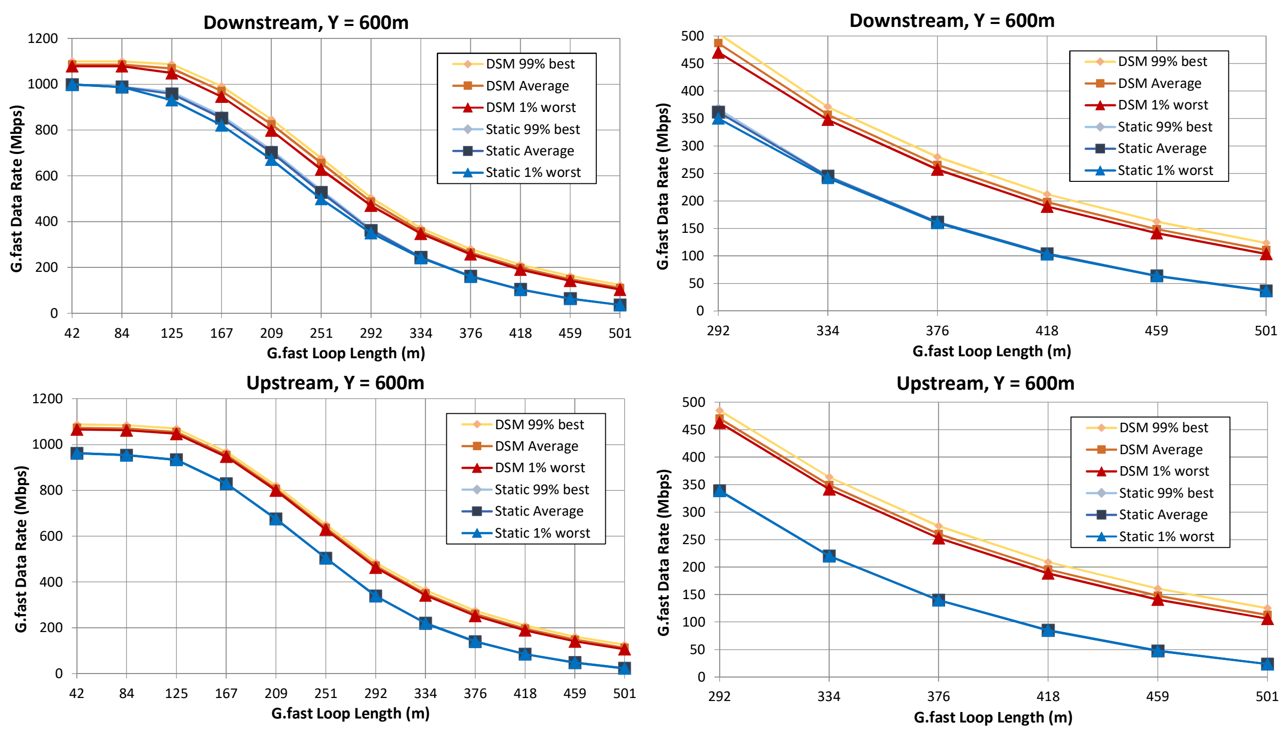


Figure 7-3 G.fast data rates. Y = 600m, Y+E+F = 2400m.

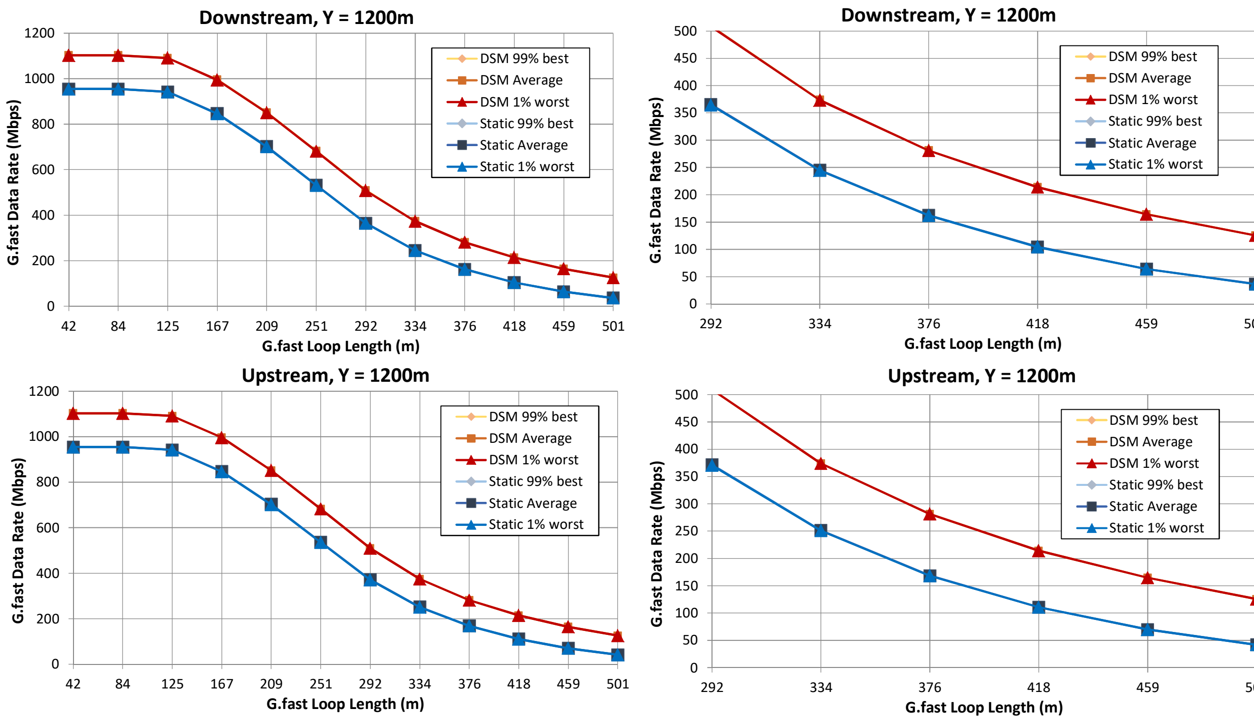


Figure 7-4 G.fast data rates. Y = 1200m, Y+E+F = 2400m.

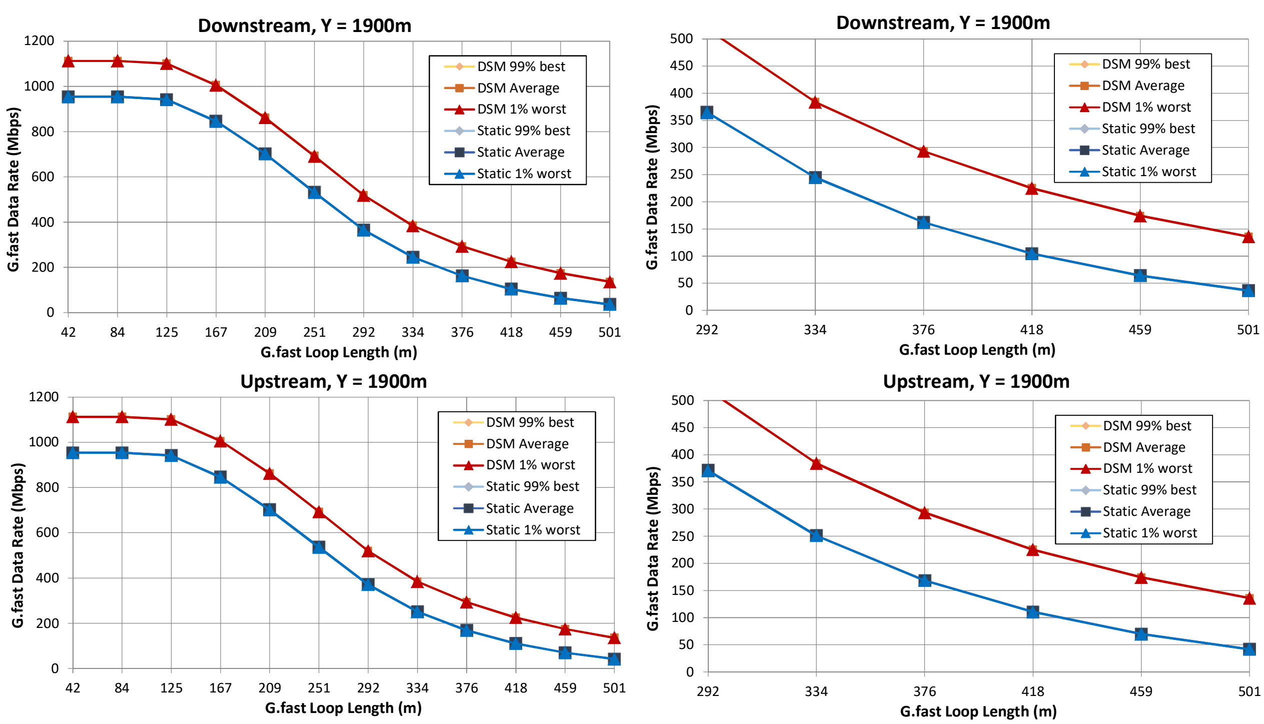


Figure 7-5 G.fast data rates. Y = 1900m, Y+E+F = 2400m.

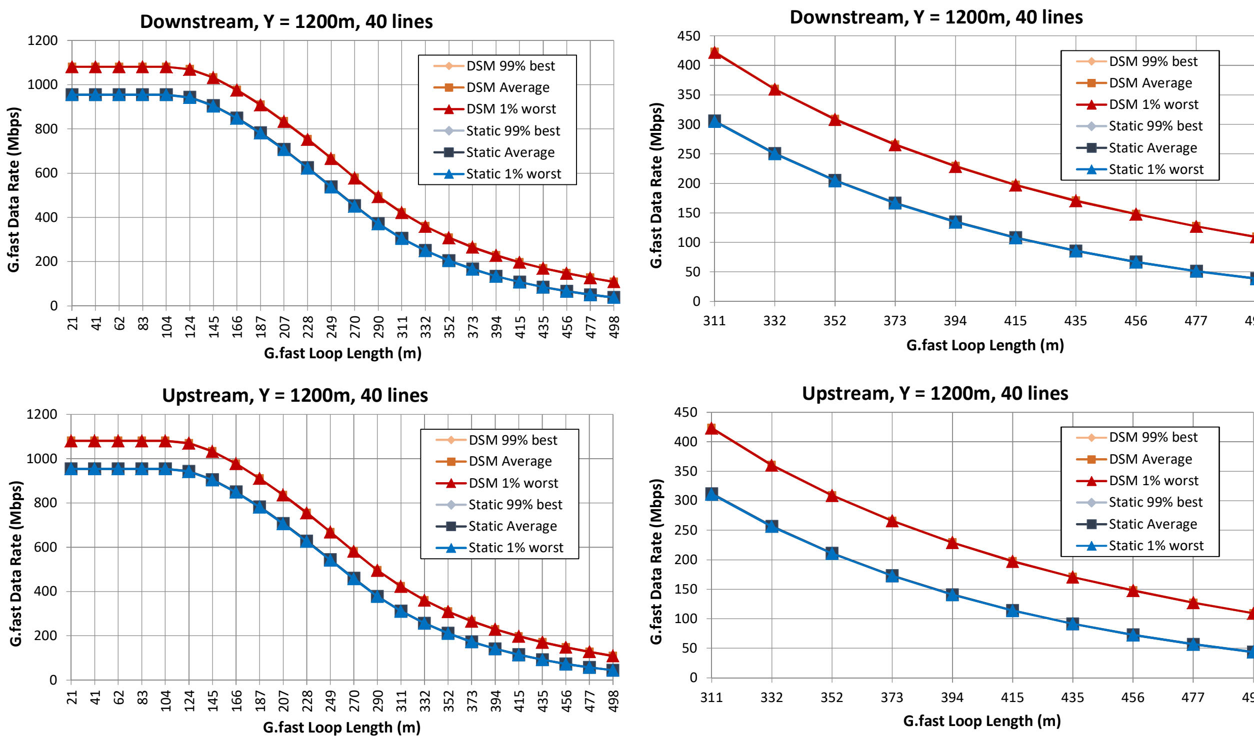


Figure 9-6 G.fast data rates. 40 lines: 24 G.fast and 16 VDSL. Y = 1200m, Y+E+F = 2400m.

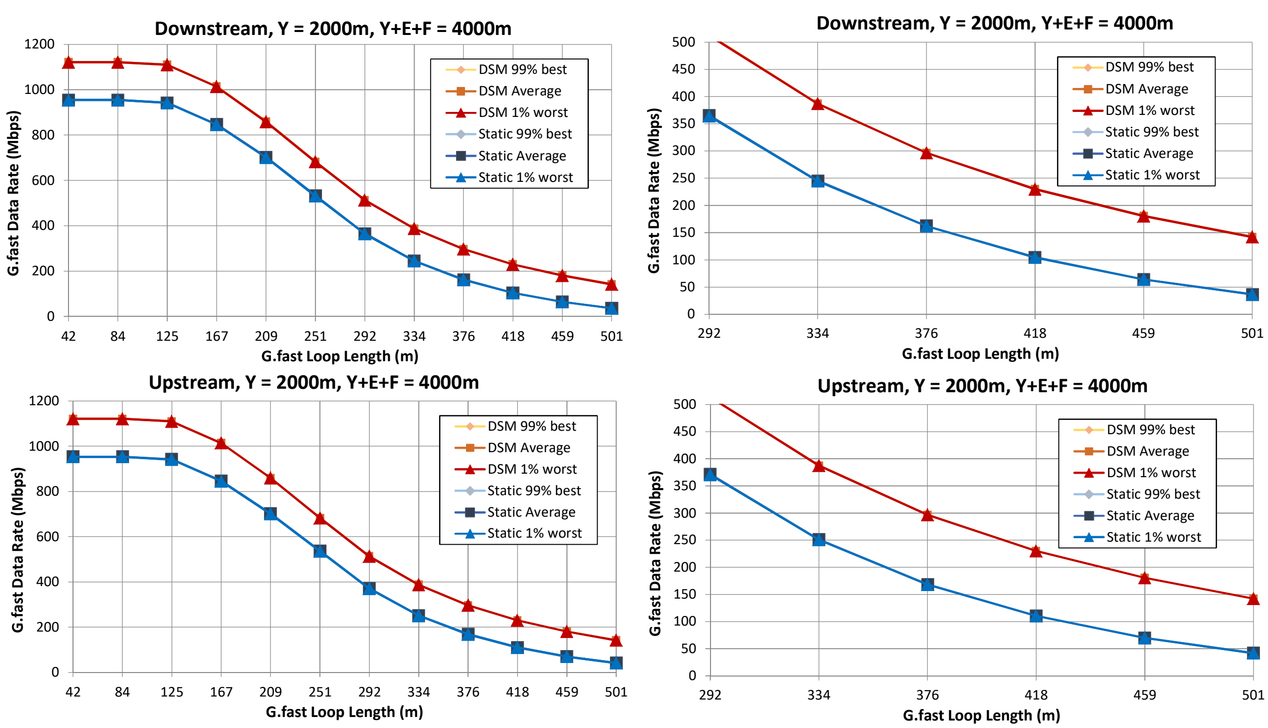


Figure 7-7 G.fast data rates. Y = 2000m, Y+E+F = 4000m.

Figure 7-8 - Figure 7-11 show plots of examples of G.fast and VDSL transmit PSDs and bit loading with DSM. Each plot shows a single G.fast line and a single VDSL.

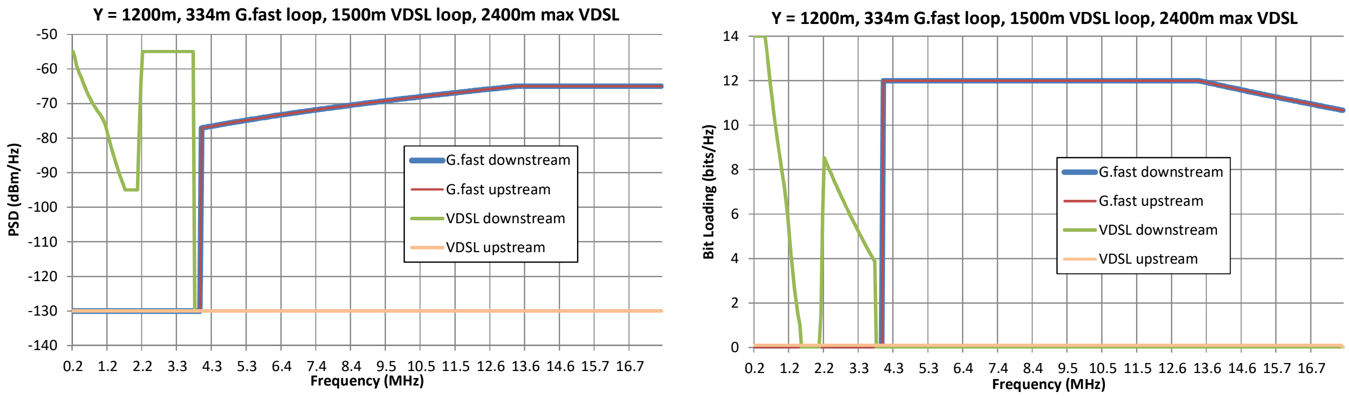


Figure 7-8 Transmit PSDs and bit loading with DSM, Y = 1200m, G.fast loop length = 334m, VDSL loop length = 1500m, max VDSL loop length = 2400m.

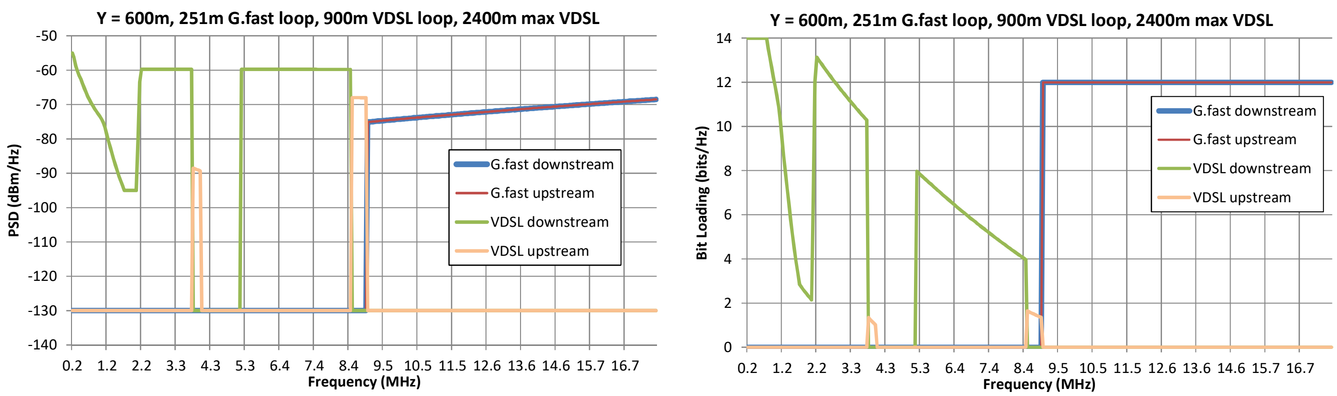


Figure 7-9 Transmit PSDs and bit loading with DSM, Y = 600m, G.fast loop length = 251m, VDSL loop length = 900m, max VDSL loop length = 2400m.

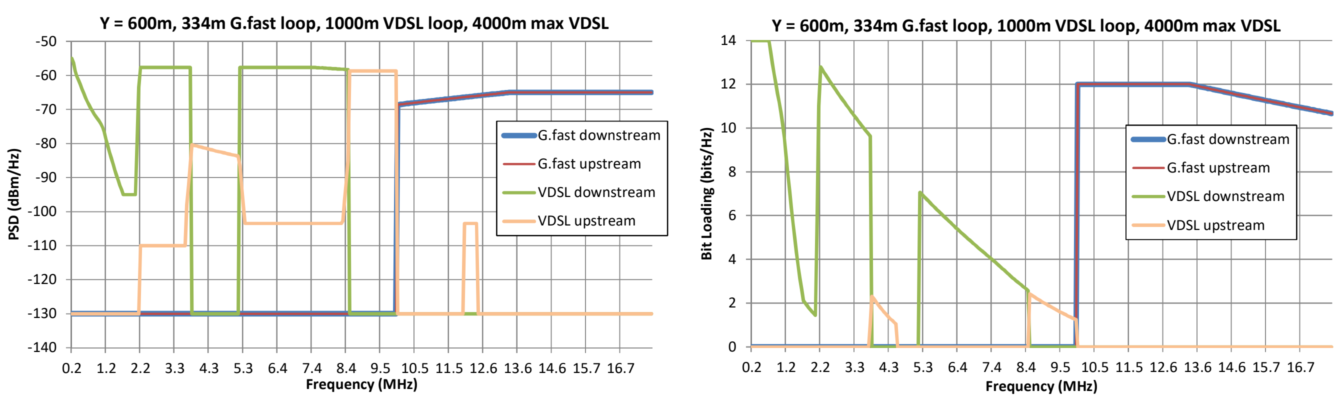


Figure 7-10 Transmit PSDs and bit loading with DSM, Y = 600m, G.fast loop length = 334m, VDSL loop length = 1000m, max VDSL loop length = 4000m.

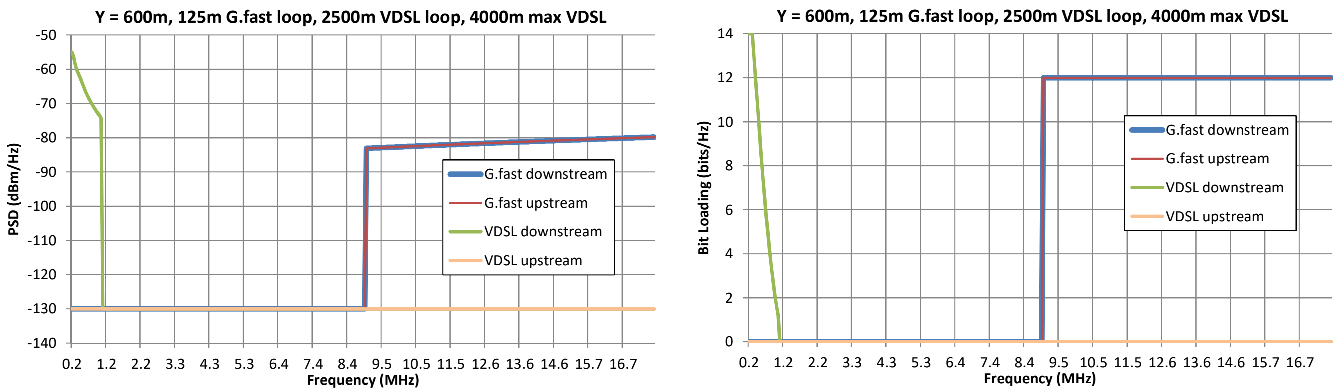


Figure 7-11 Transmit PSDs and bit loading with DSM, Y = 600m, G.fast loop length = 125m, VDSL loop length = 2500m, max VDSL loop length = 4000m.

In Figure 7-11 there is a wide gap between the frequencies used by VDSL and G.fast. This is since an fcut of 8 MHz was needed for the other, shorter, VDSL lines to achieve their per-line target rates.

Figure 7-12 and Figure 7-13 show distributions of the values of fcut computed for different lengths of Y and other simulation parameters.

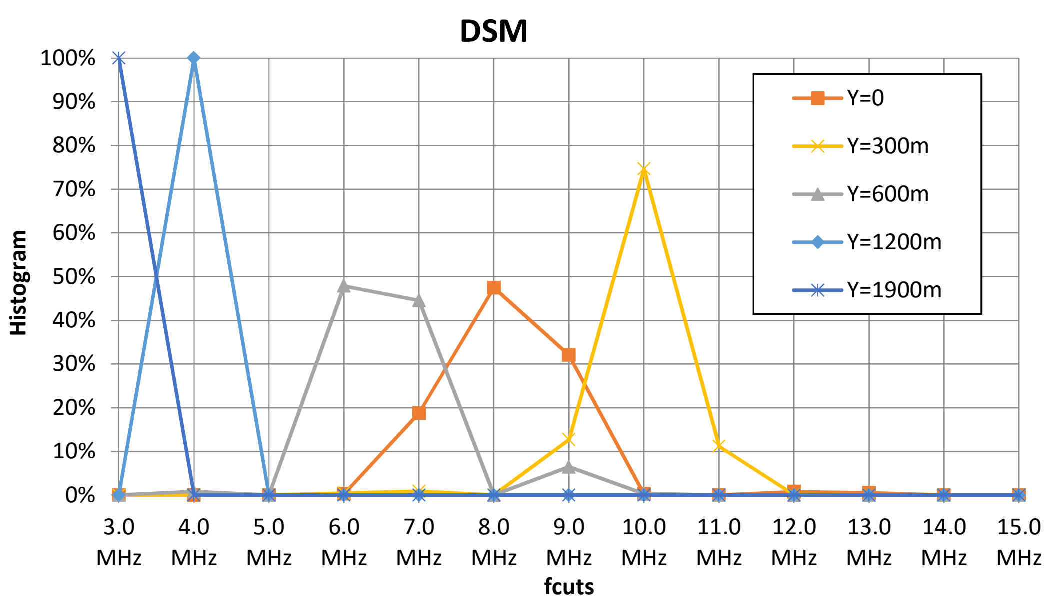


Figure 7-12 fcut values with DSM, as the VDSL cabinet to G.fast DP distance, Y, varies.

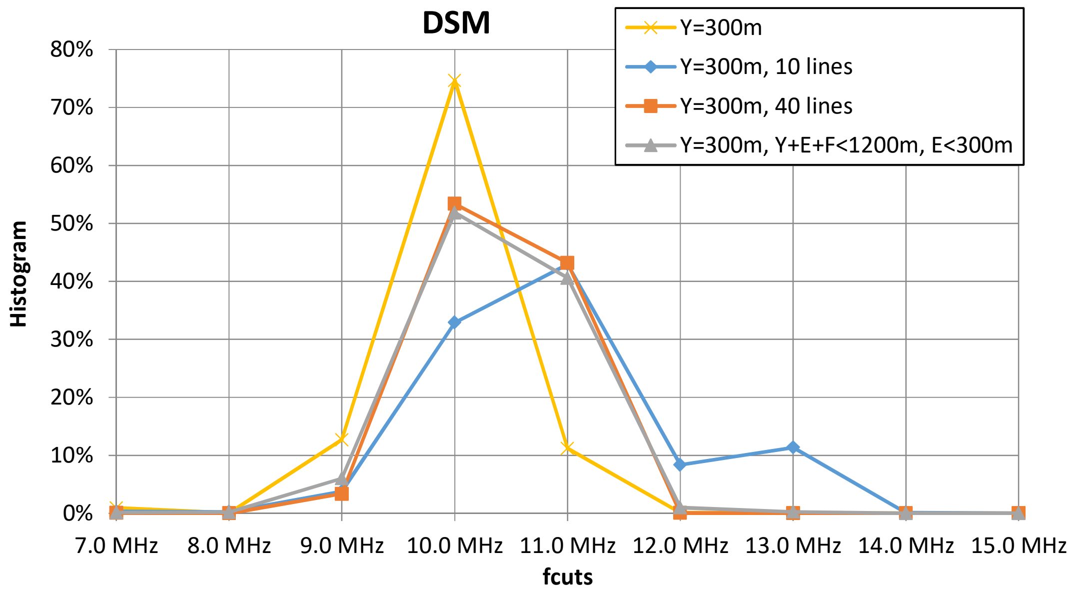


Figure 7-13 fcut values with DSM, assuming base assumptions except as noted in the figure legend

Table 7-1 99% maximum values of fcut

Case	fcut (99%) (MHz)
Y=0	12
Y=300m	11
Y=600m	9
Y=1200m	4
Y=1900m	3
Y=300m, 10 lines	13
Y=300m, 40 lines	11
Y=300m, Y+E+F<1200m, E<300m	12

As the frequency fcut increases, also the VDSL performance increases. If a single value of fcut were to be used for a particular case of numbers of lines and lengths, then a high value of fcut would assure that VDSL meets its per-line target rate. The value of fcut which is at or above 99% of all values for a particular case is shown in Table 7-1.

The value of fcut is seen to vary strongly with distance Y, but fcut only varies weakly with other lengths and with numbers of lines.

7.1.4 Summary of Results

The gains of DSM over overlapping SSM (DS3) may be higher in the 1% worst case then in the average, due to low 1% worst-case performance of overlapping SSM (DS3).

Table 7-2 Gain in average G.fast data rates, DSM – SSM (DS3) (Mbps), averaged across all G.fast lines, assuming that G.fast is transmitting either downstream or upstream 100% of the time.

# Lines	Y (m)	Y+E+F (m)		Downstream	Upstream

20	0	2400		37.6	90.7
20	300	2400		67.1	107.6
20	600	2400		105.0	118.2
20	1200	2400		131.8	128.6
40	1200	2400		133.8	132.8
20	1900	2400		142.4	139.2
20	2000	4000		145.6	142.4

Table 7-3 Gain in average G.fast data rates, DSM – SSM (DS3) (Mbps), averaged across all G.fast lines, assuming that G.fast is transmitting downstream 80% of the time and upstream 20% of the time.

# Lines	Y (m)	Y+E+F (m)		Downstream	Upstream
20	0	2400		30.1	18.1
20	300	2400		53.7	21.5
20	600	2400		84.0	23.6
20	1200	2400		105.4	25.7
40	1200	2400		107.0	26.8
20	1900	2400		113.9	27.8
20	2000	4000		116.5	28.5

Table 7-4 Gain in 1% worst-case G.fast data rates, DSM – SSM (DS3) (Mbps), averaged across all G.fast lines.

# Lines	Y (m)	Y+E+F (m)		Aggregate	80% Downstream
20	0	2400		21.2	16.9
20	300	2400		64.7	51.8
20	600	2400		102.1	81.7
20	1200	2400		134.6	107.7
40	1200	2400		138.1	110.5
20	1900	2400		144.3	115.4
20	2000	4000		150.9	120.7

The gains for DSM shown here are relative to overlapping SSM (Option 2). Sections 7.1.4 and 7.7.1 show that overlapping SSM can gain about 40 to 50 Mbps over Option 1 (existing ANFP.) DSM can achieve 40 to 50 Mbps additional gain over Option 1 (existing ANFP) in addition to the gains shown above.

7.2 Variants of SSM compared

This section covers the following high-level use case from Table 5-2:

- Case 2, overlapping PSD (SSM) for un-vectored VDSL, in case of the co-located scenario

7.2.1 Description

This section compares static spectrum management with G.fast downstream starting from 17.7MHz, 19MHz, or overlapping with the VDSL DS3 and/or DS2 frequency bands. Only G.fast data rates are calculated here. Downstream G.fast starting at 17.7 MHz or 19 MHz conforms to the ITU-T G.9700 limit mask with passband above 17.7 MHz or 19 MHz, and limited to at most -65.7 to meet an 8 dBm total power limit.

Downstream overlapping G.fast using the VDSL DS3 band (DS3 only) conforms to the PSD in Section 6.6.1. Downstream overlapping SSM VDSL sets the transmit PSD to a floor on subcarriers that cannot carry any bits (bi = 0).

For Y > 0, the downstream overlapping G.fast PSD is modified with the new type of "DPBO" for compatibility with VDSL as defined in Section 6.6.3.

Simulation assumptions are as defined in Section 6. The upstream SSM PSDs conform to the ANFP [1]. Downstream SSM PSDs conform to those described in section 7.4.2.

7.2.2 Assumptions

See section 7.1.2 where relevant to SSM.

7.2.3 Results

Figure 7-14 and Figure 7-15 include results for both downstream G.fast PSDs in the non-overlapping ANFP V6.1.1, for CGAL = 0 (co-located) and CGAL > 0 (non-co-located); for ANFP Part E: ANFP PSD Mask Definition for G-SDF

The G.fast data rates in the plots are the sum of upstream and downstream.

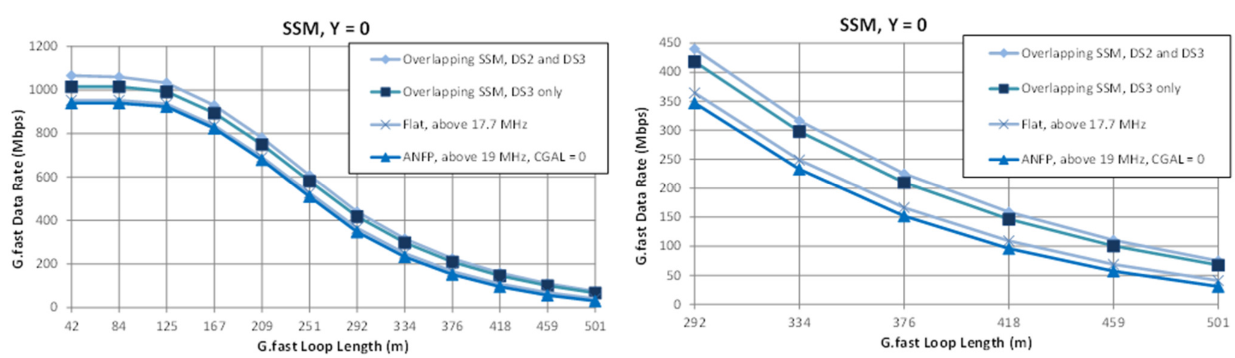


Figure 7-14 Average aggregate G.fast data rates with SSM. Y = 0m, Y+E+F = 2400m.

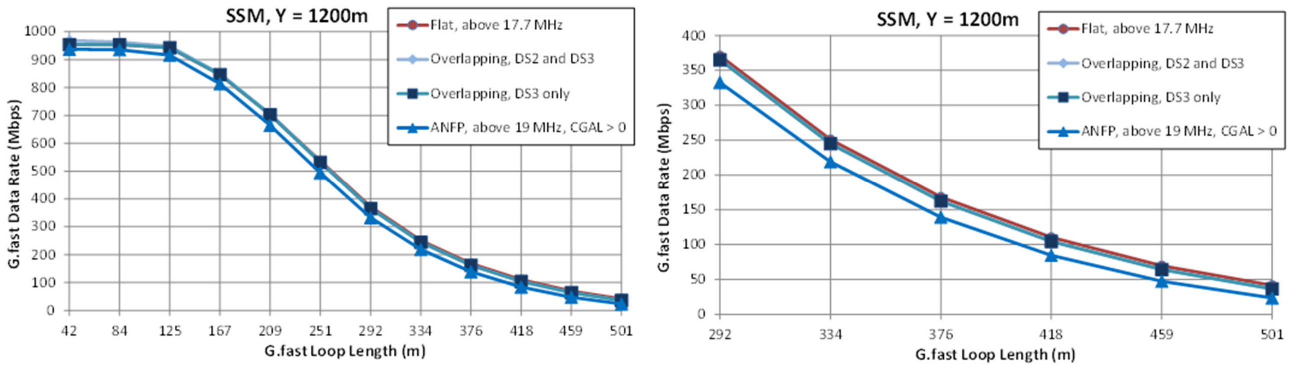


Figure 7-15 Average aggregate G.fast data rates with SSM. Y = 1200m, Y+E+F = 2400m.

In Figure 7-15, at Y = 1200m, the factor $\frac{(Y+Z)}{Z}|H(Y,f)|^2$ attenuates the G.fast PSD below 17.7 MHz so much that for SSM G.fast is essentially turned off.

7.2.4 Summary

Table 7-5 Downstream G.fast data average rate increases (80% of aggregate), (Mbps) for various G.fast SSM PSD masks.

Loop Length (m)	ANFP, above 19 MHz, CGAL > 0	+ ANFP, above 19 MHz, CGAL = 0	+ ANFP, above 17.7 MHz CGAL = 0	+ Flat PSD above 17.7 MHz	+ Overlapping SSM, DS3 only	+ Overlapping SSM, DS2 and DS3
42	749.7	2.3	6.7	3.2	50.3	40.7
84	748.1	4.0	5.6	4.2	50.2	36.0
125	732.7	5.9	4.7	5.4	45.4	32.1
167	650.9	8.5	3.9	6.3	45.6	28.3
209	531.8	10.8	2.8	7.8	46.6	24.8
251	395.3	12.1	1.8	11.6	44.1	21.1
292	266.2	11.5	1.2	12.6	43.0	17.5
334	175.2	11.3	0.5	12.1	39.4	14.6
376	111.2	10.6	0.2	11.3	34.7	12.1
418	67.5	9.4	0.1	10.4	30.0	9.9
459	38.0	7.8	0.0	9.3	25.5	7.7
500	18.7	6.0	0.0	8.0	21.2	5.9
Average	373.8	8.4	2.3	8.5	39.7	20.9

Table 7-5 shows downstream G.fast average data rate increases, (Mbps) for various G.fast SSM PSD masks. 12 G.fast lines are co-located with 8 VDSLs. Downstream is assumed to be 80% of the aggregate G.fast data rate, so numbers in this table are 0.8*aggregate. Starting from the third column, each column shows the increase over the previous column. The last row is the average across all the evaluated G.fast loop lengths. So, for example, the cumulative increase in the average from “ANFP, above 19 MHz, CGAL = 0” to “Overlapping SSM, DS3 only” is 2.3 + 8.5 + 39.7 = 50.5 Mbps.

Note that the last column of Table 7-5, overlapping SSM, DS2 and DS3 is generally not compatible with upstream VDSL.

7.3 Semi-overlap (Un-vectored)

This section covers the following high-level use cases from Table 5-2:

- Case 2, new overlapping PSD (SSM) for un-vectored VDSL.

7.3.1 Description

The goal is to design a static PSD, for the co-located scenario or a simple semi-static (only the electrical distance from cabinet to G.fast injection point required) PSD, for the non-co-located scenario.

The objective is to increase the G.fast data rates (as compared to current static G.fast PSD Masks in the ANFP) whilst fully protecting the un-vectored VDSL bit rates.

As a result, the G.fast system is only transmitting in the overlapping bands according to the VDSL band-plan in those bands. Such operation is called semi-overlap.

In addition, for the non-co-located scenario, the G.fast PSD in downstream is shaped as per section "6.6.2 G.fast PSD with "DPBO""

7.3.2 Assumptions

Downstream PSD described in section, 6.6.2, followings the VDSL PSD.

Either the G.fast DS PSD below 17.6 MHz follows the VDSL band-plan for the co-located scenario (at full PSD in the VDSL DS bands, at reduced PSD in the VDSL US bands), or the G.fast DS PSD up to 20 MHz is shaped with "DPBO "for the non-co-located scenario as described in section 6.6.2. This section assumes worst-case crosstalk and co-located CPE, which is the worst case.

As the PSDs have been designed to have no or very limited impact on VDSL (for either co-located or non-co-located G.fast), the goal of these simulations is twofold:

- Verify the VDSL performance when migrating a VDSL line to G.fast technology (using the SSM or SSSM designed PSD mask as described in section, 6.6.2)
- Evaluate the benefit for the G.fast performance when using such SSM or SSSM designed PSD mask as described in section, 6.6.2, for respectively the co-located and non-co-located scenario.

7.3.3 Results

G.fast transmission in DS – Performance

In the two figures below, we have first simulated the impact on VDSL (at the cabinet), resulting from the crosstalk of a G.fast disturber (either at the cabinet for the co-located scenario, either at a DP that is 300m away from the cabinet for the non co-located scenario). For a fair comparison, we have first simulated with 24 VDSL lines as reference, and then migrated one of the VDSL lines to G.fast to observe the impact from this migration.

As can be seen from the figures, there is almost no impact from the introduction of G.fast, when using the semi-overlapping spectrum.

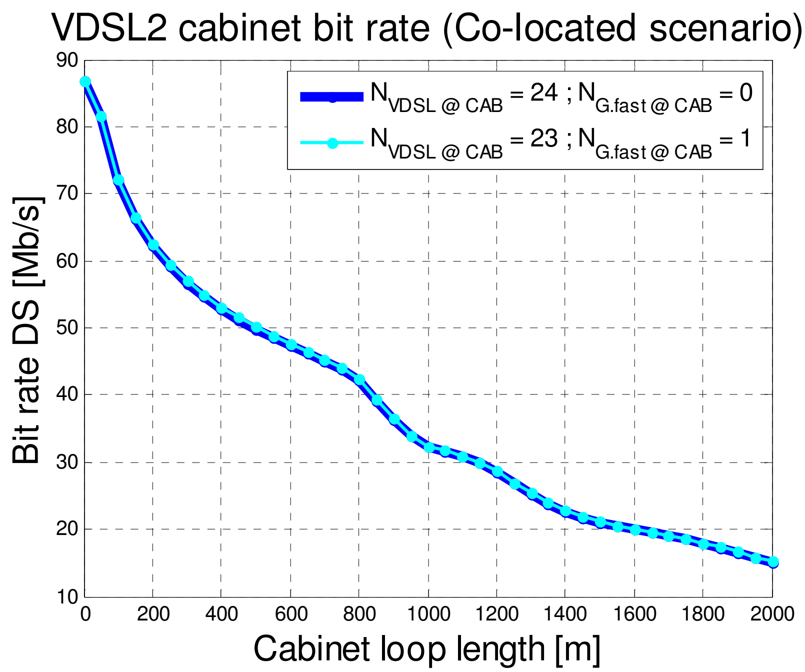


Figure 7-16 VDSL performance (co-located scenario)

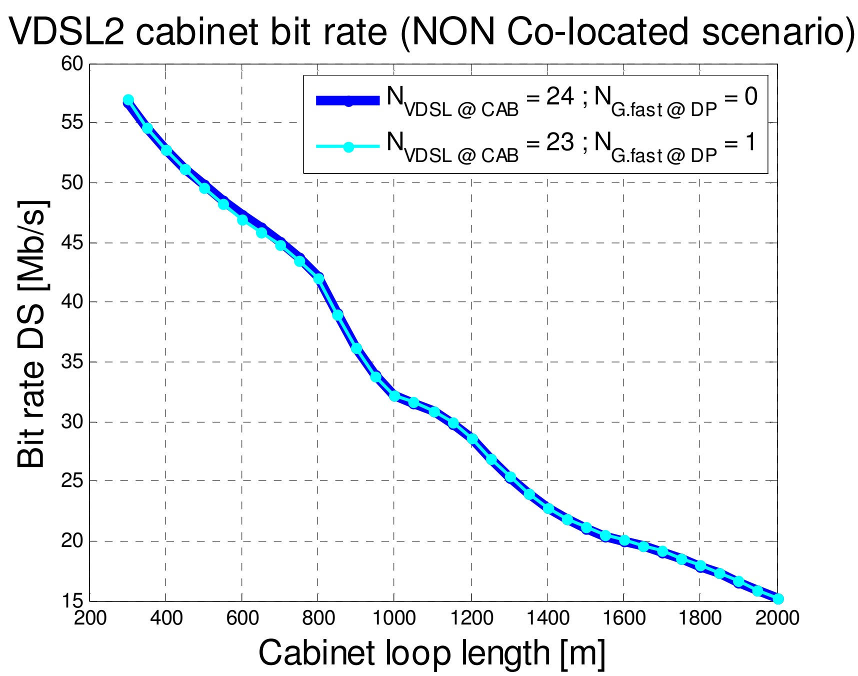


Figure 7-17 VDSL performance (NON co-located scenario)

Finally, we have been looking at the performance of G.fast in DS, when using such semi-overlapping spectrum. To better understand the benefit, we have compared 3 cases:

- Semi-overlapping spectrum (using the G.fast DS spectrum from Figure 6-3), with 23 VDSL crosstalk disturbers
- Non overlapping spectrum, so G.fast starting at 19 MHz, with 23 VDSL crosstalk disturbers
- IDEAL case with full overlapping spectrum (G.fast from 2 MHz until 106 MHz), but NO VDSL crosstalk disturbers (just to check the potential)

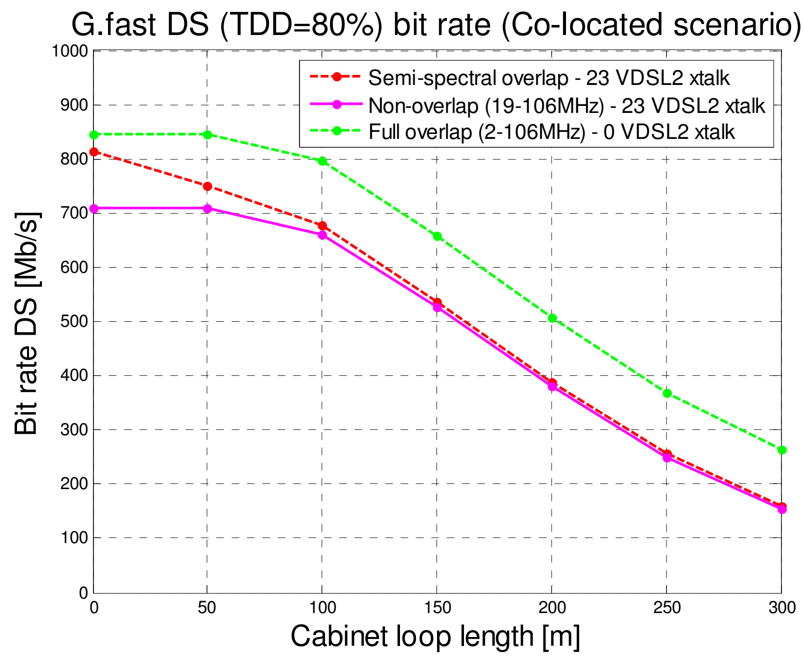


Figure 7-18 G.fast performance (co-located scenario)

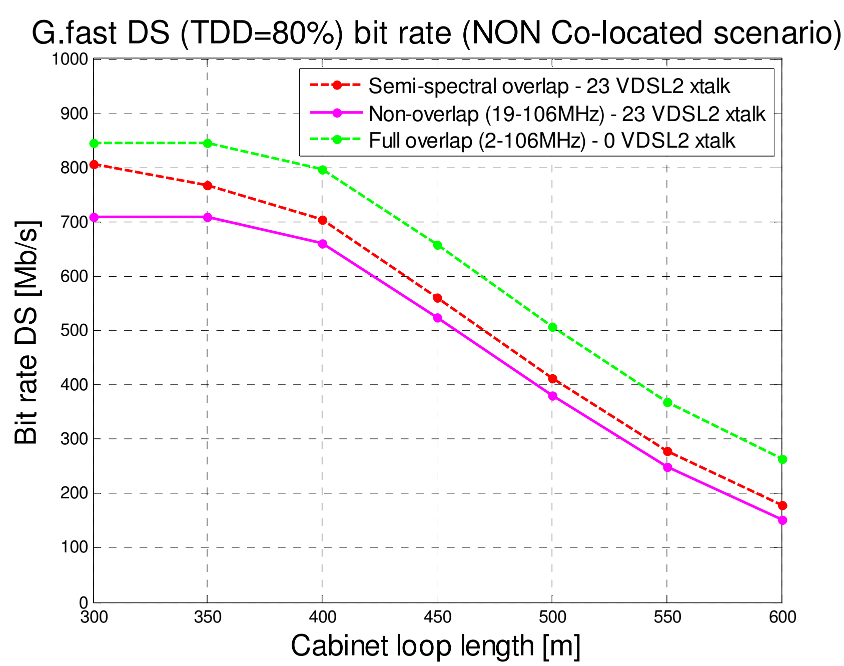


Figure 7-19 G.fast performance (non-co-located scenario)

G.fast transmission in US:

- This case is much more complicated, because
  - Short lines running VDSL use UPBO, so their PSD level is far below the PSD limit mask
  - The non-stationary aspect of G.fast transmission in US is worse than for DS, so the noise from G.fast US transmission should be much lower than the VDSL self-crosstalk.

G.fast transmission in US for the co-located scenario:

- In the VDSL US bands, the G.fast PSD should be lower than the VDSL UPBO mask
  - Therefore, it is clear that **only the usage of US2 in G.fast US PSD** can give a non-negligible contribution to the G.fast bit rate in US.
- It is questionable whether it makes sense (complexity vs benefit) for G.fast to use the VDSL upstream bands in the G.fast US transmission: due to the 20% time slot allocation in G.fast US, the bit rate from this overlapping band would give to G.fast an equivalent bit rate that is at least (G.fast PSD needs to be LOWER than the VDSL PSD) 5 times lower than the US bit rate achieved on a VDSL line.

G.fast transmission in US for the NON co-located scenario:

- In the VDSL US bands, the G.fast PSD should be lower than the PSD of the neighbouring VDSL lines
- A simplified approach would be to just take into account the distance between the VDSL node and the G.fast node, and use that as a static “UPBO” mask for G.fast US transmission in the overlapping VDSL US bands.

7.4 Variable start frequency (Vectored)

This section covers the following high-level use cases from Table 5-2:

- Case 4, Variable split frequency (SSSM) for vectored VDSL

7.4.1 Description

The goal is to design a semi-static PSD, for G.fast, derived from a target bit rate for the vectored VDSL.

The objective is to increase the G.fast data rates (as compared to current static G.fast PSD Masks in the ANFP) whilst still achieving the target service bit rate for vectored VDSL. One possible approach could be to choose a target service bit rate for the vectored VDSL (up to fcut) similar to a bit rate achieved today using un-vectored VDSL (full spectrum).

As a result, the vectored VDSL lines are only transmitting up to the fcut frequency, while the G.fast lines are only transmitting above the fcut frequency. For any fcut frequency lower or equal to 15.2

MHz, the effect of aliasing does not have to be taken into account, meaning that the guard band between G.fast and VDSL can be very limited.

7.4.2 Assumptions

The VDSL protection policy could be:

- Target data rate for VDSL (DS,US)=(100,20) Mbit/s over 400m loop,
- Maximum noise over the spectrum used by VDSL of -140 dBm/Hz.

This VDSL protection policy is chosen to introduce the concept of VDSL protection. This specific version of a protection policy does not protect all VDSL2 services and some lines beyond 400m would see reduction in service. It is noted that such VDSL protection policy will need to be chosen by the NICC DSL TG.

VDSL is vectored.

As a result, following VDSL2 cut-off frequencies have been calculated from the Figure 7-20 below:

- Downstream : 12.3 MHz
- Upstream : 5.17 MHz

The G.fast starts at slightly higher frequencies of 12.57MHz downstream and 5.175MHz upstream.

Note that if a target rate for VDSL of 80 Mb/s would be chosen in Downstream, G.fast can start in Downstream (and Upstream) from 8.5 MHz:

- The DS3 band of VDSL is then fully assigned to G.fast
- The very few US1 frequencies between 5.17 MHz and 5.2 MHz for G.fast can be assigned to VDSL (limited benefit for G.fast anyhow). Note that G.fast in US cannot use the frequencies between 5.2 MHz and 8.5 MHz to avoid NEXT into DS2.
- US2 is not used by VDSL, allowing G.fast to start both in US and DS as of 8.5 MHz

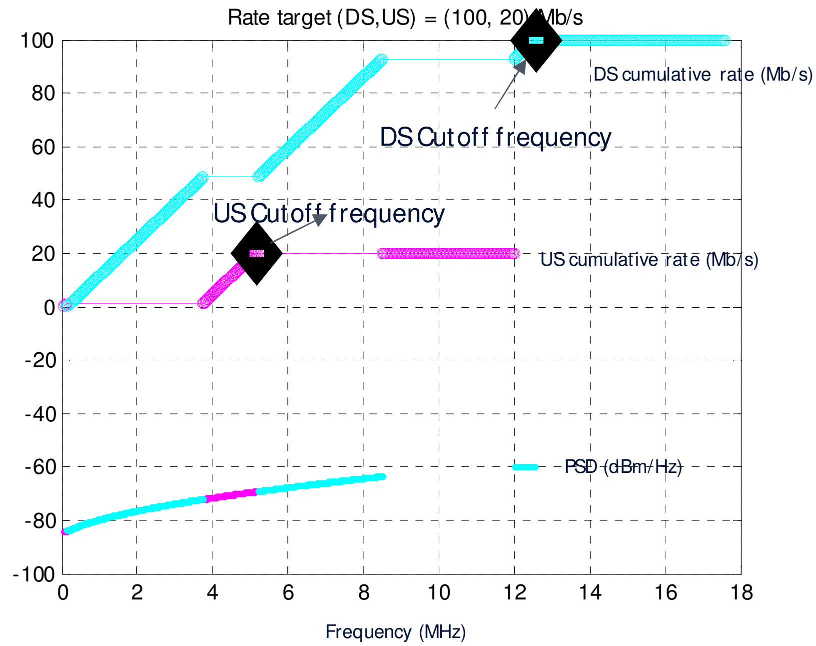


Figure 7-20 VDSL cumulative data rate and TX PSD

In the case of Vectored VDSL lines, simulations have demonstrated that Semi-spectral overlap does not bring considerable benefit (indicated in the curves of Figure 7-22 and Figure 7-23 as "Target Noise Limit").

7.4.3 Results

As can be seen from the Figure 7-21 below, VDSL is able to reach the predefined target rates at the reference loop length of 400m, with gradual reduction of the VDSL bit rate on longer loops.

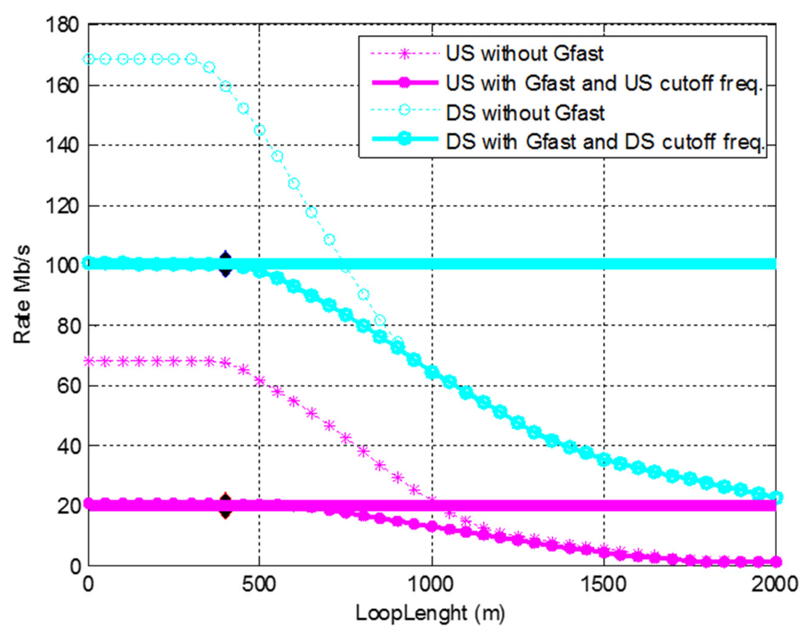


Figure 7-21 Vectored VDSL performance (Frequency split with G.fast)

In Figure 7-22 and Figure 7-23 below, the G.fast performance is shown. Note that in these simulations, NEXT is avoided up to the full 17.6 MHz, i.e., G.fast does not (yet) transmit downstream in US1 and US2 and G.fast does not (yet) transmit upstream in DS1, DS2 and DS3 (even if part of those bands is not used by VDSL). It would be sufficient to avoid NEXT into the spectrum actually used by VDSL (as determined by the band plan and the cut-off frequencies).

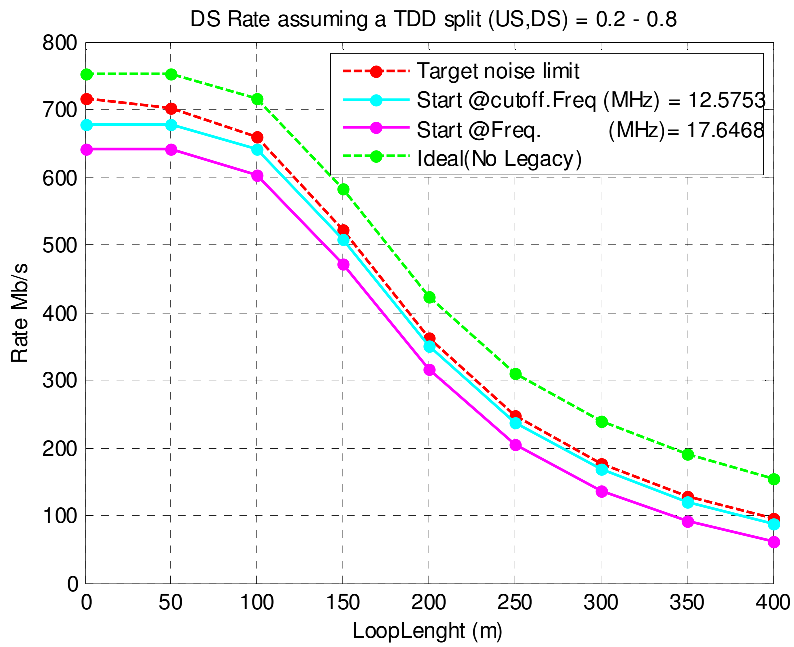


Figure 7-22 G.fast DS rate/reach assuming TDD split of (US, DS) = (0.2, 0.8)

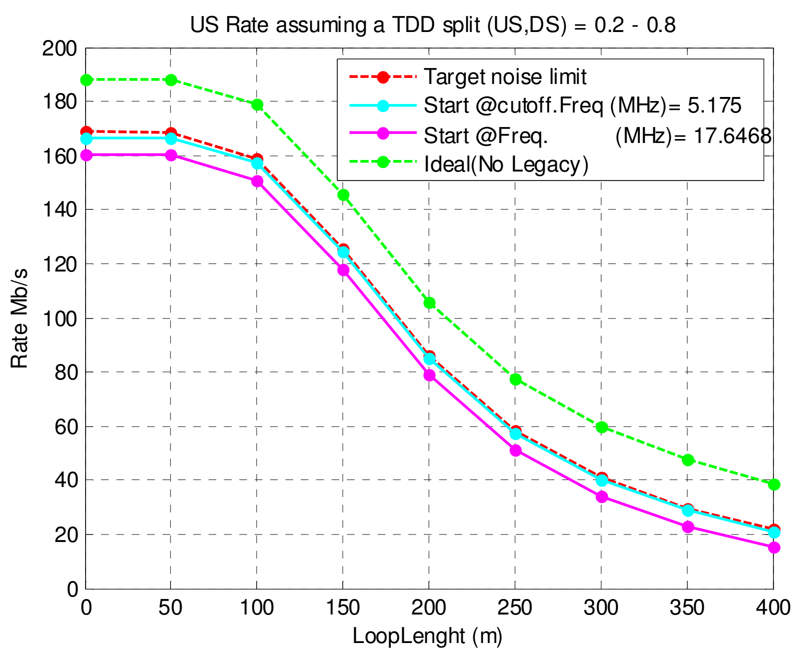


Figure 7-23 G.fast US rate/reach assuming TDD split of (US, DS) = (0.2, 0.8)

7.5 Re-farming

This section presents simulation results of re-farming spectrum between G.fast and VDSL and covers the following high-level use cases from Table 5-2:

- Case 3, re-farming

7.5.1 Simulation assumptions

Simulation assumptions are as defined in Section 6, and the simulations are similar to those in sections 7.1 and 7.2. VDSL PSDs conform to the ANFP [1]. VDSL downstream has ANFP DPBO for a CAL value of 20 dB (ESEL of 1500m). UPBO is applied to VDSL upstream as a function of loop length. VDSL uses the 26-138 kHz US0 band. G.fast has no UPBO. G.fast has a total average transmit power of 8 dBm, and a pre-coder to cancel FEXT with perfectly calculated pre-coder coefficients. 10% physical layer overhead is removed before displaying all the data rates here.

G.fast and VDSL use distinct frequencies here, with VDSL at low frequencies, below frequency fcut; and G.fast at high frequencies; above fcut. Both G.fast and VDSL are specified with a 175 kHz out-of-band roll-off, so a 350 kHz guard band centred about fcut is unused (seven 51.75 kHz G.fast subcarriers). There is no aliasing. There is no crosstalk between G.fast and VDSL. Other than changing fcut, transmit PSDs are static. Vectoring decreases crosstalk by 25 dB.

There are 12 G.fast lines and 8 VDSLs in a binder, which are spatially distributed and uniformly spaced as described in Section 5.1. The maximum G.fast loop length is 500m, and the maximum VDSL loop length is 1200m. For each simulation 1000 cases of random crosstalk couplings are run with all lines active, and statistics are collected. Here it is assumed that Y = 0 so the network end of VDSLs and G.fast lines are co-located. A non-co-located case was run, with Y = 500m, but this had the same results as the co-located case; this is since the VDSL and G.fast signals do not overlap in the frequency domain with re-farming, so only out of band energy can create crosstalk between the two which was negligible.

Simulations assume maximum 12 bits per tone for G.fast.

7.5.2 Simulation results

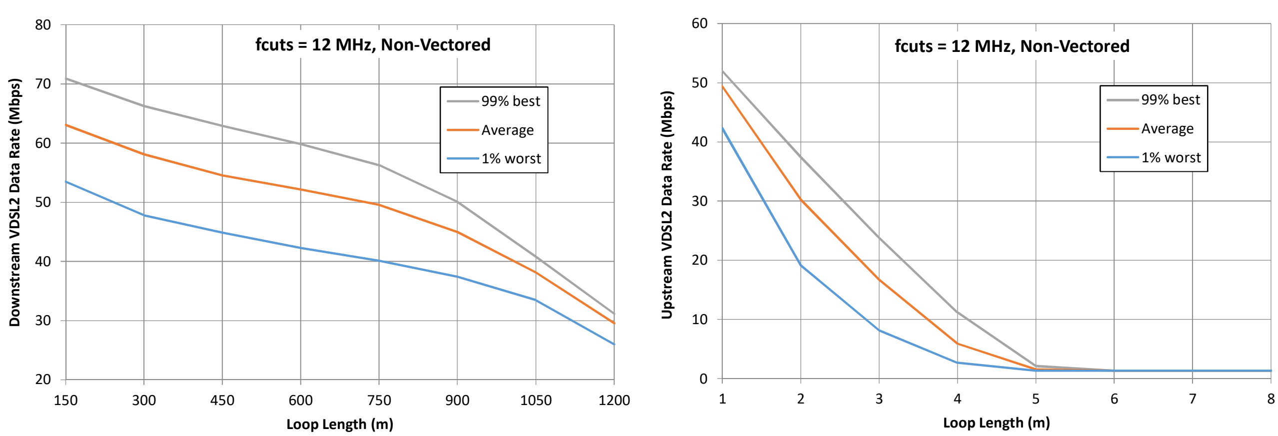


Figure 7-24 VDSL data rates, showing statistical variation due to different crosstalk couplings, fcut = 12 MHz.

First, Figure 7-24 shows 1% worst, average, and 99% best data rates of non-vectored VDSL due to the random crosstalk couplings, with fcut set to 12 MHz. Vectored VDSL and G.fast data rates show very little such statistical variation, since they are vectored.

Next, the following figures directly compare the variation of the average data rates as a function of fcut. Upstream G.fast data rates are nearly the same as downstream G.fast; so these are not plotted.

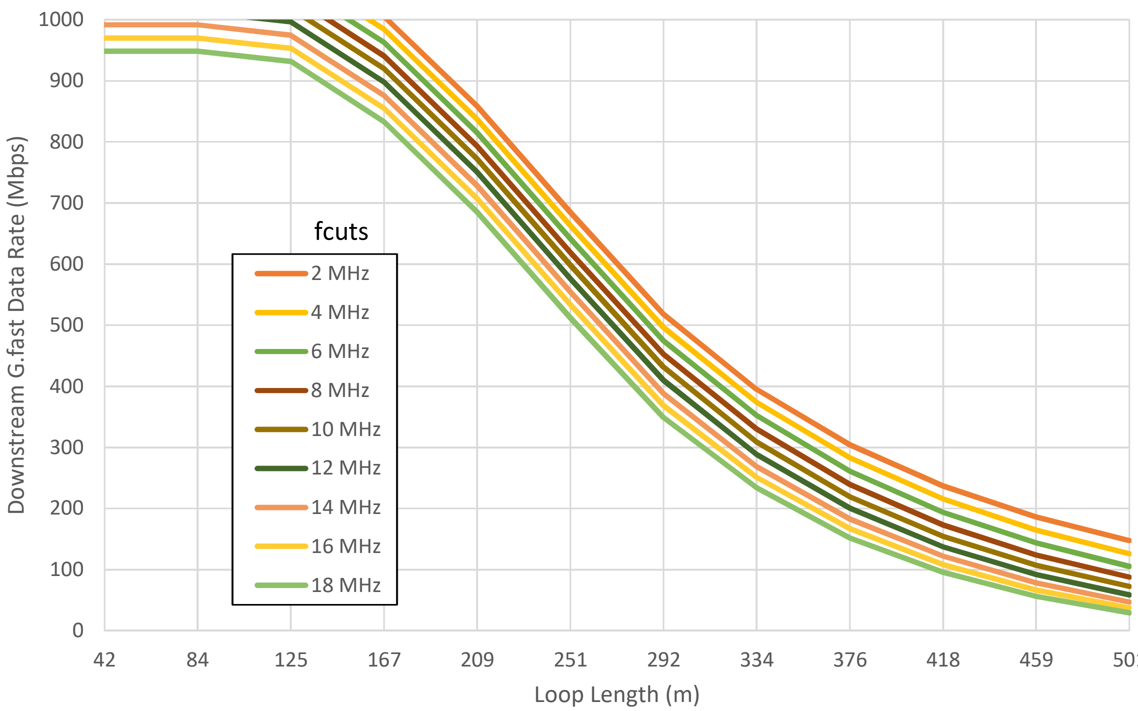


Figure 7-25 Average G.fast data rates as a function of fcut.

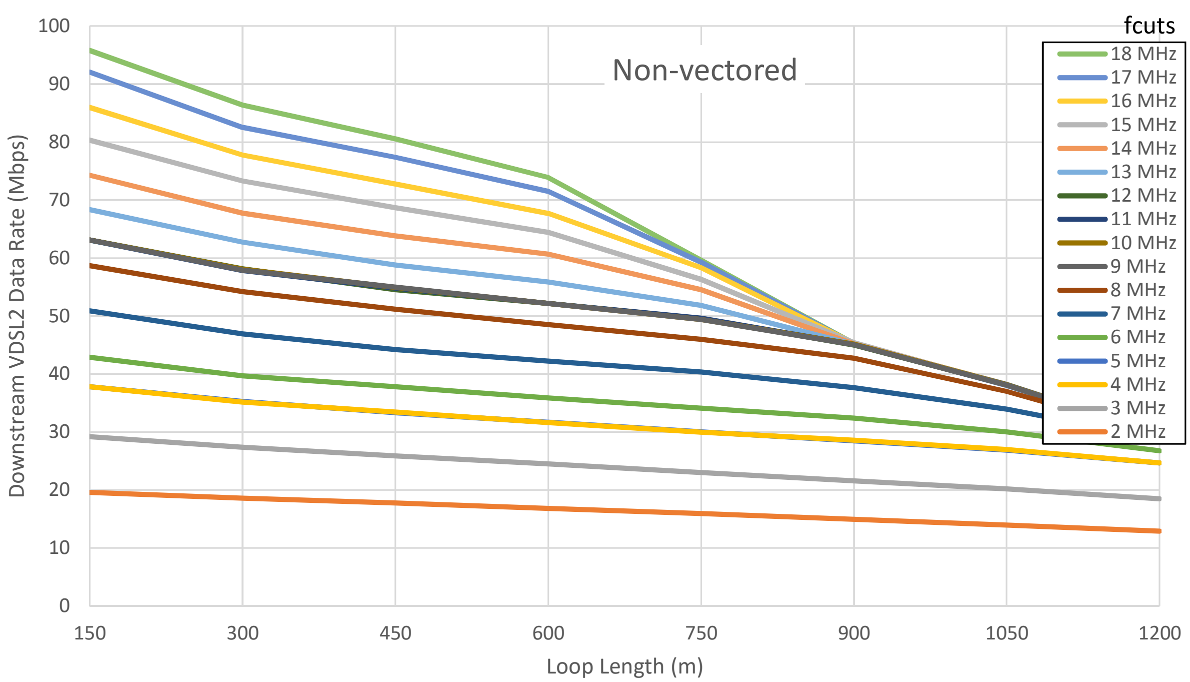


Figure 7-26 Average downstream non-vectored VDSL data rates as a function of fcut.

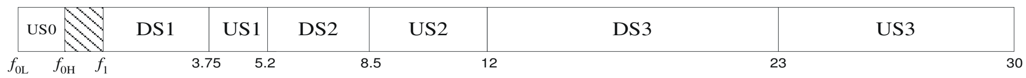


Figure A.1/ITU-T G.993.2 Annex A VDSL band plan.

Note that VDSL upstream speeds don't change if fcut doesn't cut into an upstream band, and similar for downstream.

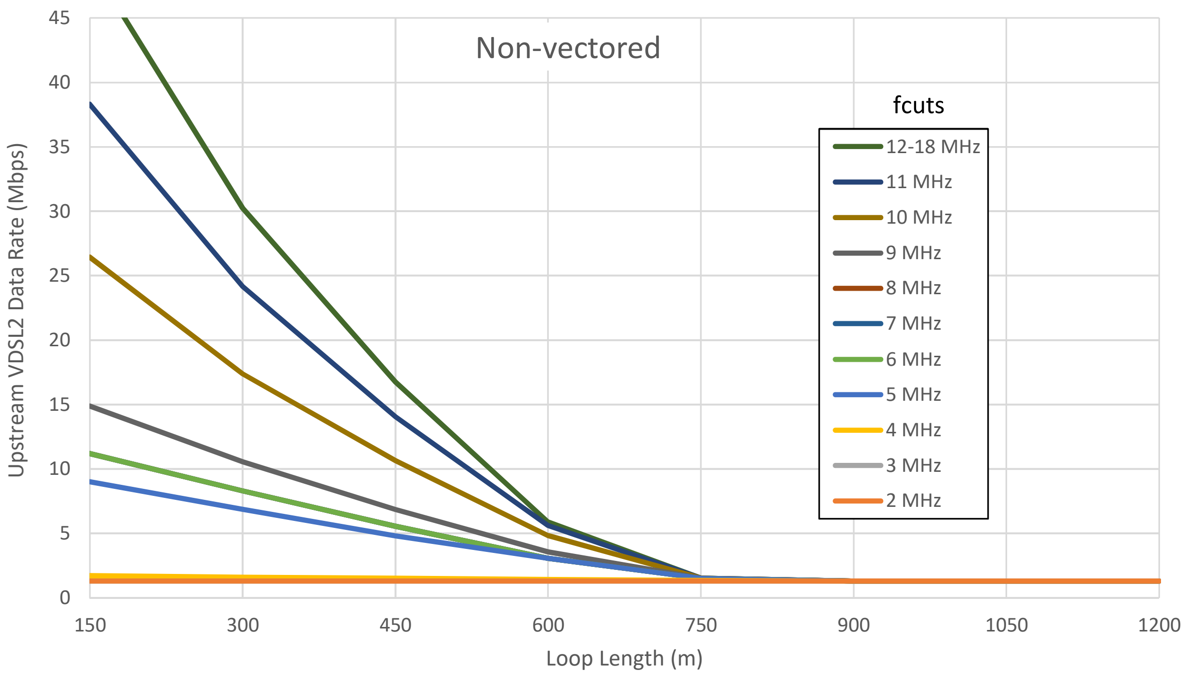


Figure 7-27 Average upstream non-vectored VDSL data rates as a function of fcut

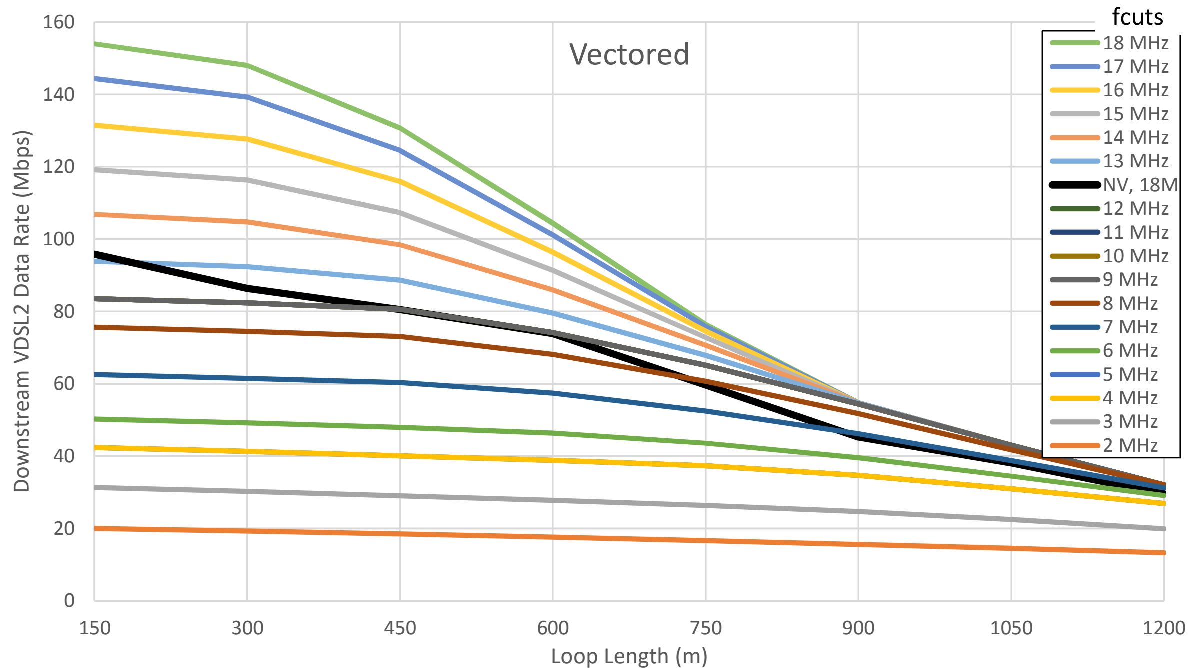


Figure 7-28 Average downstream vectored VDSL data rates as a function of fcut.

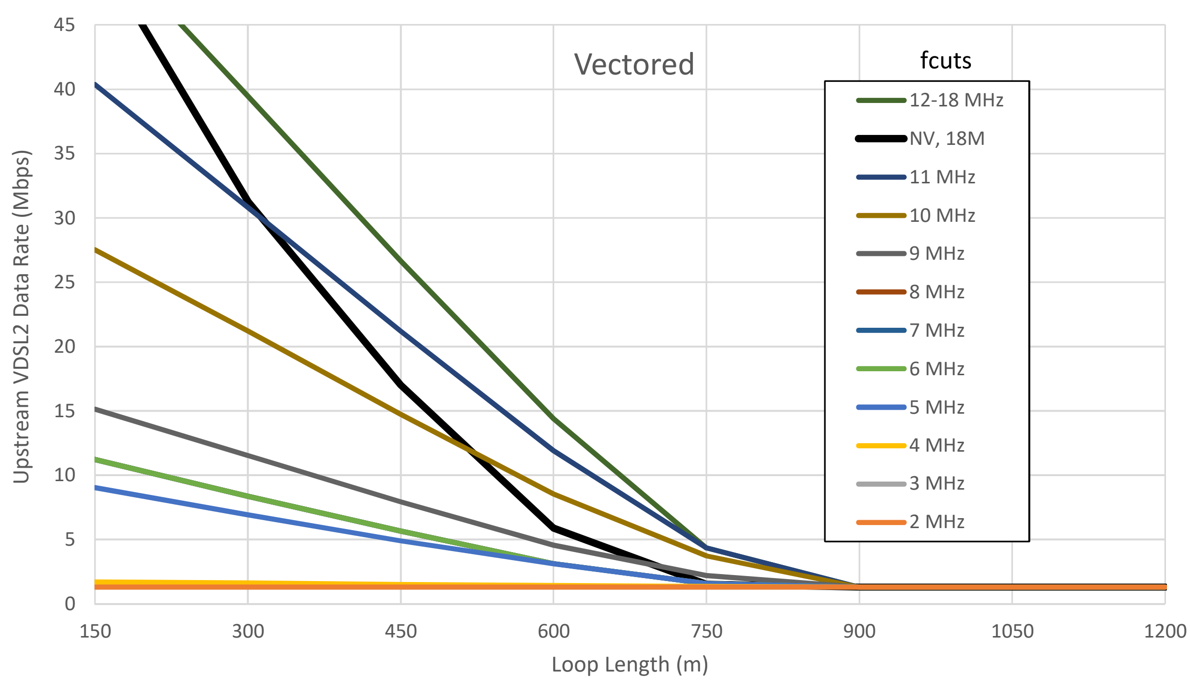


Figure 7-29 Average upstream vectored VDSL data rates as a function of fcut.

Figure 7-28 and Figure 7-29 include a thick black line “NV, 18M” which is the data rate of non-vectored VDSL with fcut = 18 MHz, which is the case of no re-farming since fcut is above 17.7 MHz.

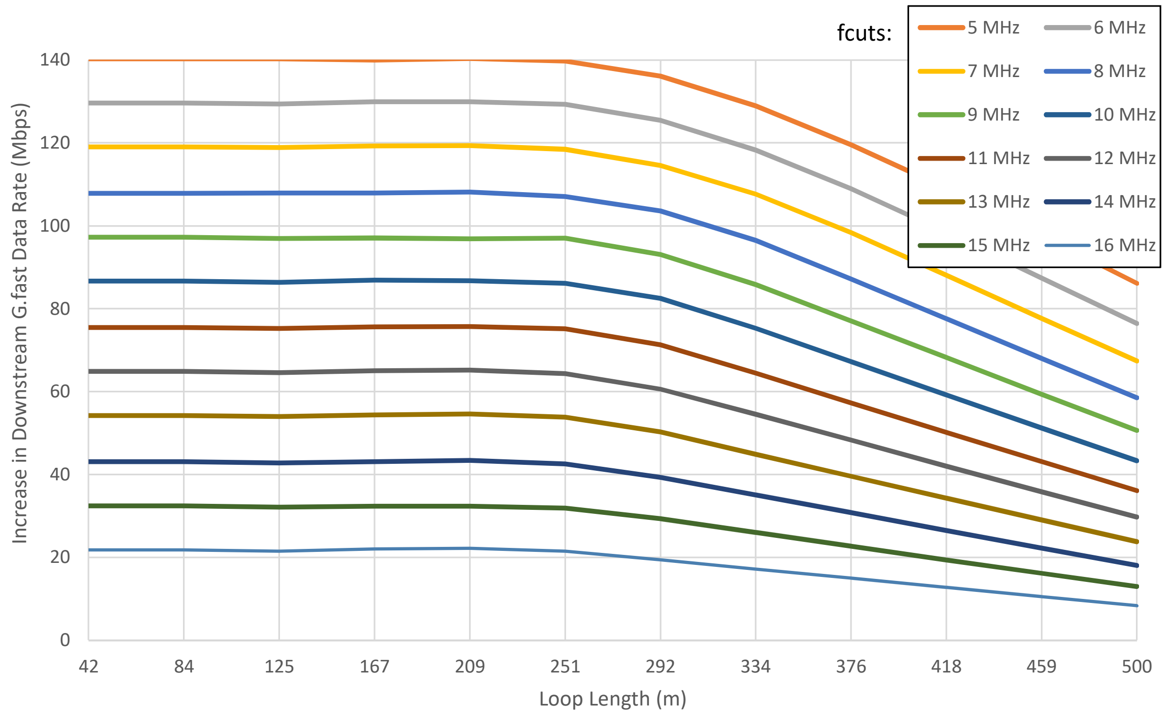


Figure 7-30 Increase in G.fast average data rates (Mbps) as fcut falls below 17.7 MHz

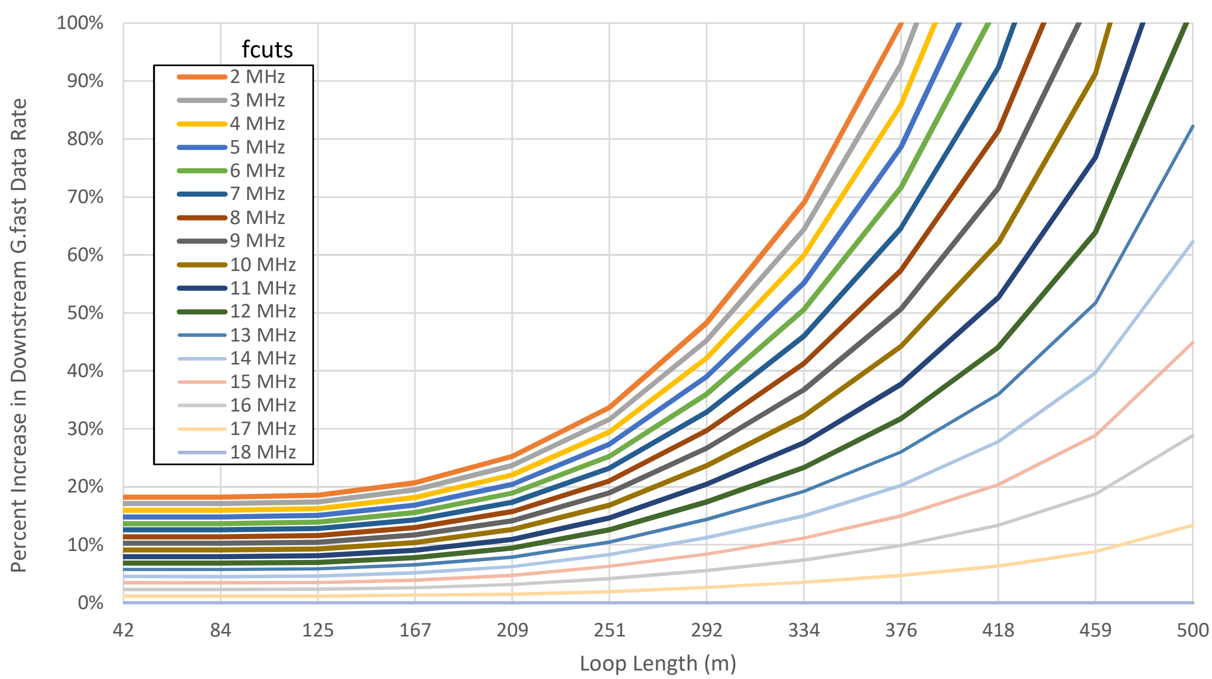


Figure 7-31 Percent increase in G.fast average data rates as fcut falls below 17.7 MHz.

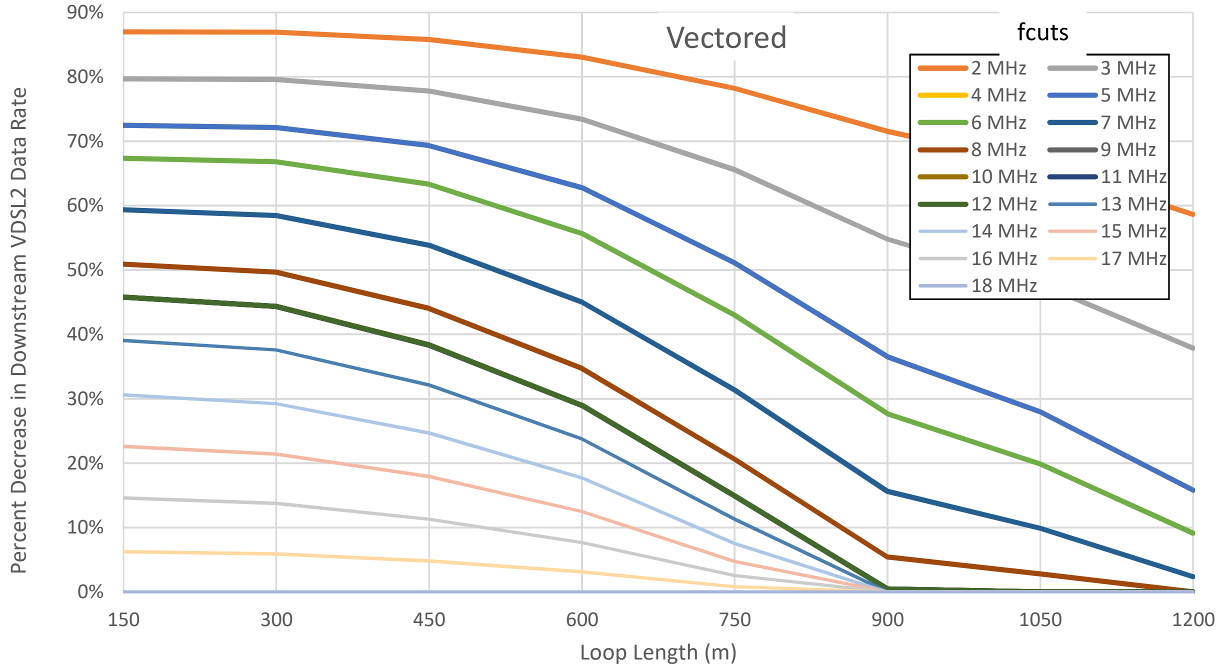


Figure 7-32 Percent decrease in downstream non-vectored VDSL average data rates as fcut falls below 17.7 MHz.

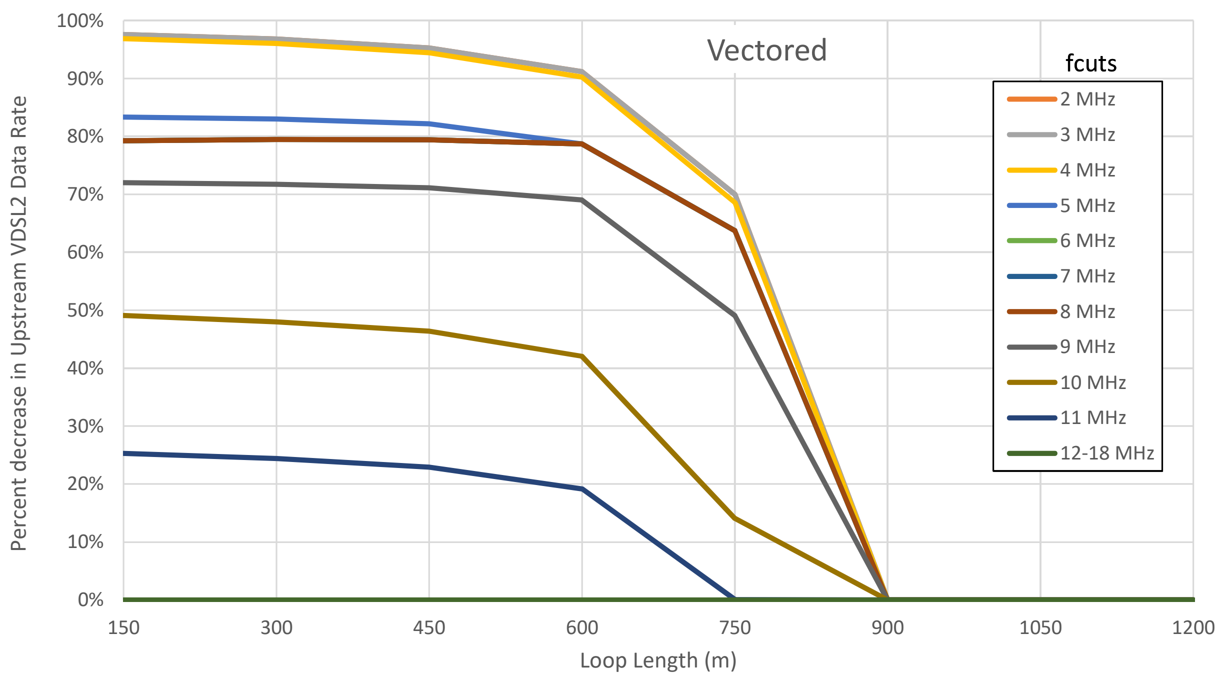


Figure 7-33 Percent decrease in upstream non-vectored VDSL average data rates as fcut falls below 17.7 MHz.

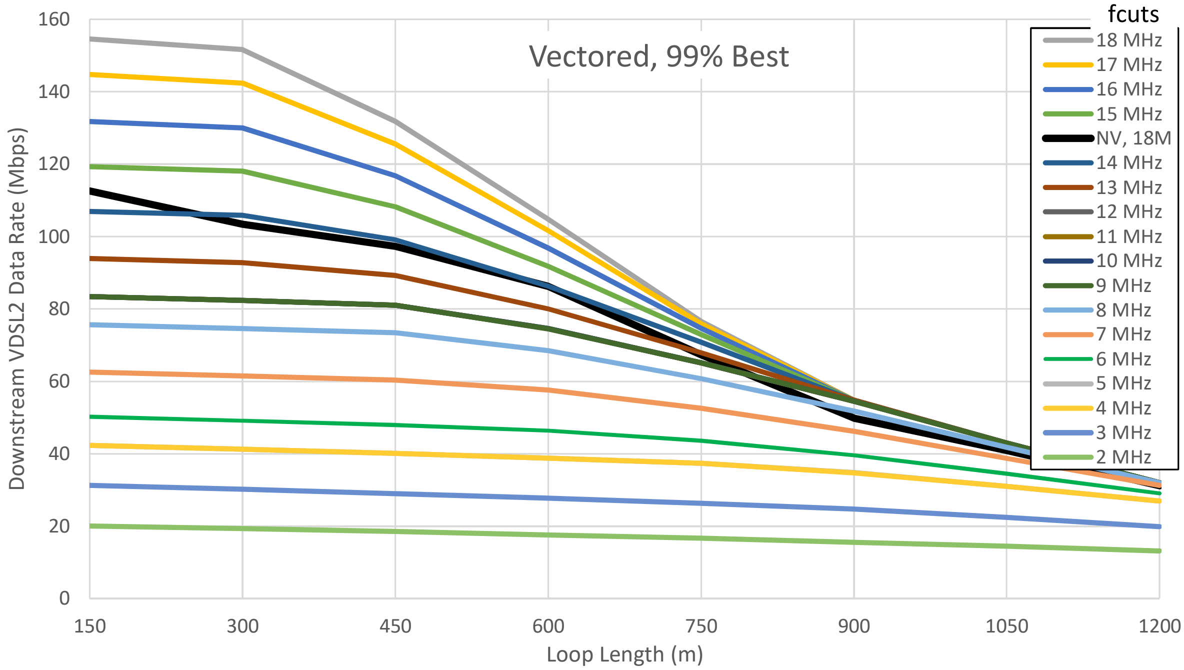


Figure 7-34 99% best downstream vectored VDSL data rates as a function of fcut.

Figure 7-34 shows the downstream non-vectored VDSL data rates for the 99% best case instead of the average. In this case there is less crosstalk and vectoring has less improvement. Here, the thick black line "NV, 18M" is the 99% best data rate of non-vectored VDSL with fcut set to 18 MHz, which is the case of no re-farming since fcut is above 17.7 MHz.

7.5.3 Summary

With re-farming, there is a steady decrease in downstream VDSL data rates as fcut decreases below 17.7 MHz, until fcut hits 12 MHz and the VDSL DS3 band is no longer affected until the DS2 band is reached. There is no decrease in upstream VDSL data rates as fcut decreases below 17.7 MHz until fcut goes below 12 MHz and cuts into the VDSL US2 band then there is a strong decrease in VDSL upstream for loops shorter than 900m.

Figure 7-28, Figure 7-29 and Figure 7-34 show that vectored VDSL re-farmed with fcut around 12 to 14 MHz supports about the same data rates as non-vectored VDSL with no re-farming. For these values of fcut, the increases in G.fast data rates are in the tables below. Note, however, that vectored VDSL would have very high attainable data rates, up to 150 Mbps, with no re-farming.

Table 7-6 Percent increase due to re-farming of average G.fast data rate for fcut = 12 to 14 MHz.

G.fast loop length (m)	42	84	125	167	209	251	292	334	376	418	459	500
12 MHz	6.8%	6.8%	6.9%	7.7%	9.4%	12.5%	17.4%	23.3%	31.8%	44.1%	63.9%	102.6%
13 MHz	5.7%	5.7%	5.8%	6.5%	7.9%	10.5%	14.4%	19.2%	26.0%	36.0%	51.7%	82.1%
14 MHz	4.5%	4.5%	4.6%	5.1%	6.3%	8.3%	11.2%	15.0%	20.2%	27.8%	39.7%	62.3%

Table 7-7 Average data rate increase (Mbps) due to re-farming for fcut = 12 to 14 MHz.

G.fast loop length (m)	42	84	125	167	209	251	292	334	376	418	459	500
12 MHz	64.8	64.8	64.7	64.4	64.8	64.2	60.6	54.5	48.3	42.1	35.9	29.7
13 MHz	54.2	54.2	54.4	54.3	54.0	53.6	50.2	44.9	39.6	34.3	29.0	23.8
14 MHz	43.0	43.0	43.0	42.9	42.9	42.6	39.2	35.0	30.8	26.5	22.2	18.0

Re-farming results in the same data rates in both co-located and non-co-located cases, since the VDSL and G.fast spectra do not overlap. Re-farming generally decreases the maximum attainable VDSL data rates, unlike DSM in Section 7.1 where VDSL is not adversely affected while G.fast data rates increase in non-co-located cases.

7.6 Frequency re-use through SSSM

This section is covers the following high-level use cases from Table 5-2:

- Case 4, Variable split frequency per DSLAM (SSSM)

This section presents simulation results of Semi-Static Spectrum Management (SSSM) for allowing G.fast to use VDSL frequencies. First the Maximum Usable Frequency (MUF) of VDSL as a function of loop length is calculated for a typical crosstalk case. Then, G.fast is allowed to transmit in frequencies down to the VDSL MUF plus a 350 kHz guard space.

In actual deployments the VDSL MUF will have more variation than assumed here, and the simulations assume a minimal guard-band of 350kHz, so these SSSM results are optimistic.

7.6.1 Simulation assumptions

Simulation assumptions are as defined in Section 6, and the simulations are similar to those in sections 7.1, 7.2, and 7.5. VDSL uses low frequencies and G.fast uses high frequencies.

VDSL downstream has ANFP DPBO for a CAL value of 20 dB (ESEL of 1500m). UPBO is applied to VDSL upstream as a function of loop length. 10% physical layer overhead is removed before displaying all the data rates here.

For the baseline for performance comparison in section 7.6, G.fast PSDs conform to the ANFP [1] with passband above 17.8 MHz. In all cases, G.fast is limited to at most -65.7 dBm/Hz at all frequencies to meet an 8 dBm total power limit. Precoded downstream G.fast is simulated.

Lines are spatially distributed and uniformly spaced as described in Sections 5.1 and 6.5. The maximum G.fast loop length is 500m, and the maximum VDSL loop length is usually 2400m.

7.6.2 VDSL Maximum Usable Frequency (MUF)

First, the maximum usable frequency (MUF) of non-vectored VDSL was calculated with 19 self-crosstalk disturbers. 10,000 cases of random crosstalk couplings were simulated, so each loop length presents statistics across 10,000 values. There is only VDSL here, no G.fast. The MUF is the highest frequency that supports at least 1 bit/Hz on either upstream or downstream. The maximum, minimum and average MUF; and the 99% highest, 80% highest, and 1% lowest MUF are shown in Figure 7-35 - Figure 7-37.

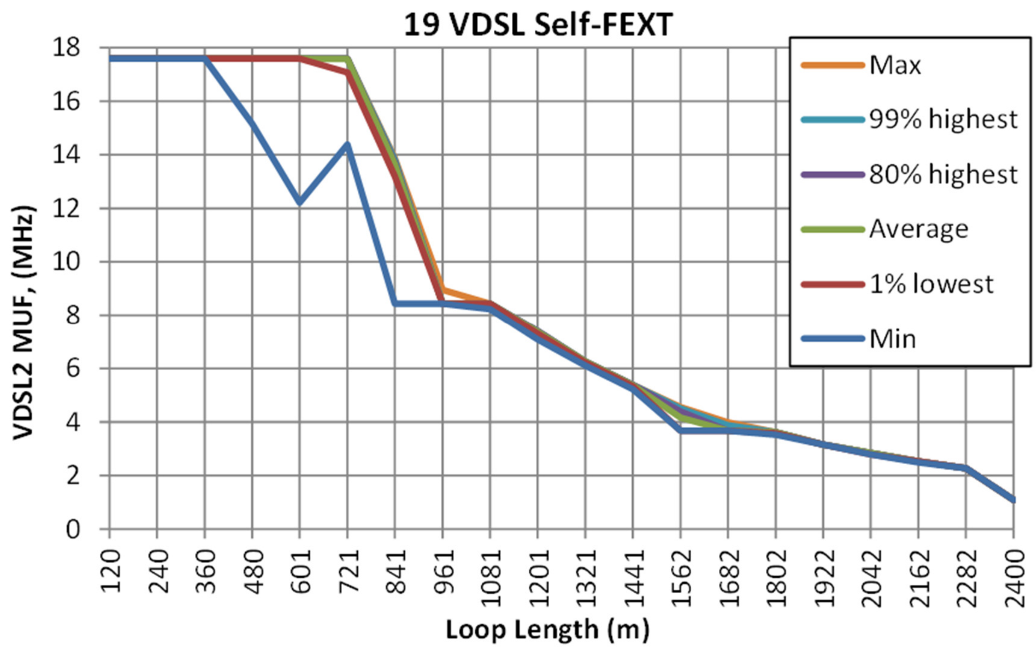


Figure 7-35 VDSL MUF, 20 non-vectored VDSLs, 2400m maximum loop length

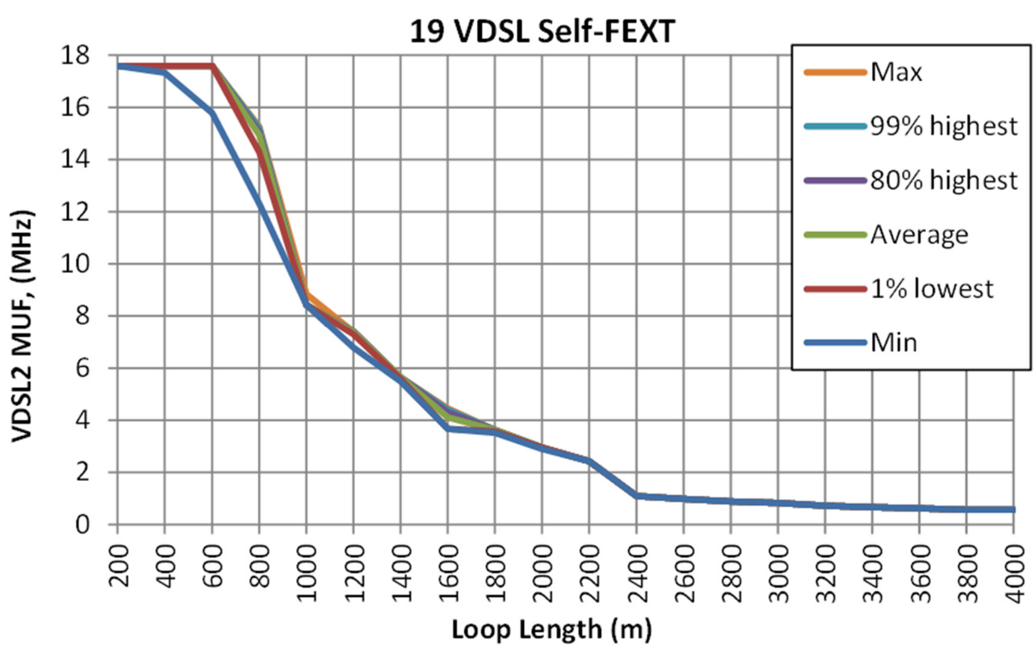


Figure 7-36 VDSL MUF, 20 non-vectored VDSLs, 4000m maximum loop length

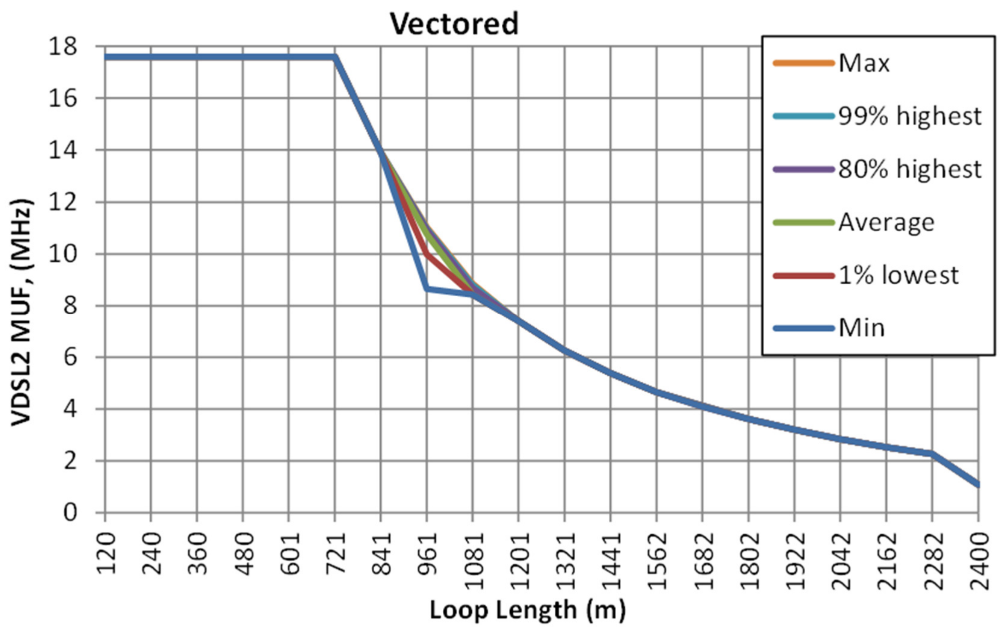


Figure 7-37 VDSL MUF, 20 vectored VDSLs, 2400m maximum loop length

Figure 7-35 - Figure 7-37 show little difference between maximum, average, 99% highest, 80% highest, and 1% lowest MUF. The minimum MUF, across all 10,000 cases, is often significantly different. A brief analysis found that near the MUF, subcarriers are loaded near 1 bit/Hz and are usually limited by attenuation and -140 dBm/Hz background noise, not by FEXT.

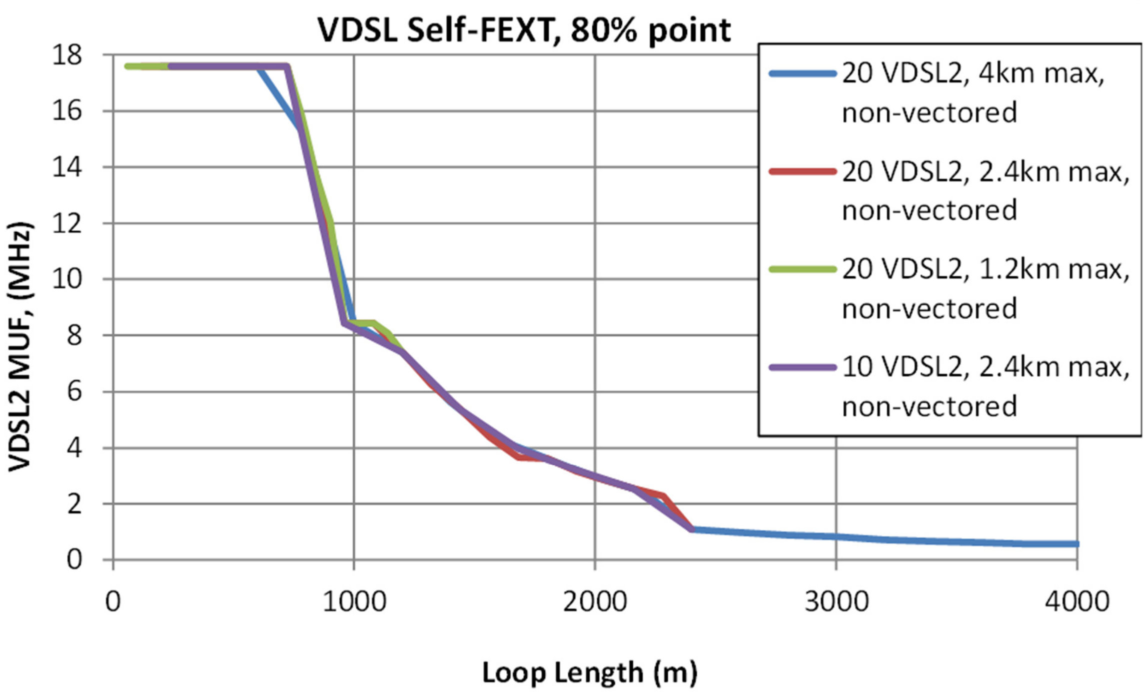


Figure 7-38 80% highest VDSL MUF, non-vectored

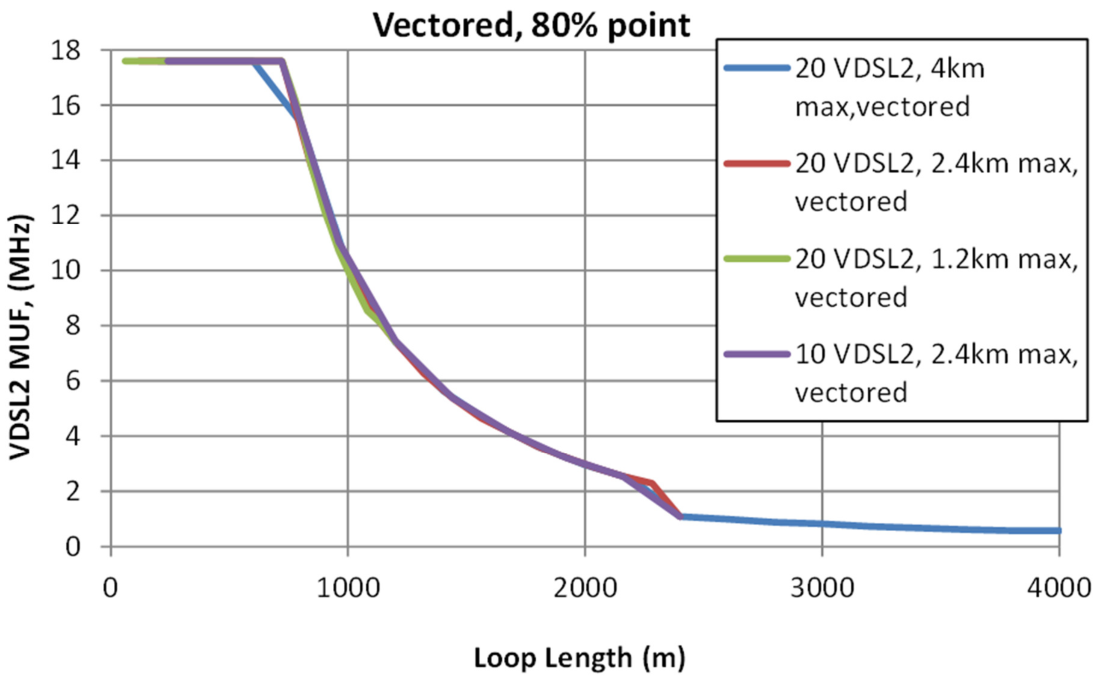


Figure 7-39 80% highest VDSL MUF, vectored

Figure 7-38 and Figure 7-39 show the 80% highest VDSL MUF for various cases. There isn't much difference between different cases. There also isn't much difference between vectored and non-vectored, except around (1000m, 9 MHz). There would be more statistical variation in the field due to radio ingress and other imperfections.

The next section assumes the 80% highest VDSL MUF across all cases shown in Figure 7-38 and Figure 7-39, including vectoring, as shown in the table below.

Table 7-8 VDSL MUF used in SSSM simulations to calculate G.fast performance.

VDSL loop length (km) To nearest 10m	VDSL MUF for SSSM simulations (MHZ)
0.12 – 0.72	17.66
0.84	13.9
0.96	10.9
1.08	8.69
1.20	7.4
1.32	6.26
1.44	5.38
1.56	4.66
1.68	4.14
1.80	3.62
1.92	3.21
2.04	2.85
2.16	2.54
2.28	2.28
2.4	1.09
2.6	0.98
2.8	0.88
3.0	0.83
3.2	0.72
3.4	0.67
3.6	0.62
3.8, 4.0	0.57

Note that on loops longer than about 900m VDSL doesn't use the DS3 band. On loops longer than about 2300m VDSL doesn't use any G.fast frequencies.

7.6.3 G.fast Performance - Above the VDSL Maximum Usable Frequency

"SSSM" is taken here to mean that G.fast transmits in all frequencies down to 350 kHz above the VDSL MUF in Table 7-8. There is no overlap of G.fast with VDSL, and so these simulations simply evaluate G.fast operating above the VDSL MUF. For a given VDSL DSLAM to G.fast DSLAM distance Y, the VDSL MUF is determined by the highest loop length in Table 7-8 which is below Y. For example, if Y = 900m, then the MUF in Table 7-8 is 13.9 MHz, corresponding to 841m. VDSL PSDs conform to the ANFP [1] with no overlapping. There is no expected overlap, so no impact on VDSL is shown here.

A guard space of 350 kHz is left unused between VDSL and G.fast, since both VDSL and G.fast specify 175 kHz roll-off. Figure 7-40 and Figure 7-41 show a data rate for G.fast transmitting 100% of the time. 10,000 cases of random crosstalk couplings were simulated. There are 12 G.fast and 8 VDSL disturbers distributed uniformly up to the maximum length for each technology.

It should be noted that in the field the VDSL MUF will have more variation then in Table 7-8, and there is a minimal guard-band, so these SSSM results are optimistic.

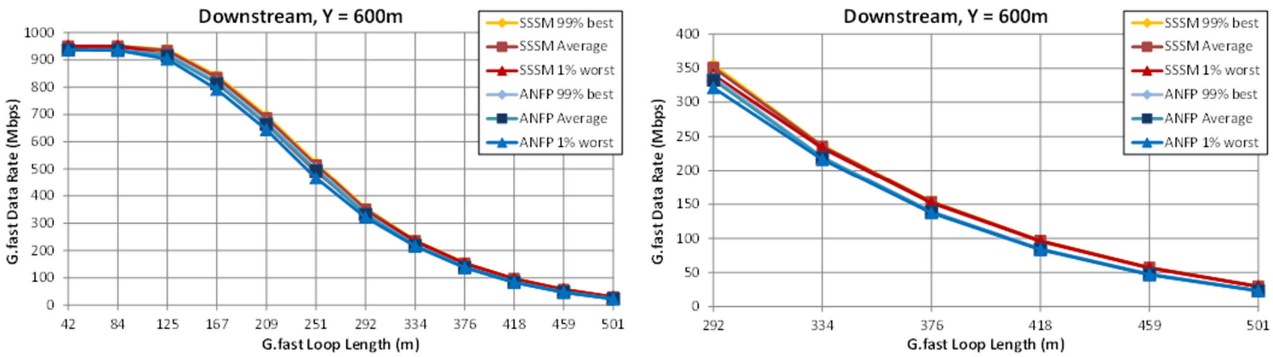


Figure 7-40 G.fast data rates with SSSM compared to ANFP 6.1.1 SSM, Y = 600m

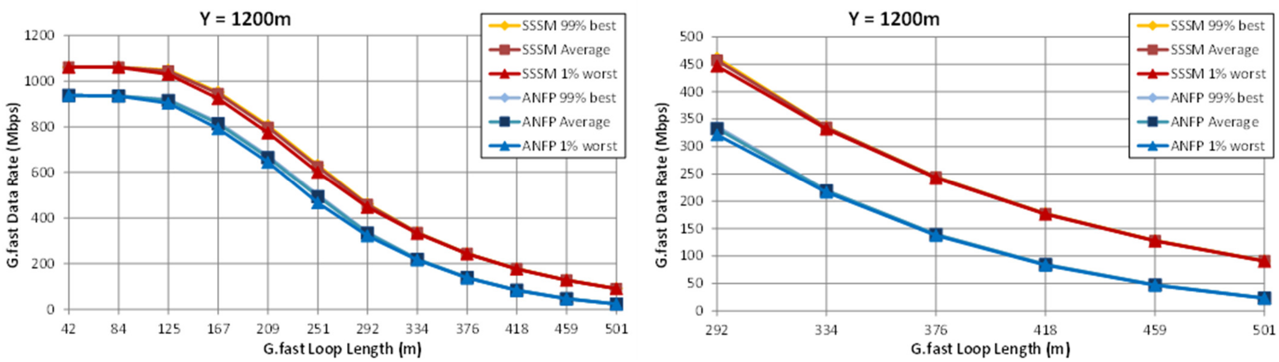


Figure 7-41 G.fast data rates with SSSM compared to ANFP 6.1.1 SSM, Y = 1200m

Table 7-9 Average SSSM gains of G.fast (Mbps) over using non-overlapping ANFP 6.1.1 SSM, averaged across all lines.

# Lines	Y (m)	Y+E+F (m)		Downstream	Upstream
20	0	2400		5.3	4.3
20	300	2400		15.8	12.6
20	600	2400		15.8	12.6
20	900	2400		48.8	39.1
20	1200	2400		113.2	90.5

Table 7-9 shows the average gain of SSSM in Mbps. The gain of the 1% worst-case was also calculated, but it is identical to the average gain in Table 7-9 so it is not shown here.

In reality the VDSL MUF at distance beyond the cabinet will vary depending on the number of crosstalk disturbers and vectoring. DSM can adapt to different crosstalk severity on a cab by cab basis but SSSM is not flexible in this regard. It follows that SSSM results will likely align closer to 1% worst DSM gains due to VDSL MUF reduction rather than average gains because of VDSL protection.

However, if a VDSL rate cap or VDSL rate reduction is allowed in a percentage of cases, SSSM fcut could be lower.

7.6.4 Using SSSM to determine the VDSL MUF and using overlapping static PSDs

SSSM can be used along with using overlapping SSM PSDs in Section 6.6.1 for downstream G.fast. Table 7-8 shows that values of VDSL DSLAM to G.fast DSLAM distance, Y, shorter than about 700m have no gain from using SSSM as defined relative to SSM here since the VDSL MUF is already at 17.7 MHz.

For Y longer than about 900m the VDSL MUF is below the VDSL DS3 band, less than 12 MHz. At these lengths SSSM will have better performance than using overlapping SSM PSDs since G.fast will transmit at lower frequencies, below the DS3 band.

One strategy could be for downstream G.fast to use an overlapping SSM PSD as in Section 6.6.1 for values of Y up to about 900m, and then allow G.fast to transmit down to the VDSL MUF (e.g., use SSSM) for values of Y greater than 900m. Performance gains would be those of overlapping SSM for Y < 900m, and those of SSSM for Y > 900m.

7.7 Simulations Summary

7.7.1 Sections 7.1, 7.2, 7.5, 7.6

Table 7-10 shows G.fast downstream data rate increases (80% of aggregate) above the current ANFP V6.1.1, averaged across all lines, for both average and 1% worst-case data rates across different coupling scenarios. In co-located cases the increase is above that of G.fast limited by the ANFP PSD mask for CGAL = 0 and transmitting only above 19 MHz. In non-co-located cases, the increase is above that of G.fast limited by the ANFP PSD mask for CGAL > 0 and transmitting only above 19 MHz. The relative changes of both the average and the 1% worst-case bit rates, averaged across all loop lengths, are summarized in Table 7-10. In Table 7-10, overlapping uses the DS3 only overlapping SSM PSD mask. The 1% worst case in the last column is the 1% worst-case data rate per scenario for the corresponding simulation. The G.fast rates were impacted by 12 disturbers of VDSL uniformly distributed up to 2.4km.

Table 7-10 G.fast downstream (80% of aggregate) data rate increases above ANFP 6.1.1, averaged across all loops.

Case	Option	Average, gain above ANFP (Mbps)	1% Worst-case, gain above ANFP (Mbps)

2a, SSM, overlapping	co-located	50.5	42.1
	co-located, 24 VDSLs < 600m	45.8	41.5
2b, SSSM, overlapping	Y = 300m	47.2	44.6
	Y = 600m	26.2	23.7
	Y = 1200m	16.3	13.8
3, re-farming	12 MHz	52.4	55.8
	13 MHz	44.9	48.6
	14 MHz	37.1	40.5
4, SSSM	Y < 700m	12.6	12.8
	Y = 900m	39.1	39.1
	Y = 1200m	90.5	90.6
5b, DSM, un-vectored	co-located	80.5	53.1
	Y = 300m	112.5	96.4
	Y = 600m	142.9	126.3
	Y = 1200m	164.3	152.3

Table 7-10 includes a case of static overlapping SSM with 24 VDSLs, co-located with G.fast, and uniformly spaced with maximum VDSL loop length = 600m.

The results for option “2b, SSSM overlapping” may be optimistic since the overlapping crosstalk in the simulation is low. Similarly, the results for option “4, SSSM” may be slightly pessimistic since as the fill decreases the maximum usable frequency for VDSL increases and less spectrum is given to G.fast.

If the number of disturbers, take-up, simulated was higher

- static, overlapping G.fast rates would reduce
- the re-farming G.fast rates would remain the same
- the SSSM re-use G.fast rates would increase

7.7.2 Sections 7.3, 7.4

A range of co-located G.fast cable lengths between 0 and 300m were simulated.

Table 7-11 shows the range of G.fast downstream data rate increases (80% of aggregate) above the current ANFP V6.1.1, for worst case coupling scenarios. The zero length loop is excluded from the summary because it is impossible in practice. The increase is above that of G.fast limited by the ANFP PSD mask for CGAL = 0 and transmitting only above 19 MHz. The G.fast rates were impacted by 24 disturbers of VDSL co-located up to 600m from their DSLAM.

Table 7-11 G.fast downstream (80% of aggregate) data rate increases above ANFP 6.1.1, in worst case crosstalk.

Case	Option	Gain above ANFP (Mb/s)

2a, SSM, overlapping	co-located	From 40 to 6Mb/s Or 5.5 to 2%
2b, SSM, overlapping	Y = 300m	From 57 to 27 Mb/s Or 7 to 19%

Table 7-12shows the range of G.fast downstream data rate increases (80% of aggregate) relative to starting G.fast at full power from 17MHz, for worst case coupling scenarios. The zero length loop is excluded from the summary because it is impossible in practice. The increase is above that of G.fast limited by the ANFP PSD mask for CGAL = 0 and transmitting only above 19 MHz.

Table 7-12 G.fast downstream (80% of aggregate) data rate increases above G.fast starting from 17.7MHz, in worst case crosstalk.

Case	**Option**	**Average, gain above starting from 17.7MHz (Mb/s)**
4, SSSM, vectored	co-located	From 37 to 25Mb/s Or 6 to 41%

8 Impact on ANFP text

The section provides a possible framework for implementation in the ANFP of addition frequency use by G.fast. Although, not a text proposal for ANFP change, this framework show in principle how each of the use cases considered in this document could be implemented in the ANFP.

Table 5-2 in section 5.4 describes 5 use cases.

1. Existing ANFP
2. Overlapping
3. Re-farming
4. Variable split frequency per DSLAM
5. Variable split frequency per line or per vector group

Use case 4 could be implemented in the ANFP through the framework presented in sections 8.2 and 8.3. Use case 3 and 5 could be added to this framework by an option that allows the G.fast start frequency to be modified and is discussed in sections 8.4 and 8.5.

8.1 Acceptable Harm/Impact

In summary; historically ANFP changes have introduced new technologies in a way which gives priority to existing services and avoids significant reduction in those services. The NICC isn't in a position to mandate significant impact on existing implementations or services. However, that doesn't mean the NICC shouldn't provide optional tools to enable such choices to be made, subject to consensus between DSLAM operator(s) and relevant Communications Providers (CPs).Section 5.5 provides more information on impact between technologies.

8.2 General to all use cases

Whatever PSD flexibility is given to technologies by the ANFP; the PSDs should be testable.

VDSL PSD limits remain unchanged.

G.fast PSD limits are modified or additional PSDs added.

8.3 Variable split freq. per DSLAM (case 4)

Expected impact on VDSL

Little or None

Key control parameters

CGAL (Co-ordinated Group Assigned Loss),

- Described in ANFP [1].
- Its value an estimate of the electrical loss, at 300 kHz, between the existing VDSL DSLAM location and a downstream G.fast DSLAM.

SDF-CC (SDF Crosstalk Cancellation).

- Value either 'P' (Prioritised) or 'N' (Not Set).
- If not set G.fast may get more PSD allowance.
- This parameter can be set, to 'P', if
    - a VDSL DSLAM at the SDF (PCP) is vectored,

- and G.fast systems related to this PCP aren't already making use of the additional PSD that configuration 'N' allows.

G.fast PSD

The PSD can be divided into two parts based one above and one below the maximum usable frequency (MUF) for VDSL.

Above VDSL MUF

- G.fast is allowed to use full G.9701 PSD [2], downstream and upstream.
- A slope might be needed at the start when the MUF is between 17.664 and 23MHz.

Below the VDSL MUF

- If VDSL vectored no allowance for either DS or US G.fast
- If VDSL un-vectored for further study. Could make use of option 2.

Effective maximum usable VDSL frequency

- Function of CGAL
- Different function depending on value of SDF-CC (Vectored or un-vectored VDSL)
- Single value for each G.fast DSLAM
- Design to be based on the harm assumption and network model assumption, including crosstalk assumption.

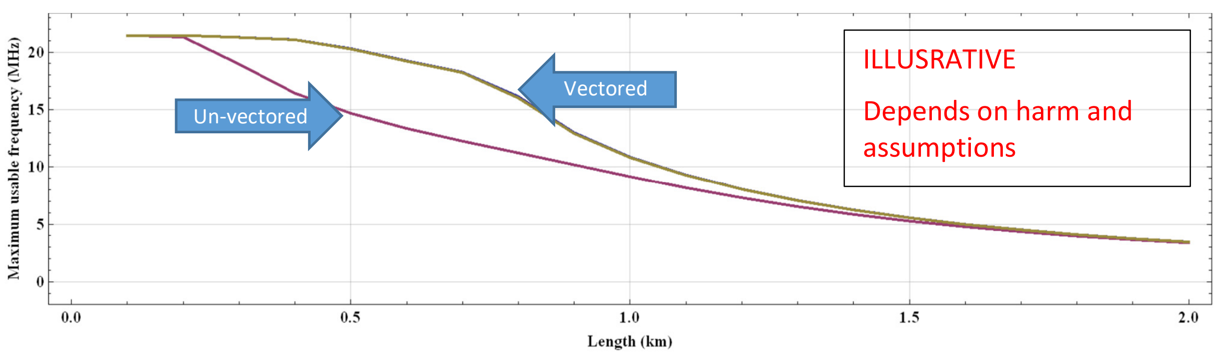


Figure 8-1 Illustration of maximum VDSL usable frequency verses VDSL loop length

Section 7.6.2 shows possible values of VDSL MUF.

8.4 Re-farming (option 3)

Expected impact on VDSL

Medium or Large

Discussion

Spectrum re-farming (taking high frequency spectrum from VDSL and giving it to G.fast) can give large increases in G.fast rates but at the expense of VDSL rate.

While it is possible to illustrate, see section 7.5, the potential gains from re-farming spectrum, the exact performance of VDSL and G.fast services are significantly dependent on operators' choices and commercial agreements including the technology implementation, service design, vectoring choices, service expectations.

Factors include

- Silicon vendor choice
- Board designs and layouts
- Product speeds and coverage
- Choices about vectoring implementation
- SLAs

Each of the range of possible choices and options could lead to a different frequency split between VDSL and G.fast.

The ANFP isn't just designed to manage harm between VDSL and G.fast and so it is necessary to specific PSD limits in the ANFP rather than no limits.

Assuming the framework for option 4 is defined as in section 8.3, re-farming would be added as option, by allowing the maximum usable frequency (MUF) to be reduced subject to negotiation between the G.fast and VDSL DSLAM operators.

8.5 Variable split freq. per line (option 5)

Expected impact on VDSL

Little or None

Discussion

The text in section 5.3.4, 6.6.4 and 7.1 covers DSM with a variable split frequency per line for an un-vectored case. Most of the recent contributions on DSM control have followed this method. The DSM based control options under SMC control would be achieved through the framework from option 4 with an option to allow the MUF to be reduced subject to consensus between DSLAM operator(s) and relevant CPs.

In addition to the split frequency some additional shaping within the PSDs defined by a variable split could be achieved by algorithms on the modems.

9 Summary

In section 5.4, Table 5-2, a number of high level control and PSD options were defined. Table 9-1 reproduces part of Table 5-2.

Table 9-1 The Options

Options	Description
1	Existing ANFP
2	Overlapping
3	Re-farming
4	Variable split freq. per DSLAM
5	Variable split freq. per line or per vector group

The options considered can be split between those with overlap between active VDSL and G.fast spectrum (option 2 and versions of option 5) and those that don't overlap spectrum (the other options). Where there is overlap allowed with VDSL the G.fast downstream and upstream PSDs below 17.7MHz usually follow the VDSL band plan. The gains from some of the overlap scenarios presented in this document may reduce once limitations on practical G.fast PSD shapes are accounted for.

The summary of the options for possible change to G.fast PSDs in the UK, in sections 9.1 to 9.5, are presented in the order described in section 5.4 of this document.

The results of simulations presented in this document are indicative of what could be achieved by each option. The numerical summary of simulations results is in Section 7.7. Note that crosstalk between G.fast and VDSL is often low in the simulation results in Table 7-10 due to: the simulated distributed topology, a small number of short VDSLs, and average case instead of worst-case.

The focus is on downstream data rates since they are typically much higher than upstream and the main concern of most customers. Also, overlapping upstream G.fast and VDSL may cause stability problems to VDSL, would complicate UPBO, and would cause NEXT coupling above 12 MHz with downstream VDSL.

9.1 Option 1, no change to existing ANFP.

The baseline used in the following comparisons is not to change the existing ANFP, or VDSL and G.fast configurations. VDSL and G.fast may be operated by different DSLAM operators and the VDSL may either be vectored or un-vectored.

9.2 Option 2, overlapping

9.2.1 New static PSD for co-located case overlapping with un-vectored VDSL

This simple to implement option uses a single PSD with no additional external parameters. The G.fast PSD would overlap frequencies with those actively used by VDSL.

The option is limited to,

- un-vectored VDSL, and
- co-location between DSLAMs.

If the VDSL was vectored overlapping PSD would cause large impact to the VDSL due to alien crosstalk.

Section 7.3 shows the results of simulations of overlapping operation. Replacing VDSL lines with G.fast lines doesn't reduce the un-vectored VDSL rates as shown in Figure 7-17. However, it would reduce vectored VDSL rates and hence overlapping would reduce the potential gains from adding vectoring to a VDSL DSLAM in the future.

This option limits G.fast so that it only transmits in the same direction as VDSL, e.g., downstream G.fast transmits in some of the downstream VDSL frequency bands. This option is most readily applied to overlapping the VDSL DS3 band downstream only. If used upstream, applying VDSL style UPBO to G.fast upstream is difficult. This UPBO is difficult to implement because there is no band dependent UPBO specified in the G.fast Recommendations [2, 3] and knowledge of an external parameter, CGAL, is required.

Further work in relevant standards bodies would be desirable to determine how much steeper the G.fast PSD slopes used to match the VDSL band plan could be than the PSDs in Section 6.6.1, and how this could change the rates.

This option can increase G.fast downstream data rates by about 50 Mbps. Note however, that in worst-case crosstalk and topology situations these G.fast gains diminish. Moreover, overlapping may cause stability problems to VDSL if G.fast is allowed to go in and out of low-power link-states, and so VDSL may need line stabilization.

9.2.2 New semi-static PSD for non-co-located case overlapping with un-vectored VDSL

This option overlaps G.fast and VDSL, and applies a new type of Downstream Power Back-Off (DPBO) to G.fast within downstream VDSL frequencies. This DPBO requires an external control parameter: the cable loss (proportional to distance Y) between VDSL DSLAM and G.fast DSLAM. Unless the distance Y is small (less than about 300 to 500m) the speed gains of G.fast with this option are low due to the new type of DPBO.

Due to the low gains, complications of the new type of DPBO, and need for overlap this is not an attractive option in non-co-located cases except perhaps for cases with small values of Y.

9.3 Option 3, re-farming; re-assigning high frequencies from VDSL to G.fast

Re-farming enables increases in G.fast rates both co-located and non-co-located cases.

Re-farming describes reducing the maximum frequency used by VDSL and allowing G.fast to use those frequencies. Where the G.fast is deployed significantly closer to the end users than the VDSL (i.e. non-co-located) reconfiguration of the VDSL may not be required because of the relative strength of G.fast to VDSL signals.

Re-farming increases G.fast performance and reach, while reducing the maximum attainable VDSL data rate, thereby performing a trade-off between G.fast and VDSL. A single re-farming configuration would result in a single trade-off across many DSLAMs or large areas of the network.

This may have limited impact on the VDSL services depending on what services rates are offered and whether the VDSL is vectored.

There are two distinct approaches to consider; one where re-farming is applied and no change is made to the VDSL other than to cap its maximum frequency, and the other where at the same time as re-farming the VDSL is upgraded to support vectoring as part of the process. For the former there is a reduction in VDSL rate and reach (unless the service is rate capped) and the latter there is an associated capital cost per DSLAM to deploy vectoring to maintain existing coverage. Adding vectoring can maintain existing coverage on lines that are cross-talk limited. Short lines with little or no crosstalk that are not rate capped may have a reduction in VDSL rate. The capital cost would vary depending on the capability of the existing DSLAMs. Note that other non-overlapping options could similarly be used with VDSL upgraded to vectoring.

The impact on VDSL and the trade-off between the two technologies is heavily linked to the choice of the fcut value separating the VDSL and G.fast.

The simulations in sections 7.4 and 7.5 are relevant to re-farming.

9.3.1 Re-farming with G.fast co-located with vectored VDSL

These results can be considered in terms of impact on existing vectored VDSL or as the outcome after re-farming and vectoring existing non-vectored VDSL.

Considering existing vectored VDSL and depending on the conditions, the G.fast rates could be improved, with limited harm to 80Mb/s coverage and a ~30% reduction (from circ. 625 to 400m) on the possible reach of a 100Mb/s product on VDSL, by re-farming vectored VDSL with an fcut value of 14MHz see Figure 9-28.

Section 7.4 details simulations allowing some reduction in VDSL performance beyond 400m where G.fast and VDSL are reconfigured with an fcut value of 12.3MHz downstream and 5.17MHz upstream in the presence of near worst case crosstalk. The G.fast bit aggregate rate is increased by 50Mb/s (35Mb/s downstream plus 15Mb/s upstream) at all loop lengths, but a 100Mb/s VDSL product isn’t possible.

Considering the transition from un-vectored to vectored VDSL at the same time as re-farming, Figure 7-28 shows that with a fcut value of 13MHz there would be an average increase in VDSL performance and Figure 7-34 shows there would be little or no harm to 99% or more of 80Mb/s VDSL services. There would be a 20 to 50Mb/s increase in average G.fast data rates depending on the loop length and a 50Mb/s average increase for the shorter lines, which are most common.

Figure 7-26 and Figure 7-28 show that if un-vectored VDSL was only required to support a 40Mb/s service G.fast could start around 8MHz and for vectored VDSL that would be around 6 or 7 MHz. However, with these values of fcut, a small percentage of the longest VDSLs would no longer reach 40 Mb/s. These start frequencies would increase the G.fast bit rate by around 100 Mb/s and 115 Mb/s respectively.

9.3.2 Re-farming with G.fast co-located with un-vectored VDSL

With un-vectored VDSL the gains for G.fast are the same for a given fcut value.

Reducing fcut would have a material impact on the coverage of an 80Mb/s service offering unless the VDSL was vectored as part of the process.

9.3.3 Re-farming with G.fast non-co-located with VDSL

Where G.fast is deployed non-co-located with far away VDSL the trade-offs change and the result becomes a mix of re-use of unused spectrum and re-farming. The G.fast re-farming speeds from a specific value of fcut are generally the same in co-located and non-co-located cases since the VDSL and G.fast PSDs do not overlap

Generally, for G.fast deployments far from the VDSL location the VDSL make less use of the higher frequencies and so the trade-offs have less impact on the VDSL headline performance for a given fcut value. Effectively in those cases re-farming is more like re-use (option 4).

9.3.4 Re-farming summary

Re-farming can scale from limited impact to large impact on VDSL with corresponding increases on G.fast speeds. The service coverage of existing un-vectored VDSL DSLAM may be maintained by vectoring the VDSL at the same time as enabling re-farming. It isn't practical to define a single version of re-farming in the ANFP because the trade-offs will be heavily affected by DSL performance, product and services offerings and consensus between the DSLAM operator(s) and relevant Communications Providers (CPs).

Re-farming has the potential to provide significant improvements in G.fast rates and could be enabled within the ANFP subject to consensus between DSLAM operator(s) and relevant CPs. Re-farming could be combined with a DSM based control approach.

9.4 Option 4, Variable split frequency per DSLAM (semi static)

This option considers G.fast with a variable start frequency (fcut) above which it can operate at full PSD and below which it is effectively 'off'. The fcut values are related to the distance Y between the VDSL and G.fast DSLAMs. The value of fcut is chosen based on the maximum usable frequency of VDSL to allow re-use of unused spectrum. For the engineering method for this option presented here, little impact on non-vectored VDSL rates is accepted relative to the crosstalk impact VDSL would have caused.

Depending on the target headline rate and coverage the fcut value can be more or less aggressive (i.e. further in the VDSL frequency range). There are two key variables, whether the VDSL is vectored and the cable loss between the VDSL and G.fast DSLAMs. Although a parameter capturing the cable loss is defined in the ANFP (CGAL), there are no currently implemented systems to compute it or interfaces to share it with CPs. There are no new functional requirements on VDSL systems, but G.fast systems must be configured with the correct start frequency and PSD.

9.4.1 Non-co-located

This option can give gains up to 113Mb/s downstream and 90Mb/s upstream for Y $\geq$ 1200m, as shown in Table 9-9.

This option only has significant G.fast gains for Y greater than about 700m as shown in Table 7-8 and Table 7-9 because most cabinets have some short lines.

9.4.2 Co-located

In co-located cases and for Y less than about 700m to 900m, overlapping operation as described in Section 7.2, could be used instead of this SSSM option. Overlapping extends G.fast down to 12 MHz, and for Y greater than about 700m to 900m VDSL doesn't use frequencies above 12 MHz anyway. As discussed in section 7.6.4, overlapping could be used for co-located cases and cases with small Y, and this SSSM option could be used for Y greater than about 700m.

When co-located with vectored VDSL full overlap below 17.7MHz would cause large harm to vectored VDSL and so isn't a viable option unless more harm is allowed.

9.4.3 Summary

In co-located cases there is no gain for G.fast from the variable split frequency per DSLAM option, beyond that from reducing the start frequency to 17.7MHz.

In non-co-located cases there is gain where Y is greater than about 700m, this gain is up to 113Mb/s.

The option as presented requires knowledge of the loss between the G.fast and VDSL DSLAM, CGAL, and may require knowledge of whether the VDSL is vectored or not. A process would be required to manage recording and distribution of loss between DSLAMs and VDSL vectoring state.

9.5 Option 5, Variable split frequency per line (dynamic)

This option considers G.fast with a variable start frequency (fcut) above which it can operate at full PSD and below which it is effectively 'off'. The fcut value is related to the distance between the VDSL and G.fast DSLAMs and chosen per line, per vector group or per DSLAM to optimise the actual data rates. DSM can also include further spectral optimisation, such as iterative water-filling (IWF) as simulated in Section 7.1.

For the way of engineering this option presented here, little impact on VDSL non-vectored rates is accepted relative to the crosstalk impact VDSL would have caused. However, DSM could implement other trade-offs. For example, a DSM system could simply allow G.fast to use all the operating spectrum not needed by VDSLs to meet their service rates at a given deployment or implement a dynamic version of re-farming. Additional gain would be available for the G.fast lines if the VDSL was vectored at the same time as a DSM solution was deployed.

In the non-co-located case there is no need to configure VDSL because due to the relative signal level between G.fast and VDSL. DSM generally will not have VDSL operating at the highest frequencies if this is chosen by the DSM algorithm. As shown in [Figures 15-17], in the non-co-located case there is little overlap of VDSL and G.fast PSDs with DSM, so most DSM gains still apply in cases that don't overlap spectra.

A Spectrum Management Centre would be required including interfaces to collect performance data from VDSL and G.fast DSLAMs, and interfaces to control the G.fast start frequency per line. Specification of such functionality and interfaces is beyond the scope of the ANFP. Data sharing for DSM is discussed in detail in ND1518 [8] Also, performance targets and trade-offs would need to be agreed between operators.

9.5.1 Co-located case, non-vectored VDSL

If the VDSL is not vectored the downstream G.fast rates could be improved by on average 80 Mb/s relative to the current ANFP [1]. There is also a potential impact on the future performance of vectoring of VDSL, to which a DSM system can adapt to but may result in trade-offs impacting some customers' services.

9.5.2 Non-co-located case, non-vectored VDSL

For the cases where G.fast is located more than 600m from the VDSL DSLAM (Y ≥ 600m) this option can on average increase the line rates relative to the current ANFP [1] by around 140 Mb/s to 164 Mb/s downstream Table 7-10. Performance relative to option 2, overlapping SSM, is summarized in Section 9.1 and ranges from 54 Mb/s to 116 Mb/s downstream for Y > 0.

9.5.3 Vectored VDSL cases

With vectored VDSL, the type of level 2 DSM spectral optimization simulated in Section 7.1 is generally not effective since overlapping G.fast can strongly impact vectored VDSL. However, DSM could flexibly implement re-farming and/or non-overlapping SSSM options similar to Sections 9.3 and 9.4 with vectored VDSL, and could additionally be tailored to the particular environment of the line, vector group or DSLAM.

9.5.4 Summary

DSM can offer improvements to downstream G.fast around 80 Mbps in co-located cases, and up to 164 Mbps in non-co-located cases relative to the current ANFP [1]. DSM by its nature has considerable flexibility, but is not amenable to being defined by simple rules.

A spectrum management centre would be required with interfaces to collect data from and configure DSLAMs see Section 5.3.4.

9.6 Possible ANFP implementation

A set of new PSD masks or PSD mask with start frequency could be added which allow G.fast to start at lower frequencies. In addition to the existing parameter related to the distance between VDSL and G.fast locations, CGAL, a parameter related to the vectored state of the VDSL DSLAM could be added.

A semi static variable split frequency per G.fast DSLAM could be allowed in the ANFP by selection from the set of PSDs or configuration of the new PSD using the two parameters.

A dynamic variable split frequency per G.fast line could be allowed in a given PCP area, subject to consensus between the DSLAM operator(s) and relevant CPs, by allowing PSD selection parameters to be overridden. The ANFP would still apply, except with the G.fast PSD selected by the dynamic algorithm rather than by topology dependant parameters.

Re-farming could be allowed in a given PCP area, subject to consensus between DSLAM operator(s) and relevant CPs, by allowing the PSD selection parameter to be overridden. The ANFP would still apply, except with the G.fast PSD selected through the agreement, rather than by topology dependant parameters.

Changes to the ANFP following ND1520 publication could enable use of re-farming or other spectrum management techniques. There will be commercial factors, including those related to any adverse impact on existing services that need addressing before these techniques are exploited. The NICC is not in a position to address commercial issues so these should be resolved in an appropriate commercial forum.

9.7 General

The results of simulations presented in this document are indicative of what could be achieved by each option, they don't directly represent real world conditions and most of the options contain flexibility in how they could be implemented. Implementation of the techniques described may not give the same results as the simulations however they should be directionally similar. Lab and field tests would provide more confidence in the levels of rate changes.

Up to 10 Mb/s benefit for G.fast could be achieved by reducing the start frequency for G.fast towards 17.7 MHz subject to a better understanding of the distribution of the impact through typical VDSL anti-aliasing filters in the network. This is applicable to all of the options. The benefit of this change is shown in Table 7-5 and could be applicable to G.fast in all deployment locations.

Vectored VDSL can use higher frequencies than un-vectored VDSL, so any method allowing G.fast to use frequencies that are not used by un-vectored VDSL or overlapped with un-vectored VDSL, may limit the ability to offer higher speed services by vectoring VDSL in the future.

If VDSL is vectored, then operating PSDs of VDSL and G.fast should not overlap, however G.fast may occupy unused VDSL spectra.

Methods that overlap the operating frequencies of VDSL and G.fast, such as allowing G.fast to use the VDSL DS3 band downstream, may lead to instabilities due to G.fast TDD operation so these need to be properly managed and studied if implemented. These methods may require new DPBO and UPBO for G.fast in standards and equipment.

If the VDSL is vectored without reconfiguration of the VDSL any reduction in the fcut value in co-located cases is effectively overlapping operation because the VDSL continues to operate in those frequencies and then there is little benefit for G.fast and significant impact to the VDSL performance. The case with reconfiguration and more harm to VDSL is considered by the re-farming option.

Following this study, it is concluded that many methods and cases of operation of G.fast below 17.7 MHz in VDSL spectrum are beneficial to G.fast performance, although in some cases there would be an impact on existing VDSL performance.

Annex A (informative): A G.fast power back-off scheme

A.1 Introduction

This Annex uses crosstalk and topology models that differ from those used in the main body of this document.

G.fast and VDSL use different duplexing techniques. While G.fast uses time division duplexing (TDD), VDSL uses frequency division duplexing (FDD).

The use of TDD and FDD in the same cable bundle causes a crosstalk scenario including near-end and far-end crosstalk that is shown in Figure A-1. The plots are measured samples of noise and signal PSDs for illustration purposes.

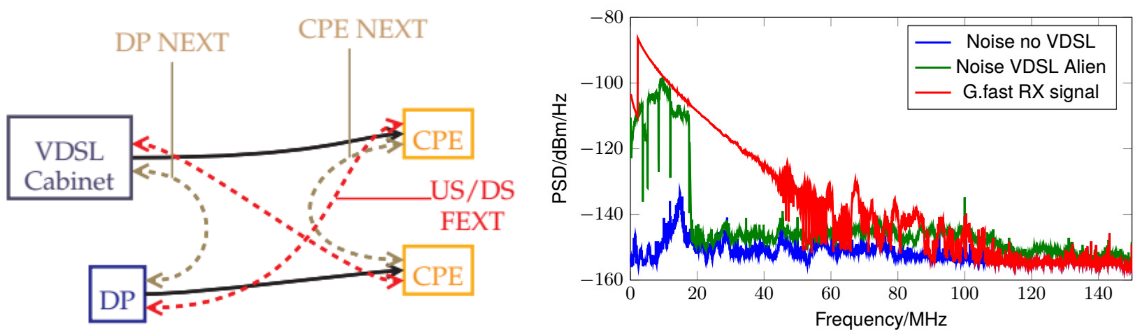


Figure A-1 Crosstalk couplings between G.fast and VDSL lines

Additionally the crosstalk scenario depends on the location of the VDSL cabinet, the G.fast DSLAM, and the corresponding CPEs. Figure A-2 show a deployment case for G.fast and VDSL that use the same cable bundle.

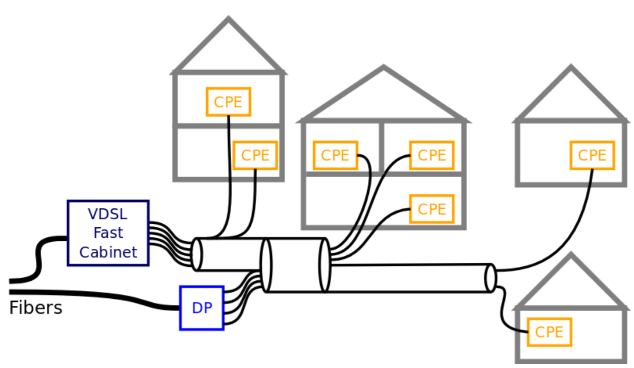


Figure A-2 A G.fast/VDSL cabinet and an additional G.fast DSLAM placed closer to the subscribers

Figure A-2 represents an envisioned network topology in UK with both VDSL and G.fast operating from the PCP, while additional G.fast DSLAM may be installed closer to the subscriber. For the purpose of this annex, the cabinet/PCP deployed modems are considered to be co-located.

Besides the different locations of G.fast and VDSL transceivers, the band plan used by the VDSL and the G.fast upstream/downstream ratio impact the actual crosstalk.

The service impact on VDSL is different for vectored and non-vectored VDSL lines, as non-vectored lines have a higher noise level.

Despite all the different cases, this annex describes a unified framework for a G.fast power back-off scheme, which allows overlapped transmit PSDs of both VDSL and G.fast so that G.fast data rates can be maximized, while impact on VDSL performance is under strict control.

A.2 Crosstalk Models

For network topologies in Figure A-2, the crosstalk path from any transmitter to any receiver is one of three types of crosstalk coupling:

1. Far-end crosstalk $h_{fextsum}(f)$,
2. Near-end crosstalk between co-located transceivers $h_{nextsum,dp}(f)$,
3. Near-end crosstalk between non co-located transceivers $h_{nextsum,cpe}(f)$.

In addition, the near-end crosstalk is attenuated by the line if the transceivers are not co-located, e.g., in the topology of Figure A-2, by the line between G.fast DSLAM location and VDSL cabinet location, $h_{dpcab}(f)$.

A comparison of the 99% worst-case crosstalk, derived from a geometrical model, with the worst-case crosstalk model defined in ETSI TS101 270 [2], indicates that for calculation of the power back-off at the overlapping frequencies both are sufficiently close, thus a simplified model is used.

The geometry model used for simulation gives a good fit to the simulation parameters mentioned in Section 6 and with published measurement data of a 0.5mm PE cable as shown in Figure A-5 and Figure A-6.

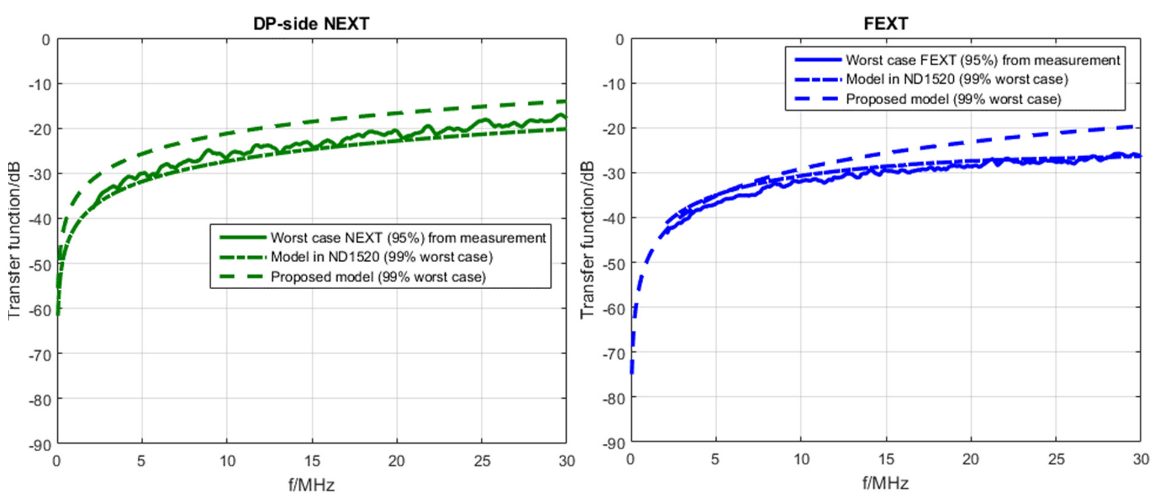


Figure A-3 Worst-case NEXT and FEXT derived from measured BT cable [3], [4] and approximation functions; Worst-case functions derived from measurement are 95% worst-case, because the binder is 20 lines.

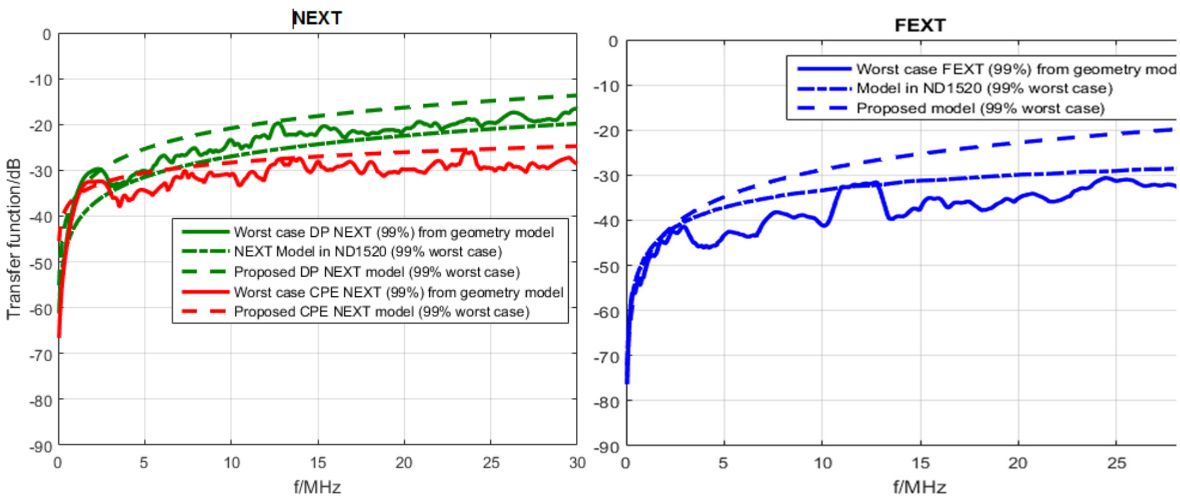


Figure A-4 Worst-case NEXT (Cabinet/DP-side and CPE-side) and FEXT derived from geometrical cable model and approximation functions

These crosstalk couplings models are different from and slightly more conservative than those used in the main body of this document, see section 6.

The following crosstalk models are used to calculate a power back-off PSD for G.fast.

- Annex A : $\left|H_{fextsum}(f)\right|^2 = N_{dist}^{0.6}\left(\frac{f}{f_0}\right)^2 \frac{d_{avg}}{1km} 10^{-\frac{50}{10}}$
- DP-side or cabinet-side NEXT: $\left|H_{nextsum,dp}(f)\right|^2 = N_{dist}^{0.6}\left(\frac{f}{f_0}\right)^{1.5} 10^{-\frac{44}{10}}$
- CPE-side NEXT: $\left|H_{nextsum,dp}(f)\right|^2 = N_{dist}^{0.6}\left(\frac{f}{f_0}\right)^{0.75} 10^{-44/10}$

where N_{dist} is the number of G.fast disturbers, f is the frequency, f_0 equals 1 MHz and d_{avg} is the average FEXT coupling length from the G.fast transceiver location to the VDSL CPEs.

The model for near-end crosstalk between CPEs is different from the one at the cabinet because for non-co-located CPEs, NEXT is attenuated by the line between the CPEs, which results in lower NEXT between CPEs, compared to NEXT at the cabinet side.

A.3 Power Back-off

The starting point of the power back-off PSD calculation, as presented in [12], is the acceptable interference level in to the VDSL lines $\psi_{nmax}(f)$. This can be a flat PSD or an arbitrary shape. A low value of $\psi_{nmax}(f)$ gives smaller performance impact on the VDSL lines and a higher value gives higher data rates on the G.fast lines.

A particular VDSL band plan is used in deriving the required G.fast PSD back-off. The examples shown in this Annex use band plan 998ADE17 from [5]. The G.fast upstream/downstream ratio in the power back-off calculation corresponds to the worst case assumption of full overlap in time. Crosstalk from G.fast into VDSL is non-stationary, as it fluctuates with the G.fast TDD frame. When using G.fast power back-off, NEXT and FEXT from the G.fast lines into each VDSL are brought approximately to the same level, which is close to the noise level expected in the VDSL lines in absence of G.fast. The TDD frame of G.fast is short compared to the VDSL SNR measurement time.

An issue may occur in case that the VDSL DMT symbol time is aligned with the TDD frame timing of G.fast. The presented G.fast power back-off method helps to avoid non-stationary noise for two reasons:

1. The crosstalk levels from VDSL into G.fast are low, e.g., close to the noise levels
2. The crosstalk from G.fast upstream and G.fast downstream into VDSL is brought approximately to the same level and thus, the noise variation observed on the VDSL line is reduced.

The knowledge of the network topology required is the number of G.fast lines N_{dist} as well as the line attenuation between G.fast and VDSL cabinet location $h_{dpcab}(f)$.

With this, the PSD after power back-off for G.fast downstream transmission $\psi_{pbo,ds}(f)$ and for G.fast upstream transmission $\psi_{pbo,us}(f)$ are given by:

$$\psi_{\mathrm{pbo,ds}}(f \in F_{\mathrm{vus}}) = \frac{\psi_{nmax}}{|H_{nextsum,dp}(f)|^2 |H_{dp,cab}(f)|^2}$$

$$\psi_{\mathrm{pbo,ds}}(f \in F_{vds}) = \frac{\psi_{nmax}}{|H_{fextsum}(f)|^2}$$

$$\psi_{\mathrm{pbo,us}}(f \in F_{vus}) = \frac{\psi_{nmax}}{|H_{fextsum}(f)|^2 |H_{dp,cab}(f)|^2}$$

$$\psi_{\mathrm{pbo,us}}(f \in F_{vds}) = \frac{\psi_{nmax}}{|H_{nextsum,cpe}(f)|^2}$$

with F_{Vds} to be the VDSL downstream bands and F_{Vus} to be the VDSL upstream bands.

Configuration for Vectored and Non-Vectored VDSL Lines

The equations above are applicable for vectored and non-vectored VDSL victim lines. However, in case of non-vectored VDSL, instead of a flat noise PSD $\psi_{nmax}(f)$, e.g., $\psi_{nmax}(f)$=-130dBm/Hz, the accepted noise level may be selected assuming presence of the native VDSL crosstalk, e.g., $\psi_{nmax}(f)$ = -60dBm/Hz + $h_{fextsum}(f)$ [dB].

Dependency on UPBO

The G.fast UPBO mechanism has the advantage that the line estimation is known for the spectrum shaping. UPBO refers to far-end crosstalk between non-vectored upstream transmissions and thus it only refers to crosstalk from G.fast upstream transmission in the VDSL upstream band. The corresponding power back-off PSD definition can be changed according to

$$\psi_{pbo,us}(f \in F_{vus}) = \min\left(\frac{\psi_{nmax}}{|H_{fextsum}(f)|^2 |H_{dp,cab}(f)|^2}, \psi_{upbo}(f)\right)$$

where $\psi_{upbo}(f)$ is the UPBO PSD.

A.4 Configuration and Management

Configuration and management is simple. Computation of the G.fast transmit PSD requires parameters listed in Table A-1.

Table A-1 Parameters associated with PSD back-off

Parameter	Description	Proposed Range

$\psi_{nmax}(f)$	Maximum allowed noise PSD for VDSL from G.fast	16 Breakpoints; -80dBm/Hz ... -150dBm/Hz in steps of 1dBm/Hz
F_{Vds}, F_{Vus}	VDSL upstream and downstream band boundaries	Band plan descriptor
N_{dist}	Number of disturbing G.fast lines	Integer, 1…256
d_{avg}	Average line length of G.fast lines	Fixed to 200m
$h_{dpcab}(f)$	Attenuation of the line between VDSL cabinet and G.fast DSLAM	-kl0 sqrt(f/1MHz) [dB]

A.5 PSD Configuration and Measurement

The power back-off rules described in section A.4 don't take the limited maximum slope of the transmit PSD when using DMT modulation into account. Figure A-5 shows that the actual transmit PSD, as it would appear on the line, includes steep slopes.

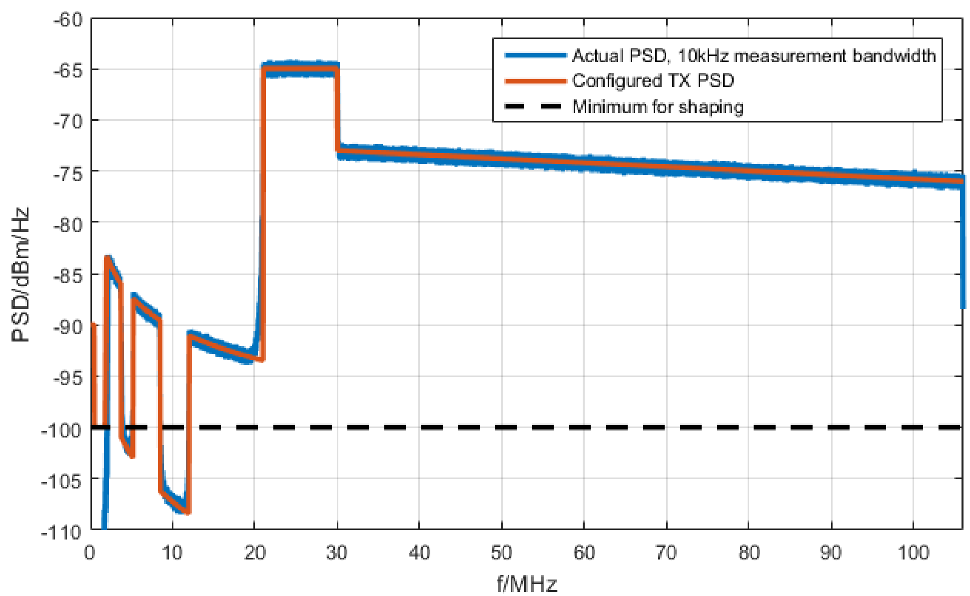


Figure A-5 Configured G.fast PSD vs. simulated output PSD with DMT modulation, 10kHz measurement bandwidth, and windowing with beta=128

In the case where the resultant PSD falls below a certain threshold, e.g., -100dBm/Hz in Figure A-5, the corresponding carriers may no longer be used for data transmission, e.g., PSD back-off is achieved by notching of the corresponding subcarriers.

Especially on the steep band edge around 20 MHz, the actual PSD deviates more substantially from the transmitted PSD. In the example, this is not of concern as the power back-off frequency is configured to protect the VDSL band edge, also. To keep the actual line PSD in the limits of the desired PSD, the maximum PSD slope can be adjusted to a configurable value, e.g. 1.5dB per carrier, as it is shown in Figure A-6.

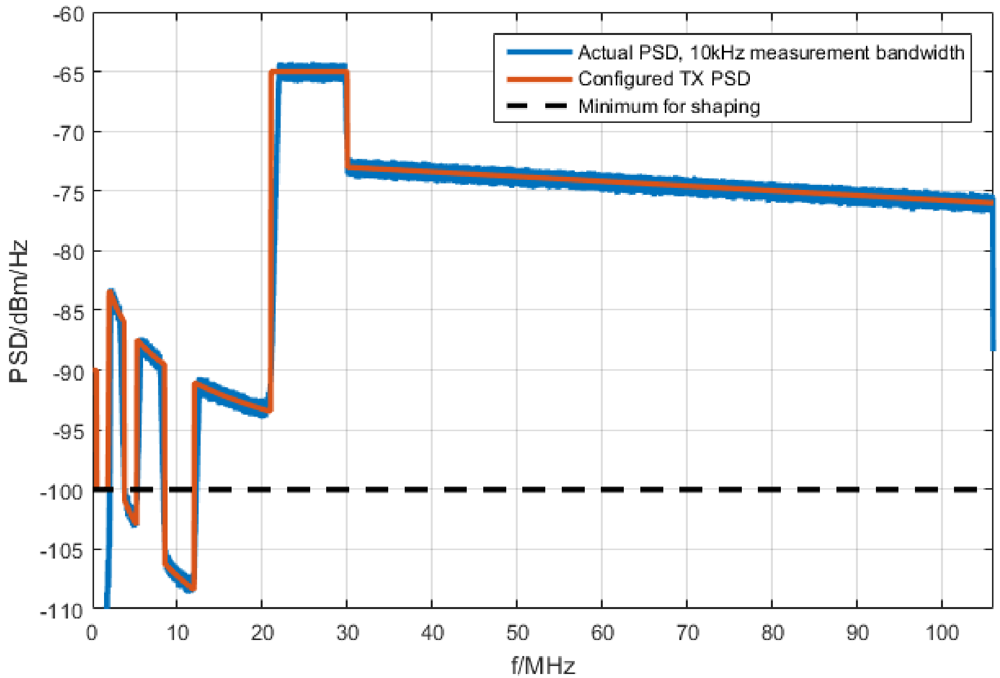


Figure A-6 Configured G.fast PSD vs. theoretical output PSD with DMT modulation, 10 kHz measurement bandwidth, using windowing with beta=128

The highest frequency to be protected by the G.fast power back-off is kept configurable, but it is recommended to be kept at a frequency that is higher than the highest used VDSL subcarrier because the out-of-band crosstalk noise is folded into the used VDSL subcarriers.

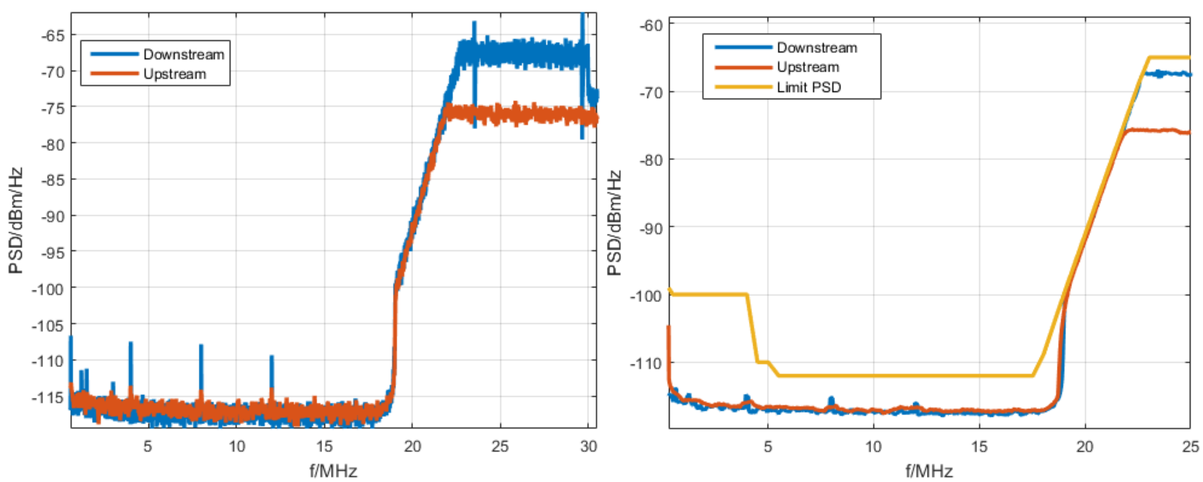


Figure A-7 Measured low frequency band edge with β=128 and 19 MHz start frequency, using a measurement bandwidth of 10kHz (left) and a measurement bandwidth of 1 MHz (right)

Figure A-7 gives an example of the measured G.fast band edge at 19 MHz using the PSD mask defined in NICC ND1602 for CGAL>0 with the windowing setting β=128 and a measurement bandwidth of 10 kHz and 1 MHz.

A.6 Bit allocation in the Overlapped Spectrum

The average bit allocation in the G.fast lines gives more insight on the benefits of overlapped spectrum operation. Figure A-8 shows the average bit allocation over frequency for the G.fast lines originated from the cabinet location.

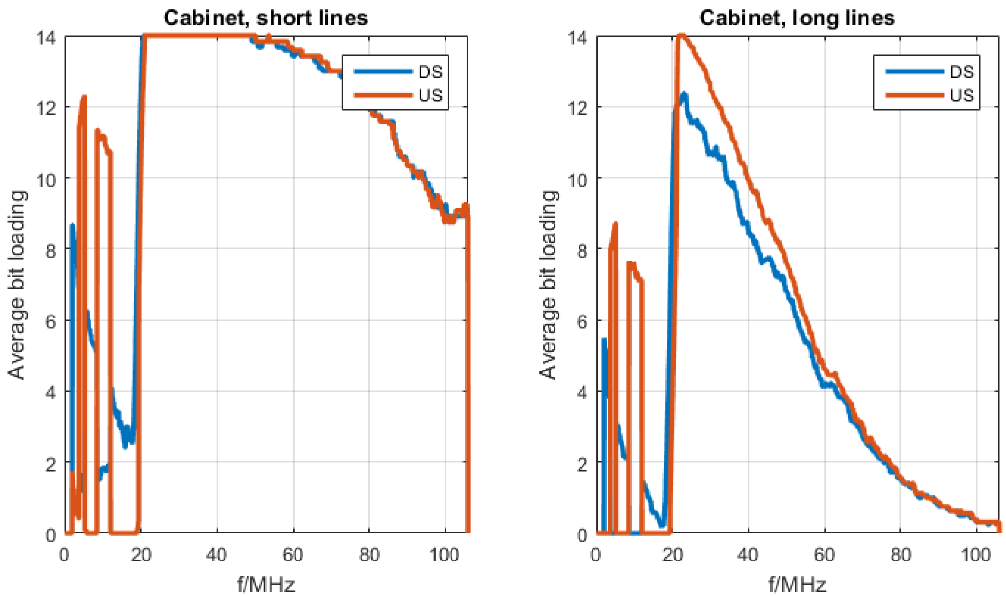


Figure A-8 Average bit allocation of G.fast lines served from the cabinet with G.fast power back-off enabled on short G.fast lines (left) and longer G.fast lines (right)

In the downstream direction (in the bands overlapping VDSL), the bit allocation in the overlapped spectrum is mainly present on the very low frequencies, because at the higher frequencies (towards 17MHz), the near-end crosstalk is stronger and more power back-off is required. In the upstream direction, the VDSL upstream bands give some rate improvement for the long and the short loops.

A difference in upstream relative to downstream bit allocation is observed above 20 MHz. This appears to be caused by the VDSL out-of-band signals and it is the dominating performance loss of G.fast upstream. For VDSL lines, the standardized worst-case out-of-band PSD is assumed to be present for this analysis.

For the longer G.fast lines originating from the cabinet, crosstalk from the DPU-served G.fast lines is another source of performance loss, mainly for the downstream direction.

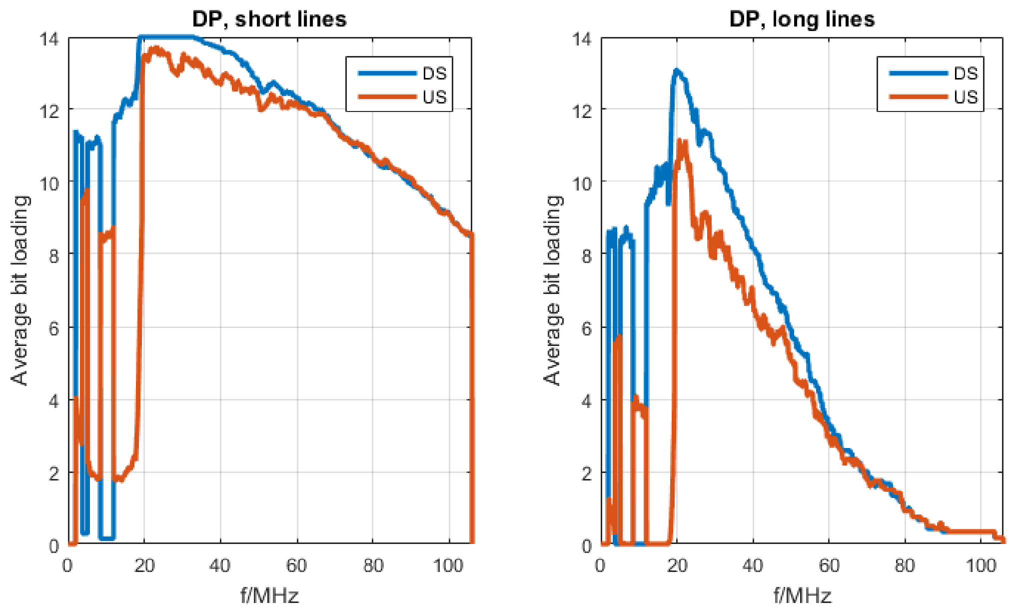


Figure A-9 Average bit allocation of G.fast lines served from the DPU with G.fast power back-off enabled on short G.fast lines (left) and longer G.fast lines (right)

G.fast lines from the DPU location benefit more from the overlapped spectrum operation than the cabinet based systems, which is also visible in the average bit allocation as shown in Figure A-9. While in the NEXT dominated parts of the spectrum the average bit allocation is low, the FEXT dominated parts of the overlapped spectrum give good data rates.

The upstream of longer loops is affected by out-of-band signal of the VDSL lines, but the effect is much weaker comparing to the case when G.fast and VDSL are co-located at the same cabinet.

A.7 Performance Simulation Results

The simulation results focus on the topology of Figure A-2, with two G.fast nodes, a G.fast/VDSL cabinet and a G.fast-only DPU. The distance between both is 400m.

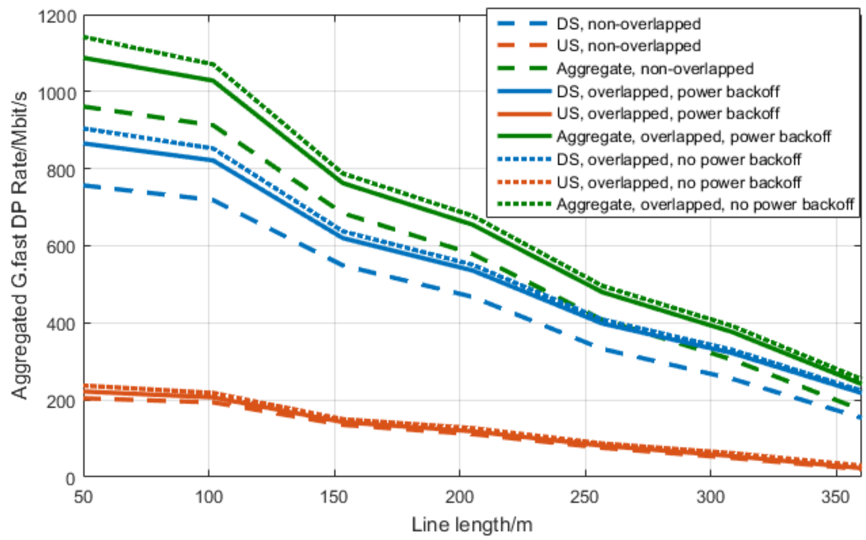


Figure A-10 G.fast lines at the DPU location. Comparison between overlapped spectrum with power back-off (sold lines), non-overlapped spectrum (dotted lines), and overlapped spectrum without power back-off (dashed lines).

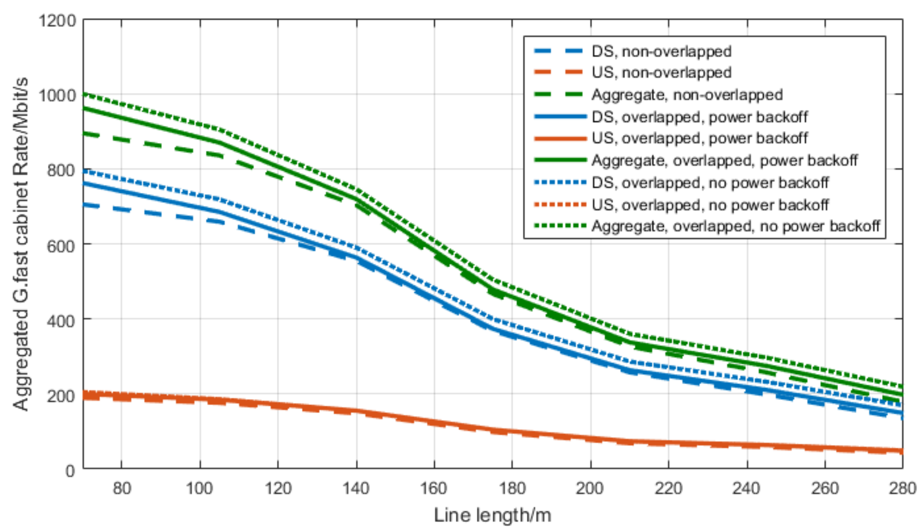


Figure A-11 G.fast lines at the Cabinet location, comparison between overlapped spectrums with power back-off (sold lines), non-overlapped spectrum (dotted lines) and overlapped spectrum without power back-off (dashed lines).

In the simulated scenario, $\psi_{nmax}(f)$=-120dBm/Hz is selected, and to protect the VDSL upstream, $\psi_{nmax}(f)$=-140dBm/Hz is used for the VDSL upstream bands for the G.fast lines at the cabinet location. For the G.fast lines served from the cabinet location, the rate improvement of overlapped spectrum, compared to non-overlapping spectrum is smaller, but still present.

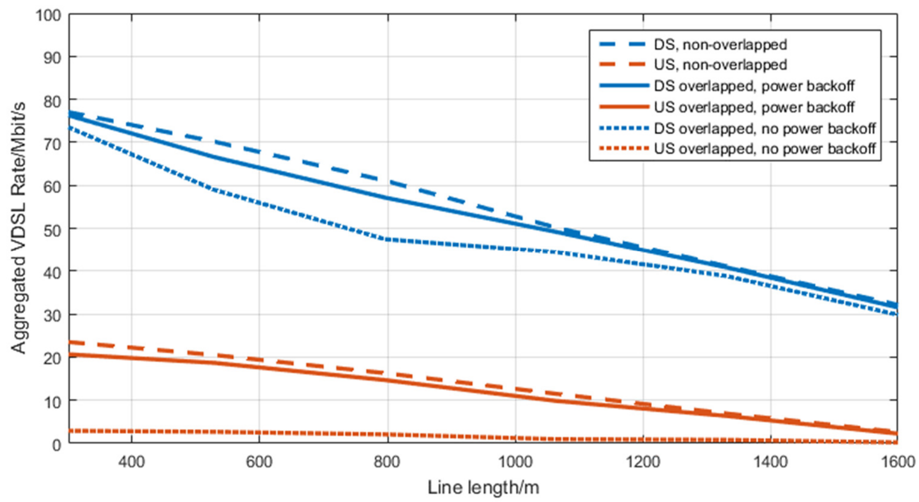


Figure A-12 Data rates of VDSL lines in the presented scenario without G.fast crosstalk (dotted lines), with G.fast using overlapped spectrum and power back-off (solid lines) and with G.fast without power back-off (dashed lines).

Concerning the VDSL lines (17 MHz profile, non-vectored), there is a small impact on the rates in upstream direction due to G.fast presence. A higher number of VDSL lines in the binder would cause a comparable effect.

A.8 Performance Simulation Parameters

For this annex, 50-pair cable binders, of 0.5mm PE cable are assumed. VDSL CPEs are non-co-located with up to 1600m length from the cabinet location. Table A-2 shows the simulation parameters used for this annex.

Table A-2 Annex A simulation parameters

Sim. Parameter	Value
Cable	BT 0.5mm PE cable, 50 pairs (CW1326)
Background noise	-140dBm/Hz below 30 MHz, -150dBm/Hz above
SNR margin	6dB
Physical overhead	10%
Coding gain	3dB
Bits per tone	Up to 14
PSD	Acc. To G.9700
Vectoring depth	40dB
Frequency band	2-106 MHz
VDSL margin	6dB
VDSL coding gain	3dB
VDSL overhead	10%
VDSL bits per tone	Up to 14

VDSL PSD	ANFP
VDSL vectoring depth	Non-vectored
VDSL alias filter/VDSL TX filter	According to Table 6-4
Number of G.fast Sources	2
Max. G.fast reach	300m (cabinet), 400m (DP)
VDSL/G.fast split	20/30
VDSL max. line length	2.0km
Number of VDSL disturbers	20
Distance from PCP to first customer	50m

History

Document history		
V1.1.1	July 2018	Initial publication