Towards a range-enhanced and spectrum-friendly G.fast

Daniel Hincapie Henao*, Jérôme Louveaux† and Gerhard Maierbacher*
*Fraunhofer ESK Institute, Hansastrasse 32, D-80686 Munich, Germany
Email: {daniel.hincapie, gerhard.maierbacher}@esk.fraunhofer.de
†ICTEAM Université catolique Louvain, Place du Levant 2 bte L5.04.04, BE-1348 Louvain-la-Neuve, Belgium
Email: jerome.louveaux@uclouvain.be

***Abstract*—The first standardized version of G.fast has been conceived to provide gigabit internet access from the distribution point (DP). Low transmit levels along its operational frequency range and low maximum aggregate transmit power (MAXATP) have been specified to restrict its electromagnetic emissions and enable the use of power available at customer premises to feed its access systems. Power constraints and a maximum bit-constellation size (B_{max}=12 bits) limit its coverage and data rates, which could discourage service providers to deploy G.fast. This work analyzes different strategies that could be potentially pursued to enhance its coverage and improve its spectral compatibility with VDSL2 systems. We carry out an extensive simulation study to evaluate a) capacity boundaries of current G.fast systems; b) benefits of increasing MAXATP, B_{max} and power spectrum density (PSD) mask levels; and c) spectral shaping as means to improve G.fast compatibility. Our simulation results show that increasing MAXATP and B_{max} boosts data rates and coverage in short loop scenarios, whereas improvements in long loops performance are only determined by MAXATP. Since such modifications generally increase the interference on legacy systems, we propose to perform power back-off (PBO) in order to improve G.fast spectrum-compatibility. As a proof of concept we adopt the PBO from VDSL2 with a fixed parameter set. Although clearly not optimized for the combination of TDD G.fast and FDD legacy systems and despite the simplicity of the adopted approach, our results indicate that spectral shaping can be an effective means to turn G.fast into a more spectrum-friendly system.**

I. Introduction

G.fast is the newest generation of digital subscriber line (DSL) systems recently standardized by ITU [1]. Using the 2.2-106 MHz frequency range, the first version of G.fast promises to deliver up to 1 Gbps of aggregate data rate from the distribution point (DP) [2]. A second version under study widens its spectrum up to 212 MHz to provide 2 Gbps [1].

Since G.fast has been designed to be densely deployed in fiber-to-the-distribution-point (FTTdp) and fiber-to-the-Building (FTTB) scenarios [2], it requires service providers to invest on numerous new access systems (in comparison with previous upgrades) to exploit its potential. In addition, the introduction of reversed power feeding [2] to overcome the physical limitations of power systems at distribution points (typically a pole, an underground utility vault or a small cabinet) may require to compensate customers for retrieving power from their premises. Both issues might discourage G.fast deployment and threaten its roll-out success.

The authors of this work have gathered the concerns of multiple service providers who coincide on the necessity of extending the coverage of G.fast. However, achieving current or higher G.fast data rates in longer loop lengths requires additional power; longer loops exhibit higher attenuation, so bit-loading algorithms demand higher power to allocate the same number of bits assigned to users with shorter loops while maintaining a desired bit error rate (BER). Systems power has been delimited in standards to avoid generating excessive electromagnetic interference, though. Accordingly, maximum transmit levels along the operative frequency range, so called PSD mask, as well as maximum aggregated transmitted power (MAXATP) have been defined. An additional restriction applies on the maximum bit-constellation size. Despite of being technologically bounded by the front-end, its regulation aims at guaranteeing multi-vendor compatibility of transceivers. Thus, increasing the achievable data rates and enhancing the coverage range of G.fast demands to redefine the standardized values of MAXATP, maximum bit-constellation size and PSD mask.

Through an extensive simulation study, this work evaluates a) the capacity boundaries of current G.fast systems; b) the benefits in terms of coverage and data rates that increasing MAXATP, maximum bit-constellation size and PSD mask levels conveys for G.fast; and c) its impact on legacy systems and the effectiveness of adopting spectral shaping mitigating their performance degradation. For our analysis, we first conduct a comparative study of the capacity of standardized G.fast 106a [3] and its profile variants when deployed in fiber-to-the-curb (FTTC), FTTdp and FTTB scenarios. We then evaluate the increment in transmit power and its impact on VDSL2 35b (enhanced data rate 35 MHz VDSL2 Annex Q) [4] performance. Our results show that increasing MAXATP, maximum bit-constellation and PSD mask levels boosts G.fast data rates and its operational range while degrading legacy systems performance. Consequently, we propose the implementation of spectrum shaping with a modified version of G.fast PSD mask as a means to turn G.fast into a spectrum-friendly system for VDSL2 with tolerable impact on its performance.

This paper is organized as follows: Section II presents the adopted system model. Section III analyses G.fast capacity in FTTC, FTTdp and FTTB scenarios and discusses the improvements of increasing the maximum bit-constellation size, MAXATP and PSD mask. Section IV compares standard and modified G.fast profiles performance coexisting with VDSL2 35b. Concluding remarks are given in Section V.

II. System model

We consider a DSL system with N users and K frequency sub-carriers. The number of bits that can be transmitted at some desired BER by user n on sub-carrier k is

$$b_k^n \triangleq \left\lfloor \log_2 \left(1 + \frac{1}{\Gamma} \frac{|h_k^{n,n}|^2 s_k^n}{\chi_k^n + \sigma_k^n} \right) \right\rfloor , \quad (1)$$

where $\lfloor \cdot \rfloor$ is the floor operation, $h_k^{n,n}$ is the insertion loss of the direct channel of user n, i.e. the twisted pair, Γ is the Shannon gap, s_k^n, σ_k^n are the PSD of the transmit signal and total additive noise of user n on sub-channel k, respectively, and χ_k^n is the crosstalk PSD on user n caused by $N-1$ users with s_k^m for $m = 1, \ldots, N$ and $m \neq n$ on carrier k. Hence, the achievable data rate R for user n is $R^n = f_s \sum_{k=1}^{K} b_k^n$, where f_s is the symbol rate of the system.

The power transmitted by user n is bounded by two parameters: the MAXATP denoted by P_{max}^n limits the aggregate power; and the standardized PSD mask $s_k^{n,mask}$ [4] specifies the maximum transmit level at which each carrier is allowed to transmit. These constraints are formally described as

$$\Delta f \sum_{k=1}^{K} s_k^n \leq P_{\text{max}}^n \ , \quad (2)$$

and

$$0 \leq s_k^n \leq s_k^{n,mask} \ , \ \forall \, n \in 1 \leq n \leq N, \quad (3)$$

where Δf is the sub-carrier bandwidth. Thus, any constraint on the maximum allowed energy entails a corresponding constraint on the maximum number of bits that can be allocated for subcarrier n according to [5]

$$b_k^n \leq b_k^{\text{max}} = \min(\text{B}_{\text{max}}, b_k^n(s_k^{n,mask})), \quad (4)$$

where B_{max}, is a possible constraint on the constellation cardinality known as *maximum bit-constellation size*. Consequently, the DSL system shall use a bit-loading algorithm to allocate the number of carried bits and the transmit power for each of the K sub-carriers of N users, solving either *the margin maximization* or *the rate maximization* problem [5].

III. G.fast capacity study

Simulations are conducted in this section to analyze 1) the data rate and coverage improvements derived from increasing the maximum bit-constellation size B_{max} and MAXATP; and 2) the benefits of modifying the PSD mask transmit levels. We consider a single user, i.e. $N = 1$, served with G.fast 106a. DSL transceivers are modeled using the optimal and efficient bit-loading algorithm described in [5] to calculate the attainable downstream and upstream data rate solving the rate maximization problem. The simulation parameters of G.fast transceivers are detailed in Table I. To use a realistic channel model, we conducted a measurement campaign and parameter fitting of a quad-based 50-pair binder largely used in the German access network, the cable A-2Y(L)50x2x0.4 (poly-ethylene isolated, 50 pairs, 0.4 mm). This allows us to implement the wide-band model for multiple input - multiple output (MIMO) applications described in [6]. Since single-line performance is studied in this section, only the direct channel of the model is considered. Crosstalk channels play a role in the simulation study presented in Section IV.

TABLE I
Simulation parameters of standard G.fast systems

Parameter	Value
Band plan and mask	106a
Carrier spacing	51.75 kHz
Noise floor σ^2	-130 dBm/Hz
Shannon gap Γ	10.75 dB
Efficiency	0.785
Bitloading cap B_{max}	12 bits
MAXATP (DS/US)	4/4 dBm

A. Enhancing G.fast coverage and rate: Long-range G.fast

In order to analyze the improvements of increasing the standardized values of MAXATP and B_{max}, we evaluate the achievable data rate as function of MAXATP for different maximum bit-constellation sizes. We select B_{max} values: The standardized value of $\text{B}_{\text{max}} = 12\,\text{bits}$, the next recommended/suggested constellation size $\text{B}_{\text{max}} = 14\,\text{bits}$ (as proposed in G.fast Amendment 2), VDSL2 $\text{B}_{\text{max}} = 15\,\text{bits}$, and the unrestricted $\text{B}_{\text{max}} = \infty\,\text{bits}$, which allows us to evaluate the upper boundaries of data rates and bit-constellation size despite of being an unfeasible value. We refer to these G.fast profiles with modified MAXATP and bit-constellations as *long-range (LR) G.fast*. Figure 1 shows the achievable aggregate rates when G.fast is deployed in typical loop lengths of FTTC, FTTdp and FTTB scenarios. Simulation results indicate that medium- (yellow curve) and long-range loop lengths (violet and green curves) improve their achievable data rates in 30 to $40\,\text{Mbps}$ when MAXATP increases. This represents about 15% to 20% in comparison with the current configuration, i.e. MAXATP $= 4$ dBm and $\text{B}_{\text{max}} = 12\,\text{bits}$; the improvements do not significantly depend on B_{max}. On the other hand, G.fast performance does depend on it in FTTB FTTdp scenarios. In contrast to long loops, the low attenuation characteristic of these topologies enables transceivers to allocate bits in many carriers at low power cost. Thus, higher values of B_{max} allows many carriers to increase their bit-load, resulting in differentiable data rates. A notable data rate increment is observed for $\text{B}_{\text{max}} = 14\,\text{bits}$, and its data rates do not largely differ from rates obtained with $\text{B}_{\text{max}} = \{15, \infty\}\,\text{bits}$. However, a general analysis of improvements in data rates indicates that the obtained benefits are proportionally very similar for every loop length range, i.e. scenario. It is important to notice that increasing MAXATP beyond $10\,\text{dBm}$ does not convey any

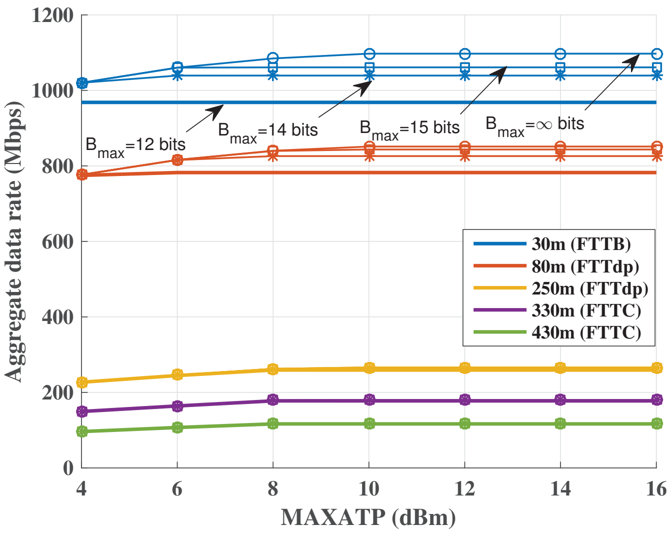


Fig. 1. Aggregate data rate as function of the maximum aggregate transmit power MAXATP for bit-constellation sizes $B_{max} = \{12, 14, 15, \infty\}$.

additional data rate benefit since such values are higher than the total available power of the standardized PSD ($10.6\,\mathrm{dBm}$). Thus, the data rates achieved with $\mathrm{B_{max}} = \infty\,$bits and $\mathrm{MAXATP} > 10.6\,\mathrm{dBm}$ are the maximum data rates that can be attained with the current G.fast PSD mask: about $1.1\,\mathrm{Gbps}$, $850\,\mathrm{Mbps}$, $270\,\mathrm{Mbps}$, $180\,\mathrm{Mbps}$ and $120\,\mathrm{Mbps}$ for $30\,\mathrm{m}$ (FTTB), $80\,\mathrm{m}$ (short FTTdp), $250\,\mathrm{m}$ (long FTTdp), $330\,\mathrm{m}$ (short FTTC) and $430\,\mathrm{m}$ (long FTTC), respectively. We would also like to report that the maximum bit-constellation size, i.e. $\max_{k\in\{1,\ldots,K\}} b_k^n$, with $\mathrm{B_{max}} = \infty\,$bits and $\mathrm{MAXATP} > 10.6\,\mathrm{dBm}$ is 17 bits, which is then the upper bit-constellation bound of the standard G.fast PSD mask.

B. Benefits of modifying the PSD mask

As it was previously mentioned, the total PSD mask power bounds achievable long-range G.fast data rates. We now analyze the impact that modifying PSD levels may convey. Doing so we are aware that changes in the allowed transmission power for each carrier may lead to higher electromagnetic interference of G.fast in its operational frequency range.

Two modified PSDs are evaluated: Flat PSD mask at $-65\,\mathrm{dBm/Hz}$ and a version with a fixed increase of $5\,\mathrm{dBm/Hz}$ with respect to the current PSD mask (which is called "offset version" below). Figure 2 shows standard and modified PSD masks, as well as their corresponding total available power. VDSL2 35b mask is also shown for comparison.

We argue that both PSD versions might be suitable: Flat PSD maintains the defined spectrum for overlapping frequencies (except for the 30 to $35\,\mathrm{MHz}$ range), whereas the offset version equals the levels of VDSL2 PSD in that range. On the other hand, they both allow higher levels in non-overlapping frequencies, i.e. starting at $35\,\mathrm{MHz}$. Deeper studies on the electromagnetic interference produced in high frequencies are required to evaluate their implementation. We show in Section IV their potential to improve G.fast spectrum compatibility with legacy systems, so the obtained benefits can be considered in contrast to the increment of electromagnetic egress.

Proceeding as in Section III-A, the impact of MAXATP and $\mathrm{B_{max}}$ on the attainable rate is analyzed. Figure 3 illustrates the achievable data rates of flat and offset PSDs. No difference in data rate is observed with respect to standard G.fast, i.e. $\mathrm{MAXATP} = 12\,\mathrm{dBm}$ and $\mathrm{B_{max}} = 12\,\mathrm{bits}$ in Figure 1. Data rate improvements are proportionally very similar for all scenarios. Indeed, some long range loops benefit more than short loops at high MAXATP values; e.g. FTTB and short FTTdp improve at most, i.e. with $\mathrm{B_{max}} = \infty\,$bits, in about 20% their data rates, whereas long FTTdp and short FTTC obtain around 30% with $\mathrm{MAXATP} = 10\,\mathrm{dBm}$. Performance does not depend on $\mathrm{B_{max}}$ in long loops, whereas it does for $\mathrm{MAXATP} > 8\,\mathrm{dBm}$ in short loops. This differs from standard PSD performance, whose dependency on $\mathrm{B_{max}}$ is notable for $\mathrm{MAXATP} > 4\,\mathrm{dBm}$. Regarding the bit-constellation boundary, it is 19 bits for the evaluated PSD masks.

The coverage enhancements obtained by long-range G.fast and its PSD variations are not explicitly visualized in the results presented until now. Thus, we compare in Figure 4 the rate-reach curve of the standardized G.fast profile and its PSD-modified versions with $\mathrm{MAXATP} = 8, 12\,\mathrm{dBm}$ and $\mathrm{B_{max}} = 14\,\mathrm{bits}$. We consider these values as possible steps in G.fast road map. The subplot details the coverage enhancement (in percent) of the modified profiles with respect to the reach achieved by standard profile data rates (thick red curve). These results show that, in general, data rates above $700\,\mathrm{Mbps}$ obtain major improvements from modified profiles. The lowest increment, i.e. 10%, is achieved by the standard PSD mask and $\mathrm{MAXATP} = 8\,\mathrm{dBm}$, whereas offset and flat PSDs improve in between 25% and 180% the data rate coverage. Rates below $200\,\mathrm{Mbps}$ achieve reach increments between 10 and 35%,

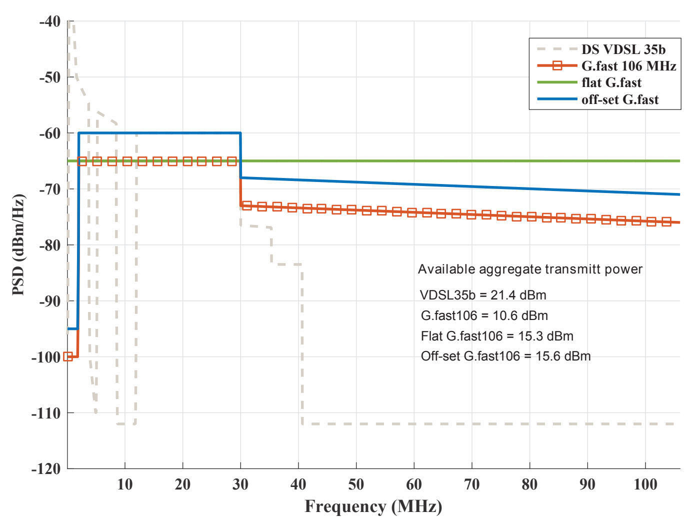
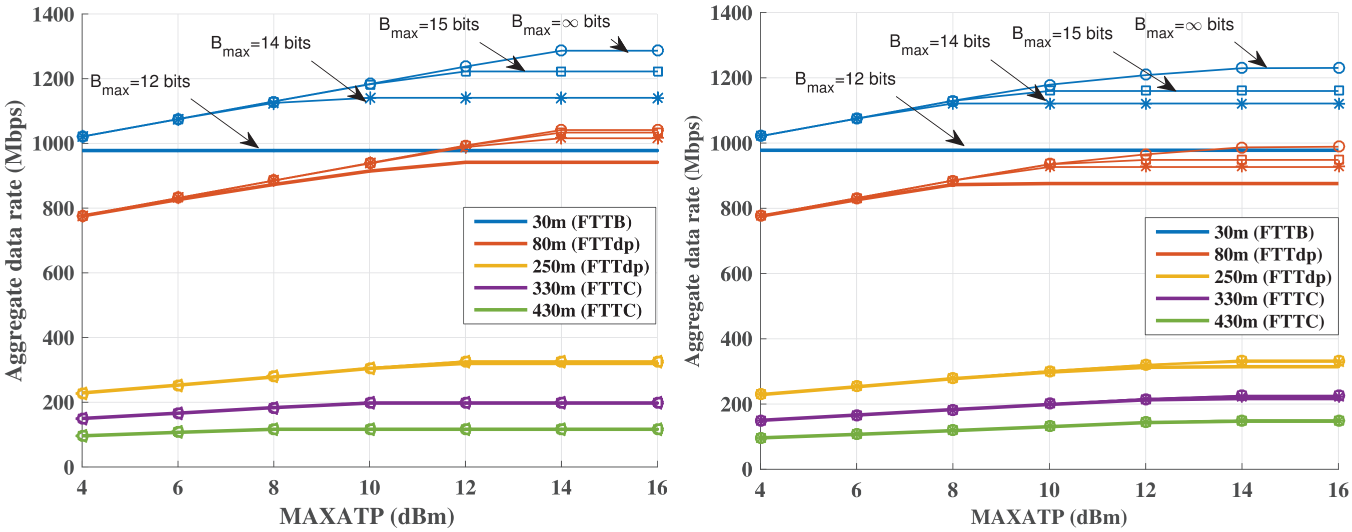


Fig. 2. Standard, flat and offset G.fast PSD masks. Downstream VDSL 2 PSD is shown as reference. Flat PSD keeps the standard spectrum in overlapping frequencies, whereas offset version equals VDSL2 PSD levels in that range.



(a) Flat G.fast PSD mask.

(b) Offset G.fast PSD mask.

Fig. 3. Aggregate rate as function of the maximum aggregate transmit power (MAXATP) and maximum bit-constellation size $B_{max} = \{12, 14, 15, \infty\}$ bits for offset and flat PSDs. Modified profiles allow to obtain significant improvements in short loops, whereas their effects on long loops is moderate.

respectively.

IV. Spectral compatibility study

Data rate and coverage improvements achieved by long-range G.fast are obtained by increasing the transmit power, which may impact coexisting systems performance. Consequently, we now study 1) the transmit power of long-range G.fast; 2) its performance and impact when jointly deployed with VDSL2 35b systems; and 3) the spectral compatibility improvements that adopting PSD shaping while modifying G.fast PSD carries. VDSL2 35b [4] is selected as coexisting system due to its wide overlapped spectrum with G.fast. Its transceivers parameters are shown in Table II. We limit our study to its coexistence with standardized G.fast with parameters shown in Table I, long-range G.fast with $\mathrm{B_{max}} = 14\,\mathrm{bits}$ and $\mathrm{MAXATP} = 8\,\mathrm{dBm}$, and its corresponding flat PSD version with $PSD = -65\,\mathrm{dBm/Hz}$. Figure 5 depicts the selected network topology; users of a building are connected to the external access network through a multi-dwelling unit (MDU) at the basement. G.fast serves its users from a DP located at $\mathrm{L_{DP\text{-}MDU}} = \{0, 50, 220, 300, 400\}\,\mathrm{m}$ far from the MDU. Chosen access network lengths correspond to FTTB ($\mathrm{L_{DP\text{-}MDU}} = 0\,\mathrm{m}$), FTTdp ($\mathrm{L_{DP\text{-}MDU}} = \{50, 220\}\,\mathrm{m}$) and FTTC ($\mathrm{L_{DP\text{-}MDU}} = \{300, 400\,\mathrm{m}\}$) topologies. VDSL2 35b is served from a cabinet at $400\,\mathrm{m}$. We use the same channel model implemented in Section III and vectoring is independently applied by systems on their corresponding users.

In order to establish indicative results on the mutual impact of N_g G.fast users jointly operating with N_v VDSL2 35b users ($N_g + N_v = N$), three cases are evaluated: dominant, non-dominant and balanced. In the dominant case, the number of G.fast users is higher than VDSL2 35 services, i.e. $N_g > N_v$; the non-dominant scenario evaluates the opposite configuration, i.e. $N_g < N_v$, whereas in the balanced case both systems

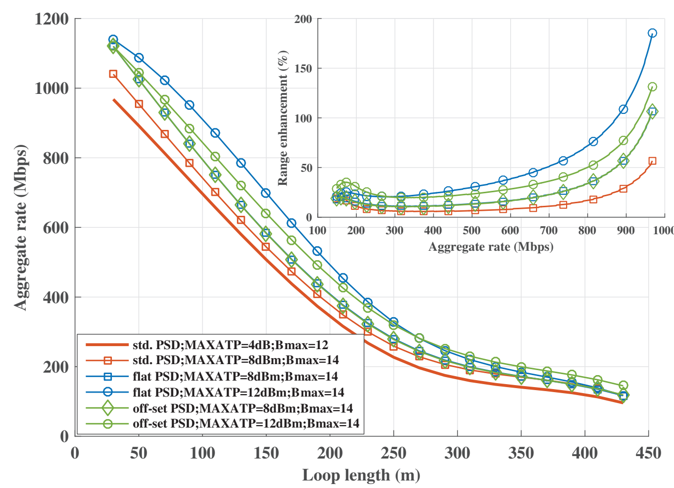


Fig. 4. Rate-reach curve of standard G.fast (thick red line), long-range G.fast and modified PSD versions. Subplot details the coverage enhancement (%) conveyed by modified G.fast versions with respect to the standard profile.

have the same number of served users; i.e. $N_g = N_v = 12$. As reference performance, we consider the case when no coexisting systems are deployed, i.e. either $N_g = 24$ or $N_v = 24$. We have repeated our simulations 100 times, whereby service positions within the binder were randomly assigned and each time new random coupling elements were drawn to reproduce the empirical evaluation for 100 different binders and obtain the average performance as seen by users with a given $\mathrm{L_{DP\text{-}MDU}}$. However, we only show the mean value of the evaluated variables and omit its confidence intervals to improve visibility of results.

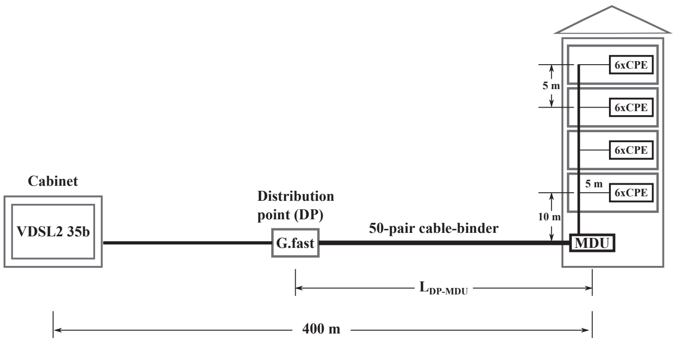


Fig. 5. Topology. 24 subscribers in a multistorey are served by G.fast and VDSL2 35b connected to the external access network through a multi-dwelling unit (MDU) distribution panel.

A. *Long-range G.fast transmit power analysis*

If standard G.fast bit-allocation is taken as reference, the availability of higher power in long-range G.fast allows to allocate additional bits to carriers for which the required transmit power, i.e. s_k^n in (1), does not violate the PSD mask constraint given in (3). Figure 6 compares the mean transmit power and bit allocation of 24 standard (dashed) and long-range G.fast (solid) users for $\mathrm{L}_{\text{DP-MDU}} = \{0, 220, 400\}\,\mathrm{m}$. In short loops (blue), standard transceivers take advantage of their low attenuation and allocate bits transmitting at levels notably lower than power mask values. Therefore, long-range G.fast increases the transmit power along all G.fast spectrum, achieving saturated transmit levels, i.e. $s_k^n \approx s_k^{n,mask}$, in carriers above $30\,\mathrm{MHz}$. Conversely, standard G.fast exhibits this saturation for frequencies higher than $30\,\mathrm{MHz}$ in long range loops (yellow and red). This means, that long-range G.fast can only allocate additional bits, and consequently higher transmit power, in low frequency carriers. Considering the high attenuation at high frequencies, we then conclude that the data rate improvements of long-range G.fast are mainly due to the allocation of additional power in frequencies below $30\,\mathrm{MHz}$. This fact is confirmed by the obtained mean bit allocation shown in Figure 6.

The additional transmit power of long-range G.fast in low frequencies yields higher impact on legacy systems. We then evaluate its performance and effects on VDSL2 35b when they are jointly deployed under the defined cases and topology.

TABLE II
SIMULATION PARAMETERS OF VDSL2 35B SYSTEMS

Parameter	Value
Band plan and mask	998ADE35-M2x-B
Carrier spacing	4.3125 kHz
Noise floor σ^2	-130 dBm/Hz
Shannon gap Γ	10.75 dB
Efficiency	0.785
Bitloading cap $\mathrm{B}_{\max}$	15 bits
MAXATP(DS/US)	17/14.5 dBm

B. *Long-range G.fast and its impact on VDSL2 35b*

We first comparatively evaluate the performance of standard and long-range G.fast. Figure 7b depicts the mean aggregate data rate of users as function of $\mathrm{L}_{\text{DP-MDU}}$ for the defined cases. Notice that $\mathrm{L}_{\text{DP-MDU}}$ does not represent users' loop length, but the average performance of users with loop length $\mathrm{L}_{loop} = \mathrm{L}_{\text{DP-MDU}} + \{15, 20, 25, 30\}\,\mathrm{m}$. Results show that the presence of VDSL2 systems slightly affect G.fast and long-range G.fast performance without exhibiting significant dependency on the number of served users. In comparison with their performance without VDSL2 systems, short loops, i.e. $\mathrm{L}_{\text{DP-MDU}} = \{0, 50\}\,\mathrm{m}$, suffer less aggregate data rate loss: about $10-20\,\mathrm{Mbps}$ for long-range G.fast and up to $35\,\mathrm{Mbps}$ for standardized G.fast. A detailed analysis of downstream and upstream data rates shows that the rate loss occurs in downstream transmission due to the proximity of VDSL2 upstream transmitters (CPEs are located at building premises). Upstream data rate remains almost unaltered. On the other hand, longer loops, i.e. $\mathrm{L}_{\text{DP-MDU}} = \{220, 300, 400\}\,\mathrm{m}$, exhibit higher loss. In this case, the loss is suffered in downstream and upstream data rates: VDSL2 transmitters located at the cabinet are closer to G.fast upstream receivers in the DP, whereas VDSL2 CPEs interference becomes dominant at G.fast downstream receivers since their desired signals, i.e. through the direct channel, experiment higher attenuation.

Concerning the impact of G.fast systems on VDSL2 35's performance, Figure 7a shows their mean aggregate data rate. The impact on systems performance is obviously higher when long-range G.fast is deployed. Contrary to G.fast performance, the number of served users affects it. The surprising similarity between the attained data rates for short and long DP-MDU lengths, i.e. $\mathrm{L}_{\text{DP-MDU}} = \{0, 400\}\,\mathrm{m}$, should be noted. Analysis of G.fast transmission power in Figure 6 clarifies these results.

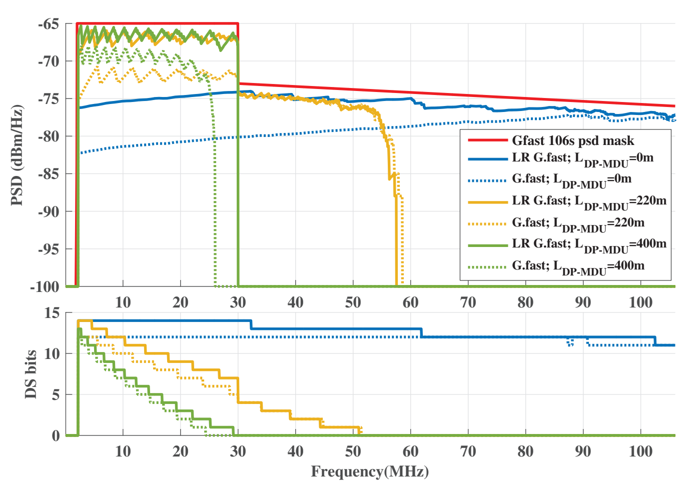
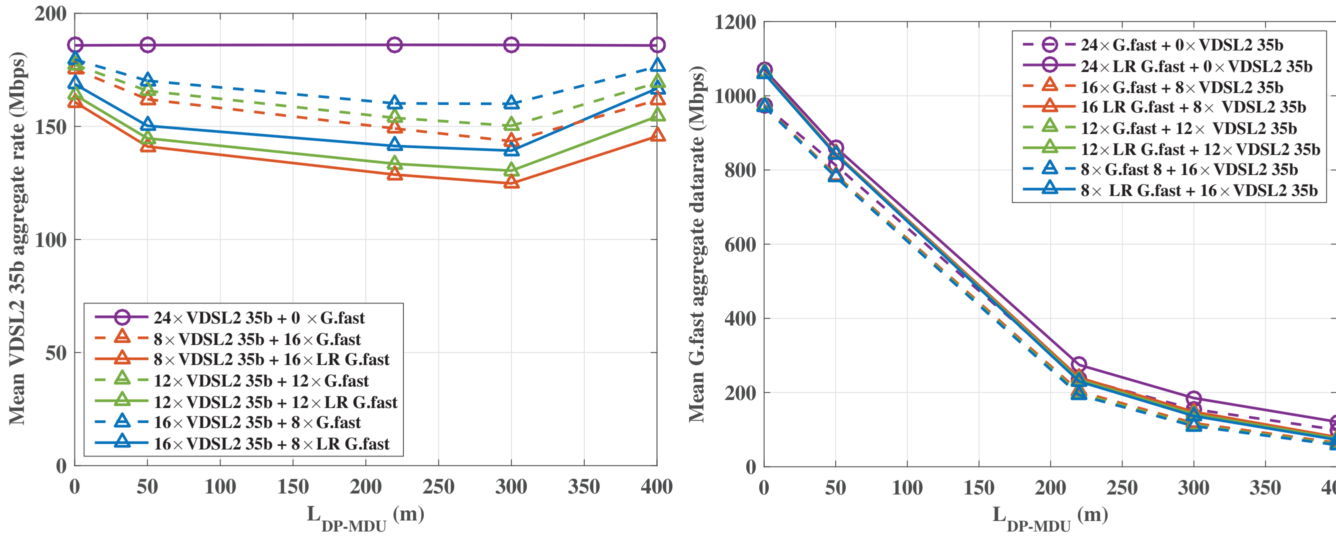


Fig. 6. Mean transmit power and bit allocation of standard and long-range (LR) G.fast with $\mathrm{L}_{\text{DP-MDU}} = \{0, 220, 400\}\,\mathrm{m}$. The transmit power levels are higher in LR G.fast, mainly in VDSL2-overlapping frequencies ($< 35\,\mathrm{MHz}$), which yield higher interference for legacy systems.



(a) VDSL2 35b. (b) G.fast.

Fig. 7. Mean G.fast, long-range (LR) G.fast and VDSL2 35b data rates in dominant, balanced and non-dominant scenarios.

Transmit levels of long-range G.fast in short loops are low (even lower than standard G.fast in long loops), then the impact on VDSL2 systems is not critical. Conversely, transceiver in longer loops require higher transmit power. Similar transmit levels of long-range G.fast in VDSL2-overlapping frequencies is observed for i.e. $L_{\text{DP-MDU}} = 220\,\text{m}$ (yellow) and $L_{\text{DP-MDU}} = 400\,\text{m}$ (green). However, loops with $L_{\text{DP-MDU}} = 220\,\text{m}$ exhibit lower attenuation, so the interference caused by G.fast at VDSL2 downstream receivers is higher than the resulting levels of loops with $L_{\text{DP-MDU}} = 400\,\text{m}$.

C. Spectrum-friendly G.fast

The implementation of G.fast profiles that are compatible with VDSL2 systems decreases considerably their data rates and range [2]. On the other hand, power back-off (PBO) has been successfully adopted in legacy systems as an effective means to mitigate the near-far problem. It performs spectrum shaping on the PSD of services with short loops to limit its transmit power in low frequencies and favor bit-allocation in high frequency carriers.

To reduce the interference caused by G.fast, we have borrowed the PBO method from VDSL2 [7, Appendix II]. This method is meant to mitigate the far-end crosstalk (FEXT) impact of systems at remote units, i.e. DP. It shapes the PSD mask according to cable- and system- dependent parameters, and the electrical length (ESEL, defined as the insertion loss in dB at $1\,\text{MHz}$) of the cable segment between the DP and the cabinet [7]. However, this approach does not consider the near-end crosstalk (NEXT) interference caused by the mixture of legacy systems implementing frequency-division duplexing (FDD) and G.fast using time domain duplexing (TDD). Nevertheless, we adopt the aforementioned PBO method as a proof-of-concept, being aware that it is not optimal for the evaluated scenario. The ESEL value shall be determined for each DP location and set accordingly in order to calculate the PSD mask. The cabinet-relative position of the DP might be unknown, though. Therefore, we use a "typical" long-range G.fast loop length of $220\,\text{m}$ to calculate its corresponding electrical length and keep it no matter what the real position of the DP might be. Then, its value and the cable and system parameters in [8] are used to obtain the corresponding PBO mask according to [7]. We adopt the flat PSD mask studied in Section III-B to calculate the PBO mask; its implementation offers higher PSD mask values to allocate bits in non-overlapping carriers, whereas transmit levels are saturated (Figure 6) in their corresponding frequencies for the standard mask. Thus, performing PBO in standard PSD would reduce the impact on VDSL2 systems at a high performance

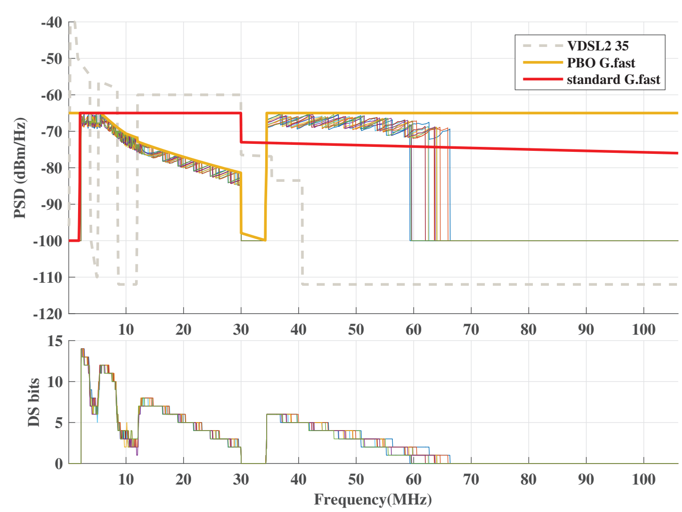


Fig. 8. PSD masks and bit allocation of flat G.fast with PBO. Transmit powers and bit-allocation of users with $L_{DP-MDU} = 220\,\text{m}$ are shown. Transmit levels in overlapping carriers are lower than in long-range G.fast (Figure 6), resulting in lower interference.

cost for G.fast. Figure 8 shows the calculated PSD mask that result from applying PBO on flat G.fast. Transmit power and bit allocation of users with $L_{\text{DP-MDU}} = 220\,\text{m}$ illustrate how PBO displaces bit-allocation from low to high frequencies.

Figure 9a shows the mean aggregate data rate for VDSL2 systems when the calculated PBO mask (Figure 8) is applied in dominant, non-dominant and balanced cases. The data rates obtained when VDSL2 coexists with long-range G.fast without PBO are shown, too. The benefits for VDSL2 systems are significant in all cases. The attained rates represent between 88 and 96% of the data rate attained by systems without coexisting with G.fast (red line with circle markers). However, effects on G.fast systems performance are expected. Figure 9b compares the performance of long-range G.fast with (applied on flat PSD mask) and without PBO for the balanced configuration (G.fast performance does not depend on the dominance degree). Due to the reduction of allowed transmit levels in overlapping carriers, which potentially have higher bit capacity, long loops with $L_{\text{DP-MDU}} > 220\,\text{m}$ exhibit the highest degradation. Conversely, short loops that can displace more bits to higher frequency carriers, do not significantly underperform. We then conclude, that the proposed strategy offers benefits for VDSL2 at moderate cost for G.fast, although more mutual benefits could be achieved with more sophisticated shaping techniques.

V. Conclusions

In this paper, we analyzed strategies that seek to enhance the attainable data rates and coverage of G.fast systems. We studied the performance improvements carried by increasing the maximum aggregate power (MAXATP), maximum bit-constellation size and PSD mask levels. We conclude that increasing MAXATP jointly with the bit-constellation size entitles benefits for G.fast systems while demanding higher transmission levels. Therefore, its impact on coexisting systems in mixed deployments is more severe. To counteract this effect, we have proposed to modify G.fast PSD mask in conjunction with a PSD shaping technique commonly used in VDSL2 systems. Our simulation results show that despite of not being optimized for G.fast, the particularities of the scenario and its simplicity, this approach reduces the degradation of coexisting systems performance at the cost of moderate loss of G.fast performance. This strategy could benefit from future research on more sophisticated spectrum shaping techniques as well as on the electromagnetic egress caused by adapted PSD masks.

Acknowledgment

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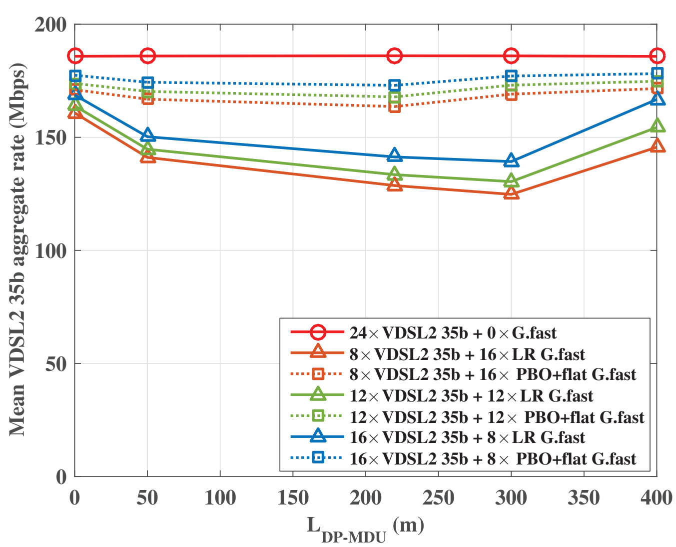
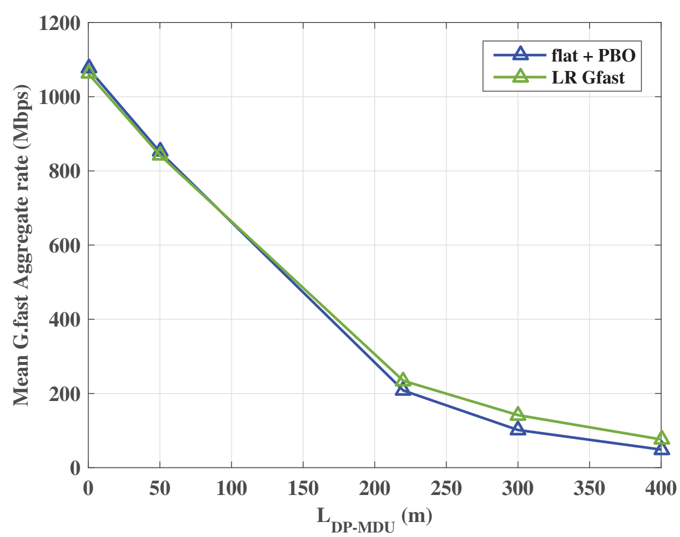


(a) VDSL2 35b.



(b) G.fast.

Fig. 9. Mean aggregate data rates of VDSL2 (a) and G.fast (b) when power back-off (PBO) is performed on flat G.fast. Impact reduction is observed when PBO is applied, although G.fast performance is slightly reduced. Higher MAXATP values would counteract the performance loss.