Dynamic IUC for OFDMA Transmission

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

In a cable plant, it is essential to manage upstream spectrum and mitigate the impact of interferences, especially for lower spectrum bands that are susceptible to various types of noise ingress. The introduction of OFDMA in DOCSIS 3.1 (D3.1) with different bit-loadings at different minislots provides the benefits of enhanced capacity, as well as all flexibility in managing the spectrum usage. Yet surprisingly, not many MSOs have taken full advantage of DOCSIS 3.1 capabilities. Part of the reason is, accompanying the enhancements in capacity and flexibility, comes the complexity in computation, as we have to deal with finer granularity in both detecting the noise levels and reacting to them fast enough.

D3.1 provides an OFDMA profile, which defines, among other properties, a bit-loading pattern that could be adopted by a group of cable modems (CMs). Further, a Profile Management Application (PMA) utilizes the power of offline servers to tackle the computation complexity. A PMA server may take performance measurements on an OFDMA channel for a considerably long time in order to calculate OFDMA profiles. However, in a typical cable plant, especially in its lower band, we may observe many random bursts of noise that vary in time, frequency and power amplitude, and such noise might come and go swiftly. Figure 1 below gives a snapshot of upstream interference in an HFC network. Therefore, using PMA alone is not enough. As upstream interference is naturally observed at the CMTS, it makes sense to augment PMA with a CMTS-based solution that adapts quickly to interference levels measured locally.

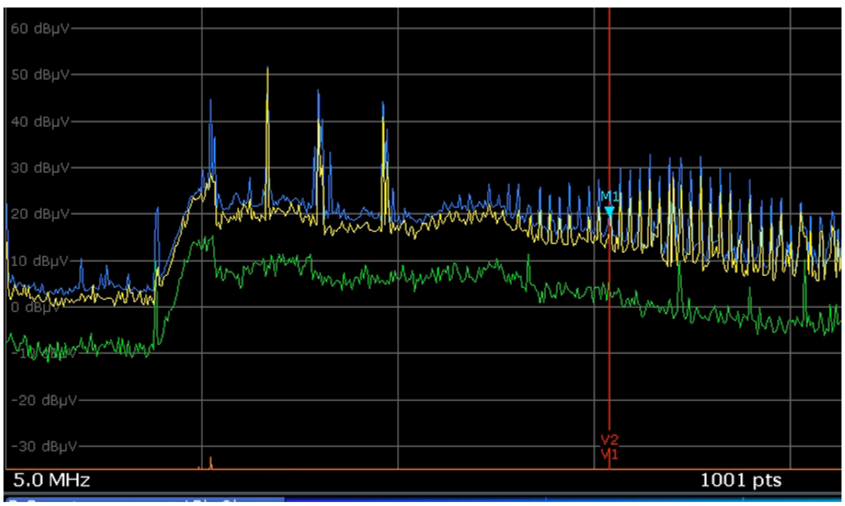

Figure 1 A Snapshot of Upstream Interferences in an HFC Network

This paper presents a novel approach that uses various OFDMA profiles with different bit-loading configurations to generate a dynamic profile. We consider upstream impairment with a duty cycle of one or a few seconds, and target a CMTS-based adaptive solution that yields optimal throughput across all CMs. To achieve the objective, we measure upstream channel impairments at a per-minislot level through constantly monitoring the receptions at the CMTS burst receiver. Based on the results, we could dynamically upgrade or downgrade IUCs. The decisions to upgrade or downgrade IUCs are considered for each individual minislot, and can take place locally and automatically without notifying the affected modems.

This approach is referred to as "Dynamic IUC" in the rest of the paper. The generated dynamic profile is referred to as "Dynamic scheduling IUC", or "DS-IUC" in short.

This approach could be combined with any existing profile management mechanisms. For example, an operator could manually configure 2 OFDMA profiles on an OFDMA channel, or alternatively, a PMA server could elect 2 such profiles based on its calculation. The CMTS could then utilize these 2 profiles, plus NULL bit-loading as a special case, to generate a DS-IUC, thus providing a 3-tier adaptation for each minislot, at an interval much shorter than that of the PMA updates.

2. Background

OFDMA transmission as introduced in D3.1 utilizes different bit-loadings at different subcarriers in the same upstream channel, so that it can adapt to different noise conditions at these subcarriers. D3.1 introduces multiple OFDMA Upstream Data Profiles (OUDPs) on an OFDMA channel, each of which defines a bit-loading pattern that could be adopted by a group of CMs at a certain time period. In particular, an OUDP includes the following information:

- An IUC number (5, 6, 9, 10, 11, 12, or 13)
- Bit-loading and pilot pattern for each minislot or consecutive minislots in order. The bit-loading number ranges from 0 (no transmission) to 12 (4096-QAM)

Per D3.1 MULPI ([1]), the content of these profiles is communicated to CMs through UCD messages. The assignment of one or two such profiles to a CM is using TCC in either registration response or DBC messages. The standard limits that a maximum of two profiles of a channel could be assigned to a CM at any given time.

For terminology, as this document considers data transmission on OFDMA channels for the most part, therefore without mentioning explicitly, we may simply use “OFDMA profile”, “data profile” or even “profile” to replace the full term of “OFDMA Upstream Data Profile”. We also use it interchangeably with “data IUC” or “IUC” without ambiguity.

2.1. Performance Measurement

There exist multiple mechanisms to measure the performance of an upstream channel, including:

- Active and Quiet Probe (see [3]). For this purpose the CMTS may schedule one or more OFDMA symbols and sends a P-MAP. In case of an Active Probe, the CMTS uses a SID assigned to an active CM, and measures RxMER of the CM at the time specified by the P-MAP. The active probe symbol for this capture normally includes all non-excluded subcarriers across the OFDMA channel. In case of a Quiet Probe, the CMTS uses an Idle SID in the P-MAP. It requires all subcarriers, including excluded ones, to be probed. Quiet probes could be used as a baseline to generate initial upstream profiles before modems come online. On the other hand, Active Probes could be scheduled periodically for each active CM in order to generate more accurate upstream profiles over time.
- MER and FEC measurement associated with data receptions. The CMTS burst receiver may provide the following information for each received burst:
  - MER
  - FEC correctable codeword count
  - FEC uncorrectable codeword count
  - Total codeword count

  With the codeword counts the CMTS could subsequently calculate FEC correctable rate (i.e., cFEC) and FEC uncorrectable rate (i.e., uFEC).

- OUDP Test (see [1]). D3.1 includes a mechanism to test an OUDP profile currently in use by providing grants with a special OUDP Test SID to the testing CM. The CM will transmit using a specific payload pattern and the CMTS could subsequently count the FEC and CRC errors in addition to measuring the MER. The OUDP Test SID has to be assigned to the CM in advance.

In this paper, we assume the above performance measurement mechanisms are available as a prerequisite. On top of that, we introduce a novel method that derives performance metrics per-minislot and per CM group, in real-time and with no or minimum overhead in bandwidth utilization.

2.2. OFDMA Profile Management

The specifications in reference [4] provide operators a way to statically configure a set of OFDMA profiles on an OFDMA channel. With such a configuration, a CMTS could locally decide which profiles to be assigned to which CMs and at what time.

Reference [2] describes an architecture using an external Profile Management Application (PMA) server. The PMA server constantly monitors the upstream spectrum, by initiating RxMER measurement for upstream subcarriers (using quiet or active probes), or triggering "OUDP Test", both through the CMTS. The PMA could also utilize information from other tests, such as upstream captures from a PNM server, as well as historical information obtained on the plant. With such information, the PMA server is able to evaluate the current upstream channel's performance and generate a set of profiles for the channel. Meanwhile, the PMA server may also designate one or two of these profiles to each CM on this channel. Reference [2] defines an API for this operation.

The above mechanisms require assignments or re-assignments of IUCs to CMs, or modification of IUC content over time. Note that there are only a limited number of IUCs that can be supported on an OFDMA channel. Besides, only one or two IUCs on this channel can be assigned to each CM at any given time. One of them is typically the lowest bit-loading IUC (IUC 13) that is required for pre-registration. Therefore, the mechanisms above require the CMTS to communicate with the corresponding CMs constantly using UCD and/or DBC messages. This imposes a limitation as for how fast the profile management functions could run, and how soon the CMTS system could adapt to channel impairment. An operator may define a time interval, which determines how often to re-evaluate the current profiles and potentially modify or re-assign these profiles to CMs.

In this paper, we assume that a profile management mechanism such as stated above is available as a prerequisite, so that at any given time, each CM will be assigned with a high profile and a low profile, denoted as IUC H and IUC L respectively. We loosely define the interval of profile modification or re-assignment as "profile management interval". On top of that, we introduce a novel method that dynamically upgrades or downgrades IUCs on an OFDMA channel, at per-minislot granularity and in reaction to real-time noise much faster than the "profile-management-interval".

3. Per-Minislot Measurements

Assume the CMTS burst receiver is able to collect FEC correctable count, FEC uncorrectable count, total word count and MER for each received burst (see 2.1). When FEC errors are detected with the received burst and the burst size is more than a minislot, it is impossible to determine which minislot has contributed to the impairment due to the effect of interleaving. In order to obtain these metrics on per minislot granularity, we designate some minislots in each OFDMA frame to be used for one-minislot grants, with a pre-defined percentage and with their positions rotate in each frame. See Figure 2 for an illustration. In this way each minislot will be scanned over time with the same frequency. For example, if we designate 1% of the minislots in an OFDMA frame to be used for single minislot grants, it takes 100 frames to scan through every minislot. Depending on the frame size (6 – 36 symbols) and Cyclic Prefix (CP) values, there could be ~1000 - ~8000 frames in a second. If for example there are 3000 frames in a second, any particular minislot will be scanned 30 times in a second, including single-minislot grants at this location assigned to any CM group.

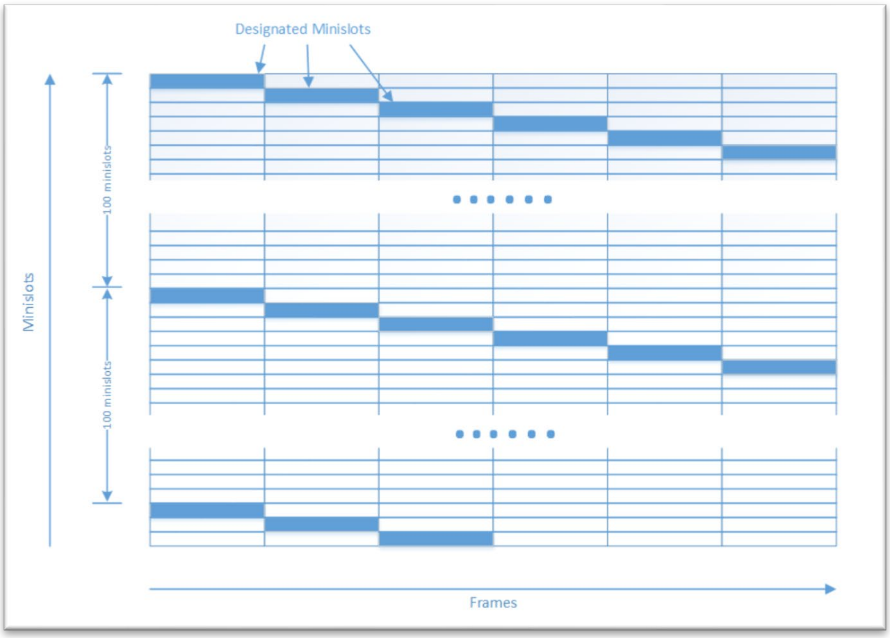

Figure 2 Designated Minislots For Single-Minislot Measurements

At the time of MAP generation, the upstream scheduler allocates grants for CM requests per the normal operation. If a grant hits one of the designated minislot location, this grant will be fragmented, and the next grant will occupy a single minislot. Then, only performance metrics of these single minislot bursts are taken into consideration, and the rest are discarded for this measurement. To be specific, when the single minislot burst is received by the CMTS, it will be measured and the performance metrics will be counted toward the group which the transmitting CM belongs to.

3.1. OUDP Test

There're several scenarios where OUDP Test could be useful, including the following:

- A CM group could possibly drop its bit-loading to NULL in some minislots, due to severe interference experienced at these minislots (see Section 4). In this case the scheduler avoids scheduling any grant for either data or ranging requests, therefore there is no subsequent measurement available on these minislots based on active data. The CMTS then has to explicitly poll these minislots using OUDP Tests, in order to determine whether the interference condition has changed.
- When there are unused minislots in an OFDMA frame, the CMTS could utilize these minislots to test the performance of any CM group of its choice, again using OUDP Tests.

4. Dynamic IUC

Assume with one or more of the "profile management" mechanisms as described in 2.2, a CM is assigned with a high profile and a low profile, denoted as IUC H and IUC L respectively. Then, in a time interval much smaller than the "profile management interval", the CMTS might switch between IUC H, IUC L, plus NULL bit-loading as a special case. Such dynamic switches could be determined for each individual minislot, and could occur locally without communicating to the CM through MMM messages.

In particular, the CMTS upstream scheduler periodically generates a "Dynamic Scheduling IUC (DS-IUC)", which adopts IUC H, or IUC L, or NULL, on a minislot-by-minislot basis. In other words, the bit-loading value at a minislot could assume bit-loading_<IUC H, minislot>, or bit-loading_<IUC L, minislot>, or 0. The scheduler could possibly encode different data IEs of the same CM with different IUC numbers if these IEs fall into different minislots in a MAP.

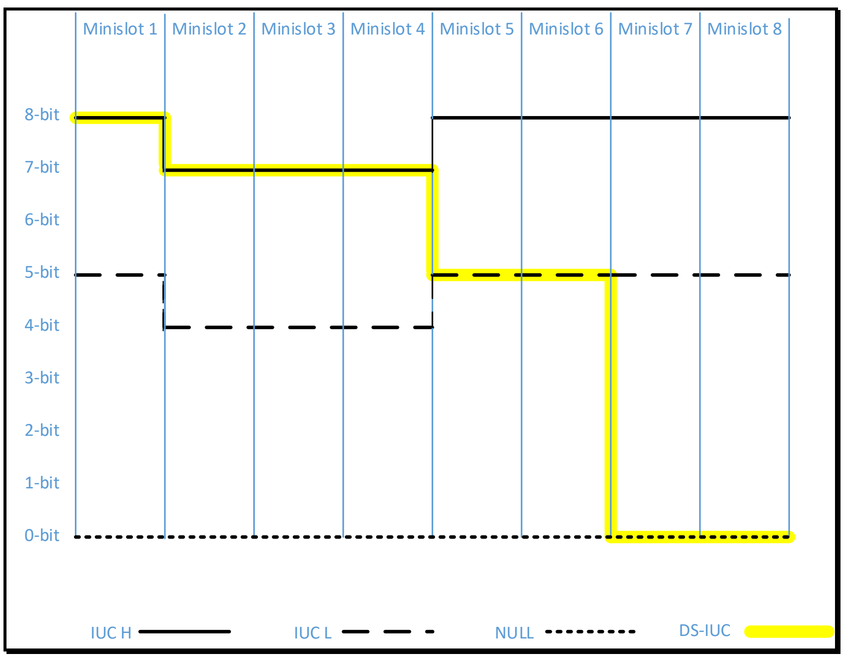

Figure 3 Dynamic Scheduling IUC

An example of DS-IUC (partial) is illustrated in Figure 3. In this example, IUC H is defined as follows:

{minislot 1: 8-bit QAM},{minislot 2-4: 7-bit QAM}, {minislot 5-8: 8-bit QAM}, …

IUC L is defined as:

{minislot 1: 5-bit QAM}, {minislot 2-4: 4-bit QAM}, {minislot 5-8: 5-bit QAM}, …

The DS-IUC adopts IUC H in minislot 1 – 4, but adopts IUC L in minislot 5 and 6, and again adopts NULL bit-loading in minislot 7 - 8. Therefore the DS-IUC is defined as:

{minislot 1: 8-bit QAM}, {minislot 2-4: 7-bit QAM}, {minislot 5-6: 5-bit QAM}, {minislot 7-8: 0-bit QAM}, …

The collection of IUC H, IUC L and NULL provides a 3-tier option for dynamic adaptation to noise conditions to a certain extent without involving the CM, and such adaptation may be different on different sub-bands. The creation and modification of DS-IUC is performed periodically. This period is referred to as "dynamic scheduling interval", which should be much smaller than the "profile management interval". For example, the dynamic scheduling interval can be chosen from sub-second to multiple seconds while the profile management interval can be chosen from sub-minute to multiple minutes or even hours.

5. Experimental Results

To demonstrate the effects of Dynamic IUC, we ran an experiment in the lab with a D3.1 CMTS from Casa Systems and a D3.1 CM from Technicolor. An OFDMA channel is configured with the frequency span of 5 – 85 MHz and with K = 18 symbols per OFDMA frame. 5 distinct Data IUCs are configured and allocated to the OFDMA channel, namely IUC 9 – IUC 13.

When the CM is online, two data IUCs, namely IUC 9 and IUC 13, are assigned to the CM based on assessment of the current condition. Here IUC 9 is the "IUC H" and IUC 13 is the "IUC L": IUC 9 has a constant bit-loading of 1024-QAM across all minislots, and IUC 13 has a constant bit-loading of 64-QAM across all minislots. Between the two IUCs assigned to the CM, the scheduler starts with IUC H for unicast data transmission until there's an issue.

Profile management interval is configured as 1000 seconds, which means for every 1000 seconds, the system could possibly update the assignment of IUC H and/or IUC L to the CM. This operation is skipped in our experiment. On the other hand, the dynamic scheduling interval is configured as 5 seconds, which means for every 5 seconds, the scheduler possibly switches among IUC H, IUC L and NULL for each minislot and each CM group, based on per-minislot performance measurements of the current 5-second interval.

Figure 4 depicts a snapshot of the OFDMA channel (partial) when there is no noise. In the figure, a) and b) reflect cMER and uMER respectively, c) is the plot of MER, and d) displays the calculated DS-IUC. At this point DS-IUC is the same as IUC 9 across all minislots. As we can see, using IUC 9 the per-minislot cFEC and uFEC are both 0, and the per-minislot MER stays between 43.1- 47.7dB. These results show IUC 9 is working appropriately across the whole channel, therefore DS-IUC is unchanged, i.e., it stays the same as IUC 9.

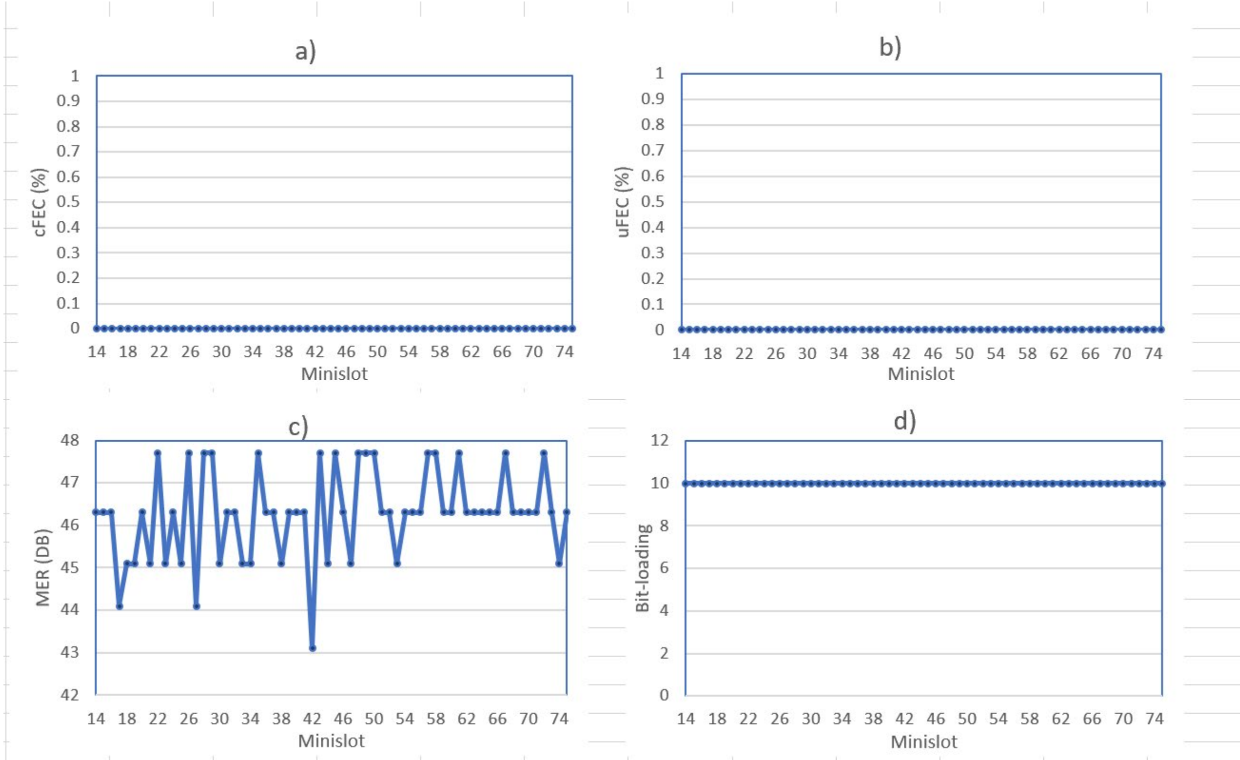

Figure 4 Per-Minislot Measurements and DS-IUC Without Noise

We then introduce some noise using a signal generator. The generated signal is a sharp tone centered at 25Mhz with a FM of 1Mhz. It is injected into the upstream port with a 2-way combiner. Figure 5 depicts a snapshot of the OFDMA channel (partial) roughly 5 seconds after the noise is injected. Again a) and b) reflect cMER and uMER respectively, c) is the plot of MER, and d) displays the calculated DS-IUC. As we can see, at this point the MER drops below 42.3dB within minislot [30 – 68], and drops below 26.7dB within minislot [46 – 53]. This forces a degradation in bit-loadings. As a result, the scheduler adopts IUC 13 for impaired regions within minislot [30 – 45] and within minislot [54 – 68]. It further adopts NULL bit-loading for a severely impaired region within minislot [46 – 53]. The rest of regions is little affected and so IUC 9 is kept unchanged.

Note the diagrams in Figure 5 illustrate measurements after the adapted DS-IUC is calculated and take into effect, which comprises IUC 9, IUC 13 and NULL at unimpaired, impaired, and severely impaired regions respectively. In the impaired regions, since modulation is reduced to IUC 13, uFEC and cFEC become 0 once again. In the severely impaired region however, as NULL bit-loading is adopted, there's no data permitted for transmission. The CMTS needs to schedule one-minislot grants for OUDP Tests, using IUC 13. Diagrams in a) and b) of Figure 5 show that the cFEC and uFEC values obtained with such OUDP Test frames are still significantly high at the severely impaired region, and so the DS-IUC stays at NULL in this region.

When the noise is removed, the per-minislot FEC and MER metrics would change accordingly to what were before. Then, with less than 5 seconds delay, the scheduler adjusts DS-IUC to adopt IUC 9 once again across all minislots. The diagrams at this moment are almost identical to those in Figure 4 and are omitted here.

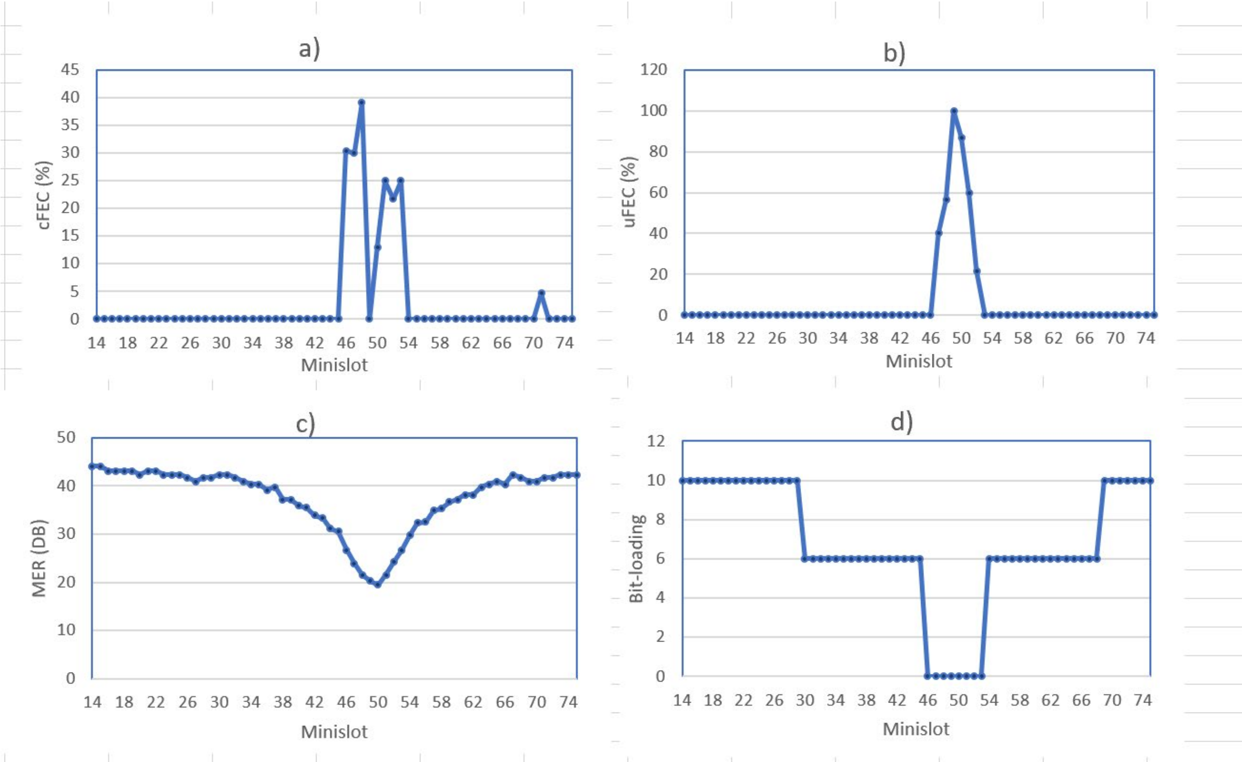

Figure 5 Per-Minislot Measurements and DS-IUC with Noise

6. Miscellaneous Notes

A few notes regarding Dynamic IUC are worth mentioning here, as detailed in the following.

6.1. Dynamic Ranging Zone

Besides utilizing the per minislot performance metrics to facilitate data transmissions, the CMTS could also use the same to direct range requests. For example, the CMTS could choose a default ranging zone to start with. Once cable modems come online and the per-minislot performance metrics are collected, if the CMTS determines that the original ranging zone is too noisy, it could optionally select a new region with the highest MER. It then moves the initial ranging and/or fine ranging zone to the selected region, i.e., the ranging IEs would contain IUC 3 or IUC 4, and contain minislots from within that region.

6.2. Partitioning CMs to CM Groups

In the previous sections we loosely refer to the term “CM group”. It is further explained in this subsection, as follows. We assume that all CMs utilizing an upstream channel could be partitioned into a limited number of groups, with each group observing the same pattern of impairment at almost all times. Different group behaviors could reflect different D3.1 CM types, or different segments of the cable plant, etc.

The methods and rules to partition CMs into CM groups depend on deployment scenarios and implementation specifics. In an extreme case, if the number of CMs is manageable and the resources (memory, cpu cycle) are sufficient, we could designate each CM as a CM group.

In another extreme case, if all CMs on the upstream channel behave uniformly across all minislots and at all times, they could be categorized as in the same CM group. Due to the "funnel effect" of upstream noises, this model could work for lots of scenarios. For example, it could work when the only source of interference is ingress noise.

With CMs on an OFDMA channel partitioned into CM groups, we could obtain FEC and MER statistics on a per CM group basis. We could also define DS-IUCs on a per CM group basis, as described in the previous sections.

The exact mechanism for how to partition CMs into CM groups could be a topic for further studies.

6.3. Single-Minislot Approximation

Special care must be given when a single minislot is not sufficient for a grant. This could happen if the combination of bit-loading and frame size is too small for the smallest LDPC codeword. In that case a smallest multi-minislot grant to fit the LDPC codeword could be scheduled, which covers the minislot being examined plus one or more neighboring minislots. The performance metrics of this minislot will be estimated based on what is measured with the multi-minislot burst. The exact mechanism as for how to obtain the estimation of the single minislot performance metrics could be a topic for further studies.

7. Conclusion

The solution of "Dynamic IUC" presented in this paper starts with selectively scheduling one-minislot grants for either active data or OUDP Test data, and measures channel impairments at a per-minislot granularity using data received at the burst receiver. Based on the above, the CMTS leverages the two OFDMA data profiles, namely IUC H and IUC L, that were previously assigned to a group of CMs, plus NULL bit-loading as a special case, in order to produce a DS-IUC with a 3-tier adaptation. The decision to choose the tier is made for each individual minislot and each CM group. Additionally, the decision takes place locally without notifying the affected CMs. Finally, it can take place immediately, i.e., one or a few seconds after onset/offset of an impairment.

Dynamic IUC could be combined with any existing profile management mechanisms, such as PMA. For example, one could use PMA to elect IUC H and IUC L for a group of CMs, and use Dynamic IUC to leverage the elected IUCs and provide a 3-tier adaptation. In this way the system is able to handle both long-term and short-term impairments, resulting in an optimal upstream throughput across all CMs.

Abbreviations

API	application programming interface
cFEC	correctable FEC
CM	cable modem
CMTS	cable modem termination system
CRC	cyclic redundancy check
D3.1	DOCSIS 3.1
DBC	dynamic bonding change
DOCSIS	data over cable service interface specification
DS-IUC	dynamic scheduling IUC
FEC	forward error correction

IE	Information element
IUC	interval usage code
LDPC	low density parity check
MAP	upstream bandwidth allocation map
MER	modulation error ratio
MMM	MAC management message
OFDMA	orthogonal frequency division multiple access
OUDP	OFDMA upstream data profile
PMA	profile management application
P-MAP	probe MAP
QAM	quadrature amplitude modulation
RxMER	receive MER
SID	service identifier
TCC	transmit channel configuration
UCD	upstream channel descriptor
uFEC	uncorrectable FEC

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