Unlocking 5% More OFDM/OFDMA Capacity with Cyclic Prefix Tuning

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1. Introduction

DOCSIS® 3.1 technology introduced orthogonal frequency division multiplexing (OFDM) waveforms in both the upstream and downstream. These offer greater spectral efficiency over legacy single-carrier quadrature amplitude modulation (SC-QAM) waveforms and provide numerous "control knobs" allowing operators to tune performance to plant conditions. Two controllable parameters of the OFDM waveform that will be discussed in this study are the cyclic prefix (CP) and the roll-off period (RP). The CP counteracts *inter-symbol interference* (ISI) when operating on a channel that exhibits echoes. The RP controls *spectral leakage* from the OFDM waveform to signals in adjacent bands. The CP in the OFDM waveform is roughly equivalent to the 24-tap T-spaced equalizer of the DOCSIS 3.0 SC-QAM waveform. The RP of the OFDM waveform is equivalent to the root raised cosine (RRCF) pulse-shaping filter in SC-QAM. In the remainder of the paper, we use OFDM to refer to both the downstream (OFDM) and upstream (OFDMA) signals, unless otherwise noted.

While the CP is necessary for preventing ISI, it carries no useful data. The longer the CP, the more protection it offers against interference, but the greater the reduction in channel efficiency. Cable operators typically configure conservative CP settings, prioritizing channel reliability at the cost of throughput. In this paper, we begin with an analysis of 23,000 representative cable modems (CMs) in the field to understand typical channel echo characteristics. Using this data, we configurate an automated laboratory test that replicates field conditions, observing the effect of CP settings on channel signal-to-noise ratio (SNR) and throughput. Finally, we determine optimal CP settings across the devices and demonstrate the potential capacity gain. Based on this study, we believe that we can achieve a capacity gain of ***greater than 5%*** with no detrimental impact on network performance.

1.1. The Anatomy of the OFDM Waveform

Compared to legacy SC-QAM, OFDM signaling is significantly more complex. In this section, we discuss only those aspects of the signal relevant to this study, namely the cyclic prefix and roll-off period. For a detailed description of OFDM modulation and demodulation, see [1]. For a discussion of OFDM as implemented in the DOCSIS protocol, see [2].

Figure 1 shows the process of forming the time-domain OFDM signal.

A. Data is modulated onto the available subcarriers using an N-point inverse fast Fourier transform (IFFT).
B. N_{cp} samples from the end of the waveform are copied to the beginning to form the *cyclic prefix*. Due to the periodic nature of the IFFT, this is equivalent to periodically extending the waveform backward in time N_{cp} samples.
C. N_{rp} samples from the beginning of the original unextended waveform are copied to the end to form the roll-off region. Again, this is equivalent to periodically extending the waveform forward in time N_{rp} samples.
D. The leading and trailing samples of the extended waveform are tapered with a raised-cosine taper over a span of N_{rp} samples. This forms the *roll-off period*.
E. The waveform is concatenated with adjacent OFDM symbols, allowing each symbol to overlap its neighbor by N_{rp} samples.

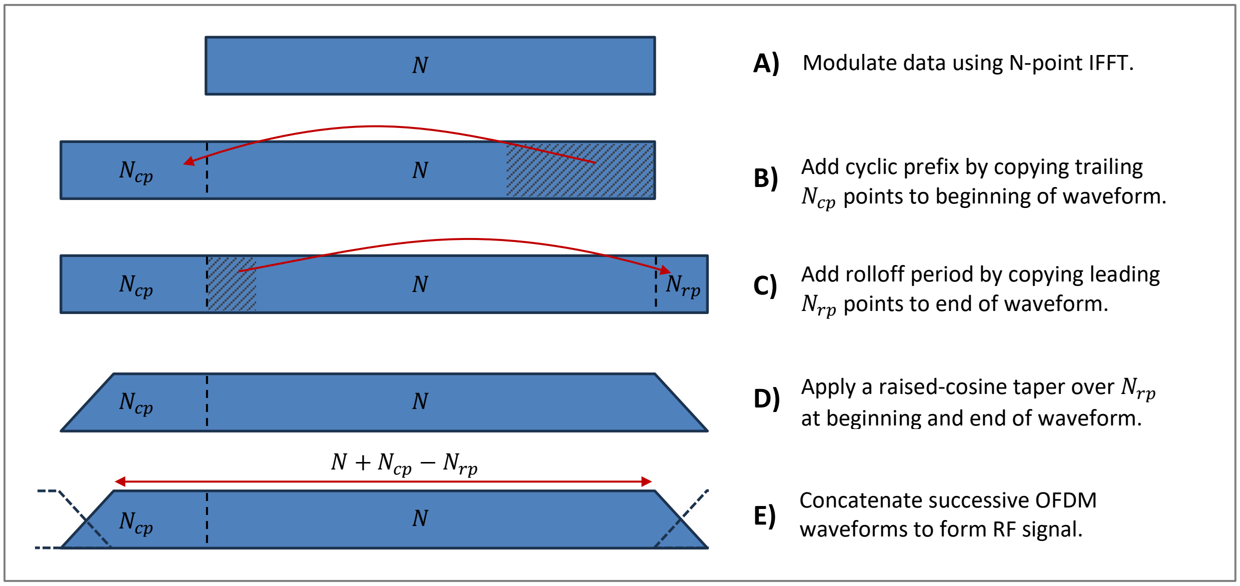

Figure 1 - The OFDM waveform including cyclic prefix and roll-off period

The OFDM mode for both the upstream and downstream can take on one of two values. To simplify our discussion, we will assume both the upstream and downstream operate 4K mode. Table 1 lists the settings used for this study.

Table 1 - OFDM parameters used in this study

Parameter	Upstream	Downstream
Mode	4K	4K
Sample rate	102.4 MHz	204.8 MHz
IDFT size	4096	4096
Subcarrier Spacing	25 kHz	50 kHz
Symbol Duration	40 us	20 us
Active Subcarriers	1776	1880
Occupied BW	45.6 MHz	94 MHz

1.1. The Cyclic Prefix

When an RF signal travels on the coaxial cable, it encounters impairments that cause the signal to spread in time. This behavior is captured by the channel's *impulse response (IR)*. Figure 2 illustrates a channel containing a "direct path" component and two reflections. The direct path signal arrives at the receiver first, and usually has the largest amplitude. In the illustration, the reflections result in two additional copies of the signal arriving at later times, and with reduced amplitude. If all (nonnegligible) echoes arrive at the receiver within the cyclic prefix duration, it is possible to find a sampling aperture that is free of echoes from adjacent symbols. Sampling at this time will result in zero ISI.

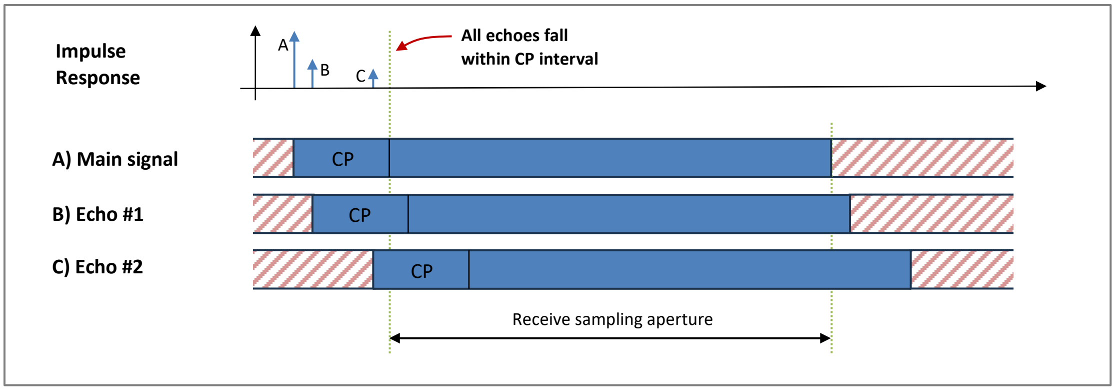

Figure 2 - Channel reflections fall within cyclic prefix region

Figure 3 illustrates a case where the impulse response duration exceeds the cyclic prefix length. The second echo causes energy from adjacent symbols to overlap, leading to ISI. Any echo energy that falls outside the CP duration leads to ISI.

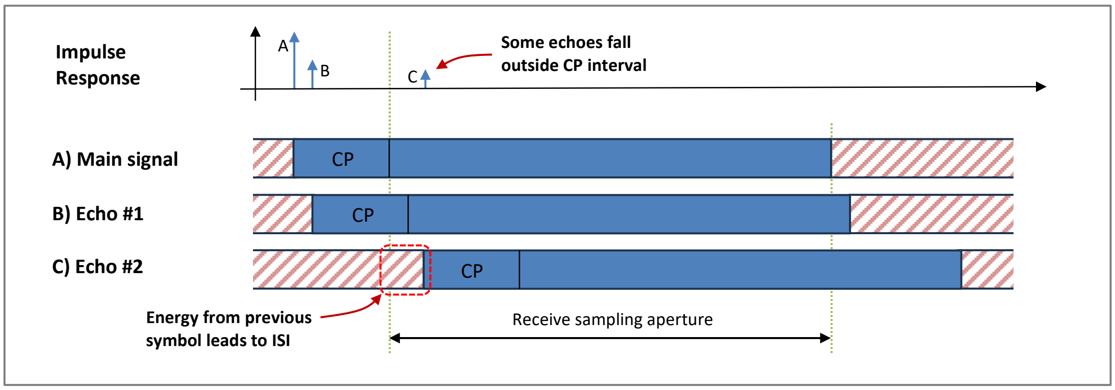

Figure 3 - Channel reflections exceed cyclic prefix region, leading to ISI

Cyclic prefix selection is directly related to channel impulse response length. In an ideal channel, with no echoes, the cyclic prefix would be unnecessary. In practice, operators should understand the echo characteristics of their plant and select a CP accordingly. While Figure 2 and Figure 3 may make CP length selection seem simple, several real-world factors complicate matters. First, real impulse responses have infinite length and decay to zero gradually, so some formal definition of IR length must be employed such that “length” is well-defined. This will be presented in Section 1.4. Second, across a population of cable modems, the IR length may vary significantly. It is generally inefficient to design to the worst performing device and we will more likely choose a CP length that is adequate for some percent of the population, realizing that other devices will experience ISI and degraded performance.

1.2. The Roll-off Period

The roll-off period of the OFDM waveform provides a smooth transition between adjacent symbols in the time domain. Without this region, the abrupt signal change would lead to spectral leakage, causing adjacent channel interference (ACI) with legacy SC-QAM signals located near the OFDM band edges. The roll-off region significantly reduces ACI and its length, N_{rp}, can be selected by the operator based on the tolerable level of ACI in the system. In Figure 1, we see that the roll-off period occurs within the span of the cyclic prefix, effectively reducing the length of the cyclic prefix. For this reason, it is desirable to keep the RP as short as possible for a given spectrum plan. In [2], an RP of 64 or 128 is recommended as a general guideline and in this study, we will keep downstream $N_{rp} = 128$ for simplicity.

1.3. Calculating Symbol Efficiency

The cyclic prefix is a redundant portion of the OFDM waveform. As such, it is desirable to keep it as short as possible. In addition, the roll-off period reduces the effective CP length, so it too should be minimized. We define the *symbol efficiency* of the OFDM waveform as $SE = N/(N + N_{cp})$. This figure represents the throughput loss due to the cyclic prefix. As the cyclic prefix length approaches zero, the efficiency approaches 100%. In addition, we define *effective cyclic prefix length* as $N_{cp-x} = N_{cp} - x$ where x is the roll-off period length. Table 2 shows the effective cyclic prefix length and symbol efficiency for upstream CP values and $RP \in [32,64,96]$. Effective CP length is given in both samples and microseconds. Table 3 shows the same data for the downstream, with values of $RP \in [64,128]$. In each table, the highlighted cells show the values used in the Comcast plant.

Table 2 - Symbol efficiency and effective CP length for select RP values, upstream

Ncp	Ncp_32	Ncp_64	Ncp_96	Ncp (us)	Ncp_32 (us)	Ncp_64 (us)	Ncp_96 (us)	SE %
96	64	32	0	0.9	0.63	0.31	0.00	**97.7**
128	96	64	32	1.3	0.94	0.63	0.31	**97.0**
160	128	96	64	1.6	1.25	0.94	0.63	**96.2**
192	160	128	96	1.9	1.56	1.25	0.94	**95.5**
224	192	160	128	2.2	1.88	1.56	1.25	**94.8**
256	224	192	160	2.5	2.19	1.88	1.56	**94.1**
288	256	224	192	2.8	2.50	2.19	1.88	**93.4**
320	288	256	224	3.1	2.81	2.50	2.19	**92.8**
384	352	320	288	3.8	3.44	3.13	2.81	**91.4**
512	480	448	416	5.0	4.69	4.38	4.06	**88.9**
640	608	576	544	6.3	5.94	5.63	5.31	**86.5**

Table 3 - Symbol efficiency and effective CP length for select RP values, downstream

Ncp	Ncp_64	Ncp_128	Ncp (us)	Ncp_64 (us)	Ncp_128 (us)	SE %
192	128	64	0.94	0.63	0.31	**95.5**
256	192	128	1.25	0.94	0.63	**94.1**
512	448	384	2.50	2.19	1.88	**88.9**
768	704	640	3.75	3.44	3.13	**84.2**
1024	960	896	5.00	4.69	4.38	**80.0**

1.4. Impact of Cyclic Prefix on Data Throughput

The achievable data throughput of the OFDM channel depends on many parameters. The number of active subcarriers, bit loading per subcarrier, error control coding rate, and symbol efficiency all factor into the calculation. If we assume a 100% symbol efficiency (e.g. no cyclic prefix is used), use the channel bandwidths from Table 1, and assume typical values for coding rates and bit loading, we can establish representative throughput values for upstream and downstream. Table 4 shows expected capacity of the upstream and downstream assuming a cyclic prefix of zero (resulting in a 100% symbol efficiency) and assuming the shortest possible CP length (96 for upstream and 192 for downstream). The general relationship is $C = C_{cp-0} * SE$, where SE is the symbol efficiency for a specific cyclic prefix length. The upstream and downstream have maximum SE of 97.7% and 95.5%, respectively, leading to the values in the C_{cp-min} column. Later, we will use this relationship to calculate the expected channel capacity increase resulting from CP length reduction.

Table 4 - Estimated channel capacity based on CP length

Direction	C_cp-0	C_cp-min
Upstream	430 Mbps	419 Mbps
Downstream	880 Mbps	843 Mbps

2. OFDM Upstream and Downstream Characteristics

Cable modem telemetry allows us to pull OFDM pre-equalization coefficients from modems in the field. The raw coefficient vector relates directly to the channel's frequency response at each OFDM subcarrier. Taking the inverse fast Fourier transform (IFFT) of the vector yields the channel's impulse response. Figure 4 shows the impulse response for two CMs in a group of 23,000 used in this study. One CM exhibits a sharp decay, corresponding to a channel with low reflection. The other exhibits a more gradual decay, corresponding to a reflective channel. In this type of channel, echo energy decays slowly, and could potentially lead to inter-symbol interference.

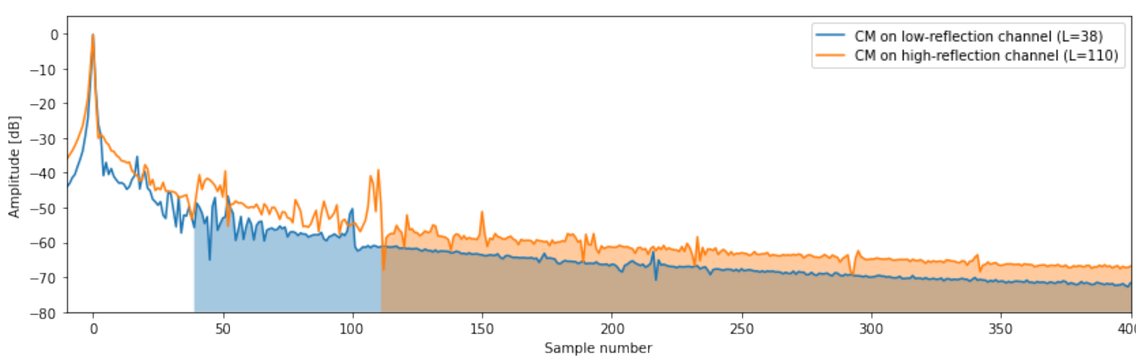

Figure 4 - Impulse response data from two CMs in the field

The impulse response of any real channel is infinitely long. In practice, we can define the impulse response length based the time needed for the signal to decay to a specified level. Here, we define the IR length as the point where the *residual echo energy* is -35 dBc with respect to the peak. The shaded portion of each curve in Figure 4 shows this. For the first response, the IR decays to this level by sample 38. Any cyclic prefix greater than 38 will result in a less than -35 dB ISI level. For the second response, the cyclic prefix must be greater than 110 samples to provide the same protection.

Figure 5 shows a histogram of downstream impulse response length, calculated for 23,000 cable modems in the field. Each vertical line on the graph represents a valid *effective* upstream cyclic prefix assuming a roll-off period of 128 (N_{cp-128} in Table 3). We see that most CMs have an impulse response length of less than 128. The same data is shown in Figure 6 as a cumulative distribution function with the y-axis showing the percent of CM population.

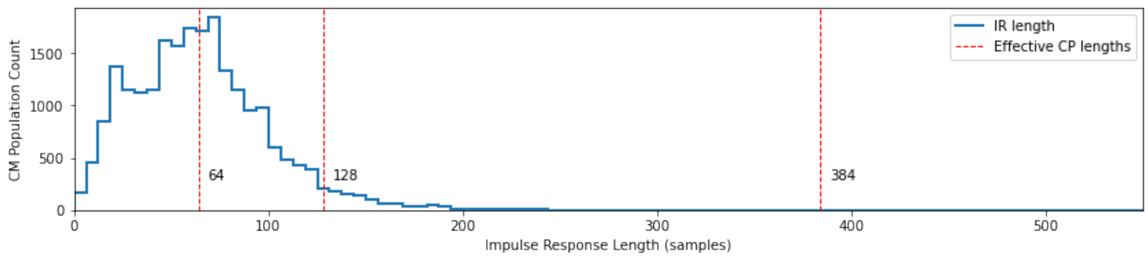

Figure 5 - Distribution of downstream impulse response lengths across 23k cable modems

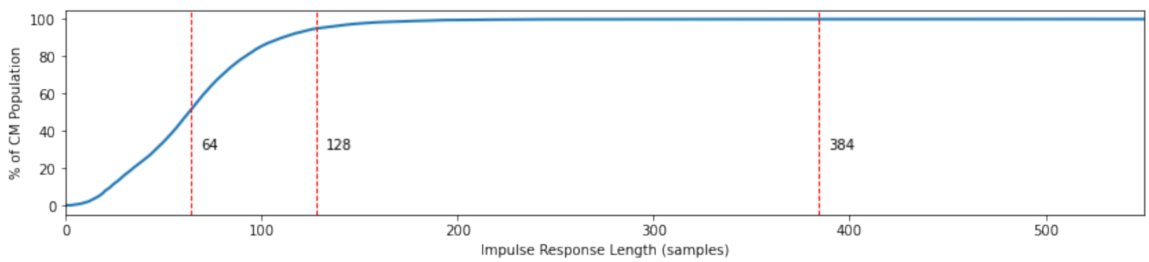

Figure 6 - CDF of IR lengths across 23k cable modems.

The data from Figure 6 is summarized in Table 5. For each valid downstream cyclic prefix, we list the effective CP (assuming $N_{rp} = 128$ and *effective CP length* defined in Section 1.3) and the percent of CMs in the sample that would be protected by that CP length. A cyclic prefix of 256, with effective length of 128, would protect 95% of the population.

Table 5 - Percent of CMs covered by each CP

Ncp	Ncp_128	% CMs
192	64	51.4%
256	128	94.9%
512	384	99.9%

Instead of choosing one global CP length to use across the footprint, we can set a unique value per RPD. By using the shortest possible CP length per PRD, we can realize increased symbol efficiency across the footprint. In Figure 7, we take the data from the 23k modems above and group by RPD. For each RPD, we determine the worst-case IR length. Instead of showing percent CMs as a function of CP length, we show percent RPDs.

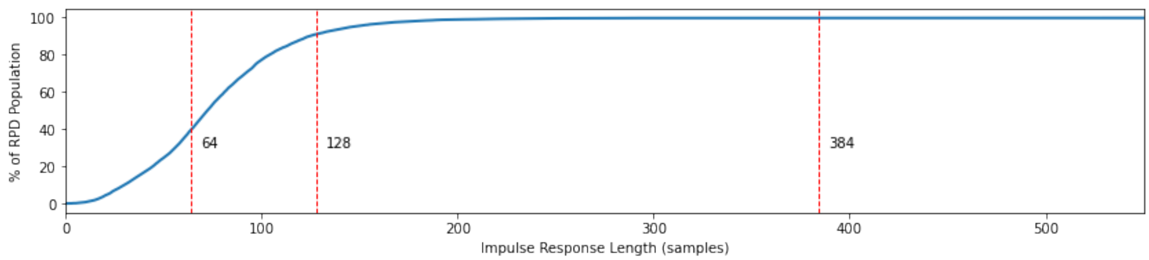

Figure 7 - CDF of worst-case impulse response length across 700 RPDs

Table 6 shows the CDF sampled at the valid upstream CP lengths. The *% RPDs* column represents the cumulative percentage of RPDs that are protected be each CP value. From the table, we see that 40% of RPDs are adequately protected by $N_{cp} = 192$ while 91% of RPDs are protected at $N_{cp} = 256$. The *Δ% RPDs* column represents the percentage of RPDs protected be each individual CP length. From the data, we see that setting a global value of $N_{cp} = 512$ would protect 99.7% of RPDs but only 8.7% of RPDs need that CP length. The rest of the population could be set to a lower CP value.

Table 6 - Worst case impulse response length over RPD population

Ncp	Ncp_128	% RPDs	Δ% RPDs
192	64	39.6%	39.6%
256	128	90.9%	51.3%
512	384	99.7%	8.7%

In later sections, we will provide strategies for CP length selection both globally and at the RPD level, and show the symbol efficiency increase that can be achieved in each case.

3. Laboratory Testing

3.1. Experimental Setup

To verify the effect of cyclic prefix length on reflective channels, we have constructed a laboratory test consisting of five cable modems, a DOCSIS 3.1 RPD, and a digital channel emulator that allows us to cycle though channel impairments in an automated and repeatable way. Figure 8 shows the laboratory setup used in this study. The cable modems are fed by a 16-way splitter and the channel emulator sits between the splitter and RPD. The test is automated by a computer that varies channel emulator settings and logs telemetry from the RPD.

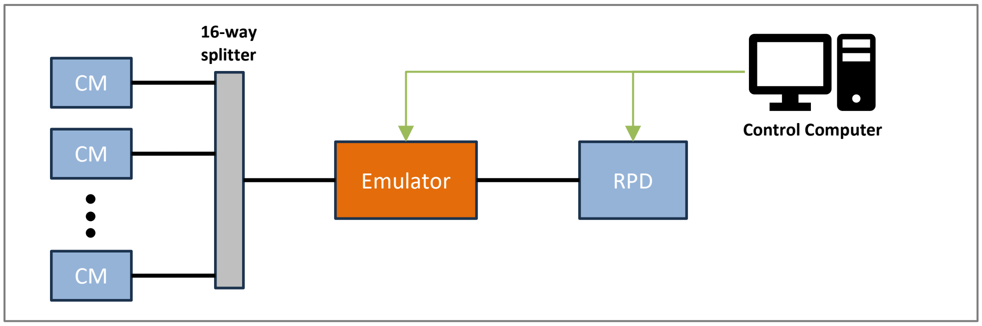

Figure 8 - Laboratory experimental setup used in the study.

3.2. The Channel Emulator

The channel emulator is a fully digital device that allows us to recreate channel impairments in an automated and repeatable manner. The prototype version used in this study is based on the Xilinx ZCU111 RFSoC evaluation board. Figure 9 shows the implementation of the channel emulator. The RFSoC's built-in data converters digitize the full DOCSIS upstream signal. Within FPGA fabric, we implement a module that creates channel reflection and tilt that can be varied in real time. Additionally, a built-in waveform generator can be used to inject ingress signals into the channel. More details about the emulator can be found in [3].

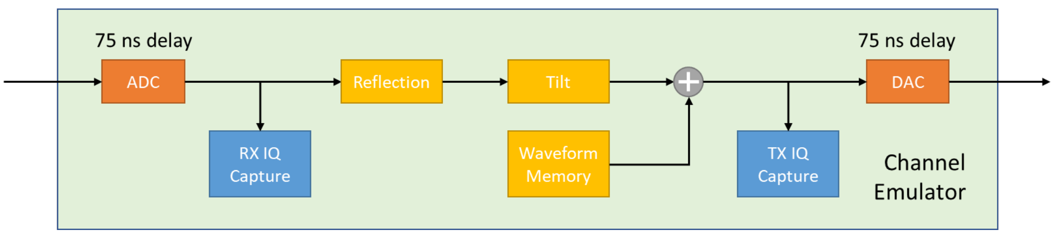

Figure 9 - DOCSIS Channel Emulator signal flow.

The emulator is packaged onto a portable 4U rack mount enclosure. The digital portion occupies the lower 2U portion and a test-specific RF interface occupies a 1U portion above. This RF interface contains the appropriate diplex filters and splitters necessary to inject reflection into the upstream and downstream.

Figure 10 - Channel emulator and interface module in rack mount enclosure.

The emulator supports two remote interfaces, a web-based GUI, and a socket interface. For this testing, a python script connects through the socket interface to automatically step through channel configurations.

3.3. The "Single Reflection" Model

The cyclic prefix is intended to guard OFDM symbols from the effects of channel echoes. In theory, a cyclic prefix of τ seconds should be able to eliminate inter-symbol interference in a channel having an impulse response of less than τ seconds. To create a controlled test, the channel emulator is configured to generate a single echo with fixed amplitude (-30 dB relative to the main path) and varying delay. Figure 11 shows the impulse response of the channel between cable modem and RPD with the channel emulator set to generate an echo at 1 us. This plot was created by taking the IFFT of the OFDMA pre-equalization coefficients, read from the cable modem.

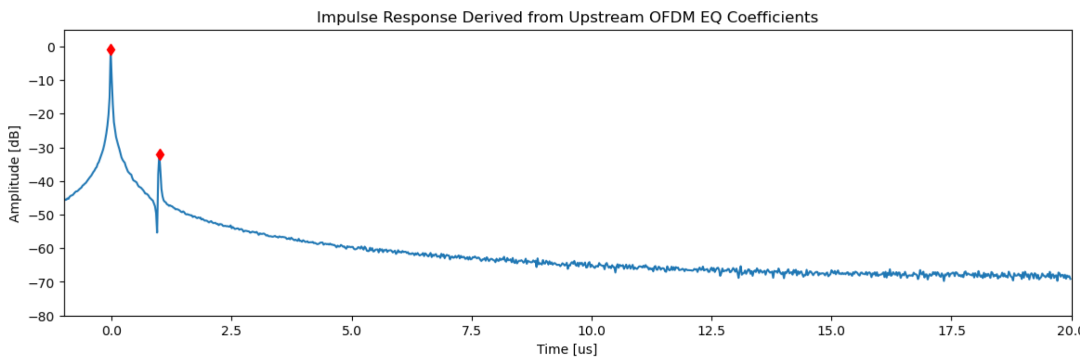

Figure 11 - Impulse Response Derived from Upstream OFDM EQ Coefficients

The in-channel frequency response (ICFR) for this echo configuration is shown in Figure 12. The portion of the ICFR below 40 MHz is constructed from the IFFT of the SC-QAM equalizer coefficients. The ICFR in the upper band is derived directly from the OFDMA pre-equalization coefficients. As expected, the ripple has a 1 MHz spacing.

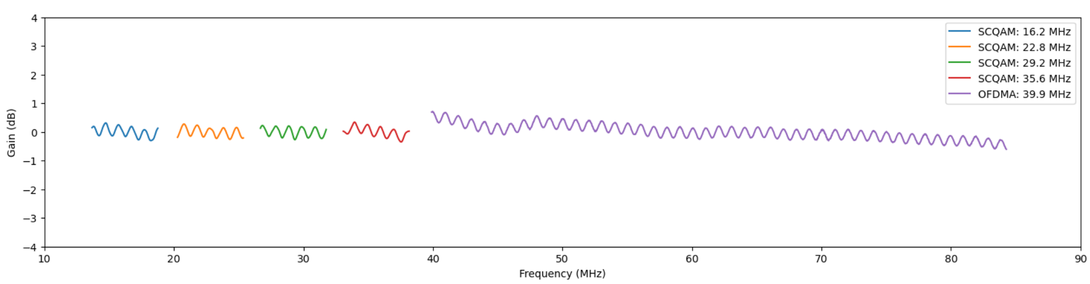

Figure 12 - In-Channel Frequency Response from EQ Coefficients

3.4. Experimental Results

The DOCSIS 3.1 upstream CP can take one of eleven values and the RP can take one of eight values. In this study, only the CP length was varied while the RP was held at $N_{rp} = 64$. Figure 13 shows the reported signal-to-noise (SNR) of the OFDMA channel as the channel emulator's echo delay was varied from 0 us to 5 us in steps of 0.2 us. The channel was fully loaded with traffic and held at each delay setting for 10 minutes. During this time, equalizer coefficients converge, and traffic is balanced across available IUCs. This experiment was repeated for three CP values.

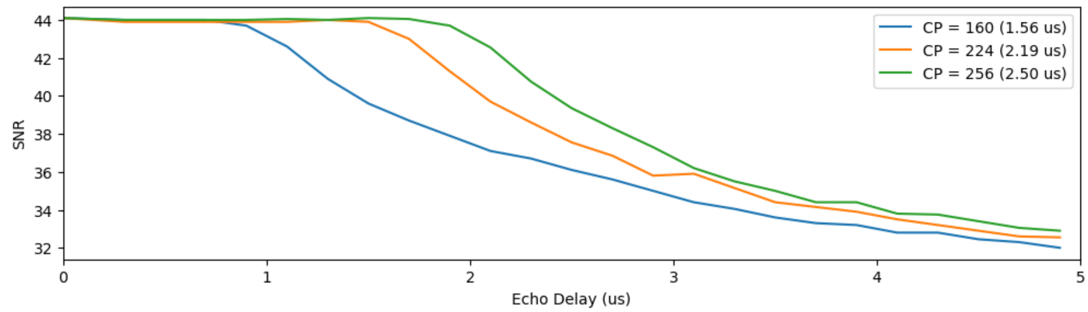

Figure 13 - SNR verses Emulator Echo Delay

Table 7 summarizes the major result from Figure 13. For each CP value (with constant $N_{rp} = 64$), we give the effective CP in (N_{cp-64}) and both samples and time. When channel echoes exceed this value, we expect to see SNR fall. The point in Figure 13 where each SNR curve drops 0.5 dB below its initial value is denoted in the table as t_{meas}. The value 0.5 dB was chosen arbitrarily to represent the onset of channel degradation. For each value of CP, the experimental results agree closely with theory.

Table 7 - Summary of laboratory results

Ncp	Ncp_64	Ncp (us)	Ncp_64 (us)	t_meas
160	96	1.6	0.94	**0.90**
224	160	2.2	1.56	**1.50**
256	192	2.5	1.88	**1.90**

4. Cyclic Prefix Selection

Since the cyclic prefix carries no data, it represents lost network capacity. In Comcast networks, the downstream OFDM channel is configured to $N = 4096$ and $N_{cp} = 512$ across the plant. As shown in Table 3, this results in a symbol efficiency of 88.9%. In Section 1.4, we extracted impulse response data from 23,000 cable modems in the field and developed a distribution of worst-case impulse response length across 700 RPDs. Using this data, we can assign a cyclic prefix length to each RPD to guard against that RPD's worst-case echoes. Table 8 shows the summary of this analysis. For each downstream CP length (up to 512), we show the effective CP length, assuming a fixed $N_{rp} = 128$. The cumulative percentage of RPDs covered by each CP length is shown (*% RPDs*) as well as the percentage of RPDs covered by just that CP length (*% RPDs Δ*). We also show the symbol efficiency (*SE %*) for each CP length.

Table 8 - Calculating mean symbol efficiency, $N_{rp} = 128$

Ncp	Ncp_128	% RPDs	% RPDs Δ	SE %	weighted SE %
192	64	39.6%	39.6%	95.5%	37.8%
256	128	90.9%	51.3%	94.1%	48.3%
512	384	99.7%	8.7%	88.9%	7.8%
				Mean Symbol Efficiency =>	**93.9%**

If each RPD is configured with its minimum effective CP length, we can calculate the *mean symbol efficiency* across the footprint as a weighted sum of the efficiency for each CP length, weighted by the percent of RPDs set to that CP length (*weighted SE %*). From the table, we see that the footprint-wide mean symbol efficiency is **93.9%** with this approach. This represents a **5.0% increase** in symbol efficiency compared to 88.9% efficiency achieved with the current global setting of $N_{cp} = 512$. This increase in symbol efficiency results in a throughput increase of $880\ Mbps * 5\% = \mathbf{44\ Mbps}$ (following from Table 4).

4.1. Varying Roll-off Period

The roll-off period is chosen to limit spectral leakage between the OFDM signal and legacy SC-QAM signals. It is determined based on the allowable adjacent channel interference (ACI) the SC-QAM signal can tolerate. As such, it is dependent on the frequency plan used on the RPD, including guard band width to the legacy signal and modulation order used by that signal. Table 9 demonstrates the potential benefit of reducing the N_{rp} from 128 to 64. This results in a longer effective cyclic prefix at each CP setting and an increase in mean symbol efficiency to **95.1%**. Reducing the roll-off period from 128 to 64 could yield a **6.2%** increase in symbol efficiency (**54 Mbps increase**). Note that the upper bound on efficiency is 95.5%, which would result from setting all RPDs across the footprint to the minimum value of $N_{cp} = 192$.

Table 9 - Calculating mean symbol efficiency, $N_{rp} = 64$

Ncp	Ncp_64	% RPDs	% RPDs Δ	SE %	partial SE %
192	128	91.9%	91.9%	95.5%	87.8%
256	192	98.9%	7.0%	94.1%	6.6%
512	448	99.7%	0.8%	88.9%	0.7%
				Mean Symbol Efficiency =>	**95.1%**

5. Conclusion

This study examined the frequency response characteristics of a representative sampling of cable modems to quantify the potential bandwidth increase by optimizing the OFDM channel cyclic prefix length. Utilizing a default downstream cyclic prefix length of 512, a roll-off period of 128, and a 192 MHz wide OFDM channel, we discovered that reducing the cyclic prefix to 256 can be achieved with minimal impact on our existing customer base. Implementing a network-wide configuration change from a CP length of 512 to 256 would yield a substantial 5% increase in capacity across all OFDM channels, equating to approximately 10,000 Gbps of reclaimed bandwidth for every 100,000 service groups. Additionally, further bandwidth recovery is possible by adjusting CP on an RPD-by-RPD basis, with even shorter CP lengths feasible on RPDs with low reflection. This strategic optimization presents a significant opportunity to enhance network efficiency and capacity.

Abbreviations

ACI	adjacent channel interference
CM	cable modem
CP	Cyclic Prefix
ICFR	In Channel Frequency Response
IFFT	Inverse Fast Fourier Transform
IR	Impulse Response
ISI	inter-symbol interference
IUC	Interval Usage Code
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
RP	Roll-Off Period
RPD	remote PHY device
RRCF	root raised cosine
SNR	Signal to Noise Ratio
SC-QAM	Single Carrier Quadrature Amplitude Modulation

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