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TECHNICAL REPORT

Compatibility Study – Analog and HD Radio Broadcasting Systems in the 88 – 108 MHz Band

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This report is a redacted version of the original report authored by CRC. The content of this report is for information and educational purposes only. ISED will have further discussions to determine if any regulatory changes to its Rules and Procedures are required.

Executive Summary

This report is the output of a laboratory measurements and analysis project, conducted by CRC at the request of DGEPS, to support technical rule making towards enabling HD Radio broadcasting operations in the 88-108 MHz band in Canada.

HD Radio is a method for transmitting both analog and digital broadcast signals at the same time over the same frequency channel. This technology allows broadcasters to use their allocated AM and FM frequency bands to transmit simultaneously both analog and digital signals. This provides enhanced sound quality, allows the transmission of additional audio programs and data services (e.g.; traffic, weather), and eases transition to full digital radio broadcasting.

If HD Radio transmissions are to be allowed in the FM broadcasting band, specific technical conditions and parameters to be used must be determined to minimize possible interference effects on the current FM broadcast operations.

In Sections 4 and 5, the report presents the results of the laboratory measurements conducted by CRC, quantifying the reception performance of present day analog FM and HD Radio receivers in clear channel conditions and the susceptibility to interference, within the same channel or from adjacent channels, and originating from either analog or HD Radio broadcasts.

Based on the measured laboratory data, a sample analysis of the coexistence between analog FM and possible future HD Radio assignments was conducted for a number of uses cases extracted from the current Canadian FM licensing database.

The conclusions of this analysis indicate that, when all BPR-3 technical rules are respected, HD Radio operations would not negatively impact the reception of the analog FM broadcast on the same and adjacent channels within the protected service contours of existing analog FM assignments. However, where short-spaced analog FM assignment pairs exist, turning on HD Radio broadcast would create impairments to the analog reception of short-spaced stations.

Measures that can be adopted to mitigate these possible interference impacts do exist, for example limiting HD Radio operations to only the stations which would not create interference, or rearranging current FM assignments to remove some of the short-spaced pairs. An in depth analysis of such possible options was outside the scope of the current study.

More details on the overall conclusions of the study, and high level considerations for possible next steps, are presented in Section 7.

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List of Acronyms

ADS	Advanced Data Services
AM	Amplitude Modulation
AWGN	Additive White Gaussian Noise
BLER	Block Error Rate
CCIR	Comité consultatif international pour la radio
C/N	Carrier-to-Noise Ratio
D/U	Desired-to-Undesired Ratio
FCC	Federal Communications Commission
FM	Frequency Modulation
HD Radio	“Trademark” for DTS, Inc. for the digital AM and digital FM band transmission technology
Hybrid FM	Waveform composed of the analog carrier plus digital subcarriers
IBOC	In-Band On-Channel
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
MPS	Main Program Service
NRSC	National Radio Systems Committee
OFDM	Orthogonal Frequency Division Multiplexing
PIDS	Primary IBOC Data Service Logical Channel
RBW	Resolution Bandwidth
RF	Radio Frequency
RMS	Root Mean Square
RUT	Receiver Under Test
SIS	Station Information Service
S/N	Signal-to-Noise Ratio
SPS	Supplemental Program Service
TOA	Threshold of Audibility
VBW	Video Bandwidth

1 Introduction

DGEPS solicited CRC to conduct technical studies to examine the compatibility of HD Radio and analog FM audio broadcasting in various markets across Canada. Specifically, CRC will study the conditions of operations for which HD Radio can offer protection to existing and future FM radio broadcasting transmissions. In performing this analysis, CRC will determine and provide recommendations regarding the parameters and procedures under which HD Radio, herein called hybrid FM, and analog FM radios may co-exist.

In hybrid mode, HD Radio digital signals exist on the channel immediately above and below the analog FM signal. The challenge for Canadian broadcasters is that ISED currently does not have any protection criteria for the introduction of HD Radio broadcasting in Canada. Therefore, it is unclear whether HD Radio can be successfully implemented everywhere in Canada without causing interference to existing analog FM. Furthermore, it would beneficial to determine potential impact on HD Radio from other analog FM and HD Radios.

Currently, broadcasters wishing to experiment and evaluate the HD Radio technology in Canada must obtain an experimental broadcasting certificate. An experimental operation is permitted on a no-interference no-protection basis relative to authorized FM broadcasting undertakings. The preliminary technical rules and conditions for the experimental HD Radio operations are provided in Broadcasting Circular BC-21, Experimental Operation of In-Band On-Channel (IBOC) Digital Radio in the FM Broadcasting Band.

If HD Radio transmissions are to be allowed in the FM broadcasting band, specific technical conditions and parameters to be used must be determined to minimize possible interference effects on the current FM broadcast operations.

1.1 Scope

The project consists of first executing laboratory measurements to determine the analog FM susceptibility to interference resulted from analog FM and hybrid FM radio audio broadcast transmissions. The objective of this evaluation is to quantify the impact of hybrid FM on existing analog FM radio.

A second set of laboratory measurements is executed to determine the digital portion of a hybrid FM susceptibility to impairments and interference. The objective is to quantity the performance for comparison with analog FM, and to evaluate the service coverage.

The last task is to perform coverage simulation based on the results found in this study to illustrate possible impact on the coverage of existing analog FM broadcasting stations.

2 Radio System Transmission – Overview

2.1 HD Radio Standard

HD Radio is a hybrid method for transmitting both analog and digital broadcast signals at the same time over the same frequency channel. HD Radio is also known as in-band on-channel (IBOC) digital audio broadcasting (DAB), which allows the transmission of data along with the traditional analog signal in either the AM or FM broadcast bands. Digital carriers are added on both sides of the station's analog channel. The digital portion of HD Radio technology offers benefits such as improved audio quality, additional content and new digital data services. It is transmitted in half the lower and upper adjacent channels as shown in the Figure 2-2 for a radio transmission in the FM band. HD Radio offers a smooth transitional solution to convert analog to all digital radio broadcasting.

HD Radio was adopted by the U.S. Federal Communications Commission (FCC) in 2002 as a digital audio broadcasting method for the United States and is the only digital system approved by the FCC for digital AM/FM broadcasts [4]. The National Radio Systems Committee (NRSC) has developed a technical standard for HD Radio, officially known as NRSC-5, with the latest version being NRSC-5-D [3]. As of 2012, over 2100 radio stations (from a total of around 15000) were broadcasting HD Radio programming in the USA [7]. The HD Radio standard was also adopted in Mexico, Panama, Philippines, and is in trials in other countries, as shown in Figure 2-1. Most major broadcast equipment manufacturers have developed HD Radio transmitters. Receiver manufacturers are also marketing HD Radio receivers.

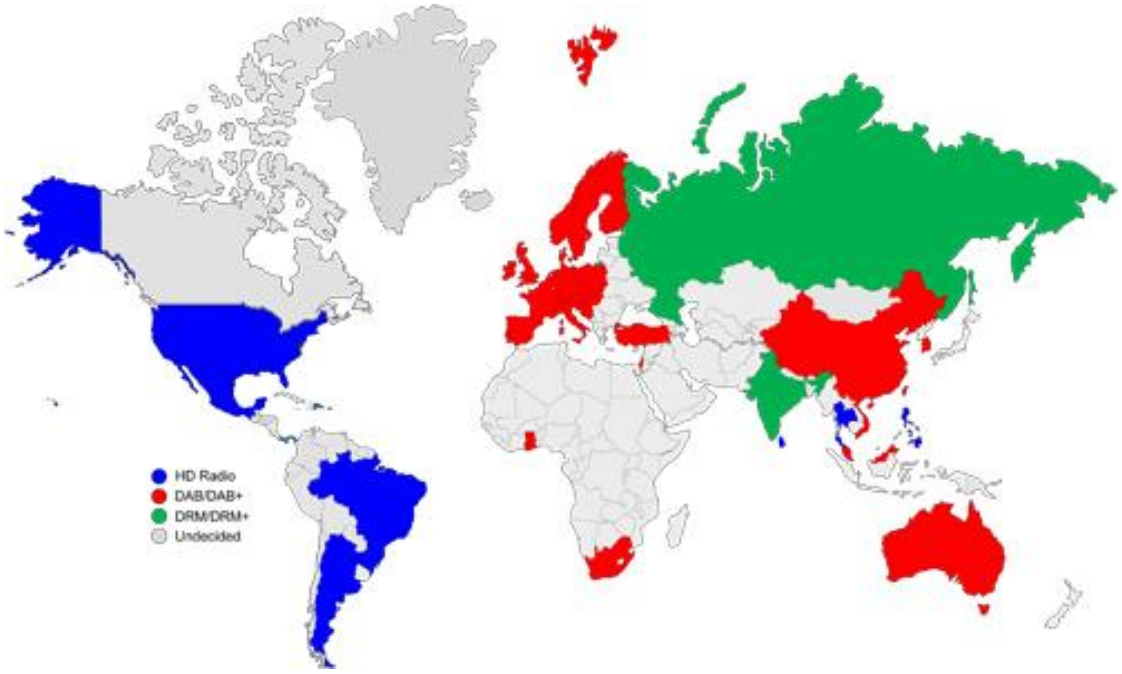

Figure 2-1: Status of digital technologies implementation (source: Harris Corporation, now GatesAir, 2012)

2.2 HD Radio Technical Overview

In HD Radio, multiple digital streams (audio streaming and/or data) are added using OFDM subcarriers on both sides of the analog FM channel edges, as shown in Figure 2-2. The information added in the lower adjacent and upper adjacent channels is duplicated for robustness purposes. The structure is based on two symmetrical subcarriers with identical information content and modulation parameters. This transmission mode including the analog and digital components is referred to as "hybrid transmission mode" herein called hybrid FM. The main advantage of such a hybrid system is enabling a smooth transition from analog to digital audio broadcasting, where both modes could coexist until the market penetration of digital capable receivers would be 100% and analog transmission would be no longer needed.

The emission mask of the HD Radio system spans for 400 kHz around the nominal center frequency. As the FM channel grid in Canada and USA is based on 200 kHz spacing, the HD Radio transmission effectively extends into half of the upper and half of the lower adjacent FM channels. While this is mitigated by transmitting the digital subcarriers at a significantly reduced power compared to the analog carrier, issues related to adjacent channel interference may still cause concern as will be shown later in this report.

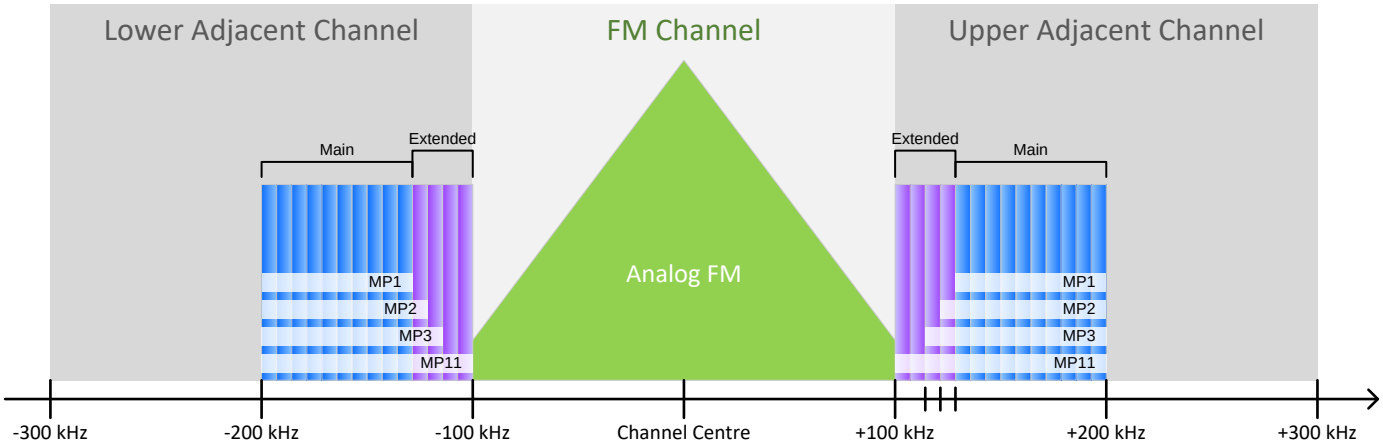

Figure 2-2: Hybrid FM spectrum usage

The two lateral digital subcarriers can be configured with various bandwidths and offsets from the centre frequency, enabling increasing amounts of digital content. The specific parameters for the digital subcarriers in various modes of operation is shown in Table 2-1.

Table 2-1: Hybrid FM digital carriers transmission characteristics

Hybrid Service Mode		MP1	MP2	MP3	MP11
Centre frequency relative to analog FM channel centre (Hz)		163,881	160,429	156,977	150,073
Bandwidth per sideband (Hz)		69,404	76,308	83,212	97,020
Nominal power per sideband at different injecting level (dBc)	-10 dBc	-13.0	-12.6	-12.2	-11.5
	-14 dBc	-17.0	-16.6	-16.2	-15.5
	-20 dBc	-23.0	-22.6	-22.2	-21.5

The service mode MP11 is not used in the current HD Radio deployments and is not implemented by the transmission equipment. Therefore, it is not covered in the scope of this document. The sum of both digital carriers signal power can be transmitted between -10 to -20 dBc, relative to the analog carrier signal power level. Three injecting levels widely used in the industry are studied: -10, -14 and -20 dBc.

Regardless of the service mode used, digital radio allows to broadcast different audio and/or data services which are grouped into three categories: core services, supplemental services and advanced data services.

Digital audio and data services are transmitted over logical channels. Logical channels are signal paths that conduct layer 2 data into layer 1 with a specific grade of service. Up to 11 logical channels are available depending on the service mode. Logical channels are divided into primary and secondary logical channels. The primary logical channels are used with hybrid and extended hybrid as well as the all digital waveforms. The secondary logical channels are used only with the all digital waveform. The secondary logical channels will not be used during this evaluation since the transmitters and receivers do not support the all digital mode.

There are five primary logical channels identified as P1 to P4 and PIDS. The PIDS transmits the Station Information Service (SIS) information. The following table indicates which logical channels are used with the various service modes.

Table 2-2: Logical channels used with each service mode

Service Mode	P1	P2	P3	P4	PIDS	Waveform
MP1	X	-	-	-	X	Hybrid
MP2	X	-	X	-	X	Extended Hybrid
MP3	X	-	X	-	X	Extended Hybrid
MP11	X	-	X	X	X	Extended Hybrid
MP5	X	X	X	-	X	Extended Hybrid, All Digital
MP6	X	X	-	-	X	Extended Hybrid, All Digital

One or multiple audio or data content is assigned to each of the available logical channels. An audio or data content cannot span multiple logical channels. The simulcast service, often referred to as HD-1, which replicates the analog content, is called the Main Program Service (MPS) and it must be transmitted in logical channel P1. HD Radio receivers switch to analog reception as the MPS reception deteriorates. In order for a seamless switch to occur, the analog program must be delayed at the transmitter by 8 seconds to be synchronized with the digital program. In cases when the 8 seconds delay is not desirable, such as for live events, the switching function is disabled and the receivers are default to analog reception only.

Up to seven Supplemental Program Services (SPS), often referred to as HD-2, HD-3, etc., are distributed amongst the available logical channels. They provide additional audio or data services without analog backup. When a receiver fails to decode an SPS service, it mutes its output.

The Advanced Data Services (ADS) category carries information not related to MPS, SIS or SPS. It is used to transmit data services such as weather and traffic information.

2.3 Status of FM Broadcasting in Canada

As of 2018, there were approximately 2600 operational FM broadcasting stations, of various power classes, licensed to operate in Canada.

2.3.1 Canadian Technical Rules

In Canada, audio broadcasting undertakings in the 88-108 MHz range (the FM band) are deployed based on technical rules specified in the Broadcasting Procedures and Rules Part 3: Application Procedures and Rules for FM Broadcasting Undertakings (BPR-3) [1].

The transmission equipment used for broadcasting in the FM band in Canada must use frequency modulation and needs to comply with the requirements in the Broadcasting Equipment Technical Standard: Technical Standards and Requirements for FM Broadcasting Transmitters (BETS-6) [2]. Further in this report this type of equipment and transmission is referred to as “analog FM”.

As per BPR-3, each application for a broadcasting certificate needs to include an interference analysis study. The following summary description excludes rules for low power transmitter, interference to television and NAV/COM services, and Canada-US border.

A primary FM assignment is defined by two service contours to provide satisfactory service to principal and secondary target centres, where the reception of the secondary target centre is achieved by outdoor receiving antennas. The field strengths required for each service contour, using F(50,50) propagation curves, are 69.5 dBµV/m (3 mV/m) and 54 dBµV/m (0.5 mV/m) respectively.

The service contour at 54 dBµV/m is also referred as the protected contour, where the permissible interfering field strength will be referred to provide the protection ratios. Protection ratios and the corresponding permissible interfering field strength levels, using F(50,10) propagation curves, at the protected contour of another frequency-related assignment or allotment are given in Table 2-3.

Table 2-3: Protection ratios (dB) and permissible interfering field strengths

Channel Relationship	Protection Ratio (dB)	Permissible Interfering Field Strength
Co-channel	20	0.05 mV/m (+34 dBµV/m)
First adjacent	6	0.25 mV/m (+48 dBµV/m)
Second adjacent	-26	10 mV/m (+80 dBµV/m)

BPR-3 does not provide specific protection ratios for analog FM stations separated by 600 or 800 kHz (i.e., operating on third or fourth adjacent channel). However, to avoid interference impairments, co-siting is strongly recommended for stations operating in the same markets, and the difference between the ERPs of the two stations shall not exceed 20 dB.

2.3.2 Spectrum Emission Mask

As per BETS-6, the analog FM transmission needs to respect the spectral emission limits as shown in Figure 2-3 which also shows the hybrid FM emission mask [3] proposed by the industry as well as a typical hybrid FM transmission represented by the grey curve.

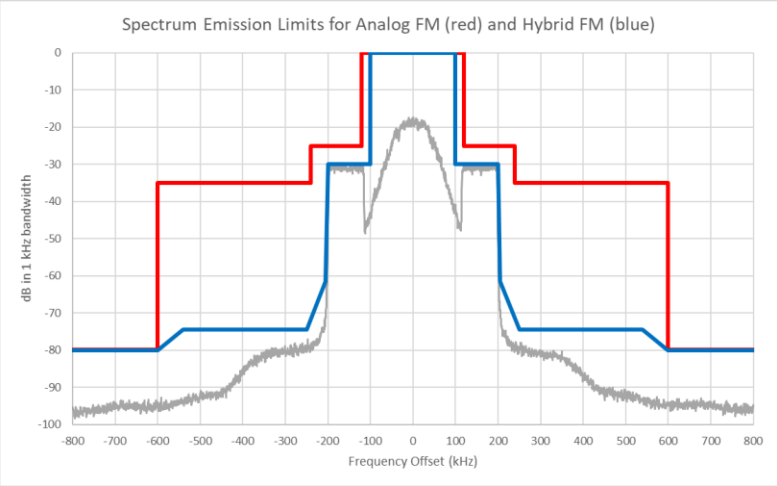

Figure 2-3: Analog FM and hybrid FM spectrum emission masks

It is noted that the hybrid FM emission mask is fully contained within the envelope of the emission mask for analog FM transmissions. This would seem to suggest, as a first level analysis, that a station already authorized to broadcast in analog mode, could “switch on” the hybrid HD Radio mode without creating interference impairments to stations operating in adjacent channels.

The current spectrum emission limits for an analog FM does not reflect the reality of a FM transmission. The European Standard ([5]; ref.: ETSI EN 302 018) has the spectrum emission mask represented in green in Figure 2-4. The blue line (light blue is in max hold) on the figure represents the analog FM transmission used in this laboratory study which comply with the mask.

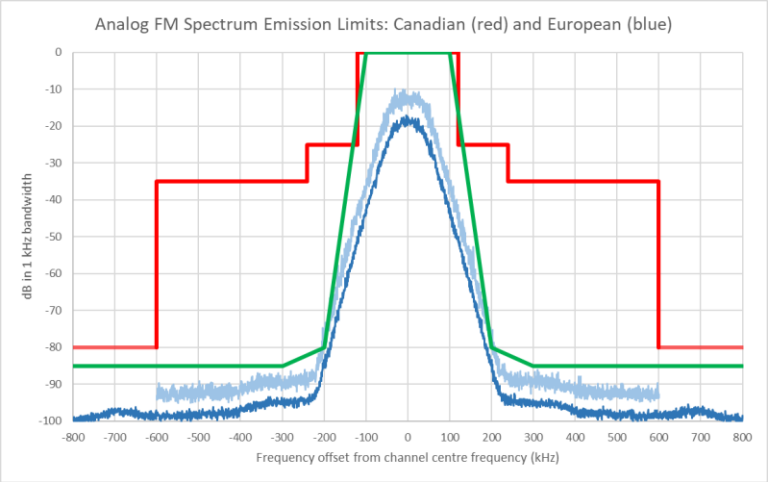

Figure 2-4: Analog FM spectrum emission masks; European vs Canadian

2.3.3 Short-spaced Situation and Consideration

The rules in BPR-3 specify minimum separation distances between adjacent broadcast stations, depending on the power class of the respective stations. These minimum separation distances were determined primarily based on the protection ratios presented in Table 2-3, the transmitter emission masks in BETS-6 shown in Figure 2-3, and on the estimated path losses based on the F(50,50) and F(50,10) curves. For convenience, the minimum separation distances provided by BPR-3 are reproduced below in Table 2-4.

Table 2-4: Minimum separation distances for operation on same or adjacent channels

Minimum Domestic Separation Distances (km)							
Relationship		**Class A1**	**Class A**	**Class B1**	**Class B**	**Class C1**	**Class C**
Class A1	Co-channel	78					
	200 kHz	45					
	400 kHz	22					
Class A	Co-channel	131	151				
	200 kHz	78	97				
	400 kHz	42	47				
Class B1	Co-channel	164	184	197			
	200 kHz	98	118	131			
	400 kHz	55	60	63			
Class B	Co-channel	189	209	222	236		
	200 kHz	117	137	150	164		
	400 kHz	68	73	77	84		
Class C1	Co-channel	223	243	256	270	291	
	200 kHz	148	168	181	195	216	
	400 kHz	90	95	99	106	119	
Class C	Co-channel	238	258	271	285	306	317
	200 kHz	166	186	199	213	234	245
	400 kHz	101	106	110	117	131	139

Over time, empirical evidence showed that the minimum separation distances estimated as above could be overly conservative in specific cases, such as, terrain obstacles providing shielding against interference, or FM transmitter with emission mask much better than BETS-6. Moreover, due to shortage of available channels, in some cases broadcasters have willingly accepted certain small impairments to existing operations, to permit new stations be brought onto service. As a result, analog FM stations were able to be deployed on adjacent channels at distances shorter than those specified by BPR-3.

An analysis of the STS licence database indicates that currently there are a about 75 pairs of stations in operation in Canada with separation distances less than as indicted in the BPR-3 (see Appendix C). Further in this document these stations pairs will be referred to as “short-spaced”.

3 Test Setup and Methodology

To evaluate the feasibility of enabling HD Radio system operations for the deployed FM broadcasting stations in Canada, laboratory measurements were conducted to determine the system susceptibility to co-channel and adjacent channel interference between analog FM and HD Radio broadcasting technologies.

The following section presents a high-level description of the test setup and methodology used for this study. This methodology is intended for the reader to understand under what conditions the results are gathered as opposed to providing a step by step test procedure.

This test methodology was developed by CRC and is based on previous analog FM evaluations. The test results, when the desired audio content is carried by the analog carrier, are based on objective measurements. The objective method is consistent, precise and repeatable. No subjective measurements were made for analog FM performance as those are subject to audio content, listener habits and other factors which are out of scope for this experiment.

Tests which were meant to establish the digital performance of hybrid FM were done using a subjective audio quality method. With digital system, that methodology is consistent and precise due to the sharp distinction between perfect and failed reception, i.e. the so called brick wall effect.

3.1 Laboratory Test Setup and Test Conditions

Figure 3-1 shows a block diagram of the laboratory test setup used for the study. The desired FM signal, either an analog FM or hybrid FM, is combined with one or two undesired FM signals and/or additive white Gaussian noise (AWGN) and fed to the receivers under test or the measuring equipment. Variable attenuators with precisions of 1 dB and 0.1 dB steps are used to adjust FM signals and noise signal levels respectively.

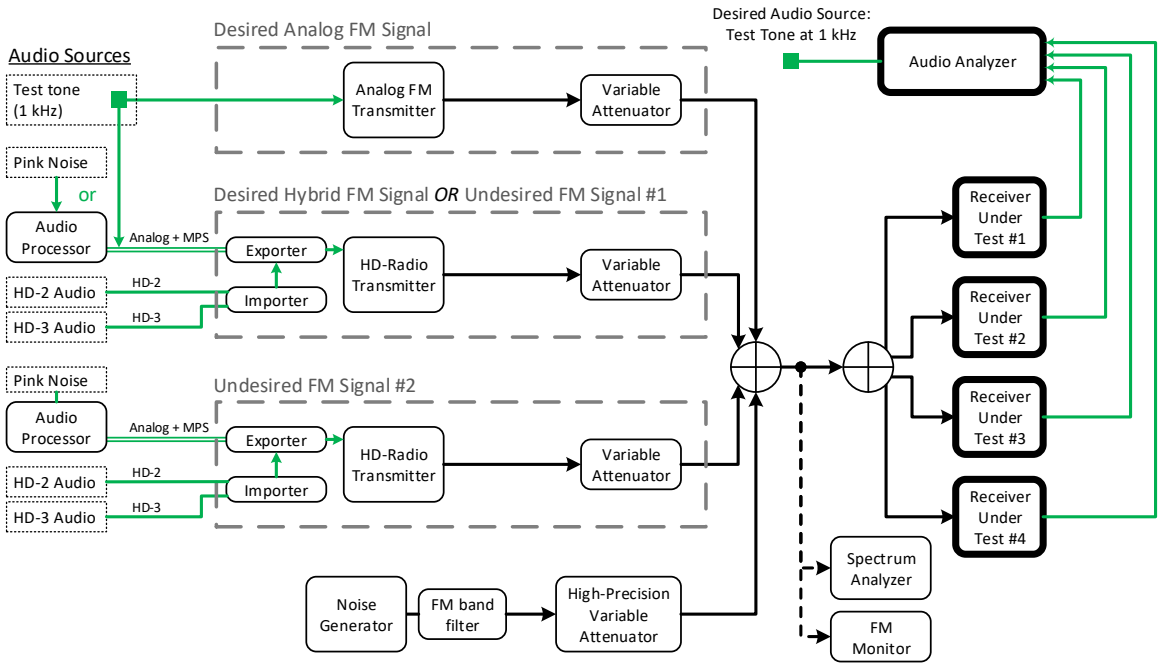

Figure 3-1: Laboratory test setup block diagram

3.1.1 RF Signal Characteristics

The desired signal is generated by either an analog FM or a HD Radio transmitter depending on the test scenario. The desired channel frequency is set to 97.5 MHz as no other local stations were transmitting on this frequency and it is near the centre of the FM frequency band.

For interference testing, the desired FM signal power level is set to either -47, -63 or -73 dBm at the receiver's input herein referred as strong, moderate and weak signal respectively. A received signal level of -63 dBm is equivalent to a field strength of 54 dBµV/m defined as the protective contour for a receiving antenna height of 9 meters above ground level assuming a perfectly matched receiving antenna with a gain of 0 dBi and no cable loss.

The undesired FM signals, used for interference testing, are generated by HD Radio transmitters which can be configured for analog only transmission, if required. The second HD Radio transmitter is used when testing scenario with multiple interferers.

A noise generator is used for testing the susceptibility to random noise of the digital portion of the hybrid FM. In some cases, it is also used to artificially increase the out-of-band emissions level of the undesired signal to replicate a more realistic high power transmitter.

For all cases, the analog portion of the FM transmitter is configured in stereo mode with 75 µs pre-emphasis. The input audio signal is adjusted in such a way that when only a left (or right) signal exists in the L + R channel, the deviation of the main carrier is equal to 45 % of the total modulation. Including the 19 kHz subcarrier pilot set to 9 %, the total modulation is calibrated to 99 % and verified with an FM monitor.

The HD Radio transmitters, when operating with digital carriers, use adaptive pre-correction to lower their out-of-band emissions in order to meet spectrum mask specifications. Being configured as low power transmitters, less than 30 W, the resulting spectrum is below the emission limits by a large margin. In consultation with the equipment manufacturer, settings were adjusted to increase the out-of-band emissions to replicate a more realistic transmission. The following figures show an analog FM and a hybrid FM configured with service mode MP3 at -10 dBc injection level, both analog carriers are modulated with a clipped pink noise.

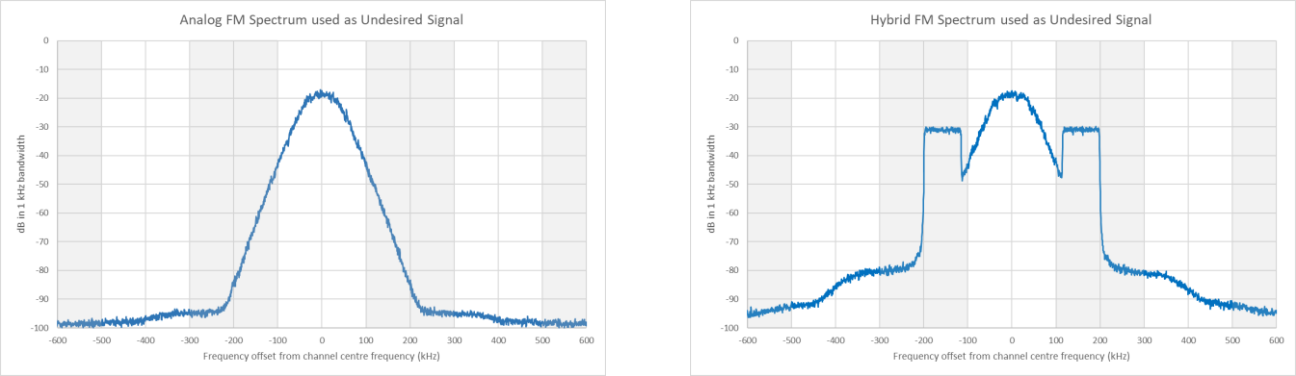

Figure 3-2: Analog and hybrid FM undesired signal spectrum plots

In the case when evaluating the digital portion of a desired hybrid FM, the transmitter is configured with service mode MP3 and the analog carrier is modulated by a clipped pink noise. Digital contents or programs are referred to as HD1, HD2, HD3, etc. where HD1, in hybrid mode, is the same audio program as the analog and the other HD programs are independent audio streams or services. The service mode MP3 is designed with two logical channels called P1 and P3, each having a different coding scheme and therefore different decoding performance. The program HD1 is always encoded in P1 and each other programs can be encoded either in P1 or in P3. In this study, in addition of HD1, two additional audio programs are used: HD2 and HD3 which are encoded in the logical channel P1 and P3 respectively.

3.1.2 Audio Sources

Several audio programs are selected depending on the test being executed and whether the audio program is feeding the desired or undesired transmitter. The following section describes the audio programs used for different test conditions, while the test methodology is explained in the next section.

To perform an objective evaluation of the audio quality of a demodulated analog FM signal, it is required to modulate the analog carrier of the desired FM transmission with a 1 kHz tone which is applied to both or one audio channels depending if audio SNR or stereo separation is being measured.

Whenever the analog portion of the FM transmission is not being decoded, the analog carrier is modulated with a clipped pink noise to approximate a modern dance music audio program. A generated stereo random pink noise is processed by an audio processor and limited by the transmitter to obtain 90% of the total modulation. Figure 3-3 shows the FM modulated clipped pink noise with frequency deviation limits as specified in Recommendation ITU-R SM.1268-4 [6].

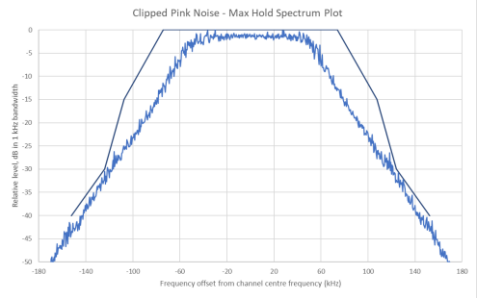

Figure 3-3: FM modulated clipped pink noise

Baseband audio quality tests, where the digital reception of HD2 and HD3 streams is assessed, are performed through subjective audio evaluation. The audio content used is an audio wave file consisting mostly of classical violin. This type of audio content makes it easier to identify reception errors.

3.1.3 Description of Receivers Under Test

The following table describes the receivers used for the study. A sampling of car, portable and cabinet radios is chosen to cover a wide range of receiver types available to the public in early 2018. The study does not extend to older or discontinued radio models.

Table 3-1: Receiver under test list

RUT short name	FM/HD	Type	Brand name	Model number	Additional Information
Rx.1A	Analog FM	-	-	-	
Rx.2A	Analog FM	-	-	-	
Rx.3A	Analog FM	-	-	-	
Rx.4A	Analog FM	-	-	-	
Rx.5A	Analog FM	-	-	-	Manual Stereo/Mono switch
Rx.6A	Analog FM	-	-	-	Mono only
Rx.11H	HD Radio	-	-	-	
Rx.12H	HD Radio	-	-	-	
Rx.13H	HD Radio	-	-	-	
Rx.14H	HD Radio	-	-	-	
Rx.15H	HD Radio	-	-	-	
Rx.16H	HD Radio	-	-	-	
Rx.17H	HD Radio	-	-	-	
Rx.18H	HD Radio	-	-	-	

All references to the Receivers Under Test (RUT) throughout this report refer to the RUT short name assigned to it as opposed to the model number and brand name. This method was chosen to make the report more readable as well as to protect the identity of the RUT should it need to be redacted. For the purpose of this report, all receivers short name ending in “A” are analog only and them ending in “H” are HD Radios.

When selecting receivers for this study, certain selection criteria were used when possible. Preference was given to receivers with RF input connectors, phono audio outputs as well as the ability to decode stereo FM broadcasts. For some classes of receivers, it was impossible to purchase radios with RF or audio connectors. Those receivers were modified to connect RF directly to the circuit board as well as divert audio from the integrated speakers to the audio analyzer. Coupling issues could exist with these modified receivers which would be perceived during baseline performance tests. The choice to favour radios capable of demodulating stereo FM broadcast is due to the majority of FM transmissions being in stereo mode and the fact that the analysis phase of this report focuses on stereo reception.

3.2 Measurement Methodology

This section covers the methodology for RF power measurement of analog FM, hybrid FM and additive white Gaussian noise used throughout this study. This section also covers the methodology for audio quality measurements.

3.2.1 RF Signal Measurement

There are three types of RF signals to be measured: analog FM, hybrid FM and Gaussian noise. All three are measured using the same methodology. The RF signal power level is measured using a spectrum analyzer channel power measurement functionality with the following characteristics:

- RBW = 1 kHz / VBW = 10 kHz
- Span = 600 kHz
- Detector: Average (RMS)
- Channel power measurement bandwidth of 200 kHz

Due to FM having a constant power regardless of content, and if the measurement bandwidth is sufficiently large, power measurements can be done with or without modulation. Whether the measured signal is an analog or a hybrid FM, the signal and noise power levels are referenced to the analog carrier measured in 200 kHz bandwidth. For hybrid FM, digital carrier power measurements are expressed in dBc, i.e. relative to the analog carrier. The digital carriers are measured using the adjacent channel power measurement functionality of the spectrum analyzer. The measurement is used as verification and validation, where the values per sideband should be close to these values:

Table 3-2: Single sideband theoretical power value in dBc

Service Mode		MP1	MP3	MP11
Centre frequency relative to analog FM channel centre (Hz)		163,881	156,977	150,073
Bandwidth per sideband (Hz)		69,404	83,212	97,020
Nominal power per sideband at different injecting level (dBc)	-10 dBc	**-13.0**	**-12.2**	**-11.5**
	-14 dBc	**-17.0**	**-16.2**	**-15.5**
	-20 dBc	**-23.0**	**-22.2**	**-21.5**

These power measurements are used to calculate the desired-to-undesired (D/U) and carrier-to-noise (C/N) ratios. The D/U ratio is the signal level difference between a desired FM signal and an undesired FM signal. If the D/U ratio is positive, the desired signal has more signal power relative to the undesired signal.

The C/N ratio is defined as the ratio of the RF modulated carrier signal power to the noise power measured at the operating frequency. This should not be mistaken with signal-to-noise (S/N) ratio which is the ratio of the baseband audio signal power to noise power after demodulation. The C/N is used to quantify the receiver performance in presence of additive white Gaussian noise (AWGN) and the S/N is used to quantify the baseband audio signal quality.

3.2.2 Objective Audio Quality Measurement

All tests measuring the baseband audio quality of the analog FM reception use an objective measurement method. This method measures the baseband audio S/N ratio as well as the stereo separation to quantify the quality of the reception. The stereo separation is defined as the ratio between the left and right audio channels when only one channel is driven.

A 1 kHz tone is generated with an audio analyzer and fed to the desired analog FM signal. The demodulated FM signal from the receiver's audio output is sent back to the audio analyzer for S/N and stereo separation measurements. The S/N ratio is obtained by measuring the signal level precisely at the test tone frequency and the noise level is obtained by using a notch filter centered on the test tone to eliminate the signal for proper noise measurement. Stereo separation is measured by applying the 1 kHz tone to one of the channels and measuring the signal level difference between the left and right audio channels.

Before a measurement, the audio signal is passed through a weighted filter which corresponds to the CCIR-1k in ITU-R 468 as well as a low pass (20 kHz). The CCIR-1k filter has no loss or gain at 1 kHz, therefore the filter only affects noise measurements.

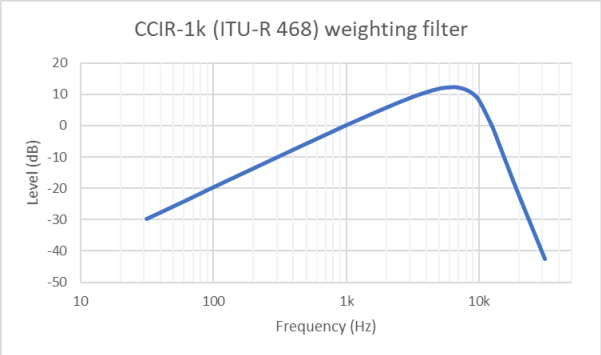

Figure 3-4: CCIR-1K frequency response

An RMS detector is used to measure both the signal and the weighted noise even though ITU-R 468 calls for a QUASI peak detector for noise measurements. It is impossible to use a different detector for noise and signal since this type of noise measurement requires the removal the modulating tone and measuring the noise during a period of silence. Modern FM receivers detect the absence of audio content and mute the output, causing the noise measurement to be artificially low and therefore invalid.

3.2.3 Subjective Audio Quality Assessment

Typically, when measuring the quality of a digital reception, a measurement of Block Error Rate (BLER) is used, which is an objective evaluation method. Since the receivers are commercial units that don't display BLER, a subjective quality evaluation method is used. The audio source of both HD2 and HD3 channels are set to a wave file as indicated in section 3.1.2 and closed headphones are used to determine the point where errors begin to occur, also known as the threshold of audibility (ToA). Due to the brick wall failure of digital transmissions, the results are repeatable and not influenced by the subjective nature of the test.

4 Analog Performance Test Results

In order to assess the impact of hybrid FM transmission on traditional analog FM, it is necessary to first analyze the system performance in the presence of analog FM and then compare it to the performance in the presence of hybrid FM.

This section summarizes the test results to evaluate receiver performance when decoding the analog signal from either an analog FM or a hybrid FM transmission in different test conditions. This evaluation consists of first doing a dynamic range test to evaluate the receiver baseline performance as well as assessing the impact of adding digital carriers beside the analog carrier, i.e. self interference. The second portion consists of performing interference testing by evaluating receivers' capabilities to decode an analog FM in presence of co- or adjacent channel interference from either an analog FM or a hybrid FM.

4.1 Baseline and Hybrid FM "Host" Interference

The basis of a dynamic range test is to study the receiver's capability to demodulate the wanted signal by varying the RF input signal power levels without impairment or interference. The following sections present results, when the wanted signal is the analog signal of either an analog FM or a hybrid FM transmission.

The receiver is presented with a "clear" analog or hybrid FM signal with no added interference or impairments. In the case of a hybrid FM, the service mode is either set to MP1, MP3 or MP11 with an injection level set to -20, -14 or -10 dBc. The RF input power level is varied from -40 dBm to -110 dBm to cover the whole operating range of the receiver under test. Over this range, the demodulated audio S/N and the corresponding stereo separation are recorded.

4.1.1 Receiver Sensitivity with an Analog FM Transmission

The following table summarizes the receiver capability to demodulate the analog signal from an analog FM transmission at different RF input signal power levels. The receiver is first presented with a FM signal at high power and without interference where the maximum demodulated stereo signal audio S/N is recorded. The FM signal power level is then decreased by 1 dB steps until the following points are achieved:

- Full Stereo Mode: minimum RF power level at which the receiver is still demodulating the FM stereo signal at its maximum stereo separation. At lower input signal levels, the receiver slowly transitions from stereo to mono decoding.
- Stereo Separation = 10 dB: RF power level at which the stereo separation is equal to 10 dB.
- Audio S/N = 30 dB: RF power level at which the demodulated mono signal audio quality is equal to 30 dB.

Table 4-1: Receiver characteristic at different received RF signal power level

Receiver Under Test	Maximum Audio S/N (stereo mode)	Receiver's RF input signal power level (dBm)		
		Full Stereo Mode	Stereo Separation = 10 dB	Audio S/N = 30 dB (mono mode)
Rx.1A	48.9	-67.0	-69.0	-103.7
Rx.2A	61.1	-66.7	-72.4	-107.0
Rx.3A	60.4	-70.6	-75.2	-107.2
Rx.4A	54.0	-60.6	-66.4	-91.4
Rx.5A	52.9	-94.6	-95.6	-102.4
Rx.6A	61.8 (mono)	N/A	N/A	-88.0
Rx.11H	62.2	-51.6	-72.4	-101.8
Rx.12H	63.1	-63.7	-76.7	-106.2
Rx.13H	59.0	-69.8	-75.0	-104.4
Rx.14H	58.6	-70.7	-75.7	-107.0
Rx.15H	63.7	-61.7	-74.9	-104.3
Rx.16H	60.6	-73.0	-81.4	-104.8
Rx.17H	61.5	-73.7	-82.5	-103.6
Rx.18H	59.7	-73.9	-82.0	-105.8

Before going further into the analysis, it is important to cover some key-element on FM radio receiving behaviour. Most modern FM receivers can decode the stereo information when the received signal level is high enough. As this level decreases, i.e. when the receiver is further away from the transmitter, the receiver slowly transitions or switches to a mono only reception. Mono reception compared to stereo reception is more robust to impairment and interference resulting in a greater audio S/N and a better audio quality without stereo functionality. Figure 4-1, which presents a typical receiver behaviour versus the received signal level, clearly shows that when the receiver is switching to mono, the audio S/N quality increases. For this reason, the analysis presented in this report focuses on results when the receiver is decoding the stereo information.

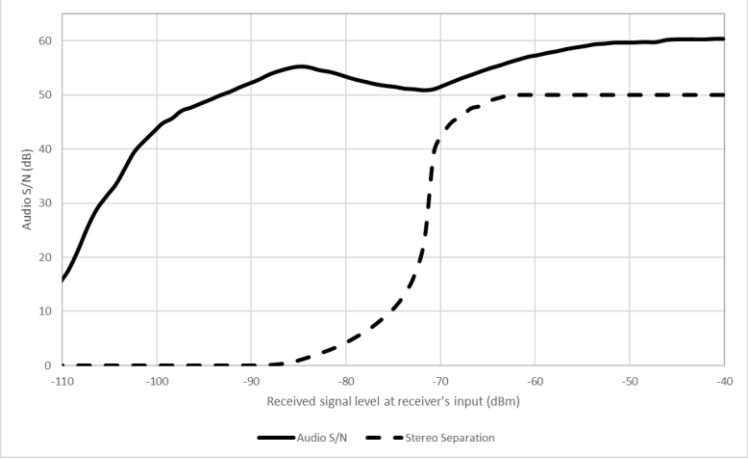

Figure 4-1: Typical radio receiver characteristic versus received signal level

In the case when the interference is increased, as opposed to the signal being decreased, most receivers will not automatically switch to mono and keep decoding the stereo information, resulting in a degraded audio S/N. Some newer receivers use a different approach where the automatic switching to mono decoding are based on the audio S/N quality instead of the received power level, and can therefore switch to mono in the presence of interference.

Since analog system suffers from a slow degradation in reception quality as opposed to digital system with its brick wall effect, it is challenging to establish a clear threshold point. As no clear reference was found and for the purpose of this study, a threshold point corresponding to an audio S/N equal to 30 dB is used. It was observed through-out the laboratory evaluation that beyond this point, receiver loses linearity and stability, causing a quick degradation in the audio quality. This point could also be considered as the end-of-coverage value for the analog FM system.

4.1.2 Self-interference

The dynamic range test is repeated multiple times to evaluate the analog reception performance when different hybrid FM configurations are enabled. Each of these tables shows the performance from an analog FM transmission and from a hybrid FM transmission with the service mode MP1, MP3 and MP11, respectively, at three different injection levels.

The following results are obtained when the desired signal level is -47 dBm. Degradation caused by the addition of digital carriers beside the analog carrier in audio S/N and/or stereo separation, if any, occurs only when the receiver is operating at a signal level capable of yielding full stereo mode. If the desired signal level is decreased to the point where switching to mono mechanism is enabled, i.e. stereo separation lower than 10 dB, the presence of digital carriers no longer affects audio quality.

Table 4-2: Impact of service mode MP1, MP3 and MP11 on analog receivers

Receiver Under Test	Analog		Digital sidebands insertion level						Hybrid FM service mode
			-20 dBc		-14 dBc		-10 dBc		
	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.	
Rx.1A	48.8	51	48.8	51	48.8	51	48.7	51	MP1
			48.5	50	47.1	49	45.8	47	MP3
			39.2	45	33.4	40	31.7	7	MP11
Rx.2A	60.9	39	60.3	39	59.8	39	58.5	34	MP1
			52.8	37	47.7	34	43.3	43	MP3
			37.9	39	32.1	38	27.9	34	MP11
Rx.3A	60.2	46	56.7	46	53.2	50	51.4	52	MP1
			49.7	54	45.6	49	43.6	47	MP3
			38.2	44	33.6	41	30.9	38	MP11
Rx.4A	53.1	35	51.8	35	49.0	35	46.6	35	MP1
			50.2	35	50.6	12	47.4	12	MP3
			44.7	12	39.2	12	35.0	12	MP11
Rx.5A	52.8	58	52.7	58	52.7	58	52.7	58	MP1
			52.6	57	51.9	56	51.1	54	MP3
			39.4	47	33.8	41	29.8	37	MP11
Rx.6A	61.6	N/A	61.2	N/A	60.0	N/A	58.5	N/A	MP1
			60.9	N/A	58.8	N/A	56.7	N/A	MP3
			59.9	N/A	57.2	N/A	53.4	N/A	MP11

* Values in red indicates a significant degradation.

Table 4-3: Impact of service mode MP1, MP3 and MP11 on HD Radio receivers

Receiver Under Test	Analog		Digital sidebands insertion level						Hybrid FM service mode
			-20 dBc		-14 dBc		-10 dBc		
	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.	
Rx.11H	61.5	36	57.8	36	53.0	36	48.8	35	MP1
			49.2	36	42.8	34	40.6	27	MP3
			36.3	35	31.2	29	30.7	23	MP11
Rx.12H	62.9	50	60.3	50	57.7	53	56.6	50	MP1
			52.7	50	49.8	47	49.7	46	MP3
			40.1	44	37.9	42	37.6	42	MP11
Rx.13H	58.7	48	56.1	52	53.3	49	52.2	52	MP1
			49.5	54	45.5	49	43.7	47	MP3
			38.3	45	33.3	40	30.6	39	MP11
Rx.14H	58.6	59	55.9	55	53.3	47	52.1	48	MP1
			49.6	54	45.5	49	43.7	47	MP3
			38.2	45	33.3	40	30.7	39	MP11
Rx.15H	63.0	48	62.2	7	63.7	3	59.4	0	MP1
			61.9	6	57.2	1	57.0	0	MP3
			52.0	5	51.7	1	54.3	0	MP11
Rx.16H	60.5	36	60.4	36	60.2	36	60.1	33	MP1
			58.2	26	56.3	12	57.4	6	MP3
			45.4	11	49.6	2	64.4	0	MP11
Rx.17H	61.3	36	61.0	36	60.9	36	60.5	30	MP1
			58.0	23	56.3	9	60.5	2	MP3
			45.3	8	68.3	0	68.0	0	MP11
Rx.18H	59.7	43	59.3	43	59.1	43	58.7	32	MP1
			56.2	24	55.2	9	59.5	2	MP3
			44.7	8	66.9	0	66.8	0	MP11

* Values in red indicates a significant degradation.

With service mode MP1, only one receiver (Rx.11H) showed minor deterioration in audio S/N quality, with a drop of more than 10 dB when transmission is changed from analog only to hybrid FM at -10 dBc injection and only one receiver (Rx.15H) lost stereo separation. These degradations should have no, or minimal, perceivable impact on the audio quality.

Compared to MP1, service mode MP3 shows more deterioration in audio quality while maintaining an audio S/N above 40 dB. Five receivers suffer performance loss in stereo separation with an injection level of -14 and -10 dBc. Degradations, if any, should have a minimal perceivable impact on the audio quality.

It should be noted that the service mode MP11 is not yet implemented in receivers and transmitters. The FM transmitter was set in a special test mode in order to enable the RF characteristics of this service mode. Subsequent tests do not include service mode MP11. A significant impact on audio S/N is observed compared to service modes MP1 and MP3. With an injection level of -10 dBc, some receivers operate below the threshold point of an audio S/N of 30 dB. At an injection level of -20 dBc, the audio S/N is below 40 dB. This means that even with a strong received power, the audio quality is degraded and therefore impact the main transmission coverage.

It is safe to say that for the near future; the vast majority of radio listening audience will still listen to analog FM over hybrid FM. This may change with receivers being incorporated into cars and consumer education. For this reason, it is

imperative that for a given station, the HD transmission should not negatively affect the audio quality of its analog broadcast. While adjacent and co-channel interference is localized, host interference from HD carriers can potentially affect the station's entire footprint. To be more specific, host interference only affects the analog audio S/N ratio when the receiver is operating in stereo mode. On average, full stereo mode occurs when receive power is above -67 dBm as presented in Table 4-1. Some receivers switch to mono based on audio S/N quality to preserve S/N ratio while sacrificing stereo reception for the entire footprint of the station. The end-of-coverage, as defined for this report, is not affected by host-interference as receivers have completely switched to mono reception. As more HD Radio receivers enter the marketplace, this situation will become less problematic as they will decode the digital signal. An exception to this rule is for live events such as sport description or outdoor concert when the switch to digital must be disabled due to the 8 seconds delay caused by the digital processing time.

4.2 Analog FM and Hybrid FM Interference into Analog FM

The purpose of this test is to determine the FM receiver performance of demodulating the analog portion under various interference scenarios from a single interferer. The test methodology is to measure the baseband audio S/N using the objective method over a range of Desired-to-Undesired (D/U) signal value, where the undesired signal is varied in operating frequency and configured in either analog only or hybrid mode.

The transmission configurations evaluated in the study are analog only and hybrid FM with service mode MP1 and MP3 at an injection level of -10, -14 and -20 dBc. The desired FM signal is set to either -47, -63 or -73 dBm at the receiver input for co-channel and first adjacent channel interference tests, and only -63 and -73 dBm for second and above adjacent channel. While only a portion of these test results is presented, the complete test results are available in Appendix A and raw data can be provided, if requested.

The following sections analyze co-channel, first and second adjacent channel interference scenarios. The analysis uses the analog FM into analog FM test results to first compare with the actual protection ratio and then as benchmark to assess the impact of a hybrid FM transmission over an analog FM.

4.2.1 Co-Channel Interference

Co-channel interference occurs when the desired signal is in presence of an undesired signal operating on the same frequency. According to BPR-3, the protection ratio (D/U) for co-channel interference is 20 dB i.e. the interfering signal must be at least 20 dB lower than the desired signal power inside the protected contour.

The table below shows the average of all receivers' performance at different audio S/N when it is decoding the stereo signal, i.e. stereo separation greater than 10 dB. The complete test results can be found in Appendix A .

Table 4-4: Co-channel average D/U at different audio S/N (stereo decoding)

Audio S/N (dB)	D/U (dB)						
	Desired @ -47 dBm		Desired @ -63 dBm		Desired @ -73 dBm		Maximum Value
	Analog	MP3-10	Analog	MP3-10	Analog	MP3-10	
50	41.6	41.7	41.6	41.8	42.0	42.1	46.9
40	30.8	30.9	30.4	30.4	28.5	28.6	32.5
30	20.8	21.3	20.2	20.5	17.4	18.1	22.4

The following figures show the D/U ratio (dB) at specific audio S/N (dB): 30, 35, 40, 45 and 50 dB. Individual receiver test result is represented by an “x” or an “o” depending if the receiver is operating in stereo or mono mode respectively, i.e. if stereo separation is greater or less than 10 dB separation between the left and right audio channels. The solid line represents the average of all receiver’s performance in presence of an analog and a hybrid FM transmission. For the hybrid FM, only the service mode MP3 with an injection level of -10 dBc is included in the analysis as no degradation is observed and the results should be the same with the other service modes and injection levels.

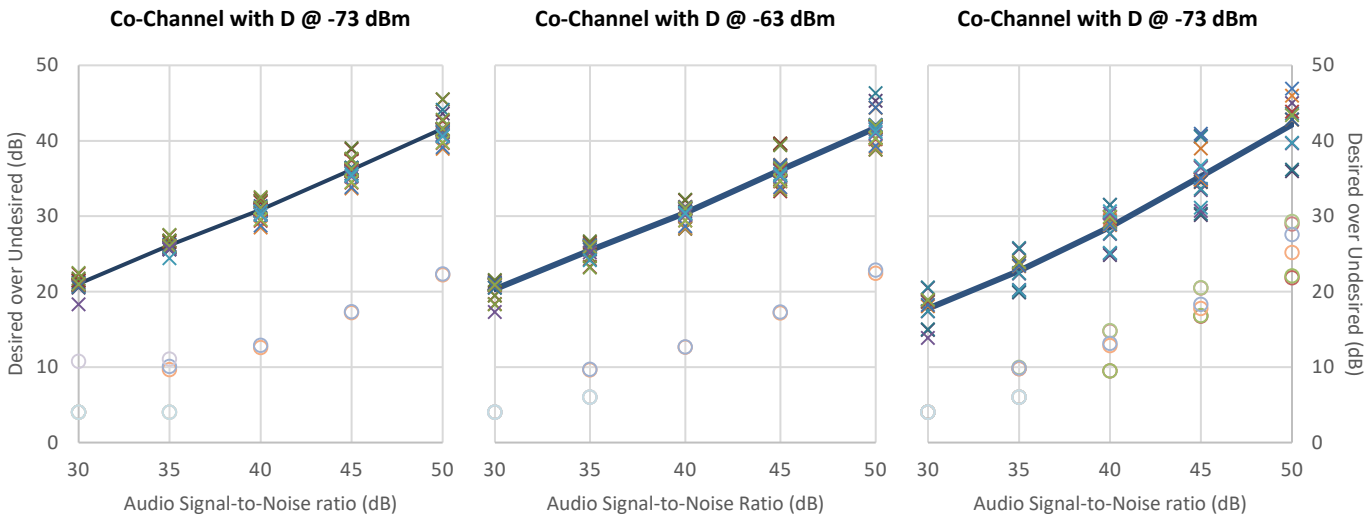

Figure 4-2: Co-channel interference at different desired signal level

It can be observed from the test results that no degradation is caused by a hybrid FM compared to an analog FM. One key information to retain is at a D/U of 20 dB, the protection ratio specified in the BPR-3 for co-channel, the audio S/N is, on average, 30 dB when the receiver is operating in stereo mode.

It was observed through-out the laboratory evaluation that audio quality with a S/N of 30 dB can be considered as the limit of the analog reception. Below this threshold, reception quality becomes unstable and degrades rapidly.

As explained earlier, most receivers’ mechanism to switch from stereo to mono decoding does not work, when the level of interference is increased. With the exception of one radio manufacturer, the process from switching to mono decoding depends only on the received power signal level. In the above tests, the desired signal strength does not change, the receivers demodulate without any issue the stereo signal. While the interference increased, the audio quality decreased without sacrificing stereo decoding and they never switch to mono, even if the audio quality could be qualified as very annoying (CCIR grade 1).

4.2.2 First Adjacent Channel Interference

First adjacent channel interference occurs when the desired signal is in presence of an undesired signal operating on the lower or upper adjacent channels. According to BPR-3, the protection ratio (D/U) for co-channel interference is 6 dB i.e. the interfering signal must be at least 6 dB lower than the desired signal power inside the protected contour.

Due to location of the digital carriers of a hybrid FM transmission, which are located in the first half of their first adjacent channels as shown in Figure 4-3, hybrid FM creates co-channel interference and it should have a significant impact compared to analog FM reception.

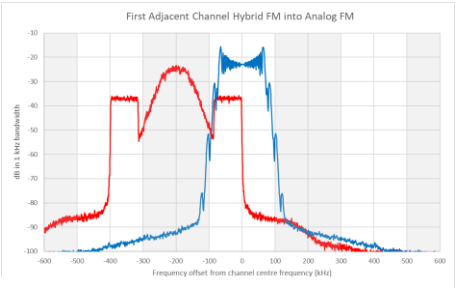

Figure 4-3: First adjacent channel hybrid FM MP3 -10 dBc into analog FM

The table below shows the maximum and average of all receivers' performance at different audio S/N, when it is decoding the stereo signal, i.e. stereo separation greater than 10 dB. The complete test results can be found in Appendix A .

Table 4-5: First adjacent maximum and average D/U at different audio S/N (stereo decoding)

Audio S/N (dB)	Statistics	D/U (dB) D @ -47 dBm				D/U (dB) D @ -63 dBm				D/U (dB) D @ -73 dBm			
		Analog	MP3 -10	MP3 -14	MP3 -20	Analog	MP3 -10	MP3 -14	MP3 -20	Analog	MP3 -10	MP3 -14	MP3 -20
50	Maximum	14.8	30.6	27.7	22.1	16.5	29.2	28.6	19.9	16.6	28.0	27.0	17.5
	Average	12.3	28.2	24.6	18.7	12.8	28.2	24.7	18.3	10.5	26.2	23.8	15.9
40	Maximum	3.4	19.5	15.4	9.5	3.3	19.0	15.2	9.2	3.2	18.5	14.6	8.9
	Average	1.5	17.9	13.9	8.0	0.6	17.4	13.4	7.7	-3.2	15.6	11.9	6.0
30	Maximum	-7.1	9.4	4.6	-1.1	-7.1	8.4	4.4	-1.3	-8.9	7.5	3.7	-2.4
	Average	-14.5	8.1	3.9	-3.1	-15.0	7.4	2.7	-3.4	-16.8	5.1	1.1	-4.9

The above statistic doesn't consider results when receiver is only decoding mono signal. The level of interference for the service mode MP1 is, on average, 0.5 dB less interference than with service mode MP3.

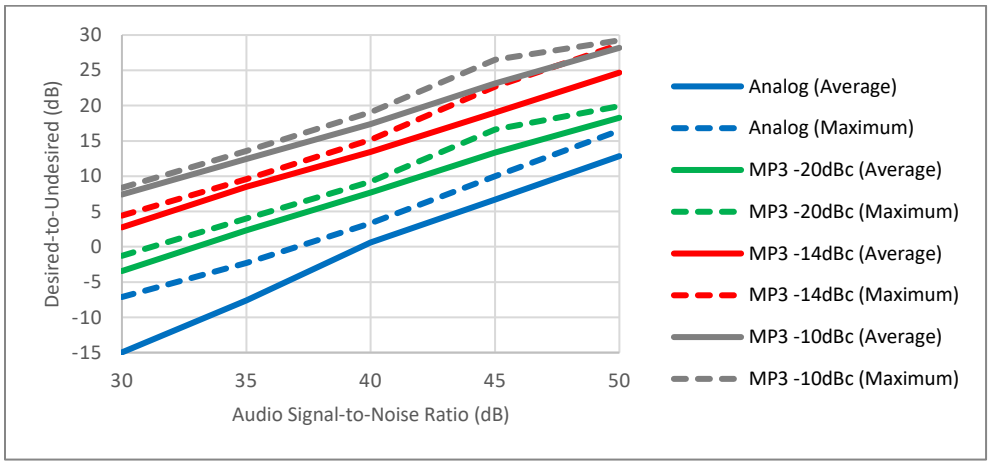

Figure 4-4: Average and maximum first adjacent channel interference

The D/U ratio for first adjacent analog into analog varies depending on the audio content of the undesired signal where rock/dance music will cause more interference than talk radio. The modulation index and mono vs stereo also play a role in the level of interference. In the case of hybrid FM into analog FM, the interference is caused by the digital carriers which have a constant power distribution independent of the content. The D/U ratio varies linearly depending on the injection level of the digital carriers.

From BPR-3, the current protection ratio for first adjacent channel interference is 6 dB. The results demonstrate that when the interference source is analog, this protection ratio is easily met with a D/U ratio of approximately -15 dB, which is 21 dB better than the specification. When the interference is switched to hybrid FM with service mode MP3 at -10 dBc injection level, the D/U ratio for an audio S/N of 30 dB is 7.4 dB for a desired signal set at -63 dBm. The value is 1.4 dB worse than the current protection ratio. For an injection level of -14 and -20 dBc, the D/U ratios are 2.7 and -3.4 dB, respectively, which meet the current protection ratio.

In summary, the current situation where only analog interference is possible, short-spaced stations might not create degradation in service, due to the 21 dB margin (at worst case 13 dB). With the integration of hybrid FM, receiver can withstand up to an undesired hybrid FM signal of 7 to 8 dB, 3 to 4 dB or -3 to -1 dB weaker than the desired signal for an injection level of -10, -14 and -20 dBc, respectively. It leaves no or minor margin with the current protection ratio and these values are at an audio S/N of 30 dB, defined as the end-of-coverage, that does not leave must room beyond this point before the signal quality becomes very annoying.

One scenario that was not studies is how much the coverage available outside the protection ratio would be affected. The further the receivers from the transmitter, the weaker the received signal, where the receivers are more likely to decode only the mono signal and is therefore less affected by the interference.

4.2.3 Second Adjacent Channel Interference

This section mainly discusses about second adjacent channel interference, which is defined as interference from a channel separated by 400 kHz, but it also covers third and fourth adjacent channel interference scenarios. The current protection ratio is only defined for second adjacent channel interference which is -26 dB. This means that within a station's protected contour, no second adjacent channel should be received at more than 26 dB above the protected station signal level. For FM stations located in the third or fourth channel and operating in the same area, BPR-3 recommends co-siting with the difference in signal power not exceeding 20 dB in any direction.

Before showing any results, it is important to mention that receiver performances are all below the protection ratio of -26 dB by a large margin. The limit of the laboratory test setup in terms of undesired FM signal power level is reached before obtaining an audio S/N of 30 dB. Therefore, the following results present the audio S/N value at specific D/U ratios, which are no interference, -16 dB, -26 dB and -36 dB. The S/N ratio results written in red have a stereo separation less than 10 dB which explains the situation where the S/N ratio increases as the interference is increased.

Table 4-6: Second upper adjacent channel interference test results

RUT	Tx Mode	Audio S/N (dB) at specific undesired signal level			
		No Interf.	D/U = -16 dB	D/U = -26 dB	D/U = -36 dB
Rx.1A	Analog	48.0	47.5	45.0	58.0
	MP3-10	48.1	46.4	57.4	49.9
Rx.2A	Analog	57.6	57.5	56.8	52.7
	MP3-10	57.6	53.2	45.3	35.7
Rx.3A	Analog	57.0	57.0	56.4	52.6
	MP3-10	57.0	53.0	45.2	35.8
Rx.4A	Analog	47.1	46.8	45.0	40.0
	MP3-10	46.9	46.5	42.1	34.2
Rx.5A	Analog	51.4	51.0	48.3	39.7
	MP3-10	51.3	48.4	41.4	31.5
Rx.6A	Analog	59.5	59.2	59.1	53.2
	MP3-10	59.4	59.0	56.6	45.8
Rx.11H	Analog	57.2	57.1	56.7	54.8
	MP3-10	57.0	54.7	47.5	37.8
Rx.12H	Analog	57.7	57.6	57.0	53.2
	MP3-10	57.6	53.5	45.3	36.2
Rx.13H	Analog	52.3	52.5	52.5	48.7
	MP3-10	52.2	50.5	44.5	35.3
Rx.14H	Analog	56.2	56.2	54.2	48.1
	MP3-10	56.3	52.8	45.0	35.5
Rx.15H	Analog	55.7	55.8	55.4	52.0
	MP3-10	55.7	52.6	47.0	38.7
Rx.16H	Analog	57.8	57.7	55.5	47.1
	MP3-10	57.8	53.4	45.1	42.9
Rx.17H	Analog	57.3	57.3	54.5	47.0
	MP3-10	57.3	54.2	47.5	43.1
Rx.18H	Analog	57.3	57.0	53.9	43.9
	MP3-10	57.1	53.5	45.8	43.3

* Value in red indicated a stereo separation less than 10 dB (mono).

The results in Table 4-6 indicate that at a D/U ratio of -26 dB, which is the current protection ratio, the minimum demodulated audio S/N ratio observed is 45 dB when the interference is analog only and 41 dB when the interference is hybrid with service mode MP3 and an injection level of -10 dBc. The average degradation in S/N ratio between no interference and a D/U of -26 dB is 2 dB with an analog interference and 10 dB with a hybrid interference. This difference in performance is due to the out-of-band emissions from the hybrid FM transmitter being higher than the analog transmitter as shown in Figure 4-5.

Since the out-of-band emissions generated by the transmitters used in this study are lower, by a large margin, than the emission limits specified in BETS-6, it was decided to re-test a sample of 4 receivers with the out-of-band emissions artificially increased to -80 dBc. For that particular test, a white random noise generator signal level is adjusted and combined with the undesired signal to obtain out-of-band emissions at 80 dB below the analog carrier, measured in an RBW of 1 kHz as shown in Figure 4-5.

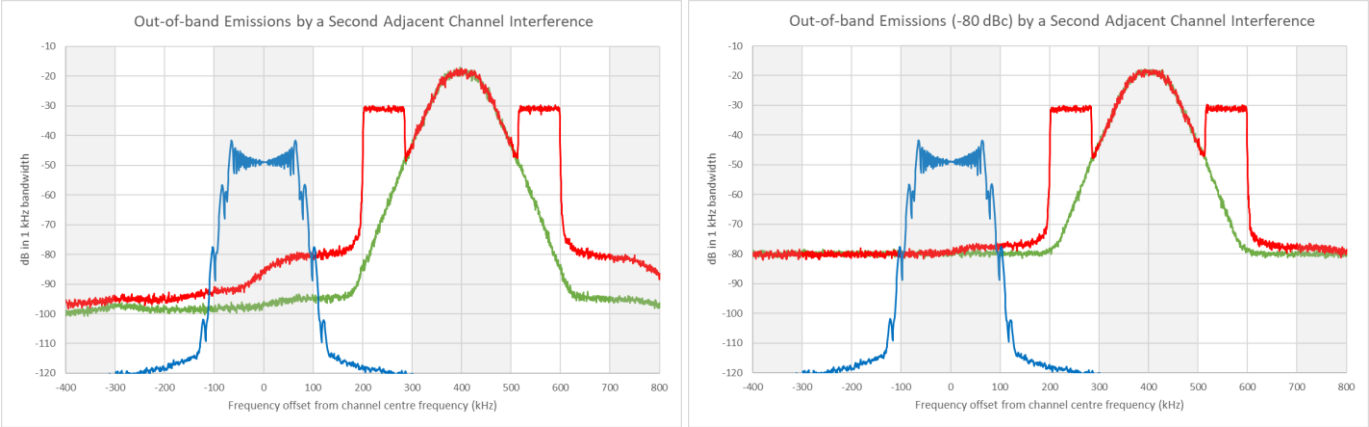

Figure 4-5: Out-of-band emissions falling in-band the desired signal

When artificially increasing the out-of-band emissions of the undesired signal to -80 dBc, it creates noise that falls in-band of the desired signal. For a D/U = -16 dB, -26 dB or -36 dB, the in-band noise level created by the undesired signal is equivalent of having a C/N = 41 dB, 31 dB or 21 dB where the noise is measured in 200 kHz BW.

Table 4-7: Second upper adjacent channel with out-of-band emissions set to -80 dBc

RUT	Tx Mode	Audio S/N (dB) at specific undesired signal level			
		No Interf.	D/U = -16 dB	D/U = -26 dB	D/U = -36 dB
Rx.2A	Analog	57.7	50.4	41.2	31.4
	MP3-10	57.5	49.2	39.9	30.0
	Equivalent C/N	**57.6**	**49.4**	**40.0**	**30.1**
Rx.3A	Analog	57.2	50.2	41.1	31.4
	MP3-10	57.1	49.1	39.7	30.0
	Equivalent C/N	**57.0**	**49.1**	**39.8**	**29.9**
Rx.4A	Analog	46.7	45.8	41.4	32.8
	MP3-10	46.9	45.6	40.3	31.4
	Equivalent C/N	**46.7**	**45.7**	**40.3**	**31.6**
Rx.17H	Analog	57.4	51.3	42.3	51.8 (mono)
	MP3-10	57.3	50.4	41.7	51.3 (mono)
	Equivalent C/N	**57.3**	**50.6**	**41.5**	51.0 (mono)

* Value in red indicated a stereo separation less than 10 dB (mono).

The results presented in Table 4-7 confirm that only the out-of-band emissions from the interferer transmitter affects reception at N+2.

Assuming that an FM receiver required a C/N = 20 dB for demodulating a stereo audio signal with a baseband audio S/N equal or greater to 30 dB. And, a station located in the second or above adjacent channel is transmitting with their out-of-band emissions near the mask limits of -80 dBc. The minimum D/U in this situation is -37 dB meaning that in that worst case scenario, the interferer can be 37 dB higher than the desired signal. In reality, most of the transmitters should have lower out-of-band emissions, so the interferer would need to be 37 dB higher than the desired signal before affecting the reception.

Again, the protection ratio of -26 dB is conservative, leaving a margin of more than 10 dB. That margin is reduced for the case of a lower second adjacent channel (N-2) where some receivers have performance issue due to intermodulation as shown in Table 4-8.

Table 4-8: Second lower adjacent channel interference with intermodulation problem

RUT	Tx Mode	Audio S/N (dB) at specific undesired signal level			
		No Interf.	D/U = -16 dB	D/U = -26 dB	D/U = -36 dB
Rx.5A	Analog	50.2	44.5	35.7	27.1
	MP3-10	51.3	42.7	33.8	24.0
Rx.11H	Analog	56.5	56.8	56.9	54.3
	MP3-10	58.0	46.8	46.4	38.3
Rx.12H	Analog	57.0	56.6	56.2	52.9
	MP3-10	57.3	43.8	43.5	36.5
Rx.16H	Analog	57.8	42.1	43.5	42.0
	MP3-10	57.9	42.7	44.8	42.7
Rx.17H	Analog	57.2	44.0	43.7	40.6
	MP3-10	57.1	45.6	45.3	40.9
Rx.18H	Analog	57.1	39.6	40.1	43.1
	MP3-10	57.1	39.3	41.1	42.8

* Value in red indicated a stereo separation less than 10 dB (mono).

This degradation is due to intermodulation products in the receiver. For these receivers, intermodulation can occur, whether the undesired is analog or hybrid, but it can be more significant for hybrid as the signal has a wider bandwidth than analog therefore affecting third and fourth adjacent channels. Since intermodulation is due to receiver design and only a small sample of the receivers tested suffered from this distortion, it will not be further discussed in this report.

In summary, without considering intermodulation issue with a few receivers, the receivers' performance in presence of a second adjacent channel is the same whether the undesired signal is analog FM or hybrid FM. The current protection ratio of -26 dB offers margin to allow short-spaced stations without any degradation in service, but it could create some degradation for receivers having intermodulation problem.

5 Digital Performance Test Results

This section summarizes the test procedures and results on the ability for the receiver to decode the digital signal of a hybrid FM transmission under different test conditions. These include conditions in the presence of random Gaussian noise with symmetrical and asymmetrical sidebands, as well as those with adjacent channel interference.

5.1 Susceptibility to Random Noise Impairment

The purpose of these tests is to determine the robustness of the digital portion of a HD Radio receiver to random noise impairment. The hybrid FM desired signal is adjusted to two RF levels: Moderate (-63 dBm) and Weak (-73 dBm). The noise level is increased until TOA is reached, and the C/N value is recorded.

The C/N corresponds to the ratio between the analog carrier signal level and the noise signal level measured in 200 kHz bandwidth. Every C/N measurement in this section is relative to the analog carrier. Since the digital carriers signal level is also relative to the analog carrier, the C/N result can be converted to obtain a value relative to digital carrier where the noise signal level is also measured in the digital bandwidth by using this formula:

$$Digital\left(\frac{C}{N}\right)_{dB} = Analog\left(\frac{C}{N}\right)_{dB} + (Sideband\ Injection)_{dBc} + 1.6$$

Where Sideband Injection is either -10, -14 or -20.

The following table contains the correction factors to convert C/N relative to analog to C/N relative to digital.

Table 5-1: C/N conversion factor from analog to digital C/N

Sideband injection level (dBc)	-20	-14	-10
Conversion factor (dB)	-18.4	-12.4	-8.4

5.1.1 Symmetrical Sidebands

The first evaluation of random noise is performed with the hybrid FM configured with the same lower and upper sidebands injection levels i.e. symmetrical. The service mode is set to MP3 with two additional audio streams, HD2 and HD3, encoded on logical channel P1 and P3 respectively. These logical channels have different system performance as they have different encoding schemes. More technical information can be found in section 2.2.

The test results presented in the following table are for a desired analog carrier signal level set to -63 dBm at the receiver's RF input. The -73 dBm test results are in the Appendix B which are similar to those at -63 dBm.

Table 5-2: Susceptibility to random noise with symmetrical sidebands

Receiver Under Test	C/N (dB) [ref. analog carrier]					
	Injection level = -10 dBc		Injection level = -14 dBc		Injection level = -20 dBc	
	HD2	HD3	HD2	HD3	HD2	HD3
Rx.12H	11.2	12.5	14.9	16.3	21.1	23.1
Rx.13H	10.8	12.0	15.0	16.4	21.0	23.0
Rx.14H	11.1	12.3	14.9	16.4	21.2	23.2
Rx.15H	10.8	12.1	14.9	16.1	21.1	23.0
Rx.16H	10.8	12.1	14.6	15.7	20.9	22.8
Rx.17H	10.8	11.9	15.0	16.1	21.0	22.7
Average	10.9	12.2	14.9	16.2	21.0	23.0
Digital C/N (dB) Average	2.5	3.8	2.5	3.8	2.6	4.6

All of the HD Radio receivers performed identically during these tests. This is expected, as the signal processing functionality for HD Radio is determined by coding and modulation schemes specified in the NRCS-5 standard. Using the conversion factor, the average digital C/N at TOA for the HD2 and HD3 stream is 2.5 dB and 3.8 dB respectively with some performance issue at the injection level of -20 dBc for HD3 stream encoded on logical channel P3.

5.1.2 Asymmetrical Sidebands

The HD Radio technology uses an upper and lower sideband to transmit digital audio. The information in these sidebands is arranged and encoded in such a way that the audio stream can be decoded with only one sideband. The system allows the transmission of both sidebands configured at different injection levels, i.e. asymmetrical. This capability is used to mitigate interference where significant first adjacent channel interference is possible such as short-spaced channel allotment. In these cases, the sideband which could interfere with the adjacent channel can be reduced to -14 or -20 dBc while the other sideband is transmitted at -10 dBc. Any value between -20 dBc and -10 dBc is valid for either of the sidebands.

The results shown in this section are obtained by configuring the desired transmitter to operate in service mode MP3 and the lower sideband set to -20 dBc and the upper sideband to -10 dBc. The analog carrier signal level is adjusted to -63 dBm at the receiver's input.

Table 5-3: Susceptibility to random noise with asymmetrical sidebands

Receiver Under Test	C/N [ref. analog carrier] (dB)	
	HD2	HD3
Rx.12H	14.3	17.7
Rx.13H	14.3	17.9
Rx.17H	14.3	17.7

Comparing the results with symmetrical sidebands test results at an injection level of -10 dBc, the receivers can decode only one sideband with a degradation of around 3.4 dB for HD2 and 5.6 dB for HD3 in required C/N. Since HD Radio upper and lower digital sidebands transmit the identical data, for symmetrical sideband case, receiver can combine the two sidebands by power and obtain a 3 dB C/N gain. The asymmetrical case does not have this signal processing gain and the C/N performance should degrade by at least 3 dB.

5.2 Input Signal RF Dynamic Range

This section looks at the ability of the HD Radio receivers to receive very weak signals in the absence of impairments or interference. For these tests, the desired hybrid signal is configured with service mode MP3 and the injection level set to either -20 dBc, -14 dBc or -10 dBc. The minimum RF signal level is determined by decreasing the RF signal level at the receiver's input until the TOA level is reached, the injection level is then changed and the test repeated.

Table 5-4: HD Radio minimum signal level sensitivity

Receiver Under Test	Minimum signal level (dBm)						
	Analog @ Audio S/N = 30 dB	Injection level = -10 dBc		Injection level = -14 dBc		Injection level = -20 dBc	
		HD2	HD3	HD2	HD3	HD2	HD3
Rx.12H	-106.2	-96.3	-94.4	-92.4	-91.4	-85.9	-83.9
Rx.13H	-104.4	-100.4	-99.4	-96.5	-95.5	-90.5	-89.0
Rx.14H	-107.0	-98.4	-97.4	-94.5	-92.4	-88.0	-86.9
Rx.15H	-104.3	-95.4	-94.4	-91.4	-90.5	-85.9	-84.0
Rx.16H	-104.8	-102.4	-101.4	-97.5	-96.4	-91.5	-90.5
Rx.17H	-103.6	-102.4	-101.4	-97.5	-96.4	-91.5	-90.6

Variation observed in the minimum RF signal test results is explained by different RF front-end design. In real life environment, the performance should be higher (worst) due to the contribution of external noise and interference, but the difference in performance between each transmission mode (analog vs digital) will remain the same.

By comparing the HD Radio receiver's performance between the required minimum signal power to decode digital signal versus that to demodulate the analog carrier with an audio quality of 30 dB in mono mode, it can be observed that the digital reception will failed before reaching the end-of-coverage for analog reception. This confirms that the HD Radio service coverage area for any FM broadcasting stations will be smaller and contained within its analog coverage footprint.

5.3 Analog FM and Hybrid FM Interference into Hybrid FM

This section analyzes the results obtained when reception of a hybrid FM signal is subjected to co-channel or adjacent channel interference. The desired hybrid FM signal is set to service mode MP3 with an injection level of -10 dBc. The signal level is set to -73 dBm at the receiver's input, referenced to the analog carrier, and the interfering signal is slowly increased until TOA is achieved. The calculated D/U ratio, relative to the analog carrier, is recorded.

5.3.1 Co-Channel Interference

Co-channel interference occurs when the desired signal is in a presence of another FM signal operating on the same frequency. The current Canadian protection ratio for analog FM transmissions state that the interfering signal must be 20 dB lower than the desired signal inside of the protected contour.

Section 4.2.1 demonstrates that D/U for co-channel FM signal into FM signal is between 22 and 16 dB at an audio S/N of 30 dB independent of the FM signal being analog or hybrid. In the case of analog FM into hybrid FM, the undesired signal level required to affect digital reception would have to be much higher. Therefore, affecting the desired analog reception before any degradation could be observed with the digital reception.

In the case of hybrid FM into hybrid FM, the digital carriers of the undesired signal appear as noise like interference into the desired digital carriers. With that notion, the D/U ratio can be calculated using C/N test results. The worst-case scenario being where the desired hybrid FM signal is set with an injection level of -20 dBc and the undesired signal set to -10 dBc. If the protection ratio of 20 dB is respected, the digital carriers of the undesired signal will still be 10 dB below the desired digital carriers. From the results in section 5.1.1, the average digital C/N at TOA, with an injection level of -20 dBc, for the HD2 and HD3 streams encoded in P1 and P3 respectively is 2.6 dB and 4.6 dB. The required D/U in order to affect digital reception is 12.6 dB and 14.6 dB for HD2 and HD3 respectively, leaving a margin of at least 5.4 dB compared to the 20 dB protection ratio for analog reception.

If the analog protection ratio is respected, the digital reception will not be affected; therefore, it was decided not to perform these measurements.

5.3.2 First Adjacent Channel Interference

First adjacent channel interference is when an undesired signal is centered 200 kHz from the centre of the desired channel. The current Canadian protection ratio states that the interfering signal level must be at least 6 dB lower than the desired signal inside its protected contour.

Hybrid FM transmission occupies more frequency bandwidth than a standard FM channel of 200 kHz. Its digital subcarriers are located in the first half of its upper and lower first adjacent channels. The analog portion of the first adjacent channel interfering signal falls in-band to one of the desired digital sidebands acting as co-channel interference. It is demonstrated in Section 5.1.2, which deals with asymmetrical sidebands, the capability of HD Radio receiver to decode the digital content from a single sideband with a small 3 to 5 dB C/N degradation. Due to this robustness, it is unnecessary to test the case of single first adjacent interference as it will not cause the receiver to fail.

In the rare case where a lower and an upper first adjacent signal interfere with the desired hybrid FM signal, each digital sideband could become impaired by the analog carrier. While this situation could be difficult to predict and could only affects a small region, it was observed that if both analog interferers are at a D/U = 6 dB, the digital reception of a hybrid FM with service mode MP3 and an injection level of -10 dBc will not work. Furthermore, having only one interferer at a D/U of 6 dB, the D/U of the other interferer needs to be greater than 14 dB for the successful digital reception.

5.3.3 Second Adjacent Channel Interference

Second adjacent channel interference refers to the analog portion of the desired and undesired signals being 400 kHz apart. Due to the digital portion of both the desired and undesired signals falling outside the 200 kHz bandwidth the upper sideband of one digital signal and the lower sideband of the second adjacent digital signal become immediately adjacent. Current regulations in Canada specify that a second adjacent channel signal level must be no more than 26 dB above the desired signal level within the protected contour.

As explained in section 4.2.3, the transmitters used in this study have relatively low out of band emissions. For this evaluation and to ease the analysis, it was decided to artificially increase the interfering signal out-of-band emissions to -85 dB relative the analog carrier signal level measured in 1 kHz resolution bandwidth.

The hybrid FM signal is configured with service mode MP3 at an injection level of -10 dBc. The signal level is set to -73 dBm at the receiver's input. For other injection levels, obtained D/U ratios for -10 dBc can be scaled linearly (in dB).

Table 5-5 presents the D/U ratios at TOA for the streams HD2 and HD3 encoded in logical channels P1 and P3 respectively. The lower or upper second adjacent channel interference is either an analog FM or a hybrid FM.

Table 5-5: Second adjacent channel interference test results

Receiver Under Test	D/U ratio (dB) at TOA where D = -73 dBm							
	Analog FM				Hybrid FM (MP3, -10 dBc)			
	N-2		N+2		N-2		N+2	
	HD2	HD3	HD2	HD3	HD2	HD3	HD2	HD3
Rx.12H	-51.1	-50.2	-51.1	-50.1	-47.9	-46.9	-48.7	-46.8
Rx.13H	-52.1	-50.1	-52.0	-50.1	-48.8	-46.8	-48.8	-46.8
Rx.17H	-50.2	-49.2	-51.2	-50.2	-41.8	-30.8	-46.9	-30.8

* Value in red indicated intermodulation issue.

Table 5-5 shows that when the second adjacent interfering signal is analog only, the D/U ratio required to decode digital content is approximately -50 dB, which is more than 24 dB better than the current protection ratio. This indicates there should be absolutely no interference problem. The D/U ratio depends on the level of the out-of-band emissions from the transmitter; in this case, it was fixed to -85 dBc, which is close to the limit permitted by the mask.

When the interfering signal is hybrid FM, the out of band emissions from the undesired signal are higher, which explains the small performance different between analog and hybrid interference. The D/U ratio for second adjacent interference, required to decode HD2 and HD3, is approximately -48 dB and -47 dB respectively. A D/U ratio higher than these values is likely caused by intermodulation products created within the receiver.

Receiver Rx.17H appears to suffer from intermodulation. The D/U ratio necessary to decode HD2 is approximately -41.8 dB when the interference signal is at N-2. If the injection level of the desired signal was set to -20 dBc, the required D/U would then be -31.8 dB. When decoding P3 subcarriers, the D/U ratio for demodulation increases to -30.8 dB for both lower and upper second adjacent channels, and -20.8 dB if the injection level was set to -20 dBc. It no longer meets the -26 dB protection ratio. Since intermodulation issues are due to receiver design as opposed to a limitation of the system design. Therefore, intermodulation products issue will not be analyzed further in this study.

6 Coverage Simulations

This section presents coverage simulations to demonstrate the impact of hybrid FM over existing analog FM. The simulations are performed with the software CRC-COVLAB and mainly cover the case for first adjacent channel interference, where short-spacing exists between stations.

Simulation results presented in this section used either the F curves propagation model or the CRC Predict v2.07 model with elevation and land cover data for a more realistic simulation. Both models are using the location and time availability set to 50 % and 50 % for the desired signal, and 50 % and 10 % for the undesired signal. The receiving interpreter is the total field strength in dBµV/m with an omnidirectional antenna at a height of 10 meters.

The D/U ratios obtained in section 4.2.2 are used to establish the interfering zone for the simulation.

Table 6-1: First adjacent channel interference into analog FM - D/U ratios

Audio S/N (dB)	D/U (dB) where D @ -63 dBm			
	Analog	MP3 -20dBc	MP3 -14dBc	MP3 -10dBc
40	1	7	13	17
30	-15	-3	3	7

The following scenario covers the case where a desired FM transmission has four FM stations operating in its lower and upper first adjacent channels and short-spaced. The following table provides transmission information for each station and the short-spaced distance between them.

Table 6-2: Coverage scenario transmission information

	Desired Signal	Undesired #1	Undesired #2	Undesired #3	Undesired #4
Station name	CHKX	WNED	CKGE	CIBU	CHRW
Location	Hamilton, ON	Buffalo, US	Oshawa, ON	Wingham, ON	London, ON
GPS coordinates	43° 12’ 21” N 79° 43’ 49” W	42° 38’ 15” N 78° 46’ 06” W	43° 57’ 15” N 78° 48’ 23” W	44° 05’ 26” N 81° 12’ 25” W	42° 59’ 09” N 81° 14’ 48” W
Frequency	**94.7 MHz**	**94.5 MHz**	**94.9 MHz**	**94.5 MHz**	**94.9 MHz**
Class	C1	C1	B	C1	A
EHAAT	140 m	220 m	148 m	215 m	107 m
ERP	100 kW	96 kW	50 kW	75 kW	6 kW
Protected contour (54 dBµV/m) distance (km)		*47 km*	*73 km*	*74 km*	*49 km*
Interfering contour (48 dBµV/m) distance (km)		*129 km*	*107 km*	*111 km*	*58 km*
Minimum separation distance		176 km	180 km	185 km	107 km
Distance from the desired transmitter		101 km	112 km	155 km	126 km
Short-spaced distance		**75 km**	**68 km**	**30 km**	**-19 km**

The protected contour distance is calculated using the antenna gain and EHAAT in the direction of the undesired station and vice-versa for the interfering contour.

The interfering zone represented by the red shading is found by using the F curves propagation model and the current protection ratio of 6 dB for the first adjacent channel.

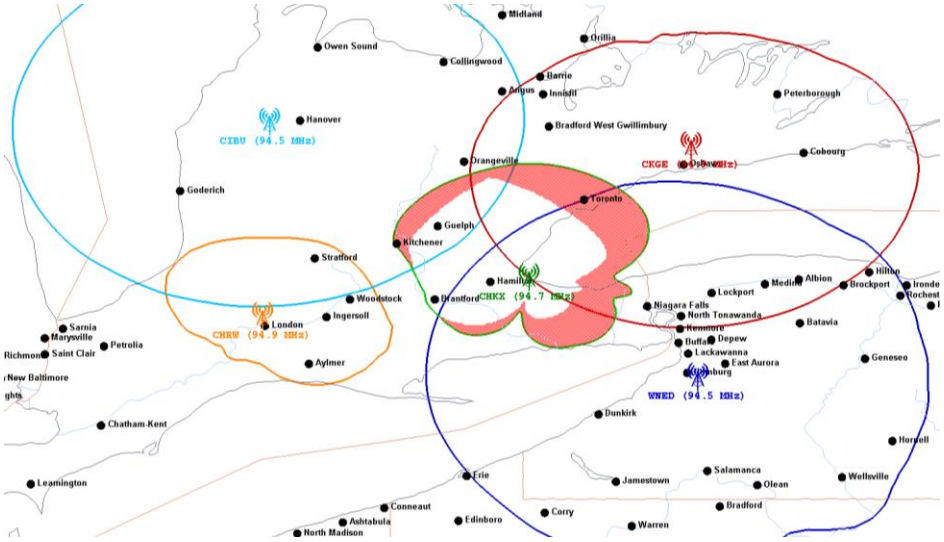

Figure 6-1: First adjacent interference study using F curves

Stations CIBU and CHRW (undesired #3 and #4) can be removed from the following simulation scenario as interference from them to the desired station is not possible due to terrain topography. The following figures show simulations with only interference from CKGE and WNED (undesired #1 and #2) but using a D/U ratio of -15 dB as the interfering zone represented by the dark blue shading. The pale blue shading represents the region where the D/U is between 1 and -15 dB, i.e. an average audio S/N between 40 and 30 dB.

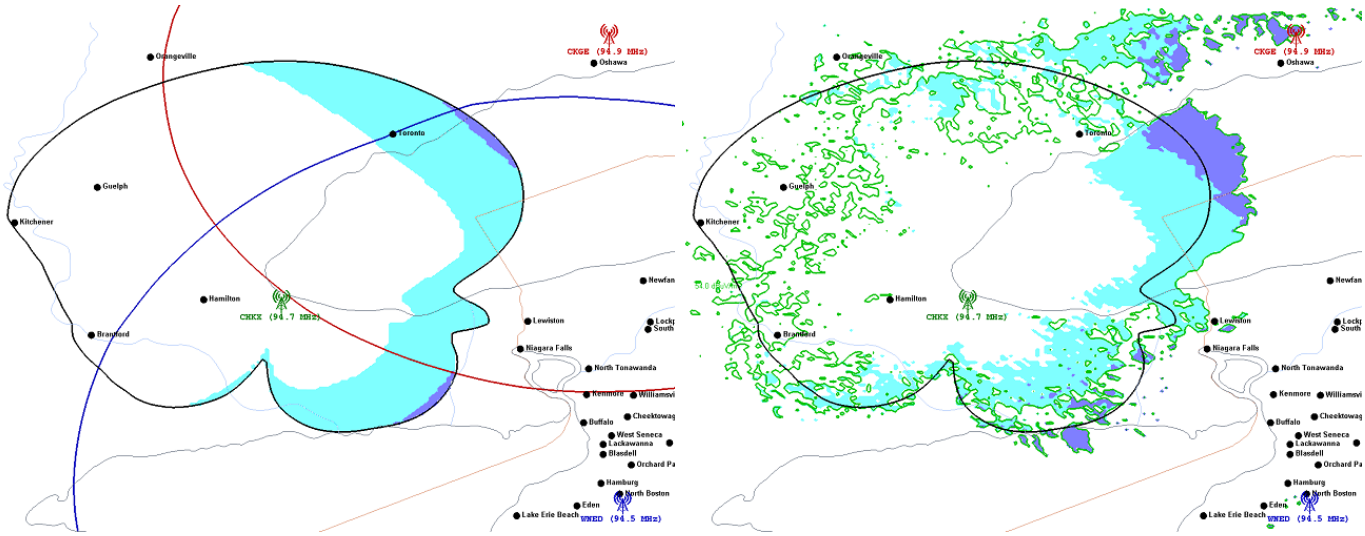

Figure 6-2: First adjacent analog FM into analog FM interference simulation

The above simulations demonstrate that with today's receiver performance, i.e. an average D/U ratio of -15 dB, it is possible to operate analog FM first adjacent channel stations short-spaced without creating noticeable degradation in service.

Doing the same simulation but setting the interfering zone for a D/U of -3 dB (red shading) therefore representing a hybrid FM interfering signal with service mode MP3 at -20 dBc injection level. The orange shading is the region where the D/U ratio is between 7 and -3 dB, i.e. an average audio S/N between 40 and 30 dB.

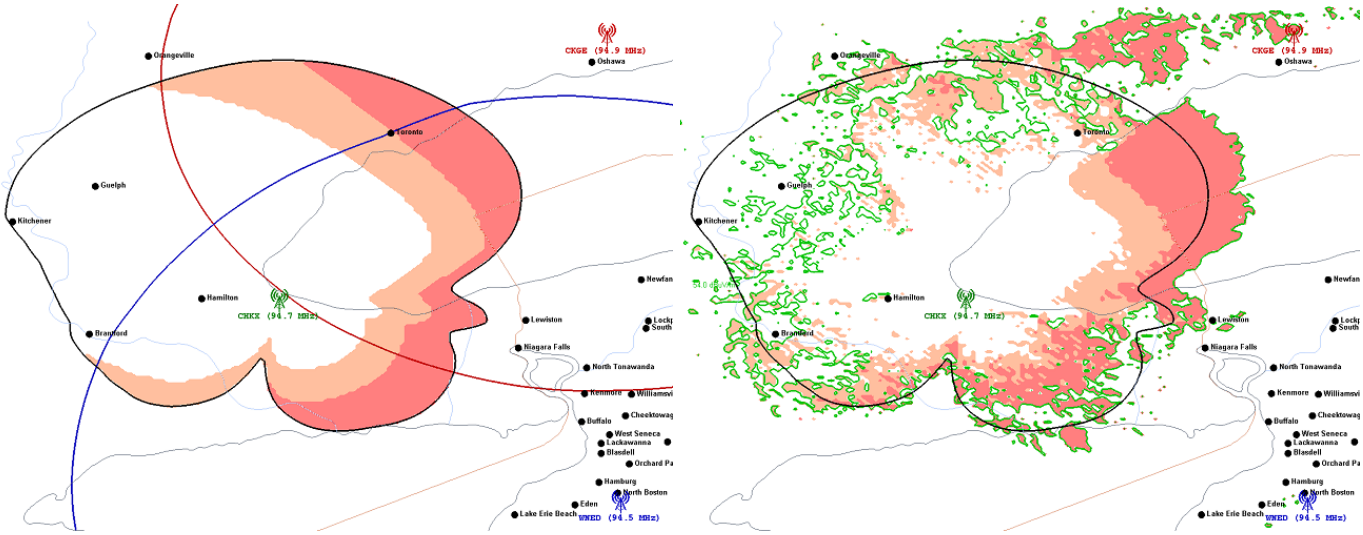

Figure 6-3: First adjacent hybrid FM (MP3 -20dBc) into analog FM interference simulation

The following figures show the interfering zone (green shading) set to 3 dB representing a hybrid FM interfering signal with service mode MP3 at -14 dBc injection level. The orange shading is the region where the D/U ratio is between 13 and 3 dB, i.e. an average audio S/N between 40 and 30 dB.

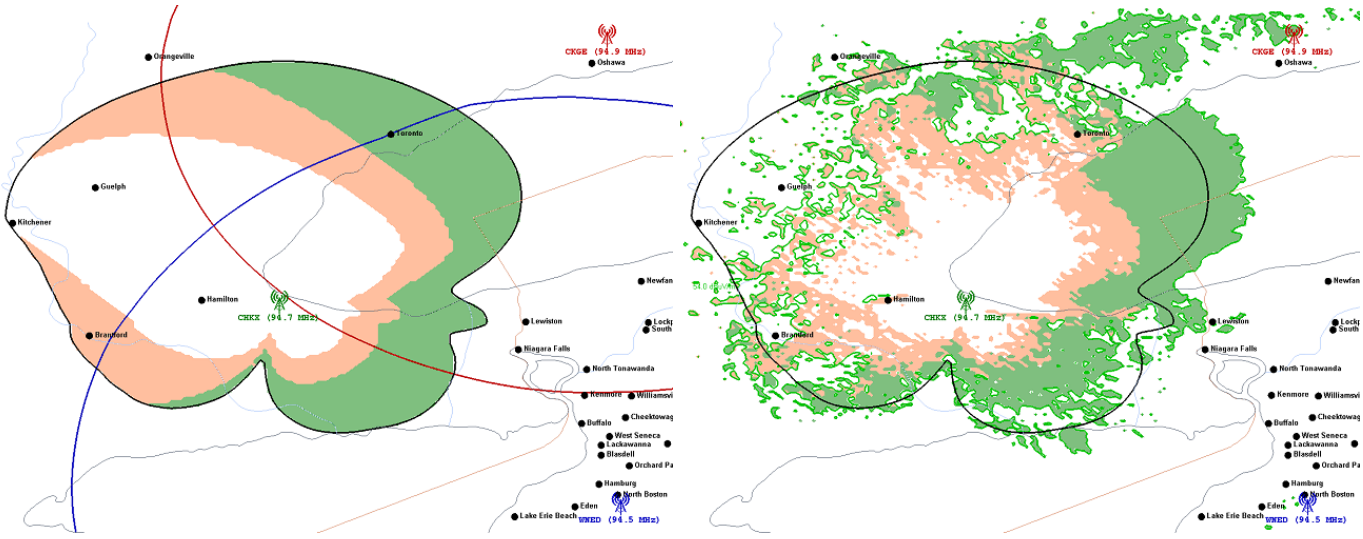

Figure 6-4: First adjacent hybrid FM (MP3 -14dBc) into analog FM interference simulation

Finally, representing a hybrid FM interfering signal (purple shading) with service mode MP3 at -10 dBc injection level, the interfering zone is set to 7 dB. The orange shading is the region where the D/U ratio is between 17 and 7 dB, i.e. an average audio S/N between 40 and 30 dB.

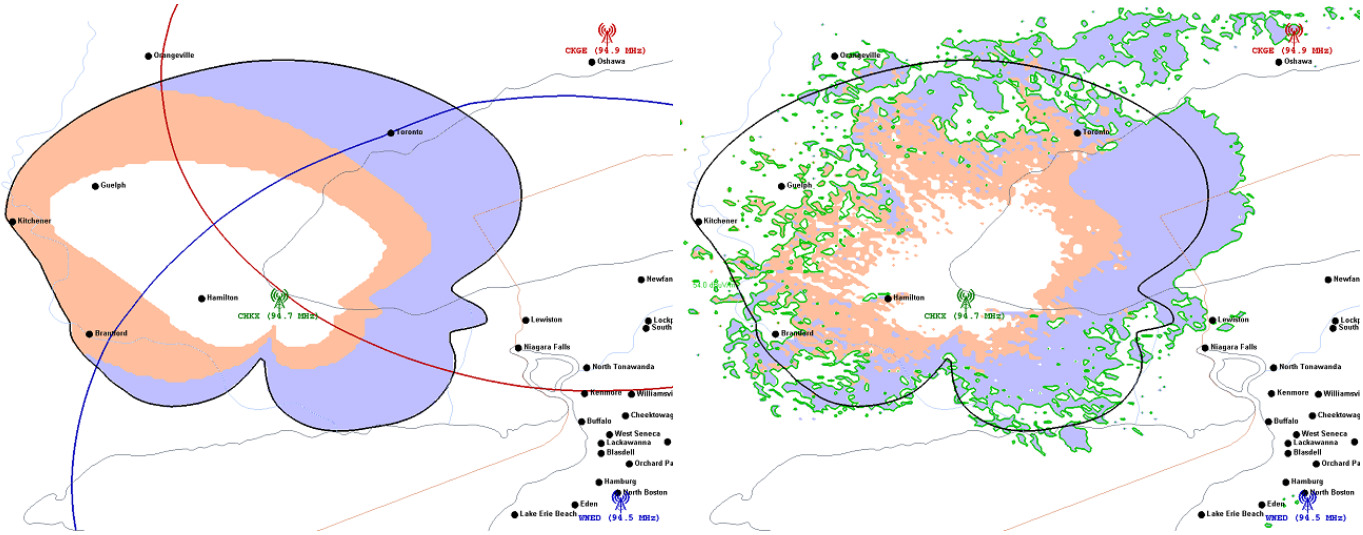

Figure 6-5: First adjacent hybrid FM (MP3 -10dBc) into analog FM interference simulation

In summary, the following figures only show D/U regions that give an average audio S/N = 30 dB or below:

- Blue: Analog interferer; D/U lower than -15 dB.
- Red: Hybrid MP3 -20 dBc interferer; D/U lower than -3 dB.
- Green: Hybrid MP3 -14 dBc interferer; D/U lower than 3 dB.
- Purple: Hybrid MP3 -10 dBc interferer; D/U lower than 7 dB.

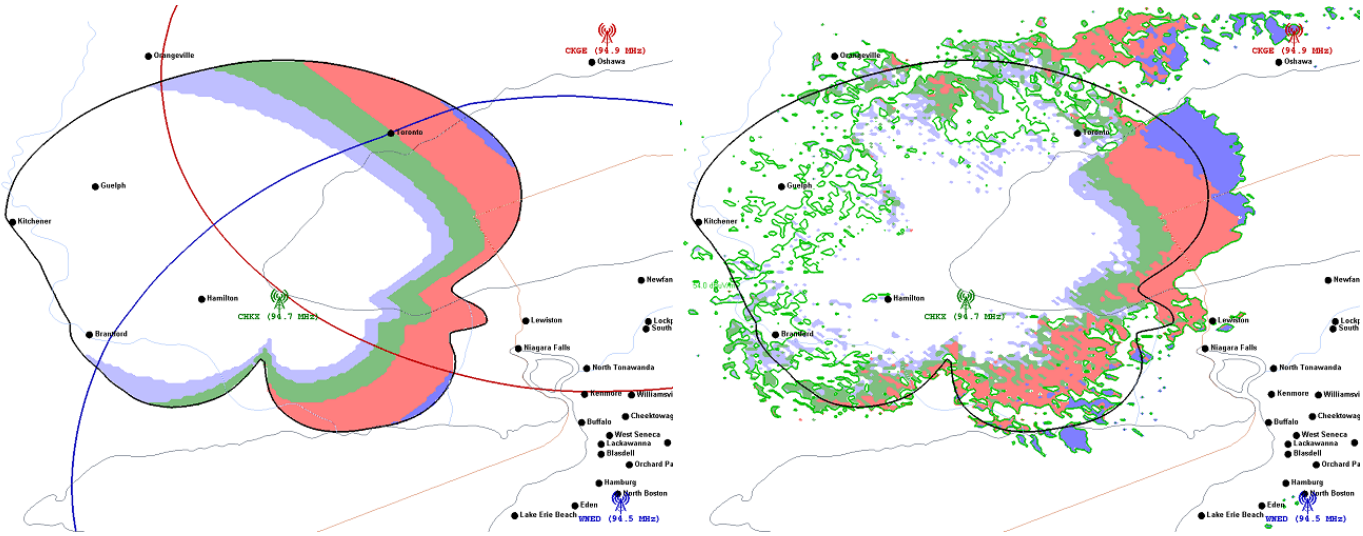

Figure 6-6: First adjacent interference simulation at different D/U ratios

7 Summary of Measurement Results and Conclusions

The study was done in two phases:

1. Analog FM and HD Radio receivers' performance evaluation to demodulate the analog carrier in different test conditions such as co-channel and adjacent channel interference as well as self-interference. The desired signal being either an analog FM or a hybrid FM.
2. HD Radio receivers' performance evaluation to decode the digital transmission in presence of noise and interference.

7.1 Summary of Measurement Results

In order to evaluate the analog signal, the demodulated audio signal was quantified using an objective methodology as opposed to a subjective evaluation which could be more precise but more time consuming. Since analog system does not have a clear point of failure, it was established during the study that the threshold point is equivalent to an audio S/N equal to 30 dB, which can be considered near the end-of-coverage for the analog FM system.

Using an audio S/N = 30 dB as reference point, the summary of the measured D/U in different test scenarios at a received signal level equivalent to the protected contour (54 dBµV/m) is as follows:

- Co-channel analog FM (or hybrid FM) into analog FM:
  - Average D/U = 20.5 dB, maximum D/U = 21.5 dB;
  - The performance is the same regardless of the interference being analog FM or hybrid FM.
- First adjacent channel:
  - Analog FM into analog FM:
    - Average D/U = -15.0 dB, maximum D/U = -7.1 dB;
    - Performance varies depending on the interferer's audio content and modulation index.
  - Hybrid FM (service mode: MP3; injection level: -20 dBc) into analog FM:
    - Average D/U = -3.4 dB, maximum D/U = -1.3 dB;
  - Hybrid FM (service mode: MP3; injection level: -14 dBc) into analog FM:
    - Average D/U = +2.7 dB, maximum D/U = +4.4 dB;
  - Hybrid FM (service mode: MP3; injection level: -10 dBc) into analog FM:
    - Average D/U = +7.4 dB, maximum D/U = +8.4 dB;
- Second adjacent channel analog FM (or hybrid FM) into analog FM:
  - The performance depends on the level of the out-of-band emissions of the interfering signal.
  - In theory, the minimum D/U is -37 dB if the out-of-band emission of the interferer are at -80 dBc.
  - Exception: for lower second adjacent channel (N-2), some receivers have intermodulation issue. By extrapolation, the equivalent D/U is -26 dB, but these receivers switch to mono reception to maintain a good audio quality.
- Third and fourth adjacent channel analog FM (or hybrid FM) into analog FM:
  - As second adjacent channel interference, the performance depends on the level of the out-of-band emissions of the interfering signal, except for some receivers having intermodulation issue.

The second phase evaluated the performance of HD Radio receivers to decode the digital signal. The summary of the laboratory measurement is as follow:

- The HD Radio service coverage is smaller and contained within the analog service coverage. By comparing with the analog carrier service coverage, i.e. when the audio quality is equal to a S/N = 30 dB, the lost in service coverage (in dB) is:
    - Between 2 dB and 12 dB with an injection level of -10 dBc.
    - Between 6 dB and 15 dB with an injection level of -14 dBc.
    - Between 12 dB and 22 dB with an injection level of -20 dBc.
- Co-channel interference exceeds by a large margin the current protection ratio for analog FM.
- First adjacent channel interference also exceeds the protection ratio for analog FM as the digital signal can be decoded with only one sideband. In the rare case where a lower and an upper first adjacent signal interfere with the desired hybrid FM signal, the required D/U will be higher but will only affect small area.
- Second (and further) adjacent channel interference has the same behaviour as with analog FM where reception is affected by the level of the transmitter's out-of-band emissions. Except for some receivers having intermodulation issue.

7.2 Overall Conclusions

Based on the results of the laboratory measurement and the simulations conducted, the following conclusions can be drawn:

1. The performance of modern analog FM equipment, both transmitters and receivers, exceeds consistently the minimum performance requirements as specified in BPR-3 and BETS-6. Please note that the current technical rules for analog FM broadcasting are based on representative equipment performance from decades ago.

2. As a result, the effective areas where the public can currently receive impairment-free FM broadcasting programming extend well beyond the stations protected contours as defined by BPR-3, with the exception of areas where these contours are determined by co-channel interference. Compared to the current protection ratios:
    a. Robustness to co-channel interference has no additional margin;
    b. Robustness to first adjacent interference has over 13 dB additional margin (average: 21 dB margin);
    c. Robustness to second adjacent interference has more than 11 dB additional margin;
3. In addition, the improved equipment performance (in terms of better out-of-band emissions from transmitters, and better selectivity from receivers) has permitted operational FM broadcasting assignments on adjacent channels at distances closer than as recommended by BPR-3 (short-spaced assignments) without creating degradation in service.

4. Comparing the system performance when the interferer is analog FM only versus HD Radio, the only interference scenario that resulted in a difference in performance is first adjacent channel.

a. Enabling HD Radio transmissions at analog FM stations will not create reception impairments within the protected contours for analog FM stations operating on first adjacent channels, as long as the distance separation between these stations is as required by BPR-3 minimum separation distance.

    i. Test results show a D/U 1 to 2 dB above the current protection ratio when the interferer is a hybrid FM with service mode MP3 at an injection level of -10 dBc. That difference is negligible and would not be perceptive in real life environment.

b. Even if the minimum separation distance is respected, a degradation in service could be noticeable by the listening public, mainly impacting areas outside the protected contours where currently good quality FM analog reception is available. This impact could be difficult to estimate as analog FM receivers are switching to monaural reception in areas with weak desired signal. The monaural reception of FM broadcasting is much less susceptible to interference compared with stereophonic reception.

c. Enabling HD Radio transmissions at analog FM stations will create reception impairments, possibly significant, within the protected contours for analog FM stations operating on first adjacent channels, if the distance separation between these stations is shorter than required by BPR-3 (short-spaced assignments).

5. Based on the HD Radio reception performance evaluation, it can be concluded that the HD Radio system, compared to the analog carrier demodulation capability, has a smaller service coverage for the considered injection levels of -10 to -20 dBc but has no issue in presence of strong interference. There is no need to adopt new or additional protection ratios to allow the introduction of hybrid FM transmissions. The protection ratios may have to be modified (likely relaxed) only when all FM stations have been converted to all digital mode.

Some remarks on the current BPR-3 and BETS-6 documents:

- The emission mask currently specified in BETS-6 for analog FM transmission does not reflect a realistic analog FM transmission from modern broadcasting equipment.
- The emission mask for HD Radio transmissions specified in the NRSC-5 standard should be adopted by adjusting the out-of-band emissions to match the level with the analog FM emission mask.
- Taking the results obtain in this study, effective protection ratios (dB) which would ensure impairment free reception of Analog and HD broadcasts may be as follows:

Protection ratios (dB) recommendations

Channel Relationship	Current Protection Ratio (dB)	Proposed Protection Ratio (dB)			
		Interferer is Analog FM	Interferer is Hybrid FM at different injection level		
			-10 dBc	-14 dBc	-20 dBc
Co-channel	20	20	20	20	20
First adjacent	6	-10	8	4	-1
Second adjacent	-26	-30	-30	-30	-30

7.3 Possible Interference Mitigation Approaches

A number of possible approaches and mitigation steps, as listed below, could be considered in the process to implement HD Radio broadcasting in Canada. Further analysis of these aspects was outside of the scope of the current study.

1. The analog FM broadcasting undertakings could be permitted to turn on HD Radio transmission on a first-come first-serve basis, while maintaining and enforcing the current protection rules for existing analog operations as specified in BPR-3. Effectively this will block some of the FM stations (short-spaced assignments) from broadcasting on digital mode. In the future, if/when the penetration of HD Radio receivers will reach levels close to, or at, 100%, protection for analog FM broadcasting would no longer be needed, and all stations could be permitted to transmit HD Radio programming.
2. A possible solution for some short-spaced stations may be to lower the injection level of their digital transmission. The HD Radio station could be required to transmit at -14 dBc or even -20 dBc to mitigate interference. To maintain a good digital coverage, the digital sidebands can be transmitted at different levels i.e. asymmetric. The sideband which could interfere with the adjacent channel can be reduced to -14 or -20 dBc while the other sideband is transmitted at -10 dBc.
3. Alternatively, FM assignments could be rearranged in a more spectrally efficient way, taking into account the better performance capabilities of modern transmission and reception equipment. Such a rearrangement would seek to eliminate any short-spaced assignments, while minimizing the number of retunes by operational FM broadcasting stations. Subsequently, the transition to HD Radio could be implemented without creating impairments to protected services areas.
4. Alternatively, if some of the FM stations at risk of being interfered by new HD Radio transmissions would switch their broadcasts to monaural mode (no stereo) this would possibly eliminate the reception impairments.

8 References

[1] *BPR-3 – Broadcasting Procedures and Rules: Part 3: Application Procedures and Rules for FM Broadcasting Undertakings*, Industry Canada, Issue 6, February 2016

[2] *BETS-6 – Broadcasting Equipment Technical Standard: Technical Standards and Requirements for FM Broadcasting Transmitters*, Industry Canada, Issue 2, August 2005

[3] *NRSC-5-D – In-band/on-channel Digital Radio Broadcasting Standard*, National Radio Systems Committee, April 2017

[4] *FCC 07-33 – Digital Audio Broadcasting Systems and Their Impact on the Terrestrial Radio Broadcast Service*, Federal Communications Commission (FCC), 22 FCC Rcd 10344, May 2007

[5] *ETSI EN 302 018 – Transmitting equipment for the Frequency Modulated (FM) sound broadcasting service; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU*, European Telecommunications Standards Institute (ETSI), version 2.1.1, April 2017

[6] *Recommendation ITU-R SM.1268-4 – Method of measuring the maximum frequency deviation of FM broadcast emissions at monitoring stations*, Spectrum Management – Radiocommunication Sector of ITU, Geneva, 2017

[7] Redmond R., *Digital Radio – A Global Perspective,* Harris Corporation, Ohio, USA, 2012. Available at https://www.gatesair.com/documents/papers/Redmond-Digital-Radio-A-Global-Perspective.pdf

Appendix A Analog Performance Tables of Results

This appendix presents the complete set of test results. The raw data can be supplied on request.

A.1 Self-Interference or Host-Interference

Table A-1: Impact of digital sidebands on analog host

RUT	Analog		Digital sidebands injection level					
			-20 dBc		-14 dBc		-10 dBc	
	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.	Audio S/N	Stereo Sep.
MP1 service mode								
Rx.1A	48.8	51	48.8	51	48.8	51	48.7	51
Rx.2A	60.9	39	60.3	39	59.8	39	58.5	34
Rx.3A	60.2	46	56.7	46	53.2	50	51.4	52
Rx.4A	53.1	35	51.8	35	49.0	35	46.6	35
Rx.5A	52.8	58	52.7	58	52.7	58	52.7	58
Rx.6A	61.6	N/A	61.2	N/A	60.0	N/A	58.5	N/A
Rx.11H	61.5	36	57.8	36	53.0	36	48.8	35
Rx.12H	62.9	50	60.3	50	57.7	53	56.6	50
Rx.13H	58.7	48	56.1	52	53.3	49	52.2	52
Rx.14H	58.6	59	55.9	55	53.3	47	52.1	48
Rx.15H	63.0	48	62.2	7	63.7	3	59.4	0
Rx.16H	60.5	36	60.4	36	60.2	36	60.1	33
Rx.17H	61.3	36	61.0	36	60.9	36	60.5	30
Rx.18H	59.7	43	59.3	43	59.1	43	58.7	32
MP3 service mode								
Rx.1A	48.8	51	48.5	50	47.1	49	45.8	47
Rx.2A	60.9	39	52.8	37	47.7	34	43.3	43
Rx.3A	60.2	46	49.7	54	45.6	49	43.6	47
Rx.4A	53.1	35	50.2	35	50.6	12	47.4	12
Rx.5A	52.8	58	52.6	57	51.9	56	51.1	54
Rx.6A	61.6	N/A	60.9	N/A	58.8	N/A	56.7	N/A
Rx.11H	61.5	36	49.2	36	42.8	34	40.6	27
Rx.12H	62.9	50	52.7	50	49.8	47	49.7	46
Rx.13H	58.7	48	49.5	54	45.5	49	43.7	47
Rx.14H	58.6	59	49.6	54	45.5	49	43.7	47
Rx.15H	63.0	48	61.9	6	57.2	1	57.0	0
Rx.16H	60.5	36	58.2	26	56.3	12	57.4	6
Rx.17H	61.3	36	58.0	23	56.3	9	60.5	2
Rx.18H	59.7	43	56.2	24	55.2	9	59.5	2
MP11 service mode								
Rx.1A	48.8	51	39.2	45	33.4	40	31.7	7
Rx.2A	60.9	39	37.9	39	32.1	38	27.9	34
Rx.3A	60.2	46	38.2	44	33.6	41	30.9	38
Rx.4A	53.1	35	44.7	12	39.2	12	35.0	12
Rx.5A	52.8	58	39.4	47	33.8	41	29.8	37
Rx.6A	61.6	N/A	59.9	N/A	57.2	N/A	53.4	N/A
Rx.11H	61.5	36	36.3	35	31.2	29	30.7	23
Rx.12H	62.9	50	40.1	44	37.9	42	37.6	42
Rx.13H	58.7	48	38.3	45	33.3	40	30.6	39
Rx.14H	58.6	59	38.2	45	33.3	40	30.7	39
Rx.15H	63.0	48	52.0	5	51.7	1	54.3	0
Rx.16H	60.5	36	45.4	11	49.6	2	64.4	0
Rx.17H	61.3	36	45.3	8	68.3	0	68.0	0
Rx.18H	59.7	43	44.7	8	66.9	0	66.8	0

A.2 Co-Channel Interference

Table A-2: D/U (dB) in presence of co-channel interference

Receiver Under Test	Audio S/N (dB)	D/U (dB) D @ -47 dBm		D/U (dB) D @ -63 dBm		D/U (dB) D @ -73 dBm	
		Analog	MP3-10	Analog	MP3-10	Analog	MP3-10
Rx.1A	50	N/R	N/R	N/R	N/R	21.8*	22.1*
	40	32.0	32.1	32.1	32.2	11.6*	9.5*
	30	21.4	21.5	21.4	21.5	< 9.6*	4.8*
Rx.2A	50	41.4	41.5	41.8	41.8	36.0	36.2
	40	30.9	31.0	31.0	31.0	24.9	25.0
	30	20.8	21.0	20.9	20.9	14.9	15.0
Rx.3A	50	41.6	41.6	42.0	42.1	42.8	42.8
	40	31.1	31.3	31.2	31.2	28.8	28.9
	30	21.0	21.2	21.1	21.1	18.6	18.7
Rx.4A	50	45.5	45.5	N/R	N/R	29.0*	29.3*
	40	31.9	32.0	30.3	30.2	14.7*	14.9*
	30	21.5	21.7	19.5	19.4	< 9.7*	< 9.7*
Rx.5A	50	43.6	44.1	45.3	46.3	N/R	N/R
	40	30.7	30.9	30.7	30.9	31.5	31.5
	30	20.5	20.6	20.5	20.5	20.5	20.6
Rx.6A	50	22.2*	22.3*	22.4*	22.8*	25.2*	27.6*
	40	12.6*	12.9*	12.6*	12.7*	12.8*	13.1*
	30	< 9.4*	< 9.3*	< 9.7*	< 9.7*	< 8.6*	< 9.7*
Rx.11H	50	42.6	42.8	38.8	38.8	31.0	31.0
	40	32.4	32.5	28.3	28.4	20.1	20.3
	30	22.3	22.4	18.4	18.3	10.3	10.6
Rx.12H	50	41.1	41.2	41.9	42.0	45.0	43.6
	40	30.8	31.1	31.0	30.9	27.7	27.7
	30	20.8	20.9	20.8	20.9	17.4	17.4
Rx.13H	50	41.5	41.5	44.4	44.4	N/R	N/R
	40	31.1	31.0	31.2	31.1	29.5	29.2
	30	20.9	20.9	20.9	21.1	18.0	18.2
Rx.14H	50	41.5	41.6	41.9	42.0	43.8	43.4
	40	30.9	31.1	31.0	31.0	29.0	29.1
	30	20.9	21.0	20.9	20.9	18.8	18.9
Rx.15H	50	40.8	40.7	41.5	41.6	39.6	39.7
	40	30.7	30.6	30.3	30.4	25.0	25.1
	30	18.3	< 9.3*	17.3	< 9.7*	13.9	< 9.7*
Rx.16H	50	38.9	39.1	39.2	39.3	45.9	46.9
	40	28.5	28.7	28.5	28.7	28.8	28.9
	30	< 9.4*	< 9.4*	< 9.7*	< 9.7*	< 9.6*	1.2*
Rx.17H	50	39.7	39.8	40.2	40.3	N/R	N/R
	40	29.4	29.6	29.4	29.4	29.8	29.9
	30	< 9.3*	< 8.2*	< 9.6*	< 9.5*	< 9.6*	< 8.5*
Rx.18H	50	40.6	40.6	41.0	41.2	N/R	N/R
	40	30.2	30.2	30.2	30.4	30.4	30.7
	30	10.8*	< 9.3*	< 9.7*	< 9.7*	9.7*	< 9.7*

* Stereo separation less than 10 dB.

A.3 Upper First Adjacent Channel Interference

Table A-3: D/U (dB) in presence of upper first adjacent channel interference

Receiver Under Test	Audio S/N (dB)	D/U (dB) D @ -47 dBm				D/U (dB) D @ -63 dBm				D/U (dB) D @ -73 dBm			
		Analog	MP3-10	MP3-14	MP3-20	Analog	MP3-10	MP3-14	MP3-20	Analog	MP3-10	MP3-14	MP3-20
Rx.1A	50	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	-8.4	10.0	6.2	0.0
	40	3.4	19.0	15.0	9.2	3.3	19.0	15.2	9.0	-8.9	-1.7	-5.5	-11.4
	30	-7.7	8.4	4.6	-1.6	-11.0	8.4	4.4	-1.6	-13.4	-3.8	-7.7	-13.6
Rx.2A	50	12.8	28.4	24.2	18.5	13.5	28.7	24.7	18.7	7.8	23.4	19.2	13.5
	40	2.9	17.9	13.7	7.9	2.5	17.9	13.9	7.9	-3.0	12.0	8.1	2.2
	30	-7.1	7.8	3.7	-2.1	-7.6	7.9	3.8	-2.1	-11.6	1.9	-2.0	-7.9
Rx.3A	50	13.1	28.6	24.4	18.7	13.8	28.9	24.9	18.9	15.1	34.8	26.5	20.8
	40	3.3	18.1	13.9	8.2	2.6	18.1	14.1	8.1	-4.4	16.0	12.0	6.1
	30	< -15.9	7.9	3.9	-2.0	< -14.6	8.0	4.0	-2.0	< -16	5.8	1.7	-4.6
Rx.4A	50	12.5	46.9	27.7	21.7	N/R	N/R	N/R	N/R	-5.2	16.7	13.4	7.1
	40	0.2	18.5	14.5	8.7	-1.4	17.1	13.1	7.0	< -15	2.7	-1.1	-7.1
	30	-10.2	8.4	4.2	-1.5	-12.0	6.3	2.1	-3.8	< -15	-4.8	-8.7	-14.7
Rx.5A	50	14.3	33.4	26.7	20.7	15.3	33.2	28.4	22.3	N/R	N/R	N/R	N/R
	40	1.1	17.6	13.7	7.6	1.0	17.6	13.8	7.6	1.6	18.4	14.5	8.5
	30	-8.8	7.4	3.5	-2.5	-9.6	7.4	3.4	-2.5	-9.6	7.5	3.5	-2.6
Rx.6A	50	-6.0	10.6	6.7	1.2	-0.4	10.6	6.9	1.2	-5.6	15.1	9.2	3.6
	40	-10.6	1.6	-1.9	-6.6	-6.3	1.6	-2.0	-6.6	-12.4	1.6	-2.4	-7.2
	30	-13.4	-2.2	-5.8	-10.4	-10.6	-2.3	-6.0	-11.0	< -15.3	-2.2	-6.1	-11.5
Rx.11H	50	11.8	30.5	25.7	19.7	8.9	26.6	22.3	16.2	1.2	18.8	14.9	9.0
	40	1.5	19.5	15.4	9.5	-4.3	15.5	11.4	5.4	< -15.4	7.5	3.5	-2.5
	30	< -15.3	9.4	4.0	-13.3	< -15.9	5.5	-7.0	-13.4	< -15.4	-2.6	-7.0	-13.4
Rx.12H	50	11.9	28.2	24.1	18.1	13.3	28.9	24.6	18.8	10.3	28.0	23.7	17.5
	40	-3.7	17.9	13.9	7.9	-4.0	18.1	13.9	8.0	-13.4	14.8	10.7	4.6
	30	< -16.3	7.9	3.9	-2.1	< -15.9	8.0	3.7	-2.2	< -15.4	4.4	0.4	-5.8
Rx.13H	50	14.6	28.6	24.7	18.7	15.9	42.4	27.0	21.3	N/R	N/R	N/R	N/R
	40	2.3	18.1	14.1	8.1	2.2	18.2	14.3	8.4	3.2	16.1	12.3	6.2
	30	< -15.3	8.0	4.0	-2.0	< -15.9	7.9	4.0	-2.2	< -15.4	5.0	1.2	-5.1
Rx.14H	50	13.2	28.7	24.7	18.8	19.5	29.1	25.0	19.2	0.0	37.0	27.0	21.2
	40	3.4	18.0	14.1	8.1	2.9	18.1	14.0	8.2	-2.2	16.4	12.3	6.4
	30	< -14.9	8.0	3.9	-2.2	< -14.6	8.0	3.9	-2.1	< -15	6.1	1.9	-4.3
Rx.15H	50	3.5	28.1	24.1	16.4	3.9	28.8	24.7	17.8	4.6	27.3	23.2	17.2
	40	< -15.3	12.8	5.4	4.4	-14.0	12.1	5.3	2.7	< -15.4	10.1	5.0	2.1
	30	< -15.3	-4.0	-7.9	-13.9	< -15.9	-8.2	-12.6	< -14.9	< -15.4	-8.6	-12.6	< -15.4
Rx.16H	50	8.7	26.2	22.4	16.3	8.9	26.6	22.6	16.4	14.2	51.1	35.3	24.0
	40	-14.1	14.4	10.0	2.5	-14.3	14.4	9.7	3.9	-14.3	13.1	-6.6	-12.2
	30	< -15.3	-4.8	-8.5	-14.5	< -15.9	-4.7	-8.6	-14.4	< -15.4	-4.7	-8.6	-14.6
Rx.17H	50	9.7	27.1	23.0	16.9	9.8	27.7	23.5	17.5	N/R	N/R	N/R	N/R
	40	-14.1	16.7	12.6	6.2	-14.3	16.7	12.6	-12.7	-14.3	16.6	12.6	-12.2
	30	< -15.3	-4.5	-8.6	-14.6	< -15.9	-4.5	-8.8	-14.5	< -15.4	-4.6	-8.7	-14.7
Rx.18H	50	10.4	28.0	24.1	17.9	10.5	28.4	24.3	18.3	15.5	53.4	51.9	30.5
	40	-13.8	17.5	13.5	7.5	-12.8	17.4	13.6	7.5	-14.3	17.8	13.9	7.8
	30	-14.3	-2.3	-5.2	-9.9	-13.0	-1.5	-6.3	-11.4	-14.7	-1.4	-4.0	-11.5

A.4 Lower First Adjacent Channel Interference

Table A-4: D/U (dB) in presence of lower first adjacent channel interference

Receiver Under Test	Audio S/N (dB)	D/U (dB) D @ -47 dBm				D/U (dB) D @ -63 dBm				D/U (dB) D @ -73 dBm			
		Analog	MP3-10	MP3-14	MP3-20	Analog	MP3-10	MP3-14	MP3-20	Analog	MP3-10	MP3-14	MP3-20
Rx.1A	50	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	-12.6	9.8	6.1	0.0
	40	0.4	18.8	15.0	8.9	-0.2	19.0	15.0	9.1	-13.6	-0.8	-4.7	-11.3
	30	-11.0	8.4	4.4	-1.6	-10.7	8.4	4.3	-1.7	< -15.1	-3.3	-7.3	-13.2
Rx.2A	50	13.1	28.4	N/D	19.2	13.8	28.8	N/D	19.7	7.7	23.5	N/D	14.1
	40	3.2	17.9	N/D	8.9	2.5	17.9	N/D	9.0	-3.2	12.1	N/D	3.1
	30	-7.2	7.9	N/D	-1.1	-7.1	7.8	N/D	-1.3	-11.2	2.0	N/D	-6.7
Rx.3A	50	14.5	28.6	24.4	19.5	14.9	29.0	24.9	19.9	14.6	36.5	26.5	21.2
	40	3.4	18.1	13.9	9.2	2.5	18.1	14.1	9.2	-2.4	16.0	12.0	6.9
	30	< -14.9	8.0	3.9	-1.5	< -14.6	8.0	4.0	-1.7	< -15	5.7	1.7	-4.3
Rx.4A	50	12.6	47.3	N/D	22.1	N/R	N/R	N/D	N/R	-4.1	15.9	N/D	7.1
	40	0.3	18.6	N/D	8.9	-1.5	16.7	N/D	7.5	< -15	2.3	N/D	-7.1
	30	-10.2	8.4	N/D	-1.2	-12.4	6.0	N/D	-3.4	< -15	-4.7	N/D	-14.4
Rx.5A	50	14.0	40.6	26.9	21.0	16.3	48.8	28.6	22.6	N/R	N/R	N/R	N/R
	40	1.2	17.7	13.8	7.7	1.0	17.8	13.8	7.9	2.1	18.5	14.6	8.9
	30	-9.2	7.5	3.6	-2.4	-9.1	7.4	3.5	-2.4	-8.9	7.3	3.7	-2.4
Rx.6A	50	-3.1	10.3	6.7	1.0	-3.8	11.1	6.7	1.5	-1.1	16.8	12.4	7.2
	40	-9.9	1.1	-2.4	-7.3	-9.2	1.8	-2.8	-7.1	-9.4	2.1	-1.8	-6.9
	30	< -15.2	-2.3	-6.0	-11.9	-14.1	-1.9	-6.2	-11.3	-14.7	-1.9	-6.0	-11.2
Rx.11H	50	12.0	30.6	25.5	19.8	8.0	26.2	22.1	16.2	1.2	18.4	14.6	8.5
	40	1.1	19.3	15.3	9.5	-0.3	15.2	11.2	5.5	< -15.3	7.4	3.5	-2.4
	30	< -16.3	9.3	3.7	-13.3	< -14.9	5.2	-1.8	-13.2	< -15.3	-2.3	-7.2	-13.2
Rx.12H	50	12.2	28.0	23.9	18.2	13.9	28.6	24.4	18.8	11.1	27.8	23.4	20.3
	40	-2.9	17.9	13.7	8.0	-3.0	17.7	13.7	8.2	-13.0	14.5	10.4	4.8
	30	< -16.3	7.7	3.7	-2.0	< -14.9	7.7	3.6	-2.1	< -15.3	4.2	0.1	-5.7
Rx.13H	50	13.1	28.5	24.6	18.9	15.1	29.2	25.6	19.7	N/R	53.0	54.7	N/R
	40	3.2	18.1	14.0	8.4	2.9	18.0	14.1	8.3	-0.8	15.6	11.5	5.6
	30	< -15.3	7.9	4.1	-1.9	< -14.9	7.8	4.0	-2.2	< -15.4	4.9	0.9	-5.0
Rx.14H	50	14.8	28.5	24.4	18.7	16.5	28.9	25.1	19.1	N/R	38.2	26.7	21.2
	40	2.5	18.0	13.8	8.1	2.1	17.8	13.8	8.2	-3.1	16.2	12.1	6.4
	30	< -15.9	7.9	3.7	-1.9	< -14.6	7.7	3.6	-2.0	< -15.1	5.8	1.8	-4.0
Rx.15H	50	11.5	28.0	24.1	18.3	11.1	28.8	24.8	19.0	13.0	27.2	22.9	17.2
	40	-15.2	16.9	10.7	4.4	-14.8	16.4	10.5	4.1	< -15.4	12.5	8.0	2.4
	30	< -15.3	-4.1	-8.2	-14.3	< -14.9	-8.7	-12.9	< -15.9	< -15.4	-8.7	-12.8	< -15.3
Rx.16H	50	9.7	26.2	22.3	16.4	10.8	26.6	22.6	16.7	16.6	46.3	34.1	23.3
	40	-11.9	-2.0	-5.6	-11.1	-12.1	-2.1	-5.9	-11.0	-12.3	-2.0	-5.8	-11.0
	30	-13.9	-3.9	-7.9	-13.7	-13.7	-4.0	-7.9	-13.6	-13.7	-4.0	-7.8	-13.6
Rx.17H	50	10.7	27.2	23.0	17.3	11.8	27.6	23.5	17.8	N/R	N/R	N/R	N/R
	40	-12.2	-1.7	-5.6	-10.6	-12.0	16.3	-5.9	-10.8	-12.2	-1.8	-5.8	-11.1
	30	-13.6	-4.0	-8.0	-13.4	-13.5	-4.2	-8.1	-13.4	-13.5	-4.1	-8.1	-13.5
Rx.18H	50	12.0	28.0	24.1	18.0	13.0	28.3	24.4	18.5	24.4	50.9	46.9	29.0
	40	-10.5	17.6	13.6	7.3	-10.7	17.7	13.4	7.3	-10.7	17.9	13.7	6.8
	30	-10.8	-1.3	-5.2	-11.2	-10.9	0.0	-5.4	-11.4	-10.9	0.1	-4.1	-10.4

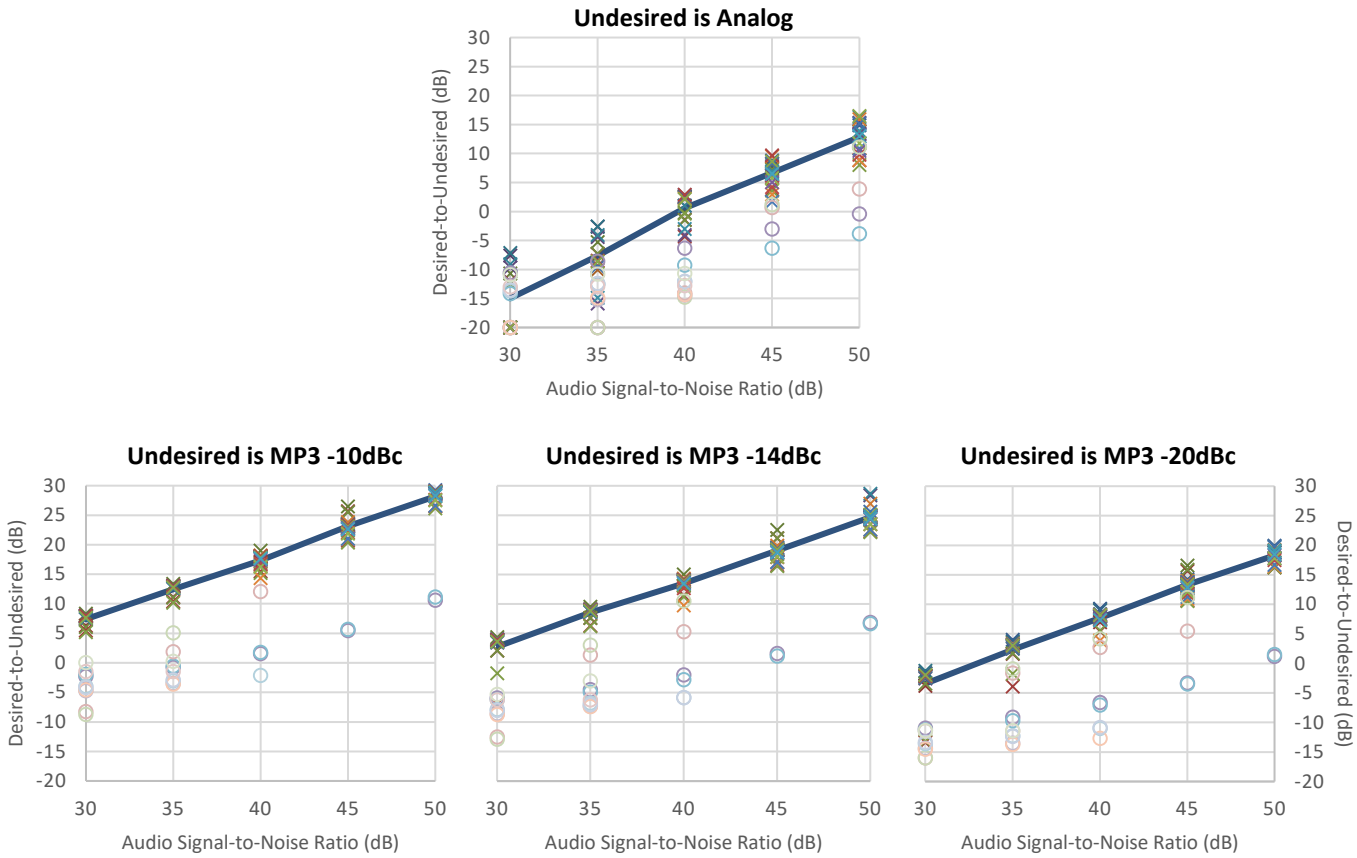

Figure A-1: First adjacent channel test results (desired at -63 dBm)

A.5 Upper Second Adjacent Channel Interference

Table A-5: Audio S/N (dB) in presence of upper second adjacent channel interference

RUT	Tx Mode	Desired signal = -63 dBm					Desired signal = -73 dBm			
		No Interf.	D/U = -16 dB	D/U = -26 dB	D/U = -36 dB	Equivalent C/N	No Interf.	D/U = -16 dB	D/U = -26 dB	D/U = -36 dB
Rx.1A	Analog	48.0	47.5	45.0	58.0	33.8*	61.5	61.6	61.5	58.9
	MP3-10	48.1	46.4	57.4	49.9	22.7*	61.6	61.4	59.1	50.8
Rx.2A	Analog	57.6	57.5	56.8	52.7	45.2	55.4	55.3	55.3	54.2
	MP3-10	57.6	53.2	45.3	35.7	26.7	55.5	54.4	49.7	40.8
Rx.3A	Analog	57.0	57.0	56.4	52.6	45.4	51.5	51.6	51.5	50.4
	MP3-10	57.0	53.0	45.2	35.8	27.0	51.6	50.6	46.0	37.3
Rx.4A	Analog	47.1	46.8	45.0	40.0	30.3*	52.0	51.8	52.0	51.7
	MP3-10	46.9	46.5	42.1	34.2	23.6*	51.7	52.0	51.6	48.6
Rx.5A	Analog	51.4	51.0	48.3	39.7	30.4	46.3	46.5	45.0	39.9
	MP3-10	51.3	48.4	41.4	31.5	22.0	46.6	45.9	41.6	32.2
Rx.6A	Analog	59.5	59.2	59.1	53.2	26.4	52.8	52.6	51.9	51.7
	MP3-10	59.4	59.0	56.6	45.8	18.0	52.8	52.6	51.5	46.1
Rx.11H	Analog	57.2	57.1	56.7	54.8	45.6	55.4	55.5	55.3	55.2
	MP3-10	57.0	54.7	47.5	37.8	26.1	55.4	55.0	52.8	45.9
Rx.12H	Analog	57.7	57.6	57.0	53.2	46.8	52.7	52.7	52.7	51.8
	MP3-10	57.6	53.5	45.3	36.2	27.1	52.7	51.7	47.5	39.4
Rx.13H	Analog	52.3	52.5	52.5	48.7	41.9	46.5	46.6	46.1	45.3
	MP3-10	52.2	50.5	44.5	35.3	26.3	49.6	49.1	46.1	37.8
Rx.14H	Analog	56.2	56.2	54.2	48.1	39.7	51.7	51.5	51.2	48.3
	MP3-10	56.3	52.8	45.0	35.5	26.4	51.7	50.7	46.0	37.3
Rx.15H	Analog	55.7	55.8	55.4	52.0	44.3	51.7	51.7	51.7	51.5
	MP3-10	55.7	52.6	47.0	38.7	29.0	51.7	51.3	49.9	42.8
Rx.16H	Analog	57.8	57.7	55.5	47.1	36.0	50.7	50.7	50.6	46.6
	MP3-10	57.8	53.4	45.1	42.9	31.5	50.8	49.8	44.7	42.3
Rx.17H	Analog	57.3	57.3	54.5	47.0	36.7	49.2	49.1	49.0	45.4
	MP3-10	57.3	54.2	47.5	43.1	32.5	49.1	48.5	45.0	43.0
Rx.18H	Analog	57.3	57.0	53.9	43.9	34.2	50.5	50.4	50.2	45.2
	MP3-10	57.1	53.5	45.8	43.3	33.5	51.1	49.4	44.9	42.8

A.6 Lower Second Adjacent Channel Interference

Table A-6: Audio S/N (dB) in presence of lower second adjacent channel interference

RUT	Tx Mode	Desired signal = -63 dBm				Desired signal = -73 dBm			
		No Interf.	D/U = -16 dB	D/U = -26 dB	D/U = -36 dB	No Interf.	D/U = -16 dB	D/U = -26 dB	D/U = -36 dB
Rx.1A	Analog	47.7	47.0	42.8	57.9	61.7	61.7	61.3	59.0
	MP3-10	47.8	45.7	58.5	50.2	61.8	61.5	59.1	52.0
Rx.2A	Analog	57.7	57.6	56.9	52.8	N/D	N/D	N/D	N/D
	MP3-10	57.5	53.7	46.0	36.1	N/D	N/D	N/D	N/D
Rx.3A	Analog	57.0	57.0	56.5	52.2	N/D	N/D	N/D	N/D
	MP3-10	57.1	53.6	45.8	36.1	N/D	N/D	N/D	N/D
Rx.4A	Analog	47.0	46.9	46.3	42.7	N/D	N/D	N/D	N/D
	MP3-10	47.2	46.7	43.1	37.0	N/D	N/D	N/D	N/D
Rx.5A	Analog	50.2	44.5	35.7	27.1	46.4	43.3	35.2	25.7
	MP3-10	51.3	42.7	33.8	24.0	46.5	42.0	33.5	23.9
Rx.6A	Analog	56.8	57.1	56.8	53.7	51.0	51.2	51.4	50.6
	MP3-10	56.8	57.1	55.9	50.2	51.0	51.3	51.0	48.3
Rx.11H	Analog	56.5	56.8	56.9	54.3	56.1	55.6	55.4	54.8
	MP3-10	58.0	46.8	46.4	38.3	55.6	52.4	52.1	46.1
Rx.12H	Analog	57.0	56.6	56.2	52.9	51.3	51.5	51.9	51.2
	MP3-10	57.3	43.8	43.5	36.5	51.8	46.3	46.0	39.7
Rx.13H	Analog	55.2	55.0	53.6	48.1	50.0	49.9	49.6	47.9
	MP3-10	55.1	52.3	45.2	35.9	49.8	49.4	46.4	38.6
Rx.14H	Analog	56.4	56.2	54.2	47.4	51.7	51.7	51.1	47.8
	MP3-10	56.3	52.9	45.4	35.8	51.7	50.7	46.2	37.5
Rx.15H	Analog	55.8	55.2	53.8	48.3	51.7	51.6	51.4	50.1
	MP3-10	55.7	52.7	47.0	40.0	51.6	51.2	49.6	43.6
Rx.16H	Analog	57.8	42.1	43.5	42.0	50.7	41.5	40.7	41.9
	MP3-10	57.9	42.7	44.8	42.7	50.7	41.4	40.8	42.4
Rx.17H	Analog	57.2	44.0	43.7	40.6	48.8	43.1	41.1	41.6
	MP3-10	57.1	45.6	45.3	40.9	48.8	42.8	40.6	41.7
Rx.18H	Analog	57.1	39.6	40.1	43.1	50.4	39.2	47.9	42.7
	MP3-10	57.1	39.3	41.1	42.8	50.2	39.2	48.4	42.8

Appendix B Digital Performance Tables of Results

B.1 Random Noise Impairment

Table B-1: C/N (dB) in presence of random noise impairment

Receiver Under Test	Injection Level (dBc)	Received FM Power (dBm)	HD2		HD3	
			C/N ref. to analog carrier (dB)	C/N ref. to digital carriers (dB)	C/N ref. to analog carrier (dB)	C/N ref. to digital carriers (dB)
Rx.12H	-20	-63	21.1	2.7	23.1	4.7
		-73	21.3	2.9	23.4	5.0
	-14	-63	14.9	2.5	16.3	3.9
		-73	15.0	2.6	16.4	4.0
	-10	-63	11.2	2.8	12.5	4.1
		-73	11.2	2.8	12.5	4.1
Rx.13H	-20	-63	21.0	2.6	23.0	4.6
		-73	21.1	2.7	23.0	4.6
	-14	-63	15.0	2.6	16.4	4.0
		-73	15.0	2.6	16.4	4.0
	-10	-63	10.8	2.4	12.0	3.6
		-73	10.7	2.4	12.1	3.8
RX.14H	-20	-63	21.2	2.8	23.2	4.8
		-73	21.2	2.8	23.3	4.9
	-14	-63	14.9	2.5	16.4	4.0
		-73	14.9	2.5	16.4	4.0
	-10	-63	11.1	2.7	12.3	3.9
		-73	11.1	2.8	12.4	4.1
Rx.15H	-20	-63	21.1	2.7	23.0	4.6
		-73	21.2	2.8	23.0	4.6
	-14	-63	14.9	2.5	16.1	3.7
		-73	15.0	2.6	16.2	3.8
	-10	-63	10.8	2.4	12.1	3.7
		-73	10.7	2.3	12.1	3.7
Rx.16H	-20	-63	20.9	2.5	22.8	4.4
		-73	21.0	2.6	22.8	4.4
	-14	-63	14.6	2.2	15.7	3.3
		-73	14.7	2.3	15.8	3.4
	-10	-63	10.8	2.4	12.1	3.7
		-73	10.7	2.3	12.1	3.7
Rx.17H	-20	-63	21.0	2.6	22.7	4.3
		-73	20.8	2.5	22.8	4.5
	-14	-63	15.0	2.6	16.1	3.7
		-73	15.0	2.6	16.0	3.6
	-10	-63	10.8	2.4	11.9	3.5
		-73	10.6	2.3	12.1	3.8

Table B-2: C/N (dB) in presence of random noise impairment with asymmetrical sidebands

Receiver Under Test	HD2		HD3	
	C/N ref. to analog carrier (dB)	C/N ref. to digital carriers (dB)	C/N ref. to analog carrier (dB)	C/N ref. to digital carriers (dB)
Rx.12H	14.3	5.9	17.7	9.3
Rx.13H	14.3	5.9	17.9	9.5
Rx.17H	14.3	5.9	17.7	9.3

Test conditions: Desired FM signal set to -63 dBm with lower and upper sidebands set to -20 and -10 dBc respectively.

B.2 Dynamic Range

Table B-3: Minimum signal level sensitivity

Receiver Under Test	Injection Level (dBc)	HD2		HD3		Analog Minimum Signal Level (Audio S/N=30dB)
		Minimum Signal Level (Ref Analog)	Minimum Signal Level (Ref Digital)	Minimum Signal Level (Ref Analog)	Minimum Signal Level (Ref Digital)	
Rx.12H	-20	-85.9	-108.0	-83.9	-106.1	-106.2
	-14	-92.4	-108.6	-91.4	-107.6	
	-10	-96.3	-108.5	-94.4	-106.6	
Rx.13H	-20	-90.5	-112.7	-89.0	-111.2	-104.4
	-14	-96.5	-112.7	-95.5	-111.7	
	-10	-100.4	-112.6	-99.4	-111.6	
Rx.14H	-20	-88.0	-110.2	-86.9	-109.1	-107.0
	-14	-94.5	-110.7	-92.4	-108.6	
	-10	-98.4	-110.6	-97.4	-109.6	
Rx.15H	-20	-85.9	-108.1	-84.0	-106.1	-104.3
	-14	-91.4	-107.6	-90.5	-106.7	
	-10	-95.4	-107.5	-94.4	-106.6	
Rx.16H	-20	-91.5	-113.3	-90.5	-112.7	-104.8
	-14	-97.5	-113.7	-96.4	-112.6	
	-10	-102.4	-114.6	-101.4	-113.6	
Rx.17H	-20	-91.5	-113.7	-90.6	-112.8	-103.6
	-14	-97.5	-113.7	-96.4	-112.6	
	-10	-102.4	-114.5	-101.4	-113.5	

Appendix C Short-Spaced Stations

The following table list the stations that are short-spaced (up to 20 %) with a first adjacent channel excluding low power (LP), US stations and including only operational stations (OP). The calculated distance between stations is based on the maximum transmission parameters for their class (ERP and EHAAT) and an omnidirectional antenna. This list does not consider the used of directional transmitting antenna and/or reduced transmission power which would reduce the required minimum domestic separation between stations. Terrain topography (mountains) is also not considered in making that list.

Table C-1: Short-spaced stations list

FM Station #1 Information				FM Station #2 Information				Minimum Domestic Distance (km)	Distance Between Stations (km)	Short-Spaced Distance (%)
Call-Sign	City	Freq.	Class	Call-Sign	City	Freq.	Class			
CBCV-FM-1	Metchosin/Sooke	99.5	A	CBUF-FM-9	Victoria	99.7	A	97	14	86
CFGE-FM-1	Magog	98.1	B	CIAX-FM	Windsor	98.3	A	137	35	75
CFZM-1-FM	Toronto	96.7	A	CKHC-FM	Toronto	96.9	A1	78	20	74
CISC-FM	Gibsons	107.5	B	CISF-FM	Surrey	107.7	A	137	43	69
CKOF-FM	Gatineau	104.7	C1	CFLG-FM	Cornwall	104.5	B	195	88	55
CJTW-FM	Kitchener/Waterloo	93.7	A	CFWC-FM	Brantford	93.9	A1	78	38	51
CKWD-FM	Calgary	95.3	C1	CJAY-FM-1	Banff	95.1	B	195	95	51
CKNC-FM	Simcoe	99.7	B1	CKKW-FM	Kitchener	99.5	B1	131	64	51
CHUP-FM	Calgary	97.7	C1	CBRC-FM	Harvie Heights	97.9	A	168	82	51
CIMA-FM	Alliston	92.1	A	CFGI-FM	Georgina Island	92.3	A	97	49	50
CICW-FM	Fergus	101.1	A	CJML-FM	Milton	101.3	A	97	49	50
CFXM-FM	Granby	104.9	B	CBME-FM-1	Montréal	104.7	A1	117	60	49
CHES-FM	Erin	91.7	A	CHIN-1-FM	Toronto	91.9	A	97	50	48
CHUC-FM	Cobourg	107.9	B	CKDO-FM-1	Oshawa	107.7	A	137	71	48
CIBL-FM	Montréal	101.5	B1	CJSO-FM	Sorel	101.7	A	118	63	46
CJSP-FM	Leamington	92.7	B1	CFCO-1-FM	Chatham	92.9	A1	98	54	45
CHAA-FM	Longueuil	103.3	A	CKOD-FM	Valleyfield	103.1	A	97	53	45
CKFM-FM	Toronto	99.9	C1	CKPT-FM	Peterborough	99.7	B	195	110	44
CHLY-FM	Nanaimo	101.7	A	CITR-FM	Vancouver	101.9	A	97	55	44
CKYR-FM	Calgary	106.7	B	CHMN-FM	Canmore	106.5	A	137	78	43
CHKX-FM	Hamilton/Burlington	94.7	C1	CKGE-FM	Oshawa	94.9	B	195	111	43
CHKX-HD	Hamilton/Burlington	94.7	C1	CKGE-FM	Oshawa	94.9	B	195	111	43
CILT-FM	Steinbach	96.7	C1	CJPG-FM	Portage La Prairie	96.5	B	195	112	42
CFCA-FM	Kitchener	105.3	C1	CHOQ-FM	Toronto	105.1	B1	181	104	42
CFMP-FM	Arnprior	107.7	A	CKDJ-FM	Ottawa	107.9	A1	78	45	42
CKEA-FM	Edmonton	95.7	C1	CKGY-FM	Red Deer	95.5	C1	216	126	42
CJIQ-FM	Paris	88.3	B	CIND-FM	Toronto	88.1	B	164	96	42
CHGK-FM	Stratford	107.7	A	CJDV-FM	Cambridge	107.5	A	97	57	41
CFEL-FM	Lévis	102.1	C1	CIGB-FM	Trois-Rivières	102.3	B	195	115	41
CHIN-FM	Toronto	100.7	C1	CKRU-FM	Peterborough	100.5	B1	181	110	39
CKLZ-FM	Kelowna	104.7	C	CKBZ-FM-1	Pritchard	104.5	A1	166	101	39
CHGA-FM	Maniwaki	97.3	B	CHLX-FM	Ottawa-Hull	97.1	B1	150	91	39
CBAF-FM-18	Grande-Anse	90.3	C	CBFX-FM-5	Gaspé	90.1	B	213	131	39
CKWR-FM	Kitchener/Waterloo	98.5	B	CKFG-FM	Toronto	98.7	B1	150	92	39
CFCA-FM	Kitchener	105.3	C1	CJED-FM	Niagara Falls	105.1	B	195	120	39
CKOT-FM	Tillsonburg	101.3	B	CICW-FM	Fergus	101.1	A	137	87	37
CHNC-FM	New-Carlisle	107.1	B1	CHNC-FM-3	Percé	107.3	B1	131	84	36
CIRA-FM-3	Victoriaville	89.3	A	CFOU-FM	Trois-Rivières	89.1	A	97	62	36
CKFM-FM	Toronto	99.9	C1	CKNC-FM	Simcoe	99.7	B1	181	117	36
CIXL-FM	Welland	91.7	B	CKBT-FM	Kitchener/Waterloo	91.5	B	164	106	35
CHVR-FM	Pembroke	96.7	C1	CFTX-FM	Gatineau	96.5	A	168	109	35
CBVX-FM-1	Ste-Anne-De-Beaupre	89.9	A1	CJNG-FM	Québec	89.7	A1	45	29	35
CHRE-FM	St Catharines	105.7	B	CHRY-FM	North York	105.5	A1	117	78	34

FM Station #1 Information				FM Station #2 Information				Minimum Domestic Distance (km)	Distance Between Stations (km)	Short-Spaced Distance (%)
Call-Sign	City	Freq.	Class	Call-Sign	City	Freq.	Class			
CKPT-FM	Peterborough	99.7	B	CFBG-FM	Bracebridge	99.5	B	164	109	34
CJXY-FM	Burlington	107.9	B	CHGK-FM	Stratford	107.7	A	137	91	33
CJBX-FM	London	92.7	B	CHTG-FM	Haldimand	92.9	B1	150	100	33
CIVL-FM	Abbotsford	101.7	A	CITR-FM	Vancouver	101.9	A	97	65	33
CKEZ-FM	Pictou	97.9	C1	CKEN-FM	Kentville	97.7	B	195	132	32
CHOD-FM	Cornwall	92.1	B	CJET-FM	Smiths Falls	92.3	B	164	112	32
CJSA-FM	Toronto	101.3	B1	CICW-FM	Fergus	101.1	A	118	81	31
CJSA-HD	Toronto	101.3	B1	CICW-FM	Fergus	101.1	A	118	81	31
CJXY-FM	Burlington	107.9	B	CKDO-FM-1	Oshawa	107.7	A	137	95	31
CHUM-FM	Toronto	104.5	C1	CIHR-FM	Woodstock	104.7	B1	181	127	30
CHUM-FM	Toronto	104.5	C1	CIHR-HD	Woodstock	104.7	B1	181	127	30
CJSQ-FM	Québec	92.7	B	CFUT-FM	Shawinigan	92.9	A	137	97	29
CIHO-FM	St-Hilarion	96.3	B	CBM-FM-2	Québec	96.1	B	164	116	29
CHKX-FM	Hamilton/Burlington	94.7	C1	CIBU-FM	Wingham	94.5	C1	216	154	29
CHKX-HD	Hamilton/Burlington	94.7	C1	CIBU-FM	Wingham	94.5	C1	216	154	29
CKUV-FM	High River/Okotoks	100.9	C1	CKEX-FM	Red Deer	100.7	C1	216	154	29
CJTW-FM	Kitchener/Waterloo	93.7	A	CJKS-FM	Ohsweken	93.5	A1	78	57	27
CIOO-FM	Halifax	100.1	C	CHTN-FM	Charlottetown	100.3	C1	234	176	25
CKKS-FM	Chilliwack	107.5	A	CISF-FM	Surrey	107.7	A	97	73	25
CHRM-FM	Matane	105.3	B	CFIC-FM	Restigouche	105.1	A	137	103	25
CIHR-FM	Woodstock	104.7	B1	CHWC-FM	Goderich	104.9	B1	131	99	24
CIHR-HD	Woodstock	104.7	B1	CHWC-FM	Goderich	104.9	B1	131	99	24
CKPC-FM	Brantford	92.1	C1	CJOS-FM	Owen Sound	92.3	B	195	148	24
CITF-FM	Québec	107.5	C1	CKOY-FM	Sherbrooke	107.7	C1	216	164	24
CIAK-FM	Lytton	102.3	B	CISW-FM	Whistler	102.1	A	137	105	23
CHIN-FM	Toronto	100.7	C1	CBLA-FM-3	Wingham	100.9	B	195	151	23
CFXY-FM	Fredericton	105.3	C1	CFAI-FM-1	Grand-Sault	105.1	A	168	130	23
CIFM-FM-2	Clearwater	92.7	B	CFBX-FM	Kamloops	92.5	A	137	107	22
CBV-FM-4	St-Pamphile	88.7	A	CBVX-FM-3	Baie St-Paul	88.9	A	97	76	21
CHST-FM	London	102.3	C1	CFNY-FM	Brampton	102.1	C1	216	170	21
CIMO-FM-1	Sherbrooke	106.9	A	CJIT-FM	Lac Mégantic	106.7	A	97	77	21
CHRE-FM	St Catharines	105.7	B	CIUX-FM	Uxbridge	105.5	A	137	109	21