FM IN-BAND ON-CHANNEL (IBOC) DIGITAL RADIO

Russ Morris
Senior Planning Officer
Australian Broadcasting Authority

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Abstract
The In-Band On-Channel (IBOC) solution to replace stereo quality FM transmission with CD quality sound using the same FM channel has had further advances in the USA. The National Radio Systems Committee (NRSC) has evaluated the iBiquity Digital Corporation's FM IBOC System to determine the compatibility of IBOC operation with analog reception of existing FM stations. This paper outlines the basic technical fundamentals of IBOC, the current status of the technology and the possible impact of IBOC on the Australian broadcasting environment.

What is IBOC
IBOC (In-Band On-Channel)[1] digital radio technology, also referred to internationally as Digital System C, facilitates the introduction of Digital Sound Broadcasting (DSB) by allowing existing FM stations to broadcast the same programming in analog and digital without the need for new spectrum allocations for the digital signal.

IBOC is capable of transmitting audio services and a variety of wireless data services. At the basic level, it will enable broadcasters to transmit data related to digital audio programming, including song title, artist and station information. The initial receiver applications are expected to include the ability to display simple text information related to audio programming. Additional data services are expected to include the delivery of paging-like services, including traffic, weather, sports scores, stock quotes and targeted messages.

The IBOC technology developed by iBiquity Digital Corporation focuses on a transition to digital that works within existing broadcasting infrastructure. The IBOC digital signal is placed within the existing analog FM spectral emissions mask, and as a result IBOC is proposed as the digital solution which may be implemented without the need for new frequency allocations or without disruption to the existing broadcasting infrastructure.

It is proposed that broadcasters use their existing transmission facilities and studio equipment with only the addition of an IBOC exciter and, in limited cases, an upgrade to the station transmitter.

Status of IBOC
The National Radio Systems Committee (NRSC) has released its FM IBOC (In Band On Channel) Digital Radio Evaluation Report, as adopted on November 29, 2001 and recommends that the iBiquity FM IBOC system as evaluated by the NRSC should be authorized by the FCC (Federal Communications Commission) as an enhancement to FM broadcasting in the United States.

The International Telecommunications Union (ITU) is in the process of including IBOC as Digital System C in Recommendation ITU-R BS.1114-2: *Systems for terrestrial digital sound broadcasting to vehicular, portable and fixed receivers in the frequency range 30-3000 MHz*.

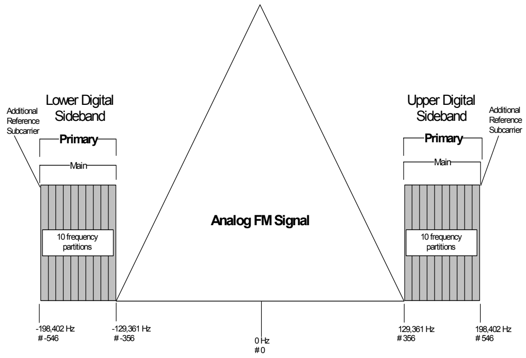
The IBOC system tested and presented in the NRSC evaluation reports used MPEG-2 AAC[2] as an audio compression technology. It is proposed by iBiquity Digital Corporation to use its own audio compression technology in commercial IBOC equipment but this substitution is not expected to impact on the IBOC test results.

[1] Information on IBOC has been extracted/sourced from US National Radio Systems Committee (NRSC) Reports and the International Telecommunications Union (ITU) recommendations for terrestrial digital sound broadcasting – The Digital Sound Broadcasting (DSB) Handbook.
[2] MPEG-2 AAC: Moving Picture Experts Group-2 Advanced Audio Coding

IBOC Modes of Operation

There are three IBOC modes of operation. IBOC allows transition from analog to digital through a *Hybrid* and *Extended Hybrid* mode of operation, before adopting an *All Digital* mode of operation. The digital signal is modulated onto a large number of subcarriers, using orthogonal frequency division multiplexing (OFDM), which are transmitted simultaneously.

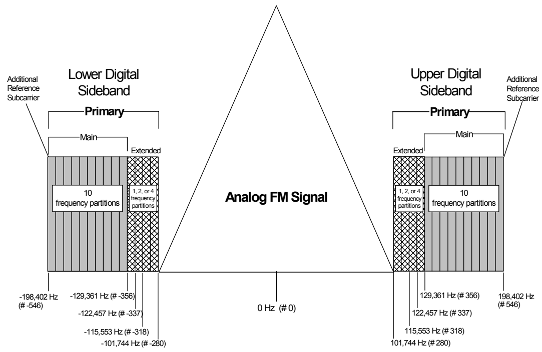
Hybrid Mode. In this mode the digital signal is inserted within a 69.041 kHz bandwidth, 129.361 kHz on either side of the analog FM signal.



The IBOC Hybrid mode digital signal is transmitted in sidebands either side of the analog FM signal and each sideband is approximately 23 dB below the total power in the FM signal. The hybrid sidebands are referred to as Primary Main (PM) sidebands.

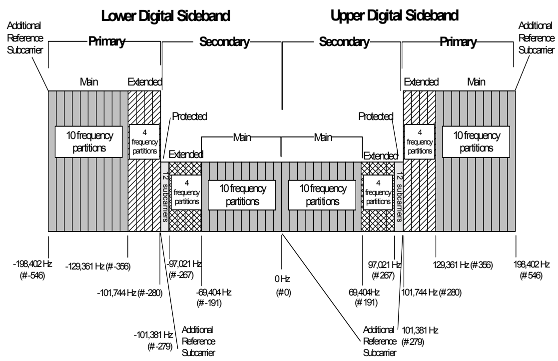
The host analog signal may be mono or stereo, and may include subsidiary communication channels. The total power of the digital sidebands is 20 dB below the nominal power of the FM analog carrier with power relative to the total analog FM power of –41.39 dB/kHz.

Extended Hybrid Mode. This mode includes the hybrid mode and additional digital signals are inserted closer to the analog signal, utilising a 27.617 kHz bandwidth, 101.744 kHz on either side of the analog FM signal.



The IBOC Extended Hybrid mode digital sidebands are extended towards the analog FM signal to increase digital capacity. The extended hybrid sidebands are referred to as Primary Extended (PX) sidebands. The total power of the digital sidebands is 20 dB below the nominal power of the FM analog carrier with power relative to total analog FM power of –41.39 dB/kHz.

All Digital Mode. This mode replaces the analog signal with additional digital signals and also includes the digital signals of the Hybrid and Extended Hybrid modes.



With IBOC All Digital, the primary digital sidebands are extended as in IBOC Extended Hybrid and the analog signal is removed and replaced by lower power digital secondary sidebands, thus expanding the digital capacity. The total power of the digital sidebands is 10 dB below the nominal power of the replaced FM analog carrier with power relative to the total analog FM power of –31.39 dB/kHz.

Of the above three IBOC modes, it should be noted that the only the IBOC Hybrid Mode has been evaluated by the NRSC.

IBOC Capabilities

IBOC enables the broadcaster to select the desired audio quality and data transmission rate however, as expected, there is a trade off between audio quality and the data transmission rate.

The audio quality and data trade off in the three modes is summarised in Table 1:

TABLE 1
Examples of trade off between audio quality and data transmission

	Capacity (kb/s)	Trade Off Audio + Data (kb/s)	
		Example 1	Example 2
Hybrid	97	96 + 1	64 + 33
Extended Hybrid	147	96 + 51	64 + 83
All Digital	277	96 + 181	64 + 213

The audio quality at 96 kb/s is near CD quality but in Hybrid mode this only allows 1 kb/s for data. IBOC allows the bit rate to be adjusted in 8 kb/s steps. By transmitting audio at the satellite DARS[3] bit rate of 64 kb/s, additional data capacity, exceeding that of the current generation of mobile phones (9 – 19kb/s), is available. At times when audio quality is not as important, the audio bit rate may be reduced to as low as 48 kb/s but audio quality will be reduced to near telephone audio quality.

IBOC incorporates a 4.5 second delay between the analog and digital audio signals. The receiver initially acquires the analog signal and takes a few seconds to begin to decode the audio on the digital sidebands. If 10% of the digital data blocks sent are corrupted during transmission, the IBOC receiver reverts to the analog signal. This is referred to as the "blend-to-analog" feature of IBOC. The blend process is perceived to have the same quality as the analog audio and the process itself does not degrade the audio quality below that of analog.

Field tests indicate that Hybrid FM IBOC digital coverage is comparable to analog coverage but IBOC reception can be obtained in areas where the analog service is currently of an unacceptable quality due to interference such as co-channel interference, impulse noise and multi-path fading.

The enhancements claimed over traditional analog FM broadcasting include:
- almost full immunity from typical FM multipath reception problems;
- significantly improved full stereo coverage;
- flexible datacasting opportunities: and
- efficient means for FM broadcasters to begin the transition to digital broadcasting
- use of OFDM in IBOC allows on-channel digital repeaters.

It is expected that there will be a trade off in audio signal-to-noise ratios in some areas where 1st adjacent (IBOC) stations overlap, but this is only expected where 1st adjacent interference currently exists with adjacent channel analog services.

The iBiquity field tests conducted with eight FM broadcasting stations in the US, concluded that digital coverage with one hundredth the power (-20dB) of analog, extended to the 45 - 50 dBu signal level.

[3] Digital Audio Radio Service

Impact on Broadcast Planning
In addressing the impact of the introduction of IBOC on broadcasting planning in Australia, there are two key issues that are worthy of noting. The first issue is IBOC's compliance with the spectral emissions mask of the Australian FM broadcasting service and the second is the effect on the required protection ratio between FM services, which determines the separation distance between FM broadcasting services.

The FM Spectral Emissions mask
The emission standard for the Australian Frequency Modulation Sound Broadcasting Service specifies the maximum values for out-of-band and spurious outputs. This is referred to as the spectral emissions mask

This limits the out-of-band and spurious outputs and restricts any emission appearing on a frequency removed from the carrier. Between 120 kHz and 240 kHz, emissions are to be attenuated by at least 25 dB below the level of the unmodulated carrier. Any output appearing on a frequency removed from the carrier by more than 240 kHz, up to and including 600 kHz, is to be attenuated by at least 35 dB below the level of the unmodulated carrier. Any output appearing at a frequency removed from the carrier by more than 600 kHz is to be attenuated by at least 43 + 10 log P dB (where P is transmitter power in watts) below the level of the unmodulated carrier, or 80 dB whichever is the lesser attenuation.

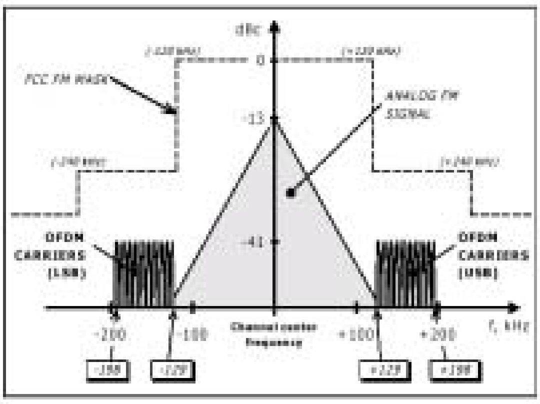


TABLE 2
RF Spectral Emissions Mask

All three IBOC digital transmission modes are proposed to operate well below the FM radio spectral emissions mask. The diagram above indicates the Hybrid Mode within the FCC's emissions mask.

IBOC Evaluation and Protection between FM Services
Compatibility testing of the Hybrid IBOC System was undertaken using the FCC's required protection ratios for the level of desired signal to the interferer (D/U) for a desired signal of -62 dBm (54 dBuV/m).

The FCC's protection ratios considered during IBOC testing include a co-channel desired-to-undesired (D/U) signal strength ratio of 20 dB; a first adjacent channel D/U of 6 dB; and a second and third adjacent channel D/U of -40 dB.

The FCC desired or service signal strength is based on median f(50,50) field strength and the undesired or interfering signal strength is based on median f(50,10) field strength.[4]

The ITU recommends protection ratios[5] of 45(37) dB[6] for co-channel protection; 7(7) dB for 200 kHz carrier frequency separations; and –20(-20) dB for 400 kHz carrier frequency separations.

[4] The f(x,y) notation represents the field strength exceeded at x percent of locations y percent of the time.
[5] Rec. ITU-R BS.412-9
[6] Protection ratios for continuous (tropospheric) interference.

The protection ratios provide an approximate 50 dB audio signal-to-noise ratio[7] for stereophonic reception.

Protection ratios used in Australia under the same conditions are based on the ITU recommendations. The protection ratios adopted include 45(37) dB for co-channel protection; 25(17) dB for 200 kHz carrier frequency separations; and -18(-18) dB for 400 kHz carrier frequency separations.

IBOC Testing and Results
The Advanced Television Technology Centre (ATTC) conducted compatibility testing of the IBOC System and submitted its report[8] to the NRSC. Again it should be noted that this testing only included the IBOC Hybrid mode. The NRSC evaluated the data provided by ATTC and concluded that:

- Listeners should not perceive an impact on the analog host signal, nor on the analog signals of carriers that are either co-channel or 2nd adjacent channel (+/- 400 kHz) with respect to the IBOC signal
- A limited number of listeners may perceive an impact outside the protected area on the analog signals of carriers that are 1st adjacent channel (+/- 200 kHz) with respect to the IBOC signal.

Host Compatability. The objective test results (attachment A) on IBOC interference to the host analog, shows that there is negligible effect on very selective receivers (automotive) but a reduction in audio signal-to- noise of up to 10 –15 dB can result with less selective receivers (home stereos and portable receivers).

The outcome of the field tests resulted in iBiquity concluding that, with IBOC turned on and off, listeners did not perceive any meaningful difference from the introduction of IBOC.

First Adjacent Channel Compatibility (200 kHz). The ATTC objective test results on IBOC interference on a 1st adjacent channel concluded that the addition of –22 dB digital sidebands on an adjacent analog channel, with a D/U protection ratio of +6 dB, degrades the audio signal-to- noise of the wanted analog service by an average of 4.2 dB.

In all receiver types tested, it was identified from objective testing that analog audio quality was reduced when IBOC digital sidebands were present on a 1st adjacent channel. The NRSC specifically identified that the audio quality of the analog aftermarket automotive radio, under moderate interference conditions was reduced from good to poor.

Field test results indicate that there is some potential impact on analog first adjacent channels, but analysis of listening patterns conclude the number of affected listeners to be exceedingly small with, on average, only 0.6% of an FM stations existing analog listeners experiencing any impact from the introduction of IBOC.

The NRSC identified that one of the greatest compatibility challenges facing FM IBOC was addressing the 1st adjacent channel interference potential to an existing analog service. This was after evaluating data in respect to moderate interference (+16 to +6 dB D/U) from subjective evaluation of audio in the field (speech programming).

As outlined above, the interference levels on which FM services are planned in Australia for 1st adjacent channels are 25 dB D/U for continuous interference and 17 dB D/U for tropospheric interference. The moderate interference signal of +16 dB D/U used in IBOC tests, that causes a

[7] Weighted quasi-peak measurement according to Rec. ITU-R BS.468
[8] Ibiquity/ATTC/Dynasat FM IBOC Test Data Report

degrading of audio quality is very similar to the protection requirement that required in Australian where +17 dB D/U is required for protection against tropospheric interference. Given a similar protection ratio (D/U), it is assumed that subjective assessment of audio quality with a moderate interference signal of +16 dB (D/U) would result in similar results in Australian under tropospheric interference conditions.

The objective test laboratory results for receivers using +16 dB D/U and +6 dB D/U protections are included at Attachment A. The analysis of the +16 dB D/U data gives a better indication as to the impact that IBOC would have in Australia under tropospheric interference conditions.

The test results show that with analog 1st adjacent channel interference, at a D/U of +6 and +16 dB, there is no difference in audio signal-to-noise with very selective receivers but the less selective receivers benefit from the greater protection ratio (D/U).

With IBOC digital 1st adjacent channel interference at 6 dB (D/U), there is approximately a 20 dB reduction in audio signal-to-noise with very selective receivers whilst at 16 dB (D/U) there is an approximate 10 dB reduction. This reduction becomes approximately 10 dB and 3 dB respectively when the channel is subject to Additive White Gaussian Noise (AWGN) at a level of 30,000K[9]. The addition of a background noise component to RF signals under test has been done to make the subjective evaluation more realistic and comparable to 'real world' conditions.

The NRSC concluded that the tradeoffs, necessary for adoption of FM IBOC in the USA, are relatively minor. One tradeoff identified is that that a small decrease in signal-to-noise will be evident to some listeners in localized areas, where 1st adjacent stations operating with the FM IBOC system, overlap the coverage of the desired analog station.

Second Adjacent Channel Compatibility (400 kHz). Results of these field tests mirror the host compatibility results, indicating no meaningful difference in the analog signal with the digital signal turned on and off.

Conclusions

The IBOC spectral emission, in all three modes of operation, falls within the emission standard for the Australian FM Sound Broadcasting Service.

Objective test results conclude that on introduction of a Hybrid IBOC digital transmission there is potential for reduction of the host analog audio quality in home stereo receivers and portable radio receivers by a substantial reduction in the signal-to-noise. This should not be noticeable in car radio receivers (very selective receivers). Subjective assessments in the US broadcasting environment did not perceive any meaningful difference from the introduction of IBOC on the host analog audio quality.

Objective test results conclude that on introduction of a Hybrid IBOC digital transmission there is potential for reduction of the 1st adjacent analog audio quality, in car radio receivers, by a reduction in the audio signal-to-noise. The reduction in audio quality was recorded in objective test results and experienced in the subjective assessments conducted in the US. This effect is not expected to be as great in Australia as a higher protection ratio is used in planning for protection against 1st adjacent channel interference. Nevertheless, objective and subjective test results show that a reduction in audio signal-to-noise results, and therefore the effect that this will have on Australian listening patterns will need to be assessed.

[9] Absolute power level of the noise is in Kelvin units and chosen to be representative of an urban noise level of 15 dBu.

The effect that an Extended Hybrid and All Digital IBOC digital transmissions have on the analog host and adjacent channel audio quality has not been assessed as tests in the USA have not yet been conducted.

ACKNOWLEDGEMENT

Information in this paper has been sourced from the National Radio Systems DAB Subcommittee (NRSC) Report on the evaluation of the iBiquity Digital Corporation IBOC system, the FM IBOC Test Data Report (from Ibiquity/ATTC /Dynasat) and the proposed International Telecommunications Union (ITU) recommendation[10] for terrestrial digital sound broadcasting.

REFERENCES

[1] US National Radio Systems Committee (NRSC) FM IBOC Evaluation Report, 29 Nov 2001
[2] Rec. ITU-R BS.412-9
[3] Rec. ITU-R BS.468
[4] Ibiquity/ATTC/Dynasat FM IBOC Test Data Report, Aug 2001
[5] Rec ITU-R BS.1114-2

ATTACHMENT:

A. IBOC Objective Test Results

[10] Rec ITU-R BS.1114-2

Attachment A

OBJECTIVE TEST RESULTS

Objective Test Results – 1st Adjacent Channel Single Interferer
Wanted signal strength: 54 dBuV/m (Moderate) with +16 dB D/U
WQP SNR (dB)

	Delphi 09394139		Pioneer KEH-1900		Technics SA-EX110		Sony CFD-S22	
Undesired	**Analog**	**Hybrid**	**Analog**	**Hybrid**	**Analog**	**Hybrid**	**Analog**	**Hybrid**
Lower 1st Adj	55.1	42.3	53.6	41.5	41.5	40.1	31.3	30.8
Lower 1st Adj*	43.4	39.9	42.5	39.1	39.6	38.6	30.7	30.3
Upper 1st Adj	55.1	43.1	53.6	42.0	40.4	38.7	32.4	31.8
Upper 1st Adj*	43.4	40.3	42.5	39.5	39.1	37.5	31.7	31.3

Objective Test Results – 1st Adjacent Channel Single Interferer
Wanted signal strength: 54 dBuV/m (Moderate) with +6 dB D/U
WQP SNR (dB)

	Delphi 09394139		Pioneer KEH-1900		Technics SA-EX110		Sony CFD-S22	
Undesired	**Analog**	**Hybrid**	**Analog**	**Hybrid**	**Analog**	**Hybrid**	**Analog**	**Hybrid**
Lower 1st Adj	55.1	32.5	53.6	31.7	31.2	30.1	21.3	20.8
Lower 1st Adj*	43.4	32.1	42.6	31.4	31.3	29.8	21.2	20.8
Upper 1st Adj	55.1	33.3	53.6	32.3	30.4	28.7	22.3	21.8
Upper 1st Adj*	43.4	32.9	42.5	31.9	30.1	28.6	22.2	21.7

Objective Test Results – IBOC Interferers into Host Analog
Wanted signal strength: 70 dBuV/m (Strong)
WQP SNR (dB)

	Delphi 09394139		Pioneer KEH-1900		Technics SA-EX110		Sony CFD-S22	
AWGN	**Analog**	**Hybrid**	**Analog**	**Hybrid**	**Analog**	**Hybrid**	**Analog**	**Hybrid**
None	59.4	59.3	56.4	56.3	58.6	49.2	50.9	35.4
30,000K	56.0	56.0	54.0	54.0	55.2	48.7	49.3	35.2

Notes:

* Channel subject to Additive White Gaussian Noise (AWGN) at a level of 30,000K

Receivers selected as representative of their respective categories:

Delphi 09394139	- Type: OEM automotive receiver (Very selective)
Pioneer KEH-1900	- Type: Aftermarket automotive receiver (Very selective)
Technics SA-EX110	- Type: Home stereo receiver (Selective)
Sony CFD-S22	- Type: Portable radio (Moderately)

This attachment contains selective results of tests conducted by the Advanced Television Technology Centre (ATTC) on the iBiquity Digital FM In-Band On-Channel (IBOC) Digital Audio Broadcasting (DAB) System as provided to the NRSC.