THE STRUCTURE AND GENERATION OF ROBUST WAVEFORMS FOR FM IN-BAND ON-CHANNEL DIGITAL BROADCASTING

Paul J. Peyla

iBiquity Digital Corporation
8865 Stanford Blvd.
Columbia, MD 21045
20 Independence Blvd.
Warren, NJ 07058

iBiquity Digital Corporation has developed a digital broadcasting solution that permits a smooth evolution from current analog FM radio to a fully digital in-band on-channel (IBOC) system. The system delivers digital audio and data services to mobile, portable, and fixed receivers from terrestrial transmitters in the existing VHF radio band. Broadcasters may continue to transmit analog FM simultaneously with the new, higher-quality and more robust digital signals. This approach allows broadcasters to convert from analog to digital radio while maintaining their current frequency allocations. This paper describes the structure, generation, and inherent flexibility of the transmitted FM IBOC waveforms.

INTRODUCTION

iBiquity's FM IBOC solution affords broadcasters the ability to tailor their digital audio broadcasts to meet their own specific needs. During the transition period to digital, each station will have the opportunity to convert at its own pace – beginning with a hybrid analog/digital waveform, and eventually turning off the analog and broadcasting an all digital signal.

To support a wide variety of program formats and broadcaster requirements, the FM IBOC system was designed with a high degree of flexibility. Each waveform – whether hybrid or all digital – can be configured in a number of ways by judiciously adjusting the throughput, latency, and robustness of the audio and data program content as it is converted into an IBOC waveform.

This paper describes the structure and generation of the FM IBOC waveforms, and presents the various configurations from which a broadcaster can choose in order to transmit digital audio or data in a manner that best supports his or her particular programming needs.

IBOC SERVICES AND PROTOCOLS

In order to provide broadcaster flexibility and enhance the listening experience, iBiquity's FM IBOC system supports a variety of digital program services. These include a main program service (MPS), personal data service (PDS), station identification service (SIS), and auxiliary application service (AAS).

The MPS delivers existing programming formats in digital audio, along with digital data that directly correlates with the audio programming. Whereas the MPS broadcasts a traditional audio program to listeners, the PDS enables listeners to select on-demand data services, thereby providing personalized, user-valued information. The SIS provides the control and identification information required to allow the listener to search and select IBOC digital radio stations and their supporting services. Finally, the AAS allows a virtually unlimited number of custom and specialized IBOC digital radio applications to co-exist concurrently. Auxiliary applications can be added at any time in the future.

Simultaneous support of these services is provided via the layered protocol stack illustrated in Figure 1. Source material (audio or data) moves down the protocol stack from layer 5 to layer 1 at the transmitter, is broadcast over the air, and is passed back up the protocol stack from layer 1 to layer 5 at the receiver.

At the transmitter, layer 5 receives audio or data program content from the broadcaster. Layer 4 provides content-specific source encoding (such as audio compression), as well as station identification and control capabilities. Layer 3 ensures robust and efficient transfer of layer 4 data, and layer 2 provides limited error detection, addressing, and multiplexing.

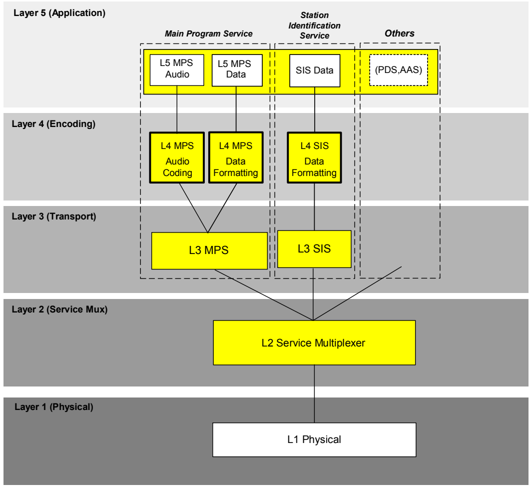

Figure 1 IBOC Protocol Stack

Layer 1 receives the formatted content from layer 2 and creates an FM IBOC waveform for over-the-air transmission in the VHF band. Since most of the signal processing required to generate an FM IBOC waveform occurs in layer 1, it is the focus of this paper.

Formatted program content is received from layer 2 in discrete *transfer frames* via multiple *logical channels*. A transfer frame is an ordered collection of bits originating in layer 2, grouped for processing through a logical channel. A logical channel is simply a signal path that conducts transfer frames from layer 2 through layer 1 with a specified grade of service. The *service mode* defines the active logical channels and their associated transmission characteristics.

This paper describes the FM IBOC system by introducing the following concepts:

- *transmitted waveforms and spectra* – describes the spectral structure of the broadcast IBOC waveforms
- *system configuration* – describes the means by which a broadcaster can tailor a particular IBOC waveform to meet his or her specific needs
- *logical channels* – describes the conduits which carry the formatted program content through layer 1, and their intended use
- *functional components* – describes the layer 1 processes used to convert logical channels of formatted program content to an FM IBOC waveform

TRANSMITTED WAVEFORMS AND SPECTRA

The iBiquity FM IBOC design provides a flexible means of transitioning to a digital broadcast system by providing three new waveform types: hybrid, extended hybrid, and all digital. The hybrid and extended hybrid types retain the analog FM signal, while the all digital type does not.

In all waveforms, the digital signal is modulated using orthogonal frequency division multiplexing (OFDM). In a single-carrier digital modulation scheme, the digital symbols are transmitted serially, with the spectrum of each symbol occupying the entire channel bandwidth during its appointed signaling interval. Conversely, OFDM is a parallel modulation scheme in which the data stream simultaneously modulates a large number of orthogonal subcarriers. Instead of a single, wideband carrier at a high signaling rate, OFDM employs a large number of narrowband subcarriers that are simultaneously transmitted at a much lower composite symbol rate. The long symbol times of OFDM provide superior robustness in the presence of multipath fading and interference.[1] OFDM is also inherently flexible, readily allowing the mapping of specific logical channels to different groups of subcarriers.

The following sections describe the transmitted spectrum for each of the three digital waveform types. Each spectrum is divided into several *sidebands*, which represent various OFDM subcarrier groupings. All spectra are illustrated at baseband, with an upper and lower sideband centered around 0 Hz.

Frequency partitions and spectral conventions

The OFDM subcarriers are assembled into *frequency partitions*. Each frequency partition is comprised of eighteen data subcarriers and one reference subcarrier, as shown in Figure 2 (ordering A) and Figure 3 (ordering B). The position of the reference subcarrier (ordering A or B) varies with the location of the frequency partition within the spectrum.[2]

For each frequency partition, data subcarriers d1 through d18 convey digital program content, while the reference subcarrier conveys system control. OFDM subcarriers are numbered from 0 at the center frequency to ±546 at either end of the channel frequency allocation.

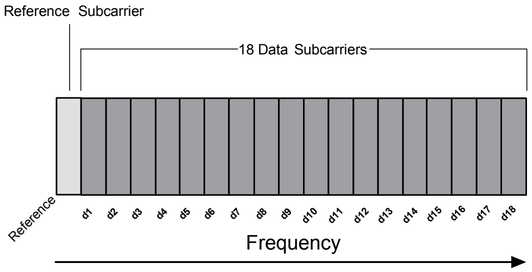

Figure 2 Frequency Partition – Ordering A

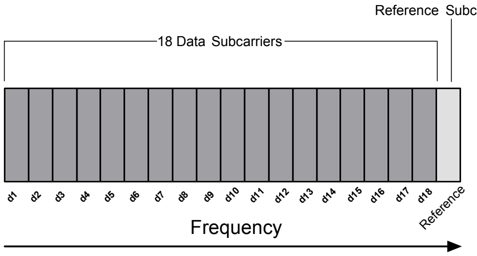

Figure 3 Frequency Partition – Ordering B

Besides the reference subcarriers resident within each frequency partition, depending on the service mode, up to five additional reference subcarriers are inserted into the spectrum at subcarrier numbers −546, −279, 0, 279, and 546. The overall effect is a regular distribution of reference subcarriers throughout the spectrum.

For notational convenience, each reference subcarrier is assigned a unique identification number between 0 and 60. All lower sideband reference subcarriers are shown in Figure 4. All upper sideband reference subcarriers are shown in Figure 5. The figures indicate the relationship between reference subcarrier numbers and OFDM subcarrier numbers.

Each spectrum described in the remaining subsections shows the subcarrier number and center frequency of certain key OFDM subcarriers. The center frequency of a subcarrier is calculated by multiplying the subcarrier number by the OFDM subcarrier spacing Δf ≈ 363.373 Hz. The center of subcarrier 0 is located at 0 Hz. In this context, center frequency is relative to the radio frequency (RF) allocated channel.

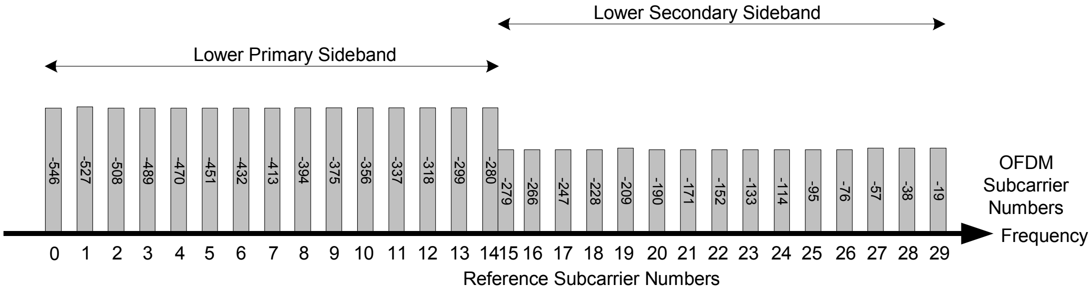

Figure 4 Lower Sideband Reference Subcarrier Spectral Mapping

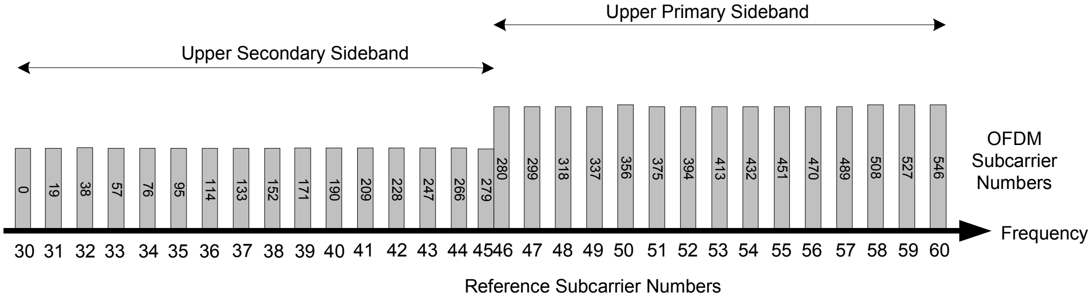

Figure 5 Upper Sideband Reference Subcarrier Spectral Mapping

Hybrid waveform

In the hybrid waveform, the digital signal is transmitted in primary main (PM) sidebands on either side of the analog FM signal, as shown in Figure 6. The analog signal may be monophonic or stereo, and may include SCA channels. Each PM sideband is comprised of ten frequency partitions, which are allocated among subcarriers 356 through 545, or -356 through -545. Subcarriers 546 and -546, also included in the PM sidebands, are additional reference subcarriers. Table 1 summarizes the upper and lower primary main sidebands for the hybrid waveform.

The power spectral density of each OFDM subcarrier in the PM sideband, relative to the host analog power, is given in Table 1. A value of 0 dB would produce a digital subcarrier whose power was equal to the total power in the unmodulated analog FM carrier. The value was chosen so that the total average power in a primary main digital sideband (upper or lower) is 23 dB below the total power in the unmodulated analog FM carrier.

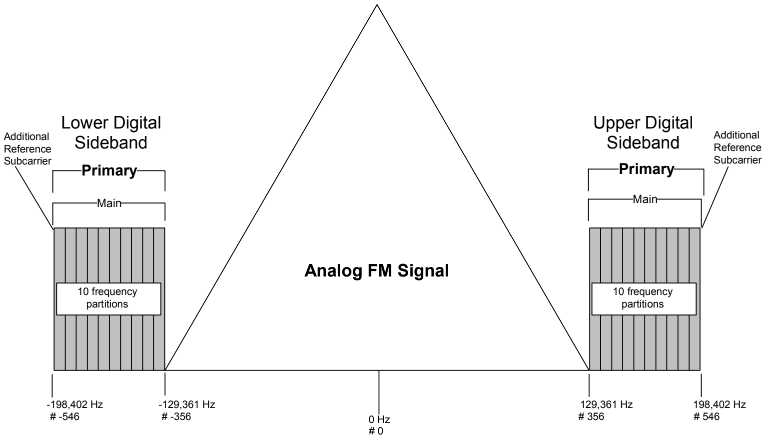

Figure 6 Spectrum of the Hybrid Waveform

Table 1 Hybrid Waveform Spectral Summary

Sideband	Number of Frequency Partitions	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Frequency Span (Hz)	Power Spectral Density (dBc per subcarrier)	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	69,041	-45.8	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	69,041	-45.8	Includes additional reference subcarrier -546

Extended hybrid waveform

The extended hybrid waveform is created by adding OFDM subcarriers to the primary main sidebands present in the hybrid waveform, as shown in Figure 7. Depending on the service mode, one, two, or four frequency partitions can be added to the inner edge of each primary main sideband. This additional spectrum is termed the primary extended (PX) sideband. Table 2 summarizes the upper and lower primary sidebands for the extended hybrid waveform.

The power spectral density of each OFDM subcarrier in the PM and PX sidebands, relative to the host analog power, is given in Table 2. Like the hybrid waveform, the value was chosen so that the total average power in a primary main sideband (upper or lower) is 23 dB below the total power in the unmodulated analog FM carrier. The level of the subcarriers in the PX sidebands is equal to the level of the subcarriers in the PM sidebands.

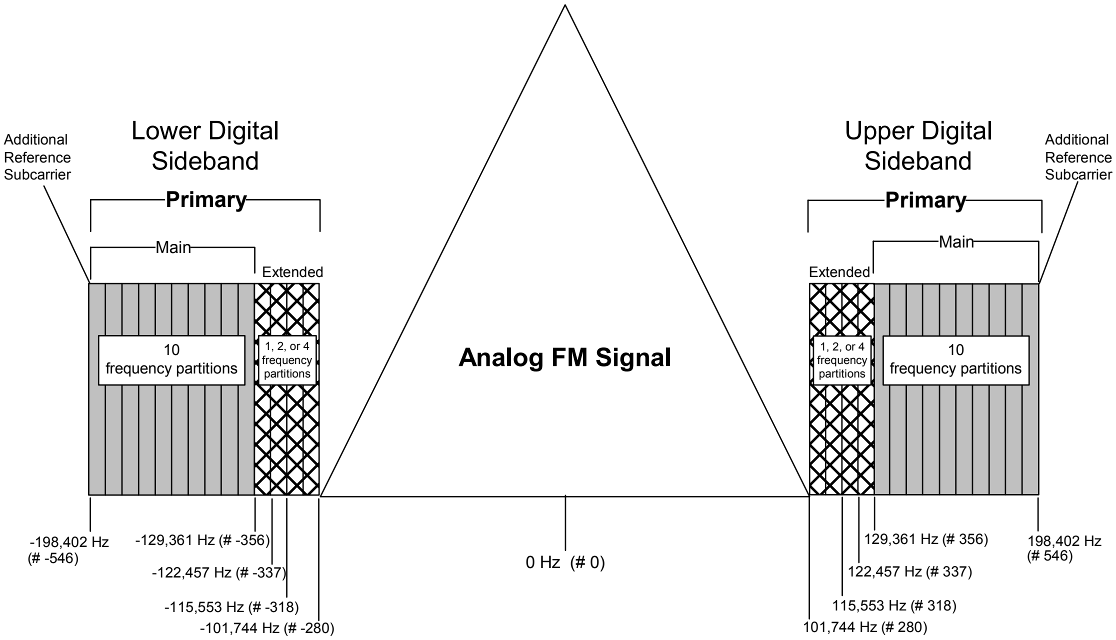

Figure 7 Spectrum of the Extended Hybrid Waveform

Table 2 Extended Hybrid Waveform Spectral Summary

Sideband	Number of Frequency Partitions	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Frequency Span (Hz)	Power Spectral Density (dBc per subcarrier)	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	69,041	-45.8	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	69,041	-45.8	Includes additional reference subcarrier -546
Upper Primary Extended (1 frequency partition)	1	A	337 to 355	122,457 to 128,997	6,540	-45.8	none
Lower Primary Extended (1 frequency partition)	1	B	-337 to -355	-122,457 to -128,997	6,540	-45.8	none
Upper Primary Extended (2 frequency partitions)	2	A	318 to 355	115,553 to 128,997	13,444	-45.8	none
Lower Primary Extended (2 frequency partitions)	2	B	-318 to -355	-115, 553 to -128,997	13,444	-45.8	none
Upper Primary Extended (4 frequency partitions)	4	A	280 to 355	101,744 to 128,997	27,253	-45.8	none
Lower Primary Extended (4 frequency partitions)	4	B	-280 to -355	-101, 744 to -128,997	27,253	-45.8	none

All digital waveform

The all digital waveform is constructed by disabling the analog signal, fully expanding the bandwidth of the primary digital sidebands, and adding lower-power secondary sidebands in the spectrum vacated by the analog signal. The spectrum of the all digital waveform is shown in Figure 8.

In addition to the ten main frequency partitions, all four extended frequency partitions are present in each primary sideband of the all digital waveform. Each secondary sideband also has ten secondary main (SM) and four secondary extended (SX) frequency partitions. Unlike the primary sidebands, however, the secondary main frequency partitions are mapped nearer to channel center with the extended frequency partitions farther from the center.

Each secondary sideband also supports a small secondary protected (SP) region consisting of 12 OFDM subcarriers and reference subcarrier 279 or -279. The sidebands are referred to as “protected” because they are located in the area of spectrum *least* likely to be affected by analog or digital interference. An additional reference subcarrier is placed at the center of the channel (0). Frequency partition ordering of the SP region does not apply since the SP region does not contain frequency partitions as defined in Figure 2 and Figure 3.

The total frequency span of the entire all digital spectrum is 396,803 Hz. Table 3 summarizes the upper and lower, primary and secondary sidebands for the all digital waveform.

The power spectral density of each OFDM subcarrier is given in Table 3. As with the hybrid and extended hybrid waveforms, the values are relative to the level of the unmodulated analog FM carrier that is allocated for a particular broadcaster (even though the analog carrier is not transmitted in the all digital waveform).

The primary sideband level sets the total average power in a primary digital subcarrier at least 10 dB above the total power in a hybrid primary digital subcarrier. Any one of four power levels may be selected for application to the secondary sidebands. The four secondary power levels set the power spectral density of the secondary digital subcarriers (upper and lower) in the range of 5 to 20 dB below the power spectral density of the all digital primary subcarriers. A single secondary power level is evenly applied to all secondary sidebands.

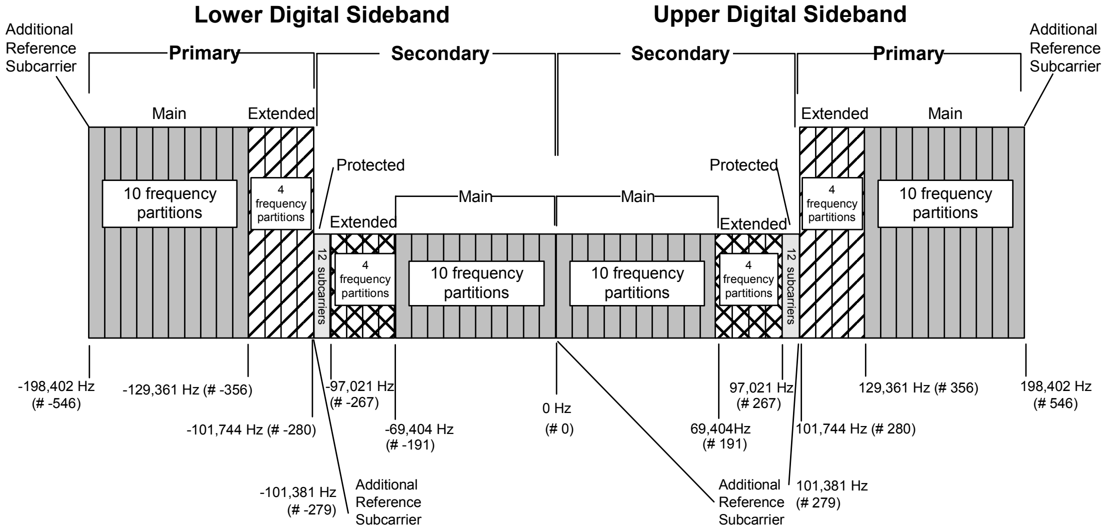

Figure 8 Spectrum of the All Digital Waveform

Table 3 All Digital Waveform Spectral Summary

Sideband	Number of Frequency Partitions	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Frequency Span (Hz)	Power Spectral Density (dBc per subcarrier)	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	69,041	-35.8	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	69,041	-35.8	Includes additional reference subcarrier -546
Upper Primary Extended	4	A	280 to 355	101,744 to 128,997	27,253	-35.8	none
Lower Primary Extended	4	B	-280 to -355	-101,744 to -128,997	27,253	-35.8	none
Upper Secondary Main	10	B	0 to 190	0 to 69,041	69,041	-40.8, -45.8, -50.8, -55.8	Includes additional reference subcarrier 0
Lower Secondary Main	10	A	-1 to -190	-363 to -69,041	68,678	-40.8, -45.8, -50.8, -55.8	none
Upper Secondary Extended	4	B	191 to 266	69,404 to 96,657	27,253	-40.8, -45.8, -50.8, -55.8	none
Lower Secondary Extended	4	A	-191 to -266	-69,404 to -96,657	27,253	-40.8, -45.8, -50.8, -55.8	none
Upper Secondary Protected	N/A	N/A	267 to 279	97,021 to 101,381	4,360	-40.8, -45.8, -50.8, -55.8	Includes additional reference subcarrier 279
Lower Secondary Protected	N/A	N/A	-267 to -279	-97,021 to -101,381	4,360	-40.8, -45.8, -50.8, -55.8	Includes additional reference subcarrier -279

Noise and emissions limits

All FM IBOC transmissions will remain within the FCC emissions mask in accordance with CFR Title 47 §73.317, as summarized in Table 4.[3] Measurements of the analog signal are made at the antenna input by averaging the power spectral density in a 1-kHz bandwidth over a 10-second segment of time.

Table 4 FCC RF Spectral Emissions Mask

Offset from Carrier Frequency (kHz)	Power Spectral Density Relative to Unmodulated Analog FM Carrier (dBc/kHz)
120 to 240	-25
240 to 600	-35
greater than 600	-80, or -43 - (10 · $\log_{10}$ [power in watts]), whichever is less, where [power in watts] refers to the total unmodulated transmitter output carrier power

SYSTEM CONFIGURATION

The FM IBOC transmission system is configured through primary and secondary service modes, analog diversity delay, and sideband power levels. The system configuration determines how the various logical channels are combined to generate the transmitted waveform.

Service modes

The service modes dictate the performance and configuration of the logical channels, which carry program content through layer 1. There are two types of service modes: primary service modes, which configure primary logical channels, and secondary service modes, which configure secondary logical channels. The seven primary service modes are MP1, MP2, MP3, MP4, MP5, MP6, and MP7. The four secondary service modes are MS1, MS2, MS3, and MS4.

Service mode MP1 is used to broadcast the hybrid waveform. Service modes MP2 through MP4 increase the capacity of the hybrid waveform by adding one, two, or four extended frequency partitions to each primary sideband. Service modes MP5 through MP7 employ all primary extended frequency partitions, and are used to broadcast the extended hybrid or all digital waveform. Service modes MS1 through MS4 configure the secondary sidebands in the all digital waveform. The allowable service modes for each FM IBOC waveform type are summarized in Table 5.

Table 5 Allowable Service Modes for FM IBOC Waveforms

Waveform	Primary Service Modes	Secondary Service Modes
Hybrid	MP1	None
Extended Hybrid	MP2 – MP7	None
All Digital	MP5 – MP7	MS1 – MS4

All waveforms require the definition of a primary and a secondary service mode. If secondary sidebands are not present (as in the hybrid or extended hybrid waveform), the secondary service mode is set to “None.” Service modes MP1 through MP4 are invalid for the all digital waveform. Only primary service modes MP5 through MP7 may be paired with secondary service modes MS1 through MS4 when broadcasting the all digital waveform. Any combination of these primary and secondary service modes is allowable.

Table 5 indicates that there are up to 19 possible combinations of service modes, thereby providing ample flexibility to the broadcaster. The actual configuration of logical channels by service mode, the assignment of program content to the active logical channels, and the subsequent mapping of the logical channels to the appropriate digital sidebands is detailed in later sections.

Analog diversity delay

To provide robust reception during outages typical of a mobile environment, the FM IBOC system applies time diversity between independent analog and digital transmissions of the same audio source. In addition, a blend function allows graceful audio degradation of the digital signal as the receiver nears the edge of a station’s coverage. The FM IBOC system can provide this capability by delaying the analog transmission by several seconds relative to the digital audio transmission. When the digital signal is corrupted, the receiver blends to analog which, by virtue of its time diversity with the digital signal, does not experience the outage.[4]

To support this feature, in service modes MP1 through MP4, the analog audio is delayed in an upper protocol layer by a fixed duration to realize time diversity with the digital audio. When the system is transmitting the extended hybrid waveform in service modes MP5 – MP7, or the all digital waveform, the analog diversity delay is automatically set to zero.

Sideband power levels

The levels of the primary and secondary sidebands are independently scaled. Primary sideband power levels are fixed, and depend on the transmitted waveform. Hybrid and extended hybrid waveforms have a different primary power level than all digital waveforms.

One of four secondary sideband power levels must be selected for application to each of the secondary sidebands. They allow the power spectral density of the secondary digital subcarriers to lie 5, 10, 15, or 20 dB below the power spectral density of the all digital primary subcarriers.

LOGICAL CHANNELS

A logical channel is a signal path that conducts program content through layer 1 with a specific grade of service, as determined by the service mode. There are ten logical channels, although not all are used in every service mode. The variety of logical channels reflects the inherent flexibility of the system.

There are four primary logical channels, denoted as P1, P2, P3, and PIDS. There are six secondary logical channels that are used only with the all digital waveform. They are denoted as S1, S2, S3, S4, S5, and SIDS. Logical channels P1 through P3 and S1 through S5 are designed to convey digital audio and data, while the PIDS and SIDS logical channels are designed to carry IBOC data service (IDS) information.

The performance of each logical channel is completely described through three characterization parameters: throughput, latency, and robustness. The service mode sets these characterization parameters by defining the spectral mapping, interleaver depth, diversity delay, and channel encoding for each active logical channel.

Characterization parameters

Throughput. Throughput defines the layer 1 audio or data capacity of a logical channel, excluding upper layer framing overhead. The block-oriented operations of layer 1 (such as interleaving) require that it process data in discrete transfer frames, rather than continuous streams. As a result, throughput is calculated as the product of transfer frame size and transfer frame rate. Spectral mapping and channel code rate determine the throughput of a logical channel, since spectral mapping limits capacity and coding overhead limits information throughput.

Latency. Latency is the delay that a logical channel imposes on a transfer frame as it traverses layer 1. The latency of a logical channel is defined as the sum of its interleaver depth and diversity delay. It does not include processing delay or delays through higher protocol layers.

The interleaver depth determines the amount of delay imposed on a logical channel by its interleaver. Diversity delay is also applied to some logical channels to improve robustness. For example, in some service modes, logical channel P1 presents dual processing paths; one path is delayed and the other is not.

Robustness. Robustness is the ability of a logical channel to withstand channel impairments such as noise, interference, and fading. There are eleven relative levels of robustness in the FM IBOC system. A robustness of 1 indicates a very high level of resistance to channel impairments, while an 11 indicates a lower tolerance for channel-induced errors.

Spectral mapping, channel code rate, interleaver depth, and diversity delay determine the robustness of a logical channel. Spectral mapping affects robustness by setting the relative power level, spectral interference protection, and frequency diversity of a logical channel. Channel coding increases robustness by introducing redundancy into the logical channel. Interleaver depth influences performance in multipath fading. Finally, some logical channels in certain service modes delay transfer frames by a fixed duration to realize time diversity. This diversity delay also affects robustness, since it mitigates the effects of the mobile radio channel.

Assignment of characterization parameters

Table 6 through Table 16 show the active logical channels and their characterization parameters – throughput, latency, and relative robustness – for a given service mode. A broadcaster might use these tables as a basis of comparison when selecting a service mode.

Table 6 Logical Channels - Service Mode MP1

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
P1	98.4	1.49	2
PIDS	0.9	0.09	3

Table 7 Logical Channels - Service Mode MP2

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
P1	98.4	1.49	2
P3	12.4	0.19	4
PIDS	0.9	0.09	3

Table 8 Logical Channels - Service Mode MP3

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
P1	98.4	1.49	2
P3	24.8	0.19	4
PIDS	0.9	0.09	3

Table 9 Logical Channels – Service Mode MP4

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
P1	98.4	1.49	2
P3	49.6	0.19	4
PIDS	0.9	0.09	3

Table 10 Logical Channels - Service Mode MP5

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
P1	24.8	4.64	1
P2	73.6	1.49	2
P3	24.8	0.19	4
PIDS	0.9	0.09	3

Table 11 Logical Channels - Service Mode MP6

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
P1	49.6	4.64	1
P2	48.8	1.49	2
PIDS	0.9	0.09	3

Table 12 Logical Channels – Service Mode MP7

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
P1	24.8	0.19	4
P2	98.4	1.49	2
P3	24.8	0.19	4
PIDS	0.9	0.09	3

Table 13 Logical Channels – Service Mode MS1

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
S4	98.4	0.19	7
S5	5.5	0.09	6
SIDS	0.9	0.09	8

Table 14 Logical Channels – Service Mode MS2

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
S1	24.8	4.64	5
S2	73.6	1.49	9
S3	24.8	0.19	11
S5	5.5	0.09	6
SIDS	0.9	0.09	10

Table 15 Logical Channels – Service Mode MS3

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
S1	49.6	4.64	5
S2	48.8	1.49	9
S5	5.5	0.09	6
SIDS	0.9	0.09	10

Table 16 Logical Channels – Service Mode MS4

Logical Channel	Throughput (kbps)	Latency (seconds)	Relative Robustness
S1	24.8	0.19	11
S2	98.4	1.49	9
S3	24.8	0.19	11
S5	5.5	0.09	6
SIDS	0.9	0.09	10

Spectral mapping

For a given service mode, each logical channel is assigned to a group of OFDM subcarriers or frequency partitions. This spectral mapping contributes to the throughput and robustness of the logical channel.

Since this is a digital system, the various logical channels are simply conduits for the delivery of bits; the *content* of the bits is immaterial. However, the service modes were designed with specific services in mind for the active logical channels. As a result, although not strictly required, the recommended use of the logical channels is described along with the spectral mapping in the following sections.

Primary spectral mapping. The following sections illustrate the assignment of primary logical channels to the primary sidebands, and describe the intended application of the logical channels for each primary service mode.

Service mode MP1 spectral mapping. The assignment of logical channels to OFDM subcarriers in service mode MP1 is shown in Figure 9. Both the P1 and PIDS logical channels are mapped to the upper and lower primary main sidebands. In service mode MP1, the P1 logical channel is designed to carry the MPS audio, while the PIDS logical channel would carry SIS data. Identical program material is carried on each sideband (upper and lower), so that the alternate sideband would be available if the other sideband were corrupted.

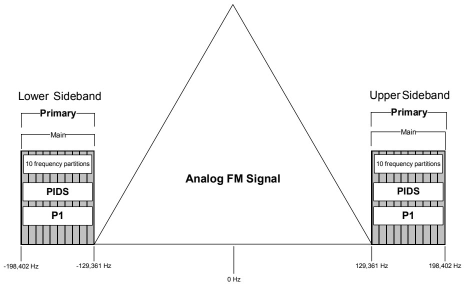

Figure 9 Spectral Mapping – Service Mode MP1

Service mode MP2 spectral mapping. The assignment of logical channels to OFDM subcarriers in service mode MP2 is shown in Figure 10. The transmitted spectrum in service mode MP2 is identical to service mode MP1, with the addition of a single extended frequency partition to each primary sideband. As in service mode MP1, the P1 and PIDS logical channels carry MPS audio and SIS data on each primary main sideband. In addition, the P3 logical channel is designed to carry additional data services, such as MPS, PDS, or AAS data, on the primary extended sidebands. Identical program material is carried on each sideband, so that the alternate sideband would be available if the other sideband were corrupted.

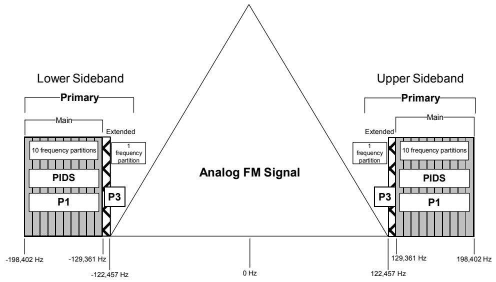

Figure 10 Spectral Mapping – Service Mode MP2

Service mode MP3 spectral mapping. The assignment of logical channels to OFDM subcarriers in service mode MP3 is shown in Figure 11. The transmitted spectrum in service mode MP3 is identical to service mode MP1, with the addition of two extended frequency partitions to each primary sideband. As in service mode MP1, the P1 and PIDS logical channels carry MPS audio and SIS data on each primary main sideband. In addition, the P3 logical channel is designed to carry additional data services, such as MPS, PDS, or AAS data, on the primary extended sidebands. Identical program material is carried on each sideband, so that the alternate sideband would be available if the other sideband were corrupted.

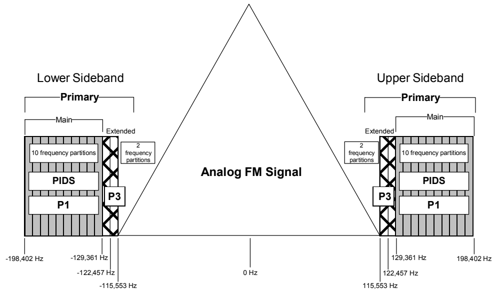

Figure 11 Spectral Mapping – Service Mode MP3

Service mode MP4 spectral mapping. The assignment of logical channels to OFDM subcarriers in service mode MP4 is shown in Figure 12. The transmitted spectrum in service mode MP4 is identical to service mode MP1, with the addition of all four extended frequency partitions to each primary sideband. As in service mode MP1, the P1 and PIDS logical channels carry MPS audio and SIS data on each primary main sideband. In addition, the P3 logical channel is designed to carry additional data services, such as MPS, PDS, or AAS data, on the primary extended sidebands. Identical program material is carried on each sideband, so that the alternate sideband would be available if the other sideband were corrupted.

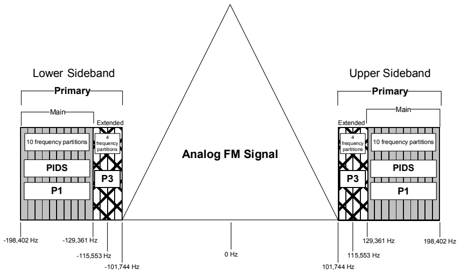

Figure 12 Spectral Mapping – Service Mode MP4

Service modes MP1 through MP4 provide essentially the same program services, with varying data capacity via the P3 logical channel on the primary extended sidebands.

Service Mode MP5 Spectral Mapping. The assignment of logical channels to OFDM subcarriers in service mode MP5 is shown in Figure 13. The transmitted spectrum is identical in service modes MP4 and MP5. However, the spectral mapping in service mode MP5 allows operation as either an extended hybrid or all digital waveform.

In service mode MP5, the MPS audio is divided into core and enhanced audio streams. The core audio is a stand-alone, low bitrate (~25 kbps), backup audio stream. When the core audio is combined with enhanced audio, the result is a virtual-CD quality (~98 kbps) audio stream. The enhanced audio is not autonomous; it can only be used in combination with the core audio stream.

In service mode MP5, the core MPS audio stream is carried by the P1 logical channel, and the enhanced audio is carried by the P2 logical channel. Both P1 and P2 are mapped together in the primary main sidebands. In addition, the same P1 logical channel is diversity delayed and separately mapped to the inner two extended frequency partitions of each primary sideband. At the receiver, the two P1 channels are combined to form a more robust backup core audio stream.

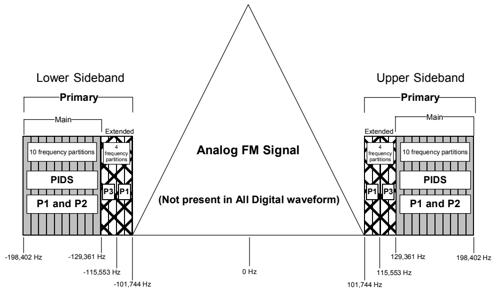

Figure 13 Spectral Mapping – Service Mode MP5

In hybrid and extended hybrid waveforms, the analog host provides fast tuning and a diversity-delayed backup channel for graceful degradation of audio near the edge of coverage. In the all digital waveform, the analog host no longer exists. In this case, the robust P1 logical channel, carrying core audio, acts as the backup for graceful audio degradation and fast tuning (since it is lightly interleaved). When the enhanced audio is not available, the receiver reverts to the backup core audio stream.

The P3 logical channel also carries additional data services, such as MPS, PDS, or AAS data, on the primary extended sidebands. As in service modes MP1-MP4, the PIDS logical channel carries SIS data over the primary main sidebands. Again, identical program material is carried on each sideband, so that the alternate sideband would be available if the other sideband were corrupted.

Service Mode MP6 Spectral Mapping. The assignment of logical channels to OFDM subcarriers in service mode MP6 is shown in Figure 14. The transmitted spectrum is identical to service mode MP5. However, in service mode MP6, the size of the core audio stream is doubled to a higher quality ~50 kbps. As a result, all four frequency partitions in the primary extended sideband are required to carry the backup core audio, and capacity is no longer available for data. Thus, the increased data capacity in service mode MP5 is traded for core audio quality in service mode MP6.

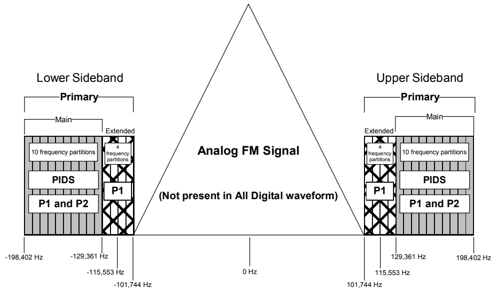

Figure 14 Spectral Mapping – Service Mode MP6

In service mode MP6, the core MPS audio stream is carried by the P1 logical channel, and the enhanced audio is carried by the P2 logical channel. Both P1 and P2 are mapped together in the primary main sidebands. In addition, the same P1 logical channel is diversity delayed and separately mapped to all four extended frequency partitions of each primary sideband. The PIDS logical channel also carries SIS data over the primary main sidebands. Identical program material is carried on each sideband, so that the alternate sideband would be available if the other sideband were corrupted.

Service Mode MP7 Spectral Mapping. The assignment of logical channels to OFDM subcarriers in service mode MP7 is shown in Figure 15. The transmitted spectrum is identical to service modes MP5 and MP6. However, service mode MP7 provides enhanced data capacity by reducing the amount of spectrum devoted to audio programming.

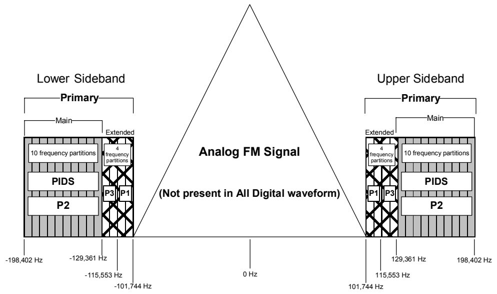

Figure 15 Spectral Mapping – Service Mode MP7

In service mode MP7, MPS audio is carried by the P1 logical channel, which is mapped to the inner two extended frequency partitions of each primary sideband. Logical channel P2 carries MPS, PDS, or AAS data over the primary main sidebands.

As in service mode MP5, the P3 logical channel carries additional data services, such as MPS, PDS, or AAS data, on the primary extended sidebands. The PIDS logical channel also carries SIS data over the primary main sidebands. As always, identical program material is carried on each sideband, so that the alternate sideband would be available if the other sideband were corrupted.

Secondary spectral mapping. The following sections illustrate the assignment of secondary logical channels to the secondary sidebands, and describe the intended application of the logical channels for each secondary service mode. Secondary sidebands are present only in the all digital waveform.

Only the secondary sidebands are presented in the following subsections; the added presence of primary digital sidebands in service modes MP5, MP6, or MP7 is implied.

Service Mode MS1 Spectral Mapping. The assignment of logical channels to OFDM subcarriers in service mode MS1 is shown in Figure 16. Service mode MS1 is intended for the transmission of secondary broadband data.

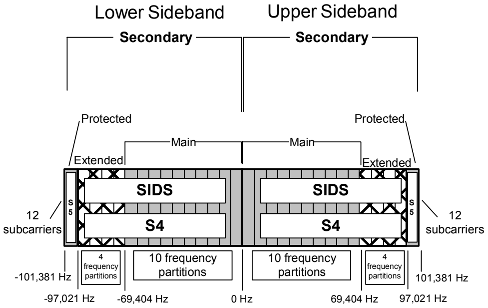

Figure 16 Spectral Mapping – Service Mode MS1

In service mode MS1, logical channel S4 carries MPS, PDS, or AAS data over the secondary main and extended sidebands. In addition, the SIDS logical channel also carries SIS data over the secondary main and extended sidebands. Finally, the S5 logical channel carries MPS, PDS, or AAS data over the secondary protected sidebands.

As with the primary sidebands, identical program material is carried on each secondary sideband (upper and lower), so that the alternate sideband would be available if the other sideband were corrupted.

Service Mode MS2 Spectral Mapping. The assignment of logical channels to OFDM subcarriers in service mode MS2 is shown in Figure 17. Service mode MS2 is the secondary equivalent of primary service mode MP5.

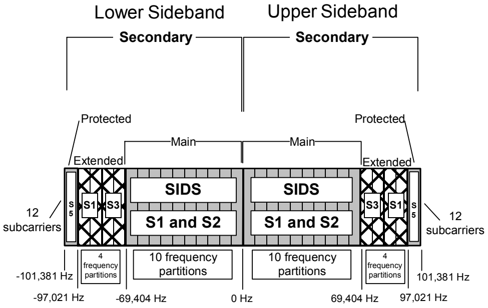

Figure 17 Spectral Mapping – Service Mode MS2

In service mode MS2, the S1 and S2 logical channels might carry core and enhanced auxiliary audio (such as surround sound), intended to enhance the MPS audio broadcast on the primary sidebands. Both S1 and S2 are mapped together in the secondary main sidebands. In addition, the same S1 logical channel is diversity delayed and separately mapped to the outer two extended frequency partitions of each secondary sideband.

The S3 logical channel carries additional data services, such as MPS, PDS, or AAS data, on the secondary extended sidebands. The SIDS logical channel also carries SIS data over the secondary main sidebands. Finally, the S5 logical channel carries MPS, PDS, or AAS data over the secondary protected sidebands. Identical program material is carried on each secondary sideband, so that the alternate sideband would be available if the other sideband were corrupted.

Service Mode MS3 Spectral Mapping. The assignment of logical channels to OFDM subcarriers in service mode MS3 is shown in Figure 18. Service mode MS3 is the secondary equivalent of primary service mode MP6.

As in service mode MS2, the S1 and S2 logical channels might carry core and enhanced auxiliary audio (such as surround sound), intended to enhance the MPS audio broadcast on the primary sidebands. However, in service mode MS3, the size of S1 is doubled, and capacity is no longer available for S3 data.

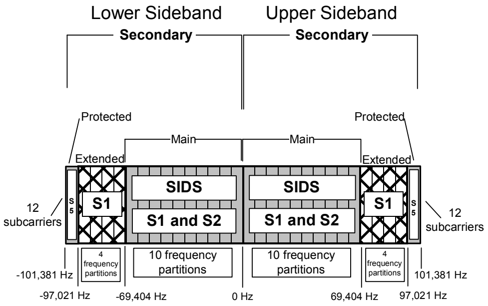

Figure 18 Spectral Mapping – Service Mode MS3

Both S1 and S2 are mapped together in the secondary main sidebands. In addition, the same S1 logical channel is diversity delayed and separately mapped to all four extended frequency partitions of each secondary sideband. The SIDS logical channel also carries SIS data over the secondary main sidebands. Finally, the S5 logical channel carries MPS, PDS, or AAS data over the secondary protected sidebands. Identical program material is carried on each sideband, so that the alternate sideband would be available if the other sideband were corrupted.

Service Mode MS4 Spectral Mapping. The assignment of logical channels to OFDM subcarriers in service mode MS4 is shown in Figure 19. Service mode MS4 is the secondary equivalent of primary service mode MP7. It is intended for broadcast of a single, low-bitrate audio stream, with the remaining capacity reserved for data services.

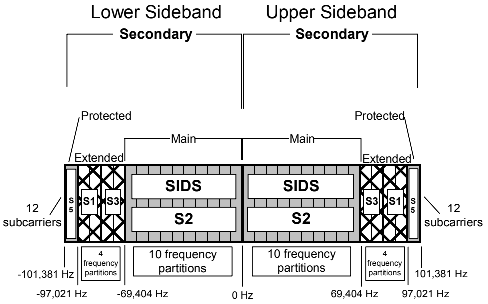

Figure 19 Spectral Mapping – Service Mode MS4

In service mode MS4, the low-bitrate audio is carried by the S1 logical channel, which is mapped to the outer two extended frequency partitions of each secondary sideband. Logical channel S2 carries MPS, PDS, or AAS data over the secondary main sidebands.

As in service mode MS2, the S3 logical channel carries additional data services, such as MPS, PDS, or AAS data, on the secondary extended sidebands. The SIDS logical channel also carries SIS data over the secondary main sidebands. As always, identical program material is carried on each sideband, so that the alternate sideband would be available if the other sideband were corrupted.

FUNCTIONAL COMPONENTS

The conversion of audio and data program content into the FM IBOC waveform is accomplished by the layered protocol stack. Source material is received from the broadcaster in layer 5, source encoded in layer 4, multiplexed into logical channels in layers 3 and 2, and formatted for over-the-air broadcast in layer 1.

This section includes a high-level description of each layer 1 functional block, and the associated signal flow. Figure 20 is a functional block diagram of layer 1 processing.

Scrambling

This function randomizes the digital data in each logical channel to mitigate signal periodicities, which could cause undesired emissions and degraded reception.

Channel encoding

A digital signal, when passed through an RF transmission channel, is likely to encounter various impairments, including noise, fading, and interference. Digital systems employ error correction techniques to correct bit errors caused by these impairments. Forward error correction (FEC) algorithms improve signal robustness by adding error correction bits to the signal prior to transmission. These FEC bits are used by the receiver to correct bit errors and regenerate the transmitted bitstream.

FEC codes are typically specified by their coding rate, which is simply the number of information bits divided by the total number of transmitted bits. For example, in a rate 1/2 code, half of the bits carry information, and the other half carry the FEC overhead.

The channel encoding function uses convolutional encoding to add redundancy to the digital data in each logical channel, in order to improve its reliability in the presence of channel impairments. The size of the logical channel transfer frames is increased in inverse proportion to the code rate. The encoding techniques are configurable by service mode. Diversity delay is also imposed on selected logical channels.

Interleaving

Interleaving re-orders the transmitted bits to disperse burst errors typical of a fading channel. The FM IBOC waveform is interleaved in both time and frequency. The custom interleaving techniques are tailored to the VHF Rayleigh fading environment and are configurable by service mode.

In this process, the logical channels lose their identities. The interleaver output is structured in a matrix format; each matrix is comprised of one or more logical channels, and is associated with a particular portion of the transmitted spectrum.

System control processing

This function generates a matrix of system control data sequences, which includes control and status (such as service mode), for broadcast on the reference subcarriers.

OFDM subcarrier mapping

This function assigns the interleaver matrices and the system control data matrix to the OFDM subcarriers. One row of each active interleaver matrix is processed every OFDM symbol time to produce one output vector $\underline{X}$, which is a frequency-domain representation of the signal. The mapping is specifically tailored to the non-uniform interference environment and is a function of the service mode.

OFDM signal generation

This function generates the digital portion of the time-domain FM IBOC waveform. The input vectors are transformed into a shaped time-domain baseband pulse, $y_n(t)$, defining one OFDM symbol.

Transmission subsystem

This function formats the baseband waveform for transmission through the VHF channel. Major subfunctions include symbol concatenation and frequency up-conversion. In addition, when transmitting the hybrid or extended hybrid waveforms, this function modulates the analog source and combines it with the digital signal to form a composite signal, s(t), ready for transmission.

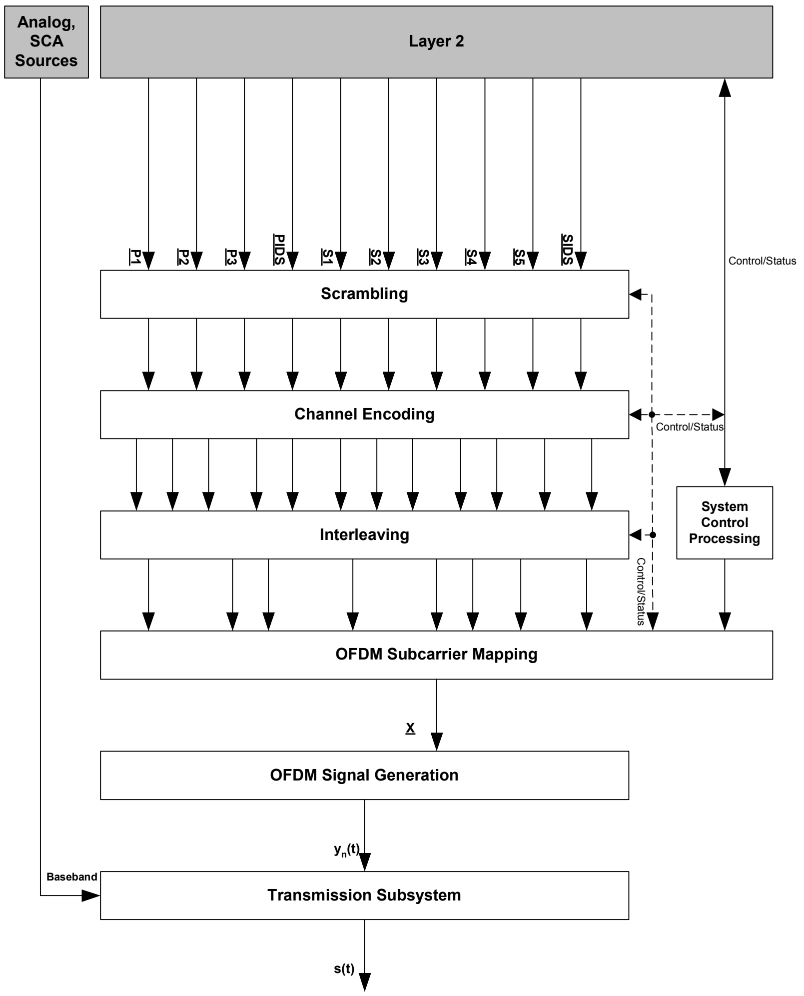

Figure 20 Layer 1 Functional Block Diagram

ACKNOWLEDGEMENTS

The author wishes to acknowledge the contributions of Brian Kroeger, Jeff Baird, Denise Cammarata, Harvey Chalmers, Ashruf El-Dinary, Rick Martinson, Stephen Mattson, Glynn Walden, and all other members of the iBiquity Digital Corporation FM technical team.

REFERENCES

[1] R.W. Chang, "High-speed multichannel data transmission with bandlimited orthogonal signals," *Bell sys. Tech. J.*, vol. 45, pp. 1775-1796, Dec. 1966

[2] B.W. Kroeger, D.M. Cammarata, "Robust Modem and Coding Techniques for FM Hybrid IBOC DAB," *IEEE Transactions on Broadcasting*, vol. 43, no. 4, pp. 412-420, Dec. 1997

[3] Federal Communications Commission, Code of Federal Regulations, Title 47, Part 73

[4] "Petition for Rulemaking to the United States Federal Communications Commission for In-Band On-Channel Digital Audio Broadcasting," Appendix C, p. 7, USA Digital Radio Corporation, October 7, 1998