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

Steven A. Johnson

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

Abstract- *A robust In-Band On-Channel (IBOC) Digital Broadcasting system for offering improved performance over existing analog AM broadcasting has been completed by iBiquity Digital Corporation. The solution is both forward and backward compatible and does not require the allocation of additional channel spectrum. Broadcasters can simultaneously transmit both analog and digital signals within the allocated channel mask allowing full compatibility with existing analog receivers. The solution also allows broadcasters to transmit an all digital signal, replacing the hybrid analog/digital signal. This paper focuses on the generation and transmission of the AM IBOC waveform, including a description of the characteristics and features of the system.*

INTRODUCTION

AM broadcast stations are licensed to operate at 10 kHz increments in the AM band with 20 kHz bandwidths, resulting in interference due to overlapping sidebands. Because of this, an AM station may be interference limited, where signals from distant stations limit potential coverage. During the daytime hours, interfering signals arrive via groundwave propagation, with additional interference arriving at night due to reflections of distance signals off the ionosphere (skywave interference).

Even in the absence of interfering stations, the AM band is subject to a number of degradations that are present in a received signal. The worst of these are Grounded Conductive Structures (GCS). Typical GCSs include bridges, power lines, overpasses and overhead signs found along highways. These impairments can cause rapid changes in the magnitude and phase of the AM waveform. Unlike higher frequency signals, propagation of AM signals is affected in part because the wavelength is large compared to the dimensions of typical GCSs.

An important feature of any IBOC digital broadcasting system is the ability to provide improved audio quality over existing analog services. However, equally as important is the requirement that the digital signal cause minimal interference to the host analog audio as well as to neighboring stations.

The design of iBiquity Digital's AM IBOC digital broadcasting system (hereafter known as the AM IBOC system) was driven by the performance goals and channel conditions listed above. Four main functional components of any IBOC digital broadcasting system include: the codec, which is a source encoding method that removes redundant information from a digital audio signal in order to reduce the bit rate, and hence the bandwidth required to transmit the signal; FEC coding which provides robustness through intelligently placed redundancy; interleaving, which provides robustness through diversity; and the modem, which modulates and demodulates the signal. This paper focuses on the last three components of the system design and the consequences of this design in terms of parameters important to broadcasters: throughput, robustness, and latency.

OVERVIEW

The AM IBOC system is capable of supporting the following services:

- **Main Program Service (MPS)**
  The Main Program Service preserves the existing analog radio-programming formats in both the analog and digital transmissions. In addition, Main Program includes digital data, which directly correlates with the audio programming.
- **Personal Data Service (PDS)**
  Unlike the Main Program Service, which broadcasts the same audio program to all listeners, the Personal Data Service enables user

to select the data services desired and when they are presented. This provides personalized, on-demand, user-valued information.

- **Station Identification Service (SIS)** The Station Identification Service provides the necessary control and identification information, which indirectly accommodates user search and selection of IBOC digital radio stations and their supporting services.
- **Auxiliary Application Service (AAS)** This service 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.

Support of the above services is provided via a layered protocol stack illustrated in Figure 1. This layered protocol stack is based on the International Standards Organization Open Systems Interconnection (ISO OSI) layered model[1]. Layer 5 (Application) accepts content from the user (i.e. program source). Layer 4 (Encoding) performs the necessary audio compression or data formatting of the various source materials. Layer 3 (Transport) provides one or more application specific protocols tailored to provide robust and efficient transfer of Layer 4 data. Layer 2 (Service Mux) provides limited error detection and addressing. Its main function is to format the data received from Layer 3 into discrete transfer frames for processing by Layer 1. Layer 1 (Physical Layer) provides the modulation, FEC, framing, and signaling necessary to convert the digital data received from higher layers into an AM IBOC waveform for transmission in an existing allocation in the MF band.

This paper focuses on Layer 1 of the AM IBOC system. Layer 1 can be thought of as simply a "pipe" to broadcast data with a specific grade of service; the source coding, formatting and multiplexing of the program content performed at the higher protocol layers. However, the AM IBOC system provides a number of different configurations, called service modes, in which the number, throughput and robustness of the "data pipes," called logical channels, can vary. Therefore, after assessing the requirements of their candidate applications, higher protocol layers select service modes that most suitably configure the logical channels. The plurality of logical channels and service modes reflects the inherent flexibility of the system, which supports simultaneous delivery of various classes of digital audio and data.

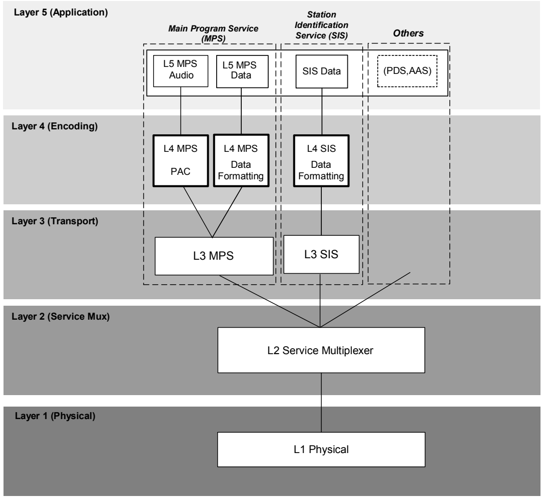

Figure 1 IBOC protocol stack.

The remaining sections of this paper are organized as follows. First, the modulation and spectral occupancy of the waveforms are described. This is followed by a description of the available service modes, as well as the various broadcaster options within each service mode. Next, the logical channels in each service mode are described in terms of their throughput, robustness, and latency. Finally, we present the functional components of AM waveform generation, describing the processing necessary to convert the digital data in the active logical channels into an AM IBOC waveform.

WAVEFORMS AND SPECTRA

Digital data and audio cannot be directly propagated over RF channels; therefore a modulator is used to modulate the digital information onto an RF carrier. The AM IBOC system employs Orthogonal Frequency Division Multiplexing (OFDM) [2-4], for robustness in the presence of adjacent channel interference and noise. OFDM is a parallel modulation scheme in which the data streams modulate a large number of orthogonal subcarriers that are transmitted simultaneously. OFDM can be tailored to fit an interference environment that is non-uniform across frequency.

The narrow AM bandwidth leads to an OFDM modulation technique that is optimized for higher throughput. iBiquity Digital's IBOC technology for AM uses Quadrature Amplitude Modulation (QAM) on each OFDM subcarrier.

In addition, the timing of the symbols is optimized to insure that duration of noise pulses is much shorter than the QAM symbol duration, insuring robust digital reception in the presence of static and noise prevalent in the AM channel. The current design calls for symbol durations of 5.8 msec. and a OFDM subcarrier spacing of 181.7 Hz.

The design of the AM IBOC system provides a flexible means of transitioning to a digital broadcast system by providing two new waveform types: hybrid and all digital. The hybrid waveform retains the analog AM signal, while the all digital waveform does not. The analog source must be monophonic, as the AM IBOC system does not support AM stereo broadcasts.

In the hybrid waveform, the OFDM subcarriers are located in primary and secondary sidebands on either side of the host analog signal, as well as underneath the host analog signal in tertiary sidebands, as shown in Figure 2[†]. Each sideband has both an upper and lower component. Furthermore, status and control information is transmitted on reference subcarriers on either side of the main carrier.

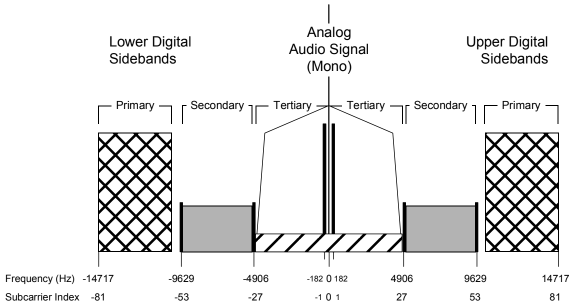

Figure 2 AM IBOC hybrid waveform spectrum.

In addition to the primary, secondary, tertiary and control subcarriers, there are two additional subcarriers between the primary and secondary and the secondary and tertiary sidebands on either side of the main carrier. These are known as IBOC Data System (IDS) subcarriers and are primarily used for low latency, low data rate applications such as SIS or RBDS, which is currently being used in FM systems.

The number of OFDM subcarriers in the secondary, tertiary, and IDS sidebands is twice the number needed to transmit the QAM constellation values. This is because the overall digital signal must maintain a 90° phase relationship (quadrature) to the AM carrier, thereby minimizing the interference to the analog signal when detected by an envelope detector. Placing these subcarriers in quadrature to the analog signal also permits demodulation of the tertiary and IDS subcarriers in the presence of the high level AM carrier and analog signal. The price paid for placing these subcarriers in quadrature with the AM carriers is that the information content on these subcarriers is only half of that for non-quadrature digital carriers.

During transmission, the phase relationship between the digital and analog signals must be maintained. Amplification of the analog and digital signals by a single transmitter is the most straightforward approach. However, it is conceivable that separate amplifiers could be used for the analog and digital signals, and the transmitter outputs could be combined. However, proper phasing of the signals would need to be maintained.

The total power of all digital sidebands, in the hybrid waveform, is significantly below the power in the AM analog signal. The power level of each OFDM subcarrier, in the primary sidebands, is fixed relative to the unmodulated main analog carrier. However, the power level of the secondary, IDS and tertiary subcarriers is adjustable.

Table 1 summarizes the spectral characteristics of the hybrid waveform. Individual subcarriers are numbered from –81 to 81 with the center subcarrier at subcarrier number 0. Table 1 lists the approximate frequency ranges, bandwidth, levels and modulation types for each sideband. In Table 1, the subcarriers 54 to 56 and –54 to –56 are not represented. This is because they are not transmitted to avoid interference with first adjacent signals.

[†] In Figure 2 and subsequent figures and tables the spectra are illustrated at baseband, with upper and lower sidebands centered on dc.

Table 1 AM hybrid waveform spectral summary.

Sideband	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Frequency Span (Hz)	Power Spectral Density, dBc/Subcarrier	Modulation Type
Primary Upper	57 to 81	10356.1 to 14716.6	4360.5	-30	64-QAM
Primary Lower	-57 to -81	-10356.1 to -14716.6	4360.5	-30	64-QAM
Secondary Upper	28 to 52	5087.2 to 9447.7	4360.5	-43 or –37	16-QAM
Secondary Lower	-28 to -52	-5087.2 to -9447.7	4360.5	-43 or –37	16-QAM
Tertiary Upper	2 to 26	363.4 to 4723.8	4360.4	To Be Announced	QPSK
Tertiary Lower	-2 to -26	-363.4 to -4723.8	4360.4	To Be Announced	QPSK
Reference Upper	1	181.7	181.7	-26	BPSK
Reference Lower	-1	-181.7	181.7	-26	BPSK
Upper IDS1	27	4905.5	181.7	-43 or –37	16-QAM
Upper IDS2	53	9629.4	181.7	-43 or –37	16-QAM
Lower IDS1	-27	-4905.5	181.7	-43 or –37	16-QAM
Lower IDS2	-53	-9629.4	181.7	-43 or –37	16-QAM

The greatest system enhancements are realized with the all digital waveform. In this waveform, the analog signal is replaced with higher power primary sidebands. The unmodulated AM carrier is retained and the secondary sidebands are moved to the higher frequencies above the primary upper sideband. In addition the tertiary sidebands are moved to the frequencies below the primary lower sideband. The secondary and tertiary sidebands use half the number of subcarriers, as compared to the hybrid waveform, because there is no longer a need to place them in quadrature with the analog signal since it is unmodulated. Finally, the power of both the secondary and tertiary sidebands is increased.

These changes result in an overall bandwidth reduction, making the all digital waveform less susceptible to adjacent channel interference. The reference subcarriers are located on either side of the unmodulated AM carrier, as in the hybrid waveform, but at a higher level. The spectrum of the all digital waveform is illustrated in Figure 3. The power level of each of the OFDM subcarriers within a sideband is fixed relative to the unmodulated analog carrier. Table 2 summarizes the spectral characteristics of the All Digital waveform.

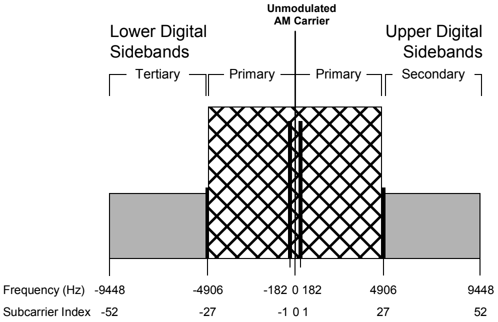

Figure 3 AM All Digital waveform spectrum.

Table 2 AM All Digital waveform spectral summary.

Sideband	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Frequency Span (Hz)	Power Spectral Density, dBc/Subcarrier	Modulation Type
Primary Upper	2 to 26	363.4 to 4723.8	4360.5	-15	64-QAM
Primary Lower	-2 to –26	-363.4 to –4723.8	4360.5	-15	64-QAM
Secondary	28 to 52	5087.2 to 9447.7	4360.5	-30	64-QAM
Tertiary	-28 to -52	-5087.2 to -9447.7	4360.5	-30	64-QAM
Reference Upper	1	181.7	181.7	-15	BPSK
Reference Lower	-1	-181.7	181.7	-15	BPSK
IDS1	27	4905.5	181.7	-30	16-QAM
IDS2	-27	-4905.5	181.7	-30	16-QAM

Both the Hybrid and All Digital waveforms conform to the currently allocated emissions mask per 47 CFR §73.44[5] and summarized in Table 3. All measurements assume a resolution bandwidth of 300 Hz.

Table 3 FCC AM spectral emissions mask.

Offset From Carrier Frequency	Level Relative To Unmodulated Carrier
10.2 to 20 kHz	-25 dBc
20 to 30 kHz	-35 dBc
30-60 kHz	-5 dBc – 1 dB/kHz
60-75 kHz	-65 dBc
> 75 kHz	-80 or [-43-log10(power in watts)] dBc, whichever is less

SERVICE MODES AND SYSTEM OPTIONS

The AM IBOC system provides four service modes: MA1, MA2, MA3 and MA4. Service modes MA1 and MA2 are used with hybrid waveforms while service modes MA3 and MA4 are used with all digital waveforms. Service modes MA2 and MA4 provide higher throughput than MA1 and MA3, at the expense of robustness. The details of the various service modes will become clear in the next section, when the logical channels for each service mode are described.

In addition to the four service modes, the broadcaster has the option of configuring service modes MA1 and MA2 using two additional controls: power level control and analog audio bandwidth control.

The power level control selects one of two levels for the secondary, tertiary, and IDS subcarriers as indicated in Table 1. The higher power levels increase the robustness of the digital signal at the expense of decreasing compatibility with certain classes of existing analog radios, namely walkmans and boombox type radios. As radio manufactures produce IBOC friendly radios or if a broadcaster is not as concerned with compatibility with these classes of existing analog radios, this option allows broadcasters to increase the robustness of the digital signal.

The analog audio bandwidth control allows the analog audio to be broadcast using either a 5-kHz bandwidth or an 8-kHz bandwidth. Broadcasting 8 kHz analog reduces the robustness of the digital signal in the presence of second adjacent interferers.

To provide robust reception during outages typical in a mobile environment, the AM 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[6]. The AM IBOC system provides 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.

LOGICAL CHANNELS

A logical channel is a signal path that conducts data through Layer 1 with a specific grade of service, determined by service mode. Layer 1 of the AM IBOC system provides four logical channels to higher layer protocols: P1, P2, P3 and PIDS. P1, P2 and P3 are intended for general purpose audio and data transfer, while the PIDS logical channel is designed to carry the IBOC data services (IDS) information.

The P1 and P2 logical channels are designed to be more robust than the P3 logical channel. Therefore, P1 and P2 typically transmit the "core" audio information, while P3 transmits the enhanced audio information (such as the stereo signal). Logical channels P1 and P3 are available for all services modes, while P2 is only available in service modes MA2 and MA4. Service modes MA2 and MA4 provide higher throughput than MA1 and MA3 by making available an additional logical channel (P2) at the expense of P1 robustness.

Logical channels are defined by their characterization parameters and configured by the service mode. For a given service mode, the grade of service of a particular logical channel may be uniquely quantified using three characterization parameters: throughput, latency, and robustness. Channel code rate, interleaver depth, diversity delay, and spectral mapping are the determinants of the characterization parameters.

The throughput of a logical channel is its allowable data rate and is typically defined in terms of kilobits per second (kbps). Latency is the delay that a logical channel imposes on the data as it transverses 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 delays in Layer 1 nor does it include delays imposed in upper layers. Robustness is the ability of a logical channel to withstand channel impairments such as noise, interference, and GCS. There are ten relative levels of robustness designed into Layer 1 of the AM IBOC system. A robustness of 1 indicates a very high level of resistance to channel impairments, while a robustness of 10 indicates a lower tolerance for channel-induced errors. As with throughput and latency, higher layers must determine the required robustness of a logical channel before selecting a service mode.

Spectral mapping, channel code rate, and interleaver depth 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 GCS and impulsive noise, thereby affecting the robustness of the logical channel. 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.

Table 4 through Table 7 show the characterization parameters of each logical channel for every service mode.

In Table 4 and Table 5, logical channels P3 and PIDS lists multiple robustness values. This is because there are two power levels associated with these logical channels. The lower relative robustness number, indicating greater robustness, is associated with the higher power level settings.

Table 4 Logical channel characterizations - Service mode MA1.

Logical Channel	Throughput (kbps)	Latency (Sec.)	Relative Robustness
P1	20.2	5.94	6
P3	16.2	1.49	7 or 10
PIDS	0.4	0.19	4 or 8

Table 5 Logical channel characterizations - Service Mode MA2.

Logical Channel	Throughput (kbps)	Latency (Sec.)	Relative Robustness
P1	20.2	5.94	9
P2	20.2	1.49	9
P3	16.2	1.49	7 or 10
PIDS	0.4	0.19	4 or 8

Table 6 Logical channel characterizations - Service mode MA3.

Logical Channel	Throughput (kbps)	Latency (Sec.)	Relative Robustness
P1	20.2	5.94	1
P3	20.2	1.49	5
PIDS	0.4	0.19	3

Table 7 Logical channel characterizations - Service mode MA4.

Logical Channel	Throughput (kbps)	Latency (Sec.)	Relative Robustness
P1	20.2	5.94	2
P2	20.2	1.49	2
P3	20.2	1.49	5
PIDS	0.4	0.19	3

For a given service mode, each logical channel is applied to a frequency sideband. Figure 4 through Figure 7 show the spectral mapping of each logical channel for every service mode.

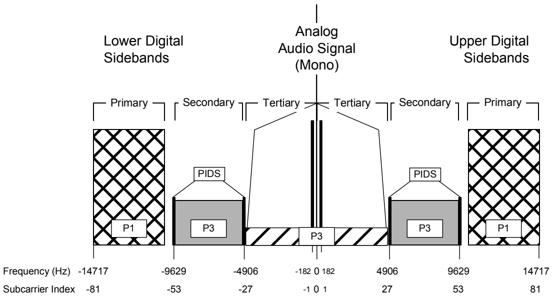

Figure 4 Logical channel spectral mapping - Service mode MA1.

Figure 4 reveals that the P1 logical channel is transmitted on both the upper and lower primary sidebands. These are redundant copies of the same information allowing the P1 logical channel to operate in the presence of a strong interferer on either the lower or upper adjacent channel. In addition to the frequency redundancy, the P1 logical channel in service mode MA1 also contains time redundancy. This is realized by transmitting redundant information that has a diversity delay imposed at the transmitter. This redundant information uses a short interleaver so that the digital audio may be acquired quickly. It also service as a backup to the non-delayed information, providing robustness to short-term outages such as those caused by GCS. This is why in Table 4 and Table 6 the latency of the P1 logical channel is larger than the other logical channels. The P1 logical channel, with its high degree of robustness was designed to transmit core audio information.

Because of the requirement to minimize interference to the host analog signal, the carriers in the secondary and tertiary sidebands are placed at low levels; and, as previously mentioned, maintain a phase relationship with the host analog signal. The P3 logical channel is transmitted on these carriers and therefore is less robust than the P1 logical channel. Because of this reduced robustness, audio enhancement information, such as the stereo signal, is typically transmitted on this logical channel. The P3 logical channel contains no time redundancy, but contains frequency redundancy in the upper and lower secondary sideband, as long as the host analog signal is transmitted with a 5 kHz bandwidth or less. If the analog audio extends into the secondary sidebands, both sidebands are needed to demodulate the digital signal. This is why the digital signal is less robust to second adjacent interferers when 8 kHz analog signals are transmitted.

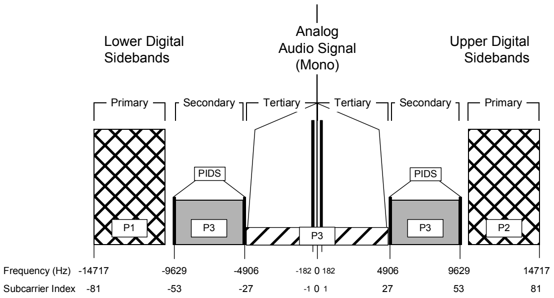

Figure 5 Logical channel spectral mapping - Service mode MA2.

Figure 5 reveals that the difference between MA1 and MA2 is that the frequency redundancy of the P1 logical channel is removed and replaced with the additional logical channel P2. In addition, the time redundancy of the P1 logical channel is also lost. The P3 logical channel remains the same.

The MA2 service mode was designed to make use of multi-descriptive audio compression technologies. In these technologies, redundancy is provided by the audio codec instead of Layer

1. The audio codec produces multiple representations of the audio source material and transmits the independently decodable descriptions on the P1 and P2 logical channels. To make up for the loss in time redundancy, the P1 logical channel is delayed at the transmitter, relative to the P2 logical channel. This can be seen in the latency characterizations of Table 5. Since either description is independently decodable, the system is robust to upper or lower adjacents as well as short-term outages caused by GCS. When both descriptions are available (i.e., clear channel conditions) the digital audio quality improves since the information rate is double.

Since both P1 and P2 logical channels use long interleaver depths in service mode MA2, the acquisition of the digital signal is longer than in service mode MA1. In addition, the robustness of the individual P1 and P2 logical channels of service mode MA2 is less than the single logical channel, P1, of service mode MA1 and therefore the digital coverage area will be less when using service mode MA2 as compared to service mode MA1.

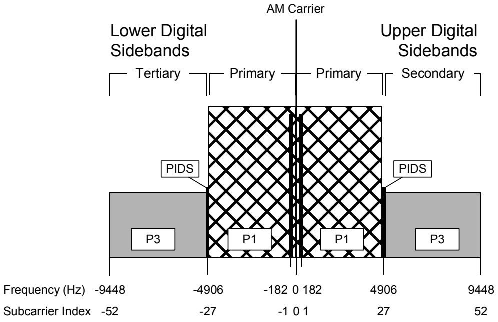

Figure 6 Logical channel spectral mapping - Service mode MA3.

Figure 6 shows that service mode MA3 is the all digital equivalent of service mode MA1. Since there is no analog signal to serve as a backup channel, the time redundancy inherent in the P1 logical channel serves this purpose.

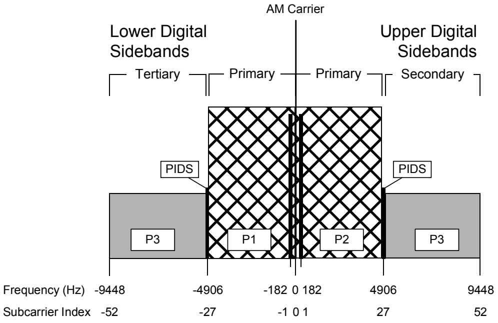

Figure 7 Logical channel spectral mapping - Service mode MA4.

Figure 7 reveals that service mode MA4 is the all digital equivalent of service mode MA2. Again, since there is no analog signal to serve as backup, the time diverse P1 and P2 logical channels serve to backup each other. Also, to provide faster acquisition of digital audio, the P1 logical channel uses a shorter interleaver.

LAYER 1 FUNCTIONAL COMPONENTS

This section describes the processing steps necessary to convert the various logical channels into an AM IBOC system waveform. Figure 8 shows a functional block diagram of the Layer 1 processing. The single underline notation for a logical channel name indicates that data is passed between the various functions as vectors. During the interleaving process, logical channels lose their identity as they are combined or split by the interleaving process.

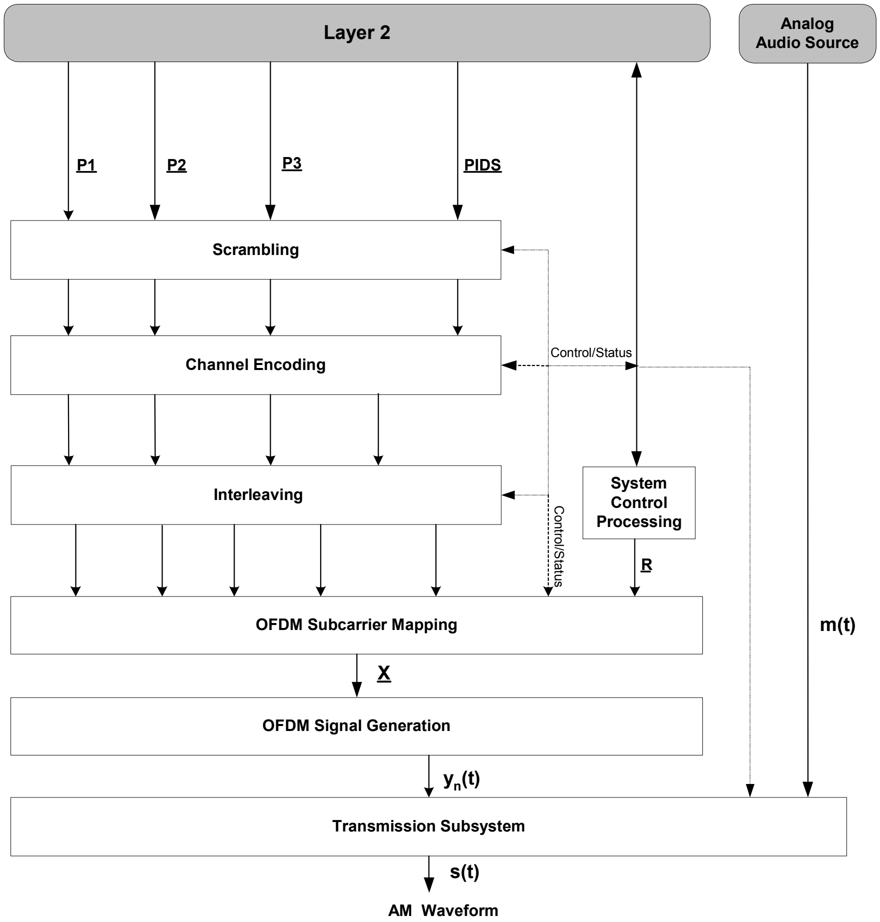

Figure 8 AM Layer 1 functional block diagram.

Scrambling. This function randomizes the digital data carried in each logical channel to mitigate signal periodicities and aid in receiver synchronization. At the output of scrambling, the logical channel vectors retain their identity.

Channel Encoding. A digital bitstream, when passed through a transmission channel, is likely to encounter various forms of impairments including noise, distortion, fading and interference. Digital systems employ various error correction techniques to restore transmission errors. These algorithms improve robustness through the introduction of error correction bits. These error correction bits are used in the receiver to verify the accuracy of the recovered bitstream, detect errors, and provide restoration of the transmitted bitstream.

Error correction codes are typically specified by their coding rate (R=information bits/total bits). For example, a coder with R=1/2 channel coding represents an algorithm where half of the bits carry information and the other half carries the overhead of the error correction algorithm.

The size of the logical channel vectors is increased in inverse proportion to the code rate. The encoding techniques are configurable by service mode. At the output of the channel encoder, the logical channel vectors retain their identity.

Interleaving. Interleaving in time and frequency is employed to mitigate the effects of burst errors. Digital error correction techniques are enhanced if errors in transmission are spread in a manner that minimizes data loss in successive bits. Interleaving is a technique that jumbles the bits in a predetermined manner upon transmission and reassembles them in the receiver. The interleaving techniques used in the AM IBOC system are tailored to the AM non-uniform interference environment and are configurable by service mode. In this process, the logical channels lose their identity. The interleaver output is structured in a matrix format. Each matrix consists of information from whole or partial logical channels and is associated with a specific portion of the transmitted spectrum. Diversity delay is also imposed on selected logical channels. It is through this function that the time redundancy of logical channel P1, in service modes MA1 and MA3, is created.

System Control Processing. This function generates a vector of system control data sequences that includes system control information received from layer 2 (such as service mode and configuration options), and status for broadcast on the reference subcarriers. This information is used at the receiver to determine how to process the AM IBOC system waveforms.

OFDM Subcarrier Mapping. This function assigns the interleaver matrices and system control vector to OFDM subcarriers. One row of each active interleaver matrix and one bit of the system control vector is processed each OFDM symbol to produce one output vector $\underline{X}$, which is a frequency domain representation of the signal.

OFDM Signal Generation. This function generates the digital portion of the time-domain AM IBOC waveform. The input vectors $\underline{X}$ 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 MF channel. Major sub-functions include, symbol concatenation, and frequency up-conversion. When transmitting a hybrid waveform, this function modulates the AM analog audio source and coherently combines it with the digital signal to form a composite hybrid signal, s(t), ready for transmission.

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