HD Radio™ Air Interface Design Description Layer 1 FM

Rev. F

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1.1 System Overview

The iBiquity Digital Corporation HD Radio™ system is designed to permit a smooth evolution from current analog *amplitude modulation* (AM) and *frequency modulation* (FM) radio to a fully digital in-band on-channel (IBOC) system. This system delivers digital audio and data services to mobile, portable, and fixed receivers from terrestrial transmitters in the existing medium frequency (MF) and very high frequency (VHF) radio bands. Broadcasters may continue to transmit analog AM and FM simultaneously with the new, higher-quality, and more robust *digital signals*, allowing themselves and their listeners to convert from analog to digital radio while maintaining their current frequency allocations.

1.2 Document Overview

This document defines the generation of *Layer 1 (L1)* FM HD Radio signals for transmission over the air to receiving equipment. It describes how control and information are passed through the Layer 1 FM air interface to generate an HD Radio signal. It focuses on the creation of the transmitted FM HD Radio signal; specific hardware and software implementation is not described.

2 Referenced Documents

[1] Federal Communications Commission, Code of Federal Regulations, Title 47, Part 11, October 1st 1994.

[2] Federal Communications Commission, Code of Federal Regulations, Title 47, Part 73, October 1st 1994.

[3] iBiquity Digital Corporation, “HD Radio™ FM Transmission System Specifications”, Doc. No. SY_SSS_1026s, Revision E.

[4] iBiquity Digital Corporation, “HD Radio™ Air Interface Design Description – Audio Transport”, Doc. No. SY_IDD_1017s, Revision E.

3 Abbreviations, Symbols, and Conventions

3.1 Introduction

Section 3 presents the following items that are pertinent to a better understanding of this document:

- Abbreviations and Acronyms
- Presentation Conventions
- Mathematical Symbols
- FM System Parameters

Note: *A glossary defining the technical terms used herein is provided at the end of this document.*

3.2 Abbreviations and Acronyms

ALFN	Absolute L1 Frame Number
AM	Amplitude Modulation
ASF	Amplitude Scale Factor Select
BC	L1 Block Count
BPSK	Binary Phase Shift Keying
EAS	Emergency Alert System
FM	Frequency Modulation
GPS	Global Positioning System
IBOC	In-Band On-Channel
IP	Interleaving Process
kbit/s	kilobits per second
L1	Layer 1
L2	Layer 2
MF	Medium Frequency
MHz	Megahertz
MP1–MP6	Primary Service Modes 1 through 6
MS1–MS4	Secondary Service Modes 1 through 4
N/A	Not Applicable
OFDM	Orthogonal Frequency Division Multiplexing
P1–P3	Primary Logical Channels 1 through 3
P3ISI	P3 Interleaver Select Indicator
PDU	Protocol Data Unit
PIDS	Primary IBOC Data Service Logical Channel
PM	Primary Main
PSM	Primary Service Mode Control
PSMI	Primary Service Mode Indicator
PX	Primary Extended
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RSID	Reference Subcarrier Identification
S1–S5	Secondary Logical Channels 1 through 5
SB	Secondary Broadband
SCA	Subsidiary Communications Authorization
SCCH	System Control Channel
SCI	Secondary Channel Indicator
SIDS	Secondary IBOC Data Service Logical Channel

SIS	Station Information Service
SM	Secondary Main
SP	Secondary Protected
SSM	Secondary Service Mode Control
SSMI	Secondary Service Mode Indicator
SX	Secondary Extended
UTC	Coordinated Universal Time
VHF	Very High Frequency

3.3 Presentation Conventions

Unless otherwise noted, the following conventions apply to this document:

- Glossary terms are presented in italics upon their first usage in the text.
- All vectors are indexed starting with 0.
- The element of a vector with the lowest index is considered to be first.
- In drawings and tables, the leftmost bit is considered to occur first in time.
- Bit 0 of a byte or word is considered the least significant bit.
- When presenting the dimensions of a matrix, the number of rows is given first (e.g., an n x m matrix has n rows and m columns).
- In timing diagrams, earliest time is on the left.
- Binary numbers are presented with the most significant bit having the highest index.
- In representations of binary numbers, the least significant bit is on the right.

3.4 Mathematical Symbols

3.4.1 Variable Naming Conventions

The variable naming conventions used throughout this document are defined below:

Category	Definition	Examples
Lower and upper case letters	Indicates scalar quantities	i, j, J, g_{11}
Underlined lower and upper case letters	Indicates vectors	$\underline{u}$, $\underline{V}$
Double underlined lower and upper case letters	Indicates two-dimensional matrices	$\underline{\underline{u}}$, $\underline{\underline{V}}$
[i]	Indicates the i^{th} element of a vector, where i is a non-negative integer	$\underline{u}[0]$, $\underline{V}[1]$
[ ]	Indicates the contents of a vector	$\underline{v} = [0, 10, 6, 4]$

Category	Definition	Examples
[i] [j]	Indicates the element of a two-dimensional matrix in the i^{th} row and j^{th} column, where i and j are non-negative integers	$\underline{\underline{u}}[i][j]$ $\underline{\underline{V}}[i][j]$
$\left[\qquad\right]$	Indicates the contents of a matrix	$\underline{\underline{m}} = \begin{bmatrix} 0 & 3 & 1 \\ 2 & 7 & 5 \end{bmatrix}$
n,…,m	Indicates all the integers from n to m, inclusive	3,…,6 = 3, 4, 5, 6
n:m	Indicates bit positions n through m of a binary sequence or binary vector	Given a binary vector: i = [0, 1, 1, 0, 1, 1, 0, 0] $i_{2:5}$ = [1, 0, 1, 1]

3.4.2 Arithmetic Operators

The arithmetic operators used throughout this document are defined below:

Category	Definition	Examples
·	Indicates a multiplication operation	3·4 = 12
INT( )	Indicates the integer portion of a real number	INT(5/3) = 1 INT(-1.8) = -1
a MOD b	Indicates a modulo operation	33 MOD 16 = 1
$\oplus$	Indicates modulo-2 binary addition	$1 \oplus 1 = 0$
|	Indicates the concatenation of two vectors	$\underline{A} = [\underline{B} \mid \underline{C}]$ The resulting vector $\underline{A}$ consists of the elements of $\underline{B}$ followed by the elements of $\underline{C}$.
j	Indicates the square-root of -1	j = $\sqrt{-1}$
Re( )	Indicates the real component of a complex quantity	If x = (3 + j4), Re(x) = 3
Im( )	Indicates the imaginary component of a complex quantity	If x = (3 + j4), Im(x) = 4
$\log_{10}$	Indicates the base-10 logarithm	$\log_{10}(100) = 2$

3.5 FM System Parameters

The FM system parameters used throughout this document are defined below:

Parameter Name	**Symbol**	**Units**	**Exact Value**	**Computed Value (To 4 significant figures)**
OFDM Subcarrier Spacing	Δf	Hz	1488375/4096	363.4
Cyclic Prefix Width	α	none	7/128	5.469×10^{-2}
OFDM Symbol Duration	T_s	s	$(1 + \alpha) / \Delta f =$ $(135/128) \cdot (4096/1488375)$	2.902×10^{-3}
OFDM Symbol Rate	R_s	Hz	$= 1/T_s$	344.5
L1 Frame Duration	T_f	s	$65536/44100 = 512 \cdot T_s$	1.486
L1 Frame Rate	R_f	Hz	$= 1/T_f$	6.729×10^{-1}
L1 Block Duration	T_b	s	$= 32 \cdot T_s$	9.288×10^{-2}
L1 Block Rate	R_b	Hz	$= 1/T_b$	10.77
L1 Block Pair Duration	T_p	s	$= 64 \cdot T_s$	1.858×10^{-1}
L1 Block Pair Rate	R_p	Hz	$= 1/T_p$	5.383
Diversity Delay Frames	N_{dd}	none	3 = number of L1 frames of diversity delay	3
Diversity Delay Time	T_{dd}	s	$= N_{dd} \cdot T_f$	4.458

4 Overview

4.1 Introduction

Layer 1 of the FM system converts information from *Layer 2 (L2)* and *system control* from the *Configuration Administrator* into the FM HD Radio waveform for transmission in the VHF band. Information and control are transported in discrete *transfer frames* via multiple *logical channels*. These transfer frames are also referred to as *Layer 2 Protocol Data Units (PDUs)*.

The L2 PDUs vary in size and format depending on the *service mode*. The service mode, a major component of system control, determines the transmission characteristics of each logical channel. After assessing the requirements of candidate applications, higher protocol layers select service modes that most suitably configure the logical channels. The plurality of logical channels reflects the inherent flexibility of the system, which supports simultaneous delivery of various combinations of digital audio and data.

Layer 1 also receives system control from the Configuration Administrator for use by the Layer 1 System Control Processor.

This section presents the following:

- An overview of the waveforms and spectra
- An overview of the system control, including the available service modes
- An overview of the logical channels
- A high-level discussion of each of the functional components included in the Layer 1 FM air interface

Note: *Throughout this document, various FM system parameters are globally represented as mathematical symbols. Refer to Subsection 3.5 for their values.*

4.2 Waveforms and Spectra

The 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. All three waveform types conform to the current *spectral emissions mask*.

The digital signal is modulated using *Orthogonal Frequency Division Multiplexing* (OFDM). OFDM is a parallel modulation scheme in which the data stream modulates a large number of orthogonal subcarriers, which are transmitted simultaneously. OFDM is inherently flexible, readily allowing the mapping of logical channels to different groups of subcarriers.

Refer to Section 5 for a detailed description of the spectra of the three waveform types.

4.2.1 Hybrid Waveform

The digital signal is transmitted in *Primary Main* (PM) *sidebands* on both sides of the analog FM signal in the Hybrid waveform. The power level of each sideband is appreciably below the total power in the analog FM signal. The *analog signal* may be monophonic or stereo, and may include Subsidiary Communications Authorization (SCA) channels.

4.2.2 Extended Hybrid Waveform

In the Extended Hybrid waveform, the bandwidth of the Hybrid sidebands can be extended toward the analog FM signal to increase digital capacity. This additional spectrum, allocated to the inner edge of each Primary Main sideband, is termed the *Primary Extended* (PX) *sideband*.

4.2.3 All Digital Waveform

The greatest system enhancements are realized with the All Digital waveform, in which the analog signal is removed and the bandwidth of the primary digital sidebands is fully extended as in the Extended Hybrid waveform. In addition, this waveform allows lower-power digital *secondary sidebands* to be transmitted in the spectrum vacated by the analog FM signal.

4.3 System Control Channel

The *System Control Channel* (SCCH) transports control and status information. Primary and secondary service mode control and amplitude scale factor select are sent from the Configuration Administrator to Layer 1, while synchronization information is sent from Layer 1 to Layer 2. In addition, several bits of the *system control data sequence* designated “reserved” are controlled from layers above L1 via the primary reserved control data interface and the secondary reserved control data interface.

The service modes dictate all permissible configurations of the logical channels.

- The active primary service modes defined by this document are MP1, MP2, MP3, MP11, MP5, and MP6. They configure the primary logical channels.
- The active secondary service modes defined by this document are MS1, MS2, MS3, and MS4. They configure the secondary logical channels.

Refer to Section 6 for a detailed description of the SCCH and refer to Section 11 for a detailed description of *System Control Processing*.

4.4 Logical Channels

A logical channel is a signal path that conducts L2 PDUs in transfer frames into Layer 1 with a specific grade of service, determined by service mode. Layer 1 of the FM air interface provides 11 logical channels to higher layer protocols. Not all logical channels are used in every service mode. Refer to Subsection 4.4.1 through Subsection 4.4.3 for details.

4.4.1 Primary Logical Channels

There are five primary logical channels that can be used with the Hybrid, Extended Hybrid, and All Digital waveforms. They are denoted as P1, P2, P3, P4, and PIDS. The PIDS channel transmits the Station Information Service (SIS) information. Table 4-1 shows the approximate information rate supported by each primary logical channel as a function of primary service mode. Calculations of the exact rates are explained in Section 7.

Table 4-1: Approximate Information Rate of Primary Logical Channels

Service Mode	**Approximate Information Rate (kbit/s)**					**Waveform**
	P1	**P2**	**P3**	**P4**	**PIDS**	
MP1	98	N/A	N/A	N/A	1	Hybrid
MP2	98	N/A	12	N/A	1	Extended Hybrid
MP3	98	N/A	25	N/A	1	Extended Hybrid
MP11	98	N/A	25	25	1	Extended Hybrid
MP5	25	74	25	N/A	1	Extended Hybrid, All Digital
MP6	50	49	N/A	N/A	1	Extended Hybrid, All Digital

4.4.2 Secondary Logical Channels

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. Table 4-2 shows the approximate information rate supported by each secondary logical channel as a function of secondary service mode. Calculations of the exact rates are explained in Section 7.

Table 4-2: Approximate Information Rate of Secondary Logical Channels

Service Mode	**Approximate Information Rate (kbit/s)**						
	S1	**S2**	**S3**	**S4**	**S5**	**SIDS**	**Waveform**
MS1	0	0	0	98	6	1	All Digital
MS2	25	74	25	0	6	1	All Digital
MS3	50	49	0	0	6	1	All Digital
MS4	25	98	25	0	6	1	All Digital

4.4.3 Logical Channel Functionality

Logical channels P1 through P4 and S1 through S5 are designed to convey audio and data, while the Primary IBOC Data Service (PIDS) and Secondary IBOC Data Service (SIDS) logical channels are designed to carry Station Information Service (SIS) information.

The performance of each logical channel is completely described through three *characterization parameters: transfer, latency,* and *robustness*. *Channel encoding*, *spectral mapping*, *interleaver depth*, and *diversity delay* are the components of these characterization parameters. The service mode uniquely configures these components within Layer 1 for each active logical channel, thereby determining the appropriate characterization parameters.

In addition, the service mode specifies the framing and synchronization of the transfer frames through each active logical channel. Refer to Section 7 for a detailed description of the logical channels and their configuration.

4.5 Functional Components

This subsection includes a high-level description of each Layer 1 functional block and the associated signal flow. Figure 4-1 is a functional block diagram of Layer 1 processing. Some processing stages shown in Figure 4-1 are denoted by a logical channel subscript. For example, logical channel designations are subscripted with an "S" after *scrambling* and with a "G" after channel encoding. In addition, the primed notation (as in $\underline{\text{P1}}'_G$) indicates that the logical channel is processed differently than the "unprimed" channel (for example see Figure 9-9 and Figure 9-10) and is destined for transmission in a different portion of the spectrum within the allocated bandwidth. The single underline notation for a logical channel name refers to the fact that data is passed between the various functions as *vectors*. Each logical channel has a dedicated scrambler and channel encoder. The configuration administrator is a system function that configures each of the layers using SCCH information or parameters which do not change often. However, dynamic SCCH parameters such as the L1 Block Count and ALFN are sent from Layer 1 to Layer 2.

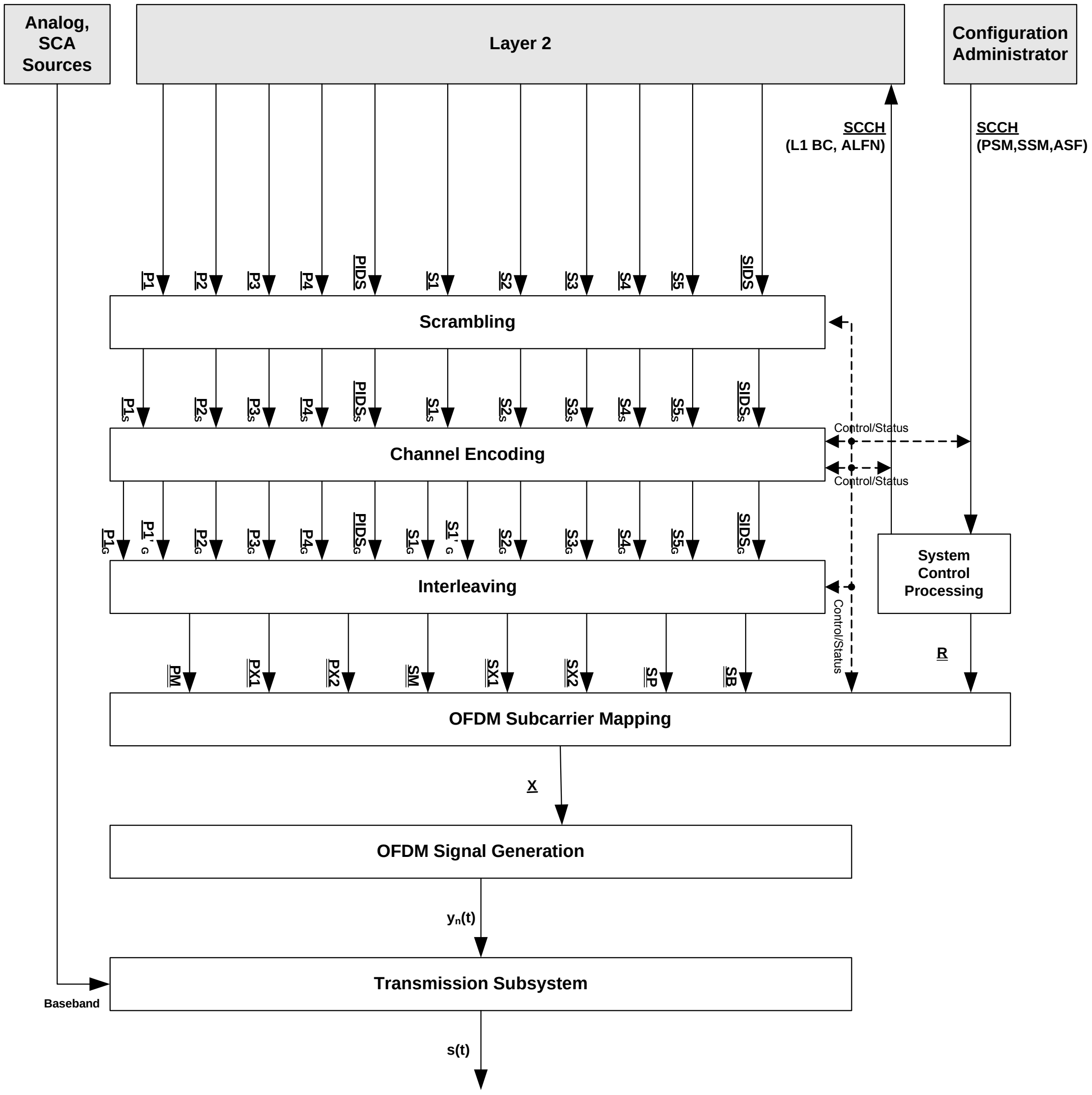


Figure 4-1: FM Air Interface Layer 1 Functional Block Diagram

4.5.1 Scrambling

This function randomizes the digital data in each logical channel to mitigate signal periodicities. At the output of the scrambling function, the logical channel vectors retain their identity, but are distinguished by the "S" subscript (e.g., "$\underline{P1}_S$"). Refer to Section 8 for a detailed description of the scrambling functional component.

4.5.2 Channel Encoding

This function uses *convolutional encoding* to add redundancy to the digital data in each logical channel to improve its reliability in the presence of channel impairments. The size of the logical channel vectors 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. At the output of the channel encoder, the logical channel vectors retain their identity, but are distinguished now by the "G" subscript (e.g., "$\underline{P1}_G$"). In a few service modes, P1 and S1 are split to provide a delayed and undelayed version at the output. Refer to Section 9 for a detailed description of the channel encoding functional component.

4.5.3 Interleaving

Interleaving in time and frequency is employed to mitigate the effects of burst errors. The interleaving techniques are tailored to the VHF *fading* 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 one or more logical channels and is associated with a particular portion of the transmitted spectrum. The *interleaver matrix* designations reflect the spectral mapping. For example, "$\underline{\underline{PM}}$" maps to the Primary Main portion of the spectrum, and "$\underline{\underline{SX1}}$" maps to the Secondary Extended (SX) portion of the spectrum. Refer to Section 10 for a detailed description of the interleaving functional component.

4.5.4 System Control Processing

This function generates a matrix of system control data sequences that include control and status (such as service mode), for broadcast on the *reference subcarriers*. This data matrix is designated "$\underline{\underline{R}}$" for "Reference." Refer to Section 11 for a detailed description of the system control processing functional component.

4.5.5 OFDM Subcarrier Mapping

This function assigns the interleaver matrices and the system control matrix to the *OFDM subcarriers*. One row of each active interleaver matrix is processed every *OFDM symbol* T_s 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. Refer to Section 12 for a detailed description of the *OFDM Subcarrier Mapping* functional component.

4.5.6 OFDM Signal Generation

This function generates the digital portion of the time-domain FM HD Radio waveform. The input vectors are transformed into a shaped time-domain baseband pulse, $y_n(t)$, defining one OFDM symbol. Refer to Section 13 for a detailed description of the *OFDM Signal Generation* functional component.

4.5.7 Transmission Subsystem

This function formats the baseband waveform for transmission through the VHF channel. Major sub-functions include symbol concatenation and frequency up-conversion. In addition, when transmitting the Hybrid waveform, this function modulates the analog source and combines it with the digital signal to form a composite Hybrid signal, s(t), ready for transmission. Refer to Section 14 for a detailed description of the *transmission subsystem* functional component.

5 Waveforms and Spectra

5.1 Introduction

This section describes the output spectrum for each of the three digital waveform types: Hybrid, Extended Hybrid, and All Digital. Each spectrum is divided into several sidebands which represent various subcarrier groupings. All spectra are represented at baseband.

5.2 Frequency Partitions and Spectral Conventions

The OFDM subcarriers are assembled into *frequency partitions*. Each frequency partition consists of eighteen data subcarriers and one reference subcarrier as shown in Figure 5-1 (Ordering A) and Figure 5-2 (Ordering B). The position of the reference subcarrier (Ordering A or B) varies with the location of the frequency partition within the spectrum.

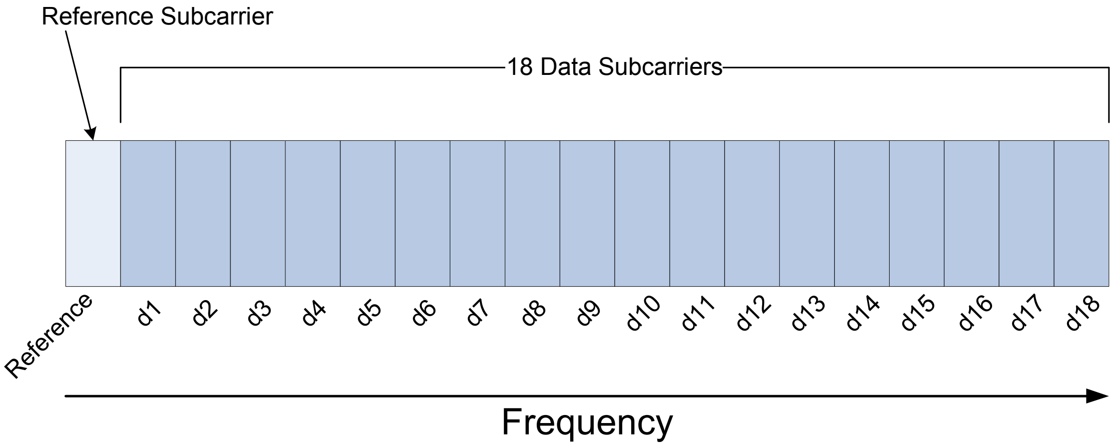


Figure 5-1: Frequency Partition – Ordering A

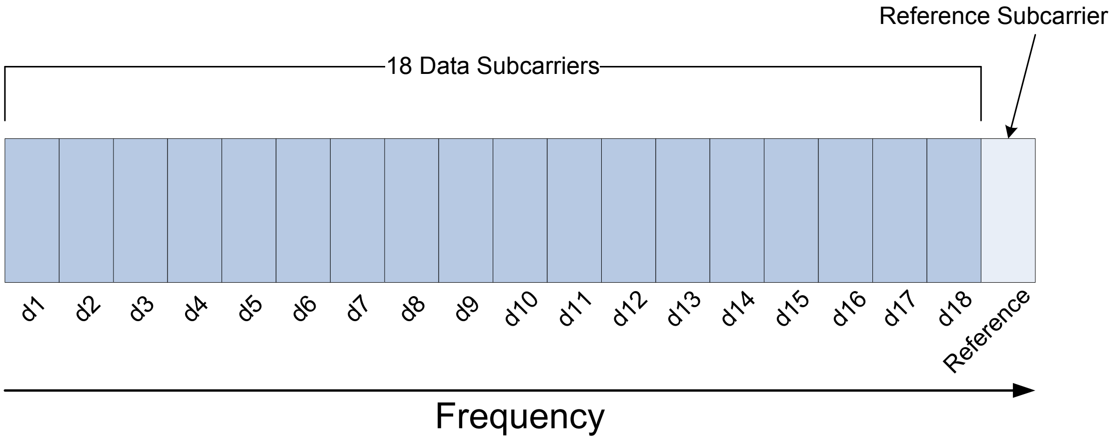


Figure 5-2: Frequency Partition – Ordering B

For each frequency partition, data subcarriers d1 through d18 convey the payload (data or encoded audio) from Layer 2 while the reference subcarriers convey L1 system control. Subcarriers are numbered from minus 546 at the lower end to zero at the center frequency to plus 546 at the upper end of the channel frequency allocation.

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 the following 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 5-3. All *upper sideband* reference subcarriers are shown in Figure 5-4. The figures indicate the relationship between reference subcarrier numbers and OFDM subcarrier numbers.

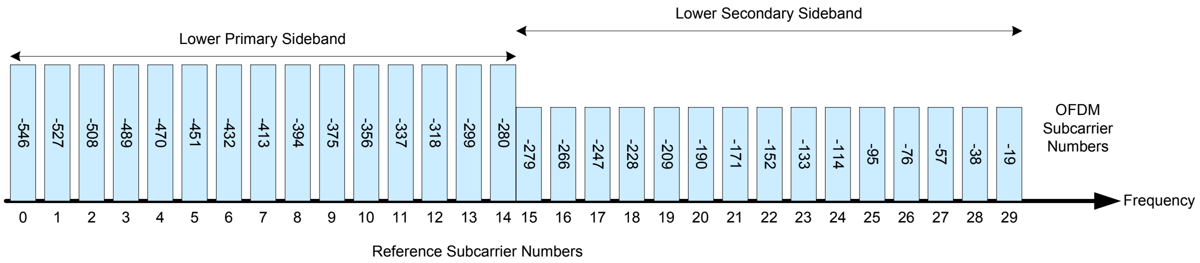


Figure 5-3: Lower Sideband Reference Subcarrier Spectral Mapping

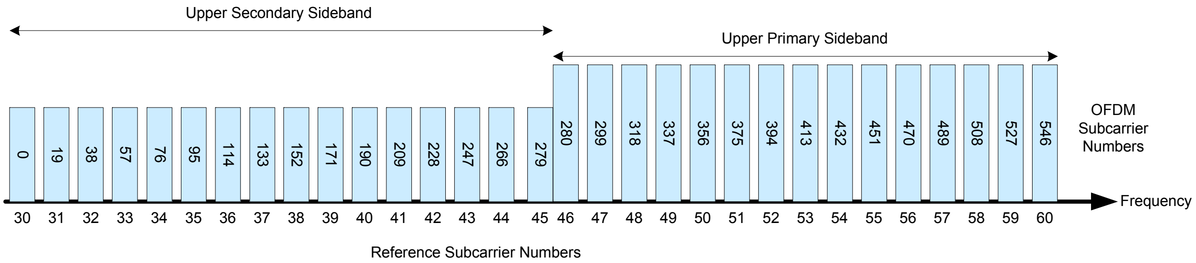


Figure 5-4: Upper Sideband Reference Subcarrier Spectral Mapping

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. The center of subcarrier 0 is located at 0 Hz. In this context, center frequency is relative to the radio frequency (RF) *allocated channel*.

For example, the upper Primary Main sideband is bounded by subcarriers 356 and 546 whose center frequencies are located at 129,361 Hz and 198,402 Hz, respectively. The frequency span of a Primary Main sideband is 69,041 Hz (198,402 Hz – 129,361 Hz).

5.3 Hybrid Spectrum

The digital signal is transmitted in PM sidebands on both sides of the analog FM signal as shown in Figure 5-5. Each PM sideband consists 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. The amplitude of each subcarrier is scaled by an *amplitude scale factor* as indicated in Table 5-1. Table 5-1 summarizes the upper and lower Primary Main sidebands for the Hybrid waveform.

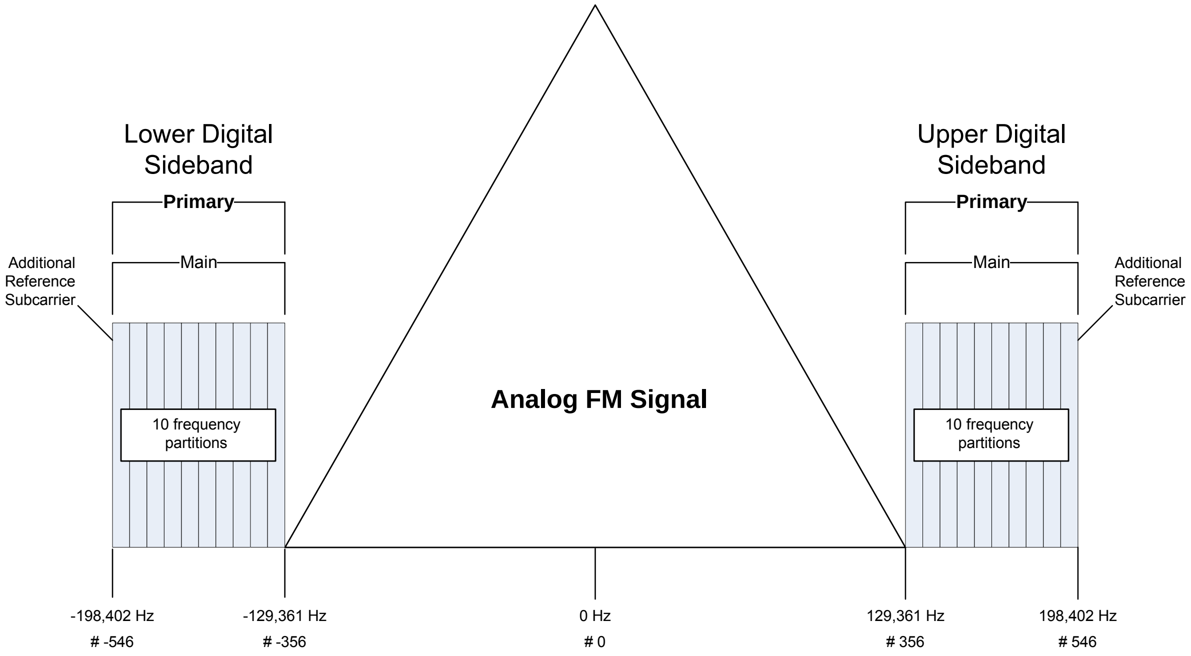


Figure 5-5: Spectrum of the Hybrid Waveform – Service Mode MP1

Table 5-1: Hybrid Waveform Spectral Summary – Service Mode MP1

Sideband	Number of Frequency Partitions	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Frequency Span (Hz)	Amplitude Scale Factor	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	69,041	a_0	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	69,041	a_0	Includes additional reference subcarrier -546

Note: *Refer to Reference [3] for details regarding the amplitude scale factors shown above.*

5.4 Extended Hybrid Spectrum

The Extended Hybrid waveform is created by adding Primary Extended sidebands to the Primary Main sidebands present in the Hybrid waveform as shown in Figure 5-6. Depending on the service mode, one, two, or four frequency partitions can be added to the inner edge of each Primary Main sideband.

Each Primary Main sideband consists of ten frequency partitions and an additional reference subcarrier spanning subcarriers 356 through 546, or -356 through -546. The upper Primary Extended sidebands include subcarriers 337 through 355 (one frequency partition), 318 through 355 (two frequency partitions), or 280 through 355 (four frequency partitions). The lower Primary Extended sidebands include subcarriers -337 through -355 (one frequency partition), -318 through -355 (two frequency partitions), or -280 through -355 (four frequency partitions). The amplitude of each subcarrier is scaled by an amplitude scale factor as indicated in Table 5-2. Table 5-2 summarizes the Upper and Lower Primary sidebands for the Extended Hybrid waveform.

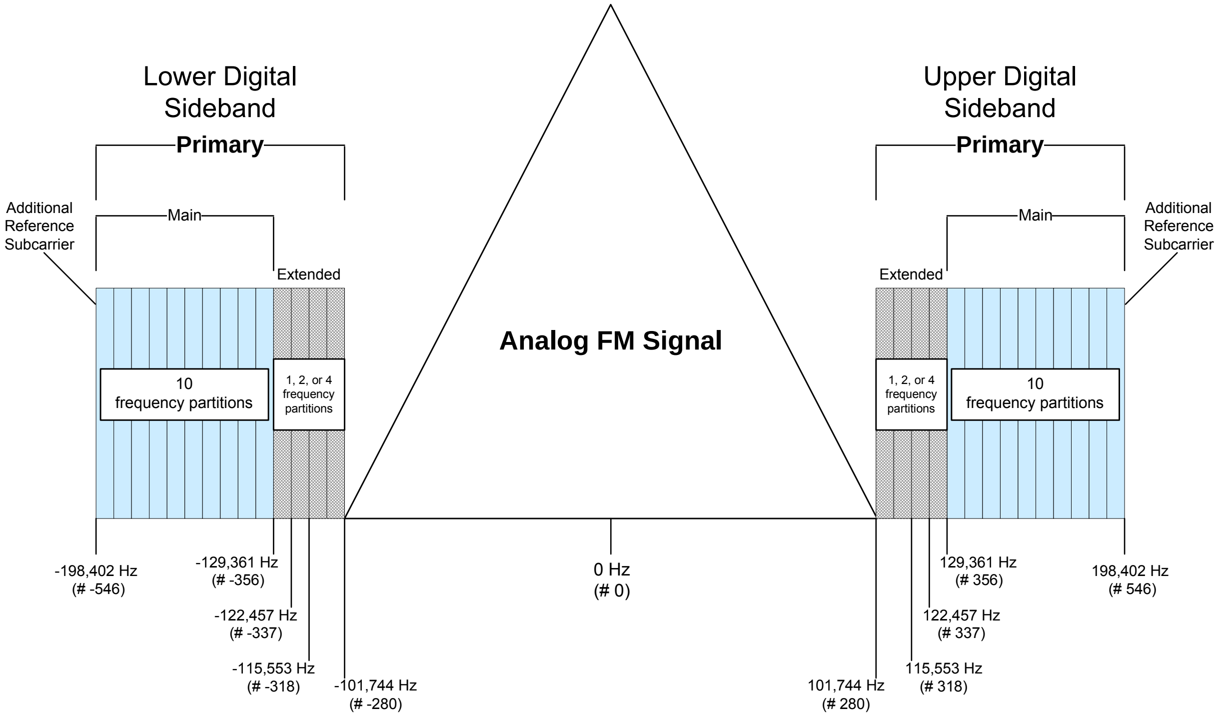


Figure 5-6: Spectrum of the Extended Hybrid Waveform – Service Modes MP2, MP3, MP11, MP5, and MP6

Table 5-2: Extended Hybrid Waveform Spectral Summary – Service Modes MP2, MP3, MP11, MP5, and MP6

Sideband	Number Of Frequency Partitions	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Freq. Span (Hz)	Ampl. Scale Factor	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	69,041	a_0	Includes additional reference subcarrier 546

Sideband	**Number Of Frequency Partitions**	**Frequency Partition Ordering**	**Subcarrier Range**	**Subcarrier Frequencies (Hz from channel center)**	**Freq. Span (Hz)**	**Ampl. Scale Factor**	**Comments**
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	69,041	a_0	Includes additional reference subcarrier -546
Upper Primary Extended (1 frequency partition)	1	A	337 to 355	122,457 to 128,997	6,540	a_0	none
Lower Primary Extended (1 frequency partition)	1	B	-337 to -355	-122,457 to -128,997	6,540	a_0	none
Upper Primary Extended (2 frequency partitions)	2	A	318 to 355	115,553 to 128,997	13,444	a_0	none
Lower Primary Extended (2 frequency partitions)	2	B	-318 to -355	-115, 553 to -128,997	13,444	a_0	none
Upper Primary Extended (4 frequency partitions)	4	A	280 to 355	101,744 to 128,997	27,253	a_0	none
Lower Primary Extended (4 frequency partitions)	4	B	-280 to -355	-101, 744 to -128,997	27,253	a_0	none

Note: *Refer to Reference [3] for details regarding the amplitude scale factors shown above.*

5.5 All Digital Spectrum

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 5-7.

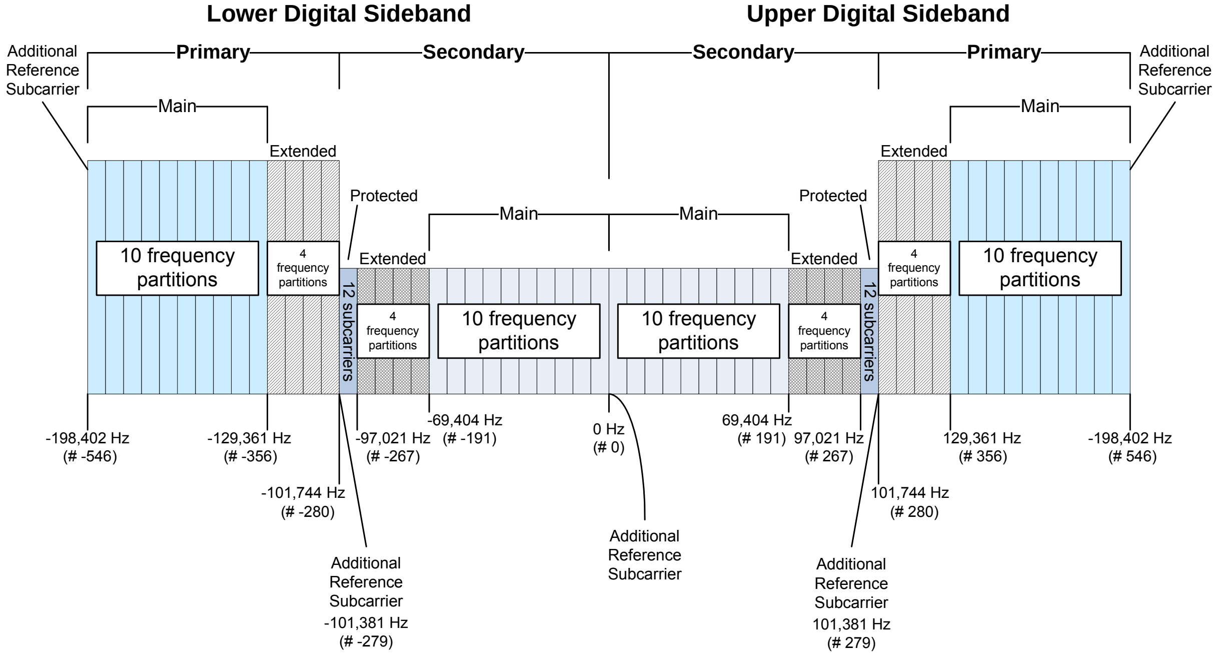


Figure 5-7: Spectrum of the All Digital Waveform – Service Modes MP5 and MP6, MS1 through MS4

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 the 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 subcarriers #279 and #-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 5-1 and Figure 5-2.

Each Secondary Main sideband spans subcarriers 1 through 190 or -1 through -190. The upper Secondary Extended sideband includes subcarriers 191 through 266, and the upper Secondary Protected sideband includes subcarriers 267 through 278, plus additional reference subcarrier 279. The lower Secondary Extended sideband includes subcarriers -191 through -266, and the lower Secondary Protected sideband includes subcarriers -267 through -278, plus additional reference subcarrier -279. The total frequency span of the entire All Digital spectrum is 396,803 Hz. The amplitude of each subcarrier is scaled by an amplitude scale factor as indicated in Table 5-3. The secondary sideband amplitude scale factors, a_2 through a_5, are user selectable. Any one of the four may be selected for application to the secondary sidebands. Table 5-3 summarizes the upper and lower, primary and secondary sidebands for the All Digital waveform.

Table 5-3: All Digital Waveform Spectral Summary – Service Modes MP5 and MP6, MS1 through MS4

Sideband	Number Of Frequency Partitions	Freq. Partition Ordering	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Freq. Span (Hz)	Ampl. Scale Factor	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	69,041	a_1	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	69,041	a_1	Includes additional reference subcarrier -546
Upper Primary Extended	4	A	280 to 355	101,744 to 128,997	27,253	a_1	none
Lower Primary Extended	4	B	-280 to -355	-101,744 to -128,997	27,253	a_1	none
Upper Secondary Main	10	B	0 to 190	0 to 69,041	69,041	a_2, a_3, a_4, a_5	Includes additional reference subcarrier located at subcarrier 0
Lower Secondary Main	10	A	-1 to -190	-363 to -69,041	68,678	a_2, a_3, a_4, a_5	none
Upper Secondary Extended	4	B	191 to 266	69,404 to 96,657	27,253	a_2, a_3, a_4, a_5	none
Lower Secondary Extended	4	A	-191 to -266	-69,404 to -96,657	27,253	a_2, a_3, a_4, a_5	none
Upper Secondary Protected	N/A	N/A	267 to 279	97,021 to 101,381	4,360	a_2, a_3, a_4, a_5	Includes additional reference subcarrier 279
Lower Secondary Protected	N/A	N/A	-267 to -279	-97,021 to -101,381	4,360	a_2, a_3, a_4, a_5	Includes additional reference subcarrier -279

Note: *Refer to Reference [3] for details regarding the amplitude scale factors shown above and Subsection 6.6 for information on how* $a_2 – a_5$ *are selected.*

6 System Control Channel

6.1 Introduction

The SCCH passes discrete transfer frames of control and status information between Layer 2, the Configuration Administrator, and Layer 1. The control information passed from the Configuration Administrator to Layer 1 consists of Primary Service Mode Control (PSM), Secondary Service Mode Control (SSM), and Amplitude Scale Factor Select (ASF). The status information passed from Layer 1 to Layer 2 consists of *Absolute L1 Frame Number* (ALFN) and *L1 Block Count* (BC). In addition, several bits of the system control data sequence designated "reserved" are controlled by the Configuration Administrator. Refer to Figure 6-1. This status information, the L1 Block Count, and indicators of the state of the control information (with the exception of ALFN) are broadcast on the reference subcarriers.

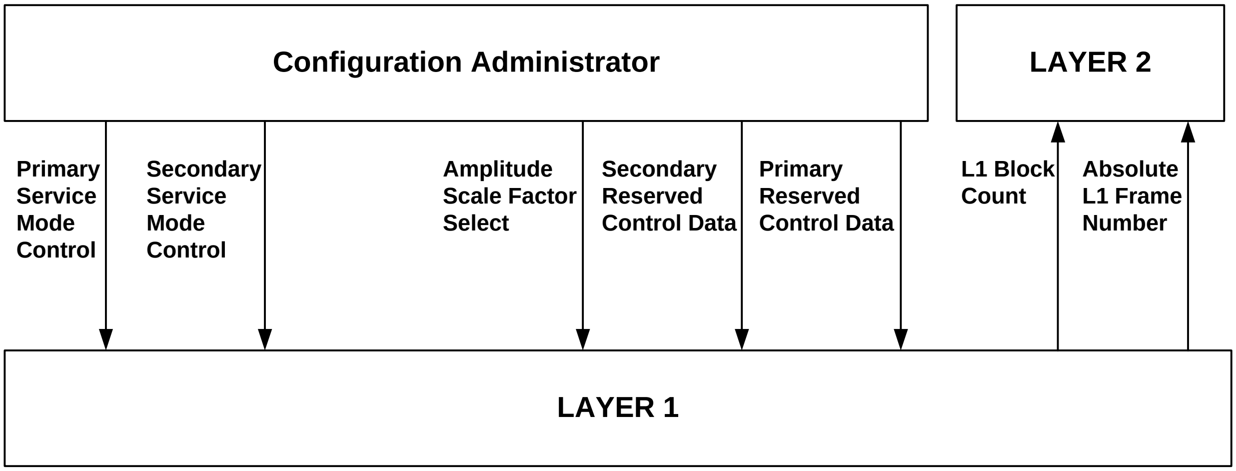


Figure 6-1: System Control Channel

The direction and rate of transfer between Layer 2, the Configuration Administrator, and Layer 1 is given in Table 6-1.

Table 6-1: Transfer through the System Control Channel (SCCH)

Data	Direction	Transfer Frame Rate	Size (bits)
Primary Service Mode Control (PSM)	Configuration Administrator → Layer 1	R_f	6
Secondary Service Mode Control (SSM)	Configuration Administrator → Layer 1	R_f	5
Amplitude Scale Factor Select (ASF)	Configuration Administrator → Layer 1	R_f	4
Primary Reserved Control Data	Configuration Administrator → Layer 1	R_f	3
Secondary Reserved Control Data	Configuration Administrator → Layer 1	R_f	6

Data	Direction	Transfer Frame Rate	Size (bits)
L1 Block Count (BC)	Layer 1 → Layer 2	R_b	4
Absolute L1 Frame Number (ALFN)	Layer 1 → Layer 2	R_f	32

6.2 Service Mode Control

The service mode dictates the configuration and performance of the logical channels. There are two basic types of service modes:

- Primary–configures primary logical channels
- Secondary–configures secondary logical channels

All waveforms require the definition of both primary and secondary service modes. If secondary sidebands are not present, the secondary service mode is set to “None” as shown in Table 6-3. The service modes support the delivery of various combinations of digital audio and data.

- The active primary service modes defined by this document are MP1, MP2, MP3, MP11, MP5, and MP6.
- The active secondary service modes defined by this document are MS1, MS2, MS3, and MS4.

Table 6-2 and Table 6-3 define the bit mapping for PSM and SSM, respectively.

Table 6-2: PSM Bit Mapping

Primary Service Mode	**Bit Assignment (bits 5:0)**					
	5	**4**	**3**	**2**	**1**	**0**
Reserved	0	0	0	0	0	0
MP1	0	0	0	0	0	1
MP2	0	0	0	0	1	0
MP3	0	0	0	0	1	1
Reserved	0	0	0	1	0	0
MP5	0	0	0	1	0	1
MP6	0	0	0	1	1	0
Reserved	0	0	0	1	1	1
…	…	…	…	…	…	…
Reserved	0	0	1	0	1	0
MP11	0	0	1	0	1	1
Reserved	0	0	1	1	0	0
…		…	…	…	…	…
Reserved	1	1	1	1	1	1

Table 6-3: SSM Bit Mapping

Secondary Service Mode	**Bit Assignment (bits 4:0)**				
	4	**3**	**2**	**1**	**0**
None	0	0	0	0	0
MS1	0	0	0	0	1
MS2	0	0	0	1	0
MS3	0	0	0	1	1
MS4	0	0	1	0	0
Reserved	0	0	1	0	1
…	…	…	…	…	…
Reserved	1	1	1	1	1

6.2.1 Primary Service Mode Backward Compatibility

Reserved primary service mode bit assignments are for future expansion. To ensure backward compatibility, all primary service modes defined as “Reserved” in Table 6-2 must maintain backward compatibility with one of the following service modes: MP1, MP2, MP3, MP11, MP5, or MP6.

As a minimum, backward compatibility includes the PIDS logical channel, the system control data sequence (matrix $\underline{\underline{R}}$) conveyed over the reference subcarriers, and at least one logical channel which can support medium-quality digital audio. Refer to Table 6-4 for a definition of the default service modes that first generation receivers will assume and with which all transmission equipment must maintain backward compatibility for all reserved primary service mode assignments. Any service mode that is backward compatible with Hybrid service modes MP1-MP3 (e.g., MP9, MP10, MP19, and MP28) is also a Hybrid service mode and the secondary service mode must be set to “None”.

MP11 is a special case. First-generation receivers will fall back to service mode MP3 and will decode the P3 logical channel and ignore the P4 logical channel. However, MP11 is fully defined in this document and is no longer reserved.

A primary service mode may maintain backward compatibility with primary service modes MP5 and MP6 in one of two configurations. Both the P1 and P1′ or only the P1′ logical channels may be supported. For each primary service mode, Table 6-4 defines which logical channels must maintain backward compatibility.

Table 6-4: Reserved Primary Service Modes – Defaults

Actual Primary Service Mode	**Bit Assignment (bits 5:0)**						**Default Primary Service Mode**	**Backward Compatible Logical Channels/Elements**
	5	**4**	**3**	**2**	**1**	**0**		
MP4	0	0	0	1	0	0	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP7	0	0	0	1	1	1	MP5	P1′, PIDS, $\underline{\underline{R}}$
MP8	0	0	1	0	0	0	MP6	P1′, PIDS, $\underline{\underline{R}}$
MP9	0	0	1	0	0	1	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP10	0	0	1	0	1	0	MP2	P1, PIDS, $\underline{\underline{R}}$, Analog
MP11	0	0	1	0	1	1	MP3	P1, P3, PIDS, $\underline{\underline{R}}$, Analog
MP12	0	0	1	1	0	0	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP13	0	0	1	1	0	1	MP5	P1, P1′, PIDS, $\underline{\underline{R}}$
MP14	0	0	1	1	1	0	MP6	P1, P1′, PIDS, $\underline{\underline{R}}$
MP15	0	0	1	1	1	1	MP5	P1′, PIDS, $\underline{\underline{R}}$
MP16	0	1	0	0	0	0	MP6	P1′, PIDS, $\underline{\underline{R}}$

Actual Primary Service Mode	**Bit Assignment (bits 5:0)**						**Default Primary Service Mode**	**Backward Compatible Logical Channels/Elements**
	5	**4**	**3**	**2**	**1**	**0**		
MP17	0	1	0	0	0	1	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP18	0	1	0	0	1	0	MP2	P1, PIDS, $\underline{\underline{R}}$, Analog
MP19	0	1	0	0	1	1	MP3	P1, P3, PIDS, $\underline{\underline{R}}$, Analog
MP20	0	1	0	1	0	0	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP21	0	1	0	1	0	1	MP5	P1, P1′, PIDS, $\underline{\underline{R}}$
MP22	0	1	0	1	1	0	MP6	P1, P1′, PIDS, $\underline{\underline{R}}$
MP23	0	1	0	1	1	1	MP5	P1′, PIDS, $\underline{\underline{R}}$
MP24	0	1	1	0	0	0	MP6	P1′, PIDS, $\underline{\underline{R}}$
MP25	0	1	1	0	0	1	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP26	0	1	1	0	1	0	MP2	P1, PIDS, $\underline{\underline{R}}$, Analog
MP27	0	1	1	0	1	1	MP11	P1, P3, P4, PIDS, $\underline{\underline{R}}$, Analog
MP28	0	1	1	1	0	0	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP29	0	1	1	1	0	1	MP5	P1, P1′, PIDS, $\underline{\underline{R}}$
MP30	0	1	1	1	1	0	MP6	P1, P1′, PIDS, $\underline{\underline{R}}$
MP31	0	1	1	1	1	1	MP5	P1′, PIDS, $\underline{\underline{R}}$
MP32	1	0	0	0	0	0	MP6	P1′, PIDS, $\underline{\underline{R}}$
MP33	1	0	0	0	0	1	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP34	1	0	0	0	1	0	MP2	P1, PIDS, $\underline{\underline{R}}$, Analog
MP35	1	0	0	0	1	1	MP3	P1, P3, PIDS, $\underline{\underline{R}}$, Analog
MP36	1	0	0	1	0	0	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP37	1	0	0	1	0	1	MP5	P1, P1′, PIDS, $\underline{\underline{R}}$
MP38	1	0	0	1	1	0	MP6	P1, P1′, PIDS, $\underline{\underline{R}}$
MP39	1	0	0	1	1	1	MP5	P1′, PIDS, $\underline{\underline{R}}$
MP40	1	0	1	0	0	0	MP6	P1′, PIDS, $\underline{\underline{R}}$
MP41	1	0	1	0	0	1	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP42	1	0	1	0	1	0	MP2	P1, PIDS, $\underline{\underline{R}}$, Analog
MP43	1	0	1	0	1	1	MP11	P1, P3, P4, PIDS, $\underline{\underline{R}}$, Analog
MP44	1	0	1	1	0	0	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP45	1	0	1	1	0	1	MP5	P1, P1′, PIDS, $\underline{\underline{R}}$
MP46	1	0	1	1	1	0	MP6	P1, P1′, PIDS, $\underline{\underline{R}}$
MP47	1	0	1	1	1	1	MP5	P1′, PIDS, $\underline{\underline{R}}$
MP48	1	1	0	0	0	0	MP6	P1′, PIDS, $\underline{\underline{R}}$
MP49	1	1	0	0	0	1	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP50	1	1	0	0	1	0	MP2	P1, PIDS, $\underline{\underline{R}}$, Analog
MP51	1	1	0	0	1	1	MP3	P1, P3, PIDS, $\underline{\underline{R}}$, Analog
MP52	1	1	0	1	0	0	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP53	1	1	0	1	0	1	MP5	P1, P1′, PIDS, $\underline{\underline{R}}$
MP54	1	1	0	1	1	0	MP6	P1, P1′, PIDS, $\underline{\underline{R}}$
MP55	1	1	0	1	1	1	MP5	P1′, PIDS, $\underline{\underline{R}}$
MP56	1	1	1	0	0	0	MP6	P1′, PIDS, $\underline{\underline{R}}$
MP57	1	1	1	0	0	1	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog
MP58	1	1	1	0	1	0	MP2	P1, PIDS, $\underline{\underline{R}}$, Analog
MP59	1	1	1	0	1	1	MP11	P1, P3, P4, PIDS, $\underline{\underline{R}}$, Analog
MP60	1	1	1	1	0	0	MP1	P1, PIDS, $\underline{\underline{R}}$, Analog

Actual Primary Service Mode	Bit Assignment (bits 5:0)						Default Primary Service Mode	Backward Compatible Logical Channels/Elements
	5	4	3	2	1	0		
MP61	1	1	1	1	0	1	MP5	P1, P1′, PIDS, R
MP62	1	1	1	1	1	0	MP6	P1, P1′, PIDS, R
MP63	1	1	1	1	1	1	MP5	P1′, PIDS, R

6.2.2 Service Mode Pairings

When broadcasting secondary sidebands in the All Digital waveform, active primary and secondary service modes are both required. Any Hybrid-only or Extended-Hybrid-only primary service modes are invalid for the All Digital waveform (e.g. MP1 through MP3 and MP11). Only primary service modes MP5 and MP6 (and future modes that are backward-compatible with MP5 and MP6) 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.

6.2.3 Service Mode Switching

Primary service mode control (PSM) and secondary service mode control (SSM) are received from the Configuration Administrator via the SCCH at the rate R_f. Service mode changes are invoked only on an *L1 frame* boundary (see Subsection 6.3).

6.3 Absolute L1 Frame Number (ALFN)

The transmitted HD Radio signal may be regarded as a series of unique L1 frames of duration T_f. In order to reference all transmissions to absolute time, each L1 frame is associated with an ALFN. This universal frame numbering scheme assumes that the start of ALFN 0 occurred at 00:00:00 Coordinated Universal Time (UTC) on January 6, 1980. The start of every subsequent L1 frame occurs at an exact integer multiple of T_f after that instant in time. The current ALFN is a binary number determined by subtracting the GPS start time (00:00:00 on January 6, 1980) from the current GPS time (making allowance for the GPS epoch), expressing the difference in seconds, and multiplying the result by the frame rate R_f.

The ALFN (which is passed to Layer 2 via the SCCH at the frame rate R_f) may be used to schedule the delivery of time-critical programming.

6.4 L1 Block Count

Each L1 frame may be considered to consist of sixteen *L1 blocks* of duration T_b. The L1 Block Count (BC) indicates the position of the current L1 block within the L1 frame. An L1 block count of zero signifies the start of an L1 frame while a BC of 15 designates the final L1 block in an L1 frame. Table 6-5 defines the L1 BC bit mapping.

The BC is passed to Layer 2 via the SCCH at the block rate R_b. It is broadcast on the reference subcarriers and is used by the receiver to aid in synchronization.

An illustration of the relationship of L1 blocks to L1 frames is shown in Figure 6-2.

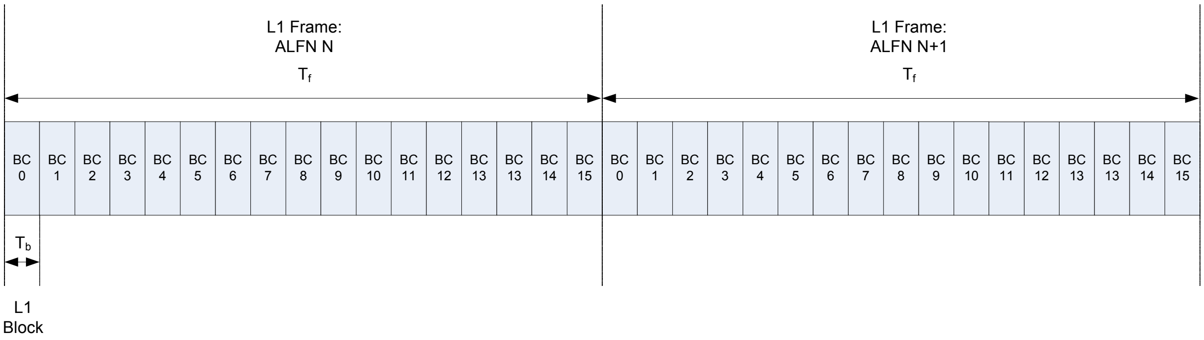


Figure 6-2: L1 Frames and L1 Blocks

Table 6-5: L1 Block Count (BC) Bit Mapping

L1 Block Count	Bit Assignment (bits 3:0)			
	3	2	1	0
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
10	1	0	1	0
11	1	0	1	1
12	1	1	0	0
13	1	1	0	1
14	1	1	1	0
15	1	1	1	1

6.5 Amplitude Scale Factor Select

The primary sidebands and secondary sidebands are independently scaled in amplitude. The primary sideband scale factors, a_0 and a_1, are fixed scale factors determined by the choice of service mode. One of the four amplitude scale factors, a_2 through a_5, is selected by the user for application to all of the secondary sidebands. The secondary sideband Amplitude Scale Factor Select (ASF) is received from the Configuration Administrator via the SCCH. When transmitting the Hybrid or Extended Hybrid waveform, this field is ignored. When transmitting the All Digital waveform, changes to ASF can be effected seamlessly at an L1 frame boundary without discontinuity or disruption in Layer 1 service.

Table 6-6 defines the ASF bit mapping.

Table 6-6: Amplitude Scale Factor (ASF) Bit Mapping

Scale Factor Selection	**ASF Bit Assignment (bits 3:0)**			
	3	**2**	**1**	**0**
Reserved	0	0	0	0
Reserved	0	0	0	1
a_2	0	0	1	0
a_3	0	0	1	1
a_4	0	1	0	0
a_5	0	1	0	1
Reserved	0	1	1	0
…	…	…	…	…
Reserved	1	1	1	1

6.6 Reserved Control Data

The primary system control data sequence contains three bits that are designated reserved and the secondary system control data sequence contains six bits that are designated reserved. These bits are controlled by the Configuration Administrator. The assignment of these bits to positions in the system control data sequence is specified in Table 6-7 and Table 6-8.

Table 6-7: Correlation of Primary Reserved Control Data Bits and System Control Data Sequence Bit Locations

Primary Reserved Control Data Bit #	**System Control Data Sequence Bit #**
0	Primary system control data sequence bit 7
1	Primary system control data sequence bit 16
2	Primary system control data sequence bit 24

Table 6-8: Correlation of Secondary Reserved Control Data Bits and System Control Data Sequence Bit Locations

Secondary Reserved Control Data Bit #	**System Control Data Sequence Bit #**
0	Secondary system control data sequence bit 6
1	Secondary system control data sequence bit 7
2	Secondary system control data sequence bit 8
3	Secondary system control data sequence bit 16
4	Secondary system control data sequence bit 19
5	Secondary system control data sequence bit 24

7 Logical Channels

7.1 Introduction

A logical channel is a signal path that conducts L2 PDUs through Layer 1 with a specified grade of service. The primary logical channels are P1, P2, P3, P4, and PIDS. The secondary logical channels are S1, S2, S3, S4, S5, and SIDS. Logical channels are defined by their characterization parameters and configured by the service mode.

7.2 Characterization Parameters

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

7.2.1 Transfer

Transfer defines the throughput of a logical channel. 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 defined in terms of *transfer frame size* (in bits) and *transfer frame rate* (in Hz, or the number of transfer frames per second). This Layer 1 framing effectively defines the alignment of L2 PDUs.

Each transfer frame is uniquely identified by its *transfer frame number*. The notation for the transfer frame number is presented as follows:

$$F_{m1:m2}^{n}$$

In the notation, the superscript n is the ALFN with which the transfer frame is associated and the subscript m1:m2 is the *BC range* that is spanned by the transfer frame within L1 frame n. Thus, the BC range indicates the position of the transfer frame within the L1 frame. The transfer frame number is not broadcast as part of the transmitted HD Radio signal.

All transfer frames are conducted through Layer 1 at one of three rates:

- the *L1 frame rate*, $R_f = \frac{1}{T_f}$
- the *L1 block rate*, $R_b = \frac{1}{T_b}$
- the *L1 block pair rate*, $R_p = \frac{1}{T_p}$

The ratio of the transfer frame rate to the L1 frame rate is termed the *transfer frame modulus*. For a transfer frame modulus of 1, the BC range is always 0:15. For a transfer frame modulus of 16, the BC range is always a single integer between 0 and 15. The transfer frame rate relationships are summarized in Table 7-1 and the transfer frame number timing relationships are illustrated in Figure 7-1.

Table 7-1: Transfer Frame Rate Relationships

Transfer Frame Type	**Transfer Frame Modulus**	**Transfer Frame Duration (seconds)**	**Transfer Frame Rate (Hz)**
L1 Block	16	T_b	$R_b = 16 \cdot R_f$
L1 Block Pair	8	$T_p = 2 \cdot T_b$	$R_p = 8 \cdot R_f$
L1 Frame	1	$T_f = 16 \cdot T_b$	R_f

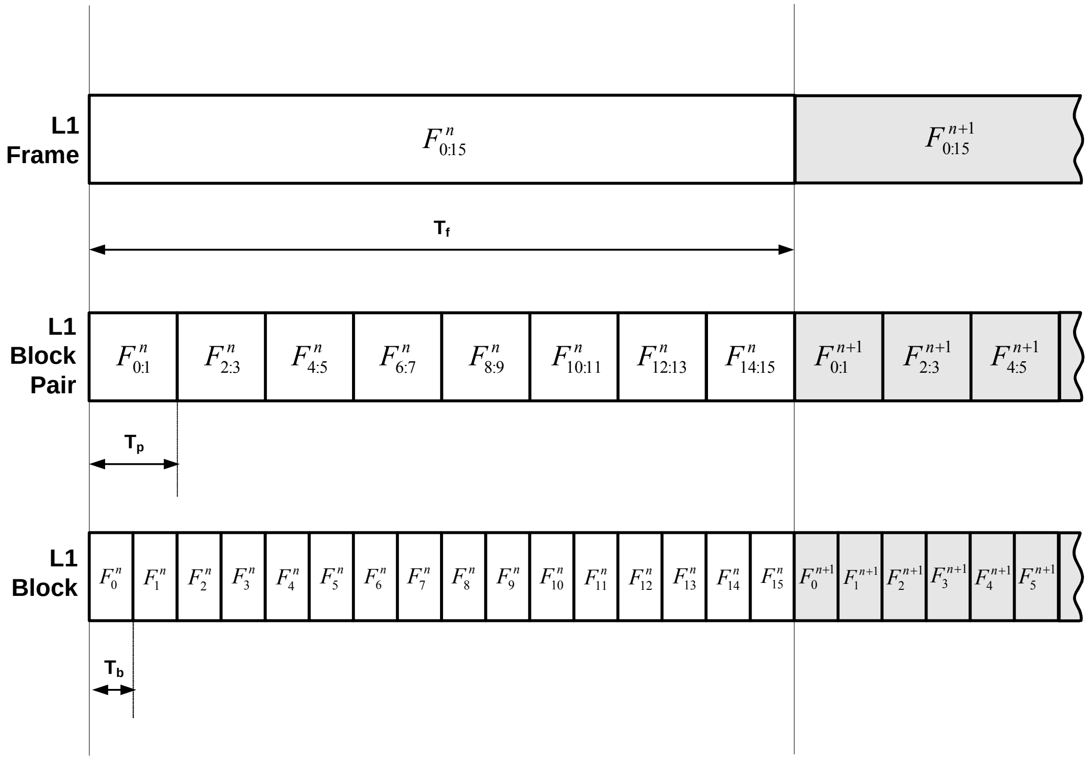


Figure 7-1: Transfer Frame Number Timing Relationship

Spectral mapping and channel code rate determine the transfer of a logical channel since spectral mapping limits capacity and coding overhead limits information throughput. Interleaver depth is also a factor because transfer frames are normally conducted through Layer 1 at rates corresponding to the interleaver depth of their logical channel.

7.2.2 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 delays in Layer 1 nor does it include delays imposed in upper layers.

The interleaver depth determines the amount of delay imposed on a logical channel by an interleaver. The FM HD Radio system employs four interleaver depths: L1 block, *L1 block pair*, L1 frame, and *L1 frame pair*. Diversity delay is also employed on some logical channels. For example, in some service modes, logical channel P1 presents dual processing paths; one path is delayed by T_{dd} from the other at the transmitter.

Higher layers assign information to logical channels with the requisite latency through service mode selection. Six latencies are specified for the system as defined in Table 7-2.

Table 7-2: Latency Summary

Description	**Delay**
L1 Block	T_b
L1 Block Pair	T_p
L1 Frame	T_f
L1 Frame Pair	$2 \cdot T_f$
L1 Block Pair plus Diversity Delay	$T_p + T_{dd}$
L1 Frame plus Diversity Delay	$T_f + T_{dd}$

7.2.3 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 Layer 1 of the FM air interface. A robustness of 1 indicates a very high level of resistance to channel impairments while a robustness of 11 indicates a lower tolerance for channel-induced errors. As with latency, higher layers must determine the required robustness of a logical channel before selecting a service mode.

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, 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.

7.2.4 Assignment of Characterization Parameters

Table 7-3 through Table 7-12 shows the characterization parameters of each logical channel for each service mode. Transfer is presented in terms of transfer frame size, transfer frame rate, and transfer frame modulus.

Table 7-3: Logical Channel Characterization – Service Mode MP1

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	**Frame Rate (Hz)**	**Frame Modulus**		
P1	146176	R_f	1	T_f	2
PIDS	80	R_b	16	T_b	3

Table 7-4: Logical Channel Characterization – Service Mode MP2

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	**Frame Rate (Hz)**	**Frame Modulus**		
P1	146176	R_f	1	T_f	2
P3	2304	R_p	8	$2 \cdot T_f$	3
PIDS	80	R_b	16	T_b	3

Table 7-5: Logical Channel Characterization – Service Mode MP3

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	**Frame Rate (Hz)**	**Frame Modulus**		
P1	146176	R_f	1	T_f	2
P3	4608	R_p	8	$2 \cdot T_f$	3
PIDS	80	R_b	16	T_b	3

Table 7-6: Logical Channel Characterization – Service Mode MP11

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	**Frame Rate (Hz)**	**Frame Modulus**		
P1	146176	R_f	1	T_f	2
P3	9216	R_p	8	$2 \cdot T_f$	3
P4	9216	R_p	8	$2 \cdot T_f$	3
PIDS	80	R_b	16	T_b	3

Table 7-7: Logical Channel Characterization – Service Mode MP5

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	Frame Rate (Hz)	Frame Modulus		
P1	4608	R_p	8	$T_p + T_{dd}$	1
P2	109312	R_f	1	T_f	2
P3	4608	R_p	8	$2 \cdot T_f$	3
PIDS	80	R_b	16	T_b	3

Table 7-8: Logical Channel Characterization – Service Mode MP6

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	Frame Rate (Hz)	Frame Modulus		
P1	9216	R_p	8	$T_p + T_{dd}$	1
P2	72448	R_f	1	T_f	2
PIDS	80	R_b	16	T_b	3

Table 7-9: Logical Channel Characterization – Service Mode MS1

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	Frame Rate (Hz)	Frame Modulus		
S4	18272	R_p	8	T_p	7
S5	512	R_b	16	T_b	6
SIDS	80	R_b	16	T_b	8

Table 7-10: Logical Channel Characterization – Service Mode MS2

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	Frame Rate (Hz)	Frame Modulus		
S1	4608	R_p	8	$T_p + T_{dd}$	5
S2	109312	R_f	1	T_f	9
S3	4608	R_p	8	T_p	11
S5	512	R_b	16	T_b	6
SIDS	80	R_b	16	T_b	10

Table 7-11: Logical Channel Characterization – Service Mode MS3

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	Frame Rate (Hz)	Frame Modulus		
S1	9216	R_p	8	$T_p + T_{dd}$	5
S2	72448	R_f	1	T_f	9
S5	512	R_b	16	T_b	6
SIDS	80	R_b	16	T_b	10

Table 7-12: Logical Channel Characterization – Service Mode MS4

Logical Channel	Transfer			Latency (seconds)	Relative Robustness
	Frame Size (bits)	Frame Rate (Hz)	Frame Modulus		
S1	4608	R_p	8	T_p	11
S2	146176	R_f	1	T_f	9
S3	4608	R_p	8	T_p	11
S5	512	R_b	16	T_b	6
SIDS	80	R_b	16	T_b	10

Information throughput of a logical channel can be calculated using these tables and the following formula:

$$\textit{throughput (bits/sec)} = \textit{transfer frame size (bits)} \cdot \textit{transfer frame rate (Hz)}$$

For example, in service mode MP1, the throughput for logical channel P1 is calculated as follows:

$$\textit{throughput (bits/sec)} = 146{,}176 \cdot \frac{44{,}100}{65{,}536} \approx 98.4 \textit{ kbit/sec}$$

7.3 Logical Channel Spectral Mapping

For a given service mode, each logical channel is applied to a group of OFDM subcarriers or frequency partitions as illustrated in Figure 7-2 through Figure 7-11. In these figures, the annotated frequencies represent offsets from the channel center frequency.

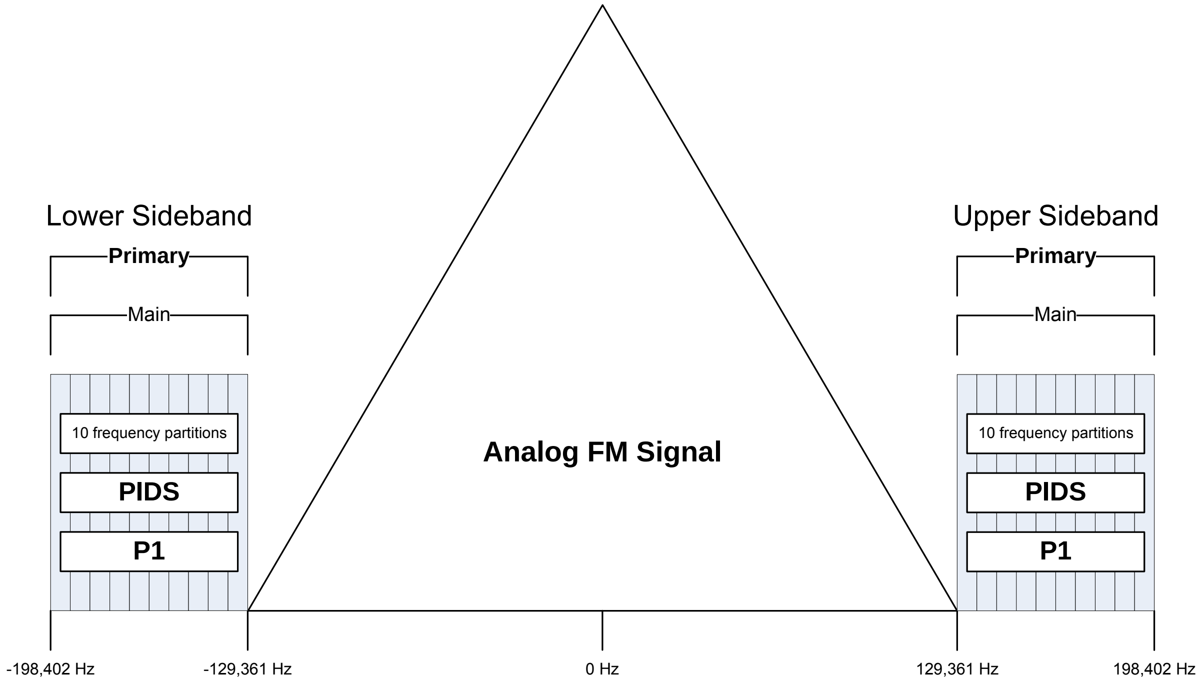


Figure 7-2: Logical Channel Spectral Mapping – Service Mode MP1

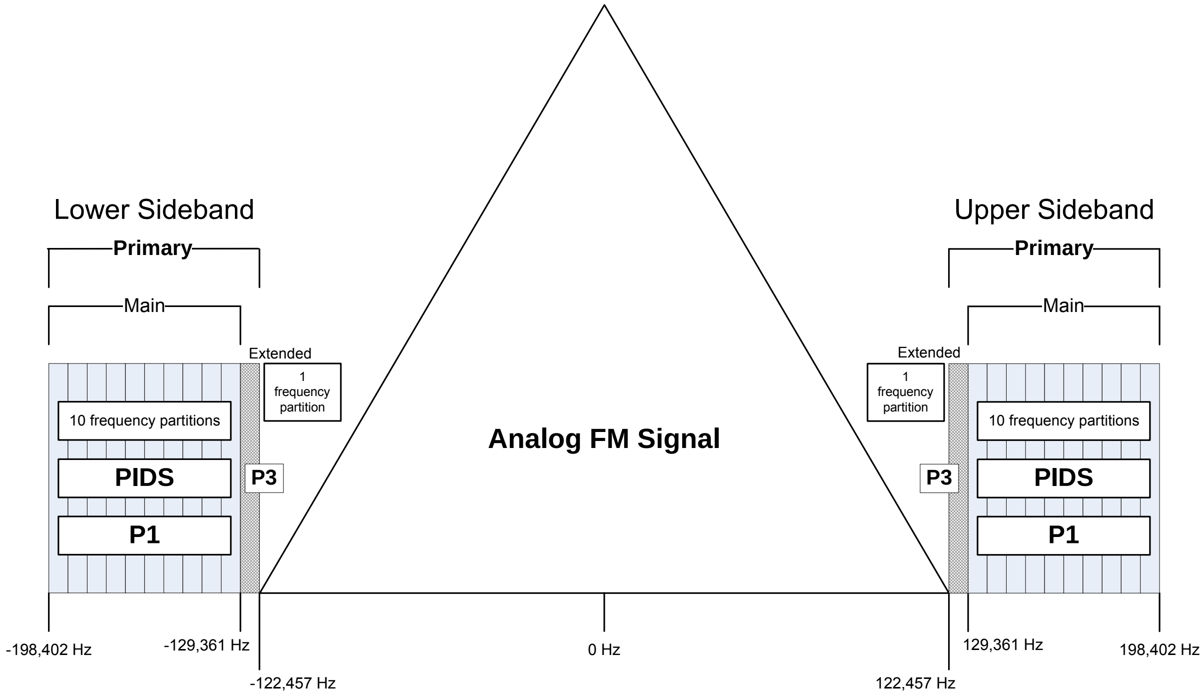


Figure 7-3: Logical Channel Spectral Mapping – Service Mode MP2

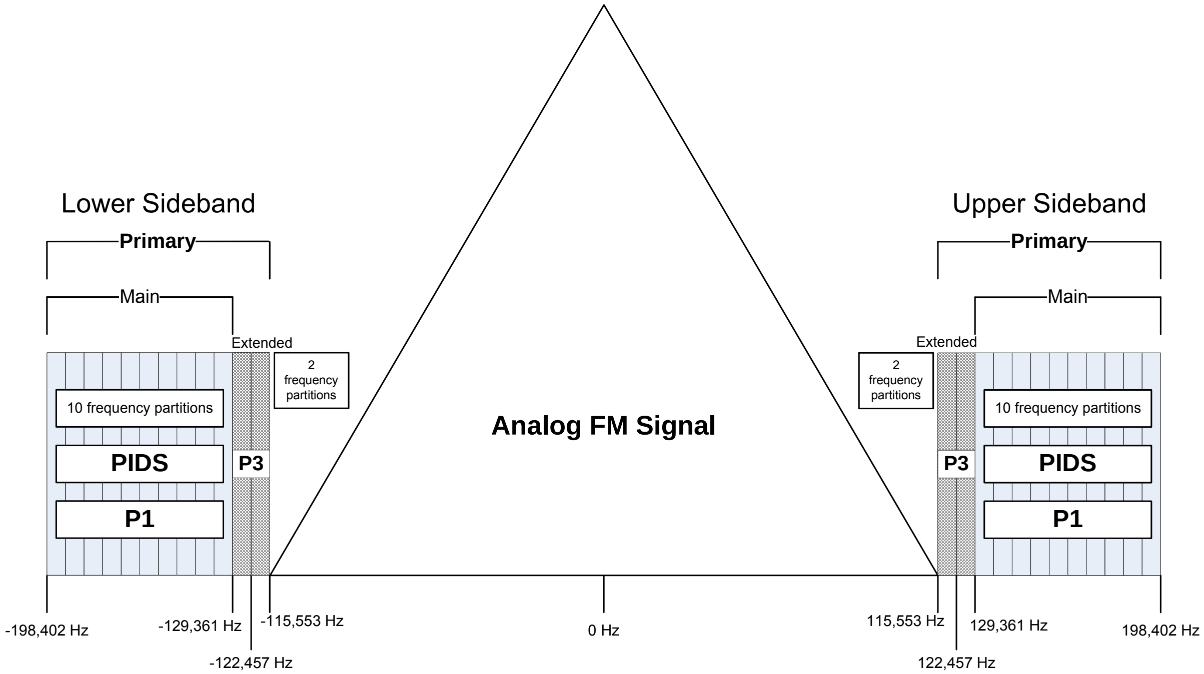


Figure 7-4: Logical Channel Spectral Mapping – Service Mode MP3

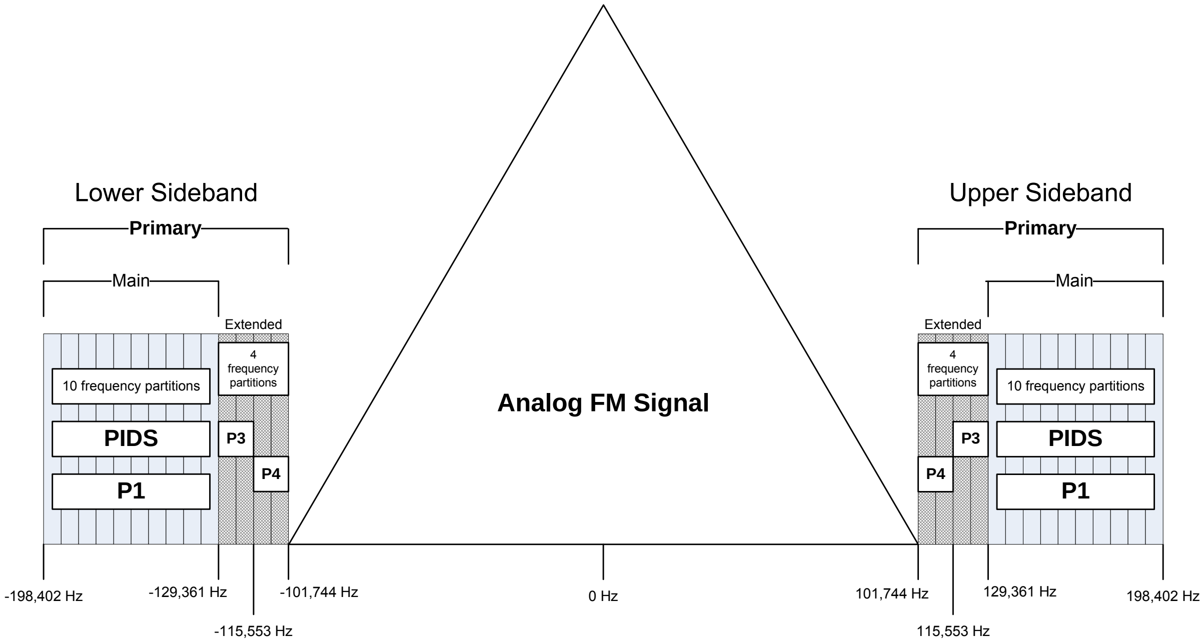


Figure 7-5: Logical Channel Spectral Mapping – Service Mode MP11

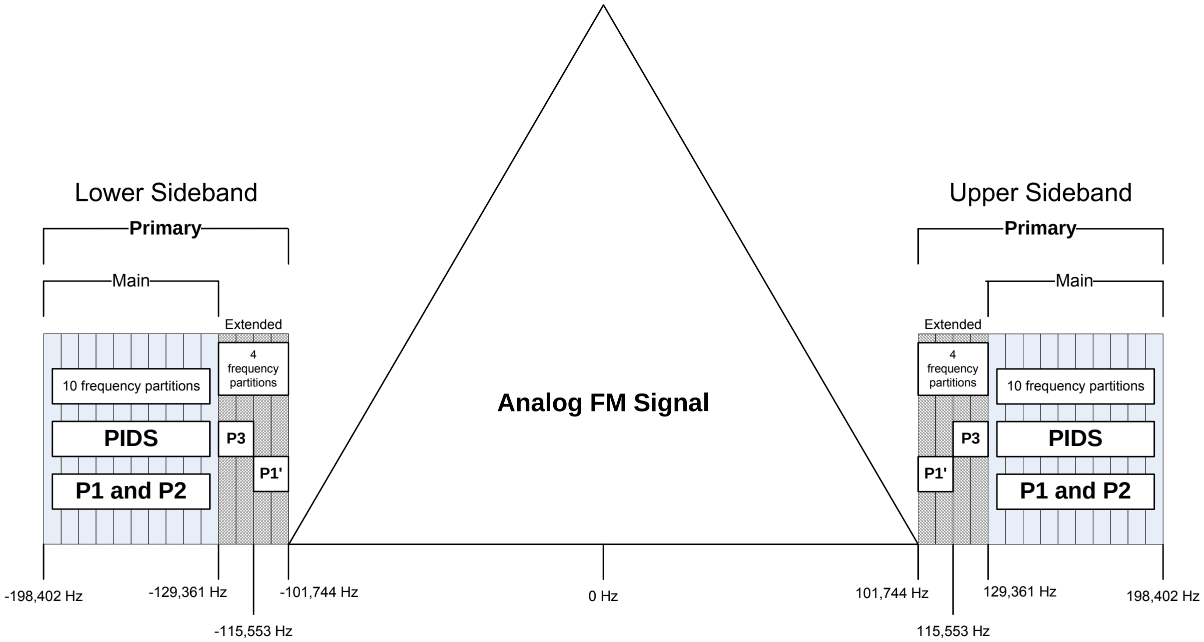


Figure 7-6: Logical Channel Spectral Mapping – Service Mode MP5

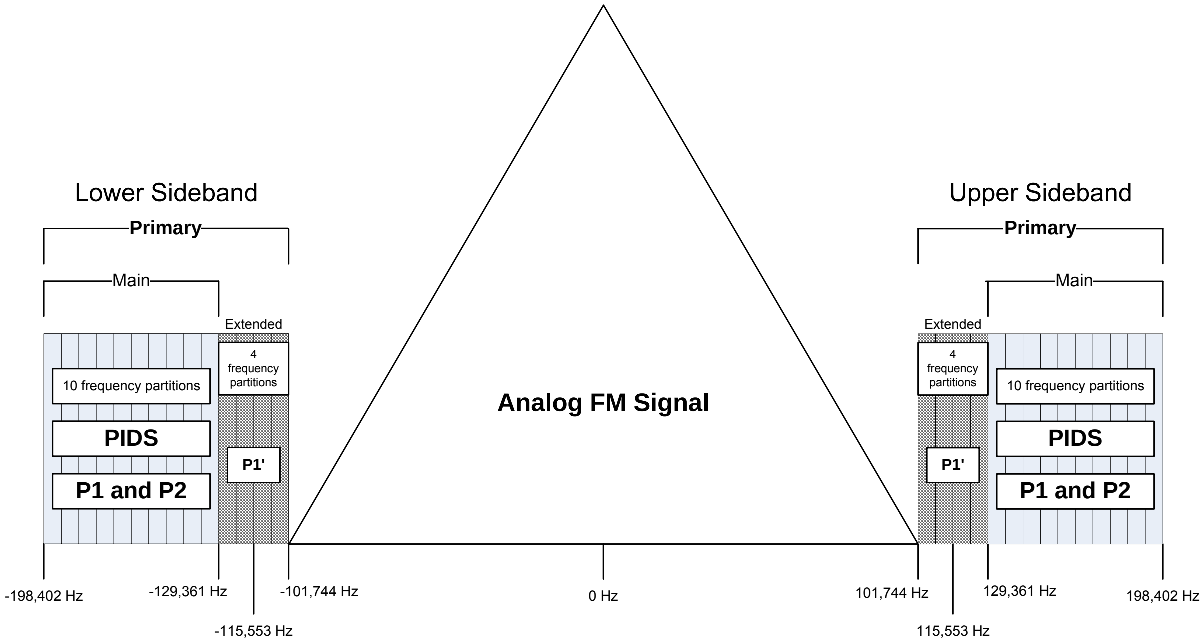


Figure 7-7: Logical Channel Spectral Mapping – Service Mode MP6

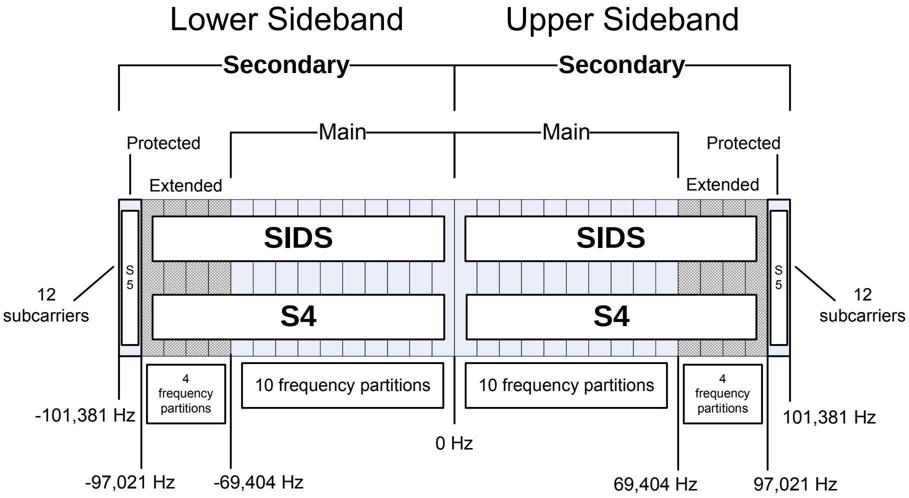


Figure 7-8: Logical Channel Spectral Mapping – Service Mode MS1

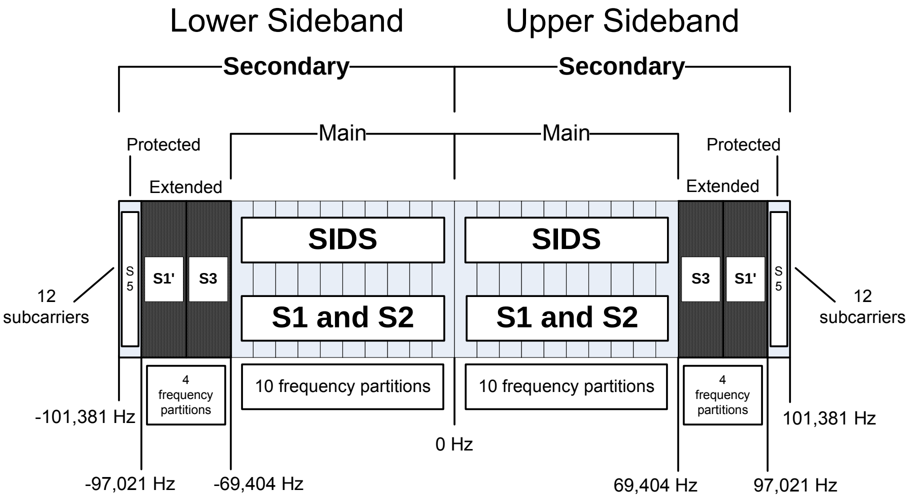


Figure 7-9: Logical Channel Spectral Mapping – Service Mode MS2

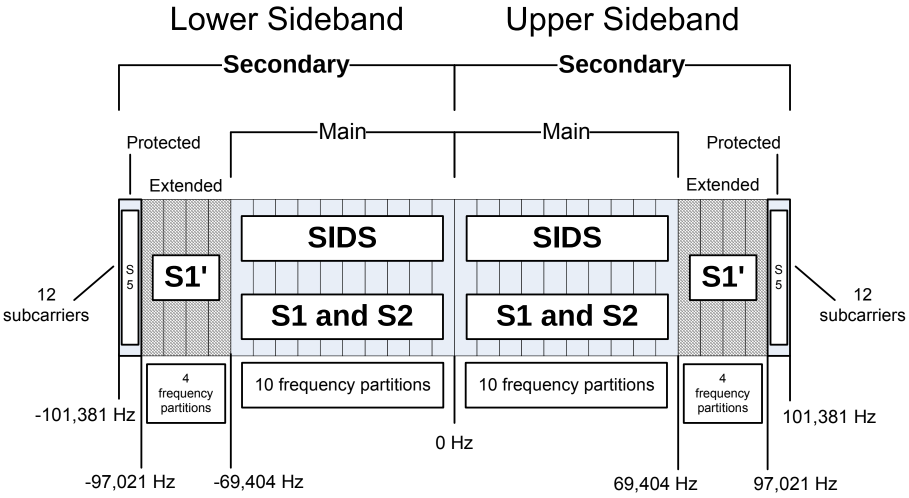


Figure 7-10: Logical Channel Spectral Mapping – Service Mode MS3

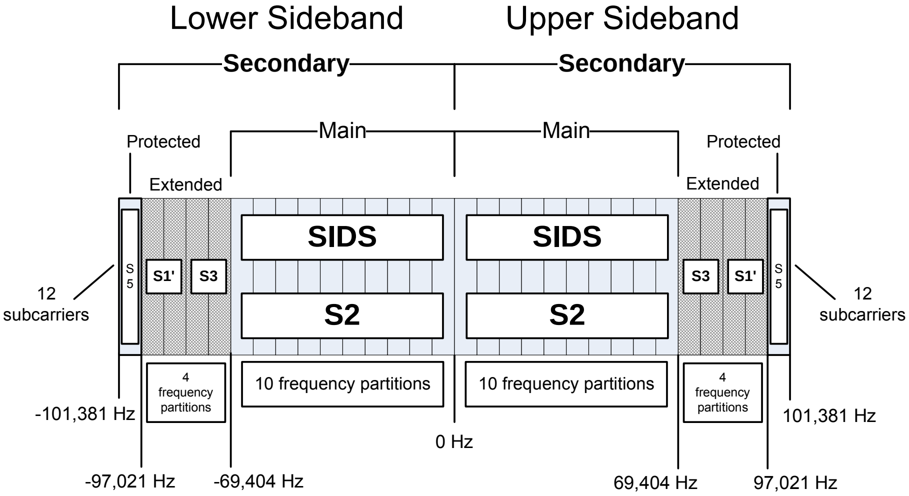


Figure 7-11: Logical Channel Spectral Mapping – Service Mode MS4

7.4 Logical Channel Framing and Synchronization

The logical channels share a common, absolute time reference so that all transfer frames are precisely aligned. As described in Subsection 7.2.1, each transfer frame is assigned a unique transfer frame number with the notation:

$$F_{m1:m2}^{n}$$

where superscript n is the ALFN and subscript $m1:m2$ is the BC range that designates the position of the transfer frame within the indexed L1 frame n.

This numbering scheme allows all transfer frames to be referenced to an absolute transmission time.

8 Scrambling

8.1 Introduction

The bits in each logical channel are scrambled to randomize the time-domain data and aid in receiver synchronization. As shown in Figure 8-1, there are eleven parallel scramblers; one for each logical channel.

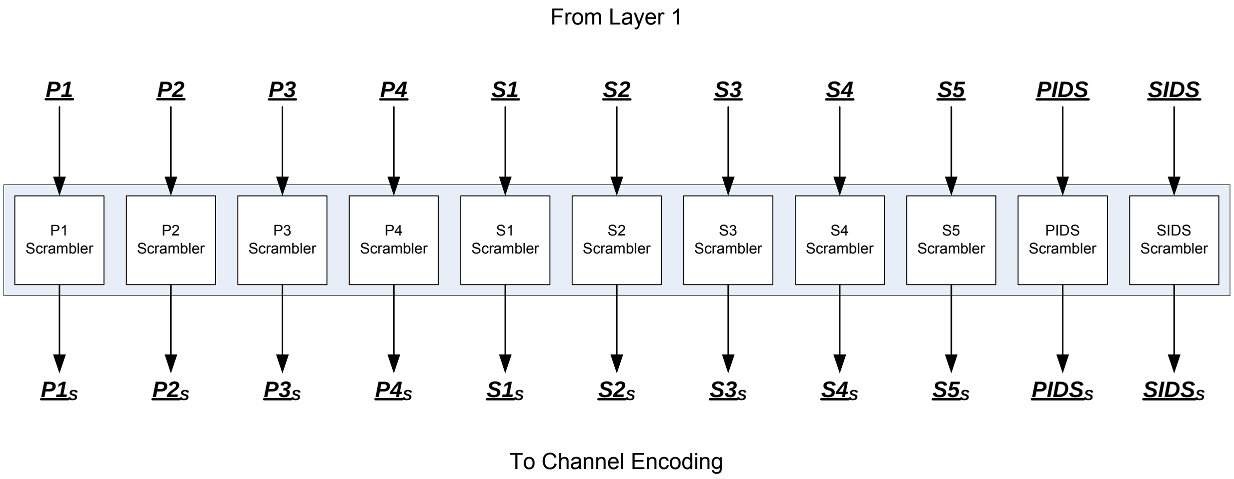


Figure 8-1: Scrambling Functional Block Diagram

The inputs to the scramblers are the active logical channels as selected by the service mode. These inputs are delivered in discrete transfer frames whose size and rate are defined in Table 7-3 through Table 7-12 for a given service mode. The outputs of the scramblers are transfer frames of scrambled bits for each of the active logical channels. These transfer frames are passed to the channel encoding process for forward error correction.

8.2 Scrambler Operation

All parallel scramblers are identical, but operate at different rates, depending on the active service mode. A detailed block diagram of the scrambler is shown in Figure 8-2. Each scrambler generates a maximal-length scrambling sequence using a linear feedback shift register with the following primitive polynomial:

$$P(x) = 1 \oplus x^2 \oplus x^{11}$$

A given bit of a scrambled transfer frame is generated by modulo-2 adding the associated input bit with the corresponding bit of the scrambling sequence.

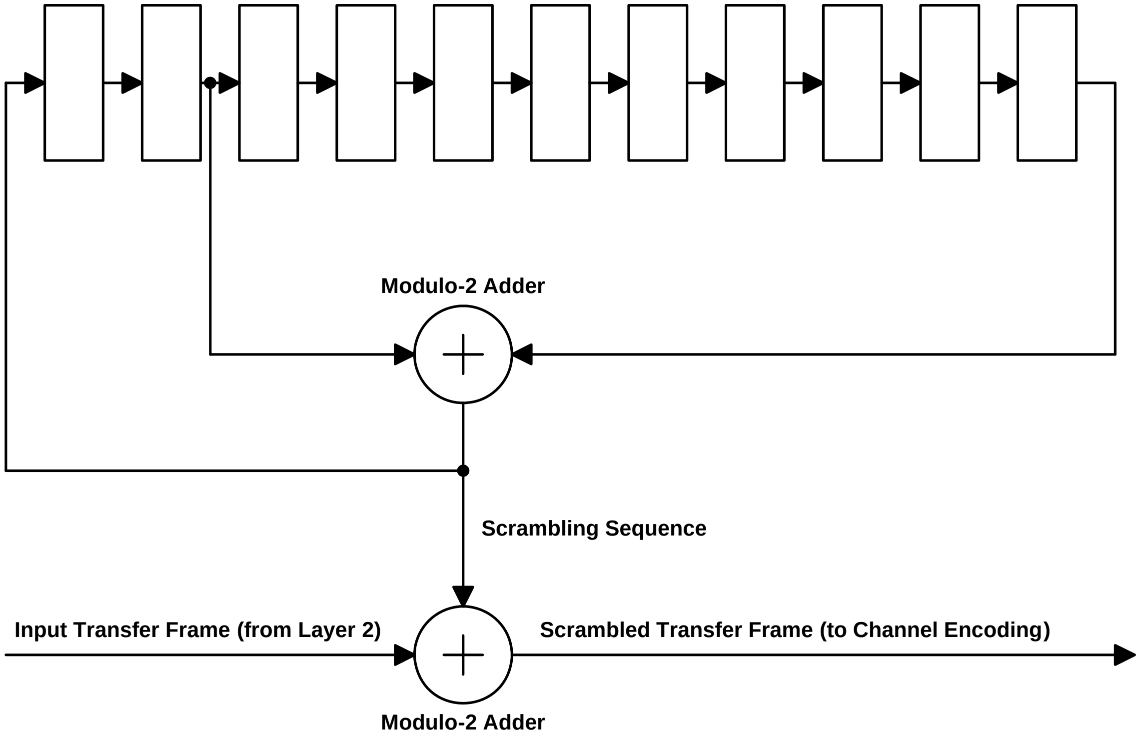


Figure 8-2: Scrambler Block Diagram

For each logical channel, the scrambler is reset to state 0111 1111 111 upon receipt of a new transfer frame. The first bit of a scrambled transfer frame is generated by modulo-2 adding the first bit of the input transfer frame with the scrambling bit generated when the shift register is set to the initial state. The process then continues until the last bit of the input transfer frame is scrambled.

9 Channel Encoding

9.1 Introduction

Channel encoding improves system performance by increasing the robustness of the signal in the presence of channel impairments. As shown in Figure 9-1, the channel encoding process is characterized by two main operations: time delay (for diversity delay and *transmit alignment*) and convolutional encoding.

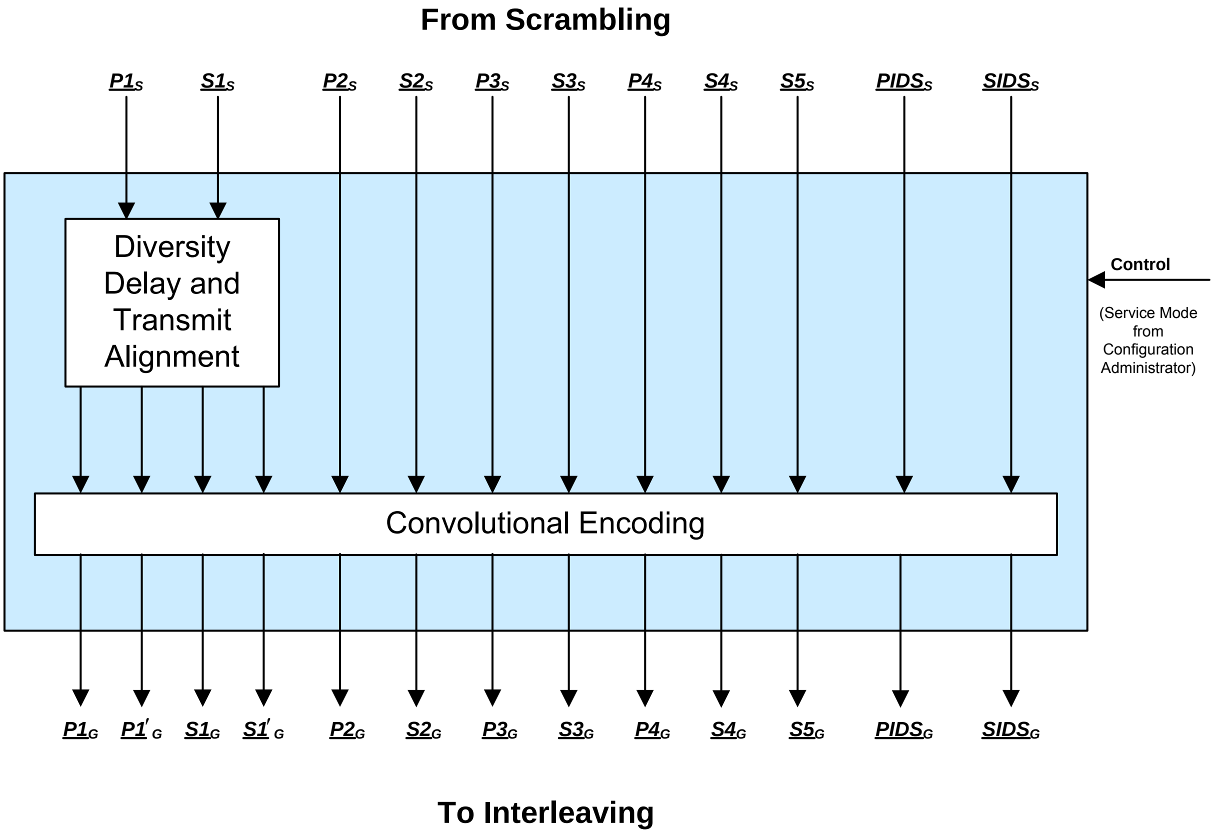


Figure 9-1: Channel Encoding Conceptual Block Diagram

The inputs to the channel encoding process are transfer frames of scrambled bits carried through the active logical channels. The size and rate of transfer are defined in Table 7-3 through Table 7-12 for a given service mode. The outputs of the channel encoding process are transfer frames of encoded bits associated with each of the active logical channels. The output transfer frames are passed to the interleaving function.

In the ensuing sections, for notational convenience, the logical channel vectors at a particular stage of processing are represented in shorthand notation by their subscript. For example, the scrambled inputs $\underline{Px}_S$ and $\underline{Sx}_S$ are represented by $\underline{S}$ while the encoded outputs $\underline{Px}_G$ and $\underline{Sx}_G$ are represented by $\underline{G}$. Also, the primed notation (as in $\underline{P1'}_G$) indicates that the logical channel vector is processed differently than the "unprimed" logical channel (for example see Figure 9-9 and Figure 9-10) and is destined for transmission in the extended sideband.

9.2 Diversity Delay and Transmit Alignment

Depending on the service mode, logical channels P1 and S1 may be split into two channels and delayed as they enter the channel encoding process. The manner in which diversity delay is applied to these logical channels is presented in Subsection 9.4 for each service mode. The delay provides time diversity to the affected logical channels. If applied, the value of the diversity delay is fixed at $N_{dd} \cdot T_f$.

In cases where digital diversity delay is applied, an additional delay called transmit alignment is imposed on the diversity delayed signals. This alignment delay ensures that the delayed channels (P1′ and S1′) are precisely positioned in time relative to the un-delayed channels (P1 and S1) with the same content to accommodate diversity combining in the receiver.

9.3 Convolutional Encoding

Convolutional encoding consists of three primary operations: *mother code* generation, *puncturing*, and parallel-to-serial conversion. Each of these operations is described below. A description of the codes employed in the FM system follows in Subsection 9.3.4.

9.3.1 Mother Code Generation

A convolutional encoder employs select generator polynomials to form a group of *mother codes*. A rate 1/n convolutional encoder outputs n encoded bits (symbolized in the matrix as $g_{h,i}$) for every input bit (s_i) of the scrambled input vector $\underline{S}$ creating a codeword matrix $\underline{\underline{G}}$ of dimension n x N:

$$\underline{\underline{G}} = \begin{bmatrix} g_{1,0} & g_{1,1} & \cdots & g_{1,N-1} \\ g_{2,0} & g_{2,1} & \cdots & g_{2,N-1} \\ \vdots & \vdots & \vdots & \vdots \\ g_{n,0} & g_{n,1} & \cdots & g_{n,N-1} \end{bmatrix}$$

For the input bits s_i: $i = 0,1,2,\ldots,N-1$ where N is the length of $\underline{S}$.

h indexes the codeword bits for a given input bit and $h = 1,2,\ldots,n$. In the FM system, $n = 3$ *or* 4.

Each column of $\underline{\underline{G}}$ represents the encoded output for a given input bit.

9.3.2 Puncturing

Some service modes require puncturing of a *mother codeword* to produce a slightly higher code rate, thereby allowing a higher information rate through the same physical bandwidth. The codeword matrix $\underline{\underline{G}}$ is punctured over a puncture period P. For every P encoded bits, certain bits ($g_{h,i}$) are not transmitted. A puncture matrix spanning the encoded bits over a puncture period defines which encoded bits are transmitted. Repeating the puncture matrix over all encoded bits of a transfer frame forms the puncture pattern.

9.3.3 Parallel-to-Serial Conversion

After the mother code bits are appropriately punctured, the parallel-to-serial converter multiplexes them by concatenating the columns of $\underline{\underline{G}}$ into a single vector $\underline{G}$ as follows:

$$\underline{G} = [\ g_{1,0}, g_{2,0}, \cdots, g_{n,0}, g_{1,1}, g_{2,1}, \cdots, g_{n,1}, \cdots, g_{1,N-1}, g_{2,N-1}, \cdots, g_{n,N-1}\ ]$$

9.3.4 Convolutional Encoders

Table 9-1 presents the four code rates used in the FM system along with their associated puncture matrices and mother code rates. A detailed description of each of these codes is provided in Subsection 9.3.4.1 through Subsection 9.3.4.4. The last 6 bits of a given transfer frame are used to initialize the delay elements of the corresponding convolutional encoder for that transfer frame. The fact that transfer frames define the encoding blocks is important in maintaining alignment between different logical channels.

Table 9-1: FM Convolutional Codes

Punctured Code Rate	Puncture Matrix	Mother Code Rate
1/3	$\begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \end{bmatrix}$	1/3
2/5	$\begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 0 \end{bmatrix}$	1/3
1/2	$\begin{bmatrix} 1 & 1 \\ 0 & 0 \\ 1 & 1 \end{bmatrix}$	1/3
2/7	$\begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \\ 1 & 0 \end{bmatrix}$	1/4

9.3.4.1 Rate 1/3 Code

The rate 1/3 mother code, with constraint length K=7, is defined by the generator polynomials shown in Table 9-2 (represented in octal format).

Table 9-2: Convolutional Encoder Generator Polynomials – Rate 1/3 Mother Code

First Generator	Second Generator	Third Generator
133	171	165

The rate 1/3 convolutional encoder is illustrated in Figure 9-2.

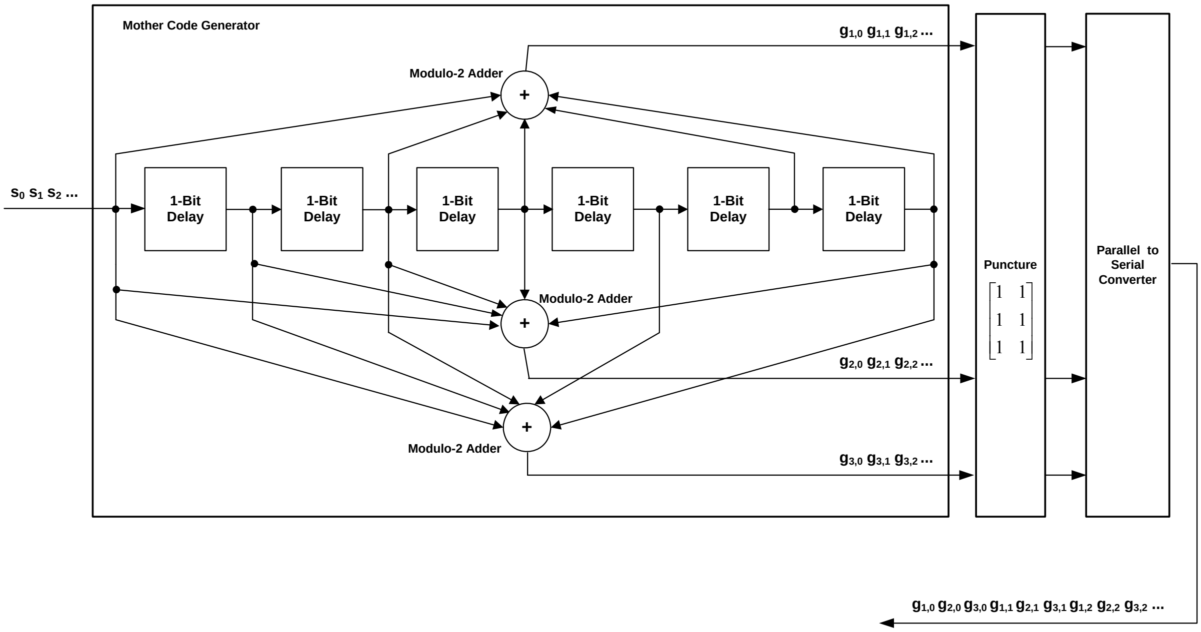


Figure 9-2: Convolutional Encoder – Rate 1/3 Code

9.3.4.2 Rate 2/5 Punctured Code

The rate 1/3 mother code is punctured to produce a rate 2/5 code. The rate 2/5 convolutional encoder is illustrated in Figure 9-3.

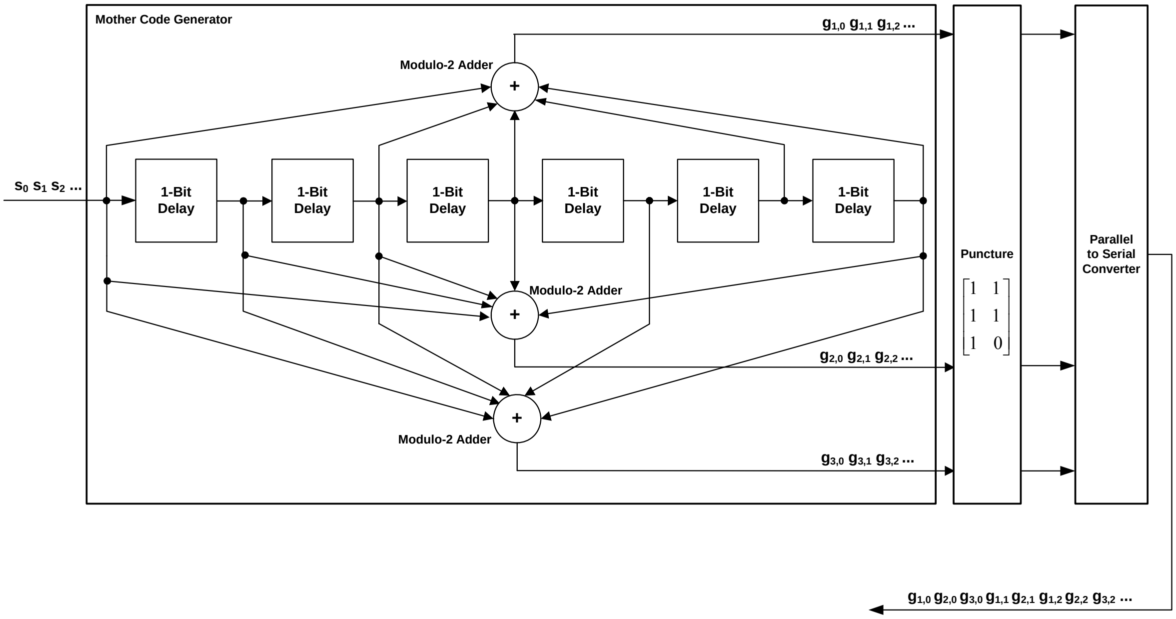


Figure 9-3: Convolutional Encoder – Rate 2/5 Code

9.3.4.3 Rate 1/2 Punctured Code

The rate 1/3 mother code is also punctured to produce a rate 1/2 code. The rate 1/2 convolutional encoder is illustrated in Figure 9-4.

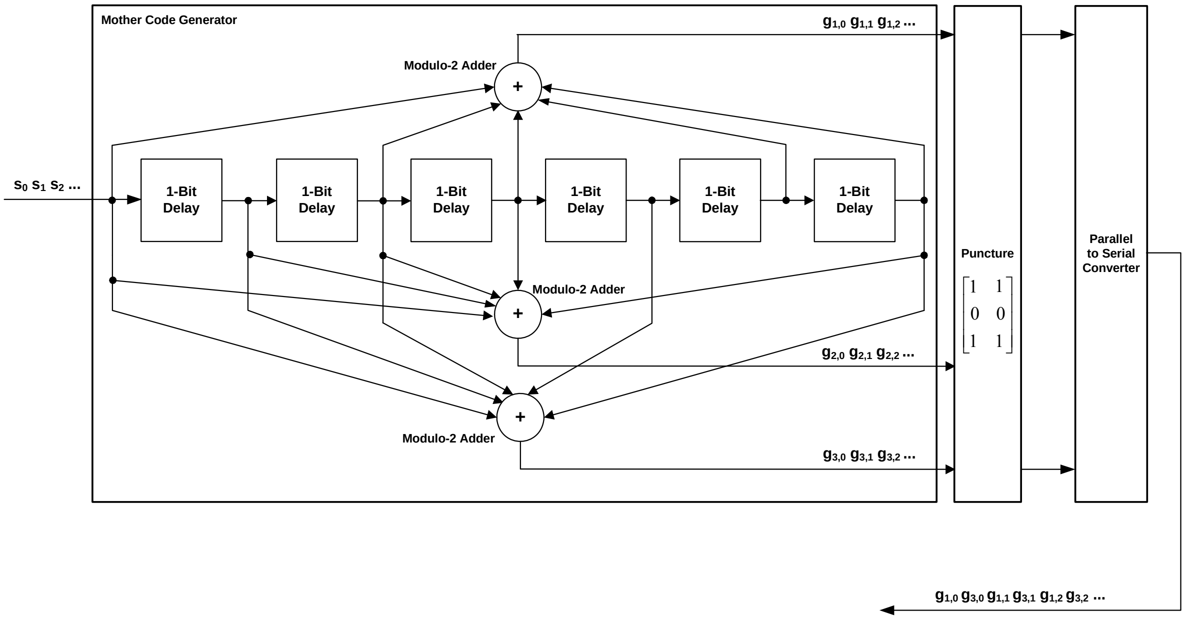


Figure 9-4: Convolutional Encoder – Rate 1/2 Code

9.3.4.4 Rate 2/7 Punctured Code

A rate 1/4 mother code with constraint length K=7 is punctured to produce a rate 2/7 code. The mother code is defined by the generator polynomials shown in Table 9-3 (represented in octal format).

Table 9-3: Convolutional Encoder Generator Polynomials – Rate 1/4 Mother Code

First Generator	Second Generator	Third Generator	Fourth Generator
133	171	165	165

The rate 2/7 convolutional encoder is illustrated in Figure 9-5.

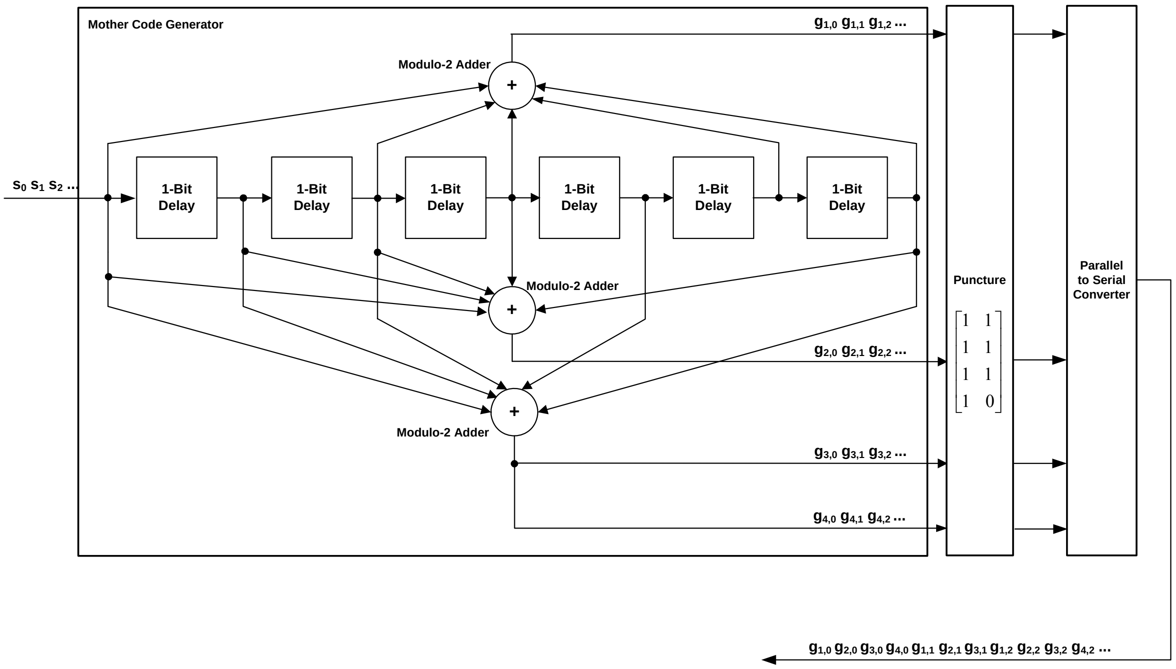


Figure 9-5: Convolutional Encoder – Rate 2/7 Code

9.4 Channel Encoding Data Flow

The channel encoding process for each logical channel in each service mode is specified in Subsection 9.4.1 through Subsection 9.4.9.

9.4.1 Service Mode MP1

Only P1 and PIDS logical channels are active in service mode MP1. The flow of their transfer frames through the channel encoding process for service mode MP1 is shown in Figure 9-6.

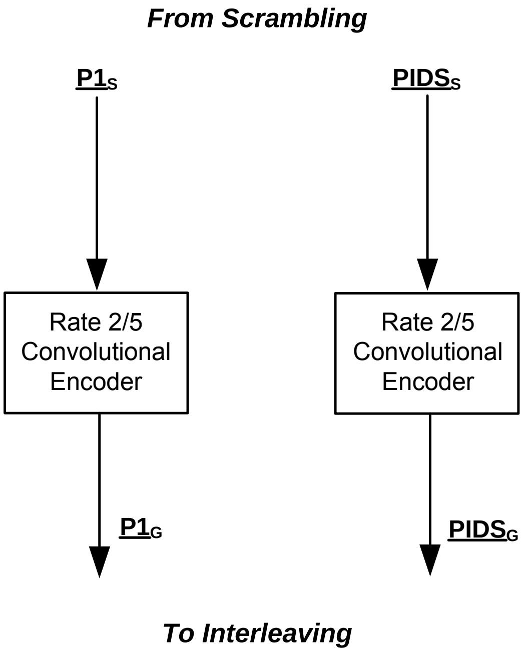


Figure 9-6: Channel Encoding – Service Mode MP1

9.4.2 Service Modes MP2 and MP3

Only P1, P3, and PIDS logical channels are active in service modes MP2 and MP3. The flow of their transfer frames through the channel encoding process for service modes MP2 and MP3 is shown in Figure 9-7.

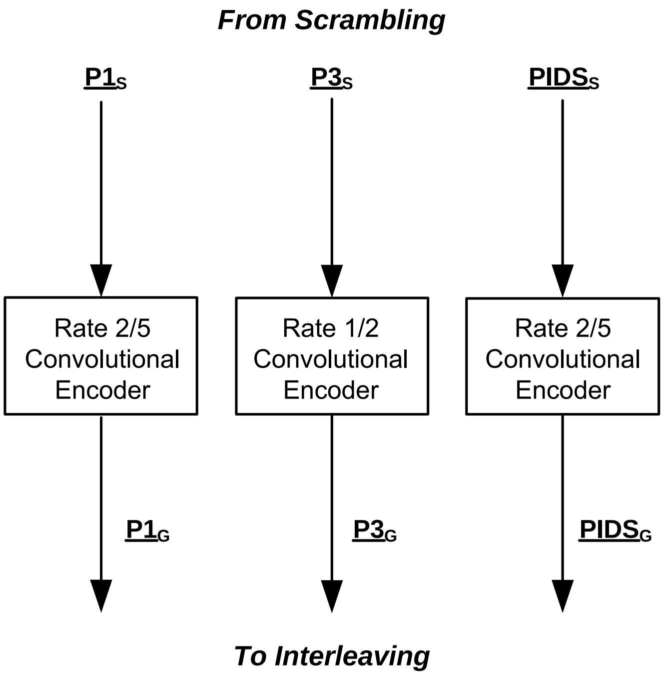


Figure 9-7: Channel Encoding – Service Modes MP2 and MP3

9.4.3 Service Mode MP11

Only P1, P3, P4, and PIDS logical channels are active in service mode MP11. The flow of their transfer frames through the channel encoding process for service mode MP11 is shown in Figure 9-8.

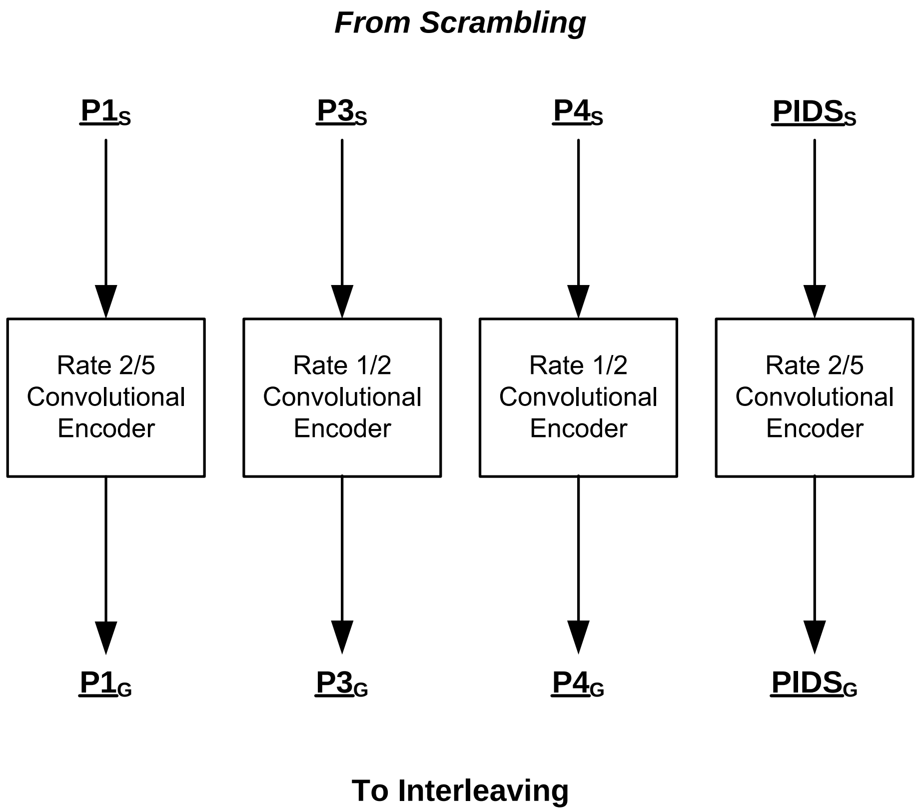


Figure 9-8: Channel Encoding – Service Mode MP11

9.4.4 Service Mode MP5

Only P1, P2, P3, and PIDS logical channels are active in service mode MP5. The flow of their transfer frames through the channel encoding process for service mode MP5 is shown in Figure 9-9.

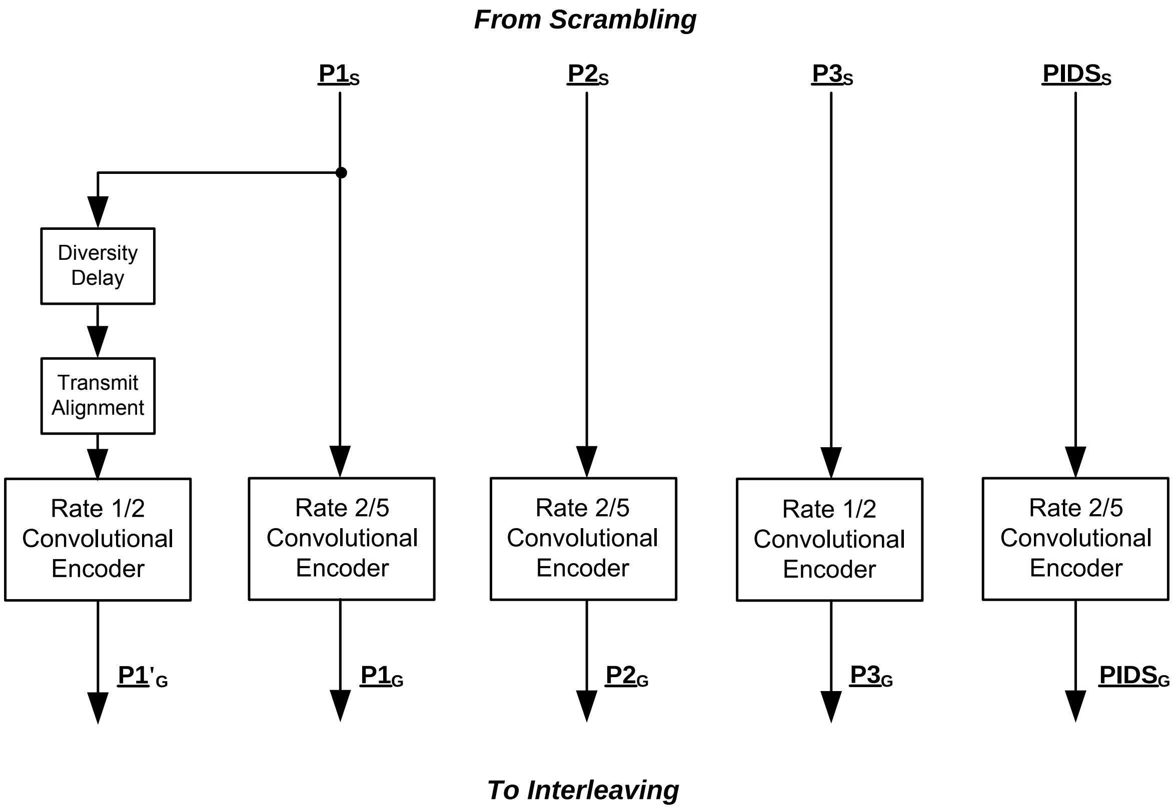


Figure 9-9: Channel Encoding – Service Mode MP5

9.4.5 Service Mode MP6

Only P1, P2, and PIDS logical channels are active in service mode MP6. The flow of their transfer frames through the channel encoding process for service mode MP6 is shown in Figure 9-10.

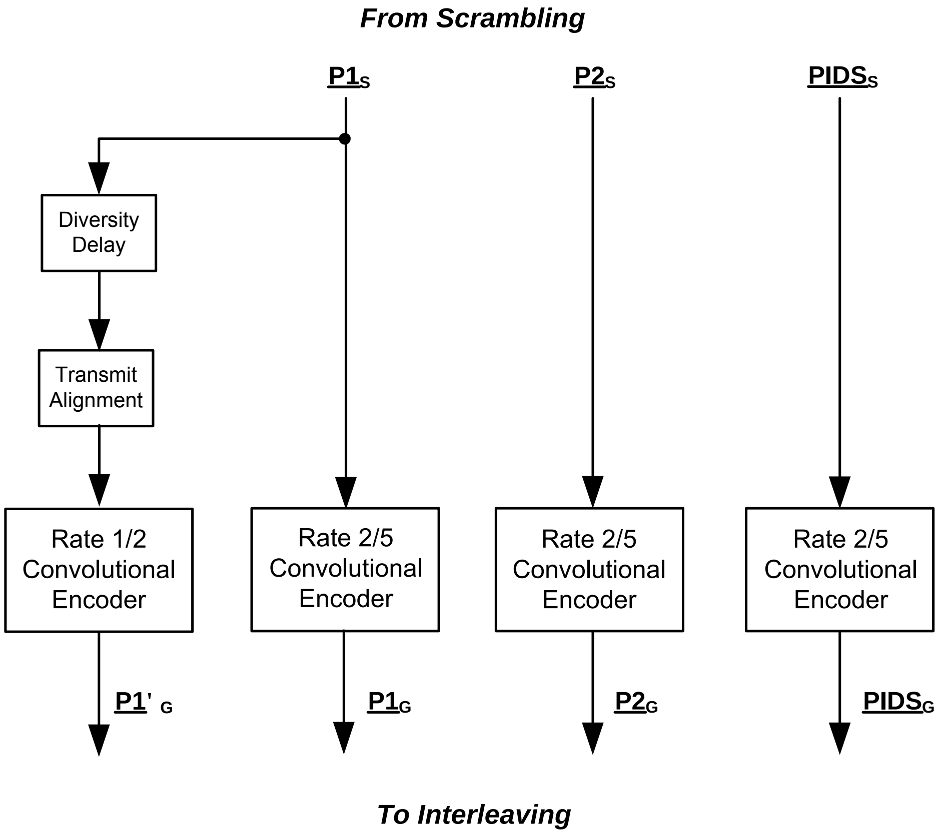


Figure 9-10: Channel Encoding – Service Mode MP6

9.4.6 Service Mode MS1

Only S4, S5, and SIDS logical channels are active in service mode MS1. The flow of their transfer frames through the channel encoding process for service mode MS1 is shown in Figure 9-11.

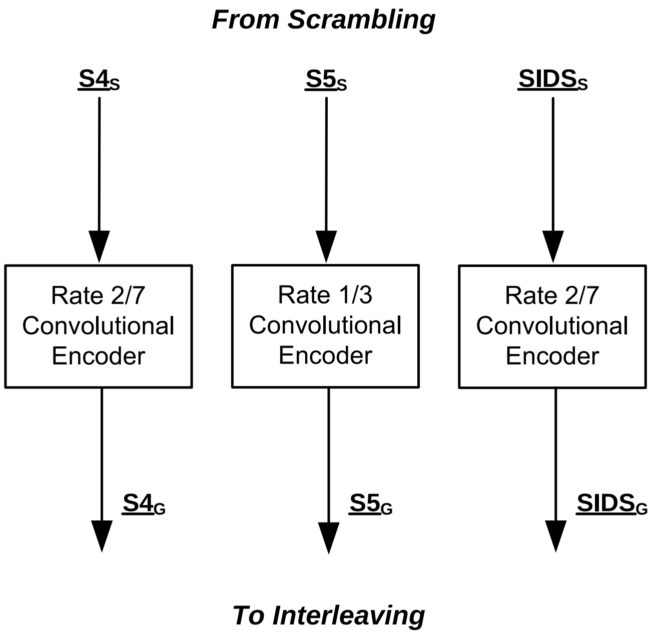


Figure 9-11: Channel Encoding – Service Mode MS1

9.4.7 Service Mode MS2

Only S1, S2, S3, S5, and SIDS logical channels are active in service mode MS2. The flow of their transfer frames through the channel encoding process for service mode MS2 is shown in Figure 9-12.

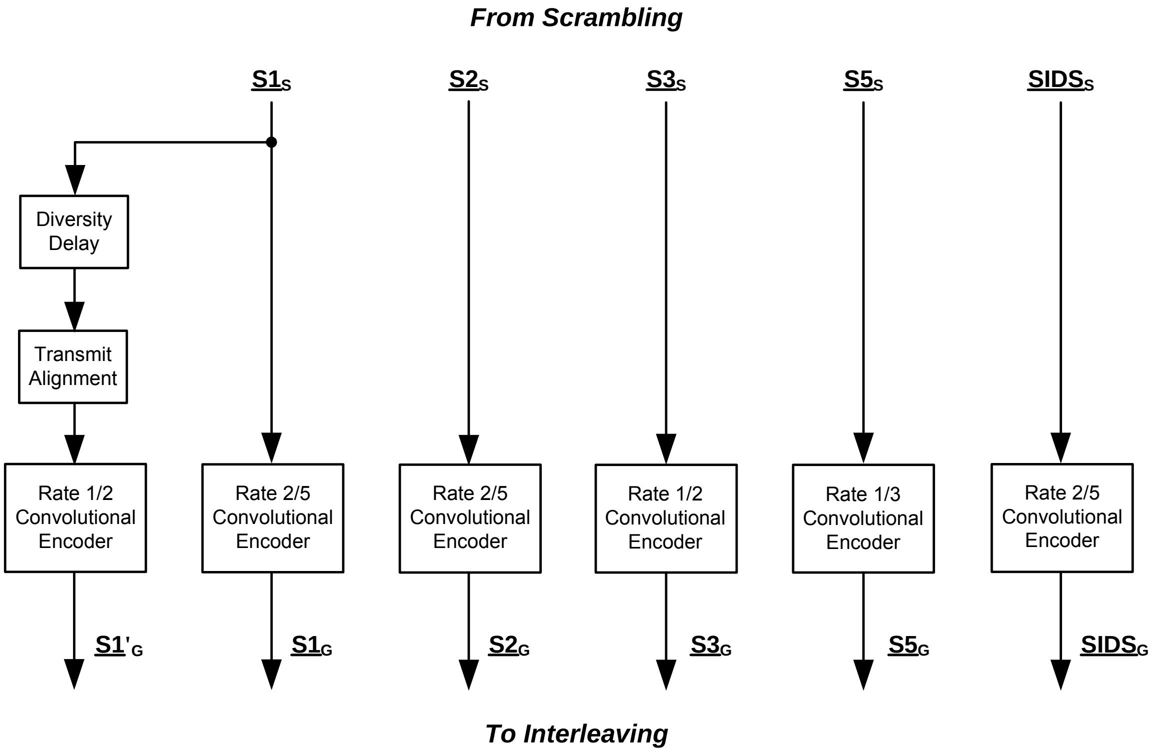


Figure 9-12: Channel Encoding – Service Mode MS2

9.4.8 Service Mode MS3

Only S1, S2, S5, and SIDS logical channels are active in service mode MS3. The flow of their transfer frames through the channel encoding process for service mode MS3 is shown in Figure 9-13.

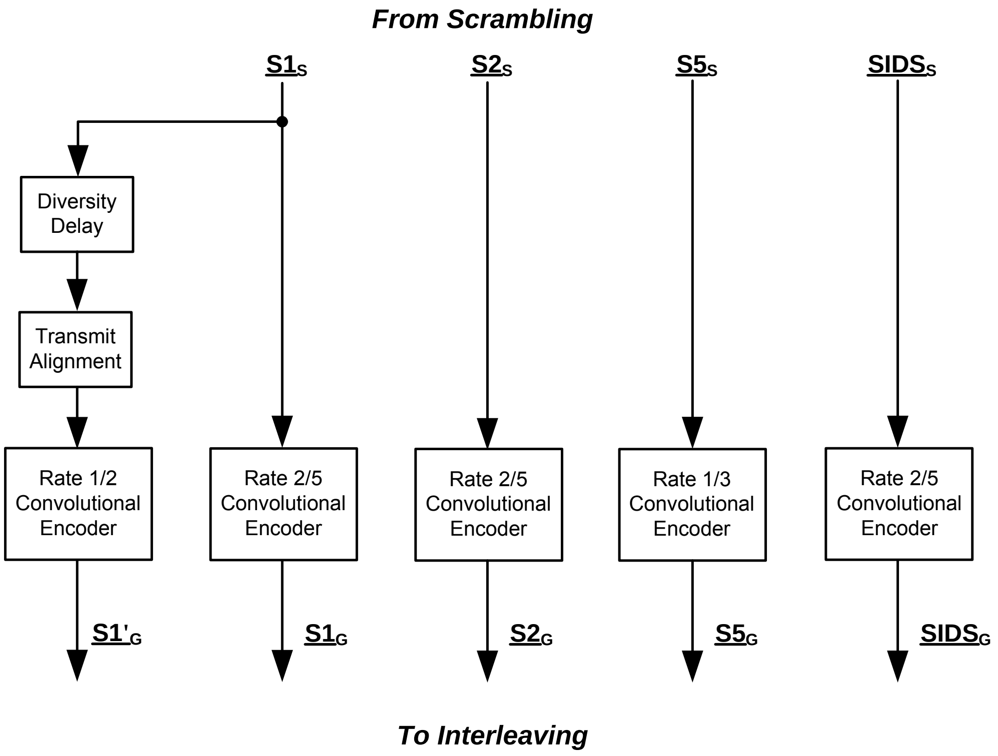


Figure 9-13: Channel Encoding – Service Mode MS3

9.4.9 Service Mode MS4

Only S1, S2, S3, S5, and SIDS logical channels are active in service mode MS4. The flow of their transfer frames through the channel encoding process for service mode MS4 is shown in Figure 9-14.

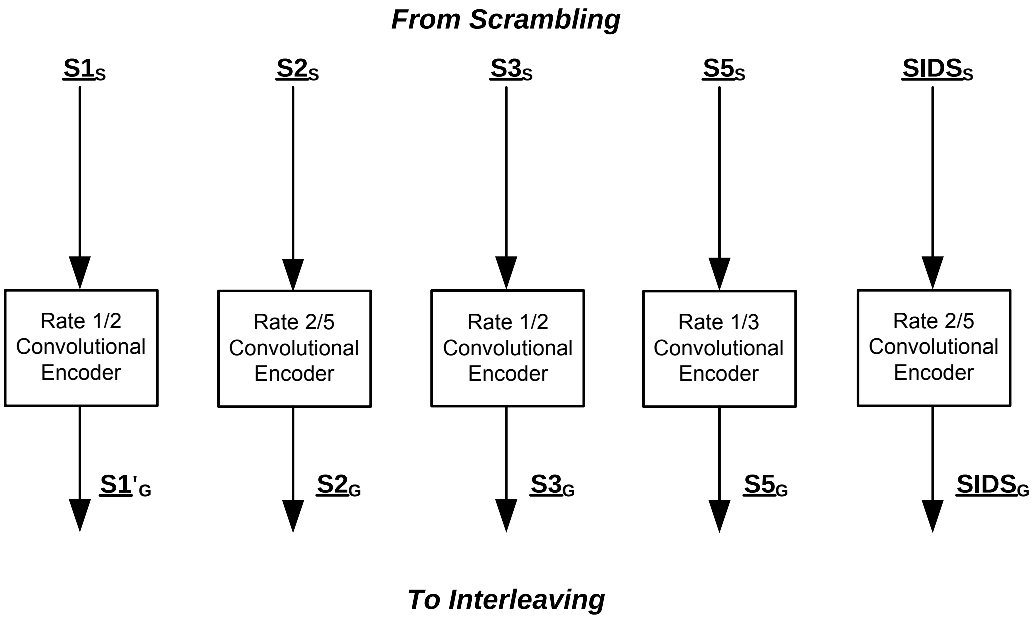


Figure 9-14: Channel Encoding – Service Mode MS4

10 Interleaving

10.1 Introduction

Interleaving consists of six parallel *interleaving processes* (IPs): PM, PX, SM, SX, SP, and SB (see Figure 10-1). An IP contains one or more interleavers, and, in some cases, a *transfer frame multiplexer*.

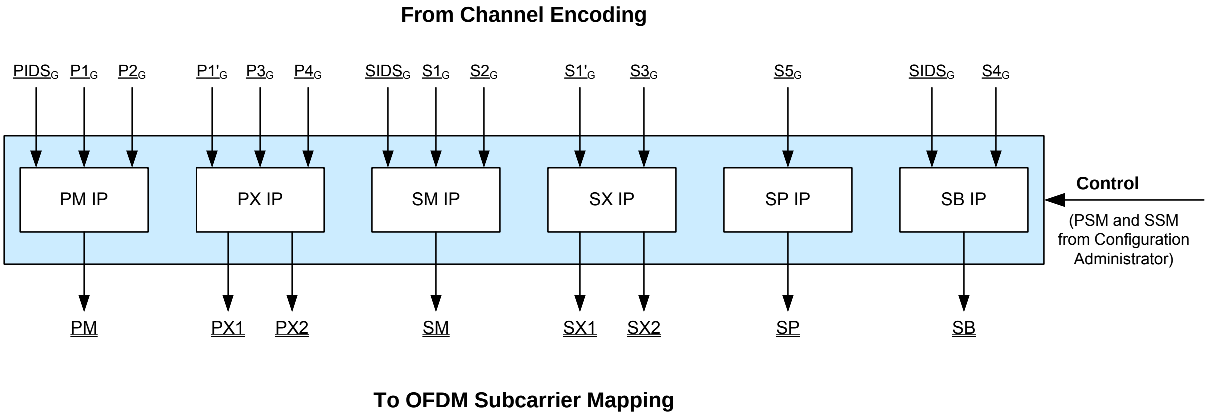


Figure 10-1: Interleaving Conceptual Block Diagram

The service mode determines which inputs and IPs are active at any given time. The universe of inputs for interleaving are the channel-encoded transfer frames from the primary logical channels P1 through P4 and PIDS and the secondary logical channels S1 through S5 and SIDS. Table 10-1 through Table 10-10 show the active IP inputs for each service mode. These tables define the size and rate of the transfer frames on each active logical channel along with the destination interleaver matrix and the number of transfer frames required to fill the destination interleaver matrix.

As shown in Table 10-2 through Table 10-5, although there is one transfer frame per PX interleaver matrix, the interleaver depth is actually two L1 frames. In this case, an internal interleaver matrix is introduced to account for the additional span of the interleaver. Refer to Subsection 10.2.2.2 for details.

Interleaver matrices of bits from all active parallel IPs are transferred to OFDM Subcarrier Mapping which maps a row of bits from each interleaver matrix to its respective upper and lower sidebands.

Table 10-1: Transfer Frame Characteristics – Service Mode MP1

Logical Channel	**Transfer Frame Size (bits)**	**Transfer Frame Rate (Hz)**	**Interleaver Matrix**	**Transfer Frames per Interleaver Matrix**
P1	365440	R_f	PM	1
PIDS	200	R_b	PM	16

Table 10-2: Transfer Frame Characteristics – Service Mode MP2

Logical Channel	**Transfer Frame Size (bits)**	**Transfer Frame Rate (Hz)**	**Interleaver Matrix**	**Transfer Frames per Interleaver Matrix**
P1	365440	R_f	PM	1
PIDS	200	R_b	PM	16
P3	4608	R_p	PX1	1

Table 10-3: Transfer Frame Characteristics – Service Mode MP3

Logical Channel	**Transfer Frame Size (bits)**	**Transfer Frame Rate (Hz)**	**Interleaver Matrix**	**Transfer Frames per Interleaver Matrix**
P1	365440	R_f	PM	1
PIDS	200	R_b	PM	16
P3	9216	R_p	PX1	1

Table 10-4: Transfer Frame Characteristics – Service Mode MP11

Logical Channel	**Transfer Frame Size (bits)**	**Transfer Frame Rate (Hz)**	**Interleaver Matrix**	**Transfer Frames per Interleaver Matrix**
P1	365440	R_f	PM	1
PIDS	200	R_b	PM	16
P3	9216	R_p	PX1	1
P4	9216	R_p	PX2	1

Table 10-5: Transfer Frame Characteristics – Service Mode MP5

Logical Channel	**Transfer Frame Size (bits)**	**Transfer Frame Rate (Hz)**	**Interleaver Matrix**	**Transfer Frames per Interleaver Matrix**
P1	11520	R_p	PM	8
P2	273280	R_f	PM	1
PIDS	200	R_b	PM	16
P1′	9216	R_p	PX2	1
P3	9216	R_p	PX1	1

Table 10-6: Transfer Frame Characteristics – Service Mode MP6

Logical Channel	Transfer Frame Size (bits)	Transfer Frame Rate (Hz)	Interleaver Matrix	Transfer Frames per Interleaver Matrix
P1	23040	R_p	PM	8
P2	181120	R_f	PM	1
PIDS	200	R_b	PM	16
P1′	18432	R_p	PX2	1

Table 10-7: Transfer Frame Characteristics – Service Mode MS1

Logical Channel	Transfer Frame Size (bits)	Transfer Frame Rate (Hz)	Interleaver Matrix	Transfer Frames per Interleaver Matrix
S4	63952	R_p	SB	1
SIDS	280	R_b	SB	2
S5	1536	R_b	SP	1

Table 10-8: Transfer Frame Characteristics – Service Mode MS2

Logical Channel	Transfer Frame Size (bits)	Transfer Frame Rate (Hz)	Interleaver Matrix	Transfer Frames per Interleaver Matrix
S1	11520	R_p	SM	8
S2	273280	R_f	SM	1
SIDS	200	R_b	SM	16
S1′	9216	R_p	SX2	1
S3	9216	R_p	SX1	1
S5	1536	R_b	SP	1

Table 10-9: Transfer Frame Characteristics – Service Mode MS3

Logical Channel	Transfer Frame Size (bits)	Transfer Frame Rate (Hz)	Interleaver Matrix	Transfer Frames per Interleaver Matrix
S1	23040	R_p	SM	8
S2	181120	R_f	SM	1
SIDS	200	R_b	SM	16
S1′	18432	R_p	SX2	1
S5	1536	R_b	SP	1

Table 10-10: Transfer Frame Characteristics – Service Mode MS4

Logical Channel	**Transfer Frame Size (bits)**	**Transfer Frame Rate (Hz)**	**Interleaver Matrix**	**Transfer Frames per Interleaver Matrix**
S2	365440	R_f	SM	1
SIDS	200	R_b	SM	16
S1′	9216	R_p	SX2	1
S3	9216	R_p	SX1	1
S5	1536	R_b	SP	1

10.2 Interleaver

An interleaver is a function that takes a vector of bits as its input and outputs a matrix of reordered bits. The reordering of bits before transmission mitigates the impact of burst errors caused by signal fades and interference.

10.2.1 Interleaver Matrix

The interleaver function uses a two-dimensional matrix to reorder a vector of channel-encoded bits. The interleaver allows individual encoded bits or groups of encoded bits to be directed to a specific *interleaver partition* within the interleaver matrix. An interleaver partition can be viewed as a smaller independent interleaver.

Figure 10-2 shows the interleaver matrix used by the PM IP. This interleaver matrix contains 20 interleaver partitions. Interleaver partition 0 is highlighted.

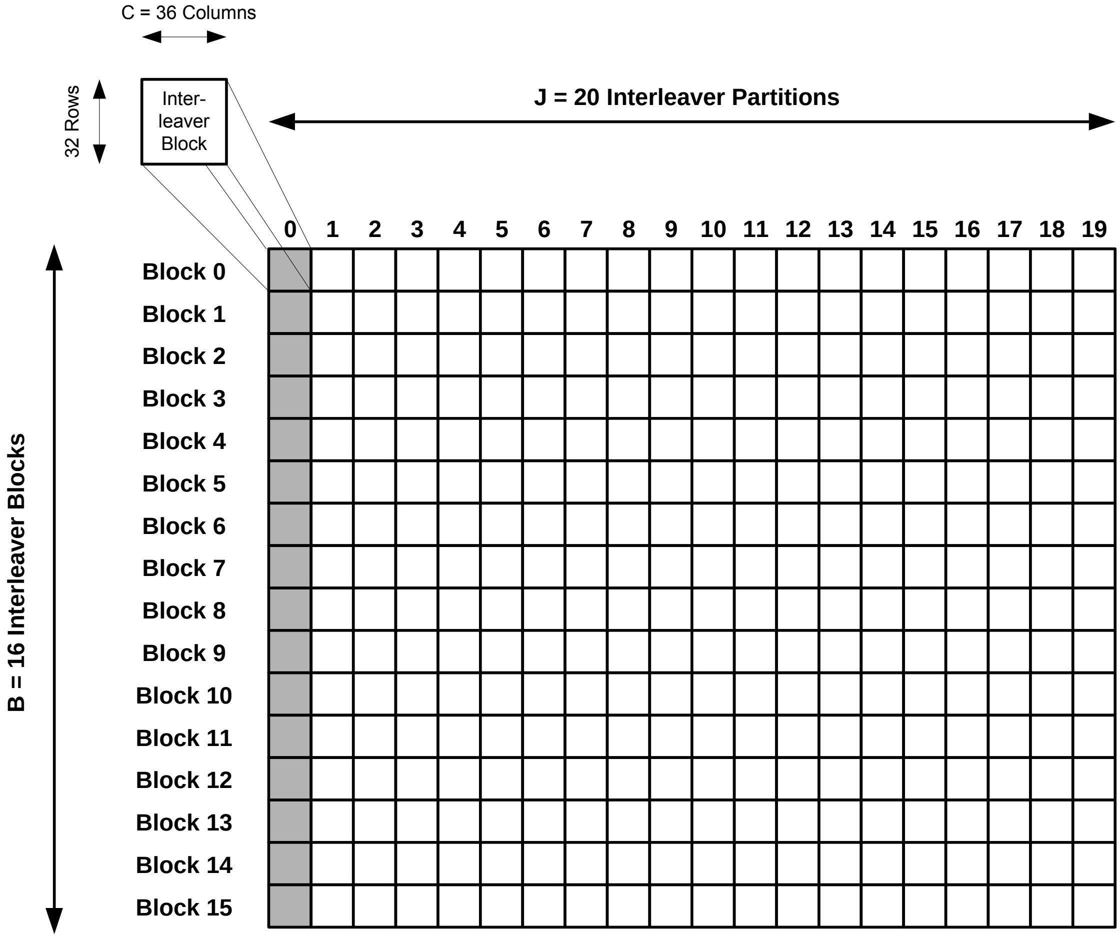


Figure 10-2: PM Interleaver Matrix

In general, the interleaver matrix is divided into J interleaver partitions. Each interleaver partition is divided into B *interleaver blocks*. An interleaver block spans 32 rows and C columns; thus, the dimensions for each interleaver partition in a given interleaver matrix are defined by the expression:

$$(B \cdot 32) \times C$$

For a given interleaver within an IP, the interleaver matrix size can vary with service mode.

10.2.2 Interleaver Computations

The input to each interleaver is a vector of channel encoded bits indexed from i = 0,1,2,…,N-1.

The output of each interleaver is a matrix of bits destined for OFDM Subcarrier Mapping; this matrix has dimensions that are defined by the following expression:

$$(B \cdot 32) \times (J \cdot C)$$

The mapping of each encoded bit to a location in the interleaver matrix is calculated using a set of equations. There are four sets of equations and thus four interleaver types: Interleaver I, Interleaver II, Interleaver III, and Interleaver IV. All four interleavers use the variable parameters shown in Table 10-11, except as noted.

Table 10-11: Interleaver Parameters

Interleaver Parameter	Interleaver Parameter Definition
J	The number of interleaver partitions per interleaver matrix.
B	The number of interleaver blocks per interleaver partition.
C	The number of columns per interleaver block.
M	Factor used in interleaver partition assignment calculation (Interleavers I, III, and IV).
$\underline{v}$	Partition assignment vector used to control the relative ordering of interleaver partitions in the interleaver matrix.
b	Number of bits per transfer frame (Interleavers II and IV).
I_0	Index offset value used in k_i calculation (Interleaver II).
N	The number of bits per interleaver input sequence. May span multiple transfer frames.

10.2.2.1 Equation Sets I, II, or III

For a given interleaver using equation set I, II, or III, the steps needed to direct each encoded bit of an input sequence of length N to an interleaver matrix location are as follows:

1. Determine which set of interleaver equations to use by inspecting the IP figures in Subsection 10.4.
2. Assign values to parameters J, B, C, M, $\underline{v}$, b, I_0, and N using the tables in Subsection 10.4.
3. For each i = 0 to N-1, calculate $partition_i$, $block_i$, k_i, row(k_i), and column(k_i). Write the i^{th} input bit to this location in the interleaver matrix.

10.2.2.2 Equation Set IV

Equation set IV implements a convolutional interleaver. With a convolutional interleaver, each write to the interleaver matrix must be followed by a read from the interleaver matrix. Since the total number of bits being interleaved is greater than the transfer frame size, an additional matrix is needed to manage this flow. Thus, the terminology associated with Interleaver IV is as follows:

- Internal interleaver matrix

  The internal interleaver matrix has the dimensions that are defined by the following expression:

  $$(B \cdot 32) \times (J \cdot C)$$

  Bits are written to the interelaver matrix using interleaver equation set IV and bits are read sequentially across rows. It may take multiple transfer frames to fill this matrix. It is full after N bits have been processed.

- Output interleaver matrix

  The ouput interleaver matrix has the dimensions that are defined by the following expression:

  $$\left(\frac{B}{N/b} \cdot 32 \right) \times (J \cdot C)$$

  The output interelaver matrix contains b interleaved bits read from the internal interleaver matrix. The number of bits in this matrix is equal to the size of the input transfer frame or parameter b. Bits are written to this matrix sequentially across rows starting at row 0, column 0. Note that the number of transfer frames per interleaver matrix equals *N/b*.

For a given interleaver using equation set IV, the steps needed to process each encoded bit of an input sequence of length N are as follows:

1. Assign values to parameters J, B, C, M, $\underline{v}$, b, and N using the tables in Subsection 10.4.
2. Initialize the partition assignment counter vector, $\underline{pt}$, to all zeros. The length of this vector equals J.
3. For each i = 0 to N-1:
   - Write a bit to the internal interleaver matrix using a calculated bit address based on the equations in Subsection 10.2.6.
   - Calculate $partition_i$, fetch $\underline{pt}$ [$partition_i$], and calculate $block_i$, row_i, and $column_i$.
   - Write the ith input bit to this location in the internal interleaver matrix.
   - Read a bit from the following row and column of the internal interleaver matrix:

$$readRow = \mathrm{INT}\left(i/_{CJ} \right)$$

$$readColumn = i \ \mathrm{MOD}\ CJ$$

- Write the bit read from the internal interleaver matrix to the following row and column of the output interleaver matrix:

$$writeRow = \mathrm{INT}\left(\frac{(i \ \mathrm{MOD}\ b)}{CJ}\right)$$

$$writeColumn = (i \ \mathrm{MOD}\ b)\ \mathrm{MOD}\ CJ$$

- Increment pt [$partition_i$]

10.2.3 Interleaver I Equations

Interleaver I is used by all IPs except the SP IP.

10.2.3.1 Interleaver Partition Assignment

Compute an index into $\underline{v}$ to retrieve interleaver partition assignment:

$$partIndex_i = \mathrm{INT}\left(\frac{i + \left(2 \cdot \mathrm{INT}\left(\frac{M}{4}\right)\right)}{M}\right) \mathrm{MOD}\ J$$

$$partition_i = \underline{v}\ [partIndex_i]$$

10.2.3.2 Interleaver Block Assignment within Interleaver Partition

For M = 1:

$$block_i = \left(\mathrm{INT}\left(\frac{i}{J}\right) + \left(partition_i \cdot 7\right)\right) \mathrm{MOD}\ B$$

For M = 2 or 4:

$$block_i = \left(i + \mathrm{INT}\left(\frac{i}{J \cdot B}\right)\right) \mathrm{MOD}\ B$$

10.2.3.3 Row and Column Assignments within Interleaver Block

$$row(k_i) = (k_i \cdot 11)\ \mathrm{MOD}\ 32$$

$$column(k_i) = \left((k_i \cdot 11) + \mathrm{INT}\left(\frac{k_i}{32 \cdot 9}\right)\right) \mathrm{MOD}\ C$$

Where the index k_i is defined as: $k_i = \mathrm{INT}\left(\frac{i}{J \cdot B}\right)$

10.2.4 Interleaver II Equations

Interleaver II is used by the PM, SM, and SB IPs. This interleaver is designed to disperse each $\underline{\text{PIDS}}_G$ (or $\underline{\text{SIDS}}_G$) transfer frame over one interleaver block (and J interleaver partitions) of the same interleaver matrix written to by Interleaver I. In essence, Interleaver II fills in the unpopulated elements ("holes") left behind by Interleaver I. The position of the holes is the same in each interleaver block of the applicable interleaver matrix.

When using Interleaver II, the parameter b is set to the size of one $\underline{\text{PIDS}}_G$ (or $\underline{\text{SIDS}}_G$) transfer frame. The variable i, however, must range over the total number of $\underline{\text{PIDS}}_G$ (or $\underline{\text{SIDS}}_G$) bits required to fill all holes of the interleaver matrix.

10.2.4.1 Interleaver Partition Assignment

Compute an index into $\underline{v}$ to retrieve interleaver partition assignment:

$$partIndex_i = i \text{ MOD } J$$

$$partition_i = \underline{\text{v}}\,[partIndex_i]$$

10.2.4.2 Interleaver Block Assignment within Interleaver Partition

$$block_i = \text{INT}\left(\frac{i}{b}\right)$$

10.2.4.3 Row and Column Assignments within Interleaver Block

$$row(k_i) = (k_i \cdot 11) \text{ MOD } 32$$

$$column(k_i) = \left((k_i \cdot 11) + \text{INT}\left(\frac{k_i}{32 \cdot 9}\right)\right) \text{MOD } C$$

Where the index k_i is defined as: $k_i = \left(\text{INT}\left(\frac{i}{J}\right) \text{MOD}\left(\frac{b}{J}\right)\right) + \left(\frac{I_0}{J \cdot B}\right)$

10.2.5 Interleaver III Equations

Interleaver III is used only by the SP IP. Interleaver matrices used by Interleaver III span only one interleaver block; therefore, no interleaver block calculation is needed. The pertinent equations are presented in Subsection 10.2.5.1 and Subsection 10.2.5.2.

10.2.5.1 Interleaver Partition Assignment

Compute an index into v to retrieve interleaver partition assignment:

$$partIndex_i = \left(i + \mathrm{INT}\left(\frac{i}{M} \right) \right) \mathrm{MOD}\ J$$

$$partition_i = \underline{v}\ [partIndex_i]$$

10.2.5.2 Row and Column Assignments within Interleaver Block

$$row(k_i) = (k_i \cdot 11)\ \mathrm{MOD}\ 32$$

$$column(k_i) = \left((k_i \cdot 11) + \mathrm{INT}\left(\frac{k_i}{32} \right) \right) \mathrm{MOD}\ C$$

Where the index k_i is defined as: $k_i = \mathrm{INT}\left(\frac{i}{J} \right)$

10.2.6 Interleaver IV Equations

Interleaver IV is used by the PX IP to interleave $\underline{P3}_G$ and $\underline{P4}_G$ transfer frames. The pertinent equations are presented in Subsection 10.2.6.1 through Subsection 10.2.6.4.

Define a supporting parameter which represents the number of bits in an interleaver block:

$$Bk\_bits = 32 \cdot C$$

Define a second supporting parameter:

$$Bk\_adj = 32 \cdot C - 1$$

10.2.6.1 Interleaver Partition Assignment

Compute an index into $\underline{v}$ to retrieve the interleaver partition assignment:

$$partIndex_i = \mathrm{INT}\left(\frac{i + \left(2 \cdot \mathrm{INT}\left(\frac{M}{4} \right) \right)}{M} \right) \mathrm{MOD}\ J$$

$$partition_i = \underline{v}\,[partIndex_i]$$

Define a vector of partition assignment counters, $\underline{pt}$, whose length is equal to the number of partitions. Fetch the appropriate counter for $partition_i$:

$$pt_i = \underline{pt}\,[partition_i]$$

The partition assignment counter for a given partition is incremented each time an allocation is made to that partition. The initial value of each of the partition assignment counters is set to 0.

10.2.6.2 Interleaver Block Assignment within Interleaver Partition

Using the applicable parameters, apply the following equation:

$$block_i = \left(pt_i + \left(partition_i \cdot 7 \right) - \left(Bk\_adj \cdot \mathrm{INT}\left(\frac{pt_i}{Bk\_bits} \right) \right) \right) \mathrm{MOD}\ B$$

10.2.6.3 Row Assignment within Interleaver Block

Using the applicable parameters, apply the following equation:

$$row_i = \mathrm{INT}\left(\frac{\left(11 \cdot pt_i\right)\ \mathrm{MOD}\ Bk\_bits}{C}\right)$$

10.2.6.4 Column Assignment within Interleaver Block

Using the applicable parameters, apply the following equation:

$$column_i = \left(pt_i \cdot 11\right)\ \mathrm{MOD}\ C$$

10.3 Transfer Frame Multiplexer

For some IPs, a transfer frame multiplexer is required. For each logical channel, the transfer frame multiplexer collects an integer number of transfer frames. The transfer frame multiplexer then concatenates all accumulated transfer frames into a single vector $\underline{U}$. Only the PM and SM IPs require transfer frame multiplexers since they intersperse multiple logical channels in a common interleaver over the same row and column spans.

The transfer frame concatenation ordering at the output of each transfer frame multiplexer is shown in Subsections 10.4.1 and 10.4.3. The first bit of the first transfer frame becomes the first bit of $\underline{U}$. The first bit of each subsequent transfer frame follows the last bit of the previous transfer frame.

10.4 Interleaving Process Descriptions

This subsection discusses the detailed provisions governing implementation of each IP for every applicable service mode.

10.4.1 PM Interleaving Process

The PM IP interleaves the bits mapped to the Primary Main sidebands depicted in Figure 7-2 through Figure 7-7. This IP is active in all primary service modes (MP1, MP2, MP3, MP11, MP5, and MP6). The PM IP disperses multiple logical channels into a single interleaver matrix, PM.

10.4.1.1 Service Modes MP1 through MP3, and MP11

Figure 10-3 shows the PM IP for service modes MP1 through MP3, and MP11. This IP utilizes two interleavers. These interleavers share a common interleaver output matrix, PM. The inputs to the PM IP are the $P1_G$ and $PIDS_G$ transfer frames. The number of transfer frames required to fill the interleaver matrix are shown in Table 10-1 through Table 10-4 for service modes MP1 through MP3 and MP11, respectively.

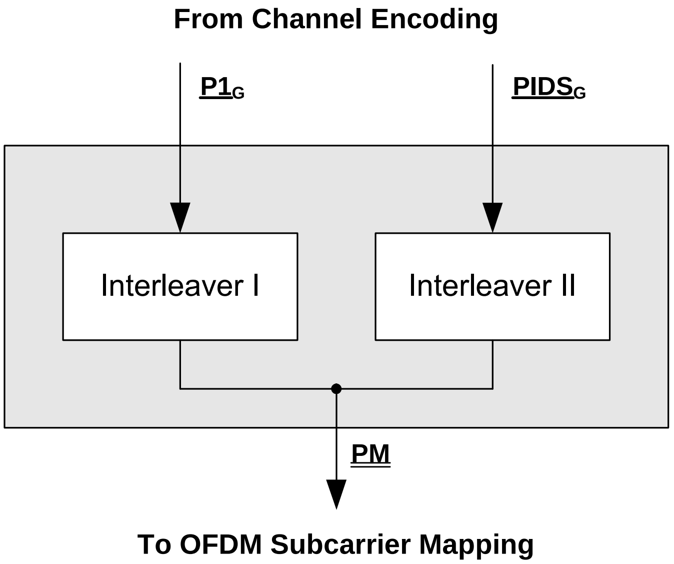


Figure 10-3: PM IP – Service Modes MP1 through MP3 and MP11

The interleaving process must maintain a specific transfer frame alignment and synchronization at its output.

For a given logical channel, the BC range *m1:m2* indicates which L1 blocks are spanned by the designated transfer frame. The ALFN *n* is the absolute L1 frame number.

The steps required to process the IP inputs for L1 frame n are given as follows:

1. ***Interleave $\underline{P1}_G$ transfer frame***

   The vector $\underline{P1}_G$ is interleaved into $\underline{\underline{PM}}$ using Interleaver I with the parameters shown in Table 10-12. The sequence P1 is dispersed over the full row and column span of $\underline{\underline{PM}}$, leaving holes to be filled by Interleaver II with $\underline{PIDS}_G$ data.

   Table 10-12: PM Interleaver I Parameter Values

J	B	C	M	$\underline{v}$	B	I_0	N
20	16	36	1	See note below	N/A	N/A	365440

   Note: *$\underline{v}$ = [10,2,18,6,14,8,16,0,12,4,11,3,19,7,15,9,17,1,13,5]*

2. ***Interleave $\underline{PIDS}_G$ transfer frames***

   Each $\underline{PIDS}_G$ transfer frame is interleaved into $\underline{\underline{PM}}$, using Interleaver II with the parameters shown in Table 10-13.

   Table 10-13: PM Interleaver II Parameter Values

J	B	C	M	$\underline{v}$	B	I_0	N
20	16	36	1	See note below	200	365440	3200

   Note: *$\underline{v}$ = [10,2,18,6,14,8,16,0,12,4,11,3,19,7,15,9,17,1,13,5]*

Interleaver II constrains the row span of each interleaved $\underline{PIDS}_G$ transfer frame to one interleaver block (32 rows). This is accomplished by properly setting the interleaver variable i before each execution of Interleaver II. Table 10-14 shows the relationship between the variable i and the BC of the $\underline{PIDS}_G$ transfer frames.

Table 10-14: Bit Numbering of $\underline{PIDS}_G$ Transfer Frames

BC	Range of variable i
0	0…199
1	200…399
2	400…599
3	600…799
4	800…999
5	1000…1199
6	1200…1399
7	1400…1599
8	1600…1799
9	1800…1999
10	2000…2199
11	2200…2399
12	2400…2599
13	2600…2799
14	2800…2999
15	3000…3199

When Interleaver I has processed one vector $\underline{P1}_G$ and Interleaver II has processed one $\underline{PIDS}_G$ transfer frame, a 32 x J *submatrix* of $\underline{\underline{PM}}$ is completely full and ready for OFDM Subcarrier Mapping. Each successive $\underline{PIDS}_G$ transfer frame is interleaved over the next successive interleaver block (for J interleaver partitions). After each $\underline{\text{PIDS}}_G$ transfer frame is processed by Interleaver II, the next 32 x J submatrix of $\underline{\underline{\text{PM}}}$ is available for OFDM Subcarrier Mapping.

After Interleaver I has processed one vector $\underline{\text{P1}}_G$ and Interleaver II has processed sixteen $\underline{\text{PIDS}}_G$ transfer frames, $\underline{\underline{\text{PM}}}$ is completely filled and the processing flow resets.

10.4.1.2 Service Modes MP5 and MP6

Figure 10-4 shows the PM IP for service modes MP5 and MP6. The processing in MP5 and MP6 is very similar to that of MP1 through MP3 and MP11. The difference lies in the number of $\underline{P1}_G$ transfer frames required to fill the interleaver. The $\underline{P2}_G$ transfer frame is now multiplexed with $\underline{P1}_G$. As shown in Table 10-5 and Table 10-6, the ratio of $\underline{P1}_G$ to $\underline{P2}_G$ transfer frames is 8:1. Before Interleaver I is invoked, the $\underline{P1}_G$ and $\underline{P2}_G$ transfer frames are multiplexed into the vector $\underline{U}$ in the manner shown in Figure 10-5.

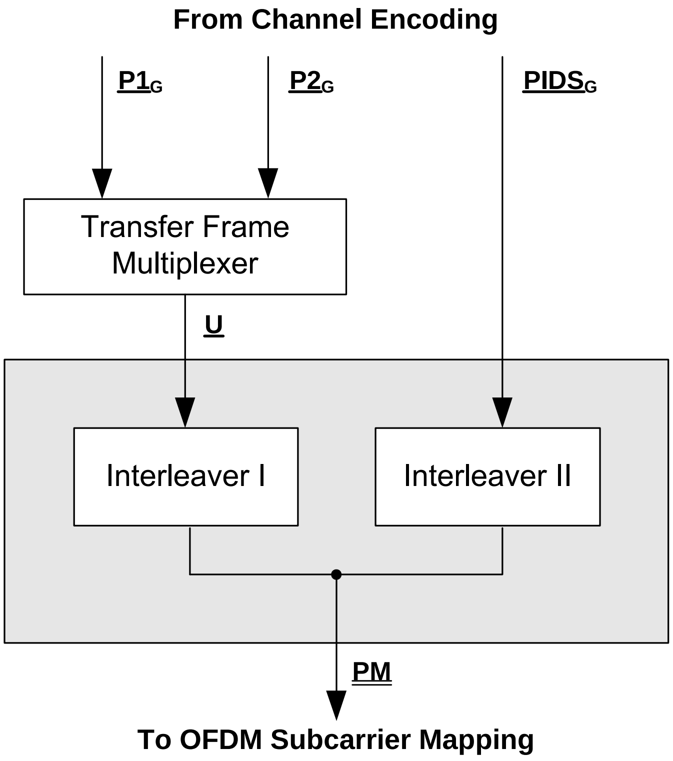


Figure 10-4: PM IP – Service Modes MP5 and MP6

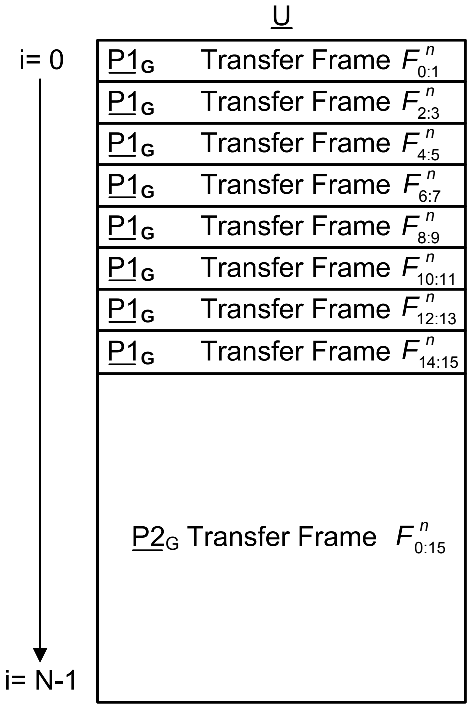


Figure 10-5: PM Transfer Frame Multiplexer Output – Service Modes MP5 and MP6

All processing details subsequent to the transfer frame multiplexer are identical to those described in Subsection 10.4.1.1.

10.4.2 PX Interleaving Process

The PX IP interleaves bits destined for the Primary Extended sidebands shown in Figure 7-3 through Figure 7-7. This IP is active in primary service modes MP2, MP3, MP5, MP6, and MP11. Up to two interleaver matrices, PX1 and PX2, are active. In service modes MP2 and MP3, only PX1 is active. In service mode MP6, only PX2 is active. In service modes MP5 and MP11, both PX1 and PX2 are active. $P3_G$ transfer frames are interleaved into PX1, and $P1'_G$ or $P4_G$ transfer frames are interleaved into PX2.

A long convolutional interleaver is applied using Interleaver IV. A single transfer frame fills the PX interleaver matrices as indicated by Table 10-2 through Table 10-6.

10.4.2.1 Service Modes MP2 and MP3

Figure 10-6 shows the PX IP for service modes MP2 and MP3. In these service modes, the PX IP interleaves $P3_G$ transfer frames into an internal interleaver matrix and outputs them to PX1 (the output interleaver matrix) using Interleaver IV. The service mode dependent Interleaver IV parameter values are shown in Table 10-15. Although the transfer frame rate is common, the size of the $P3_G$ transfer frames varies with service mode. Consequently, the number of interleaver partitions in the PX1 interleaver matrix also varies.

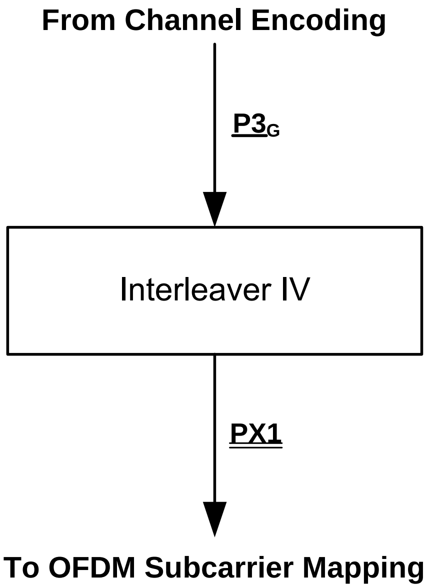


Figure 10-6: PX IP – Service Modes MP2 and MP3

Table 10-15: PX1 Interleaver IV Parameter Values – Service Modes MP2 and MP3

Service Mode	**J**	**B**	**C**	**M**	$\underline{V}$	**B**	I_0	**N**
MP2	2	32	36	4	[0,1]	4608	N/A	73728
MP3	4	32	36	2	[0,1,2,3]	9216	N/A	147456

Although the size of the internal interleaver matrix used by Interleaver IV is 16 $P3_G$ transfer frames, Interleaver IV is described as processing one $P3_G$ transfer frame at a time. Every time a bit is written to the internal interleaver matrix used by Interleaver IV, a bit is read sequentially from this matrix and output sequentially to PX1. The size of PX1 is equal to the length of one $P3_G$ transfer frame. Thus, for every $P3_G$ transfer frame processed by Interleaver IV, the PX1 output matrix is completely filled. After Interleaver IV has consumed 16 $P3_G$ transfer frames and 16 PX1 matrices have been filled and output, the internal interleaver matrix is completely filled and the processing flow resets.

In practical applications, because the interleaver is convolutional, the number of bits input to and output from Interleaver IV can be any length less than or equal to N, the capacity of the internal interleaver matrix. The concept of an internal interleaver matrix is described here for notational convenience.

10.4.2.2 Service Mode MP11

In service mode MP11, the PX IP consists of two parallel interleavers of type Interleaver IV. One interleaver processes $\underline{P3}_G$ transfer frames and outputs them to PX1, and the other processes $\underline{P4}_G$ transfer frames and outputs them to PX2, as shown in Figure 10-7.

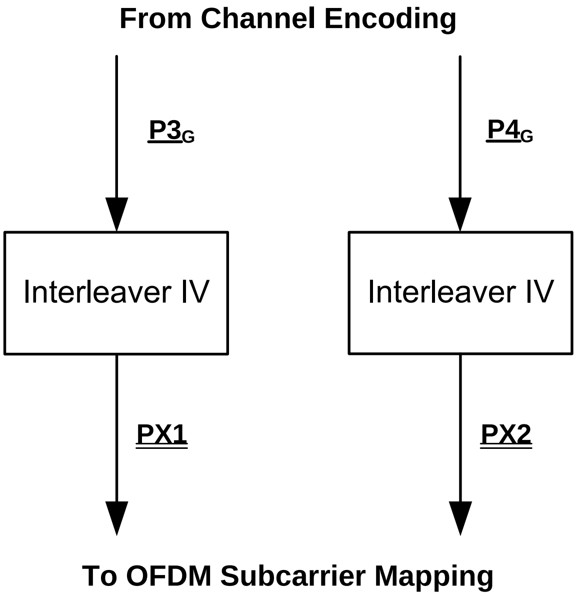


Figure 10-7: PX IP – Service Mode MP11

Because there are two convolutional interleavers, the PX IP uses two internal interleaver matrices in the manner described in Subsection 10.4.2.1. $\underline{P3}_G$ transfer frames are interleaved into the internal interleaver matrix of Interleaver IV Instance 1. $\underline{P4}_G$ transfer frames are interleaved into the internal interleaver matrix of Interleaver IV Instance 2. These processes are synchronized. Both instances of Interleaver IV are configured with the parameters shown in Table 10-16.

The description for each of these parallel processes is as described in Subsection 10.4.2.1.

Table 10-16: Interleaver IV Parameter Values – Service Mode MP11

Service Mode	J	B	C	M	$\underline{V}$	B	I_0	N
MP11	4	32	36	2	[0,1,2,3]	9216	N/A	147456

10.4.2.3 Service Mode MP5

In service mode MP5, the PX IP consists of two parallel interleavers, one of type Interleaver I, and the other of type Interleaver IV. Interleaver I processes $\underline{P1'}_G$ transfer frames, and Interleaver IV processes $\underline{P3}_G$ transfer frames. Figure 10-8 shows the PX IP in service mode MP5.

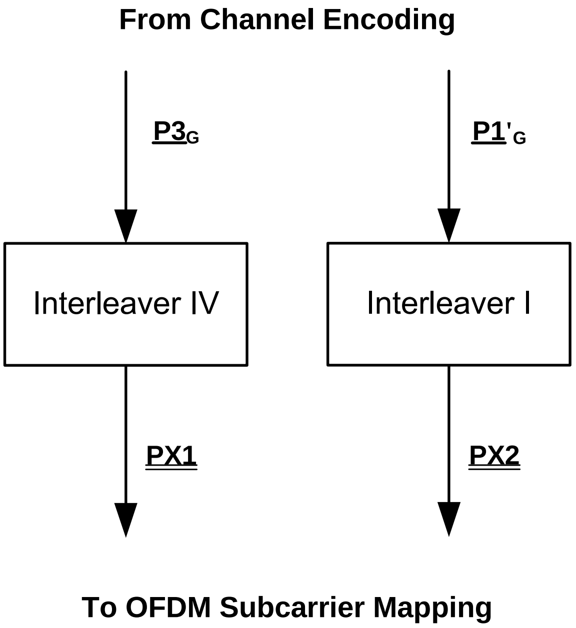


Figure 10-8: PX IP – Service Mode MP5

Interleaver I is configured with the parameters shown in Table 10-17; while Interleaver IV is configured with the parameters shown in Table 10-18.

Table 10-17: PX Interleaver I Parameter Values – Service Mode MP5

Service Mode	J	B	C	M	$\underline{v}$	b	I_0	N
MP5	4	2	36	2	[0,1,2,3]	N/A	N/A	9216

Table 10-18: PX Interleaver IV Parameter Values – Service Mode MP5

Service Mode	J	B	C	M	$\underline{v}$	b	I_0	N
MP5	4	32	36	2	[0,1,2,3]	9216	N/A	147456

After Interleaver I has processed one $\underline{P1'}_G$ transfer frame, $\underline{\underline{PX2}}$ is completely filled and its processing flow resets. After Interleaver IV has consumed 16 $\underline{P3}_G$ transfer frames and output 16 $\underline{\underline{PX1}}$ matrices, its internal interleaver matrix is completely filled and the processing flow resets.

10.4.2.4 Service Mode MP6

Figure 10-9 shows the PX IP for service mode MP6. In this service mode, the PX IP interleaves $\underline{P1}'_G$ transfer frames using Interleaver I, configured with the parameter values shown in Table 10-19.

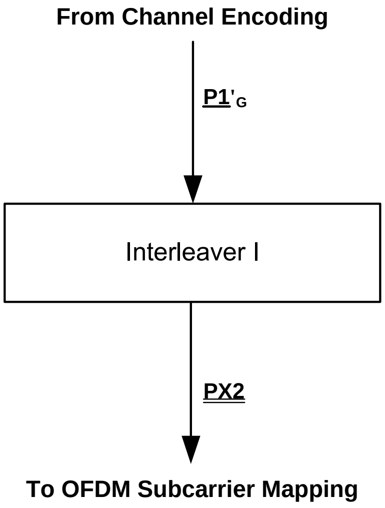


Figure 10-9: PX IP – Service Mode MP6

Table 10-19: PX2 Interleaver I Parameter Values – Service Mode MP6

Service Mode	J	B	C	M	$\underline{v}$	b	I_0	N
MP6	8	2	36	1	[0,1,3,2,4,5,7,6]	N/A	N/A	18432

After Interleaver I has processed one $\underline{P1}'_G$ transfer frame, $\underline{\underline{PX2}}$ is completely filled and the processing flow resets.

10.4.3 SM Interleaving Process

The SM IP interleaves bits destined for the Secondary Main sidebands depicted in Figure 7-9 through Figure 7-11. This IP is active in secondary service modes MS2 through MS4. Its operation in service modes MS2 and MS3 is similar to that of the PM IP in service modes MP5 and MP6. The SM IP disperses multiple logical channels into a single interleaver matrix, $\underline{\underline{SM}}$.

10.4.3.1 Service Modes MS2 and MS3

Figure 10-10 shows the SM IP for service modes MS2 and MS3. This IP utilizes a transfer frame multiplexer and two interleavers. These interleavers share a common interleaver matrix, $\underline{\underline{SM}}$. The inputs to the SM IP are the $\underline{S1}_G$, $\underline{S2}_G$, and $\underline{SIDS}_G$ transfer frames. The number of transfer frames required to fill the interleaver matrix are shown in Table 10-8 and Table 10-9 for each logical channel.

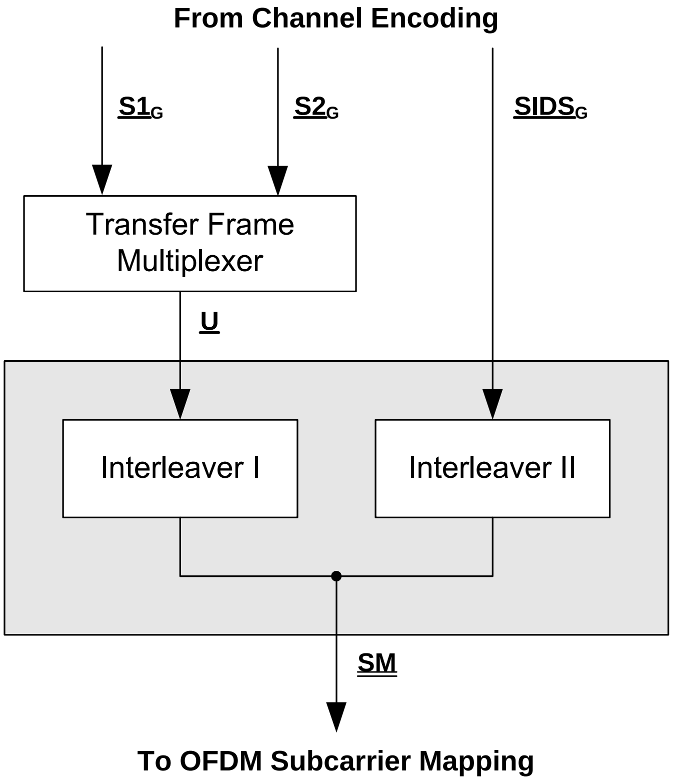


Figure 10-10: SM IP – Service Modes MS2 and MS3

The steps required to process the IP inputs for L1 frame n are given as follows:

1. ***Multiplex $\underline{S1}_G$ and $\underline{S2}_G$ transfer frames***
   The $\underline{S1}_G$ and $\underline{S2}_G$ transfer frames are multiplexed into the vector $\underline{U}$ as shown in Figure 10-11.

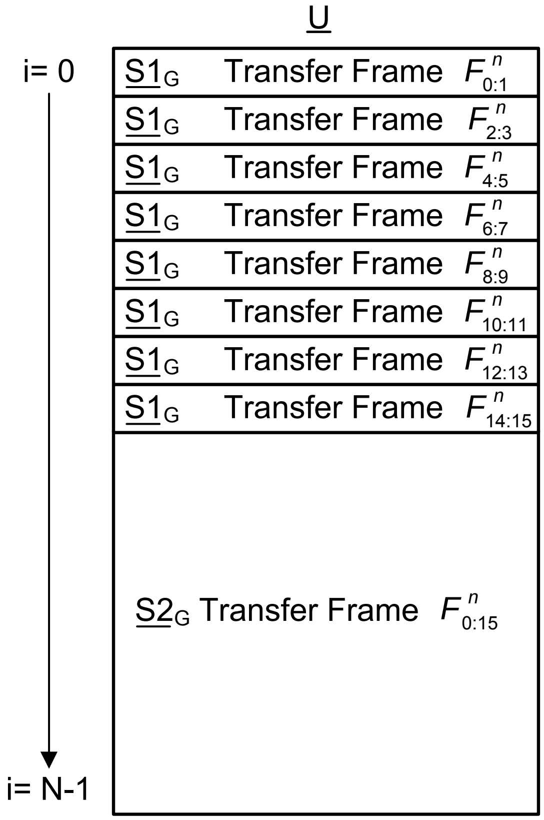


Figure 10-11: SM Transfer Frame Multiplexer Output – Service Modes MS2 and MS3

2. ***Interleave multiplexer output***
   The vector $\underline{U}$ is interleaved into $\underline{\underline{SM}}$ using Interleaver I with the parameters shown in Table 10-20. The vector $\underline{U}$ is dispersed over the full row and column span of $\underline{\underline{SM}}$, leaving holes to be filled in with $\underline{SIDS}_G$ data by Interleaver II.

Table 10-20: SM Interleaver I Parameter Values – Service Modes MS2 and MS3

J	**B**	**C**	**M**	**$\underline{v}$**	**b**	**I_0**	**N**
20	16	36	1	See note below	N/A	N/A	365440

Note: *$\underline{v}$ = [19,7,11,3,15,1,13,9,17,5,18,6,10,2,14,0,12,8,16,4]*

3. ***Interleave $\underline{SIDS}_G$ transfer frames***
   Each $\underline{SIDS}_G$ transfer frame is interleaved into $\underline{\underline{SM}}$, using Interleaver II with the parameters shown in Table 10-21.

Table 10-21: SM Interleaver II Parameter Values – Service Modes MS2 and MS3

J	**B**	**C**	**M**	**$\underline{v}$**	**b**	**I_0**	**N**
20	16	36	1	See note below	200	365440	3200

Note: *$\underline{v}$ = [19,7,11,3,15,1,13,9,17,5,18,6,10,2,14,0,12,8,16,4]*

Interleaver II constrains the row span of each interleaved $\underline{\text{SIDS}}_G$ transfer frame to one interleaver block (32 rows). This is accomplished by properly setting the interleaver variable i before each execution of Interleaver II. Table 10-22 shows the relationship between the variable i and the BC of the $\underline{\text{SIDS}}_G$ transfer frames.

Table 10-22: Bit Numbering of $\underline{\text{SIDS}}_G$ Transfer Frames

BC	Range of Variable i
0	0…199
1	200…399
2	400…599
3	600…799
4	800…999
5	1000…1199
6	1200…1399
7	1400…1599
8	1600…1799
9	1800…1999
10	2000…2199
11	2200…2399
12	2400…2599
13	2600…2799
14	2800…2999
15	3000…3199

When Interleaver I has processed one vector $\underline{U}$ and Interleaver II has processed one $\underline{\text{SIDS}}_G$ transfer frame, a 32 x J submatrix of $\underline{\underline{SM}}$ is completely full and ready for transmission. Each successive $\underline{\text{SIDS}}_G$ transfer frame is interleaved over the next successive interleaver block (for J interleaver partitions). After each $\underline{\text{SIDS}}_G$ transfer frame is processed by Interleaver II, the next 32 x J submatrix of $\underline{\underline{SM}}$ is available to OFDM Subcarrier Mapping.

After Interleaver I has processed one vector $\underline{U}$ and Interleaver II has processed 16 $\underline{\text{SIDS}}_G$ transfer frames, $\underline{\underline{SM}}$ is completely filled and the processing flow resets.

10.4.3.2 Service Mode MS4

Figure 10-12 shows the SM IP for service mode MS4. In this service mode, only $\underline{S2}_G$ data is input to Interleaver I, so no transfer frame multiplexer is required. All interleaver parameters for Interleaver I and Interleaver II are identical to those defined in Table 10-20 and Table 10-21**,** respectively.

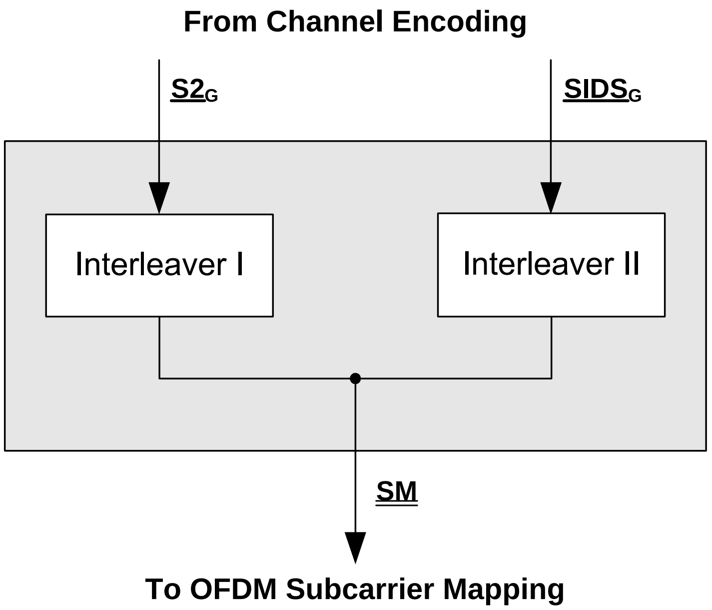


Figure 10-12: SM IP – Service Mode MS4

As implied by Table 10-10, after Interleaver I has processed one $\underline{S2}_G$ transfer frame, and Interleaver II has processed 16 $\underline{SIDS}_G$ transfer frames, $\underline{\underline{SM}}$ is completely filled and the processing flow resets.

10.4.4 SX Interleaver Process

The SX IP interleaves bits destined for the Secondary Extended sidebands depicted in Figure 7-9 through Figure 7-11. This IP is active in secondary service modes MS2 through MS4. Its operation in service modes MS2 and MS4 is similar to that of the PX IP in service mode MP5. Service mode MS3 operation is similar to that of the PX IP in service mode MP6. Like the PX IP, the SX IP disperses a single transfer frame from a single logical channel into each of its interleaver matrices.

10.4.4.1 Service Modes MS2 and MS4

In service modes MS2 and MS4, the SX IP consists of two parallel interleavers of type Interleaver I. One interleaver processes $\underline{S1}'_G$ transfer frames and the other processes $\underline{S3}_G$ transfer frames. Both instances of Interleaver I are configured with the parameters shown in Table 10-23. Figure 10-13 shows the SX IP in service modes MS2 and MS4.

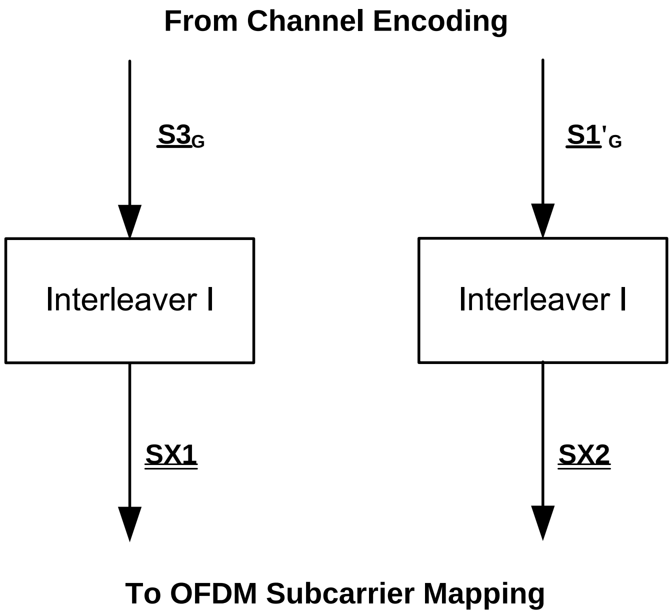


Figure 10-13: SX IP – Service Modes MS2 and MS4

Table 10-23: SX Interleaver I Parameter Values – Service Modes MS2 and MS4

Service Mode	J	B	C	M	$\underline{v}$	b	I_0	N
MS2	4	2	36	2	[0,1,2,3]	N/A	N/A	9216
MS4	4	2	36	2	[0,1,2,3]	N/A	N/A	9216

After each instance of Interleaver I has processed one transfer frame from its respective logical channel, $\underline{SX1}$ and $\underline{SX2}$ are completely filled and the processing flow resets.

10.4.4.2 Service Mode MS3

Figure 10-14 shows the SX IP for service mode MS3. In this service mode, the SX IP interleaves $\underline{S1}'_G$ transfer frames using Interleaver I, configured with the parameter values shown in Table 10-24.

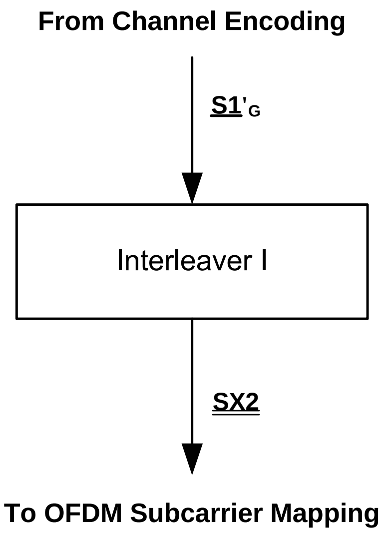


Figure 10-14: SX IP – Service Mode MS3

Table 10-24: SX2 Interleaver I Parameter Values – Service Mode MS3

Service Mode	J	B	C	M	$\underline{v}$	b	I_0	N
MS3	8	2	36	1	[0,1,3,2,4,5,7,6]	N/A	N/A	18432

After Interleaver I has processed one $\underline{S1}'_G$ transfer frame, $\underline{\underline{SX2}}$ is completely filled and the processing flow resets.

10.4.5 SB Interleaver Process

The Secondary Broadband (SB) IP is active only in secondary service mode MS1. Table 10-7 shows the number of transfer frames from each logical channel dispersed over the interleaver matrix $\underline{\underline{SB}}$. Rows of bits from $\underline{\underline{SB}}$ are mapped to the Secondary Main and Secondary Extended sidebands as depicted in Figure 7-8. Figure 10-15 presents the SB IP.

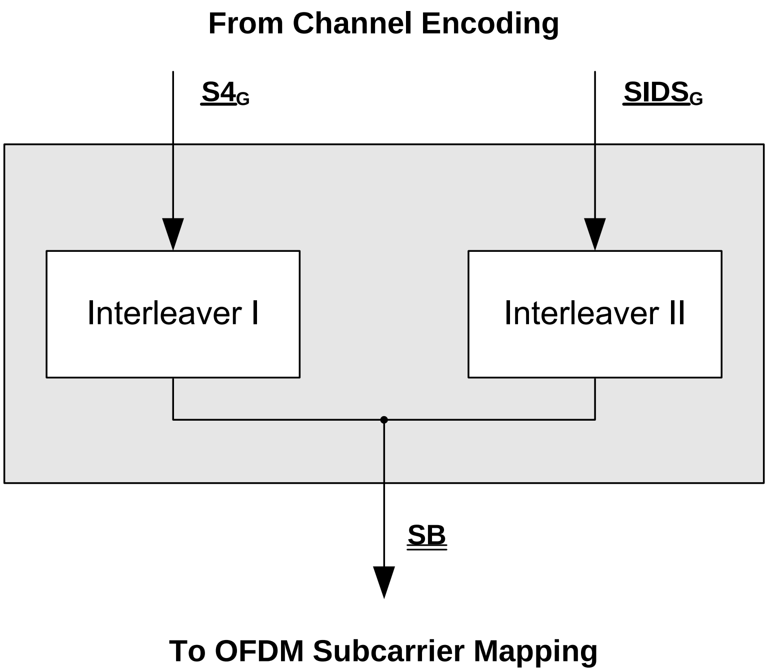


Figure 10-15: SB IP – Service Mode MS1

In this service mode, only $\underline{\underline{S4}}_G$ data is input to Interleaver I, so no transfer frame multiplexer is required. Using the parameters shown in Table 10-25, an $\underline{\underline{S4}}_G$ transfer frame is dispersed over the full row and column span of $\underline{\underline{SB}}$ leaving holes to be filled in with $\underline{\underline{SIDS}}_G$ data. $\underline{\underline{SIDS}}_G$ transfer frames are interleaved into $\underline{\underline{SB}}$, using Interleaver II with the parameters shown in Table 10-26.

Table 10-25: SB Interleaver I Parameter Values

J	B	C	M	$\underline{v}$	b	I_0	N
28	2	36	1	See note below	N/A	N/A	63952

Note: $\underline{v}$ *= [27,7,19,12,3,23,10,1,21,9,14,25,5,17,26,6,18,13,2,22,11,0,20,8,15,24,4,16]*

Table 10-26: SB Interleaver II Parameter Values

J	B	C	M	$\underline{v}$	b	I_0	N
28	2	36	1	See note below	280	63952	560

Note: $\underline{v}$ *= [27,7,19,12,3,23,10,1,21,9,14,25,5,17,26,6,18,13,2,22,11,0,20,8,15,24,4,16]*

As implied by Table 10-7, after Interleaver I has processed one $\underline{\underline{S4}}_G$ transfer frame, and Interleaver II has processed two $\underline{\underline{SIDS}}_G$ transfer frames, $\underline{\underline{SB}}$ is completely filled and the processing flow resets.

10.4.6 SP Interleaver Process

The SP IP interleaves the bits destined for the Secondary Protected sidebands depicted in Figure 7-8 through Figure 7-11. This IP is active in all secondary service modes (MS1 through MS4). Figure 10-16 presents the SP IP.

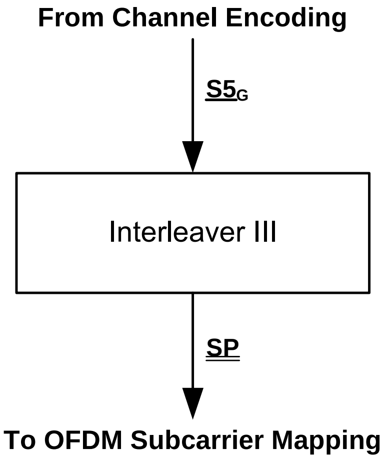


Figure 10-16: SP IP – Service Modes MS1 through MS4

The SP IP interleaves $\underline{S5}_G$ transfer frames using Interleaver III, configured with the parameter values shown in Table 10-27.

Table 10-27: SP Interleaver Parameter Values

J	B	C	M	$\underline{v}$	b	I_0	N
2	1	24	6	[1,0]	N/A	N/A	1536

After Interleaver III has processed one $\underline{S5}_G$ transfer frame, $\underline{\underline{SP}}$ is completely filled, and the processing flow resets.

11 System Control Processing

11.1 Introduction

Under the direction of the upper layers, System Control Processing assembles and differentially encodes a sequence of bits (system control data sequence) destined for each reference subcarrier, as shown in Figure 11-1. There are up to 61 reference subcarriers, numbered 0 through 60 that are distributed throughout the OFDM spectrum (see Figure 5-3 and Figure 5-4). The number of reference subcarriers broadcast in a given waveform depends on the service mode; however, System Control Processing always outputs all 61 system control data sequences, regardless of service mode.

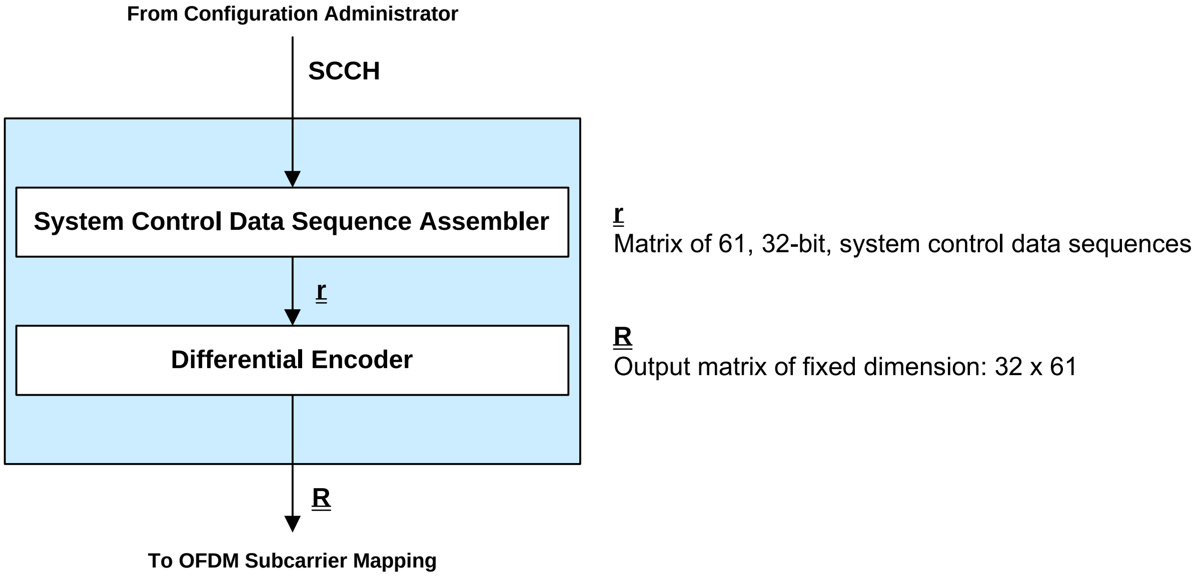


Figure 11-1: System Control Processing Conceptual Diagram

As shown in Figure 11-1, System Control Processing receives inputs from the Configuration Administrator via the SCCH. This system control is defined in Section 6 and is composed of the primary and secondary service modes plus primary and secondary reserved bits. The size and rate of this transfer is defined in Section 6.

Using the system control inputs, the System Control Data Sequence Assembler creates the system control bit sequence over T_b for each of the 61 reference subcarriers. This is a matrix $\underline{\underline{r}}$ (lowercase) of 61, 32-bit, system control data sequences. The Differential Encoder then differentially encodes each bit sequence in time. The resulting output is a matrix $\underline{\underline{R}}$ (uppercase) of fixed dimension 32 x 61. The row dimension of $\underline{\underline{R}}$ corresponds to the number of OFDM symbols per T_b and the column dimension corresponds to the maximum number of active reference subcarriers per OFDM symbol.

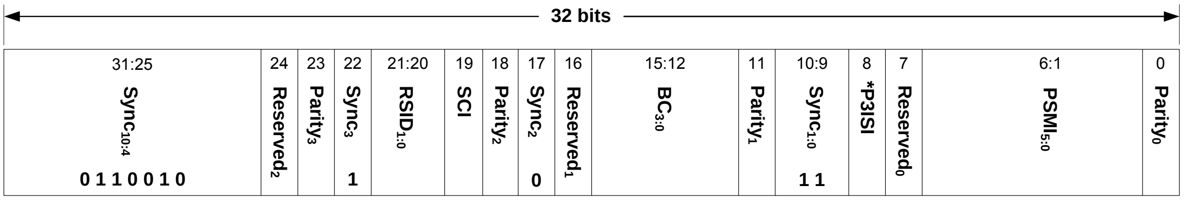
The matrix $\underline{\underline{R}}$ is available to OFDM Subcarrier Mapping at the rate R_b. In addition, System Control Processing provides the L1 block count to Layer 2 at the rate R_b via the SCCH.

11.2 System Control Data Sequence Assembler

The System Control Data Sequence Assembler collects all system control information from the Configuration Administrator and, together with some layer control information, develops a matrix $\underline{\underline{r}}$ of 61, 32-bit, system control data sequences. The rows of $\underline{\underline{r}}$ are numbered 0,1,2,3,…,31 and the columns are numbered 0,1,2,3,…,60. Each row of $\underline{\underline{r}}$ contains one bit of the system control data sequence for each reference subcarrier (before *differential encoding*) and is transmitted in the same OFDM symbol. Row 0 is populated first. Any given column of $\underline{r}$ contains the system control data sequence for a single reference subcarrier over 32 OFDM symbols.

The system control data sequence consists of bit fields that represent the various system control components. Reference subcarriers located in primary sidebands have different fields that reference subcarriers located in secondary sidebands. Information in the primary reference subcarriers applies only to primary services and information in the secondary reference subcarriers applies only to secondary services. Refer to Table 12-12 for the column indices of $\underline{\underline{R}}$ that map to primary reference subcarriers; refer to Table 12-13 for the column indices of $\underline{\underline{R}}$ that map to secondary reference subcarriers.

The primary reference subcarrier system control data sequence is depicted in Figure 11-2 and defined in Table 11-1. Bits 31 through 0 map to rows 0 through 31 of $\underline{r}$, respectively.



***P3ISI must be 1**

Figure 11-2: Primary Reference Subcarrier System Control Data Sequence

Table 11-1: Primary System Control Data Sequence Bit Map

Field	Bit Index	Bit Length	Description
$\text{Sync}_{10:4}$	31:25	7	$\text{Sync}_{10:4}$ = 0110010
Reserved_2	24	1	Controlled by the Configuration Administrator
Parity_3	23	1	Even parity for Reserved_2
Sync_3	22	1	Sync_3 = 1
Reference Subcarrier Identification ($\text{RSID}_{1:0}$)	21:20	2	Fixed two-bit identifier per reference subcarrier
Secondary Channel Indicator (SCI)	19	1	0 = primary only (Hybrid or Extended Hybrid) 1 = primary and secondary (All Digital)
Parity_2	18	1	Even parity for SCI and $\text{RSID}_{1:0}$
Sync_2	17	1	Sync_2 = 0
Reserved_1	16	1	Controlled by the Configuration Administrator
L1 Block Count ($\text{BC}_{3:0}$)	15:12	4	Modulo-16 count, which increments every 32 OFDM symbols
Parity_1	11	1	Even parity for $\text{BC}_{3:0}$ and Reserved_1
$\text{Sync}_{1:0}$	10:9	2	$\text{Sync}_{1:0}$ = 11
P3 Interleaver Select Indicator (P3ISI) This function is obsolete	8	1	Must be set to 1 for backward compatibility with first-generation receivers

Field	Bit Index	Bit Length	Description
Reserved$_0$	7	1	Controlled by the Configuration Administrator
Primary Service Mode Indicator (PSMI$_{5:0}$)	6:1	6	Primary service mode value
Parity$_0$	0	1	Even parity for PSMI$_{5:0}$, Reserved$_0$, and P3ISI

The secondary reference subcarrier system control data sequence is depicted in Figure 11-3 and defined in Table 11-2. Bits 31 through 0 map to rows 0 through 31 of $\underline{\underline{r}}$, respectively.

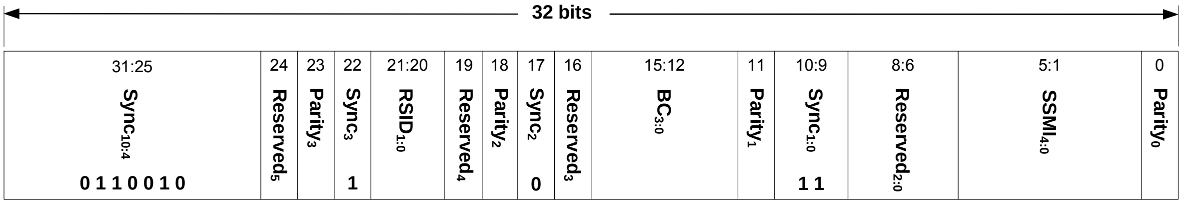


Figure 11-3: Secondary Reference Subcarrier System Control Data Sequence

Table 11-2: Secondary System Control Data Sequence Bit Map

Field	Bit Index	Bit Length	Description
Sync$_{10:4}$	31:25	7	Sync$_{10:4}$ = 0110010
Reserved$_5$	24	1	Controlled by the Configuration Administrator
Parity$_3$	23	1	Even parity for Reserved$_5$
Sync$_3$	22	1	Sync$_3$ = 1
Reference Subcarrier Identification (RSID$_{1:0}$)	21:20	2	Fixed two-bit identifier per reference subcarrier
Reserved$_4$	19	1	Controlled by the Configuration Administrator
Parity$_2$	18	1	Even parity for RSID$_{1:0}$ and Reserved$_4$
Sync$_2$	17	1	Sync$_2$ = 0
Reserved$_3$	16	1	Controlled by upper layers of the protocol stack
L1 Block Count (BC$_{3:0}$)	15:12	4	Modulo-16 count, which increments every 32 OFDM symbols
Parity$_1$	11	1	Even parity for Reserved$_3$ and BC$_{3:0}$
Sync$_{1:0}$	10:9	2	Sync$_{1:0}$ = 11
Reserved$_{2:0}$	8:6	3	Controlled by the Configuration Administrator
Secondary Service Mode Indicator (SSMI$_{4:0}$)	5:1	5	Secondary service mode value
Parity$_0$	0	1	Even parity for Reserved$_{2:0}$ and SSMI$_{4:0}$

11.2.1 Block Synchronization

The sync bits serve to aid in receiver synchronization. The sync bit pattern is distributed over the system control data sequence as shown in Figure 11-2 and Figure 11-3.

11.2.2 P3 Interleaver Select Indicator

The function of this bit is obsolete and must be set to 1 to preserve backward compatibility with first-generation receivers. There is no P3ISI bit in the secondary system control data sequence; instead, a reserved bit occupies this position.

11.2.3 Reference Subcarrier Identification

The Reference Subcarrier Identification ($\text{RSID}_{1:0}$) is a two-bit value that is applied to each reference subcarrier across the OFDM spectrum. The reference subcarrier identification maps to the reference subcarriers (columns of $\underline{\underline{r}}$) as specified in Table 11-3. The Reference Subcarrier ID does not uniquely identify a subcarrier. One use of this parameter is to assist the receiver in frequency acquisition and tracking.

Table 11-3: Reference Subcarrier Identification

Column Number of $\underline{\underline{r}}$	**$\text{RSID}_{1:0}$ (bits 21:20)**		**Column Number of $\underline{\underline{r}}$**	**$\text{RSID}_{1:0}$ (bits 21:20)**		**Column Number of $\underline{\underline{r}}$**	**$\text{RSID}_{1:0}$ (bits 21:20)**		**Column Number of $\underline{\underline{r}}$**	**$\text{RSID}_{1:0}$ (bits 21:20)**	
	21	**20**		**21**	**20**		**21**	**20**		**21**	**20**
0	1	0	16	1	0	32	1	0	48	1	0
1	0	1	17	0	1	33	1	1	49	1	1
2	0	0	18	0	0	34	0	0	50	0	0
3	1	1	19	1	1	35	0	1	51	0	1
4	1	0	20	1	0	36	1	0	52	1	0
5	0	1	21	0	1	37	1	1	53	1	1
6	0	0	22	0	0	38	0	0	54	0	0
7	1	1	23	1	1	39	0	1	55	0	1
8	1	0	24	1	0	40	1	0	56	1	0
9	0	1	25	0	1	41	1	1	57	1	1
10	0	0	26	0	0	42	0	0	58	0	0
11	1	1	27	1	1	43	0	1	59	0	1
12	1	0	28	1	0	44	1	0	60	1	0
13	0	1	29	0	1	45	1	1			
14	0	0	30	0	0	46	0	0			
15	1	1	31	0	1	47	0	1			

11.2.4 Secondary Channel Indicator

Since the secondary sidebands are not transmitted in all waveforms, the primary reference subcarriers must indicate their presence or absence. The Secondary Channel Indicator (SCI) is a single bit in the primary system control data sequence. It is set to 1 when the signal has secondary sidebands; otherwise, it is set to 0. There is no SCI bit in the secondary system control data sequence; instead, a reserved bit occupies this position.

11.2.5 L1 Block Count

The four-bit L1 block count ($BC_{3:0}$) is a modulo-16 count which increments every 32 OFDM symbols. The first L1 block count inserted into the system control data sequence is 0. The same value is applied to each of the 61 system control data sequences. The value of BC contained in the primary reference subcarrier system control data sequence is always the same as the BC contained in the secondary reference subcarrier system control data sequence. Refer to Subsection 6.4 for further definition.

The L1 block count bit map is shown in Table 11-4.

Table 11-4: L1 Block Count Bit Map

L1 Block Count	**$BC_{3:0}$ Bit Assignment (bits 15 :12)**			
	15	**14**	**13**	**12**
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
10	1	0	1	0
11	1	0	1	1
12	1	1	0	0
13	1	1	0	1
14	1	1	1	0
15	1	1	1	1

11.2.6 Primary Service Mode Indicator

The primary service mode in Layer 1, as defined in Section 6, conveys various combinations of digital audio and data. Six bits in the system control data sequence of the primary reference subcarriers have been allocated to the Primary Service Mode Indicator ($PSMI_{5:0}$), as defined in Table 11-5.

Table 11-5: PSMI$_{5:0}$ Mapping for Primary Service Modes

Primary Service Mode	**PSMI$_{5:0}$ (bits 6:1)**					
	6	**5**	**4**	**3**	**2**	**1**
None	0	0	0	0	0	0
MP1	0	0	0	0	0	1
MP2	0	0	0	0	1	0
MP3	0	0	0	0	1	1
Reserved	0	0	0	1	0	0
MP5	0	0	0	1	0	1
MP6	0	0	0	1	1	0
Reserved	0	0	0	1	1	1
…		…	…	…	…	…
Reserved	0	0	1	0	1	0
MP11	0	0	1	0	1	1
Reserved	0	0	1	1	0	0
…		…	…	…	…	…
Reserved	1	1	1	1	1	1

Each of the reserved primary service modes must maintain backward compatibility as defined in Subsection 6.2.1. Thus, first generation receivers will always configure themselves to one of the basic operational modes MP1, MP2, MP3, MP5, or MP6 when one of the reserved modes is detected.

11.2.7 Secondary Service Mode

The secondary service mode in Layer 1, as defined in Section 6, conveys various combinations of digital audio and data. Five bits in the system control data sequence of the secondary reference subcarriers have been allocated to the Secondary Service Mode Indicator (SSMI$_{4:0}$), as defined in Table 11-6.

Table 11-6: SSMI$_{4:0}$ Mapping for Secondary Service Modes

Secondary Service Mode	**SSMI$_{4:0}$ (bits 5:1)**				
	5	**4**	**3**	**2**	**1**
None	0	0	0	0	0
MS1	0	0	0	0	1
MS2	0	0	0	1	0
MS3	0	0	0	1	1
MS4	0	0	1	0	0
Reserved	0	0	1	0	1
…	…	…	…	…	…
Reserved	1	1	1	1	1

11.2.8 Reserved

The value of the reserved bits is determined by the Configuration Administrator as discussed in Section 6. The reserved bits remain the same during the duration of the L1 frame.

11.3 Differential Encoder

The bits in each column of the 32 x 61 matrix r, assembled by the System Control Data Sequence Assembler, are differentially encoded in accordance with Figure 11-4 and are output to the matrix R in the same order. Conceptually, this process can be viewed as 61 parallel differential encoders. For an individual differential encoder, the bits of a single column j of r are processed sequentially, from i = 0,1,2,3,…,31. One system control data sequence bit is input to a differential encoder at a time. This input bit is modulo-2 added with the previously stored output bit R[i-1][j] to form the latest output bit, R[i][j]. The resulting output bit stream will reverse polarity each time the input bit is a 1. The initial state of each differential encoder is 0.

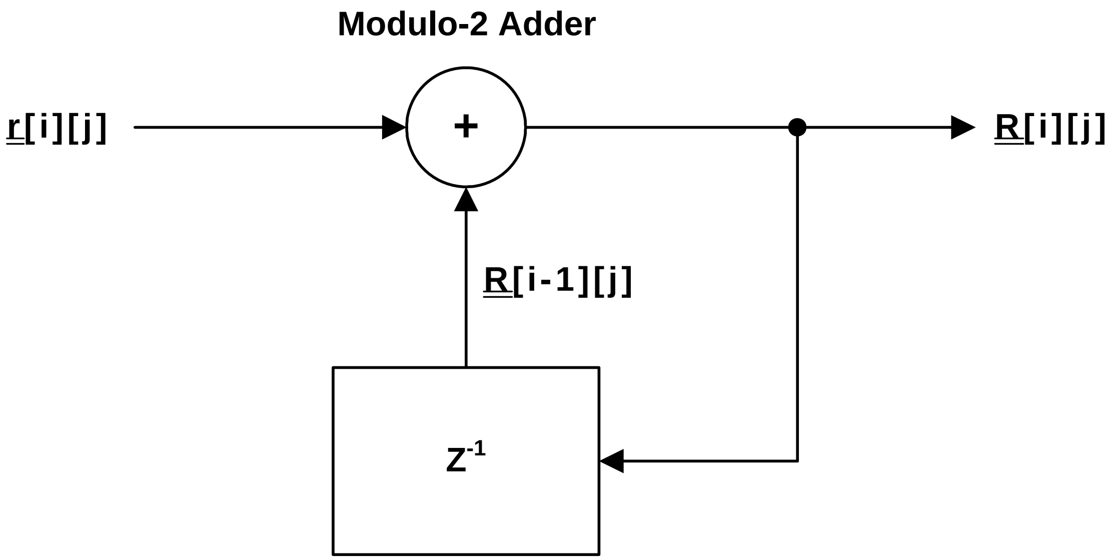


Figure 11-4: Differential Encoder

12 OFDM Subcarrier Mapping

12.1 Introduction

OFDM Subcarrier Mapping assigns interleaver partitions to frequency partitions. For each active interleaver matrix, OFDM Subcarrier Mapping assigns a row of bits from each interleaver partition to its respective frequency partition in the complex output vector $\underline{X}$. In addition, system control data sequence bits from a row of $\underline{\underline{R}}$ are mapped to the active reference subcarrier locations in $\underline{X}$. The service mode dictates which interleaver matrices and which elements of $\underline{\underline{R}}$ are active. Figure 12-1 shows the inputs, output, and component functions of OFDM Subcarrier Mapping.

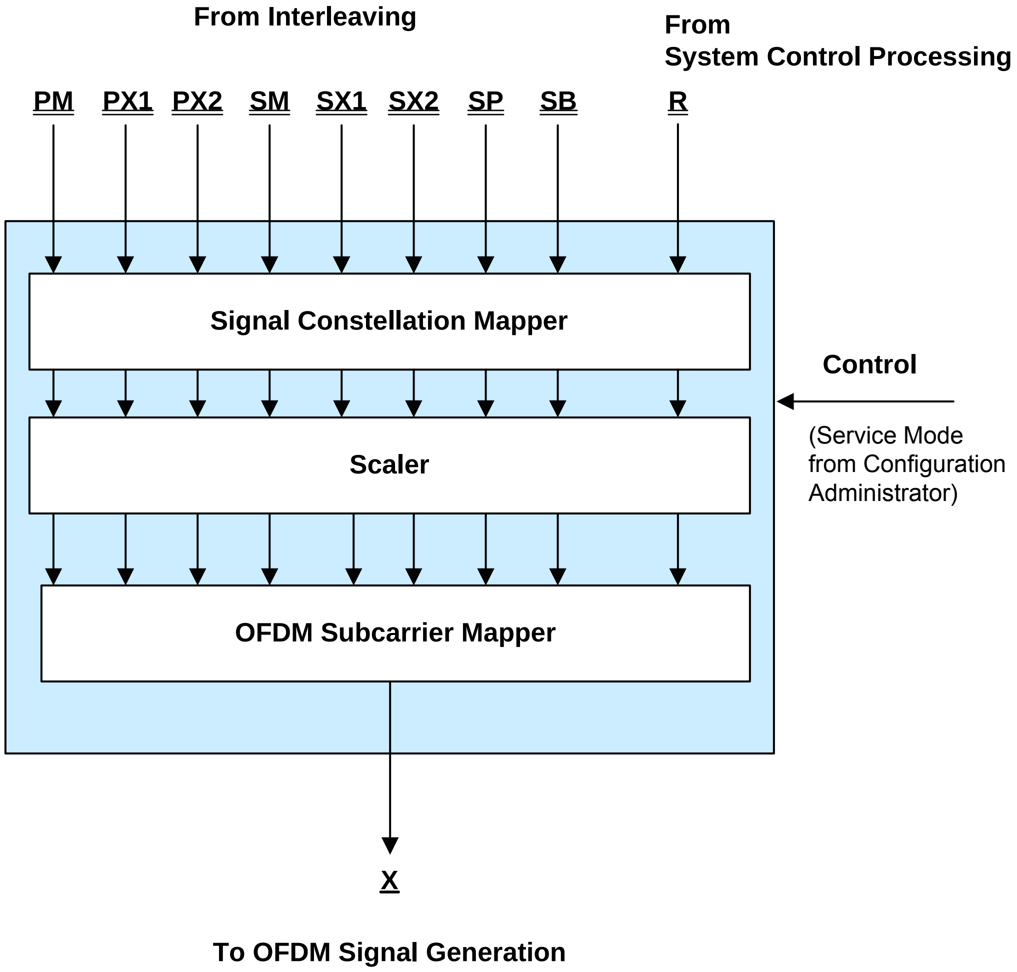


Figure 12-1: OFDM Subcarrier Mapping Conceptual Block Diagram

The inputs to OFDM Subcarrier Mapping are a row of bits from each active interleaver matrix and a row of bits from $\underline{\underline{R}}$, the matrix of system control data sequences.

The output from OFDM Subcarrier Mapping for each OFDM symbol is a single complex vector, $\underline{X}$, of length 1093. The vector is indexed from k = 0,1,2,…,1092. The k^{th} element of $\underline{X}$ corresponds to subcarrier (k – 546), as shown in Figure 12-2.

Index into $\underline{X}$	0	1	2	■ ■ ■	1090	1091	1092
Subcarrier Number	-546	-545	-544		544	545	546

Figure 12-2: Assignment of Elements of Output Vector X to Subcarriers

Active elements in a row of $\underline{\underline{R}}$ and the associated row from each active interleaver matrix are assigned to the same instance of $\underline{X}$.

The *Signal Constellation Mapper* translates pairs of bits read from interleaver partitions and individual bits read from $\underline{\underline{R}}$ to complex constellation values. The Scaler function applies the appropriate amplitude scale factor to these complex values. The OFDM Subcarrier Mapper maps the scaled complex constellation values to the appropriate elements of the output vector $\underline{X}$. Elements of $\underline{X}$ corresponding to unused subcarriers are set to the complex value $0 + j0$.

12.2 OFDM Subcarrier Mapping Procedures

The OFDM Subcarrier Mapping procedures are specified in Subsection 12.2.1 and Subsection 12.2.2.

12.2.1 Data Subcarriers

For each active interleaver matrix, a row of bits is processed every T_s. Rows are processed sequentially, starting with the first row (row 0). When all rows of an interleaver matrix have been processed, the next instance of that interleaver matrix is processed, starting with the first row.

For a given row of an interleaver matrix, bits are processed by interleaver partition. Pairs of adjacent columns within an interleaver partition are mapped to individual, complex, *Quadrature Phase Shift Keying* (QPSK)-modulated, data subcarriers within a frequency partition. This mapping proceeds sequentially. The first two columns (0 and 1) of an interleaver partition are mapped to the starting subcarrier number of a frequency partition and the last two columns of an interleaver partition are mapped to the ending subcarrier number of a frequency partition. Table 12-3 through Table 12-11 shows the mapping of interleaver matrix column numbers to subcarrier numbers for each interleaver partition in the active interleaver matrices.

To map each adjacent *column pair* within an interleaver partition to a subcarrier location within the vector $\underline{X}$, the following steps are taken:

1. Read a pair of bits from adjacent columns within an interleaver partition. For a given column pair, the bit read from the lower indexed column is mapped as an I bit, and the bit read from the higher indexed column is mapped as a Q bit.
2. Map the bit pair from Step 1 to a complex constellation value using Table 12-1. The I bit maps to the real component and the Q bit maps to the imaginary component of the constellation value.
3. Scale the I and Q components of the complex constellation value from Step 2 using the appropriate amplitude scale factor from Table 5-1 through Table 5-3. The amplitude scale factor is chosen based on subcarrier location and, for the secondary sidebands, the value of ASF.

4. Map the scaled constellation value from Step 3 to the appropriate element of X using Table 12-3 through Table 12-11 and Figure 12-2.

Table 12-1: Signal Constellation Mapping for Data Subcarriers

I Bit	Q Bit	Constellation Value
0	0	$(-1 - j1)$
0	1	$(-1 + j1)$
1	0	$(1 - j1)$
1	1	$(1 + j1)$

12.2.2 Reference Subcarriers

R is read one row at a time and a row of R is processed every T_s. Each row of R is a vector of bits of length 61, indexed from 0 to 60. Selected bits of this vector are mapped to reference subcarriers according to the service mode as shown in Table 12-12 and Table 12-13.

Since the output vector X contains complex values, the following steps are taken to map a row of R to an element of X:

1. Read a bit value from a row vector of R.
2. Map the bit to a complex, *binary phase shift keying* (BPSK)-modulated constellation value using Table 12-2.
3. Scale the I and Q components of the complex constellation value using the appropriate amplitude scale factor from Table 5-1 through Table 5-3 and, for secondary subcarriers, according to the state of ASF.
4. Map the scaled constellation value to the appropriate element of X using Figure 12-2, Table 12-12, and Table 12-13 for the current service mode.

Table 12-2: Signal Constellation Mapping for Reference Subcarriers

Bit Value	Constellation Value
0	$(-1 - j1)$
1	$(1 + j1)$

12.3 OFDM Subcarrier Mapping Tables

Subsection 12.3.1 presents the mapping tables for the data subcarriers. Subsection 12.3.2 presents the mapping tables for the reference subcarriers.

12.3.1 Data Subcarrier Mapping Tables by Service Mode

The tables defining the data subcarrier mapping by service mode are presented in Subsection 12.3.1.1 through Subsection 12.3.1.9. The subcarrier numbers can be translated to indices of X by adding 546. For example, data subcarrier -545 maps to index 1 of X.

12.3.1.1 Service Mode MP1

In service mode MP1, the PM interleaver partitions are mapped to the subcarriers as presented in Table 12-3.

Table 12-3: Data Subcarrier Mapping – Service Mode MP1

Starting Subcarrier Number	Ending Subcarrier Number	Interleaver Matrix	Interleaver Partition	Interleaver Matrix Starting Column Number	Interleaver Matrix Ending Column Number
-545	-528	PM	0	0	35
-526	-509	PM	1	36	71
-507	-490	PM	2	72	107
-488	-471	PM	3	108	143
-469	-452	PM	4	144	179
-450	-433	PM	5	180	215
-431	-414	PM	6	216	251
-412	-395	PM	7	252	287
-393	-376	PM	8	288	323
-374	-357	PM	9	324	359
357	374	PM	10	360	395
376	393	PM	11	396	431
395	412	PM	12	432	467
414	431	PM	13	468	503
433	450	PM	14	504	539
452	469	PM	15	540	575
471	488	PM	16	576	611
490	507	PM	17	612	647
509	526	PM	18	648	683
528	545	PM	19	684	719

12.3.1.2 Service Mode MP2

In service mode MP2, the PM and PX1 interleaver partitions are mapped to the subcarriers as presented in Table 12-4.

Table 12-4: Data Subcarrier Mapping – Service Mode MP2

Starting Subcarrier Number	Ending Subcarrier Number	Interleaver Matrix	Interleaver Partition	Interleaver Matrix Starting Column Number	Interleaver Matrix Ending Column Number
-545	-528	PM	0	0	35
-526	-509	PM	1	36	71
-507	-490	PM	2	72	107
-488	-471	PM	3	108	143
-469	-452	PM	4	144	179
-450	-433	PM	5	180	215
-431	-414	PM	6	216	251
-412	-395	PM	7	252	287
-393	-376	PM	8	288	323
-374	-357	PM	9	324	359
-355	-338	PX1	0	0	35
338	355	PX1	1	36	71
357	374	PM	10	360	395
376	393	PM	11	396	431
395	412	PM	12	432	467
414	431	PM	13	468	503
433	450	PM	14	504	539
452	469	PM	15	540	575
471	488	PM	16	576	611
490	507	PM	17	612	647
509	526	PM	18	648	683
528	545	PM	19	684	719

12.3.1.3 Service Mode MP3

In service mode MP3, the PM and PX1 interleaver partitions are mapped to the subcarriers as presented in Table 12-5.

Table 12-5: Data Subcarrier Mapping – Service Mode MP3

Starting Subcarrier Number	Ending Subcarrier Number	Interleaver Matrix	Interleaver Partition	Interleaver Matrix Starting Column Number	Interleaver Matrix Ending Column Number
-545	-528	PM	0	0	35
-526	-509	PM	1	36	71
-507	-490	PM	2	72	107
-488	-471	PM	3	108	143
-469	-452	PM	4	144	179
-450	-433	PM	5	180	215
-431	-414	PM	6	216	251
-412	-395	PM	7	252	287
-393	-376	PM	8	288	323
-374	-357	PM	9	324	359
-355	-338	PX1	0	0	35
-336	-319	PX1	1	36	71
319	336	PX1	2	72	107
338	355	PX1	3	108	143
357	374	PM	10	360	395
376	393	PM	11	396	431
395	412	PM	12	432	467
414	431	PM	13	468	503
433	450	PM	14	504	539
452	469	PM	15	540	575
471	488	PM	16	576	611
490	507	PM	17	612	647
509	526	PM	18	648	683
528	545	PM	19	684	719

12.3.1.4 Service Mode MP11

In service mode MP11, the PM, PX1, and PX2 interleaver partitions are mapped to the subcarriers as presented in Table 12-6.

Table 12-6: Data Subcarrier Mapping – Service Mode MP11

Starting Subcarrier Number	**Ending Subcarrier Number**	**Interleaver Matrix**	**Interleaver Partition**	**Interleaver Matrix Starting Column Number**	**Interleaver Matrix Ending Column Number**
-545	-528	PM	0	0	35
-526	-509	PM	1	36	71
-507	-490	PM	2	72	107
-488	-471	PM	3	108	143
-469	-452	PM	4	144	179
-450	-433	PM	5	180	215
-431	-414	PM	6	216	251
-412	-395	PM	7	252	287
-393	-376	PM	8	288	323
-374	-357	PM	9	324	359
-355	-338	PX1	0	0	35
-336	-319	PX1	1	36	71
-317	-300	PX2	2	72	107
-298	-281	PX2	3	108	143
281	298	PX2	4	144	179
300	317	PX2	5	180	215
319	336	PX1	6	216	251
338	355	PX1	7	252	287
357	374	PM	10	360	395
376	393	PM	11	396	431
395	412	PM	12	432	467
414	431	PM	13	468	503
433	450	PM	14	504	539
452	469	PM	15	540	575
471	488	PM	16	576	611
490	507	PM	17	612	647
509	526	PM	18	648	683
528	545	PM	19	684	719

12.3.1.5 Service Mode MP5

In service mode MP5, the PM, PX1, and PX2 interleaver partitions are mapped to the subcarriers as presented in Table 12-7.

Table 12-7: Data Subcarrier Mapping – Service Mode MP5

Starting Subcarrier Number	Ending Subcarrier Number	Interleaver Matrix	Interleaver Partition	Interleaver Matrix Starting Column Number	Interleaver Matrix Ending Column Number
-545	-528	PM	0	0	35
-526	-509	PM	1	36	71
-507	-490	PM	2	72	107
-488	-471	PM	3	108	143
-469	-452	PM	4	144	179
-450	-433	PM	5	180	215
-431	-414	PM	6	216	251
-412	-395	PM	7	252	287
-393	-376	PM	8	288	323
-374	-357	PM	9	324	359
-355	-338	PX1	0	0	35
-336	-319	PX1	1	36	71
-317	-300	PX2	0	0	35
-298	-281	PX2	1	36	71
281	298	PX2	2	72	107
300	317	PX2	3	108	143
319	336	PX1	2	72	107
338	355	PX1	3	108	143
357	374	PM	10	360	395
376	393	PM	11	396	431
395	412	PM	12	432	467
414	431	PM	13	468	503
433	450	PM	14	504	539
452	469	PM	15	540	575
471	488	PM	16	576	611
490	507	PM	17	612	647
509	526	PM	18	648	683
528	545	PM	19	684	719

12.3.1.6 Service Mode MP6

In service mode MP6, the PM and PX2 interleaver partitions are mapped to the subcarriers as presented in Table 12-8.

Table 12-8: Data Subcarrier Mapping – Service Mode MP6

Starting Subcarrier Number	Ending Subcarrier Number	Interleaver Matrix	Interleaver Partition	Interleaver Matrix Starting Column Number	Interleaver Matrix Ending Column Number
-545	-528	PM	0	0	35
-526	-509	PM	1	36	71
-507	-490	PM	2	72	107
-488	-471	PM	3	108	143
-469	-452	PM	4	144	179
-450	-433	PM	5	180	215
-431	-414	PM	6	216	251
-412	-395	PM	7	252	287
-393	-376	PM	8	288	323
-374	-357	PM	9	324	359
-355	-338	PX2	0	0	35
-336	-319	PX2	1	36	71
-317	-300	PX2	2	72	107
-298	-281	PX2	3	108	143
281	298	PX2	4	144	179
300	317	PX2	5	180	215
319	336	PX2	6	216	251
338	355	PX2	7	252	287
357	374	PM	10	360	395
376	393	PM	11	396	431
395	412	PM	12	432	467
414	431	PM	13	468	503
433	450	PM	14	504	539
452	469	PM	15	540	575
471	488	PM	16	576	611
490	507	PM	17	612	647
509	526	PM	18	648	683
528	545	PM	19	684	719

12.3.1.7 Service Mode MS1

In service mode MS1, the SB and SP interleaver partitions are mapped to the subcarriers as presented in Table 12-9.

Table 12-9: Data Subcarrier Mapping – Service Mode MS1

Starting Subcarrier Number	Ending Subcarrier Number	Interleaver Matrix	Interleaver Partition	Interleaver Matrix Starting Column Number	Interleaver Matrix Ending Column Number
-278	-267	SP	0	0	23
-265	-248	SB	0	0	35
-246	-229	SB	1	36	71
-227	-210	SB	2	72	107
-208	-191	SB	3	108	143
-189	-172	SB	4	144	179
-170	-153	SB	5	180	215
-151	-134	SB	6	216	251
-132	-115	SB	7	252	287
-113	-96	SB	8	288	323
-94	-77	SB	9	324	359
-75	-58	SB	10	360	395
-56	-39	SB	11	396	431
-37	-20	SB	12	432	467
-18	-1	SB	13	468	503
1	18	SB	14	504	539
20	37	SB	15	540	575
39	56	SB	16	576	611
58	75	SB	17	612	647
77	94	SB	18	648	683
96	113	SB	19	684	719
115	132	SB	20	720	755
134	151	SB	21	756	791
153	170	SB	22	792	827
172	189	SB	23	828	863
191	208	SB	24	864	899
210	227	SB	25	900	935
229	246	SB	26	936	971
248	265	SB	27	972	1007
267	278	SP	1	24	47

12.3.1.8 Service Modes MS2 and MS4

In service modes MS2 and MS4, the SM, SX1, SX2, and SP interleaver partitions are mapped to the subcarriers as presented in Table 12-10.

Table 12-10: Data Subcarrier Mapping – Service Modes MS2 and MS4

Starting Subcarrier Number	Ending Subcarrier Number	Interleaver Matrix	Interleaver Partition	Interleaver Matrix Starting Column Number	Interleaver Matrix Ending Column Number
-278	-267	SP	0	0	23
-265	-248	SX2	0	0	35
-246	-229	SX2	1	36	71
-227	-210	SX1	0	0	35
-208	-191	SX1	1	36	71
-189	-172	SM	0	0	35
-170	-153	SM	1	36	71
-151	-134	SM	2	72	107
-132	-115	SM	3	108	143
-113	-96	SM	4	144	179
-94	-77	SM	5	180	215
-75	-58	SM	6	216	251
-56	-39	SM	7	252	287
-37	-20	SM	8	288	323
-18	-1	SM	9	324	359
1	18	SM	10	360	395
20	37	SM	11	396	431
39	56	SM	12	432	467
58	75	SM	13	468	503
77	94	SM	14	504	539
96	113	SM	15	540	575
115	132	SM	16	576	611
134	151	SM	17	612	647
153	170	SM	18	648	683
172	189	SM	19	684	719
191	208	SX1	2	72	107
210	227	SX1	3	108	143
229	246	SX2	2	72	107
248	265	SX2	3	108	143
267	278	SP	1	24	47

12.3.1.9 Service Mode MS3

In service mode MS3, the SM, SX2, and SP interleaver partitions are mapped to the subcarriers as presented in Table 12-11.

Table 12-11: Data Subcarrier Mapping – Service Mode MS3

Starting Subcarrier Number	Ending Subcarrier Number	Interleaver Matrix	Interleaver Partition	Interleaver Matrix Starting Column Number	Interleaver Matrix Ending Column Number
-278	-267	SP	0	0	23
-265	-248	SX2	0	0	35
-246	-229	SX2	1	36	71
-227	-210	SX2	2	72	107
-208	-191	SX2	3	108	143
-189	-172	SM	0	0	35
-170	-153	SM	1	36	71
-151	-134	SM	2	72	107
-132	-115	SM	3	108	143
-113	-96	SM	4	144	179
-94	-77	SM	5	180	215
-75	-58	SM	6	216	251
-56	-39	SM	7	252	287
-37	-20	SM	8	288	323
-18	-1	SM	9	324	359
1	18	SM	10	360	395
20	37	SM	11	396	431
39	56	SM	12	432	467
58	75	SM	13	468	503
77	94	SM	14	504	539
96	113	SM	15	540	575
115	132	SM	16	576	611
134	151	SM	17	612	647
153	170	SM	18	648	683
172	189	SM	19	684	719
191	208	SX2	4	144	179
210	227	SX2	5	180	215
229	246	SX2	6	216	251
248	265	SX2	7	252	287
267	278	SP	1	24	47

12.3.2 Reference Subcarrier Mapping Tables by Service Mode

The tables defining the reference subcarrier mapping by service mode are presented in Subsection 12.3.2.1 and Subsection 12.3.2.2. The reference subcarrier numbers can be translated to indices of X by adding 546. For example, reference subcarrier -546 maps to index 0 of X.

12.3.2.1 Primary Service Modes

Table 12-12 presents the mapping of columns of R to subcarriers for each primary service mode.

Table 12-12: Primary Reference Subcarrier Mapping

Subcarrier Number	Service Mode					
	MP1	MP2	MP3	MP11	MP5	MP6
-546	0	0	0	0	0	0
-527	1	1	1	1	1	1
-508	2	2	2	2	2	2
-489	3	3	3	3	3	3
-470	4	4	4	4	4	4
-451	5	5	5	5	5	5
-432	6	6	6	6	6	6
-413	7	7	7	7	7	7
-394	8	8	8	8	8	8
-375	9	9	9	9	9	9
-356	10	10	10	10	10	10
-337	N/A	11	11	11	11	11
-318	N/A	N/A	12	12	12	12
-299	N/A	N/A	N/A	13	13	13
-280	N/A	N/A	N/A	14	14	14
280	N/A	N/A	N/A	46	46	46
299	N/A	N/A	N/A	47	47	47
318	N/A	N/A	48	48	48	48
337	N/A	49	49	49	49	49
356	50	50	50	50	50	50
375	51	51	51	51	51	51
394	52	52	52	52	52	52
413	53	53	53	53	53	53
432	54	54	54	54	54	54
451	55	55	55	55	55	55
470	56	56	56	56	56	56
489	57	57	57	57	57	57
508	58	58	58	58	58	58
527	59	59	59	59	59	59
546	60	60	60	60	60	60

12.3.2.2 Secondary Service Modes

Table 12-13 presents the mapping of columns of $\underline{\underline{R}}$ to subcarriers for each secondary service mode.

Table 12-13: Secondary Reference Subcarrier Mapping

Subcarrier Number	**Service Mode**
	MS1 to MS4
-279	15
-266	16
-247	17
-228	18
-209	19
-190	20
-171	21
-152	22
-133	23
-114	24
-95	25
-76	26
-57	27
-38	28
-19	29
0	30
19	31
38	32
57	33
76	34
95	35
114	36
133	37
152	38
171	39
190	40
209	41
228	42
247	43
266	44
279	45

13 OFDM Signal Generation

13.1 Introduction

OFDM Signal Generation receives complex, frequency-domain, OFDM symbols from OFDM Subcarrier Mapping, and outputs time-domain pulses representing the digital portion of the FM HD Radio signal. A conceptual block diagram of OFDM Signal Generation is shown in Figure 13-1.

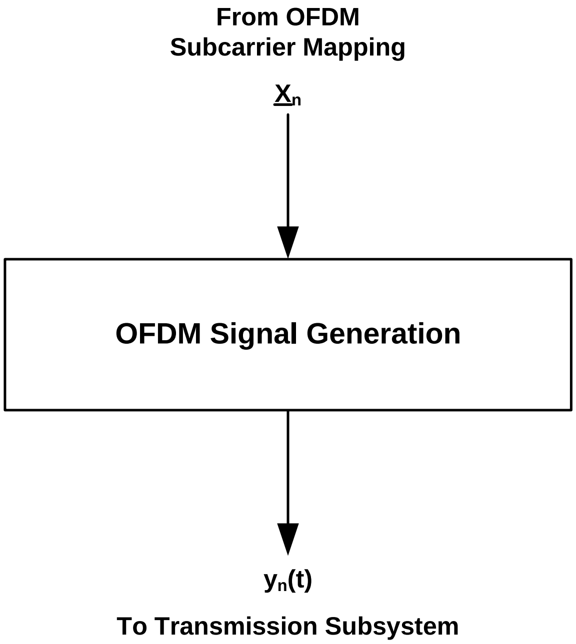


Figure 13-1: OFDM Signal Generation Conceptual Block Diagram

The input to OFDM Signal Generation is a complex vector $\underline{X}_n$ of length L, representing the complex constellation values for each OFDM subcarrier in OFDM symbol n. For notational convenience, the output of OFDM Subcarrier Mapping described in Section 12 did not use the subscript n. Rather, it referred to the vector $\underline{X}$ as representing a single OFDM symbol. In this section, the subscript is appended to $\underline{X}$ because of the significance of n to OFDM Signal Generation.

The output of OFDM Signal Generation is a complex, baseband, time-domain pulse $y_n(t)$, representing the digital portion of the FM HD Radio signal for OFDM symbol n.

13.2 Functionality

Let $\underline{X}_n[k]$ be the scaled constellation points from OFDM Subcarrier Mapping for the nth symbol, where k indexes the OFDM subcarriers such that k = 0,1,2,3,…,L-1.

Let $y_n(t)$ denote the time-domain output of OFDM Signal Generation for the nth symbol. Then, $y_n(t)$ is written in terms of $\underline{X}_n[k]$ as follows:

$$y_n(t) = h(t - nT_s) \cdot \sum_{k=0}^{L-1} \underline{X}_n[k] \cdot e^{j2\pi \cdot \Delta f \left[k - \frac{(L-1)}{2} \right] \cdot (t - nT_s)}$$

where n = 0,1,2,3,…,∞ and $0 \le t < \infty$.

L = 1093 is the total number of OFDM subcarriers.

T_s and Δf are the OFDM symbol duration and OFDM subcarrier spacing, respectively, as defined in Subsection 3.5.

The *pulse-shaping function* h(ξ) is defined as:

$$h(\xi) = \begin{cases} \cos\left(\pi \dfrac{\alpha T - \xi}{2\alpha T} \right) & \text{if} \quad 0 < \xi < \alpha T \\ 1 & \text{if} \quad \alpha T \le \xi \le T \\ \cos\left(\pi \dfrac{T - \xi}{2\alpha T} \right) & \text{if} \quad T < \xi < T(1+\alpha) \\ 0 & \text{elsewhere} \end{cases}$$

where α is the cyclic prefix width defined in Subsection 3.5.

T = 1/Δ*f* is the reciprocal of the OFDM subcarrier spacing.

14 Transmission Subsystem

14.1 Introduction

The Transmission Subsystem formats the baseband FM HD Radio waveform for transmission through the VHF channel. Functions include symbol concatenation and frequency up-conversion. In addition, when transmitting the Hybrid or Extended Hybrid waveforms, this function modulates the baseband analog signal before combining it with the digital waveform.

The input to this module is a complex, baseband, time-domain, OFDM symbol, $y_n(t)$, from the OFDM Signal Generation function. When transmitting the Hybrid or Extended Hybrid waveform, a diversity-delayed, baseband, analog signal m(t), plus optional Subsidiary Communications Authorization (SCA) signals, are also inputs to this module. The output of this module is the VHF FM HD Radio waveform.

Refer to Figure 14-1 for a functional block diagram of the All Digital Transmission Subsystem; refer to Figure 14-2 for a functional block diagram of the Hybrid and Extended Hybrid Transmission Subsystems.

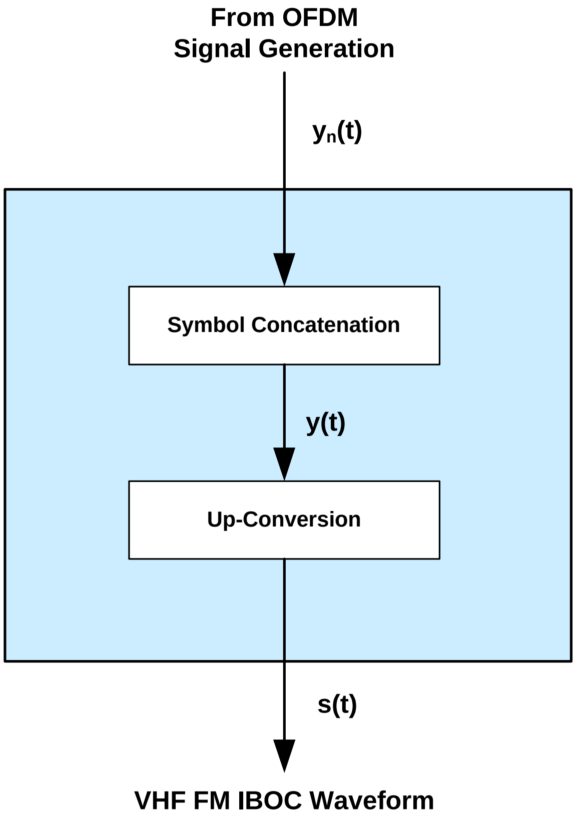


Figure 14-1: All Digital Transmission Subsystem Functional Block Diagram

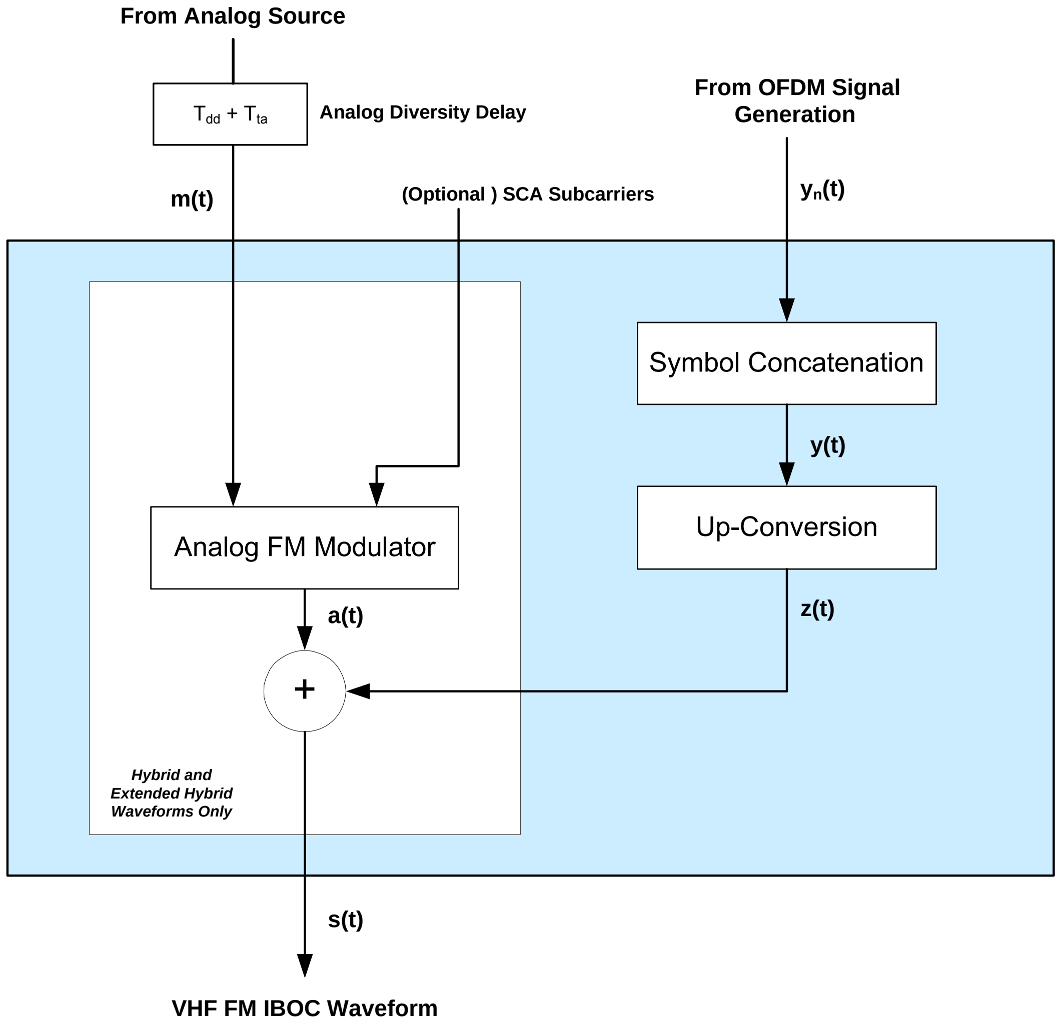


Figure 14-2: Hybrid/Extended Hybrid Transmission Subsystem Functional Block Diagram

14.2 Functional Components

The functional components of the Transmission Subsystem are specified in Subsection 14.2.1 through Subsection 14.2.5.

14.2.1 Symbol Concatenation

The individual time-domain OFDM symbols generated by OFDM Signal Generation are concatenated to produce a continuum of pulses over t = 0,1,2,3,…,∞ as follows:

$$y(t) = \sum_{n=0}^{\infty} y_n(t)$$

14.2.2 Up-Conversion

The concatenated digital signal y(t) is translated from baseband to the RF carrier frequency as follows:

$$z(t) = \mathrm{Re}\left(e^{j 2 \pi f_c t} \cdot y(t) \right)$$

where j is the unitary imaginary number, f_c is the VHF *allocated channel* frequency, and Re( ) denotes the real component of the complex quantity. For the All Digital waveform, the output of the up-converter is the transmitted VHF FM HD Radio waveform, and therefore, s(t) = z(t).

The carrier frequency spacing and channel numbering scheme are compatible with Title 47 CFR §73.201. (See Reference [2]). The carriers retain their 200-kHz spacing over the 88.0- to 108.0-MHz frequency range. Channels are numbered from 201 to 300 where channel 201 is centered on 88.1 MHz and channel 300 is centered on 107.9 MHz. The absolute accuracy of the carrier frequency is defined in Reference [3].

14.2.3 Diversity Delay

When broadcasting the Hybrid and Extended Hybrid waveforms, the digital signal is combined with the analog FM signal as shown in Figure 14-2. However, diversity delay is first applied to the baseband analog FM signal.

In the HD Radio system, the analog and digital signals carry the same audio program with the analog audio delayed from the corresponding digital audio at the output of the analog/digital combiner. This delay consists of a fixed portion T_{dd}, as defined in Section 3.5 (FM System Parameters), plus an adjustable portion T_{ta}. The delay T_{ta} is adjusted so that the audio content in the analog and digital paths has a time diversity of precisely T_{dd} at the transmit antenna. The delay accounts for processing delay differences in the two signal paths.

The absolute accuracy of the diversity delay, when enabled, is defined in [3].

Ball-game mode: A radio station can disable the analog diversity delay for specialized broadcasts. The state of the analog diversity delay is indicated by the Blend Control bits in the Audio Transport layer (See Reference [4]). However, changing the state of the analog diversity delay may result in a discontinuity during reception as the receiver blends from analog to digital. Some receivers may disable digital reception entirely when analog diversity delay is disabled.

14.2.4 Analog FM Modulator

For the Hybrid and Extended Hybrid waveforms, the baseband analog signal m(t) is frequency modulated to produce an RF analog FM waveform identical to existing analog signals. The FM-modulated analog signal, including any SCAs, will maintain compatibility with Title 47 CFR Part 73, Subparts B, C, and H. In addition, the analog signal will be compatible with the Emergency Alert System (EAS) as specified in Title 47 CFR Part 11 (See Reference [1]).

14.2.5 Analog/Digital Combiner

When broadcasting the Hybrid or Extended Hybrid waveform, the analog-modulated FM RF signal is combined with the digitally-modulated RF signal to produce the VHF FM HD Radio waveform, s(t). Both the analog and digital portions of the waveform are centered on the same carrier frequency.

The levels of each digital sideband in the output spectrum are appropriately scaled by OFDM Subcarrier Mapping. These scale factors, as well as the ratio of the total power in the analog FM signal to the total power in the digital sidebands, are provided in Reference [3].

The spectral emissions limits of the composite HD Radio RF signal are defined in Reference [3].

15 Glossary

In order to better understand the terms and concepts in this document, the following definitions apply:

Absolute L1 Frame Number (ALFN)
A number assigned to each transmitted L1 frame that provides a reference to absolute time. The start of ALFN 0 occurred at 00:00:00 Coordinated Universal Time (UTC) on January 6, 1980. The start of every subsequent L1 frame occurs at an exact integer multiple of T_f after that instant in time.

All Digital waveform
The transmitted waveform composed entirely of digitally modulated subcarriers (subcarriers -546 to +546) without an analog FM signal. Use of this waveform will normally follow an initial transitional phase utilizing Hybrid waveforms incorporating both analog and digital modulation. (See *Hybrid waveform* and *Extended Hybrid waveform.*)

allocated channel
One of the one hundred possible frequency assignments in the FM band, as defined in Reference [2].

amplitude modulation (AM)
Modulation in which the amplitude of a carrier wave is varied in accordance with the amplitude of the modulating signal.

amplitude scale factor
A factor which multiplies the baseband components of a particular OFDM subcarrier of the transmitted spectrum to constrain the radiated power to a prescribed level.

analog signal
Refers to signals that are modulated on the main carrier by conventional high-modulation-index frequency modulation. (See *digital signal.*)

BC range
The range of L1 Blocks, m1:m2, spanned by a transfer frame, indicating its position within an L1 frame.

binary phase shift keying (BPSK)
A form of digital phase modulation that assigns one of two discrete phases, differing by 180 degrees, to the carrier. Each BPSK symbol conveys one bit of information.

channel encoding
The process used to add redundancy to each of the logical channels to improve the reliability of the transmitted information.

characterization parameters
The unique set of defining parameters for each logical channel for a given service mode. The channel encoding, interleaving, spectral mapping, and diversity delay of the logical channel determine its characterization parameters.

code rate
Defines the increase in overhead on a coded channel resulting from channel encoding. It is the ratio of information bits to the total number of bits after coding.

column pair
Bits from adjacent columns in an interleaver partition that represent the I and Q bit pair to map to a QPSK symbol.

convolutional encoding
A form of forward-error-correction channel encoding that inserts coding bits into a continuous stream of information bits to form a predictable structure. Unlike a block encoder, a convolutional encoder has memory; its output is a function of current and previous inputs.

Configuration Administrator
The Configuration Administrator is a system function that configures each of the layers using SCCH information or parameters which do not change often.

differential encoding
Encoding process in which signal states are represented as changes to succeeding values rather than absolute values.

digital signal
Refers to signals that are digitally modulated on subcarriers by OFDM (q.v.). (See *analog signal.*)

diversity delay
Imposition of a fixed time delay in one of two channels carrying the same information to defeat non-stationary channel impairments such as fading and impulsive noise.

Extended Hybrid waveform
The transmitted waveform composed of the analog FM signal plus digitally modulated primary main subcarriers (subcarriers +356 to +546 and -356 to -546) and some or all primary extended subcarriers (subcarriers +280 to +355 and -280 to -355). This waveform will normally be used during an initial transitional phase preceding conversion to the All Digital waveform. (See *All Digital waveform* and *Hybrid waveform.*)

fading
The variation (with time) of the amplitude or relative phase (or both) of one or more frequency components of a received signal.

frequency modulation (FM)
Modulation in which the instantaneous frequency of a sine wave carrier is caused to depart from the channel center frequency by an amount proportional to the instantaneous amplitude of the modulating signal.

frequency partition
A group of 19 OFDM subcarriers containing 18 data subcarriers and one reference subcarrier.

Hybrid waveform
The transmitted waveform composed of the analog FM-modulated signal, plus digitally modulated Primary Main subcarriers (subcarriers +356 to +546 and -356 to -546). This waveform will normally be used during an initial transitional phase preceding conversion to the All Digital waveform. (See *All Digital waveform* and *Extended Hybrid waveform.*)

interleaver block
A logical subdivision of an interleaver partition. Each interleaver block contains 32 rows and C columns (where C = 24, or C = 36).

interleaver depth
The number of rows in an interleaver matrix. The system employs three interleaver depths: L1 block (32 rows); L1 block pair (64 rows); L1 frame (512 rows); L1 frame pair (1024 rows).

interleaver matrix
A two-dimensional array containing the output of an interleaving process.

interleaver partition
A logical subdivision of the overall interleaver matrix. Each interleaver partition contains C columns (C= 24 or 36) and 32·B rows where B is the number of interleaver blocks.

interleaving
A reordering of the message bits to distribute them in time (over different OFDM symbols) and frequency (over different OFDM subcarriers) to mitigate the effects of signal fading and interference.

interleaving process
A series of manipulations performed on one or more coded transfer frames (vectors) to reorder their bits into one or more interleaver matrices whose contents are destined for a particular portion of the transmitted spectrum.

L1 block
A unit of time of duration T_b. Each L1 frame is comprised of 16 L1 blocks.

L1 Block Count
An index that indicates one of 16 equal subdivisions of an L1 frame.

L1 block pair
Two contiguous L1 blocks. A unit of time duration T_p.

L1 block pair rate
The rate, equal to the reciprocal of the L1 block pair duration, $\left(\frac{1}{T_p}\right)$, at which selected transfer frames are conducted through Layer 1.

L1 block rate

The rate, equal to the reciprocal of the L1 block duration, $\left(\frac{1}{T_b}\right)$, at which selected transfer frames are conducted through Layer 1.

L1 frame
A specific time slot of duration T_f identified by an ALFN. The transmitted signal may be considered to consist of a series of L1 frames.

L1 frame pair
Two contiguous L1 frames. A unit of time duration $2 \cdot T_f$

L1 frame rate

The rate, equal to the reciprocal of the L1 frame duration $\left(\frac{1}{T_f}\right)$, at which selected transfer frames are conducted through Layer 1.

latency
The time delay that a logical channel imposes on a transfer frame as it traverses Layer 1. One of the three characterization parameters. (See *robustness* and *transfer.*)

Layer 1 (L1)
The lowest protocol layer in the HD Radio Protocol Stack (also known as the waveform/transmission layer). Primarily concerned with the transmission of data over a communication channel. Includes framing, channel coding, interleaving, modulation, etc. over the FM radio link at the specified service mode.

Layer 2 (L2)
The Channel Mux layer in the HD Radio Protocol Stack. Multiplexes data from the higher layer services into logical channels (partitioned into L1 frames, block pairs, and blocks) for processing in Layer 1.

Layer 2 protocol data units (L2 PDUs)
Units of user content and upper layer protocol control information transferred from Layer 2 to Layer 1.

logical channel
A signal path that conducts transfer frames from Layer 2 through Layer 1 with a specified grade of service.

lower sideband
The group of OFDM subcarriers (subcarriers number -1 through -546) below the carrier frequency.

mother code
The complete code sequence generated by a convolutional encoder. (See *puncturing.*)

mother codeword
A code sequence generated by a convolutional encoder. (See *puncturing.*)

OFDM Signal Generation
The function that generates the modulated baseband signal in the time domain.

OFDM subcarrier
A discrete frequency-domain signal within the allocated channel that encodes digital data through its amplitude and/or phase. The total set of subcarriers, taken in aggregate for a period of T_s, provides the digital data for that time interval. (See *OFDM symbol.*)

OFDM Subcarrier Mapping
The function that assigns the interleaved logical channels (interleaver partitions) to the OFDM subcarriers (frequency partitions).

OFDM symbol
Time domain pulse of duration T_s, representing all the active subcarriers and containing all the data in one row from the interleaver and system control data sequence matrices. The transmitted waveform is the concatenation of successive OFDM symbols.

Orthogonal Frequency Division Multiplexing (OFDM)
A parallel multiplexing scheme that modulates a data stream onto a large number of orthogonal subcarriers that are transmitted simultaneously. (See *OFDM symbol.*)

parity
In binary-coded data, a condition maintained so that in any permissible coded expression, the total number of “1”s or “0”s is always odd, or always even.

Primary Extended (PX) sideband
The portion of the primary sideband that holds the additional frequency partitions (1, 2, or 4) inside the main partitions in the FM Extended Hybrid and All Digital waveforms. It consists, at most, of subcarriers 280 through 355 and -280 through -355.

Primary Main (PM) sidebands
The ten partitions in the primary sideband consisting of subcarriers 356 through 545 and -356 through -545.

Protocol Data Unit (PDU)
A Protocol Data Unit (PDU) is the structured data block in the HD Radio system that is produced by a specific layer (or process within a layer) of the transmitter protocol stack. The PDUs of a given layer may encapsulate PDUs from the next higher layer of the stack and/or include content data and protocol-control information originating in the layer (or process) itself. The PDUs generated by each layer (or process) in the transmitter protocol stack are inputs to a corresponding layer (or process) in the receiver protocol stack.

pulse-shaping function
A time-domain pulse superimposed on the OFDM symbol to improve its spectral characteristics.

puncturing
The process of removing selected bits from the mother codeword to increase FEC code rate.

Quadrature Phase Shift Keying (QPSK)
A form of digital phase modulation that assigns one of four discrete phases, differing by 90 degrees, to the carrier. Each QPSK symbol conveys two bits of information.

reference subcarrier
A dedicated OFDM subcarrier in L1 of the HD Radio system used to convey L1 system control and status information contained in the system control data sequence. The number of reference subcarriers broadcast in a given waveform depends on the service mode. Reference subcarriers are typically used by receivers as an acquisition and synchronization aid.

robustness
The ability of a logical channel to withstand channel impairments such as noise, interference, and fading. There are eleven distinct levels of robustness designed into Layer 1 of the FM air interface. One of the three characterization parameters. (See *latency* and *transfer.*)

scrambling
The process of modulo 2 summing the input data bits with a pseudo-random bit stream to randomize the time domain bit stream.

secondary sidebands
The sidebands to be added in the spectrum vacated by the analog signal. The secondary sidebands are divided into the Secondary Main (SM) sidebands containing ten frequency partitions, Secondary Extended (SX) sidebands containing four frequency partitions and the Secondary Protected (SP) sidebands containing two groups of twelve protected subcarriers. The secondary sidebands consist of subcarriers −279 through +279.

service mode
A specific configuration of operating parameters specifying throughput, performance level, and selected logical channels.

Signal Constellation Mapper
The function in OFDM Subcarrier Mapping that associates I, Q bit pairs with specific QPSK states, or associates single bits from $\underline{\underline{R}}$ with specific BPSK states.

spectral emissions mask
A specification setting the maximum level of out-of-band components of the transmitted signal.

spectral mapping
The association of specific logical channels with specific subcarriers or groups of subcarriers.

submatrix
A matrix extracted from a larger matrix; one or more of its dimensions is less than that of the larger matrix

system control
Data from the Configuration Administrator conveying control such as service mode, power level, analog audio bandwidth, and analog diversity delay.

System Control Channel (SCCH)
A channel which transports control information from the Configuration Administrator to Layer 1 and also conveys status information from Layer 1 to Layer 2, through the system control processing.

system control data sequence
A sequence of bits destined for each reference subcarrier representing the various system control components relayed between the Configuration Administrator and Layer 1.

system control processing
The function that generates the system control data sequence.

system protocol stack
The protocols associated with operation of the layers of the HD Radio system.

system time alignment, T_{st}
Internal time delay to absorb variations in internal processing time to maintain message alignment with L1 blocks Frames.

transfer
A measure of the data throughput through a logical channel. One of the three characterization parameters. (See *latency* and *robustness.*)

transfer frame
An ordered, one-dimensional collection of data bits of specified length grouped for processing through a logical channel for exchange with the physical layer.

transfer frame modulus
The number of transfer frames in an L1 frame.

transfer frame multiplexer
A device that combines two or more transfer frames into a single vector.

transfer frame number
A number, $F^{n}_{m1:m2}$, that specifies the ALFN, n, and BC range, m1:m2, associated with a particular transfer frame, in order to relate the transfer frame to absolute time.

transfer frame rate
The number of transfer frames per second.

transfer frame size
The number of bits in a transfer frame.

transmission subsystem
The functional component used to format and up-convert the baseband HD Radio waveform for transmission through the very-high frequency (VHF) channel.

transmit alignment, T_{T1a}
An adjustment applied to make the time diversity between P1 and P1′ and S1 and S1′ be precisely T_{dd} at the transmit antenna.

upper sideband
The group of OFDM subcarriers (subcarrier numbers 0 through +546) above the carrier frequency.

vector
A one-dimensional array.