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Re:	IEEE 802.16m-08/053r1, "Call for Comments and Contributions on Project 802.16m Amendment Working Document"
Abstract	This contribution proposes a design for the IEEE 802.16m Synchronization Channel (SCH).
Purpose	To review and adopt the proposed text in the next revision of the 802.16m amendment working document.
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SCH Design for the 802.16m System Amendment

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1 Introduction

This contribution describes initial design input for the IEEE 802.16m Synchronization Channel (SCH). Some features of the proposed design are as follows:

- SCH sequences serve as codewords that enable the unique identification of macrocells, femtocells, and relay stations.
- The length of the SCH sequences matches the number of allocated subcarriers. Hence, their correlation and spectral properties are not diminished by padding or truncation.
- The SCH design facilitates the addition of new cell identifiers, this may be required if the 802.16m system increases in size. For example, the SCH design should be scalable in order to support numerous femtocells and relay stations that may be overlaid onto macrocells.
- The SCH sequences are orthogonal.
- The SCH sequences have good correlation properties. The SCH sequences have low correlation side lobes and high correlation peaks.
- The SCH sequences have flat power spectrums. The PAPR of SCH sequences is small (approximately 2.5 dB). This helps minimize clipping due to transmitter nonlinearity allowing maximal possible transmit power and increased system range.
- The P-SCH sequences are suitable for fast AGC adjustment.
- The SCH design supports different bandwidths.
- The SCH design supports multi-carrier implementations.
- The SCH sequences are well-suited for receiver signal estimation tasks such as signal quality estimation, channel estimation, and location estimation for location-based services (LBS).
- The SCH sequences may be generated and detected using low computational complexity implementations. The SCH sequence design minimizes the number of detection hypothesis tests for cell/sector identification.

The first sections of this contribution contain the proposed text for the IEEE 802.16m amendment working document. This is followed by sections with some background on the SCH design decisions.

2 Proposed Amendment Text

15.3.7.2.1 Synchronization Channel (SCH)

The synchronization channel (SCH) is a DL physical channel used as reference signal for time/frequency synchronization, signal quality estimation, channel estimation, and location estimation for location-based services (LBS). The SCH is also used for encoding cell/sector identifiers. The SCH consists of a P-SCH (Primary-SCH) and an S-SCH (Secondary-SCH). P-SCH symbols are used for time and frequency synchronization, P-SCH mode identification, cell cluster identification, and cell sector identification. S-SCH symbols are used for cell identification. Both the P-SCH and S-SCH may be used for signal quality estimation, channel estimation, and location estimation.

15.3.7.2.1.1 Cell Identifiers for the SCH

Cells and sectors are logical network elements that are assigned unique physical layer SCH sequences. A group of multiple cells is defined as a cell cluster. A cluster is repeated throughout a network coverage area. Each cell within a cluster may be populated by a number of macrocell transmitters, a number of femtocell transmitters, and a number of relay station transmitters. Each macrocell, femtocell and relay station transmitter has its own unique identifier called a cell identifier. The set of cell identifiers is defined as

$$\mathcal{I}_{N_{IDs}} = \{Cell\_ID_0, Cell\_ID_1, \ldots, Cell\_ID_{N_{IDs}-1}\} \tag{1}$$

The pth identifier is defined as

$$Cell\_ID_p = f\{i, j, k\} \tag{2}$$

Integers i, j and k are defined as follows:

$$\begin{array}{ll} \text{Cell Cluster Index} & i \in \{0, 1, \ldots, N_{Clusters} - 1\} \\ \text{Cell Index} & j \in \{0, 1, \ldots, N_{Cells} - 1\} \\ \text{Cell Sector Index} & k \in \{0, 1, \ldots, N_{Sectors} - 1\} \end{array} \tag{3}$$

Integers $N_{Clusters}$, N_{Cells} and $N_{Sectors}$ denote the number of cell clusters, the number of cells per cluster, and the number of sectors per cell. These values are currently defined as $N_{Clusters} = 4$, $N_{Cells} = 48$, and $N_{Sectors} = 3$. The values may be changed as the system expands. The number of cell identifiers currently supported is

$$N_{IDs} = N_{Clusters} \cdot N_{Cells} \cdot N_{Sectors} = 576 \tag{4}$$

The one-to-one function $f\{i, j, k\}$ defines a look-up table operation that maps indices i, j and k to a $Cell\_ID_p$ in $\mathcal{I}_{N_{IDs}}$. Table 1 defines the look-up table mapping for each $Cell\_ID_p$ in $\mathcal{I}_{N_{IDs}}$.

Indices i, j and k are encoded in transmitted P-SCH and S-SCH sequences. Transmitted P-SCH and S-SCH sequences are obtained from a P-SCH sequence codebook $\mathcal{P}$ and an S-SCH sequence codebook $\mathcal{S}$. P-SCH sequences within $\mathcal{P}$ are orthogonal. Each sequence within $\mathcal{P}$ encodes a cell cluster index i and a cell sector index k. Frequency-domain detection of a sequence within $\mathcal{P}$ produces both a cluster index i and a sector index for a cell identifier $Cell\_ID_p = f\{i, j, k\}$. S-SCH sequences within $\mathcal{S}$ are orthogonal. Each sequence within $\mathcal{S}$ encodes a cell index j. Frequency-domain detection of an S-SCH sequence produces a cell index j for a cell identifier $Cell\_ID_p = f\{i, j, k\}$.

15.3.7.2.1.2 Primary Synchronization Channel (P-SCH)

The P-SCH transmits a sequence from a P-SCH sequence codebook $\mathcal{P}$. Each P-SCH sequence within $\mathcal{P}$ encodes a cell cluster index i, a cell sector index j and a P-SCH mode. Some characteristics of the P-SCH are as follows:

- Fixed bandwidth of 5 MHz
- Frequency reuse of 1
- P-SCH codebook $\mathcal{P}$ common to all cell clusters
- Carries partial cell ID information (cell cluster and sector indices)

Cell Identifiers					
Cell Cluster Index $i = 0$			**Cell Cluster Index $i = 1$**		
Cell ID	**Cell Index j**	**Sector Index k**	**Cell ID**	**Cell Index j**	**Sector Index k**
$Cell\_ID_0$	0	0	$Cell\_ID_{288}$	0	0
$Cell\_ID_1$	0	1	$Cell\_ID_{289}$	0	1
$Cell\_ID_2$	0	2	$Cell\_ID_{290}$	0	2
$Cell\_ID_3$	1	0	$Cell\_ID_{291}$	1	0
$Cell\_ID_4$	1	1	$Cell\_ID_{292}$	1	1
$Cell\_ID_5$	1	2	$Cell\_ID_{293}$	1	2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$Cell\_ID_{141}$	47	0	$Cell\_ID_{429}$	47	0
$Cell\_ID_{142}$	47	1	$Cell\_ID_{430}$	47	1
$Cell\_ID_{143}$	47	2	$Cell\_ID_{431}$	47	2
Cell Cluster Index $i = 2$			**Cell Cluster Index $i = 3$**		
Cell ID	**Cell Index j**	**Sector Index k**	**Cell ID**	**Cell Index j**	**Sector Index k**
$Cell\_ID_{144}$	0	0	$Cell\_ID_{432}$	0	0
$Cell\_ID_{145}$	0	1	$Cell\_ID_{433}$	0	1
$Cell\_ID_{146}$	0	2	$Cell\_ID_{434}$	0	2
$Cell\_ID_{147}$	1	0	$Cell\_ID_{435}$	1	0
$Cell\_ID_{148}$	1	1	$Cell\_ID_{436}$	1	1
$Cell\_ID_{149}$	1	2	$Cell\_ID_{437}$	1	2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$Cell\_ID_{285}$	47	0	$Cell\_ID_{574}$	47	0
$Cell\_ID_{286}$	47	1	$Cell\_ID_{575}$	47	1
$Cell\_ID_{287}$	47	2	$Cell\_ID_{576}$	47	2

Table 1: Table of cell identifiers.

- Supports system signaling using P-SCH modes
- Supports signal quality estimation, channel estimation, and location estimation for location-based services (LBS).

15.3.7.2.1.2.1 P-SCH Modes

The P-SCH can be configured to operate in a number of P-SCH modes. P-SCH modes signal cell type, relay station, system bandwidths and RF carrier usage for multi-carrier support. P-SCH modes also facilitate the frequency-domain detection of subsequently transmitted S-SCH sequences, they specify the subcarriers used in S-SCH symbols. Table 2 defines the current list of modes supported. If a vendor's system does not support all P-SCH modes a subset of the modes can be used.

15.3.7.2.1.2.2 P-SCH Codebook and Sequences

The P-SCH sequence codebook is defined as the orthogonal sequence set

$$\mathcal{P} = \{\mathbf{p}_0, \mathbf{p}_1, \ldots, \mathbf{p}_{107}\} \tag{5}$$

P-SCH Modes			
P-SCH Mode	**Cell Type or Relay Station**	**System Bandwidth**	**Number of Subcarriers N_{FFT}**
0	Macrocell (full RF carrier usage)	5 MHz	512
1	Macrocell (full RF carrier usage)	7, 8.75, and 10 MHz	1024
2	Macrocell (full RF carrier usage)	20 MHz	2048
3	Macrocell (partial RF carrier usage)	5 MHz	512
4	Macrocell (partial RF carrier usage)	7, 8.75, and 10 MHz	1024
5	Macrocell (partial RF carrier usage)	20 MHz	2048
6	Femtocell/Relay Station	5 MHz	512
7	Femtocell/Relay Station	7, 8.75, and 10 MHz	1024
8	Femtocell/Relay Station	20 MHz	2048

Table 2: P-SCH modes are encoded using P-SCH sequences. Each mode is associated with a cell or relay station and its used bandwidth. The number of modes can be increased by simply addding another P-SCH sequence to encode the mode.

The ith P-SCH sequence in $\mathcal{P}$ is defined as

$$\mathbf{p}_i = \{p_i[k]\}_{k=0}^{L_P-1} = \{g_P[(k-i) \bmod L_P]\}_{k=0}^{L_P-1}, \ i = 0, 1, \ldots, L_P - 1 \tag{6}$$

where

$$g_P[k] = e^{j\frac{\pi}{L_P}k(k-L_P)} \tag{7}$$

is P-SCH codebook generator sequence. If a vendor's system does not support all P-SCH modes a subset of the sequences can be used. The chosen sequences correspond with the modes supported.

Sequences within $\mathcal{P}$ are of fixed length $L_P = 216$. Each sequence within the codebook $\mathcal{P}$ encodes a unique P-SCH mode, cell cluster index i and a unique cell sector index k. Frequency-domain detection of a sequence $\mathbf{p}_i$ produces a P-SCH mode and a cell cluster index i and a cell sector index k for a cell identifier $Cell\_ID_p = f\{i, j, k\}$. Table 3 shows the map for encoding P-SCH modes, cell cluster indices i, and cell sector indices k.

15.3.7.2.1.2.3 P-SCH Sequence to Subcarrier Mapping

Samples of the P-SCH sequence $\mathbf{p}_i$ are mapped to the subcarriers of a downlink OFDMA symbol in the manner shown in Table 4. Every other subcarrier is used, even-valued subcarriers including the DC subcarrier are not used. As a result, the time-domain version of the sequence $\mathbf{p}_i$ is repeated once. The left and right guard band lengths are $L_{RG} = L_{LG} = 40$.

The mapping of $\mathbf{p}_i$ to a frequency domain P-SCH symbol $\mathbf{p}_{Symbol}$ is defined as

$$\mathbf{p}_{Symbol} = \begin{bmatrix}\mathbf{g}_L & \texttt{kron}(\mathbf{p}_i, [1\ 0]) & \mathbf{g}_R\end{bmatrix} \tag{8}$$

$\texttt{kron}(\mathbf{p}_i, [1\ 0])$ denotes the Kronecker product of $\mathbf{p}_i$ in row-vector form and the two element row vector $[1\ 0]$. Zero-valued row vectors $\mathbf{g}_L$ and $\mathbf{g}_R$ denote length-L_{LG} and length-L_{RG} guard bands. $\mathbf{p}_{Symbol}$ is constructed from the row vector concatenation of $\mathbf{g}_L$, $\texttt{kron}(\mathbf{p}_i, [1\ 0])$, and $\mathbf{g}_R$.

15.3.7.2.1.3 Secondary Synchronization Channel (S-SCH)

The S-SCH transmits a sequence from a S-SCH sequence codebook $\mathcal{S}$. Each S-SCH sequence within $\mathcal{S}$ encodes a cell index j. Some characteristics of the S-SCH are as follows:

P-SCH Sequences for Clusters 0 to 3					
Cell Cluster Index $i = 0$			**Cell Cluster Index $i = 2$**		
Cell Sector k	**P-SCH Mode**	**P-SCH Sequence**	**Cell Sector k**	**P-SCH Mode**	**P-SCH Sequence**
0	0	$\mathbf{p}_0$	0	0	$\mathbf{p}_{54}$
1	0	$\mathbf{p}_1$	1	0	$\mathbf{p}_{55}$
2	0	$\mathbf{p}_2$	2	0	$\mathbf{p}_{56}$
0	1	$\mathbf{p}_3$	0	1	$\mathbf{p}_{57}$
1	1	$\mathbf{p}_4$	1	1	$\mathbf{p}_{58}$
2	1	$\mathbf{p}_5$	2	1	$\mathbf{p}_{59}$
⋮	⋮	⋮	⋮	⋮	⋮
0	8	$\mathbf{p}_{24}$	0	8	$\mathbf{p}_{78}$
1	8	$\mathbf{p}_{25}$	1	8	$\mathbf{p}_{79}$
2	8	$\mathbf{p}_{26}$	2	8	$\mathbf{p}_{80}$
Cell Cluster Index $i = 1$			**Cell Cluster Index $i = 3$**		
Cell Sector k	**P-SCH Mode**	**P-SCH Sequence**	**Cell Sector k**	**P-SCH Mode**	**P-SCH Sequence**
0	0	$\mathbf{p}_{27}$	0	0	$\mathbf{p}_{81}$
1	0	$\mathbf{p}_{28}$	1	0	$\mathbf{p}_{82}$
2	0	$\mathbf{p}_{29}$	2	0	$\mathbf{p}_{83}$
0	1	$\mathbf{p}_{30}$	0	1	$\mathbf{p}_{84}$
1	1	$\mathbf{p}_{31}$	1	1	$\mathbf{p}_{85}$
2	1	$\mathbf{p}_{32}$	2	1	$\mathbf{p}_{86}$
⋮	⋮	⋮	⋮	⋮	⋮
0	8	$\mathbf{p}_{51}$	0	8	$\mathbf{p}_{105}$
1	8	$\mathbf{p}_{52}$	1	8	$\mathbf{p}_{106}$
2	8	$\mathbf{p}_{53}$	2	8	$\mathbf{p}_{107}$

Table 3: Orthogonal P-SCH sequences encode the cell type or relay station type, the system bandwidth used by the cell or relay station, and the cell sector in which the cell or relay station is located..

- Variable bandwidths of 5, 7, 8.75, 10 and 20 MHz
- Frequency reuse of 3
- S-SCH codebook $\mathcal{S}$ common to all cell clusters
- Carries partial cell ID information (cell indices)
- Supports signal quality estimation, channel estimation, and location estimation for location-based services (LBS).

15.3.7.2.1.3.1 S-SCH Codebook and Sequences

The S-SCH sequence codebook is defined as the set of orthogonal sequences

	Subcarrier Number	P-SCH Sample
Left Guard Band	-255	0
	⋮	⋮
	-216	0
P-SCH Sequence Samples	-215	$p_i[0]$
	-214	0
	-213	$p_i[1]$
	⋮	⋮
	-3	$p_i[106]$
	-2	0
	-1	$p_i[107]$
	0	0
	+1	$p_i[108]$
	+2	0
	+3	$p[109]$
	⋮	⋮
	+213	$p_i[214]$
	+214	0
	+215	$p_i[215]$
Right Guard Band	+216	0
	⋮	⋮
	+256	0

Table 4: Table defining P-SCH sequence to subcarrier mapping..

$$\mathcal{S} = \left\{ \left(\mathbf{s}_0^{S0}, \mathbf{s}_0^{S1}, \mathbf{s}_0^{S2}\right), \left(\mathbf{s}_1^{S0}, \mathbf{s}_1^{S1}, \mathbf{s}_1^{S2}\right) \ldots, \left(\mathbf{s}_{N_{Cells}-1}^{S0}, \mathbf{s}_{N_{Cells}-1}^{S1}, \mathbf{s}_{N_{Cells}-1}^{S2}\right) \right\} \tag{9}$$

The S-SCH codebook generator sequence is defined as

$$g_S[k] = e^{j\frac{\pi}{L_S}k(k-L_S)} \tag{10}$$

Sequences for Sector 0 are defined as

$$\mathbf{s}_0^{S0} = \left\{g_S\left[k \bmod L_S\right]\right\}_{k=0}^{L_S-1} \tag{11}$$

$$\mathbf{s}_1^{S0} = \left\{g_S\left[(k-1) \bmod L_S\right]\right\}_{k=0}^{L_S-1} \tag{12}$$

$$\vdots \tag{13}$$

$$\mathbf{s}_{N_{Cells}-1}^{S0} = \left\{g_S\left[\left(k - \left[\frac{L_S}{3} - 1\right]\right) \bmod L_S\right]\right\}_{k=0}^{L_S-1} \tag{14}$$

Sequences for Sector 1 are defined as

$$\mathbf{s}_0^{S1} = \left\{ g\left[\left(k - \frac{L_S}{3} \right) \bmod L_S \right] \right\}_{k=0}^{L_S-1} \tag{15}$$

$$\mathbf{s}_1^{S1} = \left\{ g_S\left[\left(k - \left[\frac{L_S}{3} + 1 \right] \right) \bmod L_S \right] \right\}_{k=0}^{L_S-1} \tag{16}$$

$$\vdots \tag{17}$$

$$\mathbf{s}_{N_{Cells}-1}^{S1} = \left\{ g_S\left[\left(k - \left[\frac{2L_S}{3} - 1 \right] \right) \bmod L_S \right] \right\}_{k=0}^{L_S-1} \tag{18}$$

Sequences for Sector 2 are defined as

$$\mathbf{s}_0^{S2} = \left\{ g_S\left[\left(k - \frac{2L_S}{3} \right) \bmod L_S \right] \right\}_{k=0}^{L_S-1} \tag{19}$$

$$\mathbf{s}_1^{S2} = \left\{ g_S\left[\left(k - \left[\frac{2L_S}{3} + 1 \right] \right) \bmod L_S \right] \right\}_{k=0}^{L_S-1} \tag{20}$$

$$\vdots \tag{21}$$

$$\mathbf{s}_{N_{Cells}-1}^{S2} = \{ g_S \left[(k - [L_S - 1]) \bmod L_S \right] \}_{k=0}^{L_S-1} \tag{22}$$

Sequences within $\mathcal{S}$ are of equal lengths. The lengths are defined as $L_S = 144$, 288 and 576 for $N_{FFT} =$ 512, 1024 and 2048. Each S-SCH sequence within $\mathcal{S}$ encodes a unique cell index j. Frequency-domain detection of a sequence in $\mathcal{S}$ produces a cell index j for a cell identifier $Cell\_ID_p = f\{i, j, k\}$. Table 5 shows the map for encoding cell indices j using sequences in $\mathcal{S}$.

S-SCH Sequences for Clusters 0 to 3		
Cell Index j	**Cell Sector** k	**S-SCH Sequence**
0	0	$\mathbf{s}_0^{S0}$
0	1	$\mathbf{s}_0^{S1}$
0	2	$\mathbf{s}_0^{S2}$
1	0	$\mathbf{s}_1^{S0}$
1	1	$\mathbf{s}_1^{S1}$
1	2	$\mathbf{s}_1^{S2}$
$\vdots$	$\vdots$	$\vdots$
47	0	$\mathbf{s}_{47}^{S0}$
47	1	$\mathbf{s}_{47}^{S1}$
47	2	$\mathbf{s}_{47}^{S2}$

Table 5: Orthogonal S-SCH sequences encode the cell sector index.

15.3.7.2.1.3.2 S-SCH Sequence to Subcarrier Mapping

Samples of the S-SCH sector sequences $\mathbf{s}_i^{S0}, \mathbf{s}_i^{S1}$, and $\mathbf{s}_i^{S2}$ are mapped to the subcarriers of a downlink OFDMA symbol according to the manner shown in Table 6. The sector sequences are interlaced within an OFDMA symbol. The left and right guard band lengths are $L_{LG} = 39$, $L_{RG} = 40$ for $N_{FFT} = 512$, $L_{LG} = 79$, $L_{RG} = 80$ for $N_{FFT} = 1024$, and $L_{LG} = 159$, $L_{RG} = 160$ for $N_{FFT} = 2048$.

	Number of Subcarriers $N_{FFT} = 512$		Number of Subcarriers $N_{FFT} = 1024$		Number of Subcarriers $N_{FFT} = 2048$	
	Subcarrier Number	**S-SCH Sample**	**Subcarrier Number**	**S-SCH Sample**	**Subcarrier Number**	**S-SCH Sample**
Left	-255	0	-511	0	-1023	0
Guard	⋮	⋮	⋮	⋮	⋮	⋮
Band	-217	0	-433	0	-865	0
S-SCH Sequence Samples	-216	$s_i^{S0}[0]$	-432	$s_i^{S0}[0]$	-864	$s_i^{S0}[0]$
	-215	$s_i^{S1}[0]$	-431	$s_i^{S1}[0]$	-863	$s_i^{S1}[0]$
	-214	$s_i^{S2}[0]$	-430	$s_i^{S2}[0]$	-862	$s_i^{S2}[0]$
	⋮	⋮	⋮	⋮	⋮	⋮
	-3	$s_i^{S0}[71]$	-3	$s_i^{S0}[143]$	-3	$s_i^{S0}[287]$
	-2	$s_i^{S1}[71]$	-2	$s_i^{S1}[143]$	-2	$s_i^{S1}[287]$
	-1	$s_i^{S2}[71]$	-1	$s_i^{S2}[143]$	-1	$s_i^{S2}[287]$
	0	0	0	0	0	0
	+1	$s_i^{S0}[72]$	+1	$s_i^{S0}[144]$	+1	$s_i^{S0}[288]$
	+2	$s_i^{S1}[72]$	+2	$s_i^{S1}[144]$	+2	$s_i^{S1}[288]$
	+3	$s_i^{S2}[72]$	+3	$s_i^{S2}[144]$	+3	$s_i^{S2}[288]$
	⋮	⋮	⋮	⋮	⋮	⋮
	+214	$s_i^{S0}[143]$	+430	$s_i^{S0}[287]$	+862	$s_i^{S0}[575]$
	+215	$s_i^{S1}[143]$	+431	$s_i^{S1}[287]$	+863	$s_i^{S1}[575]$
	+216	$s_i^{S2}[143]$	+432	$s_i^{S2}[287]$	+864	$s_i^{S2}[575]$
Right	+217	0	+433	0	+865	0
Guard	⋮	⋮	⋮	⋮	⋮	⋮
Band	+256	0	+512	0	+1024	0

Table 6: Table defining S-SCH sequence to subcarrier mapping..

The mapping of sector sequences $\mathbf{s}_i^{S0}, \mathbf{s}_i^{S1}$, and $\mathbf{s}_i^{S2}$ to a frequency domain S-SCH symbol $\mathbf{s}_{Symbol}$ is defined as

$$\mathbf{s}_0 = \texttt{kron}(\mathbf{s}_i^{S0}, [1\ 0\ 0]) \tag{23}$$

$$\mathbf{s}_1 = \texttt{kron}(\mathbf{s}_i^{S1}, [0\ 1\ 0]) \tag{24}$$

$$\mathbf{s}_2 = \texttt{kron}(\mathbf{s}_i^{S2}, [0\ 0\ 1]) \tag{25}$$

$$\mathbf{s} = \mathbf{s}_1 + \mathbf{s}_2 + \mathbf{s}_3 \tag{26}$$

$$\mathbf{s}_{Symbol} = \begin{bmatrix} \mathbf{g}_L & \mathbf{s} & \mathbf{g}_R \end{bmatrix} \tag{27}$$

For $\mathbf{s}_0$ $\texttt{kron}(\mathbf{s}_i^{S0}, [1\ 0\ 0])$ denotes the Kronecker product of $\mathbf{s}_i^{S0}$ in row-vector form and the two element row vector [1 0 0]. Similarly for $\mathbf{s}_1$ and $\mathbf{s}_2$. Zero-valued row vectors $\mathbf{g}_L$ and $\mathbf{g}_R$ denote length-L_{LG} and length-L_{RG} guard bands. $\mathbf{s}_{Symbol}$ is constructed from the row vector concatenation of $\mathbf{g}_L$, $\mathbf{s}$, and $\mathbf{g}_R$.

3 Some Properties of the SCH Sequence Codebooks

Let $\mathbb{Z}$ denote the set of integers (positive, negative or zero) and $\mathbb{Z}_{L_S} = \{0, 1, ..., L_S - 1\}$ be the additive group of integers $\mathbb{Z}$ modulo L_S. A Constant Amplitude Zero Autocorrelation (CAZAC) is a L_S-periodic sequence $\{s[k]\}_{k=0}^{L_S-1}$ sequence with the following properties:

- **Constant Amplitude (CA)**: For all $k \in \mathbb{Z}_{L_S}$ the sequence's magnitude is $|s[k]| = 1$.
- **Zero Autocorrelation (ZAC)**: For all time delays $m \geq 0$ the magnitude of the sequence's periodic autocorrelation is

$$\left|\tilde{R}_{ss}[m]\right| = \left|\tilde{R}_{ss}[-m]\right| = \frac{1}{L_S}\sum_{k=0}^{L_S-1} s[k]s^*[(k+m) \bmod L_S] = \begin{cases} 1 & \text{if } m \bmod L_S = 0 \\ 0 & \text{otherwise} \end{cases} \quad (28)$$

CAZAC sequences are important SCH symbol candidates because of their defining properties: CA ensures optimal transmission efficiency. CA allows the transmission of peak power throughout the duration of an SCH symbol. This allows more power to be transmitted thereby increasing received SINR. ZAC provides tight time localization. Sharp cross-correlation peaks obviate distortion and interference in the received waveform.

If $\{s[k]\}_{k=0}^{L_S-1}$ is a CAZAC sequence then $\{s[k]\}_{k=0}^{L_S-1}$ has the following properties:

Property 1: The complex-conjugated sequence $\{s^*[k]\}_{k=0}^{L_S-1}$ is also a CAZAC sequence.

Property 2: For any integer m the time-shifted sequence $\{s[k+m]\}_{k=0}^{L_S-1}$ is also a CAZAC sequence.

Property 3: For any complex number κ the sequence $\{\kappa s[k]\}_{k=0}^{L_S-1}$ is also a CAZAC sequence.

Property 4: The discrete Fourier transform of $\{s[k]\}_{k=0}^{L_S-1}$ is also a CAZAC sequence.

Property 5: A CAZAC sequence is a full bandwidth sequence with unity power spectrum.

Property 6: For any nth root of unity W_n and any integer m the cyclically shifted sequence $\{s[k]W_n^m\}_{k=0}^{L_S-1}$ is also a CAZAC sequence.

There are different types of CAZAC sequences of any given length L_S. The different types may be useful for different applications. The different types result in different behavior with respect to Doppler and additive noise and interference. The different types of CAZAC sequences can be categorized into two distinct categories: quadratic-phase CAZAC sequences and quadratic-residue CAZAC sequences. Quadratic-phase CAZAC sequences are linearly swept frequency sequences. Quadratic residue CAZACs are small alphabet CAZACs since elements can be of at most three distinct values.

A quadratic-phase CAZAC sequence has elements in the form $s[k] = e^{j\frac{2\pi a}{L_S}P(k)}$ where $P(k)$ is a quadratic polynomial. A length L_S quadratic-phase CAZAC sequence $\{s[k]\}_{k=0}^{L_S-1}$ for $k \in \mathbb{Z}_{L_S}$ can be parametrized by writing its elements as

$$s[k] = e^{j\frac{2\pi a}{L_S}P(k)} = \begin{cases} e^{j\frac{2\pi a}{L_S}\left(\frac{k^2}{2}+bk\right)} & \text{if } L_S \text{ is even} \\ e^{j\frac{2\pi a}{L_S}\left(\frac{k^2}{2}+[2b+1]\frac{k}{2}\right)} & \text{if } L_S \text{ is odd} \end{cases} \quad (29)$$

Parameters a and b are integers in $\mathbb{Z}$; a and L_S are relatively prime meaning they have no common factor other than 1. Hence, sequence codebooks can be constructed by changing the values of parameters a and b. For example, setting $b = -1$, $L_S = 64$ and setting a equal to the seventeen values 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59 and 61 gives a sequence codebook of size seventeen. We set $a = 1$ and $b = -i$ where $i \geq 0$ is an integer. We then write $s[k]$ in the parametrized form

$$s_i[k] = \begin{cases} e^{j\frac{\pi}{L_S}k(k-2i)} & \text{if } L_S \text{ is even} \\ e^{j\frac{\pi}{L_S}k(k-2i+1)} & \text{if } L_S \text{ is odd} \end{cases} \tag{30}$$

We define a cyclically shifted CAZAC sequence codebook as the set

$$\mathcal{S} = \{\mathbf{s}_0, \mathbf{s}_1, \ldots, \mathbf{s}_{L_S-1}\} \tag{31}$$

where the ith sequence set is defined as a row of the unitary L_S-by-L_S matrix

$$\mathbf{S} = \begin{bmatrix} \mathbf{s}_0 \\ \mathbf{s}_1 \\ \mathbf{s}_2 \\ \vdots \\ \mathbf{s}_{L_S-2} \\ \mathbf{s}_{L_S-1} \end{bmatrix} = \begin{bmatrix} s_i[0] & s_i[1] & \ldots & s_i[L_S-2] & s_i[L_S-1] \\ s_i[L_S-1] & s_i[0] & \ldots & s_i[L_S-3] & s_i[L_S-2] \\ s_i[L_S-2] & s_i[L_S-1] & \ldots & s_i[L_S-4] & s_i[L_S-3] \\ \vdots & \vdots & & \vdots & \vdots \\ s_i[2] & s_i[3] & \ldots & s_i[0] & s_i[1] \\ s_i[1] & s_i[2] & \ldots & s_i[L_S-1] & s_i[0] \end{bmatrix} \tag{32}$$

and

$$s_i[k] = \begin{cases} e^{j\frac{\pi}{L_S}k(k-2i)} & \text{if } L_S \text{ is even} \\ e^{j\frac{\pi}{L_S}k(k-2i+1)} & \text{if } L_S \text{ is odd} \end{cases} \tag{33}$$

Matrix $\mathbf{S}$ is a right circulant matrix constructed from the generator or mother sequence $\mathbf{s}_0 = \{s_i[k]\}_{k=0}^{L_S-1}$. The r_{shift}th row of $\mathbf{S}$ is defined as

$$\mathbf{s}_{r_{\text{shift}}} = \{s_i[(k + r_{\text{shift}}) \bmod L_S]\}_{k=0}^{L_S-1}\ ,\ r_{\text{shift}} = L_S - 1, L_S - 2, \ldots, 0 \tag{34}$$

A right circulant matrix is special type of Toeplitz matrix, each row is a cyclic right shift of the row above. A right circular matrix is determined by its first row, hence we can write

$$\mathbf{S} = \text{circ}\,(\mathbf{s}_0) = \text{circ}\,(s_i[0], s_i[1], \ldots, s_i[L_S-1]) \tag{35}$$

where circ($\mathbf{s}_0$) denotes the right circulant matrix constructed from $\mathbf{s}_0$. Sequences within $\mathbf{S}$ are orthonormal so

$$\frac{1}{L_S}\mathbf{s}_i^H\mathbf{s}_j = \frac{1}{L_S}\left|\sum_{k=0}^{L_P-1} s_i^*[k]s_j[k]\right| = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases} \tag{36}$$

4 A Note on SCH Detector Complexity

To support a large number of identifiers the detection process requires a large number of cross correlations. However, for cyclically shifted sequences the detection process is simplified since only the generator sequence needs to be periodically cross correlated with a received sequence. When the generator sequence and a received sequence are cross correlated the magnitude of the periodic cross correlation will have a peak equal to the cyclic shift of the received sequence. The detected cyclic shift encodes the identifier.

Assume that the length of the SCH is a power of two. At the receiver the sequence can zero padded to a power of two if its length does not equal a power of two. The periodic cross correlation can then be computed more efficiently in the frequency domain using two FFT operations and one IFFT operation. In the time domain the number of complex multiplications required for the periodic cross correlation of L_S complex-valued length-L_S sequences is $2L_S^2$. The main benefit of using FFT operations is to reduce the number of complex multiplications from approximately $2L_S^2$ to approximately $2L_S(1 + \log_2(L_S))$. For a practical example, let L_S be 256; then the number of complex multiplications will be 4608 by applying the FFT. In contrast, the number of complex multiplications will be $2L_S^2 = 131,072$ using a time domain correlation.

Specifically, the periodic correlation lags $\tilde{R}_{\mathbf{s}_0\mathbf{s}_{r_{\text{shift}}}}[m]$, $m = 0, 1, \ldots, L_S - 1$, can be computed efficiently as

$$\left[\left|\tilde{R}_{\mathbf{s}_0\mathbf{s}_{r_{\text{shift}}}}[0]\right| \quad \left|\tilde{R}_{\mathbf{s}_0\mathbf{s}_{r_{\text{shift}}}}[1]\right| \quad \ldots \quad \left|\tilde{R}_{\mathbf{s}_0\mathbf{s}_{r_{\text{shift}}}}[L_S - 1]\right|\right] = |\ \texttt{ifft(conj(fft(}\mathbf{s}_0\texttt{))} \circ \texttt{fft(}\ \mathbf{s}_{r_{\text{shift}}}\ \texttt{)}\ | \qquad (37)$$

where:

- fft($\mathbf{s}_0$) denotes the FFT applied to $\mathbf{s}_0$
- conj(fft($\mathbf{s}_0$)) denotes the complex conjugate of fft($\mathbf{s}_0$)
- fft($\mathbf{s}_{r_{\text{shift}}}$) denotes the FFT applied to a received version of $\mathbf{s}_{r_{\text{shift}}}$. The shift is detected by the periodic cross correlation.
- The operator $\circ$ denotes the Hadamard product ((element-by-element product) of the two vectors conj(fft($\mathbf{s}_0$)) and fft($\mathbf{s}_{r_{\text{shift}}}$)
- $|$ifft$(\cdot)|$ denotes the magnitude of inverse FFT.

Note that the conj(fft($\mathbf{s}_0$) can be computed once and stored in memory. Hence one fft, one Hadamard product and one ifft operation are required. The total number of complex multiplications is approximately $4L_S(1 + \log_2(L_S)) + 2L_S$. For $L_S = 256$ this number equals 9728 which is still significantly less when compared to the time domain approach which requires $2L_S^2 = 131,072$ complex multiplications.

5 Determination of the Cluster Size

Cells and sectors are logical network elements that can be assigned physical layer resources such as SCH sequences and frequencies. Similar to frequency reuse a sequence reuse scheme can also be implemented. Sequence reuse can decrease the number of required sequences and therefore decrease P-SCH synchronization time and S-SCH identifier detection time.

For sequence reuse a cell cluster is a number of cells grouped together with each cell allocated a certain number of SCH sequences. The cluster is then repeated throughout a required network coverage area. Due to the geometry of the cell (modeled as hexagon), the number of cells per cluster can only have certain values. These values are determined by the equation

$$N_{Cells} = i^2 + ij + j^2 \qquad (38)$$

where i and j denote integers. Each cluster is repeated by a linear shift i steps along one direction and j steps in the other direction. To find the nearest co-sequence cells using the shift parameters i and j the following steps may be followed:

1. Move i cells along any chain of hexagons.
2. Turn 60 degrees clock wise or counter clock wise and move j cells.

The distance between the center of two co-sequence cells is the sequence reuse distance; it may be computed as $D_{ij} = R\sqrt{3N_{ij}}$ where R denotes the the cell radius. D_{ij} is also the distance to the first tier of interfering co-sequence cells (see Figure 1). In terms of the cluster size it can be shown an MS's signal-to-interference power ratio can be approximated by

Cluster Size N_{Cells}	Signal-to-Interference Power Ratio $(S/I)_{dB}$
7	18.7
9	20.8
12	23.3
13	24.0
16	25.8
19	27.3
21	28.2
25	29.7
27	30.4
48	35.4
259	50.0

Table 7: Example of received SIR based on cluster size

$$\left(\frac{S}{I}\right)_{dB} \approx 10\log_{10}\left[\frac{(3N_{Cells})^{\gamma/2}}{N_I}\right] + \delta_{dB} \tag{39}$$

where δ_{dB} is a constant associated with antenna directivity and N_I the number of interferers. The antenna directivity term δ_{dB} is typically 3 to 5 decibels depending on antenna beamwidth. The term γ denotes the path loss exponent or slope. As γ increases the path loss slope increases and the interference decreases. Some values for γ are $\gamma = 2$ (free space), $\gamma = 2.5$ (rural areas), $\gamma = 3$ to 3.5 (suburban areas), $\gamma = 3.5$ to 4 (urban environments), and $\gamma = 4$ to 4.5 (dense urban environments). The cluster size is dictated by the first tier of interferers so $N_I = 6$. However, with three 120 degree sectors per cell it can be shown that the interference is only from two cells instead of six so $N_I = 2$. The resulting S/I increase is approximatley 4.77 dB.

Assume that cluster size is sufficient so the contribution of additional interferers for second and above tiers is marginal. Given an desired S/I target value and an exponent γ we can estimate an appropriate cluster size N_{Cells} by solving

$$\frac{S}{I} = \delta_{dB}\frac{(3N_{Cells})^{\gamma/2}}{N_I} \tag{40}$$

which gives

$$N_{Cells} \geq ceil\left(\frac{1}{3}\left(N_I \cdot \frac{S}{\delta_{dB} I}\right)^{2/\gamma}\right) \tag{41}$$

The following table gives some examples for $\gamma = 4$ and $N_I = 6$.