ATSC Candidate Standard: B2X System Discovery and Signaling

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Revision History

Version	Date
Candidate Standard approved	9 July 2026

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1. SCOPE

This Standard uses concepts from [2] and specifies the normative structure of the bootstrap that provides the entry point to a B2X Physical Layer waveform. The syntax and semantics defined herein apply to system discovery and signaling of B2X Virtual Frames. Other ATSC B2X Standards may further constrain or supplement this bootstrap specification.

This Standard does not modify [2] or any other ATSC 3.0 Standard. It is designed to support independent discovery and entry into a B2X Physical Layer waveform and is optimized for B2X services delivered to B2X Endpoints (BXE) in both broadcast and IMT bands.

1.1 Introduction and Background

Future broadcast networks are expected to support multiple wireless services in addition to television. Such services may be multiplexed in time and frequency using OFDMA within a single RF carrier or across multiple RF carriers of a B2X Radio Access Network (BRAN). To enable discovery and entry in the BRAN, a bootstrap signal provides a universal entry point into the waveform, allowing BXEs to identify the signal type and determine how to receive the services associated with it.

Two bootstrap signal types are defined: Virtual Frame Start (VFS) and Slice Start (SS), each serving a distinct role in discovery and access.

The bootstrap is a short signal preceding a longer data-bearing signal. It is defined by a known configuration (sampling rate, bandwidth, subcarrier spacing, and time-domain structure) and conveys information that enables detection, synchronization, and decoding of the subsequent transmission. This ensures that the broadcast spectrum can adapt to carry new signal types while maintaining a common entry point.

The B2X bootstrap is constructed as a complex I/Q sequence formed by a Zadoff-Chu (ZC) sequence combined with a pseudo-noise (PN) sequence. The combined sequence has Constant Amplitude Zero Autocorrelation (CAZAC) properties, near-ideal autocorrelation, and low cross-correlation. Orthogonal cyclic shifts of the ZC root sequence, enhanced by the PN sequence, provide multiple orthogonal bootstrap sequences.

A B2X Virtual Frame begins with a ZC+PN bootstrap sequence. One of 16 cyclic shifts is used to indicate the RF carrier bandwidth. Supported RF bandwidths are 5, 6, 7, 8, 10, 12, 14, 15, 16, 18, 20, 21, 24, 30, 40, and 50 MHz.

Each B2X Virtual Frame may contain one or more Virtual Sub-Frames. A Slice Start (SS) bootstrap symbol indicates the start of each Virtual Sub-Frame within the OFDMA time/frequency grid [3].

This specification defines bootstrap mechanisms that may be used to support discovery of Service Categories (SC); interpretation and system-level use of SC values are outside the scope of this document.

In addition to these RF bandwidths, Scaled Bootstrap formats are defined to support discovery of services delivered via narrower Virtual Bandwidth Parts, as specified in Section 6.

This document specifies the bootstrap signaling used for B2X system discovery and entry into the Physical Layer waveform. The bootstrap provides synchronization, verification, and limited signaling required to locate subsequent VFS L1 Signaling and SS L1 Signaling, as well as service content within the B2X transmission. Additional L1 Signaling transmitted after the bootstrap, including those used for service configuration and resource mapping, are specified in the B2X Physical Layer Protocol [3].

This document specifies the bootstrap signal as observed at the air interface and does not define the internal transmitter architecture or functional placement of bootstrap generation within the B2X RAN.

1.2 Organization

This document is organized as follows:

- Section 1 – Outlines the scope of this document and provides a general introduction.
- Section 2 – Lists references and applicable documents.
- Section 3 – Provides a definition of terms, acronyms, and abbreviations for this document.
- Section 4 – B2X bootstrap overview
- Section 5 – B2X bootstrap symbol types and their specifications
- Section 6 - Normal and Scaled Bootstraps in OFDMA Virtual Bandwidth Parts
- Annex A - Example of scaled VFS bootstrap generation (informative)

2. REFERENCES

All referenced documents are subject to revision. Users of this Standard are cautioned that newer editions might or might not be compatible.

2.1 Normative References

The following documents, in whole or in part, as referenced in this document, contain specific provisions that are to be followed strictly in order to implement a provision of this Standard.

[1] IEEE: “Use of the International System of Units (SI): The Modern Metric System,” Doc. SI 10, Institute of Electrical and Electronics Engineers, New York, N.Y.

[2] ATSC: “ATSC Standard: System Discovery and Signaling,” Doc. A/321:2026-04, ATSC, Washington, DC, 14 April 2026.

[3] ATSC: “ATSC Standard: B2X Physical Layer Protocol,” Doc. A/392-22 Working Draft, ATSC, Washington, D.C. This document is a work in progress within ATSC. It can be made available upon request.

[4] ATSC: “ATSC Standard: B2X Link-Layer Protocol,” Doc. A/392-30 Working Draft, ATSC, Washington, D.C. This document is a work in progress within ATSC. It can be made available upon request.

[5] IEEE: “IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems,” Doc. IEEE Std 1588-2019, Institute of Electrical and Electronics Engineers, New York, NY, 2019.

2.2 Informative References

The following documents contain information that may be helpful in applying this Standard.

[6] R. Frank, S. Zadoff, and R. Heimiller, “Phase shift pulse codes with good periodic correlation properties,” IEEE Transactions on Information Theory, pp. 381–82, Oct. 1962

[7] J. Chu, “Polyphase codes with good periodic correlation properties,” IEEE Transactions on Information Theory, pp. 531–32, July 1972

[8] J. G. Andrews, "A Primer on Zadoff–Chu Sequences," arXiv preprint arXiv:2211.05702, Nov. 2022

3. DEFINITION OF TERMS

With respect to definition of terms, abbreviations, and units, the practice of the Institute of Electrical and Electronics Engineers (IEEE) as outlined in the Institute's published standards [1] shall be used. Where an abbreviation is not covered by IEEE practice or industry practice differs from IEEE practice, the abbreviation in question will be described in Section 3.3 of this document.

3.1 Compliance Notation

This Section defines compliance terms for use by this document:

shall – This word indicates specific provisions that are to be followed strictly (no deviation is permitted).

shall not – This phrase indicates specific provisions that are absolutely prohibited.

should – This word indicates that a certain course of action is preferred but not necessarily required.

should not – This phrase means a certain possibility or course of action is undesirable but not prohibited.

3.2 Treatment of Syntactic Elements

This document contains symbolic references to syntactic elements used in the audio, video, and transport coding subsystems. These references are typographically distinguished by the use of a different font (e.g., restricted), may contain the underscore character (e.g., sequence_end_code) and may consist of character strings that are not English words (e.g., dynrng).

3.2.1 Reserved Elements

One or more reserved bits, symbols, fields, or ranges of values (i.e., elements) may be present in this document. These are used primarily to enable adding new values to a syntactical structure without altering its syntax or causing a problem with backwards compatibility, but they also can be used for other reasons.

The ATSC default value for reserved bits is '1.' There is no default value for other reserved elements. Use of reserved elements except as defined in ATSC Standards or by an industry standards-setting body is not permitted. See individual element semantics for mandatory settings and any additional use constraints. As currently-reserved elements may be assigned values and meanings in future versions of this Standard, receiving devices built to this version are expected to ignore all values appearing in currently-reserved elements to avoid possible future failure to function as intended.

3.3 Acronyms and Abbreviations

B2X	Broadcast to Everything
BRAN	B2X Radio Access Network
BXE	B2X Endpoint
CAZAC	Constant Amplitude Zero Autocorrelation
CR	Continuous Reception
CS	Cyclic Shift
DRX	Discontinuous Reception

FFT Fast Fourier Transform
IEEE Institute of Electrical and Electronic Engineers
IFFT Inverse Fast Fourier Transform
IoT Internet of Things
I/Q In-phase / Quadrature
kHz kilohertz
LFSR Linear Feedback Shift Register
LSB Least Significant Bit
MHz Megahertz
ms millisecond
MSB Most Significant Bit
OFDMA Orthogonal Frequency Division Multiple Access
NBW Narrow Bandwidth
PN Pseudo-Noise
PRB Physical Resource Block
PTP Precise Time Protocol (IEEE 1588)
RAN Radio Access Network
RedCap Reduced Capability
RE Resource Element
RF Radio Frequency
SC Service Category
SCS Sub-carrier Spacing
SS Slice Start
TAI International Atomic Time
uimsbf unsigned integer most significant bit first
µs microsecond
UTC Universal Time Coordinated
VBP Virtual Bandwidth Part
VFS Virtual Frame Start
VRB Virtual Resource Block
ZC Zadoff-Chu
$\lfloor X \rfloor$ The greatest integer less than or equal to X

3.4 Terms

The following terms are used within this document.

bootstrap – A predefined physical-layer signal transmitted at the start of a B2X Virtual Frame or Virtual Sub-Frame that enables detection, synchronization, verification, and bootstrap-level signaling required to locate subsequent signaling and service content.

bootstrap-level signaling – Information conveyed using bootstrap signal parameters (e.g., cyclic shifts of bootstrap sequences) to support discovery, verification, or indication of subsequent L1 Signaling. The specific information conveyed via bootstrap-level signaling depends on the bootstrap type and is specified elsewhere in this Standard.

L1 Signaling – Physical-layer signaling transmitted after bootstrap symbols within a B2X Virtual Frame. L1 Signaling includes VFS L1 Signaling and SS L1 Signaling, which are associated respectively with the VFS and SS regions of the Virtual Frame. L1 Signaling conveys configuration, timing, and resource information necessary for service reception. The detailed encoding, modulation, and mapping of L1 Signaling are specified in the B2X Physical Layer Protocol [3].

Normal Bootstrap – A B2X bootstrap signal employing a Zadoff–Chu sequence of prime length Nzc = 1499, providing a wideband entry point for system discovery, synchronization, and verification across the full RF carrier bandwidth.

Scaled Bootstrap –A B2X bootstrap signal employing a Zadoff–Chu sequence of shorter prime length than the Normal Bootstrap, optimized for discovery and synchronization of services delivered via narrower Virtual Bandwidth Parts (VBPs), including support for reduced-capability B2X Endpoints.

Service Category (SC) – An identifier used to associate a Virtual Sub-Frame with a class of services for discovery purposes. An SC identifies the service class carried within a Virtual Sub-Frame but does not define payload structure, scheduling behavior, or service semantics. The method by which an SC is conveyed (e.g., via bootstrap-level signaling or subsequent L1 Signaling) is specified elsewhere in this Standard.

reserved – Set aside for future use by a Standard.

3.5 Extensibility

This Standard is designed to support independent discovery and entry into a B2X Physical Layer waveform without modification to existing ATSC 3.0 Standards, and to allow future extensions through updated versions of this Standard.

4. B2X BOOTSTRAP SIGNAL STRUCTURE

4.1 B2X Virtual Frame

Figure 4.1 shows the B2X OFDMA Virtual Frame structure used for system discovery and signaling. The Virtual Frame spans 1000 ms and incorporates two bootstrap symbol types: Virtual Frame Start (VFS), and Slice Start (SS). Both bootstrap types consist of Zadoff-Chu (ZC) sequences combined with Pseudo-Noise (PN) sequences [6], [7]. ZC sequences are used due to their CAZAC properties [8].

This specification defines two classes of bootstrap signals for B2X system discovery and entry into the Physical Layer waveform. The first class, referred to in this document as the Normal Bootstrap, employs a Zadoff–Chu sequence of prime length Nzc = 1499 and provides a wideband entry point for discovery, synchronization, and verification across the full RF carrier bandwidth. The Normal Bootstrap does not convey explicit Service Category identifiers via bootstrap-level signaling; service identification and configuration for payload reception is provided by subsequent L1 Signaling.

The second class, referred to as Scaled Bootstraps, employs shorter Zadoff–Chu sequence lengths and is optimized for discovery and synchronization of services delivered via narrower Virtual Bandwidth Parts (VBPs). Scaled Bootstraps support reduced-capability BXEs and may convey Service Category identifiers using bootstrap-level signaling, as specified in Section 6.

As illustrated in Figure 4.1, each Virtual Frame begins with a VFS bootstrap, followed by one or more SS bootstraps. Each SS bootstrap marks the entry point of a Virtual Sub-Frame occupying a defined time-frequency region of the OFDMA grid. In this specification, a Service Category (SC) is used as an identifier associated with a Virtual Sub-Frame to support discovery and service identification. The SC identifies the class of service carried within the Sub-Frame but does not define the structure, scheduling, or semantics of the payload itself.

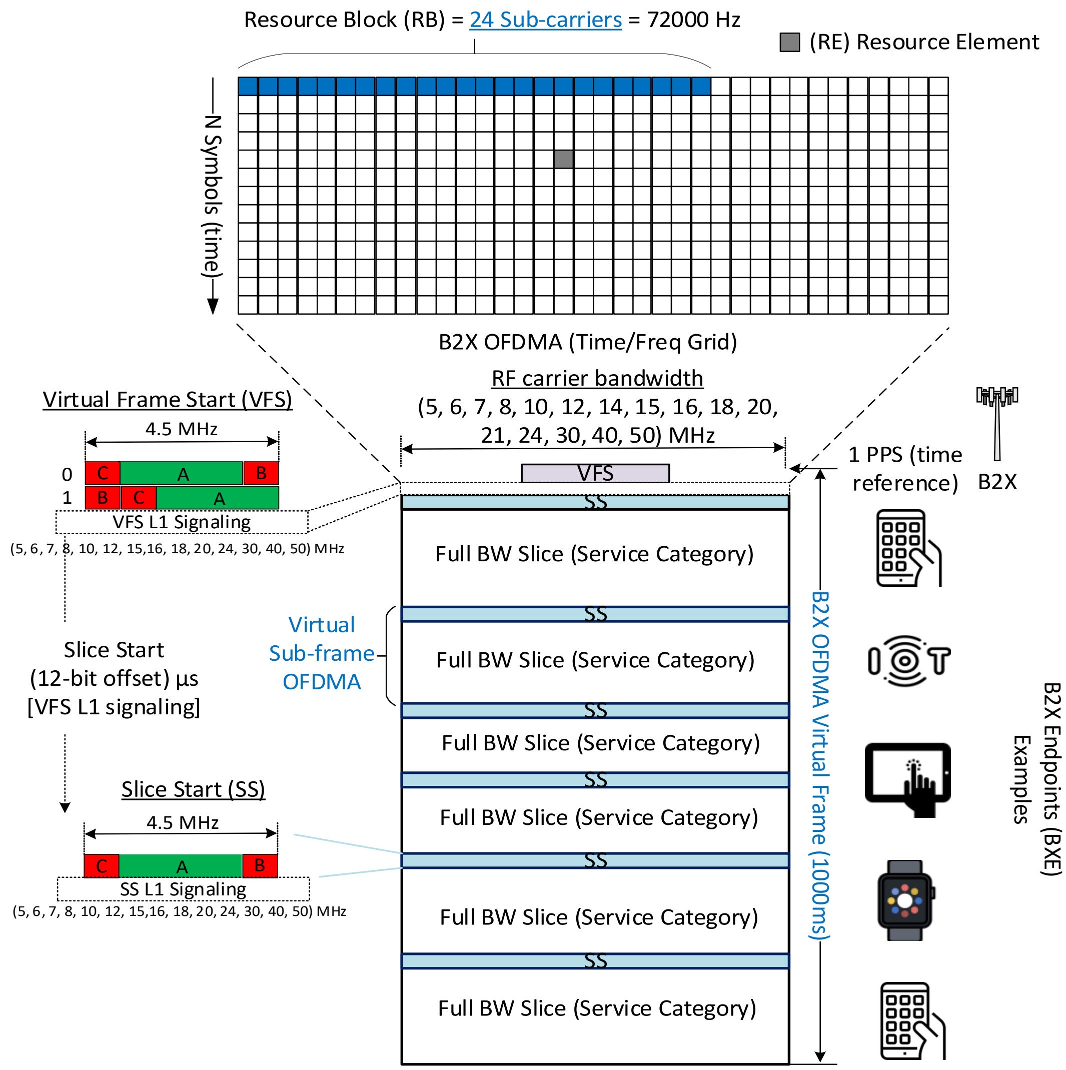

Figure 4.1 B2X Virtual Frame for Discovery and Signaling.

The bandwidth of the VFS and SS symbols shall be 4.5 MHz. The bandwidth of L1 Signaling and user data symbols within a Virtual Sub-Frame associated with a Service Category (SC) shall be one of (5, 6, 7, 8, 10, 12, 14, 15, 16, 18, 20, 21, 24, 30, 40, 50) MHz.

A B2X Endpoint (BXE) is expected to be configured with, or otherwise have prior knowledge of, the RF carrier bandwidth prior to bootstrap processing. The VFS ZC cyclic shift encodes the RF carrier bandwidth and permits verification of correct reception of the intended Virtual Frame configuration, as defined by the lookup table in Section 5.1.

The starting VFS symbol (symbol 0) shall be aligned with the PTP Epoch [5] and a 1 PPS reference derived from a common absolute time source aligned to TAI, as observed at the air interface of the transmit antenna. Each 1000 ms Virtual Frame is associated with a Virtual Frame number through VFS L1 Signaling. This number shall correspond to the lower 32 bits of the 48-bit PTP second count [5]. This PTP count is a continuous count of seconds referenced to the PTP epoch and aligned to TAI (i.e., not subject to leap second adjustments), and is used in B2X signaling, as specified in [3], [4].

This alignment permits time transfer (TAI/UTC) to the BXE after synchronization, facilitated through VFS L1 Signaling. VFS symbols are designed to support synchronization, discovery, frequency offset estimation, and initial channel estimation. Bootstrap-level signaling is conveyed via cyclic-shift mechanisms as specified in this section.

An SS bootstrap symbol shall indicate the entry point of a Virtual Sub-Frame within the OFDMA time-frequency grid. Each Virtual Sub-Frame contains payload data and associated control signaling carried within a Virtual Bandwidth Part (VBP), as defined by the B2X Physical Layer Protocol. Where specified, signaling may associate a Virtual Sub-Frame with a Service Category (SC), as specified in Section 6. Multiple SS bootstrap symbols may be present within a Virtual Frame to support multiple Virtual Sub-Frames and payload regions.

In this specification, "bootstrap-level signaling" refers only to information conveyed by bootstrap symbol parameters (e.g., cyclic-shifts and, where specified, symbol or sequence selection). L1 Signaling transmitted after the bootstrap may include VFS L1 Signaling, which conveys Virtual Frame-level configuration, and SS L1 Signaling, which conveys Virtual Sub-Frame or service-related configuration as defined in the B2X Physical Layer Protocol [3]. The encoding, modulation, and mapping of this signaling are also specified in [3].

4.2 Signal Dimensions

Unless otherwise specified in this Standard (e.g., Section 6), the Normal Bootstrap VFS and SS symbols shall use fixed parameters defined in this section. These parameters align with the A/321 bootstrap numerology.

f_S is the sampling rate of the bootstrap
T_S is the duration of the bootstrap
$BW_{\text{Bootstrap}}$ is the bandwidth of the bootstrap
N_{FFT} is the FFT size of the bootstrap
f_Δ is the subcarrier spacing of the bootstrap
T_{symbol} is the duration of the bootstrap symbol
Ns is the number of bootstrap symbols

The bootstrap shall use a fixed sampling rate of 6.144 M samples/second and a fixed bandwidth of 4.5 MHz:

$$f_S = 6.144 \text{ Ms/sec},\ T_S = 1/f_S,\ BW_{\text{Bootstrap}} = 4.5 \text{ MHz}$$

An FFT size, $N_{FFT} = 2048$ shall be used, yielding:

$$f_\Delta = f_S/N_{FFT} = 3 \text{ kHz}$$

Each bootstrap symbol shall have a duration, $T_{\text{symbol}} = 500\ \mu s$. The number of bootstrap symbols, Ns shall determine the bootstrap duration. The VFS bootstrap shall consist of two symbols (total duration 1 ms). The SS bootstrap shall consist of one symbol (duration 500 µs).

4.3 Frequency Domain Sequence

The VFS bootstrap shall consist of two OFDM symbols generated in the frequency domain by applying a Zadoff–Chu (ZC) sequence multiplied by a pseudo-noise (PN) sequence as shown in Figure 4.2.

The ZC sequence shall be cyclic shifted from higher index to lower index such that:

$$\tilde{z}_q(k) = z_q(k + K)$$

One of sixteen cyclic shifts K shall be applied, each mapped to one of the sixteen possible RF carrier bandwidths (see Table 5.1). The same cyclic shift shall be applied to both VFS symbols.

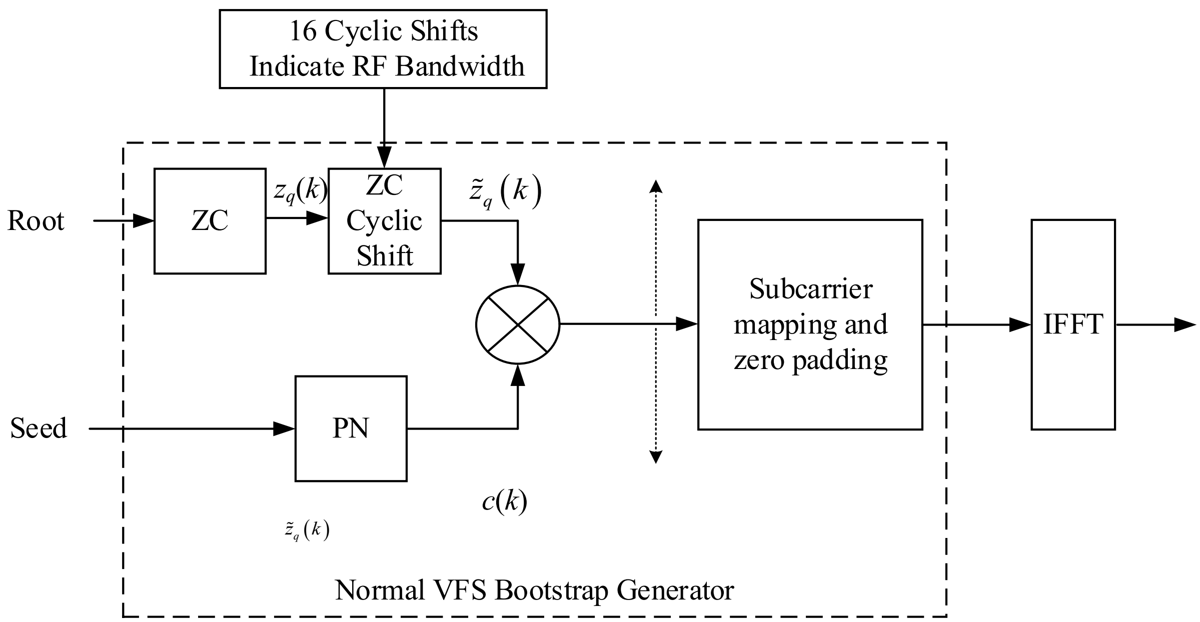

Figure 4.2 Frequency domain processing for VFS Bootstrap generation.

The frequency-domain ZC sequence defined in Section 4.3.1 shall be multiplied, on a per-subcarrier basis, by the PN sequence defined in Section 4.3.2 to form a combined ZC+PN sequence. This multiplication shall introduce phase rotations of 0 or π across subcarriers, thereby preserving CAZAC properties of the ZC sequence while randomizing the autocorrelation properties. The resulting combined ZC+PN sequence shall be mapped to the IFFT on a per-subcarrier basis as illustrated in Figure 4.2.

The Slice Start (SS) bootstrap symbol shall be generated using the same ZC+PN sequence construction and sub-carrier mapping, as illustrated in Figure 4.3, except that no frequency-domain cyclic shift shall be applied (i.e., $\tilde{z}_q(k) = z_q(k)$).

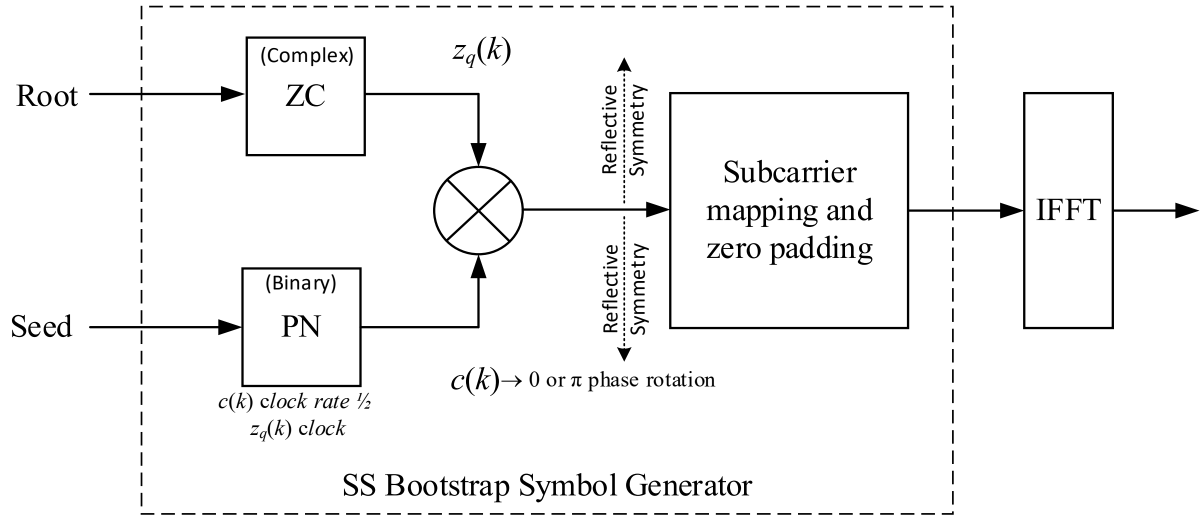

Figure 4.3 Frequency domain processing for SS Bootstrap generation**.**

4.3.1 ZC Sequence Generation

The ZC sequence $z_q(k)$ shall have length $N_{ZC} = 1499$, the largest prime number yielding a channel bandwidth not greater than 4.5 MHz at subcarrier spacing $f_\Delta = 3$ kHz.

The ZC sequence shall be parameterized by a root, q, such that:

$$z_q(k) = e^{-j\pi q\frac{k(k+1)}{N_{ZC}}} \quad , q \in \{1, 2, \dots, N_{ZC} - 1\}$$

where:

N_{ZC} is the sequence length,

k is the sequence index, $k = 0, 1, 2, \dots, N_{ZC} - 1$

4.3.2 Pseudo-Noise (PN) Sequence Generation

The PN sequence generator shall be implemented using a Linear Feedback Shift Register (LFSR) of length $l = 11$ as illustrated in Figure 4.4. The taps of the LFSR shall be defined by a generator polynomial $g(x)$. Together with the initial register state r_{init}, the generator polynomial shall define the PN initialization seed.

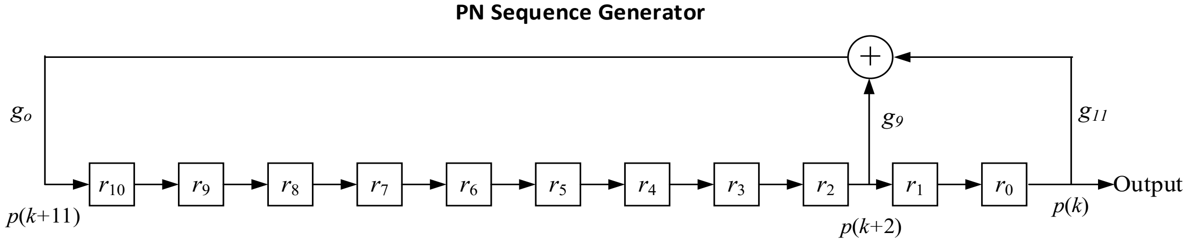

Figure 4.4 Pseudo-noise sequence generator**.**

The register state shall be initialized to r_{init} prior to the generation of the first symbol of a bootstrap. For the VFS bootstrap, the generator shall continue sequencing from the first to the second symbol without reinitialization. For the SS bootstrap, which consists of a single symbol, the generator shall be re-initialized for each occurrence.

The output of the generator shall be denoted as $p(k)$, where each bit shall take a value of 0 or 1. The first bit, $p(0)$, shall be equal to the output of the generator immediately after initialization with r_{init}, prior to any clocking of the shift register. A new bit $p(k)$ shall be produced each time the register is shifted one position.

The generator polynomial for the maximal-length sequence shall be:

$$g(x) = x^{11} + x^9 + 1$$

The initialization seed shall be defined in hexadecimal format. When represented in hexadecimal, the seed may include a leading zero beyond the 11-bit LFSR length; the 11 least significant bits shall define the initial register state r_{init}.

For example, if the seed is 0x136, the corresponding binary register state is:

$$r_{init} = [0001\ 0011\ 0110]$$

In this example, the PN sequence begins with:

$$[p(0)\ p(1)\ \mathrm{p}(2)\ \ldots.p(10)] = [01101100100]$$

The recurrence relation shall be:

$$p(k + 11) = p(k) \oplus p(k + 2)\ ,\ \mathrm{k}=0,\ 1,\ \ldots$$

4.3.3 PN Sequence Multiplication

Each element of the ZC sequence shall be multiplied by the corresponding PN sequence value defined in Section 4.3.2. Define:

$$c(k) = 1 - 2p(k), \qquad c(k) \in \{+1, -1\}$$

The modulated sequence shall be:

$$z'_q = z_q(k) \cdot c(k),$$

This multiplication shall preserve the CAZAC properties of the ZC sequence while randomizing the autocorrelation response.

For the VFS bootstrap, the PN generator shall continue from symbol 0 to symbol 1 without re-initialization.

For the SS bootstrap, which consists of a single symbol, the PN generator shall be re-initialized for each occurrence.

4.3.4 Subcarrier Mapping and Modulation Frequency Domain

Figure 4.5 illustrates the mapping of the ZC+PN product sequence to OFDM subcarriers.

The ZC sequence value corresponding to the DC subcarrier (i.e., $z_q((N_{ZC} - 1)/2)$) shall be set to zero, thereby nulling the DC subcarrier.

The product sequences shall exhibit reflective symmetry about the DC subcarrier. This symmetry shall be ensured by mirror-reflecting the PN sequence values assigned below DC onto the subcarriers above DC (e.g., the PN values at −1 and +1 shall be identical).

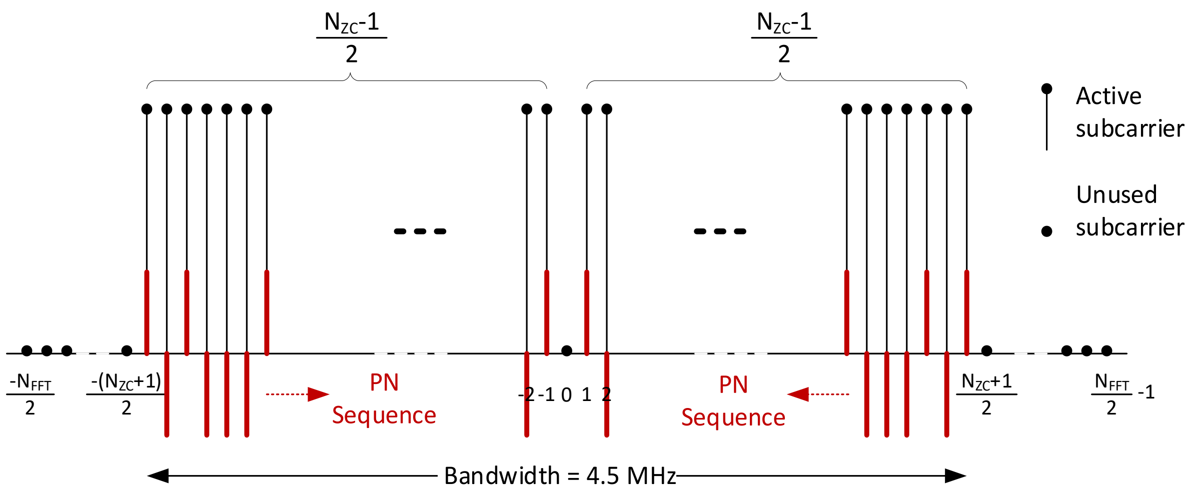

Figure 4.5 Sequence mapping to subcarriers.

For the n-th bootstrap symbol ($0 \le n < Ns$), the mapped values shall be:

$$s_n(k) = \begin{cases} \tilde{z}_q(k + N_H) \times c\big((n+1) \times N_H + k\big) & -N_H \le k \le -1 \\ \tilde{z}_q(N_H - k) \times c\big((n+1) \times N_H - k\big) & 1 \le k \le N_H \\ 0 & \text{otherwise} \end{cases}$$

where $N_H = (N_{ZC} - 1)/2$.

The VFS bootstrap shall consist of two symbols (n=0, 1, and Ns=2), with the PN sequence advancing (not reinitializing) between the first and second symbol.

The SS bootstrap shall consist of one symbol (n=0 and Ns=1) of 500 µs duration.

4.3.5 Inverse Fast Fourier Transform

The mapped frequency domain sequence $s_n(k)$ shall be translated to a time domain sequence $\tilde{A}_n(t)$ using an $N_{FFT} = 2048$ point IFFT:

$$\tilde{A}_n(t) = \frac{1}{\sqrt{(Nzc - 1)}} \left(\sum_{k=-(N_{ZC}-1)/2}^{-1} s_n(k)\, e^{j2\pi k f_\Delta t} + \sum_{k=1}^{(N_{ZC}-1)/2} s_n(k) e^{j2\pi k f_\Delta t} \right)$$

For the SS bootstrap symbol (n=0), no time domain cyclic shift shall be applied:

$$A_0(t) = \tilde{A}_0(\mathrm{t})$$

For the VFS symbol 1 a time domain cyclic shift shall be applied as described in Section 4.3.8.

4.3.6 VFS Signaling Bits

Information shall be conveyed via bootstrap-level signaling using the VFS bootstrap symbol with n=1 using cyclic shifts of the time domain sequence $\tilde{A}_1(t)$. With $N_{FFT} = 2048$ there are 2048 distinct cyclic shifts, permitting up $\log_2(2048) = 11$ bits to be represented.

In this specification, $N_b = 8$ bits shall be used. Let the signaling bits be denoted $\{b_0\ ,\ldots\ ,\ b_{N_b-1}\}$, each taking a value of 0 or 1.

4.3.7 VFS Bootstrap 1 Signaling using Gray Code Cyclic Shift

Let M $(0 \leq M < N_{FFT})$ represent the time domain cyclic shift for VFS bootstrap symbol 1. M shall be calculated from the signaling bits using Gray coding.

Let the binary representation of M be $\{m_{10}\ m_9 \ldots\ m_1 m_0\}$. Each bit m_i shall be computed from the signaling bits $\{b_0\ ,\ldots\ ,\ b_{N_b-1}\}$ as:

$$m_i = \begin{cases} \left(\sum_{k=0}^{10-i} b_k\right) \bmod 2 & i > 10 - N_b \\ 1 & i = 10 - N_b \\ 0 & i < 10 - N_b \end{cases}$$

This Gray code mapping ensures adjacent values differ by only one bit, providing tolerance to estimation errors.

VFS symbol 1 cyclic shifts in the time domain shall therefore use 8 signaling bits, constrained to 256 cyclic shifts out of the 2048 available. A Gray code shall be employed to enhance receiver robustness. Table 4.1illustrates an example mapping of 8-bit signaling values to Gray-coded cyclic shifts.

Table 4.1 Example Gray-coded Signaling Bits (8-bit case)

Example: Mapping of Eight Signaling Bits to Gray Code Cyclic Shifts			
Signaling Bits (Binary)	**Cyclic Shift (Gray Code)**	**Cyclic Shift (Decimal)**	
0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0 1 0 0	4	256 Cyclic Shifts
0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 1 1 0 0	12	
0 0 0 0 0 0 1 1	0 0 0 0 0 0 1 0 1 0 0	20	
0 0 0 0 0 0 1 0	0 0 0 0 0 0 1 1 1 0 0	28	
0 0 0 0 0 1 1 0	0 0 0 0 0 1 0 0 1 0 0	36	
0 0 0 0 0 1 1 1	0 0 0 0 0 1 0 1 1 0 0	44	
0 0 0 0 0 1 0 1	0 0 0 0 0 1 1 0 1 0 0	52	
0 0 0 0 0 1 0 0	0 0 0 0 0 1 1 1 1 0 0	60	
………	………	………	
………	………	………	
1 0 0 0 0 1 0 0	1 1 1 1 1 0 0 0 1 0 0	1988	
1 0 0 0 0 1 0 1	1 1 1 1 1 0 0 1 1 0 0	1996	
1 0 0 0 0 1 1 1	1 1 1 1 1 0 1 0 1 0 0	2004	
1 0 0 0 0 1 1 0	1 1 1 1 1 0 1 1 1 0 0	2012	
1 0 0 0 0 0 1 0	1 1 1 1 1 1 0 0 1 0 0	2020	
1 0 0 0 0 0 1 1	1 1 1 1 1 1 0 1 1 0 0	2028	
1 0 0 0 0 0 0 1	1 1 1 1 1 1 1 0 1 0 0	2036	
1 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1 1 0 0	2044	
8 signaling bits Gray code with maximum error tolerance ±3 cyclic shifts, using 2048 IFFT			

4.3.8 VFS Symbol 1 Absolute Cyclic Shift

The cyclic shift M shall be applied to obtain the time domain sequence for VFS bootstrap symbol 1:

$$A_0(t) = \tilde{A}_0(\mathrm{t}),\ A_1(t) = \tilde{A}_1\big((t + M) \bmod N_{FFT}\big).$$

The cyclic shift shall be from higher to lower index as illustrated in Figure 4.6.

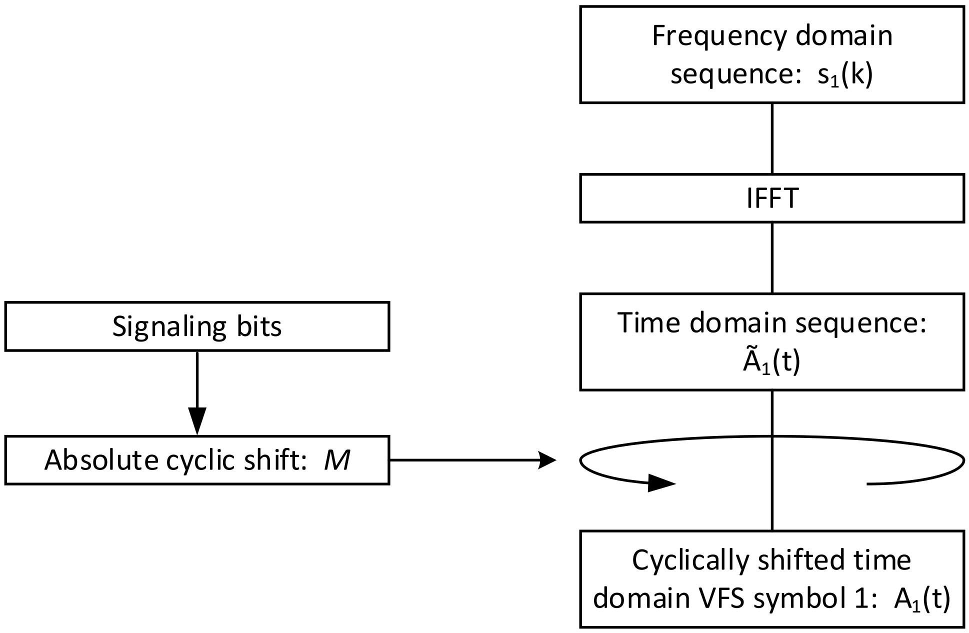

Figure 4.6 Cyclically **s**hifted time domain **s**equence**.**

4.4 Time Domain Structure (CAB/BCA)

Each bootstrap symbol shall be composed of three parts: A, B, and C, where each consists of a sequence of complex-valued time domain samples. Part A shall be derived as the IFFT of the frequency domain structure with an appropriate cyclic shift applied as shown in Figure 4.6. (i.e. part A shall be equal to $A_n(t)$). Parts B and C shall each be composed of samples taken from part A.

Part A shall consist of $N_A = N_{FFT} = 2048$ samples. Each bootstrap symbol consists of $N_A + N_B + N_C = 3072$ samples for an equivalent duration of 500 µs.

There shall be two variants of the time domain symbol structure: CAB and BCA. The following Sections detail the structures for the VFS and SS bootstrap symbols.

4.4.1 VFS symbol 0 CAB Structure

VFS symbol 0 shall use the CAB time domain structure as shown in Figure 4.7 with $N_A = N_{FFT} = 2048$, $N_B = 512$ and $N_C = 512$ samples respectively.

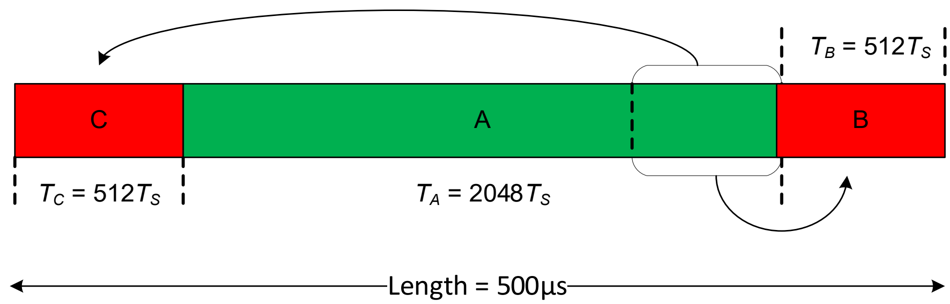

Figure 4.7 VFS Symbol 0 CAB time domain symbol structure.

For the VFS CAB structure, part C shall be composed of the last N_C samples of part A, while part B shall be composed of the last N_B samples of part A, as shown in Figure 4.7. The VFS CAB structure shall be generated by the following equation:

$$S_{CAB}^{n}(t) = \begin{cases} A_n(t + 1536T_S) & 0 \le t < 512T_S \\ A_n(t - 512T_S) & 512T_S \le t < 2560T_S \\ A_n(t - 1024T_S) & 2560T_S \le t < 3072T_S \\ 0 & \text{otherwise} \end{cases}$$

4.4.2 VFS Symbol 1 BCA Structure

VFS symbol 1 shall use the BCA time domain structure as shown in Figure 4.8 with $N_A = N_{FFT} = 2048$, N_B =512 and $N_C = 512$ samples respectively.

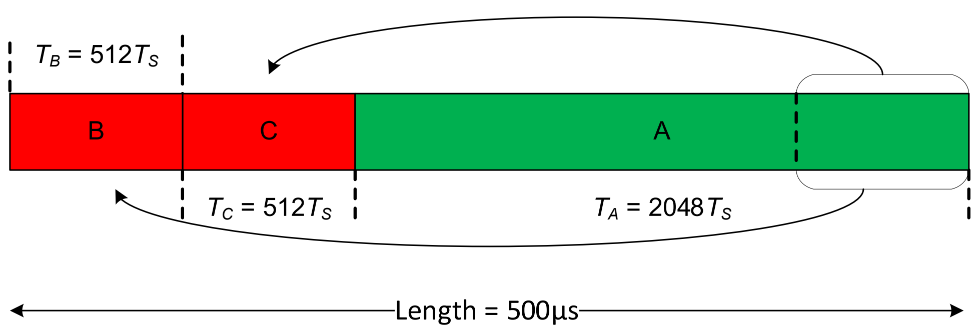

Figure 4.8 VFS BCA time domain **s**ymbol **s**tructure**.**

For the VFS BCA structure, part C shall be composed of the last N_C samples of part A. Part B shall be composed of the first N_B samples of part C. The VFS BCA structure shall be generated by the following equation:

$$S_{BCA}^{n}(t) = \begin{cases} A_n(t + 1536T_S) & 0 \le t < 512T_S \\ A_n(t + 1024T_S) & 512T_S \le t < 1024T_S \\ A_n(t - 1024T_S) & 1024T_S \le t < 3072T_S \\ 0 & \text{otherwise} \end{cases}$$

4.4.3 SS Symbol CAB Structure

The SS CAB time domain structure shall be as shown in Figure 4.9 with $N_A = N_{FFT} = 2048$, N_B = 496 and $N_C = 528$ samples respectively.

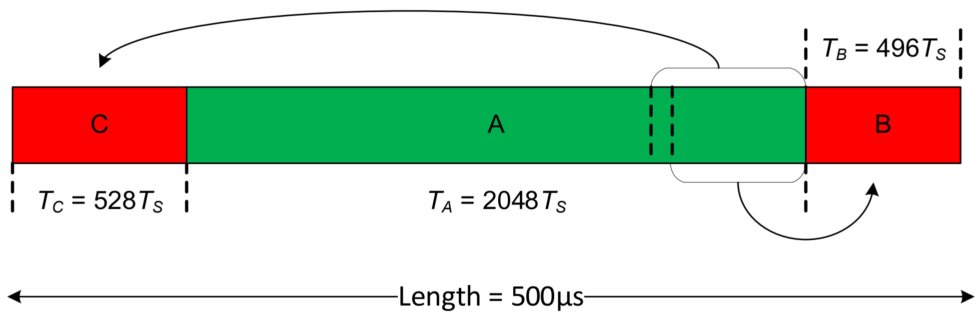

Figure 4.9 SS CAB time domain symbol **s**tructure**.**

For the SS CAB structure, part C shall be composed of the last N_C samples of part A, while part B shall be composed of the last N_B samples of part A, as shown in Figure 4.9. The SS CAB structure shall be generated by the following equation:

$$S_{CAB}^{n}(t) = \begin{cases} A_n(t + 1520T_S) & 0 \leq t < 528T_S \\ A_n(t - 528T_S) & 528T_S \leq t < 2576T_S \\ A_n(t - 1024T_S) & 2576T_S \leq t < 3072T_S \\ 0 & \text{otherwise} \end{cases}$$

5. B2X BOOTSTRAP SYMBOL SPECIFICATIONS

This Section defines two bootstrap symbol types used by the Normal Bootstrap: the Virtual Frame Start (VFS) symbol, and the Slice Start (SS) symbol. When used together, as shown in Figure 5.1, these symbols shall provide synchronization and discovery. Verification and bootstrap-level signaling shall be conveyed via the VFS symbols.

The sequence generators for the VFS and SS symbols (Figure 4.2 and Figure 4.3) define the syntax and semantics of the bootstrap symbols used for discovery and verification. For the Normal Bootstrap, Service Category (SC) identification is not conveyed via bootstrap-level signaling; service identification is provided by subsequent L1 Signaling. For Scaled Bootstraps, SC-related bootstrap-level signaling is specified in Section 6.

The parameters for VFS symbols shall be as specified in Table 5.1. The Zadoff–Chu sequence with length N_{ZC}=1499 shall apply one of 16 possible frequency domain cyclic shifts, each mapping to the RF carrier bandwidth of the upcoming B2X Virtual Frame.

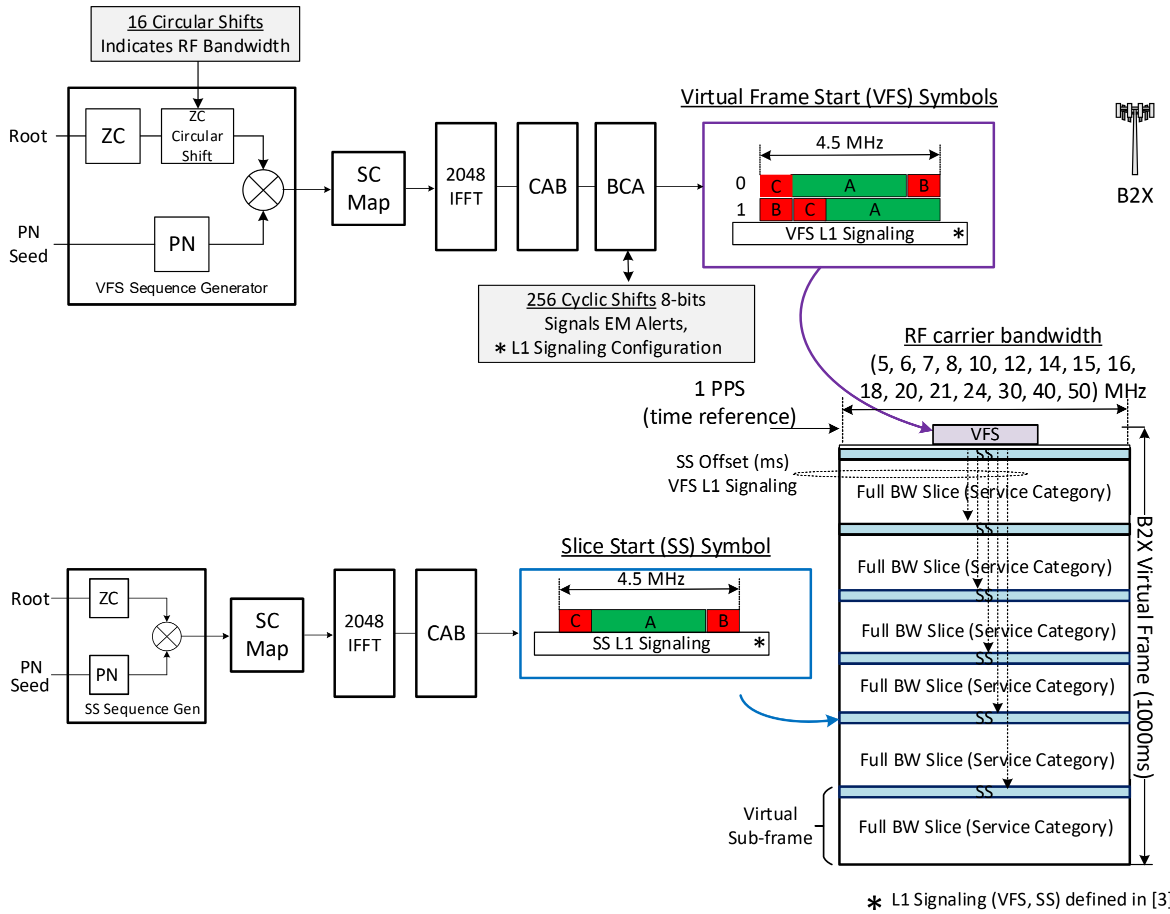

Figure 5.1 B2X VFS, SS **s**ymbols and **s**ervice **r**eception.

VFS symbol 1 shall use a Gray-coded time domain cyclic shift to convey 8 signaling bits, as specified in Table 5.2 and Section 4.3.7.

The parameters for SS symbols shall be as specified in Table 5.3. An SS bootstrap symbol shall be present in the time/frequency grid of the OFDMA Virtual Frame (1000 ms) to demarcate the start of a Virtual Sub-Frame containing payload data associated with a Service Category (SC). The SS bootstrap symbol shall provide an entry point for reception of the associated Virtual Sub-Frame. Due to the CAZAC properties of the SS sequence and its location in the OFDMA time/frequency grid, multiple SS entry points may be supported within a Virtual Frame, enabling multiplexing of multiple services within an RF carrier.

5.1 Virtual Frame Start (VFS) Symbols

The RF bandwidth of the Virtual Frame shall map to VFS bootstrap using one of sixteen predefined ZC cyclic shifts, as shown in Table 5.1, permitting verification of correct reception of the intended Virtual Frame configuration. This selection shall utilize the VFS sequence generator defined in Figure 4.2.

Table 5.1 VFS Symbols: ZC Cyclic Shift Indicating RF Bandwidth

RF Bandwidth	Zadoff-Chu Root value	PN Seed value	ZC Cyclic Shift *K*
5 MHz	1013	0x136	47
6 MHz	1013	0x136	140
7 MHz	1013	0x136	233
8 MHz	1013	0x136	326
10 MHz	1013	0x136	419
12 MHz	1013	0x136	512
14 MHz	1013	0x136	605
15 MHz	1013	0x136	698
16 MHz	1013	0x136	791
18 MHz	1013	0x136	884
20 MHz	1013	0x136	977
21 MHz	1013	0x136	1070
24 MHz	1013	0x136	1163
30 MHz	1013	0x136	1256
40 MHz	1013	0x136	1349
50 MHz	1013	0x136	1442

The values in Table 5.1 define the ZC cyclic shifts used for VFS bootstrap generation corresponding to the RF carrier bandwidth of the Virtual Frame. Detection of the transmitted ZC cyclic shift permits verification of correct reception of the intended Virtual Frame configuration.

VFS symbol 0 shall provide coarse synchronization, frequency offset estimation, initial channel estimation, and related functions.

VFS symbol 1 shall support 256 time domain cyclic shifts, corresponding to 8 bootstrap-level signaling bits. The signaling shall be Gray-coded as defined in Section 4.3.7. Detection of the transmitted cyclic shift permits recovery of the VFS symbol 1 signaling bits.

The syntax of the 8-bit signaling conveyed in VFS symbol 1 shall be as specified in Table 5.2.

Table 5.2 VFS Symbol 1 Syntax (Time Domain Cyclic Shift)

VFS Symbol 1 Syntax Cyclic Shift	No. of Bits	Format
VFS symbol 1 {		
em_alert_active	1	uimsbf
VFS_L1_signaling_config_table	3	uimsbf
VFS_L1_signaling_code_rate	2	uimsbf
VFS_L1_signaling_Pboost	2	uimsbf
}		

em_alert_active – A 1-bit field. A value of 0 indicates that no emergency alerts are active, while a value of 1 indicates that one or more emergency alerts are active, as defined in [3].

VFS_L1_signaling_config_table – A 3-bit field indicating the selection of a configuration entry (row) in the VFS L1 Signaling configuration table for the current B2X Virtual Frame. The structure and interpretation of this table shall be as defined in [3].

VFS_L1_signaling_code_rate – A 2-bit field indicating the code rate configuration associated with VFS L1 Signaling for the current B2X Virtual Frame. The mapping of this field to specific coding rates shall be as defined in [3].

VFS_L1_signaling_Pboost – A 2-bit field indicating the selection of a pilot amplitude boosting factor applied to pilot cells of the VFS L1 Signaling symbols. The mapping of this field to specific boosting values shall be as defined in [3].

In this specification, "bootstrap-level signaling" refers to information conveyed by bootstrap symbol parameters (e.g., cyclic shifts and, where specified, symbol/sequence selection). L1 Signaling transmitted after the bootstrap, including VFS L1 Signaling and SS L1 Signaling, is defined in the B2X Physical Layer Protocol [3].

5.2 Slice Start (SS) Symbol

The SS symbol parameters shall be as specified in Table 5.3 and shall be generated using the SS generator shown in Figure 4.3. The SS symbol shall use the same ZC root and PN seed values as the VFS symbol in Table 5.1, but with no ZC cyclic shift applied.

Accordingly, SS symbols shall remain orthogonal to VFS symbols and retain excellent CAZAC properties.

Table 5.3 SS Symbol Parameters

ZC Root Value	PN Seed Value
1013	0x136

6. B2X NORMAL AND SCALED BOOTSTRAPS IN OFDMA VIRTUAL BANDWIDTH PARTS

The Normal Bootstrap uses a Zadoff–Chu sequence of prime length Nzc = 1499.

Unless otherwise specified in this section, Scaled Bootstraps reuse the bootstrap numerology and symbol structure conventions used by the Normal Bootstrap (including Δf = 3 kHz, a 500 µs symbol duration, the CAB/BCA time-domain construction, and the VFS/SS symbol counts), with modified ZC sequence lengths, FFT sizes, mapping rules, and signaling semantics as defined herein.

In the B2X OFDMA framework [3] the physical layer frequency domain shall be partitioned into Physical Resource Blocks (PRBs). Each PRB shall consist of 24 subcarriers with a subcarrier spacing of 3 kHz, yielding a PRB width of 72 kHz. Payload data and associated control signaling, including L1 Signaling shall be mapped to the OFDMA grid using integer numbers of PRBs, while the RF carrier bandwidth determines the total number of PRBs available.

The bootstrap sequence with Nzc = 1499 shall occupy a bandwidth of 4.5 MHz. Figure 6.1 illustrates that the bootstrap supports Virtual Bandwidth Parts (VBPs), which may be narrower or wider than the bootstrap bandwidth and may extend across the full RF carrier bandwidth.

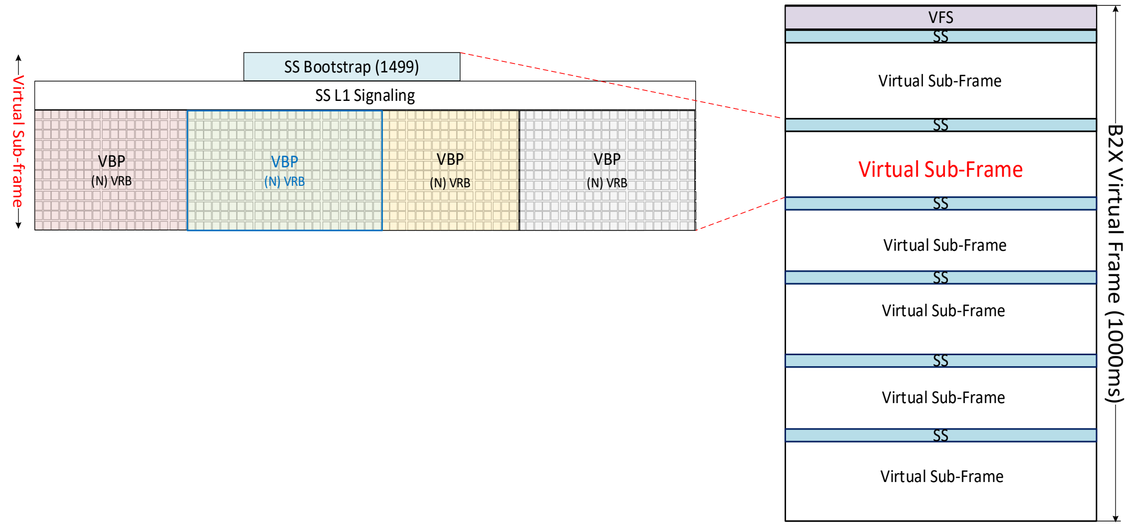

Figure 6.1 B2X OFDMA Framework and Virtual Bandwidth Parts (VBPs).

A B2X Virtual Frame shall have a duration of 1000 ms and shall begin with VFS bootstrap symbols. Each Virtual Frame shall contain Virtual Sub-Frames, each beginning with an SS Bootstrap located in the OFDMA time/frequency grid. The SS Bootstrap shall indicate the entry point of a Virtual Sub-Frame carrying payload data associated with a Service Category (SC).

Groups of PRBs shall form Virtual Resource Blocks (VRBs). Sets of *N* VRBs shall form a Virtual Bandwidth Part (VBP). The OFDM numerology for the Normal Bootstrap (Nzc =1499) and associated VBPs shall be as specified in Table 6.1.

Table 6.1 OFDMA Numerology and Virtual Bandwidth Parts (VBPs) for the Normal Bootstrap

RF Carrier BW (MHz)	Bootstrap Prime Length Nzc	#PRB	VBP Useful BW (MHz)	Transmitter IFFT Size N_{tx}	ΔF (Hz)	Tx fs: =.384 MHz x [N]
5	1499	1- 66	.072 - 4.752	2048	3000	[N =16] 6.144 MHz
6	1499	1- 80	.072 - 5.760	2048	3000	[N =16] 6.144 MHz
7	1499	1- 94	.072 - 6.768	4096	3000	[N =32] 12.288 MHz
8	1499	1- 108	.072 - 7.776	4096	3000	[N =32] 12.288 MHz
10	1499	1- 134	.072 - 9.648	4096	3000	[N =32] 12.288 MHz
12	1499	1- 162	.072 - 11.664	4096	3000	[N =32] 12.288 MHz
14	1499	1- 190	.072 - 13.680	8192	3000	[N =64] 24.576 MHz
15	1499	1- 204	.072 - 14.688	8192	3000	[N =64] 24.576 MHz
16	1499	1- 218	.072 - 15.696	8192	3000	[N =64] 24.576 MHz
18	1499	1- 246	.072 - 17.712	8192	3000	[N =64] 24.576 MHz
20	1499	1- 274	.072 - 19.728	8192	3000	[N =64] 24.576 MHz
21	1499	1- 288	.072 - 20.736	8192	3000	[N =64] 24.576 MHz
24	1499	1- 328	.072 - 23.616	8192	3000	[N =64] 24.576 MHz
30	1499	1- 412	.072 - 29.664	16384	3000	[N =128] 49.152 MHz
40	1499	1- 550	.072 - 39.600	16384	3000	[N =128] 49.152 MHz
50	1499	1- 682	.072 - 49.104	16384	3000	[N =128] 49.152 MHz

L1 Signaling (including VFS L1 Signaling and SS L1 Signaling) identifies the PRBs and VRBs associated with a given Virtual Bandwidth Part (VBP). When a VBP occupies less than the full RF carrier bandwidth, a BXE may process only the corresponding subcarriers using a receiver FFT size smaller than the transmitter IFFT size, thereby conserving power and supporting efficient reception of services within the same RF carrier. When a VBP spans the full RF carrier bandwidth, the receiver FFT size may correspond to the transmitter IFFT size. This flexible reception model provides greater efficiency than conventional OFDM systems in which all receivers are constrained to use the same FFT size as the transmitter.

6.1 B2X Scaled Bootstraps in OFDMA Virtual Bandwidth Parts

The Zadoff-Chu sequence length Nzc used for Scaled Bootstraps shall be a prime number to retain CAZAC properties.

Figure 6.2 illustrates the Normal Bootstrap (Nzc= 1499) together with Scaled Bootstraps (Nzc= 127, 241, 467, 839). Scaled Bootstraps shall be derived in the frequency domain using shorter prime-length Zadoff-Chu sequences, resulting in the reduced bandwidths specified in Table 6.2.

The subcarrier spacing (SCS) for Scaled Bootstraps shall be identical to that of the Normal Bootstrap, Δf = 3000 Hz. The duration of a Scaled bootstrap symbol shall be 500 µs. Each Scaled Bootstrap shall consist of two VFS symbols and one SS symbol. The signaling syntax and semantics of Scaled VFS bootstraps shall differ from those of the Normal Bootstrap, being optimized for narrow-bandwidth VBPs.

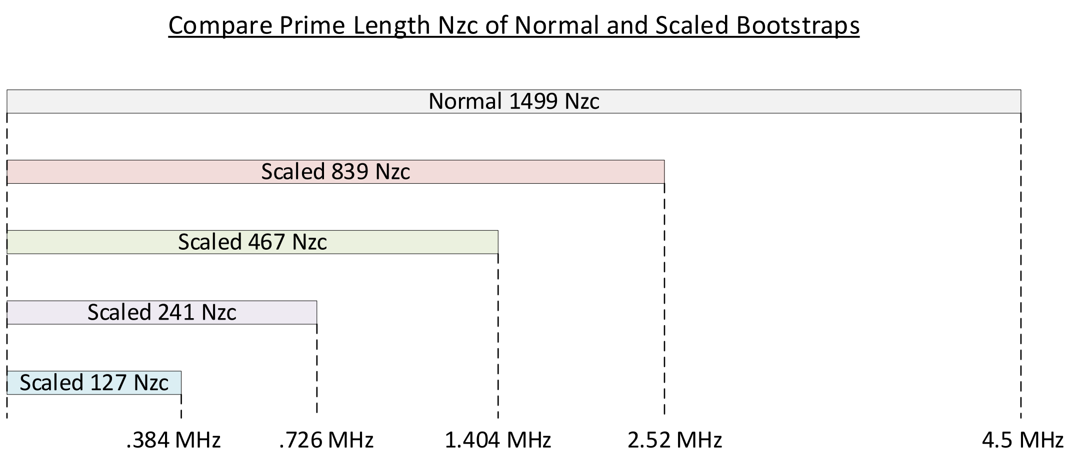

Figure 6.2 Prime Lengths Nzc of Normal and Scaled Bootstraps**.**

Scaled VBPs shall be constrained within the bandwidth of the associated scaled bootstrap, as specified in Table 6.2. Scaled Bootstraps provide entry points for synchronization and discovery of narrow-bandwidth services associated with Service Categories (SCs) delivered via VBPs. Scaled Bootstraps are designed to support reduced-capability BXEs by enabling synchronization and discovery for narrow-bandwidth services associated with Service Categories (SCs).

Scaled VFS bootstraps may be located at frequency offsets from the RF carrier center frequency, as specified in Table 6.14. These services may be hosted within RF carriers of bandwidths from 6 MHz to 50 MHz, while BXEs may be agnostic to the overall carrier bandwidth and are expected to determine the bootstrap location using the offsets specified in Table 6.14 and detection of the corresponding bootstrap waveform.

Unlike the adaptive VBP bandwidths supported by the Normal Bootstrap, Scaled Bootstraps define fixed, narrow-bandwidth VBPs. Scaled and Normal Bootstraps may coexist within the same OFDMA RF carrier.

Subsequent Sections introduce Scaled VFS and SS symbol signaling, followed by a description of their combined operation with Normal Bootstraps within the same Virtual Frame and RF carrier. Annex A provides an example of scaled VFS bootstrap generation.

In the Scaled Bootstrap framework, the Scaled VFS provides a reduced-bandwidth entry point for synchronization and conveys limited signaling via time-domain cyclic shift of Scaled VFS symbol 1. The Scaled SS provides the entry point to a Virtual Sub-Frame within the corresponding scaled region of the OFDMA grid. Where specified, a Service Category (SC) may be conveyed by selection of Scaled SS sequence parameters.

6.2 Scaled Bootstraps Frequency Domain Sequences

Two Scaled Virtual Frame Start (VFS) symbols, numbered 0 and 1, shall be used to indicate the start of reduced-bandwidth Virtual Bandwidth Parts (VBPs) within a B2X Virtual Frame.

Scaled VFS bootstrap symbol 0 shall be generated in the frequency domain using a Zadoff-Chu (ZC) sequence multiplied by a pseudo-noise (PN) sequence, as shown in Figure 6.3. For symbol 1, the PN sequence shall continue without re-initialization, as specified in Section 4.3.2. The Scaled VFS bootstrap symbol 1 shall likewise be generated in the frequency domain as shown in Figure 6.3.

The resulting scaled VFS complex sequence shall be mapped to the allocated subcarriers at the IFFT input as per Table 6.14 and Figure 6.5. The IFFT size N_{tx} is defined in Table 6.14.

Scaled VFS bootstrap symbol 1 shall have a cyclic shift applied in the time domain after the IFFT. This cyclic shift shall be used for signaling as described in Section 6.3.4.

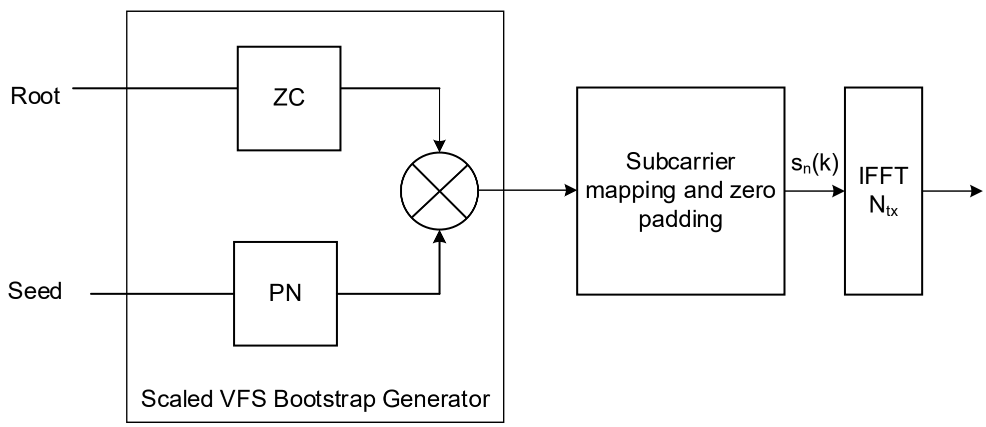

Figure 6.3 Frequency Domain Processing Scaled VFS Sequence Generation**.**

Scaled Slice Start (SS) bootstrap symbols shall likewise be generated in the frequency domain using a ZC sequence multiplied by a PN sequence, as shown in Figure 6.4.

For the SS bootstrap, the PN sequence shall be initialized as specified in Section 4.3.2. The resulting scaled SS complex sequence shall then be mapped to the allocated subcarriers at the IFFT input.

The transmit IFFT size for SS mapping shall be as defined in [3] and subject to minimum FFT sizes shown in Table 6.2.

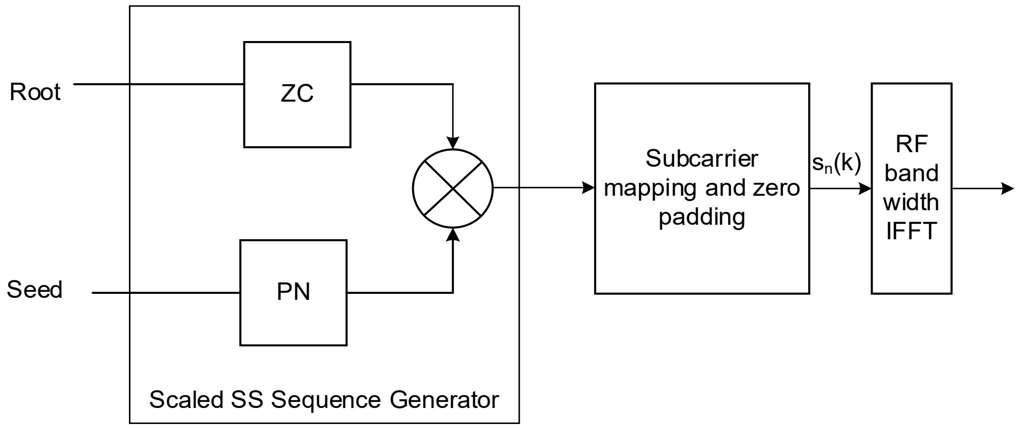

Figure 6.4 Frequency Domain Processing of Scaled SS Sequence Generation**.**

Each scaled SS bootstrap symbol shall indicate the entry point of a Virtual Sub-Frame associated with a Service Category (SC). Where specified (e.g., Table 6.10 and Table 6.11), a Service Category may be conveyed by selection of the SS sequence parameters (e.g., ZC root and PN seed). Continuing the PN sequence across the two scaled VFS symbols maintains consistency with the Normal Bootstrap structure and avoids unnecessary re-initialization steps.

6.3 Scaled Bootstraps Signal Dimensions

The Zadoff-Chu (ZC) sequence $z_q(k)$ shall have prime lengths Nzc, as listed in **Table 6.2**. These prime lengths enable narrow-bandwidth BXEs with a subcarrier spacing of $f_\Delta = 3$ kHz. The ZC sequence lengths are defined to support reduced-capability BXEs by ensuring detectability of Scaled VFS and SS Bootstrap signals.

For reduced-capability BXEs, N_{rx} is assumed to be a power of 2 and greater than the corresponding ZC sequence length (Nzc). The corresponding minimum BXE sampling frequency is:

$$f_S = 3{,}000\ \times N_{rx}$$

The ZC sequence shall be parameterized by a root, q, such that:

$$z_q(k) = e^{-j\pi q \frac{k(k+1)}{N_{ZC}}}$$

where $q \in \{1, 2, \dots, N_{ZC} - 1\}$ and $k = 0, 1, 2, \dots, N_{ZC} - 1$.

The minimum FFT size and sampling frequency for each Nzc value are specified in Table 6.2.

Table 6.2 Scaled Bootstraps: Minimum FFT Size and Sampling Rate for Reduced-Capability BXEs

Bootstrap Prime Length Nzc	Minimum FFT Size N_{rx}	f_Δ Hz	Minimum f_s (MHz)	VBP Useful BW PRB / MHz	Symbol Length (µs)
127	128	3000	0.384	1 - 5 PRB /.072 - 0.360	500
241	256	3000	0.768	1 - 10 PRB /.072 - 0.720	500
467	512	3000	1.536	1 - 19 PRB /.072 - 1.368	500
839	1024	3000	3.072	1 - 34 PRB /.072 - 2.448	500

The transmitter sampling frequency of the scaled bootstrap VFS symbols shall be 3000 x N_{tx} samples per second. The transmitter sampling frequency of the Scaled SS Bootstrap symbol shall be 3000 x N_{tx}, consistent with the B2X OFDMA framework [3], and the FFT sizes shown in Table 6.2.

The total time duration of the Scaled VFS Bootstrap (two symbols), shall be 1 ms, and the Scaled SS Bootstrap (one symbol) shall be 500 µs.

6.3.1 Scaled Bootstraps Inverse Fast Fourier Transform

The mapped frequency domain sequence $s_n(k)$ shall be transformed to a time domain sequence $\tilde{A}_n(t)$ using an IFFT of size N_{IFFT}.

- For scaled VFS symbols $N_{IFFT} = N_{tx} \in \{2048, 4096\}$
- For scaled SS symbols N_{IFFT} shall be as defined in [3] and Table 6.2.

Unmapped frequency domain subcarriers shall be set to $s_n(k) = 0$. The time domain sequence $\tilde{A}_n(t)$ shall be given by:

$$\tilde{A}_n(t) = \frac{1}{sqrt(N_{used})}\left(\sum_{k=-(N_{IFFT}-1)/2}^{-1} s_n(k)\, e^{j2\pi k f_\Delta t} + \sum_{k=1}^{(N_{IFFT}-1)/2} s_n(k) e^{j2\pi k f_\Delta t}\right)$$

where N_{used} is the number of non-zero subcarriers.

For scaled VFS symbol 0 and the scaled SS symbol, no time domain cyclic shift shall be applied:

$$A_0(t) = \tilde{A}_0(\mathrm{t})$$

For scaled VFS symbol 1, a time domain cyclic shift of M samples, shall be applied:

$$A_1(t) = \tilde{A}_1\big((t + M) \bmod N_{tx}\big)$$

6.3.2 Scaled Bootstraps Time Domain Structure

There shall be two variants of the time domain symbol structure: CAB and BCA.

- Scaled VFS symbol 0 shall employ the CAB structure.
- Scaled VFS symbol 1 shall employ the BCA structure.
- The scaled SS bootstrap shall consist of a single CAB symbol.

The transmit IFFT size (N_{tx}) for scaled VFS shall be either 2048 or 4096, as specified in Table 6.14.

- If N_{tx} = 2048, the CAB and BCA structures shall be defined as in Sections 4.4.1 and 4.4.2.
- If N_{tx} = 4096, all parameters (N_A, N_B, N_C) and indices in the $S^n_{CAB}(t)$ and $S^n_{BCA}(t)$ equations shall be doubled relative to the 2048-definitions.

For scaled SS bootstraps, the CAB structure defined in Section 4.4.3 shall be applied with scaling proportional to N_{tx} / 2048, as specified in Table 6.1.

The CAB or BCA structures shall be applied after the IFFT as shown in Figure 6.3 and Figure 6.4.

6.3.3 Scaled VFS Bootstrap Parameters

The parameters for scaled VFS symbols shall be as specified in Table 6.3.

Table 6.3 Scaled VFS Symbol Parameters

VFS (Nzc)	ZC Root Value	PN Seed Value
127	109	0x100
241	163	0x100
467	3	0x100
839	3	0x100

6.3.4 Scaled VFS Bootstrap Symbol 1 Signaling Cyclic Shifts

Information shall be signaled via cyclic shifts in the time domain of scaled VFS symbol 1.

The minimum BXE FFT sizes (N_{rx}) and corresponding maximum shifts are:

- N_{rx} = 128 → 127 shifts
- N_{rx} = 256 → 255 shifts
- N_{rx} = 512 → 511 shifts
- N_{rx} = 1024 → 1023 shifts

These configurations provide a theoretical signaling capacity of 7–10 bits, depending on N_{rx}. In practice, fewer bits shall be used as follows:

- N_{rx} = 128 → Nb = 4
- N_{rx} = 256 → Nb = 5
- N_{rx} = 512 → Nb = 6
- N_{rx} = 1024 → Nb = 7

Each signaling bit $\{b_0, \dots, b_{N_b-1}\}$ shall have a value of 0 or 1.

6.3.5 Scaled VFS Symbol 1 Absolute Cyclic Shift

Scaled VFS symbol 0 shall not be cyclically shifted in the time domain.

Scaled VFS symbol 1 shall apply a cyclic shift M, to the time-domain sequence after the IFFT operation. The cyclic shift index M shall be computed as:

$$M = \widetilde{M} \times N_{tx}/N_{rx}$$

where:

- $N_{tx}$is the transmitter IFFT size,
- N_{rx} is the minimum receiver FFT size, and
- $\widetilde{M}$ is derived from the Gray-coded mapping described in Section 6.3.6.

This cyclic shift shall be applied from higher index to lower index, consistent with the convention defined for the Normal VFS bootstrap in Section 4.3.8.

6.3.6 Scaled VFS Symbol 1 Gray Code Mapping

The cyclic shift index $\widetilde{M}$ shall be derived from the valid signaling bits of scaled VFS bootstrap symbol 1 using Gray code mapping. The value $\widetilde{M}$ shall satisfy $0 \leq \widetilde{M} < N_{rx}$ where N_{rx} is the minimum FFT size.

The signaling capacity depends on N_{rx} as follows:

- For N_{rx} = *128:* N_b = *4* signaling bits
- For N_{rx} = *256:* N_b = *5* signaling bits
- For N_{rx} = *512:* N_b = *6* signaling bits

- For N_{rx} = *1024:* N_b = *7* signaling bits

For each case, the binary representation of $\widetilde{M}$ shall be expressed as $\{m_X, m_{X-1}, \ldots, m_0\}$, where X = 6, 7, 8, 9 for N_{rx} = 128, 256, 512, 1024 respectively.

Each bit m_i shall be computed as:

$$m_i = \left\{\left(\sum_{k=0}^{X-i} b_k\right) mod\ 2\right.$$

This Gray code mapping ensures that adjacent values of $\widetilde{M}$ differ by only one bit, thereby maximizing robustness against cyclic shift estimation errors at the receiver.

6.3.7 VFS Symbol 1 Receiver Binary Signaling Bits Recovery

Binary signaling bits conveyed by VFS bootstrap symbol 1 are obtained by mapping the detected cyclic-shift index $\widetilde{M}$ according to the inverse of the Gray code mapping defined in Section 6.3.6.

The signaling structure of Scaled VFS bootstrap symbol 1 depends on the ZC sequence length (Nzc) and associated service type and is specified in the following tables.

Table 6.4 specifies the 4-bit conveyed by cyclic shifts of VFS Bootstrap (127) symbol 1 for Nzc = 127, used to support discontinuous reception (DRX) and BXE extended battery savings as defined in [3].

Table 6.4 VFS Bootstrap (127) Symbol 1

VFS Bootstrap (127) Symbol 1	No. of Bits	Format
VFS symbol 1 {		
mode	1	uimsbf
check_DRX_service_active	3	uimsbf
}		

mode – A 1-bit field.

When set to ‘0’, the BXE is expected to operate in normal DRX mode.

When set to ‘1’, the BXE is expected to access VFS L1 Signaling immediately following the bootstrap to determine DRX service configuration and other parameters [3].

check_DRX_service_active – A 3-bit field.

When mode = 0, the BXE is expected to use the check_DRX_service_active field to determine whether the service it is monitoring (as configured by the network) is active in the current B2X Virtual Frame.

A value of ‘1’ indicates the service is active and has data to transmit during the current Virtual Frame. In this case, the BXE is expected to access VFS L1 Signaling following the bootstrap to receive the service.

A value of ‘0’ indicates, that the service is not active during the current Virtual Frame. In this case, the BXE is expected to return to a low-power state until the next scheduled check for DRX service activity.

For N_{rx} = *128*, with N_b = *4*, three Service Categories (0–2) may be signaled. The valid signaling combinations shall be as specified in Table 6.8.

Table 6.5 specifies the 5-bit signaling conveyed by cyclic shifts of VFS Bootstrap symbol 1 for Nzc = 241, used to support discontinuous reception (DRX) and extended battery operation for BXEs as defined in [3].

Table 6.5 VFS Bootstrap (241) Symbol 1

VFS Bootstrap (241) Symbol 1	No. of Bits	Format
VFS symbol 1 {		
mode	1	uimsbf
check_DRX_service_active	4	uimsbf
}		

mode – A 1-bit field.

When set to ‘0’ the BXE is expected to operate in normal DRX mode.

When set to ‘1’ the BXE is expected to access the VFS L1 Signaling following the bootstrap to determine DRX service configuration and other parameters as specified in [3].

check_DRX_service_active – A 4-bit field.

When mode = 0, the BXE is expected to use the check_DRX_service_active field to determine whether the service it is monitoring is active in the current B2X Virtual Frame.

A value of ‘1’ indicates that the service is active and has data to transmit during the current Virtual Frame. In this case, the BXE is expected to access the VFS L1 Signaling following the bootstrap to receive the service.

A value of ‘0’ indicates that the service is not active during the current Virtual Frame. In this case, the BXE is expected to return to a low-power state until the next scheduled check for DRX service activity.

This behavior enables discontinuous reception (DRX) operation and supports extended battery life for power-constrained BXEs.

For N_{rx} = *256*, with N_b = *5*, four Service Categories (0–3) may be signaled. The valid signaling combinations shall be as specified in Table 6.9.

Table 6.6 specifies the 6-bit signaling conveyed by cyclic shifts of VFS Bootstrap symbol 1 for Nzc = 467, used for Reduced Capability (RedCap) services as defined in [3].

Table 6.6 VFS Bootstrap (467) Symbol 1

VFS Bootstrap (467) Symbol 1	No. of Bits	Format
VFS symbol 1 {		
em_alert_active	1	uimsbf
RedCap_L1_signaling_config_table	2	uimsbf
RedCap_L1_signaling_code_rate	2	uimsbf
VFS_L1_signaling_Pboost	1	uimsbf
}		

em_alert_active – A 1-bit field. A value of 0 indicates that no emergency alerts are active, while a value of 1 indicates that one or more emergency alerts are active, as defined in [3].

RedCap_L1_signaling_config_table – A 2-bit field indicating the selection of a row from the RedCap VFS (467) L1 Signaling configuration table for the current B2X Virtual Frame. The structure and interpretation of this table shall be as defined in [3].

RedCap_L1_signaling_code_rate – A 2-bit field indicating the code rate associated with RedCap VFS (467) L1 Signaling for the current B2X Virtual Frame. The mapping of this field to specific code rates shall be as defined in [3].

VFS_L1_Signaling_Pboost – A 1-bit field indicating the selection of a pilot amplitude boosting factor applied to pilot cells of the VFS L1 Signaling symbols. The mapping of this field to specific boosting values shall be as defined in [3].

Table 6.7 specifies the 7-bit signaling conveyed by cyclic shifts of VFS Bootstrap symbol 1 for Nzc = 839, used for Narrow Bandwidth (NBW) services as defined in [3].

Table 6.7 VFS Bootstrap (839) Symbol 1

VFS Bootstrap (839) Symbol 1	No. of Bits	Format
VFS symbol 1 {		
em_alert_active	1	uimsbf
NBW_L1_signaling_config_table	3	uimsbf
NBW_L1_signaling_code_rate	2	uimsbf
VFS_L1_signaling_Pboost	1	uimsbf
}		

em_alert_active – A 1-bit field. A value of 0 indicates that no emergency alerts are active, while a value of 1 indicates that one or more emergency alerts are active, as defined in [3].

NBW_L1_signaling_config_table – A 3-bit field indicating the selection of a row from the NBW VFS (839) L1 Signaling configuration table for the current B2X Virtual Frame. The structure and mapping of this table shall be as defined in [3].

NBW_L1_signaling_code_rate – A 2-bit field indicating the code rate configuration associated with VFS (839) L1 Signaling for the current B2X Virtual Frame. The mapping of this field to specific code rates shall be as defined in [3].

VFS_L1_Signaling_Pboost – A 1-bit field indicating the selection of a pilot amplitude boosting factor applied to pilot cells of the VFS L1 Signaling symbols. The mapping of this field to specific boosting values shall be as defined in [3].

Table 6.8 N_{rx}=128 DRX Active Service Category Signaling

MSB			LSB
Mode	**Service Category 0**	**Service Category 1**	**Service Category 2**
0	0	0	0
0	0	0	1
0	0	1	0
0	0	1	1
0	1	0	0
0	1	0	1
0	1	1	0
0	1	1	1
1	0	0	0
1	0	0	1
1	0	1	0
1	0	1	1
1	1	0	0

1	1	0	1
1	1	1	0
1	1	1	1

Table 6.9 N_{rx} =256 DRX Active Service Category Signaling

MSB				LSB
Mode	**Service Category 0**	**Service Category 1**	**Service Category 2**	**Service Category 3**
0	0	0	0	0
0	0	0	0	1
0	0	0	1	0
0	0	0	1	1
0	0	1	0	0
0	0	1	0	1
0	0	1	1	0
0	0	1	1	1
-	-	-	-	-
-	-	-	-	-
1	1	0	1	0
1	1	0	1	1
1	1	1	0	0
1	1	1	0	1
1	1	1	1	0
1	1	1	1	1

6.3.8 Scaled SS (CAB) Bootstrap Parameters

The parameters for Scaled SS bootstrap symbols shall be as specified in Table 6.10 through Table 6.13. For Table 6.10, Table 6.11 each ZC sequence length Nzc, a unique combination of ZC root value and PN seed value shall be defined for each Service Category.

Where Scaled SS bootstrap sequences are assigned per Service Category (SC) (e.g., Table 6.10 and Table 6.11), the detected SS sequence identifies the SC. Subsequent SS L1 Signaling may further associate the SC with service configuration as specified in [3].

Table 6.10 Scaled SS Bootstrap Parameters Nzc=127

SS (Nzc)	ZC Root Value	PN Seed Value	Service Category
127	101	0x111	0
127	101	0x333	1
127	101	0x555	2

Table 6.11 Scaled SS Bootstrap Parameters Nzc=241

SS (Nzc)	ZC Root Value	PN Seed Value	Service Category
241	97	0x111	0
241	97	0x333	1
241	97	0x555	2
241	97	0x777	3

Table 6.12 Scaled SS Bootstrap Parameters Nzc=467

SS (Nzc)	ZC Root Value	PN Seed Value
467	103	0x111

Table 6.13 Scaled SS Bootstrap Parameters Nzc=839

SS (Nzc)	ZC Root Value	PN Seed Value
839	107	0x111

These parameters shall ensure orthogonality of Scaled SS bootstrap symbols and enable robust detection of Service Categories across all defined ZC sequence lengths.

6.4 Combining Normal and Scaled Reduced-Capability Services using OFDMA

Normal and Scaled Bootstraps may coexist within the same OFDMA RF carrier. The placement of bootstraps shall be as illustrated in Figure 6.5 and specified in Table 6.14.

The Normal bootstrap (Nzc =1499) shall be located at the center frequency of the RF carrier. Scaled Bootstraps (Nzc= 127, 241, 467, 839) shall be located at defined frequency offsets from the RF carrier center frequency as specified in Table 6.14.

Scaled VFS Bootstrap symbol 0 shall be used by reduced-capability BXEs for narrow-bandwidth synchronization. Scaled VFS bootstrap symbol 1 shall apply a time-domain cyclic shift to signal the Scaled VFS Symbol 1 signaling fields defined in this section for the current Virtual Frame.

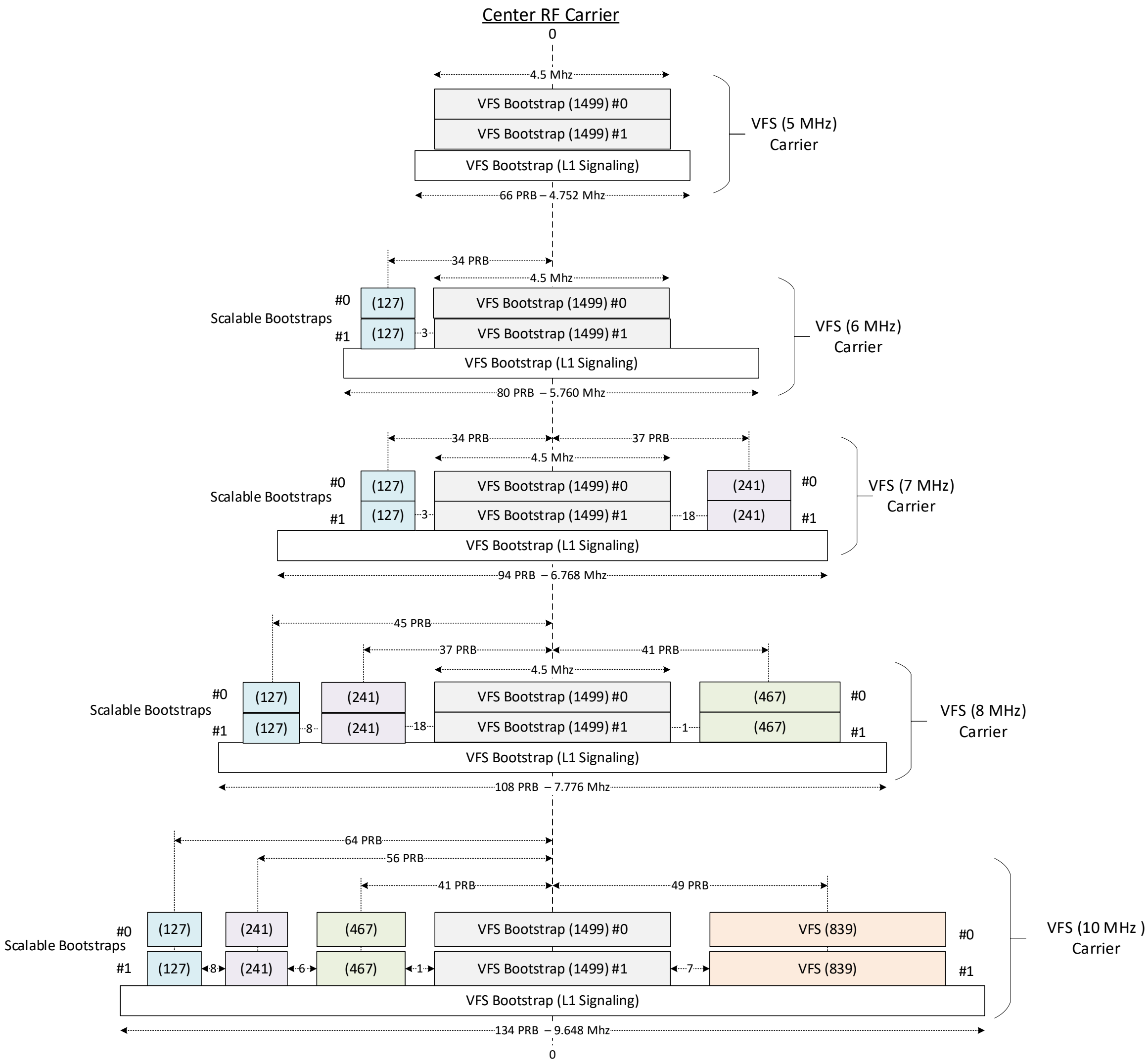

Figure 6.5 Normal and Scaled VFS Bootstraps with RF carrier offsets.

Table 6.14 shall specify the B2X RF bandwidths, the locations of Normal and Scaled VFS bootstraps relative to the carrier center in PRB units (72 kHz), and the transmitter IFFT size used to generate them. This allows BXEs to quickly synchronize to the appropriate bootstrap position at the start of each Virtual Frame in the OFDMA time/frequency grid.

Table 6.14 B2X RF Carriers and VFS Bootstraps Offset From Carrier Center

B2X RF Bandwidth (MHz)	VFS Bootstrap (1499) Offset (PRB)	VFS Bootstrap (839) Offset (PRB)	VFS Bootstrap (467) Offset (PRB)	VFS Bootstrap (241) Offset (PRB)	VFS Bootstrap (127) Offset (PRB)	Transmitter IFFT size Ntx
5	0					2048
6	0				-34	2048
7	0			+37	-34	2048
8	0		+41	-37	-45	4096
10	0	+49	-41	-56	-64	4096

12	0	+49	-41	-56	-64	4096
14	0	+49	-41	-56	-64	4096
15	0	+49	-41	-56	-64	4096
16	0	+49	-41	-56	-64	4096
18	0	+49	-41	-56	-64	4096
20	0	+49	-41	-56	-64	4096
21	0	+49	-41	-56	-64	4096
24	0	+49	-41	-56	-64	4096
30	0	+49	-41	-56	-64	4096
40	0	+49	-41	-56	-64	4096
50	0	+49	-41	-56	-64	4096

Figure 6.6 through Figure 6.8 provide examples of combined operation of Normal and Scaled Bootstraps within different RF carrier bandwidths. VFS bootstrap L1 Signaling directs the BXE to the center frequency of the SS region. These figures are illustrative only.

Figure 6.6 shows an 8 MHz RF carrier with a Virtual Sub-Frame containing both a Normal (*Nzc = 1499*) Bootstrap and a Scaled (*Nzc = 127*) Bootstrap. Other Scaled Bootstraps (*Nzc = 241, 467*) are not shown in this example but may be present in other Virtual Sub-Frames.

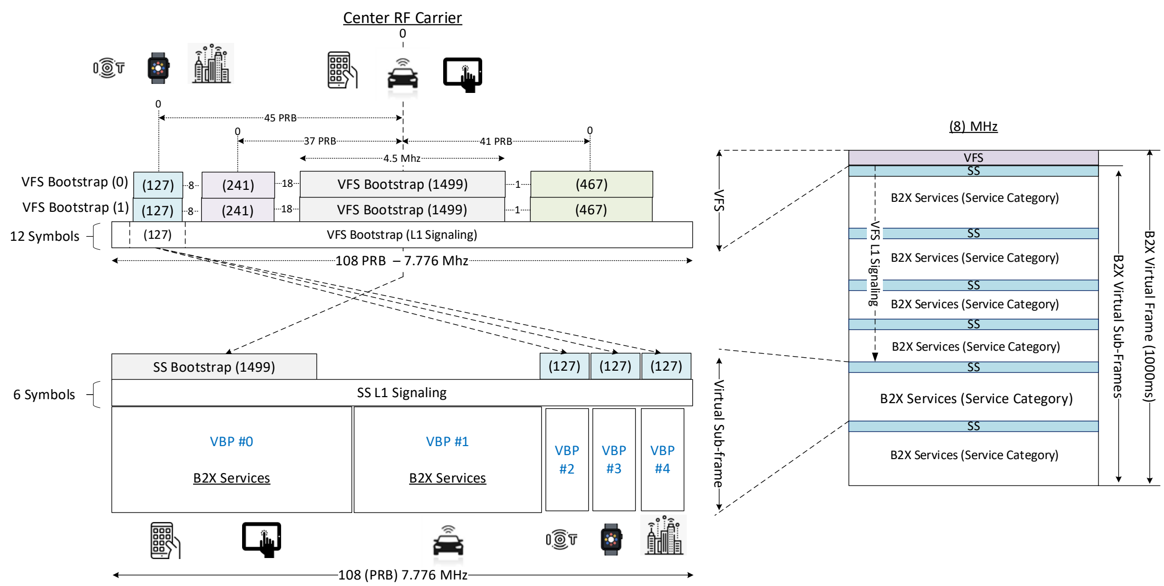

Figure 6.6 Example of 8 MHz RF carrier with Normal and Scaled Bootstraps.

Figure 6.7 shows a 24 MHz RF carrier including the Normal Bootstrap (*Nzc = 1499*) and four reduced-capability services mapped to Scaled Bootstraps (*Nzc = 127, 241, 467, 839*).

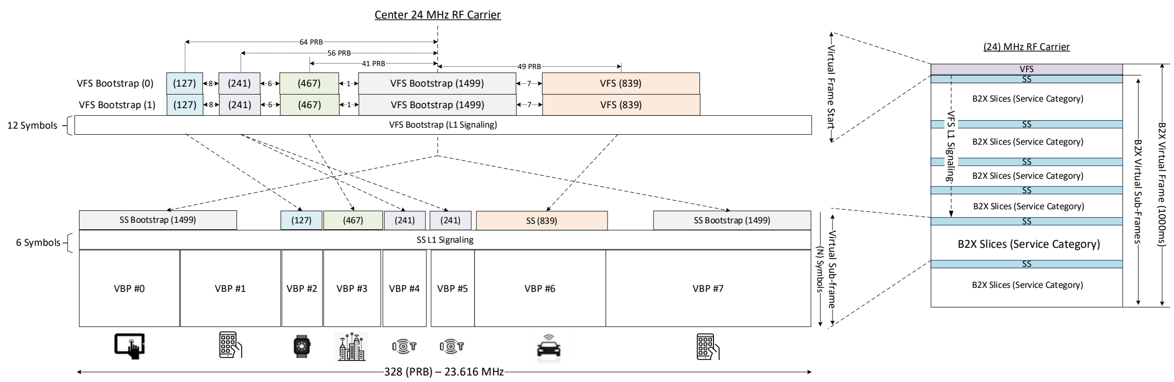

Figure 6.7 Example of 24 MHz RF carrier with Normal and Scaled Services.

Figure 6.7 illustrates Gray-coded cyclic shifts in the time domain for Scaled VFS symbol 1 with *Nrx* = *128* (four signaling bits). The cyclic shifts signal the activity state of up to three DRX Service Categories. In this example, the received binary pattern 0111 corresponds to normal mode (mode = 0), with all three categories (0, 1, 2) being active.

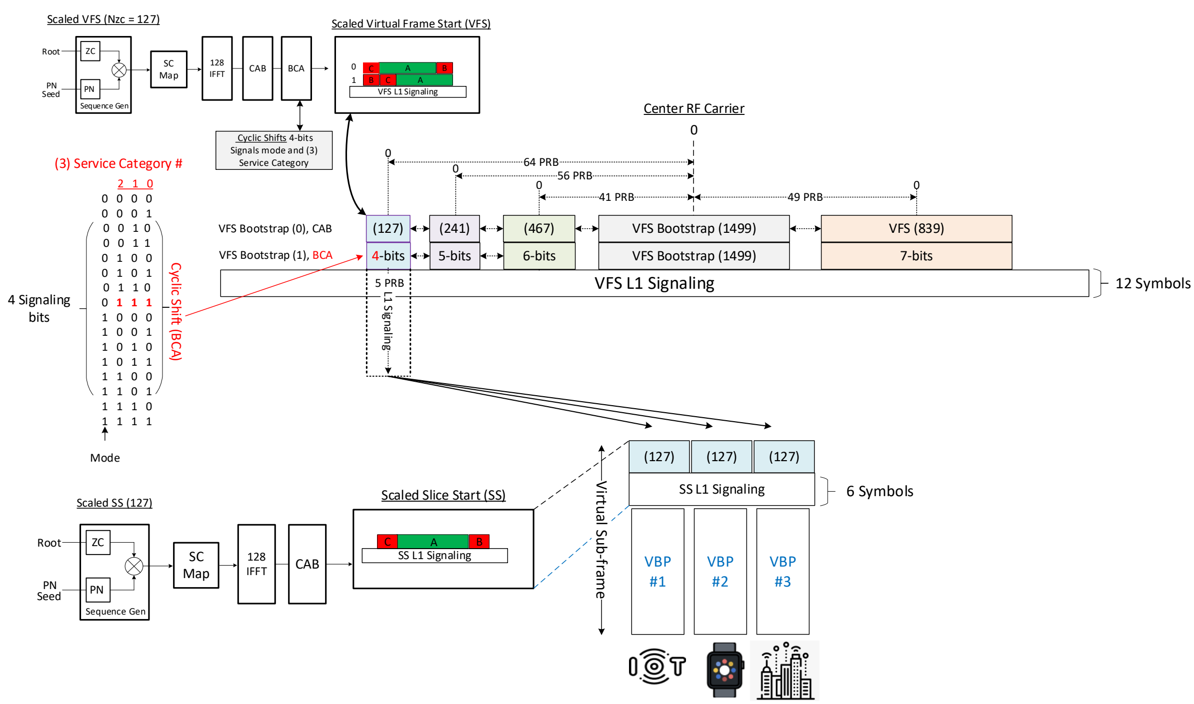

Figure 6.8 Example detection of DRX Service Categories.

Scaled VFS symbol 1 signaling, as defined in Table 6.4, Table 6.5, enables DRX BXEs to quickly determine whether their desired Service Category is active in the current Virtual Frame.

If the desired Service Category is not active, the BXE may immediately return to a low-power state.

The cadence at which a BXE rechecks the bootstrap shall be determined by higher-layer procedures and shall be aligned with system timing (e.g., PTP).

This mechanism shall support battery-efficient operation for IoT and other power-constrained use cases termed extended battery DRX [3].

Each Service Category may be associated with one or more B2X service instances identified by higher-layer signaling. Multiple service instances may coexist across Normal and Scaled Bootstraps within the same RF carrier, thereby supporting diverse Service Categories for both full-capability and reduced-capability BXEs.

Annex A: Example of Generating Scaled VFS (Informative)

This annex provides an informative example illustrating two possible approaches for generating a scaled Virtual Frame Start (VFS) bootstrap sequence as specified in this Standard. The example is provided for explanatory purposes only and does not introduce additional requirements; alternative implementation approaches consistent with this Standard may also be used.

The scalable VFS includes Virtual Bandwidth Parts (VBPs), as shown in Figure 6.5. The frequency domain processing for each VBP is shown in Figure 6.3. Depending on the RF bandwidth, the number of VBPs may vary from 1 to 5. Symbol 1 of each VBP applies a time domain cyclic shift M as described in Section 6.3.5. The cyclic shift may differ for each VBP. One implementation approach is for each VBP to apply its own IFFT to implement the time domain cyclic shift.

Alternatively, to allow all VBPs to be processed using a single IFFT, the equivalent cyclic shift may be applied in the frequency domain prior to IFFT processing. In this approach, the k'th subcarrier of the frequency domain VFS symbol (Figure A-1), is multiplied by v_k , given by:

$$v_k = exp\left(j2\pi\widetilde{M}k/N_{rx}\right) \quad , \quad -N_{rx}/2 \leq k \leq N_{rx}/2 - 1$$

For VFS symbol 0, $\widetilde{M} = 0$. For VFS symbol 1, $\widetilde{M}$ corresponds to the decimal value of the cyclic shift as calculated in Section 6.3.6. N_{rx} is the corresponding receiver FFT size as defined in Table 6.2 and Section 6.3.6.

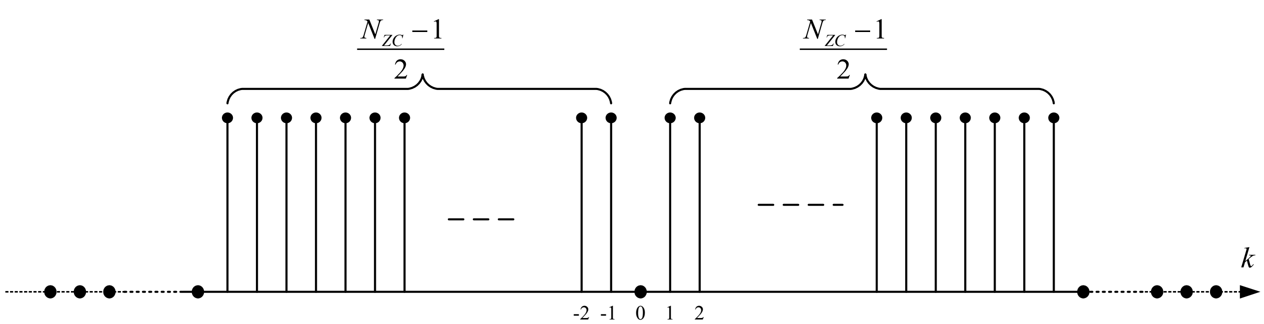

Figure A.1 Subcarriers of VBP with ZC Sequence Length N_{ZC}.

After multiplication with v_k , the VFS symbols may be scaled by a suitable gain and mapped to the appropriate subcarriers, as defined in Table 6.14 and Figure 6.5. The center frequency (k=0 in Figure A.1) may be offset by the value indicated in Table 6.14. Once all VBPs have been mapped, an IFFT may be applied, followed by either the CAB or BCA time domain structure. The processing is shown in Figure A.2.

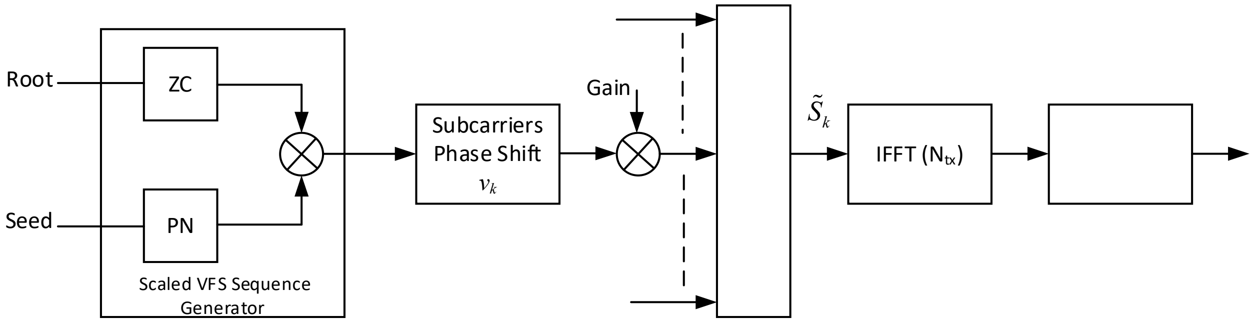

Figure A.2 Example processing flow for generating VFS Symbols.

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