SWiG Standard for
2-Channel acoustic networks

Subsea Wireless Group

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Draft submitted 21 April, 2022

Draft Revisions

Draft corrected 21 December, 2022

Corrected erroneous center frequency table in draft standard.
Added references to amateur radio standards for HDC modulations.
Corrected missing link to range/bit rate data for HDC modulators

Draft corrected 16 June, 2023

Corrected name to “SWiG Level 1 Extended” in text, figures, and legends

Draft corrected 22 June, 2023

Corrected QPSK bandwidth to 0.6 times the bit rate
Corrected “OM” to “OFDM”

Abstract: Physical layer (PHY) and medium access control (MAC) sublayers for acoustic undersea communications are provided for a 2-channel communications system. The standard permits operation of a low-data-rate shared simultaneous multiple access channel (SMAC) enabling network management and data exchange along with a high data rate (HD) channel to provide higher data rate dedicated link. The standard provides for simultaneous operations of both the SMAC and HD under suitable conditions.

Notices and Disclaimers

Initial Authors

Neil Judell, Optimal Systems Laboratory, Inc. (under contract to QinetiQ)

Edmary Altamiranda Maldonado, Aker BP ASA

Introduction

Draft standard for undersea acoustic communications

Contents

SWiG Standard for
2-Channel acoustic networks

1 Overview

1.1 Scope

This standard defines a physical layer (PHY) and media access control (MAC) sublayer for a split-function undersea acoustic network. In providing for both low data rate long-range communication and more flexible high data rate shorter-range communication, the MAC and PHY definitions are split between these two modes. Furthermore, the extremely low bit rates of an acoustic network force both definition types to be far simpler than employed in radio frequency or optical standards. Additionally, this standard deliberately leaves open the possibility of closed, proprietary waveforms for the high data rate operation – leaving some PHY and MAC definitions open.

1.2 Purpose

This standard sets forth a method for operating an acoustic network with both long-range, low-bit rate communications as well as short-range, high-bit rate communications. It establishes open source for achieving these goals, as well as permitting closed, proprietary methods without compromising the overall network.

2 Normative References

The SWiG Standard: SWiGacoustic specification of 22 November 2021 forms the basis of a PHY and MAC description for an acoustic channel. This document is the basis of the proposed standard for the shared simultaneous multiple access channel. Extensions in both PHY and MAC are part of this document.

The IEEE standard Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications of IEEE Std 80.22-2020 provides the basis for PHY specification in this document. IEEE SA - IEEE 802.11-2020

The ongoing Excel spreadsheet of SWiG parameters provides a parallel listing of MAC elements for the shared multiple access channel. It is intended that this spreadsheet will remain synchronized with any draft standards. SWiG parameters not directly involved in network MAC functionality are not directly listed in this document.

3 Definitions, acronyms, and abbreviations

3.1 Definitions

Fast Frequency Hopping Spread Spectrum: A frequency hopping spread spectrum technique in which multiple hops are employed to encode a single symbol. This method is extremely robust against interference and permits large numbers of simultaneous users. Unfortunately, it is also extremely spectrally inefficient, with bit rates that are simply not compatible with undersea communication requirements.

Frequency Division Multiple Access: A technique in which multiple signals coexist with minimal interference, by specifying non-overlapping spectral regions for each signal.

High Data-rate Channel: An acoustic channel intended for non-shared high-data rate communications, either between two nodes, or broadcast from one node to multiple nodes.

Simultaneous Multiple Access Channel: An acoustic channel with media access control and physical layer that permits simultaneous access by multiple nodes. The nodes share the joint channel capacity of an acoustic channel. This channel permits networking among a multiplicity of nodes.

Slow Frequency Hopping Spread Spectrum: A frequency hopping spread spectrum technique in which a single hop is employed to encode a single symbol.

Two-channel protocol: Media access control and physical layer definitions that permit operation of Simultaneous Multiple Access Channel and one or more High Data-rate Channels. Configuration management permits simultaneous operation of these channels, trading bit rate and channel occupancy between/among them.

3.2 Acronyms and abbreviations

16-QAM:	16-level (4 bit) quadrature amplitude modulation
64-QAM:	64-level (6 bit) quadrature amplitude modulation
BFSK:	Binary Frequency Shift Keying
DBFSK:	Differential Binary Frequency Shift Keying

BFSK-FHSS:	A slow FHSS system in which only two tones are possible at each hop, encoding one bit per hop
BPSK:	Binary phase shift keying
CDMA:	Code division multiple access modulation
CSMA:	Carrier Sense Multiple Access
DBPSK:	Differential binary phase shift keying
DQPSK:	Differential quadrature phase shift keying
DSSS:	Direct sequence spread spectrum
SMACMA:	Frequency division multiple access
FEC:	Forward error correction coding
FHSS:	Frequency hopping spread spectrum
HDC:	High Data-rate Channel
LSB:	Least significant bit
MAC:	Media access control
MSB:	Most significant bit
MSK:	Minimum phase-shift keying (linear phase +/- pi/2 radians per chip)
OSMACM:	Orthogonal frequency division multiplexing modulation
PHY:	Physical layer
QPSK:	Quadrature phase shift keying
RF:	Radio frequency
S2C:	Swept sine carrier
SFD	Start Frame Delimiter
SMAC:	Simultaneous Multiple-Access Channel
SNR:	Signal to Noise Ratio (typically in dB – dimensionless)
TDMA:	Time division multiple access

4 General description

4.1 Introduction

Undersea acoustic communication has been dominated by proprietary modulation methods, making interoperability among vendors difficult. This is further complicated by the nature of undersea acoustics, in which information exchange is limited by several factors, many unique to the environment:

- Standard information-theoretic bounds on the ratio of energy-per-bit to noise power spectral density (Eb/N0)
- Complex propagation – with refraction, surface reflection, bottom bounce. Some of these lead to complex arrival patterns, while some (such as bottom bounce) tend to decohere the waveforms.
- Absorption of acoustic energy by seawater is a strong function of frequency, and significantly reduces range capabilities at higher frequencies. This characteristic of seawater tends to force higher bit rate communication to be at shorter and shorter distances.
- Propagation channels tend to change quite rapidly, not only degrading performance relative to information-theoretic bounds, but also requiring sophisticated receiver techniques to build appropriate equalizers.
- Propagation of sound in seawater is many orders of magnitude slower than propagation of electromagnetic waves. Typical sound speed is around 1500 meters per second. A message traveling 10 km takes more than 6.5 seconds just to begin reaching its destination. Add to that a typical transmission speed of 100 bits per second, and we see that packets can readily require minutes to fully propagate and be acknowledged.

There is great disparity in communications requirements among different pieces of equipment. Some equipment must be able to communicate at low bit rates over distances of multiple kilometers. Some equipment needs to be able to transmit a large amount of data in a burst. Some equipment needs to relay video imagery.

This leads toward creation of a network with split functionality:

- A simultaneous multiple access channel (SMAC) capable of supporting multiple, simultaneous low data-rate exchanges and
- A high data rate unshared channel (HDC) capable of supporting a single transmitter at higher data rates

A simple example showing how SMAC and HDC can be used in a very small network is shown in Figure 1. Nodes 1 and 2 communicate back and forth using SMAC. Nodes 1 and 3 communicate back and forth using SMAC. Node 2 transmits to node 3 using HDC, while node 3 transmits back to node 2 using SMAC. Generally, nodes are not required to be capable of simultaneous transmit and receive functions (full-duplex), though the standard does permit such operation for capable nodes.

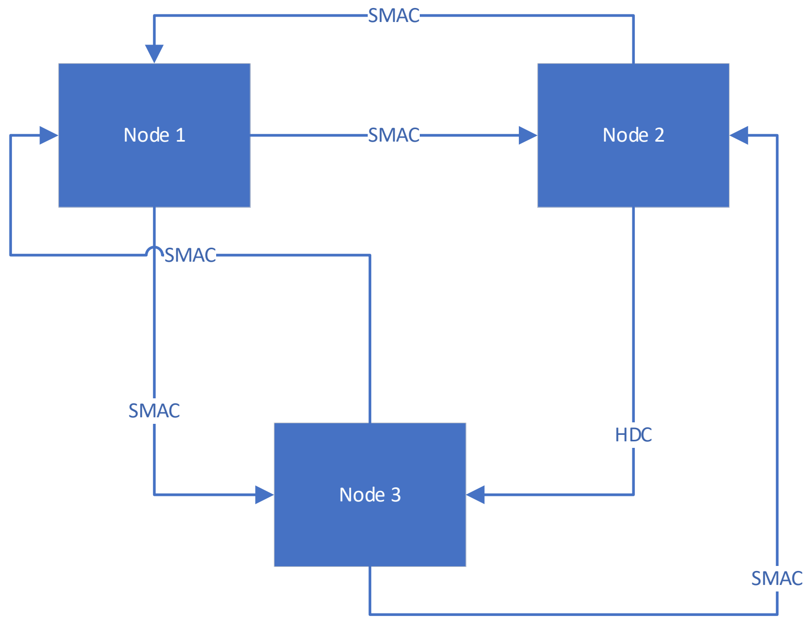

Figure 1: Simple example showing communications paths for SMAC and HDC

Simultaneous operation of channels with disparate function simultaneously requires more sophisticated configuration than typical acoustic communications. The standard specifies methods for time-and-frequency scaling modulation waveforms to adjust the spectrum of the modulator. This flexibility permits the use of FDMA to keep the SMAC and HDC from interfering with each other.

Undersea acoustic communications are typically several orders of magnitude slower than even the slowest of electrical or RF communications systems. Typical bit rates for "fast" acoustic transfers in the 50 kHz regime are in the low 10's of kilobits per second. Typical bit rates for simultaneous multiple access transfers are around 100 bits per second.

4.1.1 Notes regarding MAC layers and PHY layers

The SMAC and HDC have disparate requirements. The SMAC is a shared, low bit rate channel, with large connectivity. The HDC is a high bit rate, single transmitter point-to-point channel. As most nodes in the SMAC will not receive HDC messages during a given transmission, it makes a great deal of sense to have different MAC protocols for the SMAC and for the HDC.

The SMAC is a shared, low bit rate channel. With that in mind, the MAC for the SMAC must be dramatically simpler and occupy a smaller number of bits than other network protocols employ. A typical network MAC with 511 bits would occupy a minimum of 5 seconds for every packet and every node in the SMAC – operating at its highest rate. At lower rates, during sharing, that could rise to more than 20 seconds. This MAC is dedicated to network operation and management, passing small messages and performing ranging operations. This MAC will also be dedicated to configuring and scheduling shared use of SMAC and HDC.

The HDC is a short-term, dedicated link, typically between two nodes only. And typically, only in one direction – with the return path possible via SMAC. Since the HDC is not carrying significant routing or configuration information, this MAC can be extremely simple. ***Furthermore, the intent is that this standard will permit use of closed source, proprietary communications in the HDC***. To this end, the HDC MAC may even be unspecified.

The SMAC PHY will employ only open-source waveforms. At the moment, the only well-defined open-source waveform available with simultaneous multiple access is the BFSK-FHSS modulation contained in the SWiGacoustic standard. It is hoped that future editions of this standard will outline CDMA and S2C waveforms for the SMAC PHY. The SMAC PHY must be configurable in bandwidth and center frequency, to permit spectrum sharing with the HDC PHY

The HDC PHY will support several open-source waveforms outlined in this document. These waveforms all support configurable center frequency and bandwidth for spectrum sharing. Proprietary waveforms will be permitted, so long as they have configurable bandwidth and center frequency, with sufficient frequency control as to not interfere with the SMAC waveforms.

Since much of the SMAC MAC layer is dedicated to the configuration of the SMAC and HDC PHY layer, this standard will reverse the usual specifications – specifying PHY layers before specifying the MAC layers.

4.2 Network topologies

4.2.1 SMAC topologies

The SMAC is used for communications and routing among a plurality of nodes. As such, different topologies must be configurable to support a wide range of potential operations.

As has been mentioned elsewhere in this document, acoustic communications system performance is extremely difficult to predict. Typically, acoustic communication systems lose 5% to 10% of all packets, even when the link budget establishes that bit rate errors should be small. Applications and networks must be designed to be robust under these conditions. Some messages, such as nominal status messages, can afford to these loss rates. Others, such as configuration messages must not be lost. Network topology design can accommodate these requirements, as well as reduce latency.

4.2.1.1 Point-to-point

Simplest topology, in which each node addresses a message directly to either another single node, or a list of nodes.

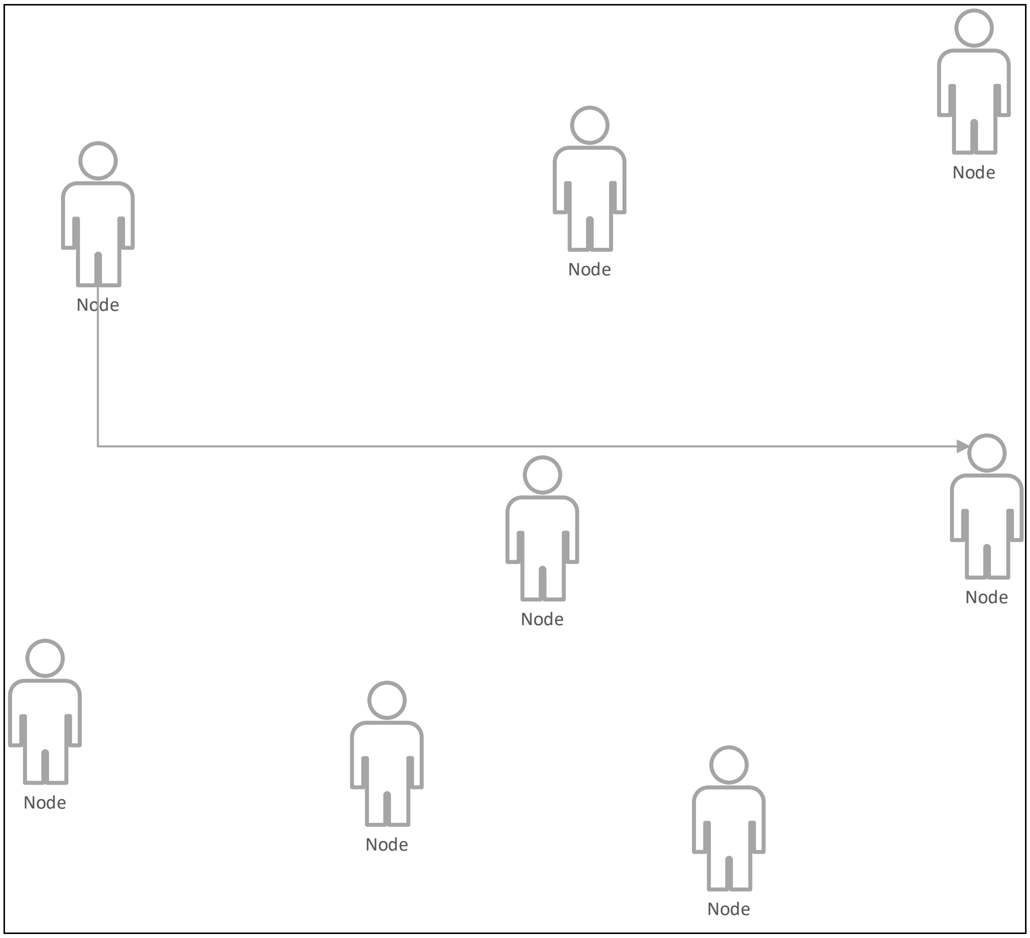

Figure 2: Point-to-point topology

The point-top-point topology has the benefit of simplicity. However, it has a distinct disadvantage if one node attempts to send a message to another node – but link budget or other constraints prohibit any form of direct communication.

4.2.1.2 Store-and-forward

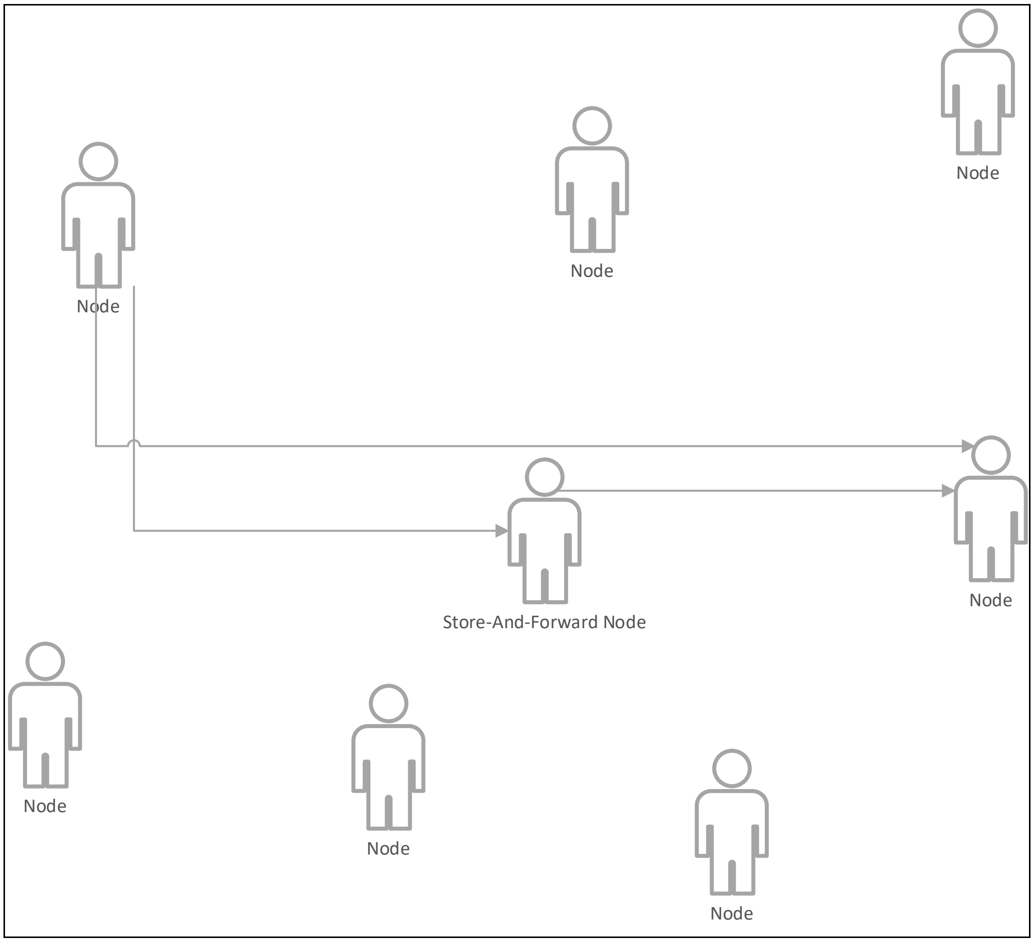

Figure 3: Store-and-forward topology

The store-and-forward network designates certain nodes to operate as store-and-forward operators. The designated store-and-forward nodes are provided a list of destination (client) nodes for which they provide service. If a store-and-forward node receives a message from any node, but directed to one of its client nodes, it will repeat that message, helping to ensure that the client node receives the message. The client node may also have received the message directly. While this topology can overcome connectivity issues, it can result in excess use of the shared capacity and even flooding.

4.2.1.3 Mesh

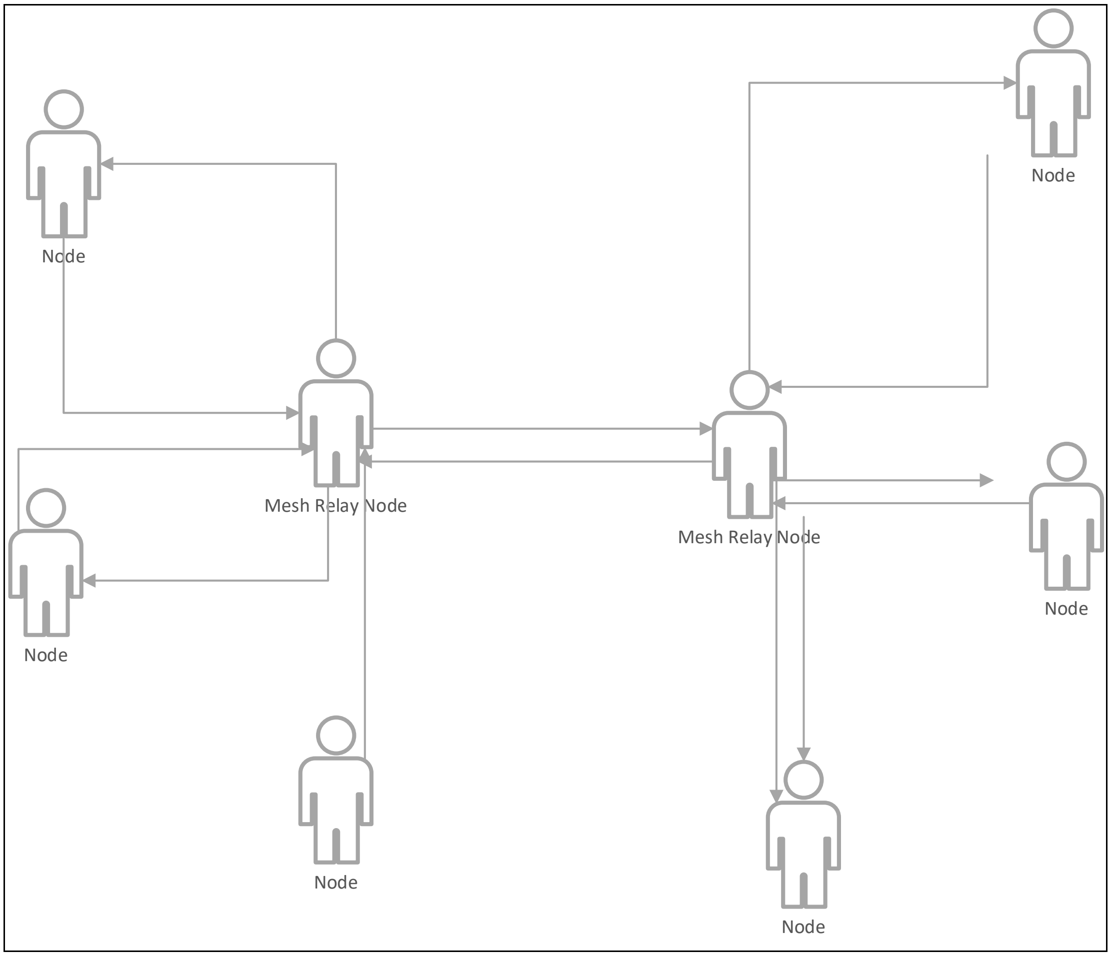

Figure 4: Mesh network topology

The mesh network topology permits more flexible design than store-and-forward. Each node has a designated mesh relay node – and communicates directly only with that node. Mesh relay nodes communicate with one another to pass messages along from node to node.

4.2.1.4 Ad hoc

A special form of point-to-point topology in which the network is self-forming by announcement and consensus.

4.2.2 HDC topologies

The HDC supports a very limited array of different types of operations. It will typically be high bit rate, short distance, between two nodes – with either asymmetric speeds (high speed transmission, low speed response), symmetric speeds, or broadcast from one node to a few nearby nodes.

4.2.2.1 Point-to-point

Because the HDC is not simultaneous multiple access, only one transmitter at a time can access the channel. With the bandwidth and time limitations of acoustic communication, point-to-point with a very small number of nodes is the most logical choice. If certain packets are critical, acknowledgment can be configured to be either via the HDC or the SMAC.

4.2.2.2 Broadcast

Broadcasting of high data rate messages to all nodes in its vicinity that are capable of receipt is possible. However, to prevent channel flooding, any acknowledgment of the data by the recipients must be via the SMAC.

4.2.2.3 Unspecified

Because the HDC is to support closed-source proprietary methods (under suitable conditions), the network topology can be unspecified in the published standard and may be handled directly by the vendor implementing the HDC PHY and MAC.

5 PHY specifications

5.1 Overview

PHY specification for this standard is a bit different from standard PHY, because of the required time-frequency scaling requirements.

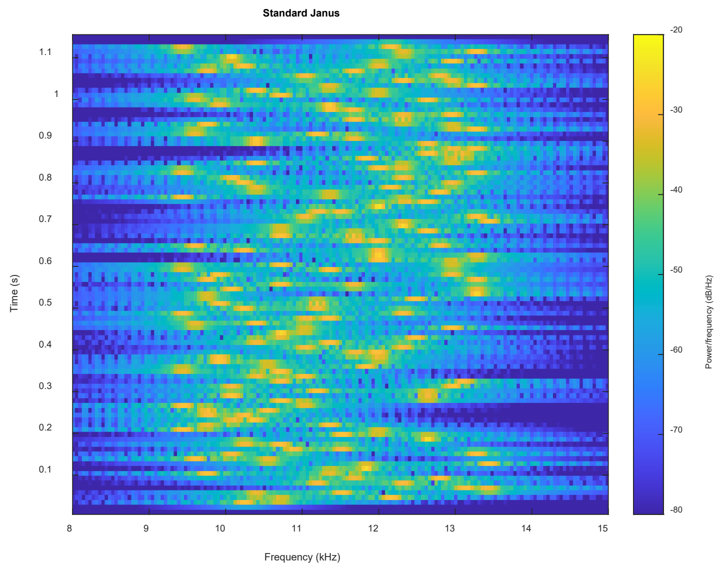

Figure 5: Spectrogram of standard JANUS waveform

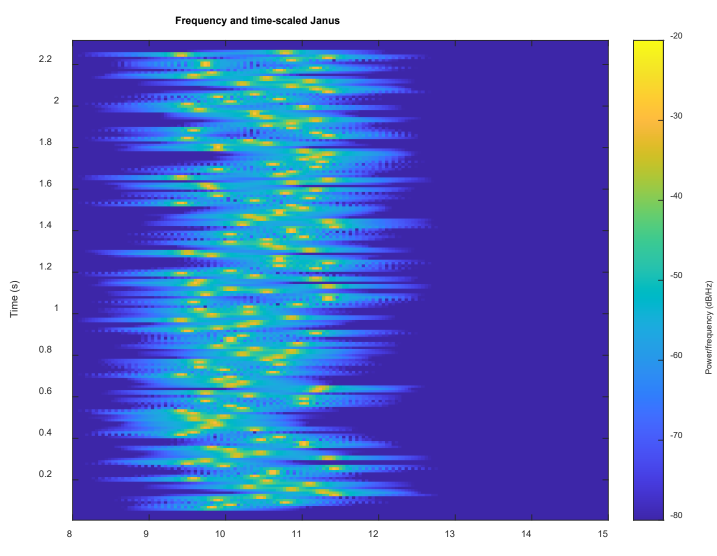

Figure 6: Spectrogram of time-frequency scaled JANUS (1/2 standard bandwidth)

Figure 5 and Figure 6 show the effects of time-frequency scaling and frequency-shifting a standard JANUS BFSK-FHSS waveform (JANUS forms the basis of SWiGacoustic). By scaling the time by a factor of two, the bandwidth is reduced by a factor of two. Sliding the center frequency down permits the whole scaled waveform of the message to occupy just the bottom half of the original spectrum. The tradeoff is that the bit rate is halved. At the same time, since the acoustic power level remains constant, increasing the Eb/N0 by 3 dB.

The same type of time-frequency scaling is possible with CDMA.

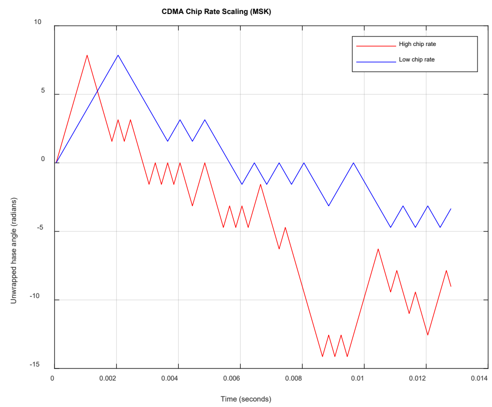

Figure 7: Time domain phase angle of MSK CDMA

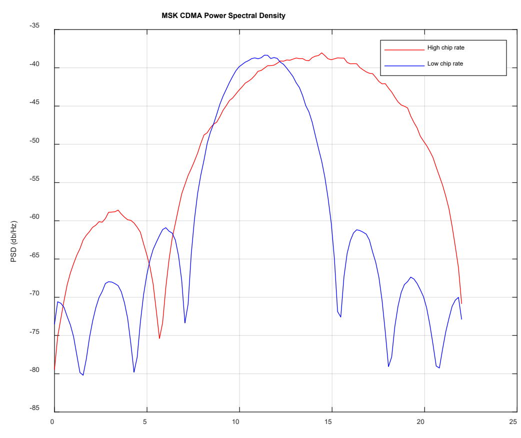

Figure 8: Power spectral density showing time-frequency scaling of MSK CDMA

Figure 7 and Figure 8 show the effects of time-frequency scaling with an MSK CDMA. This chip rate is slowed by a factor of two – reducing the bandwidth by a factor of two. Shifting the carrier frequency permits the time-frequency scaled signal to occupy the bottom half normally occupied by full-rate signaling.

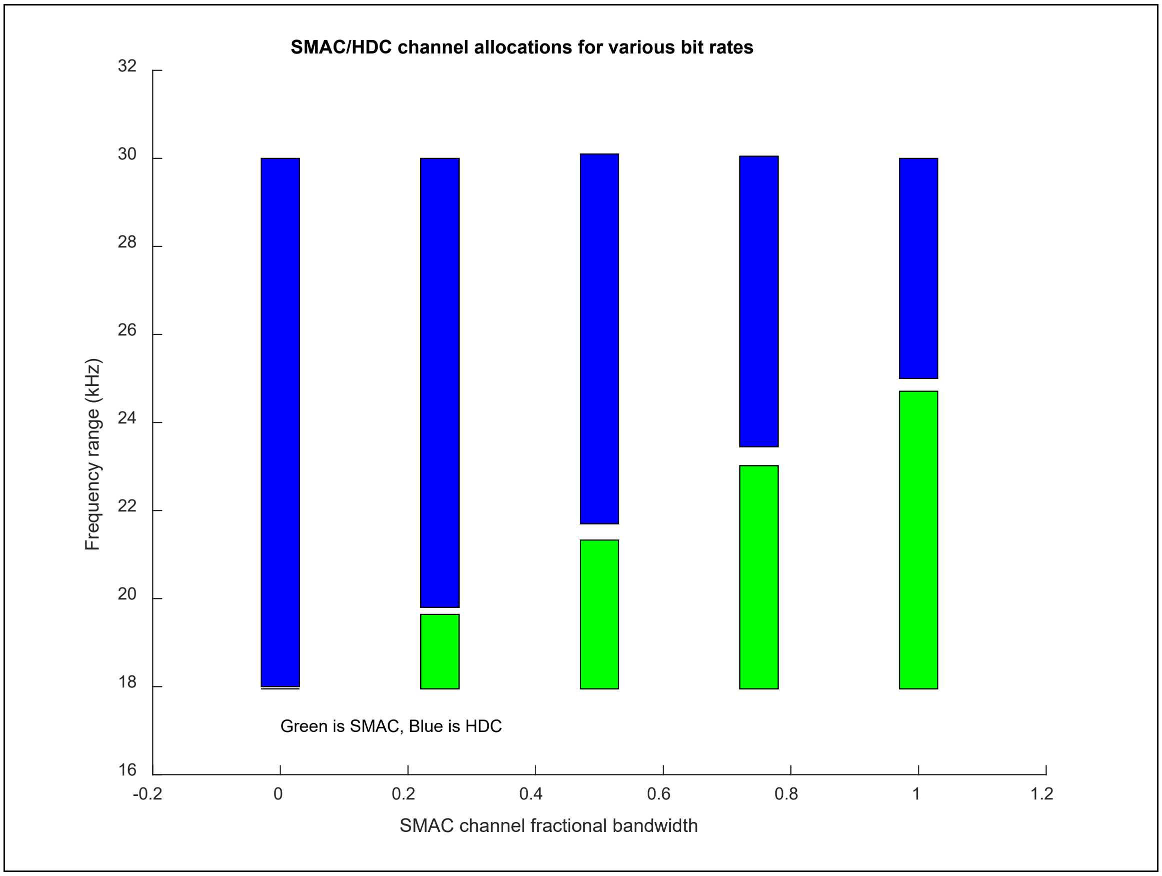

Figure 9: Frequency stacking SMACMA by time-frequency scaling

Figure 9 shows how time-frequency scaling can be used to permit flexible operation of SMAC and HDC. The far left bar shows the proposed QPSK HDC operating at full bandwidth and rate – temporarily shutting down the SMAC operation. The next bar shows the SMAC operating at ¼ bit rate, with the HDC operating at roughly 80% bit rate. As we go further to the right, we see trading bandwidth for bit rate between the channels, ending with the SMAC operating at full rate, while HDC operates at roughly 1/3 rate.

5.2 SMAC PHY

5.2.1 Guardband requirements

Implementors of SMAC modulators, amplifiers and projectors are responsible for ensuring minimization of out-of-band energy transmission to permit interoperability with HDC. Implementors will be responsible for reporting and publishing guard band values to enable network design.

5.2.2 SWiG Level 1 Extended

The present SWiGacoustic standard nearly meets the requirements for SMAC PHY. It lacks the ability to do time-frequency scaling. We adopt the following elements of the SWiGacoustic standard for SMAC:

- CRC

- FEC
- Interleaver
- Preamble
- Symbol mapping to hop tone number
- Chip windowing
- SWiG packet structure

These are to be implemented as the PHY, but with tone spacing, tone center frequency and tone duration scaled to permit a wider range of bit rates, and flexibility in spectrum allocation.

Tone lower edge frequency [Hz]	Symbol to be encoded	FH sequence number
24450	1	12
24190	0	
23930	1	11
23670	0	
23410	1	10
23150	0	
22890	1	9
22630	0	
22370	1	8
22110	0	
21850	1	7
21590	0	
21330	1	6
21070	0	
20810	1	5
20550	0	
20290	1	4
20030	0	
19770	1	3
19510	0	
19250	1	2
18990	0	
18730	1	1
18470	0	
18210	1	0
17950	0	

Table 1: Standard SWiGacoustic tones

Table 1 shows the standard tones from the SWiGacoustic standard. These tones yield a bit rate of up to 110 bps. It is a bandwidth (BW) of 6760 Hz, with a center frequency (Fc) of 21330. We note that there is a frequency slot width (FSw) of 260 Hz between tones, and that the chip duration (Cd) is 0.003846 seconds (1/FSw).

These relationships permit us to define a scalable frequency hopping spread spectrum (FHSS) system.

Tone lower edge frequency [Hz]	Symbol to be encoded	FH sequence number
Fc+12*FSw	1	12
Fc+11*FSw	0	
Fc+10*FSw	1	11
Fc+9*FSw	0	
Fc+8*FSw	1	10
Fc+7*FSw	0	
Fc+6*FSw	1	9
Fc+5*FSw	0	
Fc+4*FSw	1	8
Fc+3*FSw	0	
Fc+2*FSw	1	7
Fc+1*FSw	0	
Fc+0*FSw	1	6
Fc-1*FSw	0	
Fc-2*FSw	1	5
Fc-3*FSw	0	
Fc-4*FSw	1	4
Fc-5*FSw	0	
Fc-6*FSw	1	3
Fc-7*FSw	0	
Fc-8*FSw	1	2
Fc-9*FSw	0	
Fc-10*FSw	1	1
Fc-11*FSw	0	
Fc-12*FSw	1	0
Fc-13*FSw	0	

Table 2: Time-frequency scaled tones for SWiG Level 1 Extended

Rate value code	FSw	BW	Cd	Max bit rate
0	65 Hz	1690 Hz	0.015385 sec	27.5 bps
1	130 Hz	3380 Hz	0.00769 sec	55 bps
2	195 Hz	5070 Hz	0.005128 sec	82.5 bps
3	260 Hz	6760 Hz	0.003486 sec	110 bps
4	325 Hz	8450 Hz	0.0031 sec	137.5 bps
5	390 Hz	10140 Hz	0.002564 sec	165 bps
6	455 Hz	11830 Hz	0.0022 sec	192.5 bps
7	520 Hz	13520 Hz	0.00192 sec	220 bps

Table 3: Rate values, slot widths, bandwidth etc.

The FHSS can slide up or down in frequency, by changing Fc.

Fc value code	Fc
0	18795 Hz
1	19640 Hz
2	20485 Hz
3	21330 Hz
4	23465 Hz
5	24310 Hz
6	25155 Hz
7	26000 Hz

Table 4: Center frequency codes and values

Rate value code	Fc value code	Lowest frequency	Highest Frequency	Max bit rate
0	0	17950 Hz	19640 Hz	27.5 bps
1	1	17950 Hz	21330 Hz	55 bps
2	2	17950 Hz	23020 Hz	82.5 bps
3	3	17950 Hz	24710 Hz	110 bps
4	4	19240 Hz	27690 Hz	137.5 bps
5	5	19240 Hz	29380 Hz	165 bps
6	6	19240 Hz	31070 Hz	192.5 bps
7	7	19240 Hz	32490 Hz	220 bps

Table 5: Recommended rate and center frequency combinations

It should be noted that with rate code 3 and Fc code 3, the resulting FHSS modulator will be exactly the present SWiG Level 1 modulator. The combinations of codes 0 through 3 is selected to fix the lower band edge to that of SWiG Level 1, while changing bandwidth to permit sharing with HDC1. These permit operating with any SWiG Level 1 transducer system.
Codes of 4 and above fix the lower edge at 19240 Hz, adjusting the upper edge from 27690 Hz to 32490 Hz. These combinations permit operation with smaller and more readily available transducers.

5.2.3 BPSK-CDMA

TBD – but may be taken from modified BPSK-CDMA PHY for HDC

5.2.4 S2C

TBD

5.3 Expected Range/Bit rate Performance for SMAC Modulators

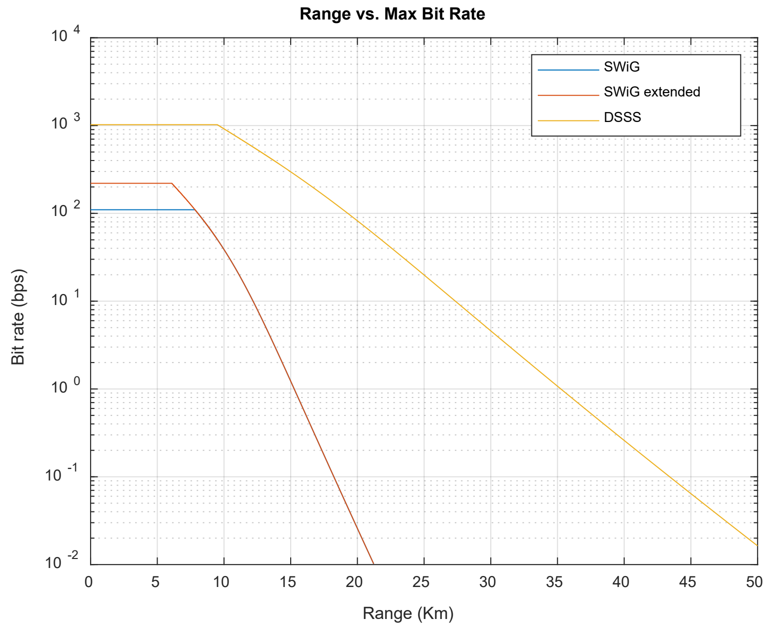

Figure 10: Expected range/bit rate performance for SMAC modulators

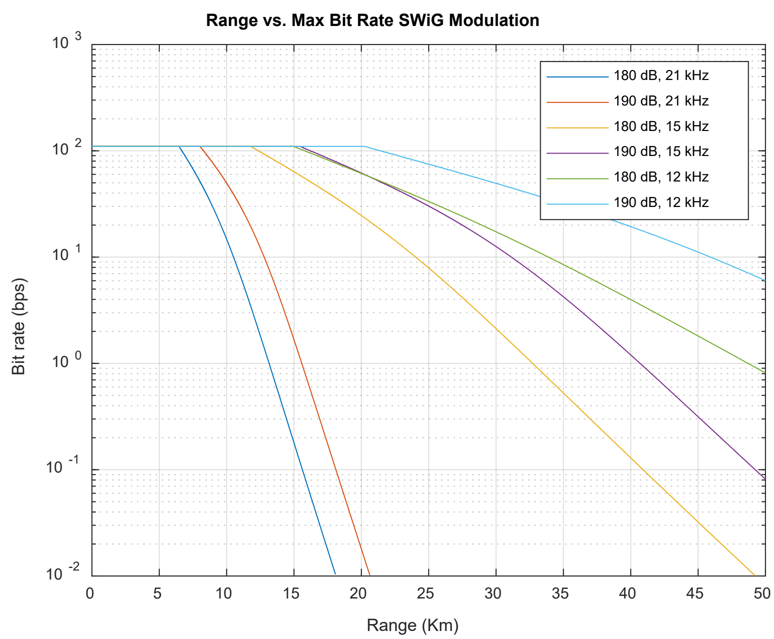

Figure 11: Expected range/bit rate performance for SWiG modulator under varying power and center frequency

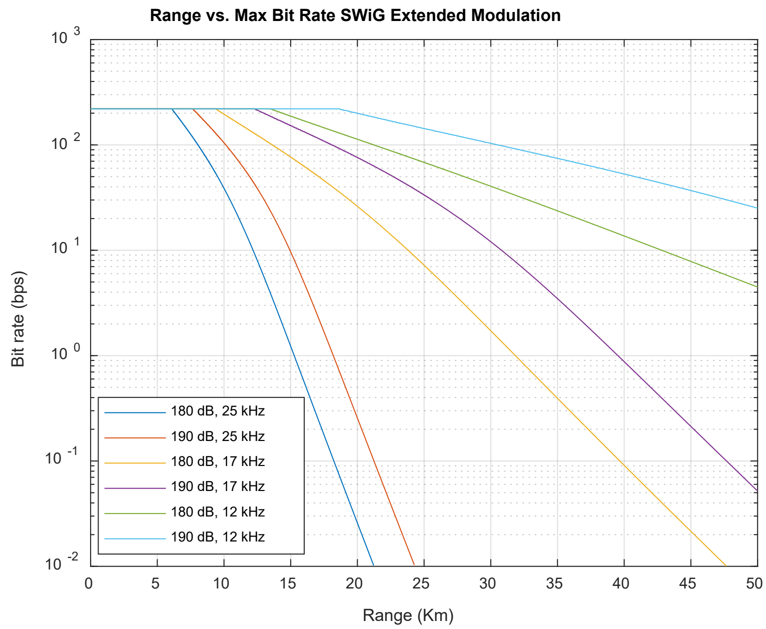

Figure 12: Expected range/bit rate performance for SWiG Enhanced modulator under varying power and center frequency

Range/bit rates based on link budget using minimum Eb/N0 of 9 dB, reliable acoustic path propagation, sea state 3, shipping noise of 70 dB re 1 micro Pascal per root-Hz.

5.4 HDC PHY

5.4.1 Guardband requirements

Implementors of HDC modulators, amplifiers and projectors are responsible for ensuring minimization of out-of-band energy transmission to permit interoperability with SMAC. Implementors will be responsible for reporting and publishing guard band values to enable network design.

5.4.2 Open-source modulators

5.4.2.1 BPSK streaming

Modified from amateur radio standard QPKS31. (Wikipedia, n.d.)

5.4.2.1.1 Differential binary phase shift keying (DBPSK) – one bit per symbol
5.4.2.1.2 Streaming data – all formatting to be determined by the user
5.4.2.1.3 Convolutional coding with form of poly2trellis(5, [23,35]) (2:1 encoding)
5.4.2.1.4 Intersymbol interference (ISI) filter – which also removes sidelobes to permit interoperability:
5.4.2.1.5 Root-raised cosine
5.4.2.1.6 Filter span of 16 symbols
5.4.2.1.7 Rolloff factor of 0.2
5.4.2.1.8 The bandwidth of this signal is 1.2 times the input bit rate. Transducers supporting SWiG level 1 will generally also support transmission in the 20 kHz to 30 kHz regime.

Therefore, the following carrier frequencies and bit rates will be supported:

5.4.2.1.8.1 24 kHz carrier, 5 Kbits/sec – SMAC channel shut down completely during HD use

5.4.2.1.8.2 24.9 kHz carrier, 4.25 Kbits/sec – SMAC channel will operate at ¼ rate

5.4.2.1.8.3 25.6 kHz carrier, 3.667 Kbits/sec – SMAC channel will operate at ½ rate

5.4.2.1.8.4 26.5 kHz carrier, 3 Kbits/sec – SMAC channel will operate at ¾ rate

5.4.2.1.8.5 27.5 kHz carrier, 2.083 Kbits/sec – SMAC channel operates at full capacity

5.4.2.1.9 PHY parameters

5.4.2.1.9.1 Code for rate (0-4)

5.4.2.2 BPSK packet

5.4.2.2.1 Point-to-point, with time, source and destination specified in the SMAC channel negotiation

5.4.2.2.2 Differential binary phase shift keying (DBPSK) – one bit per symbol

5.4.2.2.3 Packet data

5.4.2.2.4 Coding

5.4.2.2.4.1 BCH(511,250) hard BCH without CRC (250 bits/packet) or

5.4.2.2.4.2 BCH(511,259) soft BCH with CRC-8-CCITT (251 bits/packet)

5.4.2.2.5 Intersymbol interference (ISI) filter – which also removes sidelobes to permit interoperability:

5.4.2.2.5.1 Root-raised cosine

5.4.2.2.5.2 Filter span of 16 symbols

5.4.2.2.5.3 Rolloff factor of 0.2

5.4.2.2.6 The packet shall be preceded by a training/channel probe waveform of a length 127 m-sequence using BPSK modulation (and ISI filter).

5.4.2.2.6.1 Generating polynomial: z^7 + z^3 + 1

5.4.2.2.6.2 Initial state: all ones

5.4.2.2.7 This training waveform will be followed by 32 symbol periods of silence

5.4.2.2.8 The packet waveform will then be transmitted

5.4.2.2.9 The bandwidth of this signal is 1.2 times the input bit rate. Transducers supporting SWiG level 1 will generally also support transmission in the 20 kHz to 30 kHz regime. Therefore, the following carrier frequencies and bit rates will be supported:

5.4.2.2.9.1 24 kHz carrier, 5 Kbits/sec – SMAC channel shut down completely during HD use

5.4.2.2.9.2 24.9 kHz carrier, 4.25 Kbits/sec – SMAC channel will operate at ¼ rate

5.4.2.2.9.3 25.6 kHz carrier, 3.667 Kbits/sec – SMAC channel will operate at ½ rate

5.4.2.2.9.4 26.5 kHz carrier, 3 Kbits/sec – SMAC channel will operate at ¾ rate

5.4.2.2.9.5 27.5 kHz carrier, 2.083 Kbits/sec – SMAC channel operates at full capacity

5.4.2.2.10 PHY Parameters

5.4.2.2.10.1 Code for rate (0-4)

5.4.2.2.10.2 Code for CRC/no CRC (1/0)

5.4.2.3 QPSK streaming

Modified from amateur radio standard QPKS31. (Wikipedia, n.d.)

5.4.2.3.1 Differential quadrature phase shift keying (DQPSK) – two bits per symbol
5.4.2.3.2 Streaming data – all formatting to be determined by the user
5.4.2.3.3 Convolutional coding with form of poly2trellis(5, [23,35]) (2:1 encoding)
5.4.2.3.4 Intersymbol interference (ISI) filter – which also removes sidelobes to permit interoperability:

5.4.2.3.4.1 Root-raised cosine

5.4.2.3.4.2 Filter span of 16 symbols

5.4.2.3.4.3 Rolloff factor of 0.2

5.4.2.3.5 The bandwidth of this signal is 0.6 times the input bit rate. Transducers supporting SWiG level 1 will generally also support transmission in the 20 kHz to 30 kHz regime. Therefore, the following carrier frequencies and bit rates will be supported:

5.4.2.3.5.1 24 kHz carrier, 10 Kbits/sec – SMAC channel shut down completely during HD use

5.4.2.3.5.2 24.9 kHz carrier, 8.5 Kbits/sec – SMAC channel will operate at ¼ rate

5.4.2.3.5.3 25.6 kHz carrier, 7.333 Kbits/sec – SMAC channel will operate at ½ rate

5.4.2.3.5.4 26.5 kHz carrier, 6 Kbits/sec – SMAC channel will operate at ¾ rate

5.4.2.3.5.5 27.5 kHz carrier, 4.166 Kbits/sec – SMAC channel operates at full capacity

5.4.2.3.6 PHY Parameters

5.4.2.3.6.1 Code for rate (0-4)

5.4.2.4 QPSK packet

5.4.2.4.1 Point-to-point, with time, source and destination specified in the SMAC channel negotiation
5.4.2.4.2 Differential quadrature phase shift keying (DQPSK) – two bits per symbol
5.4.2.4.3 Packet data
5.4.2.4.4 Coding

5.4.2.4.4.1 BCH(511,250) hard BCH without CRC (250 bits/packet) or

5.4.2.4.4.2 BCH(511,259) soft BCH with CRC-8-CCITT (251 bits/packet)

5.4.2.4.5 Intersymbol interference (ISI) filter – which also removes sidelobes to permit interoperability:

5.4.2.4.5.1 Root-raised cosine

5.4.2.4.5.2 Filter span of 16 symbols

5.4.2.4.5.3 Rolloff factor of 0.2

5.4.2.4.6 The packet shall be preceded by a training/channel probe waveform of a length 127 m-sequence using BPSK modulation (and ISI filter).

5.4.2.4.6.1 Generating polynomial: z^7 + z^3 + 1

5.4.2.4.6.2 Initial state: all ones

5.4.2.4.7 This training waveform will be followed by 32 symbol periods of silence
5.4.2.4.8 The packet waveform will then be transmitted
5.4.2.4.9 The bandwidth of this signal is 0.6 times the input bit rate. Transducers supporting SWiG level 1 will generally also support transmission in the 20 kHz to 30 kHz regime. Therefore, the following carrier frequencies and bit rates will be supported:

5.4.2.4.9.1 24 kHz carrier, 10 Kbits/sec – SMAC channel shut down completely during HD use

5.4.2.4.9.2 24.9 kHz carrier, 8.5 Kbits/sec – SMAC channel will operate at ¼ rate

5.4.2.4.9.3 25.6 kHz carrier, 7.333 Kbits/sec – SMAC channel will operate at ½ rate

5.4.2.4.9.4 26.5 kHz carrier, 6 Kbits/sec – SMAC channel will operate at ¾ rate

5.4.2.4.9.5 27.5 kHz carrier, 4.166 Kbits/sec – SMAC channel operates at full capacity

5.4.2.4.10 PHY Parameters

5.4.2.4.10.1 Code for rate (0-4)

5.4.2.4.10.2 Code for CRC/no CRC (1/0)

5.4.2.5 BFSK packet

5.4.2.5.1 Point-to-point, with time, source and destination specified in the SMAC channel negotiation

5.4.2.5.2 Differential BFSK with one bit per symbol

5.4.2.5.3 Tone duration equal to 1/Bandwidth

5.4.2.5.4 Tukey window may optionally be applied to each tone to reduce spectral spreading

5.4.2.5.5 Packet data

5.4.2.5.6 Coding

5.4.2.5.6.1 BCH(511,250) hard BCH without CRC (250 bits/packet) or

5.4.2.5.6.2 BCH(511,259) soft BCH with CRC-8-CCITT (251 bits/packet)

5.4.2.5.7 The packet shall be preceded by a training/channel probe waveform of a length 127 m-sequence using DBFSK

5.4.2.5.7.1 Generating polynomial: z^7 + z^3 + 1

5.4.2.5.7.2 Initial state: all ones

5.4.2.5.8 The packet waveform will then be transmitted

5.4.2.5.9 PHY Parameters:

5.4.2.5.9.1 Option for Tukey window (0/1)

5.4.2.5.9.2 Bandwidth in 10s of Hz (10-32767)

5.4.2.5.9.3 Center frequency in 10s of Hz (100-32767)

5.4.2.6 BPSK-CDMA

5.4.2.6.1 Point-to-point, with time, source and destination specified in the SMAC channel negotiation

5.4.2.6.2 CDMA Gold sequence

5.4.2.6.2.1 Generating polynomial 1: z^7 + z^3 + 1

5.4.2.6.2.2 Initial state 1: all zeros, followed by one

5.4.2.6.2.3 Generating polynomial 2: z^7 + z^3 + z^2 + z^1 + 1

5.4.2.6.2.4 Initial state 2: all zeros, followed by one

5.4.2.6.2.5 Code selection (in the range 0 to 127)

5.4.2.6.3 Each bit incorporates a full 127-chip Gold sequence

5.4.2.6.4 Gold sequence modulation is BPSK

5.4.2.6.5 First symbol sent is for training and phase acquisition, does not include any data

5.4.2.6.6 Remaining symbols are differential phase from data bits

5.4.2.6.7 Interchip interference (ICI) filter – which also removes sidelobes to permit interoperability:

5.4.2.6.7.1 Root-raised cosine

5.4.2.6.7.2 Filter span of 16 chips

5.4.2.6.7.3 Rolloff factor of 0.2

5.4.2.6.8 Chip rate is equal to bandwidth/1.2

5.4.2.6.9 Packet data

5.4.2.6.10 Coding

5.4.2.6.10.1 BCH(511,250) hard BCH without CRC (250 bits/packet) or

5.4.2.6.10.2 BCH(511,259) soft BCH with CRC-8-CCITT (251 bits/packet)

5.4.2.6.11 PHY Parameters

5.4.2.6.11.1 Code for CRC/no CRC (1/0)

5.4.2.6.11.2 Bandwidth in 10's of Hz (10-32767)

5.4.2.6.11.3 Center frequency in 10's of Hz (100-32767)

5.4.2.7 OFDM

5.4.2.7.1 OFDM for HDC shall incorporate the following features and elements of 802.11a OFDM PHY

5.4.2.7.1.1 Preamble

5.4.2.7.1.2 SYNC

5.4.2.7.1.3 SFD

5.4.2.7.1.4 SIGNAL field

5.4.2.7.1.5 SERVICE field

5.4.2.7.1.6 LENGTH field

5.4.2.7.1.7 CRC

5.4.2.7.1.8 Data scrambler

5.4.2.7.1.9 OFDM guard times

5.4.2.7.1.10 OFDM pilot subchannels

5.4.2.7.1.11 Cyclic prefix

OFDM for HDC differs from 802.11a OFDM PHY in that the bandwidth and center frequency for the channel are specified in configuration.

5.4.2.7.2 OFDM time-frequency scaling characteristics for HDC PHY

Modulation	**Coding rate (R)**	**Coded bits per subcarrier (N_{BPSC})**	**Coded bits per OFDM symbol (N_{CBPS})**	**Data bits per OFDM symbol (N_{DBPS})**	**Data bits per second**	**Code for selection**
BPSK	1/2	1	48	24	24*BW/80	0
BPSK	3/4	1	48	36	36*BW/80	1
QPSK	1/2	2	96	48	48*BW/80	2
QPSK	3/4	2	96	72	72*BW/80	3

16-QAM	1/2	4	192	96	96*BW/80	4
16-QAM	3/4	4	192	144	144*BW/80	5
64-QAM	2/3	6	288	192	192*BW/80	6
64-QAM	3/4	6	288	216	216*BW/80	7

Table 6: OFDM modulation, coding and bit rates

5.4.2.7.3 PHY Parameters:

5.4.2.7.3.1 Code (see Table 6) (0-7)

5.4.2.7.3.2 BW specified in 10s of Hz (10-32767)

5.4.2.7.3.3 Center frequency specified in 10s of Hz (100-32767)

5.4.2.8 MIMO-OTFS TBD

It is expected that once this modulation is accepted into 5G or 6G communications, SWiG will adopt a time-frequency scaled version for use in HDC.

5.4.2.9 Proprietary PHY for HDC

To be determined by vendors. Vendors to propose codes to designate modulation type, center frequency, time-frequency scaling and any other essential parameters needed by them to specify the PHY

5.4.3 Expected Range/Bit rate Performance for HDC Modulators

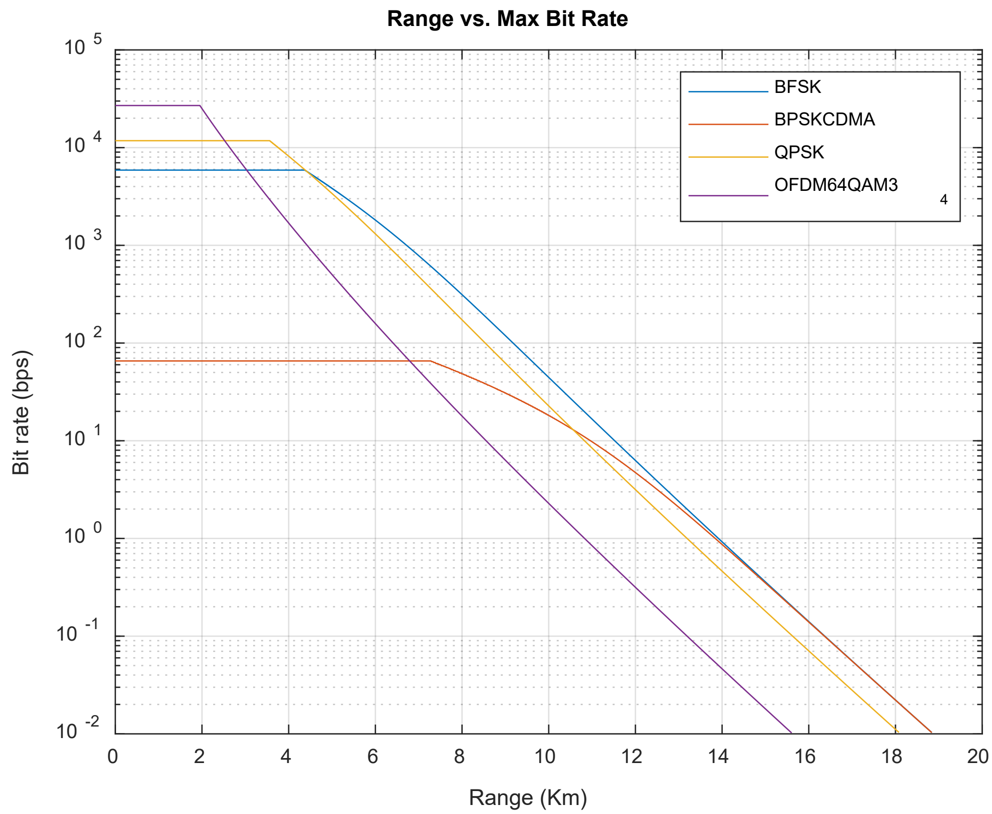

Figure 13 Expected Range/Bit rate Performance for HDC Modulators

6 MAC protocol specifications

6.1 MAC functional description SMAC

The MAC for SMAC must be flexible enough to permit network configuration and operation, but at the same time, be lightweight enough to be supportable at very low bit rates. Definition of this MAC will always be at odds between capability and bit rate.

6.1.1 MAC Physical access

Physical access to SMAC can be direct access, CSMA or TDMA. CSMA provides backward compatibility with SWiGacoustic standard, while direct access will help support higher network throughput, at the expense of complexity of modem and possibly power consumption of modem. The choice of CSMA nor direct access is made at deployment time and may not be changed. A mixed network of CSMA and direct access modems is permissible and will function. Mixing TDMA access with either CSMA or direct access is risky and not recommended.

6.1.2 Baseline MAC block

6.1.3

Bits	Value
1-4 (4 bits)	Version number
5 (1 bit)	Schedule: always 1
6 (1 bit)	Source present: always 1
7 (1 bit)	Destination present: always 1
8-13 (7 bits)	From table 1 of SWiG Level 1 standard, sufficient for number of bits in message
14-21 (8 bits)	Source ID
22-29 (8 bits)	Destination ID. If Destination ID equals Source ID, then special addressing will be attached
30-38 (9 bits)	Command (i.e. SWiG parameter index)
39 (1 bit)	ACK required
40-47 (8 bits)	Number of additional blocks to follow. NOTE: each additional block will have 56 useable data bits, along with an 8-bit CRC (same algorithm as baseline Application Data Block). This permits message lengths up to 14 Kbits.
48-56 (7 bits)	CRC-7 of all remaining 56-bit user data, with p(x)= $x^7 + x^3 + 1$, init=0. This is used as a message hash to permit message identification for acknowledgment.
57-64 (8 bits)	CRC as per SWiG Level 1 specification

Table 7: Baseline SMAC MAC block

6.1.3.1 Subsequent blocks if special addressing

6.1.3.1.1 Follow-on special addressing block 1

6.1.3.1.2

Bits	Value
1-56 (56 bits)	One bit for each destination address – little-endian, addresses 0 through 55
57-64 (8 bits)	CRC as per SWiG Level 1 specification

6.1.3.1.3 Follow-on block 2

Bits	Value
1-56 (56 bits)	One bit for each destination address – little-endian, addresses 56 through 101
57-64 (8 bits)	CRC as per SWiG Level 1 specification

6.1.3.1.4 Follow-on special addressing block 3

Bits	Value
1-56 (56 bits)	One bit for each destination address – little-endian, addresses 102 through 157
57-64 (8 bits)	CRC as per SWiG Level 1 specification

6.1.3.1.5 Follow-on special addressing block 4

Bits	Value
1-56 (56 bits)	One bit for each destination address – little-endian, addresses 158 through 213
57-64 (8 bits)	CRC as per SWiG Level 1 specification

6.1.3.1.6 Follow-on special addressing block 5

Bits	Value
1-42 (42 bits)	One bit for each destination address – little-endian, addresses 214 through 255
57-64 (8 bits)	CRC as per SWiG Level 1 specification

6.1.3.2 Follow-on data block 1

Bits	Value
1-7 (7 bits)	Number of valid bits in last follow-on-block (permits messages shorter than exact multiple of 56 bits)
8-23 (16 bits)	Type code – designates function of following blocks
24-56 (33 bits)	Reserved
57-64 (8 bits)	CRC as per SWiG Level 1 specification

6.1.3.3 Follow-on blocks after data block 1

6.1.3.3.1 Code 1 through code 106

6.1.3.3.2 Contribution to SWiG Commands

The ongoing Excel spreadsheet of SWiG parameters provides a parallel listing of MAC elements for the shared multiple access channel. It is intended that this spreadsheet will remain synchronized with any draft standards. SWiG parameters not directly involved in network MAC functionality are not directly listed in this document. These codes represent more generic access than network MAC access requires.

6.1.3.3.3 Code 107 – schedule HDC access

Note that because this is a scheduled event, it self-reports its present time, to allow for clock synchronization, to overcome clock drift

Bits	Value
1-6 (6 bits)	Present hour (24 hour format)
7-13 (7 bits)	Minutes
14-20 (7 bits)	Seconds
21-25 (6 bits)	Start hour
26-32 (7 bits)	Start minutes
33-39 (7 bits)	Start seconds
40-55 (16 bits)	Duration in seconds
56-71 (16 bits)	SMAC Fc value code (unsigned)
72-83 (12 bits)	SMAC rate value code (unsigned)
84-93 (10 bits)	HDC PHY Parameter 1 (typically a code of some kind)
94-109 (16 bits)	HDC PHY Parameter 2 (typically bandwidth in 10's of Hz)
110-125 (16 bits)	HDC PHY Parameter 3 (typically center frequency in 10's of Hz)
126-133 (8 bits)	Control node/master transmitter of HDC (typically this node ID)

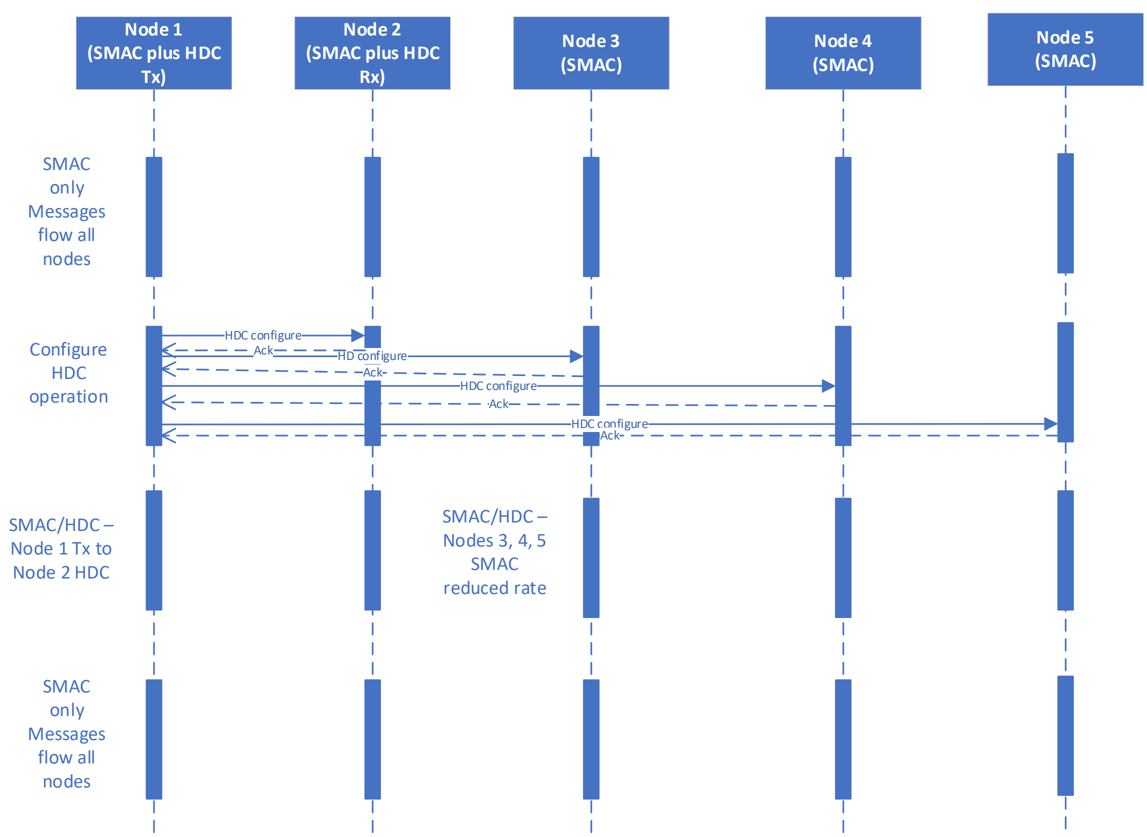

Figure 14: HDC messaging and operational sequence

Entity initiating scheduled HDC access is responsible for ensuring that there is not merely no overlap between HDC and SMAC bands, but that sufficient guardband exists based on implementor's published specifications.

6.1.3.3.4 Code 108 – User data

Bits	Value
1-56 (56 bits)	Data
57-64 (8 bits)	CRC as per SWiG Level 1 specification

6.1.3.3.5 Code 109 – ACK

Bits	Value
1-7 (7 bits)	CRC-7 value taken from Baseline Application Data block of originator – used as a hash to ensure ACK is for correct message
8-56 (49 bits)	Reserved
57-64 (8 bits)	CRC as per SWiG Level 1 specification

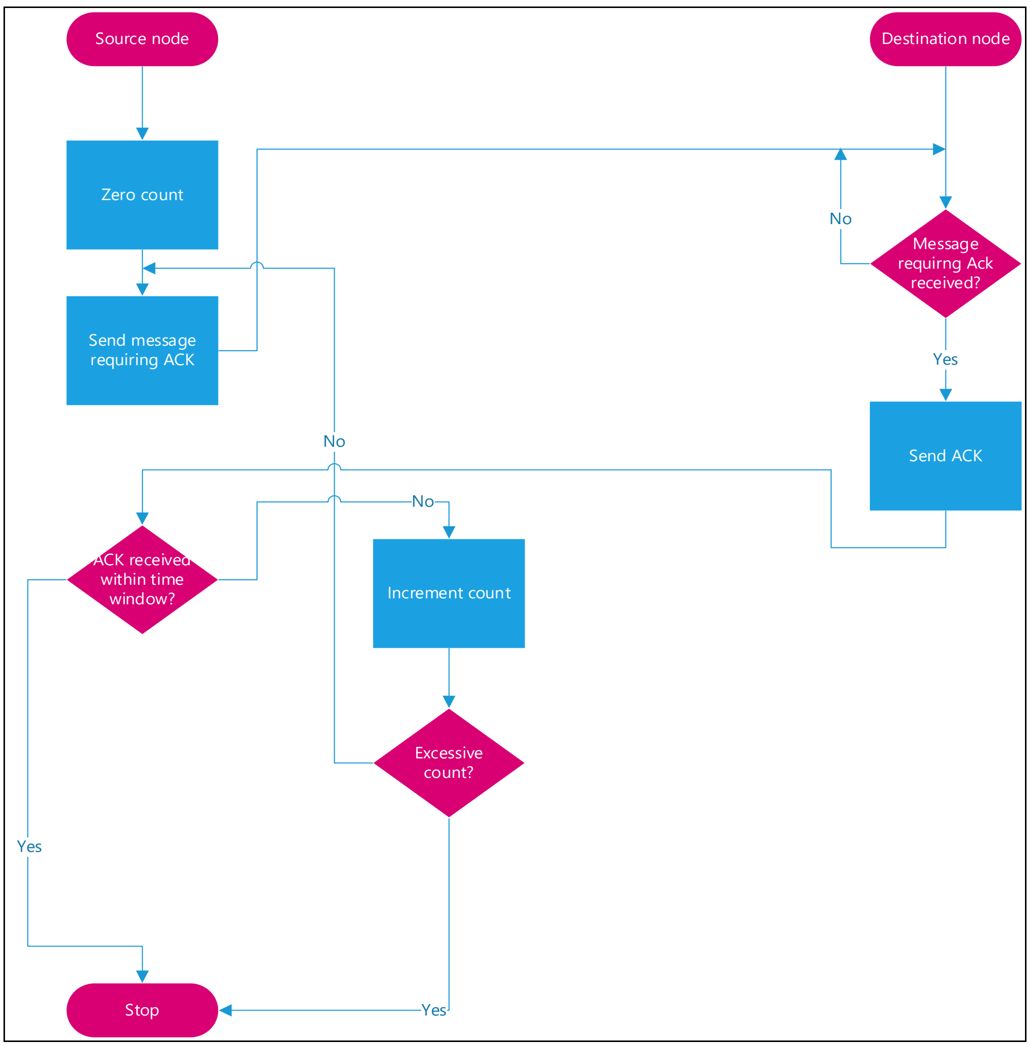

Figure 15: ACK messaging sequence

6.1.3.3.6 Code 110 – UUID Announcement

Bits	Value
1-32 (32 bits)	UUID

33-40 (8 bits)	Requested Short ID

6.1.3.3.7 Code 111 – UUID ACK
No follow-on data

6.1.3.3.8 Code 112 – UUID NACK
No follow-on data

6.1.3.3.9 Code 113 – Default SMAC modulator declaration

Bits	Value
1-6 (6 bits)	Present hour (24 hour format)
7-13 (7 bits)	Minutes
14-20 (7 bits)	Seconds
21-36 (16 bits)	SMAC Fc value code (unsigned)
37-48 (12 bits)	SMAC rate value code (unsigned)

6.1.3.3.10 Code 114 – Relay node designation

Bits	Value
1-8 (8 bits)	Number of client nodes (n)
9-as needed (8*n bits)	8-bit code of each client

6.1.3.3.11 Code 115 – Relay node de-assignment
No follow-on data

6.1.3.3.12 Code 116 – Mesh node designation

1-8 (8 bits)	Number of mesh nodes connected to designated node (Nm)
9-16 (8 bits)	Number of client nodes connected to designated node (Nc)
17-forward (8*Nm bits)	8-bit code of each mesh node connected to designated node
Forward (8*Nc bits)	8-bit code of each client node connected to designated node

6.1.3.3.13 Code 117 – Mesh node de-assignment
No follow-on data

6.1.3.3.14 Code 118 – Network full reset

Bits	Value
1-6 (6 bits)	Present hour (24-hour format)
7-13 (7 bits)	Minutes
14-20 (7 bits)	Seconds

6.1.3.3.15 Code 119 – TDMA timeslot designation

Bits	Value
1-6 (6 bits)	Present hour (24-hour format)
7-13 (7 bits)	Minutes
14-20 (7 bits)	Seconds
21-26 (6 bits)	Hour for start of TDMA
27-33 (7 bits)	Minutes for start of TDMA
34-40 (7 bits)	Seconds for start of TDMA
41-56 (16 bits)	Duration of each time slot in seconds

57-72 (16 bits)	Number of timeslots in round robin
73-88 (16 bits)	Node timeslot number

6.1.3.3.16 Code 120 – TDMA de-assignment
No follow-on data

6.1.3.3.17 Code 121 – CSMA designation
No follow-on data

6.1.3.3.18 Code 122 – CSMA de-designation
No follow-on data

6.1.3.3.19 Code 123 – Keepalive

Sent by a master node. Keepalive messages permit the network to operate without reset. However, if a node fails to receive a keepalive message as of its last known reset time, it will reset itself to basic function.

Bits	Value
1-6 (6 bits)	Present hour (24 hour format)
7-13 (7 bits)	Minutes
14-20 (7 bits)	Seconds
21-26 (6 bits)	Hour for reset
27-33 (7 bits)	Minutes for reset
34-40 (7 bits)	Seconds for reset

6.1.3.3.20 Code 124 – Request SMAC modem capabilities
No follow-on data

6.1.3.3.21 Code 125 – Report SMAC modem capabilities

Bits	Value
1-8	Bitfield – support for SWiG SWiG enhanced BPSK-CDMA S2C Other bits reserved
9	Supports CSMA
10	Supports self-cancellation
11	Supports time-frequency scaling (needed for legacy equipment)

6.1.3.3.22 Code 126 – Request HDC modem capabilities
No follow-on data

6.1.3.3.23 Code 127 – Report HDC modem capabilities

Bits	Value
1-16	Number of HDC modulation types supported
N x 16	Codes for each modulation type supported: 0 – BPSK stream

	1 – BPSK packet 2 – QPSK stream 3 – QPSK packet 4 – BFSK packet 5 – OFDM 6 – OTFS Remaining codes reserved

6.2 MAC functional description HDC

The HDC is dedicated primarily to point-to-point communications that are predetermined by the MAC configuration within SMAC. It supports streaming, packet, broadcast, and vendor-defined operation. Because the use of HDC is limited, MAC functionality may also be limited. For vendor-specific applications, a more complex MAC may be specified.

6.2.1 Streaming MAC

None needed

6.2.2 Packet/broadcast MAC

6.2.2.1 Physical access

Physical access shall be by CSMA

6.2.2.2 MAC header

Each application packet shall be preceded by a MAC header

6.2.2.2.1 Source (8 bits)
6.2.2.2.2 Destination (8 bits)
6.2.2.2.3 Broadcast/not broadcast (1/0)
6.2.2.2.4 ACK Required (1 bit)
6.2.2.2.5 ACK Channel (HDC/SMAC) (1/0)
6.2.2.2.6 Number of PHY packets in data group (16 bits unsigned)

6.2.3 Vendor-defined MAC

TBD

Note: HDC is intended to permit vendors, users, and others to experiment with new methods of modulation. To ensure motivation for vendors to invest in new methods, waveforms, coding methods and transmission methods may be kept proprietary, as an aid to competition. The MAC for these new methods must be open source. This encourages adoption of these methods over the greater undersea wireless community.

7 List of Tables

8 List of Figures