Dual Channel Acoustic Communication Protocol

Aker BP – QinetiQ SWiG Review. April 2022

Dr. Edmary Altamiranda, Aker BP ASA – Technology R&D
Neil Judell, Optimal Systems Lab on behalf of QinetiQ

Summary from Previous Review

- Challenges and Motivation Drivers (Why)
- Dual Channel Acoustic Communication Protocol (What)
- Protocol Requirements Definition Process (How):

  Result of Previous work, Survey & Use Cases. All inputs from SWiG members
- Review of Preliminary Deliverables (Protocol Requirements Definition Document, Signaling, Routing, Physical Layer Access, Protocols document, Simulation Software & document)
- Comments Registered for implementation

Actions from Previous Review - Status

1. Define ad hoc net and dynamic config . Available in Simulator. Definition in draft standard
2. Address noise model with noise class – modulator must specify noise Eb/N0 as well as interference level . Noise incorporated into channel model
3. Integrate with SWiG commands (moving target). Done however SWiG commands still under definition
4. Add moving node class . Done & tested
5. Changing channel name FDC1 to SMAC1 for simultaneous access channel. Done
6. Nodes must have capability of announcing capability to the network . Included in MAC
7. Broadcast messages Included in MAC
8. Add power output level for modulator Done & tested
9. Add channel propagation class to node/modulator. Done – but only for RAP path, based on absorption and 1/R^2
10. Need commands to force full reset and restart of network . Included in MAC
11. Include a requirement to avoid intentional misalignment on frequency scaling on multiple nodes in HD channel. Simulate effect of misalignment if requirements are not followed. Readily modeled in the simulator, and used in debugging channel behavior
12. Address power consumption impact on the different network configurations, considering high and less capable demodulators. Done: can configure Eb/N0, effective cancellation of interfering demodulation signals (equivalent to limiting number of simultaneous demodulations), capabilities for CSMAC, presence and limits of self-cancellation.
13. Physical Layer shall be formalized: Done. PHY & MAC documented in draft standard as per IEEE Standard format. IEEE Std 80.22-2020 provides the basis for PHY specification [IEEE SA - IEEE 802.11-2020]

«Information Exchange between Systems - Local and Metropolitan Area Networks--Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications»

Key Presentation Updates from previous Review

- Draft standard, in style of IEEE protocol standards, including specifications for PHY and MAC
- Definitions for various open-source modulations: BPSK, BFSK, BPSK-CDMA, OFDM in addition to QPSK previously defined
- Extension of SWiG Level 1 to higher bit rates, specific recommended bandwidths and center frequencies
- Updated simulator functionality: open-source modulations, MAC functionality, channel model, ocean noise model, equipment noise class, better emulation of packet loss due to noise and interference, modeling moving nodes and rest of actions documented in slide 3.
- Used Broadband inference data from Naxys Passive Acoustic Monitoring Systems to support noise modeling & interference simulation
- Added Contribution to SWiG commands table
- Change in terminology: SMAC (Simultaneous Multiple Access Channel) and HDC (High-Data-rate Channel) in place of FDC1 and HDC2

Challenges (Why)

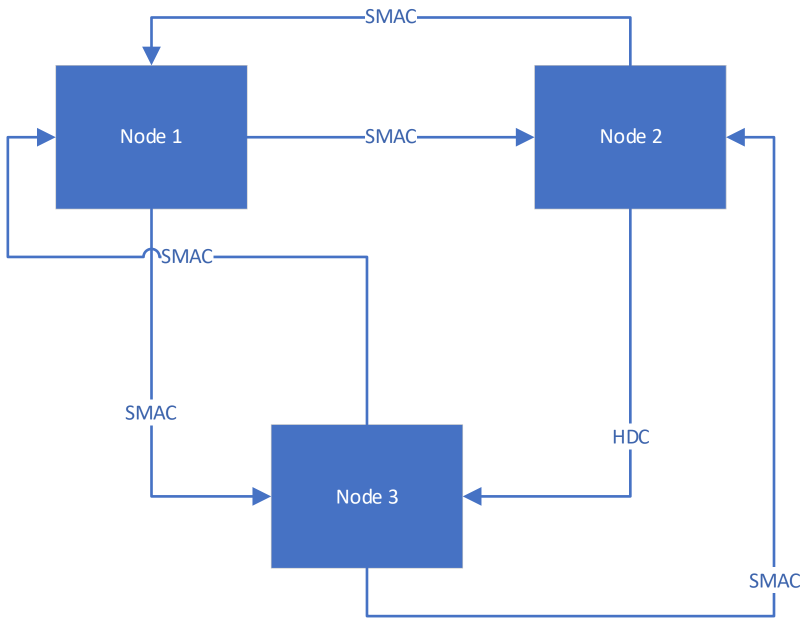
Limitation Factors for multiple nodes to interoperate in an underwater acoustic network and share large amounts of data

- Physics of Underwater Environment
- Efficiency of traditional Half Duplex methods
- Limited capacity for shared channels among users
- High data-rate, high spectral efficiency modulations are not compatible with SMAM (Simultaneous Multiple Access Modulation)
- Available standard (JANUS) has limited capabilities. SWiG level 1 is based on JANUS

Motivation & Value Creation Drivers (Why)

- Increased interoperability across devices for different applications and backward compatibility with half duplex legacy devices. Including compatibility with SWiG Accoustic Level 1 & JANUS.
- Enable efficient management of various types of data transmission in a network
- Enable improved data throughput in an underwater network and situational awareness among all nodes
- Increased flexibility to support a wide range of applications, in terms of frequency range and modulation
- Develop an attractive standard for suppliers to adopt freely inside and outside Oil & Gas domain
- Accelerate protocol development, documentation and standard delivery
- Contribute with value adding initiatives to SWiG

Dual Channel Acoustic Communication Protocol (What)



SMAC – Simultaneous Multiple Access Channel to cover cases of network nodes coordinating, negotiating & exchanging small bits of information. It can operate in full duplex or half duplex mode at low bit rates.

HDC – a High Data-rate Channel, single access channel for high-speed communications. Coexists with SMAC on an as-needed basis.

Dual Channel, Full Duplex Acoustic Communication Network Protocol (What)

High Level Scope

1. **Protocol Requirements definition**

1.1 Establish Network Requirements

1.2 Establish modem requirements, system performance requirements

1.3 Identify ideal modem functionality and capability to be simulated

1.4 Identify available modem functionality and capability to be implemented for verification of simulation (Next Phase)

Deliverable - Agreed on Requirements Documentation (Discussed during last meeting and implemented comments)

2. **Protocol Development**

2.1 Develop protocol – handling strategies for re-queuing and dealing with legacy (half-duplex) modems

2.2 Review protocol with SWiG via teleconference meeting

2.3 Simulate protocol for evaluation and development for the ideal modem

2.4 Simulate protocol for available modem (Next Phase)

2.5 Determine minimum decoupling/cancellation requirements needed for protocol (At this stage, it can be determined using simulator)

2.6 Identify key parameters for protocol compliance and initial requirements for compliance testing. (Next Phase, Initial Physical Testing needed)

2.7 Protocol Definition –Standard Documentation and Simulation Report

Deliver proposed protocol definition in IEEE standard format with simulation report.

Protocol Requirements Definition (How)

- **Preliminary Work:**
  - Meeting with SWiG to present Dual Channel Protocol Concept
  - Sent a Survey to gather inputs on proposed concept relevant and comments prior starting the work
  - Meeting with SWiG to present survey results and proposed way forward considering member inputs
  - Defined Stakeholder Requirements based on preliminary SWiG inputs. **(Strong focus on backward compatibility with existing half duplex devices without hardware changes to accelerate implementation as base case)**

- **System Requirements Identification:**

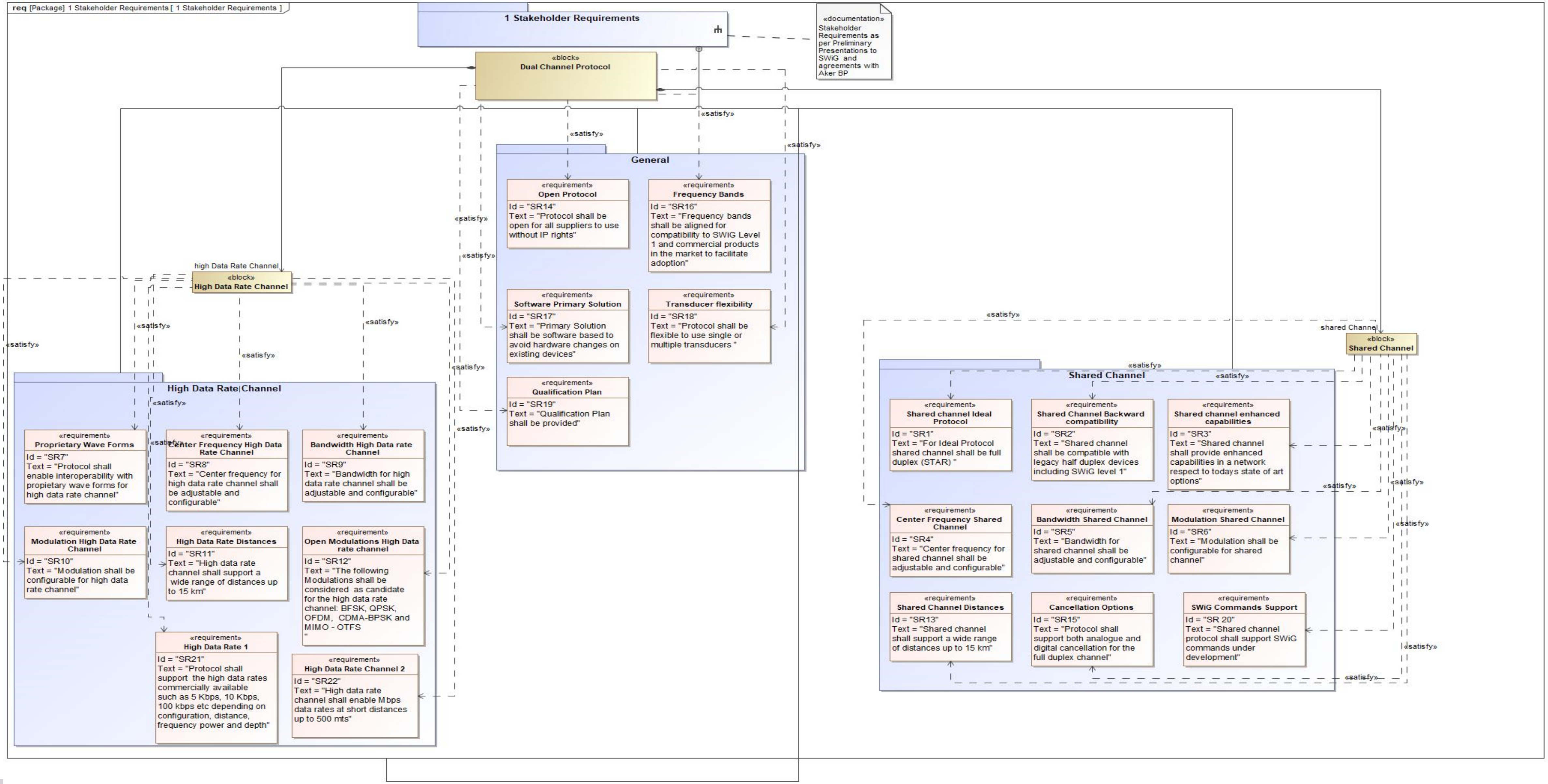
✓ A Survey was developed and sent to SWiG members to identify the needs on :
  - -Network Requirements
  - -Shared (Low data rate) Channel Requirements (SMAC)
  - -High Data Rate Channel Requirements (HDC)

✓ Existing SWiG use cases and case studies were mapped, analysed and expanded with additional SWiG members inputs

✓ Information from Survey and Use cases was collated to define system requirements

✓ Ongoing work on commands definition for the SWiG main document have been also considered

Stakeholders Requirements Definition (from Preliminary Work)



Systems Requirements Definition Inputs

Survey Developed and Submitted to SWiG Members to capture Network Physical Characteristics and Data Requirements covering details on

1.1.1.1 Desired number of nodes
1.1.1.2 Desired geometry (i.e. range, distribution within range)
1.1.1.3 Messaging requirements for command/status:
- 1.1.1.3.1 Number of payload bits
- 1.1.1.3.2 Number of messages per node per minute/hour/day
- 1.1.1.3.3 Destinations of messages
- 1.1.1.3.4 Active acknowledgement required?

1.1.1.4 Messaging requirements for large data transfer (if needed)
- 1.1.1.4.1 Fraction of nodes with this requirement for TX
- 1.1.1.4.2 Fraction of nodes with this requirement for RX
- 1.1.1.4.3 Fraction of nodes with this requirement for TX/RX (i.e. high speed required in both directions)
- 1.1.1.4.4 Number of payload bits
- 1.1.1..4.5 Number of messages per node per minute/hour/day
- 1.1.1.4.6 Destinations of messages
- 1.1.1.4.7 Active acknowledgement required?

1.1.1.5 Special needs
- 1.1.1.5.1 Mesh network has been requested.
- 1.1.1.5.2 Store/forward requirements?
- 1.1.1.5.3 Broadcast requirements?
- 1.1.1.5.4 Large, blank area for special requirements
- 1.1.1.5.5 Special waveform or MIMO requirements for HD channel

Note: Numbering above as per Scope / Detailed tasking Document

Summary of survey results

- Number of nodes ranged 2 to 200 (combination of fixed and moving nodes)
- Bits per second per node from 0 to 44 bps (for SMAC channel)
- Water column depth 1-5000 meters
- Point to point range 1 meter to 15 km
- Interference sources: Other acoustic equipment using same frequency, Vessel noise (dynamic positioning), production system noise: choke movements, leaks, AUVs, ocean life acoustic noise (shrimps, mammals,...), IMR/I&C nearby activity. Other interference in the form of acoustic reflections, at boundaries (sea floor, sea surface and equipment).
- User packet size 100 bits to 800 bits
- Message per hour: 50-200 messages
- Network Definition: Ad hoc networks (with first-contact protocol) and pre-programed formation
- Routing: Point to point, store & forward and mesh networks
- Mixed use ranging / communication
- TDMA needed for some SWiG members
- UUID not mandatory but may be required in the future
- Waveforms for HDC: SISO ASK or FSK, BFSK, QPSK,OFDM, CDMA-BPSK and MIMO-OTFS
- Special needs: Doppler tolerance to 5 mts/sec

  Adjustable center frequency and bandwidth

  Open -source platform independent desirable

Systems Requirements Definition Inputs

Existing SWiG use cases and case studies were mapped, analysed and expanded with additional SWiG members inputs. Some summary results are listed as follows

- Application & Technology Area: structures monitoring, drilling control, BOP wireless control, cathodic protection monitoring, dredging, environmental monitoring, tsunami monitoring, seismic survey, seabed subsidence monitoring, riser lifecycle monitoring, asset vibration monitoring, pipeline monitoring, outflow monitoring, Wireless WOCS, Resident & Non-resident UID data exchange with docking stations, surface vessels, rigs, subsea structures, other UID and ROV, Supervised autonomy, Swarm of AUVs, etc.
- Modulations: FHSS, MSK, DSSS, QPSK, CDMA, S2C
- Center Frequency (kHz): 10 kHz to 63 kHz
- Bandwidth (kHz): 3 kHz – 30 kHz
- Point to point range (m): 1-15000 m
- Area long dimension (m): 15000 -30000 m
- Area short dimension (m): 1-5000 m
- Burst bit rate (bps): 100-2400 bps
- Water depth (m): 20-6000 m
- Power Level (dB): 177-202 [dB re 1 microPa at 1m]
- Number of nodes: 2-4000 nodes (However for definition of this protocol, a Max of 200 nodes has been used)
- MAC : Yes
- Routing: Point to point, one way & bi-directional enabled
- Usage: ranging and data
- Network throughput low & high estimates (bps) (100-10000).

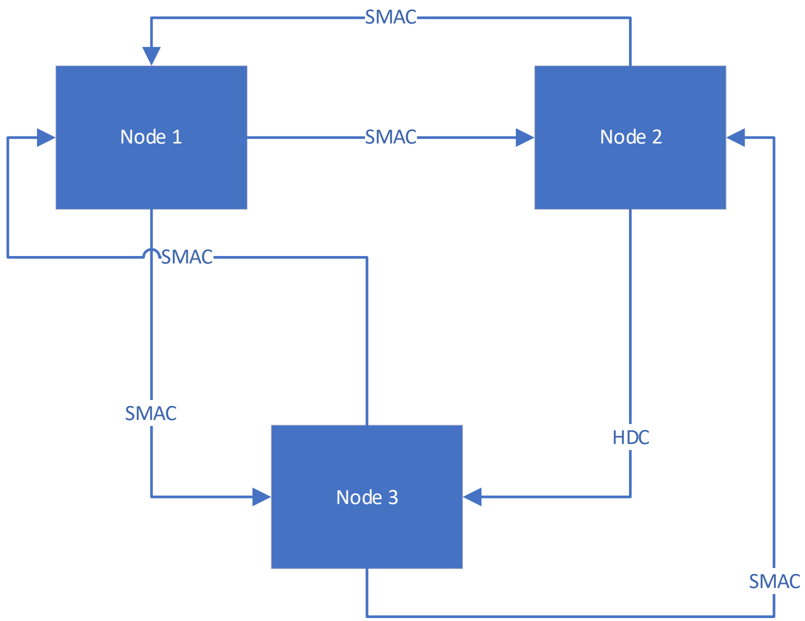
  Much higher data rates are desired for some applications, but the defined range is set as base, considering the majority of the use cases and can be expandable.
- Duration: From 5 days to 365 days and from 1 to more than 10 years

Seismic use case with 4000 nodes not considered at this stage as use case significantly exceeds SISO multiuser channel capacity. A separate development will need to be considered to address this case

SWiG 2-Channel Acoustic Protocol

Neil Judell, Optimal Systems Laboratory, Inc.
On behalf of QinetiQ

Network Architecture - 2 Channels



- SMAC – Simultaneous Multiple Access Channel. Channel capable of reconfiguring to lower bandwidth, lower bit-rate to permit operation of
- HDC – High Data-rate Channel, single access channel for high-speed communications. Coexists with SMAC on an as-needed basis. Both channels can operate simultaneously by frequency division multiple access (FDMA)

Points of note

- Software-based protocol
- Immensely flexible, supporting:
    - Single-transducer half-duplex, receiving only SMAC or HDC at a time
    - Single-transducer half-duplex, receiving both SMAC and HDC simultaneously
    - Multiple-transducer, supporting wide frequency range for HDC
    - Multiple-transducer, supporting full-duplex
    - Both open-source and proprietary modulations for HD channel
    - Point-to-point, store-and-forward, mesh routing

Relationship to OSI model

Layer		Protocol Data Unit	Function	Dual Channel Protocol
7	Application	Data	High level APIs	User level
6	Presentation		Translation of data between network and application	User level
5	Session		Managing communication sessions	User level
4	Transport	Segment, datagram	Reliable communication, including segmentation, acknowledgement (ACK) & multiplexing (MUX)	ACK and MUX defined in protocol, segmentation at user level
3	Network	Packet	Addressing, routing & traffic control	Defined in packet bits
2	Data link	Frame	Reliable transmission of data frames	Forward error correction, preamble
1	Physical	Bit, symbol	Transmission and reception of raw streams	Modulator definition

Delivered items

- Protocol Requirements Definition document
  - Network requirements, modulation requirements, operational requirements, configuration requirements
- Signaling, Routing, Physical Layer Access, Protocols document
  - Brief document summarizing multiple access modulations, media access control (MAC), routing, configuration, and the simulator
- Draft standard
  - IEEE formatting and style (except reversal of order of PHY and MAC sections)
  - PHY definitions for SWiG Level 1 improved, open-source modulations
- Simulation document
  - In-depth detail document, describes the simulation software classes, describes the protocol elements that are defined by the software classes, as well as relevant simulation results
- Simulation software
  - Matlab objects that define the protocol and its behaviors, as well as simulation scripts using these objects to simulate relevant scenarios based on stakeholder requirements

Network Requirements Summary (Requirements Document)

Distilled from down-selected use cases and survey

Characteristic	Min	Max	Median	Detailed Tasking Paragraph number
Number of nodes	2	200	40	1.1.1.1
Point-to-point-range	1 meters	15,000 meters	5,000 meters	1.1.1.2
Doppler	0	5 meters/sec	N/A	1.1.1.5.4 (From member)
Ranging pulses per node per hour	0	30	30	1.1.1.5.4 (From use case)
TDMA	NO	YES		1.1.1.5.4 (From Survey)
Ad hoc network	Yes	Yes	Yes	1.1.1.5.4
Acknowledgement required	NO	Critical messages only		1.1.1.4.7
Packet size (small) (bits)	80	800	100	1.1.1.3.1
Small packets per node per second	0	0.06	0.06	1.1.1.3.2
Node throughput (BPS - FD)	0	44	44	1.2.2.1
Network throughput (BPS – FD)	10	2400	480	1.2.2.2
Network throughput (BPS - HD) (NOTE – this is the same as node-node for HD)	100	10000	2400	1.2.2.2
Message passing	Point-to-point	Store-forward/mesh	N/A	1.1.1.5.2
Power level (dB)	177	202	190	Based on use cases
Center Frequency	10 kHz	63 kHz	16.5 kHz	Based on use cases
Bandwidth	3 kHz	30 kHz	8 kHz	Based on use cases

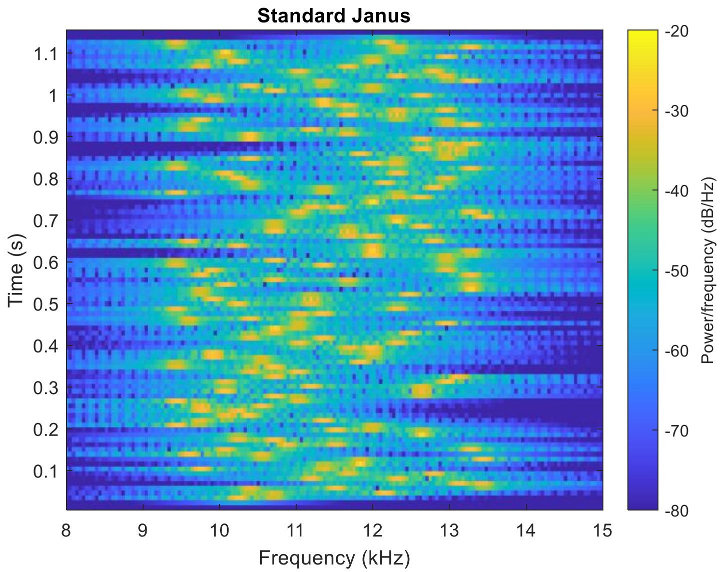
Potential SMAC-Channel (low data-rate, shared) Modulations (Requirements Document)

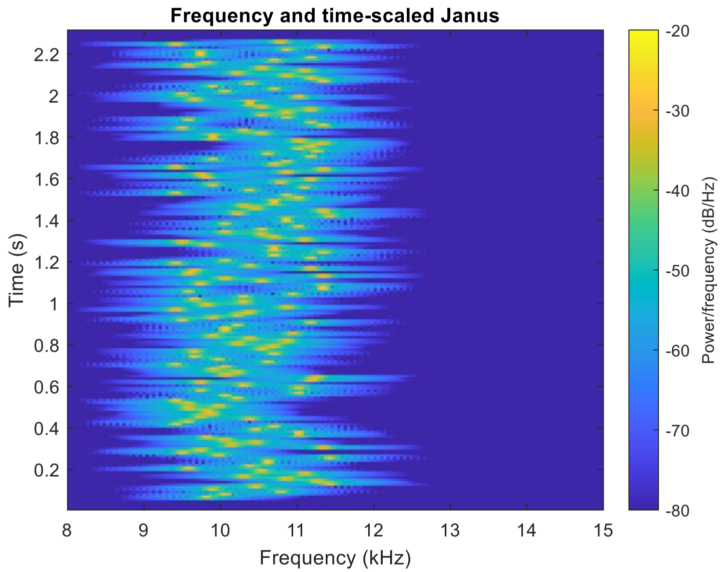
Modulation method	Network throughput	Doppler behavior	Ranging behavior	Other
SWiG level 1 (slow FHSS - BFSK)	110 bps	Poor	Poor	Poor collision behavior
SWiG Level 1 modified bandwidth/center frequency	Up to 250 bps	Poor	Poor	Poor collision behavior
Zadoff-Chu slow FHSS	Up to 250 bps	Excellent	Good	Good collision behavior
CDMA	Up to 4,000 bps	Fair (requires somewhat complex algorithm)	Excellent	Good collision behavior
SSC/S2C	Up to 4,000 bps	Good	Good	Good collision behavior

Frequency & Time Scaling Modulation

- Needed for configuring channel for reduced bandwidth, reduced bit rate for SMAC/HDC sharing

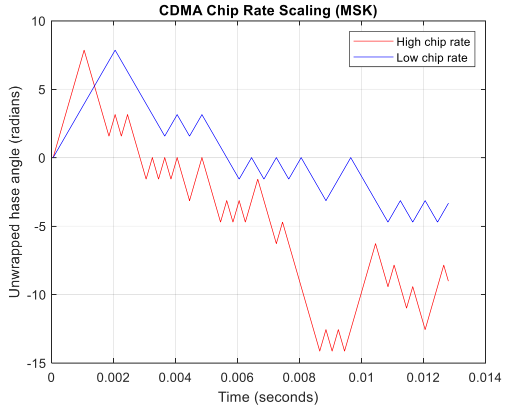
FHSS: scale tone intervals down, scale duration up.

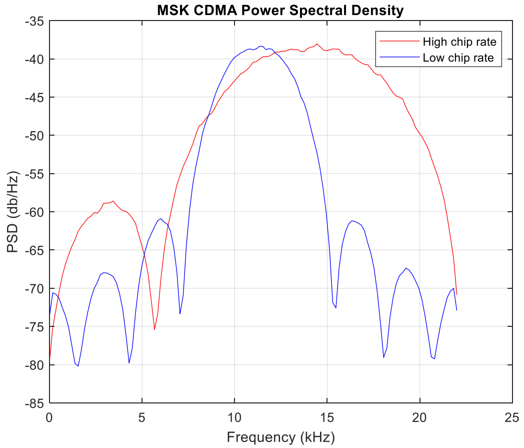




Frequency & Time Scaling Modulation

For CDMA: time scale the chip rate, but keep codes constant. Shift carrier frequency to match lower edge. Result is occupying a lower fraction of original spectrum, at reduced bit rate





Improved SWiG Level 1

- 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

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.

Improved SWiG Level 1

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 improved

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.

Improved SWiG Level 1

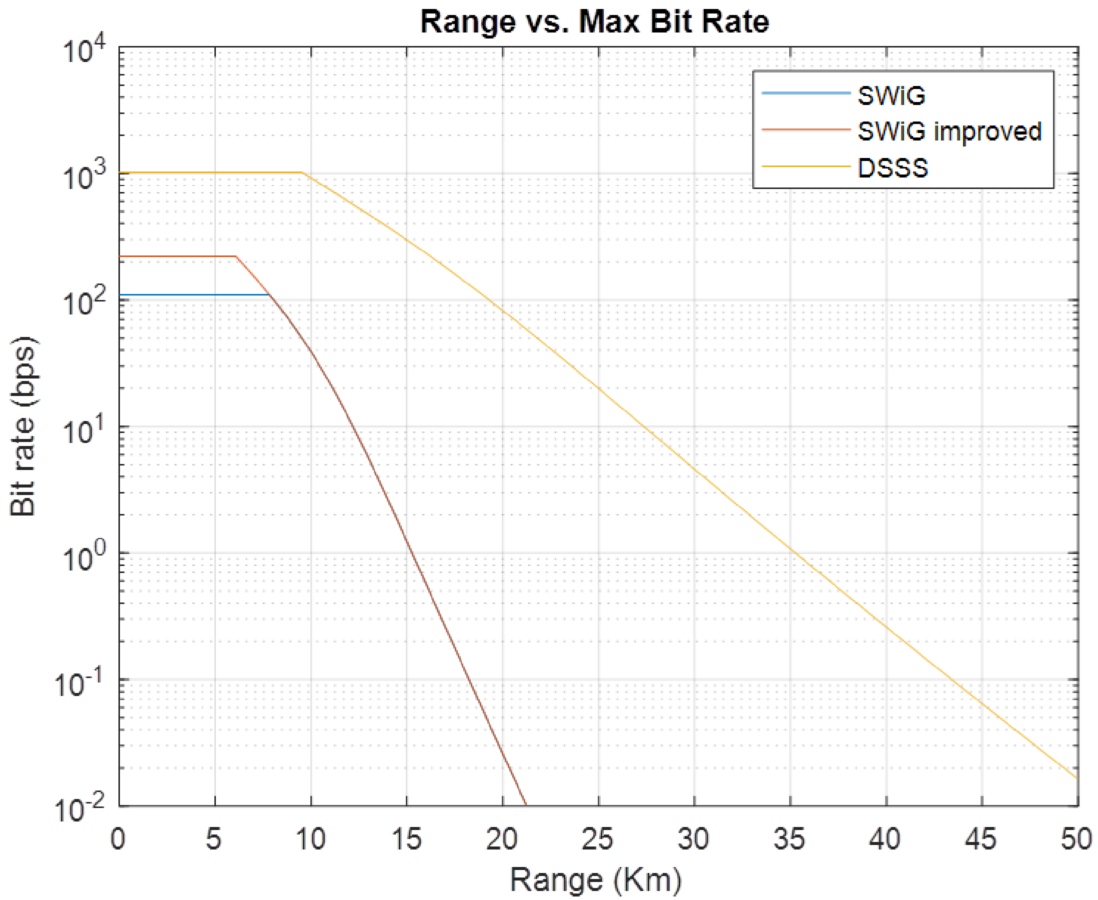
Fc value code	Fc
0	18795 Hz
1	19640 Hz
3	20485 Hz
4	23465 Hz
5	24310 Hz
6	25155 Hz
7	26000 Hz

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

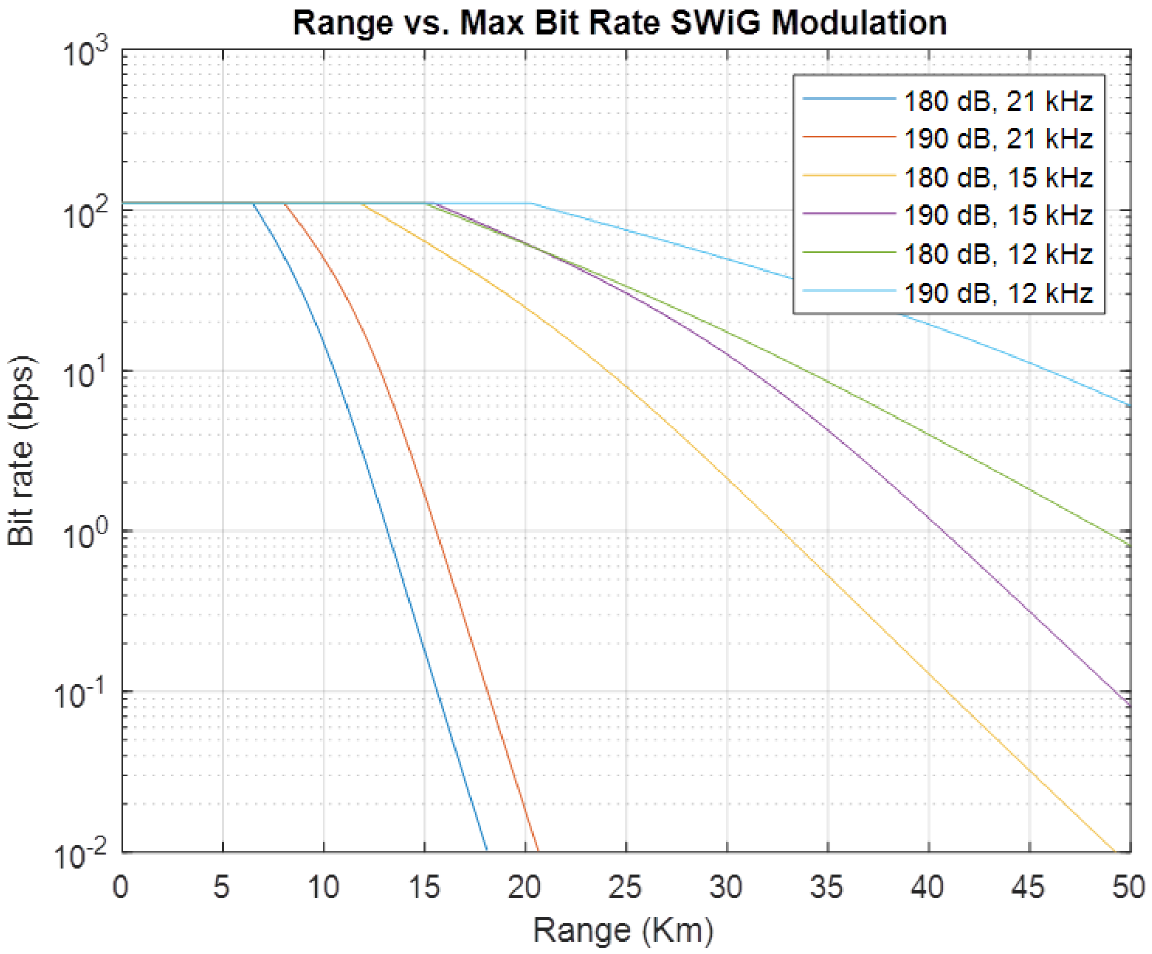
Table 5: Recommended rate and center frequency combinations

Range vs. Max Bit Rate (SMAC Modulations)



Assumptions: Standard noise models based on shipping traffic levels, sea state – both of which are configurable within the channel model class. Propagation model is RAP (reliable acoustic path), which includes 1/r^2 and seawater absorption.

Range vs. Max Bit Rate SWiG 1 Modulation



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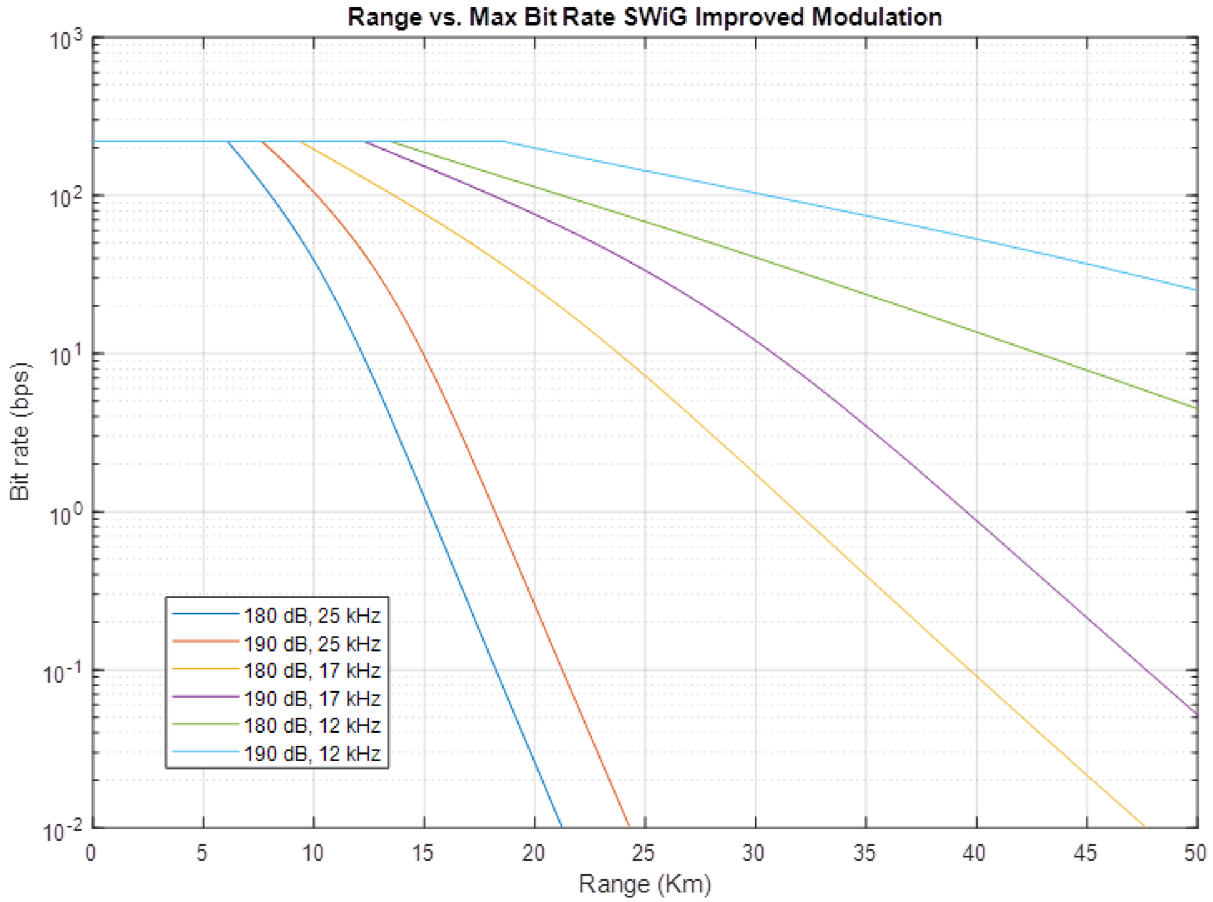
Range vs. Max Bit Rate SWiG Improved Modulation



Assumptions: Standard noise models based on shipping traffic levels, sea state – both of which are configurable within the channel model class. Propagation model is RAP (reliable acoustic path), which includes 1/r^2 and seawater absorption.

Modulations and Configurations Specified (Requirements Document and Draft Standard)

- SMAC
  - Modulation methods (such as SWiG level 1 improved, CDMA, S2C)
  - Reduced symbol rate, with bandwidth of 0, ¼, ½ and ¾ full SMAC bandwidth
  - Access methods (such as CSMA, TDMA, SMAHD, SMAFD)
- HDC
  - BPSK streaming
    - DBPSK differential coding
    - 2:1 convolutional code
    - ISI filter
    - Rates: 5 Kbits/sec, 4.3 Kbits/sec, 3.6 Kbits/sec, 3Kbits/sec, 2.1 Kbits/sec
  - BPSK packets
    - BPSK with ISI header/training waveform
    - Short silence
    - DBPSK with ISI coded either BCH(511,250) hard without CRC or BCH(511,259) soft with CRC
  - QPSK streaming
    - DQPSK differential coding
    - 2:1 convolutional code
    - ISI filter
    - Rates: 10 Kbits/sec, 8.6 Kbits/sec, 7.3 Kbits/sec, 6Kbits/sec, 4.2 Kbits/sec
  - QPSK packets
    - BPSK with ISI header/training waveform
    - Short silence
    - DQPSK with ISI coded either BCH(511,250) hard without CRC or BCH(511,259) soft with CRC

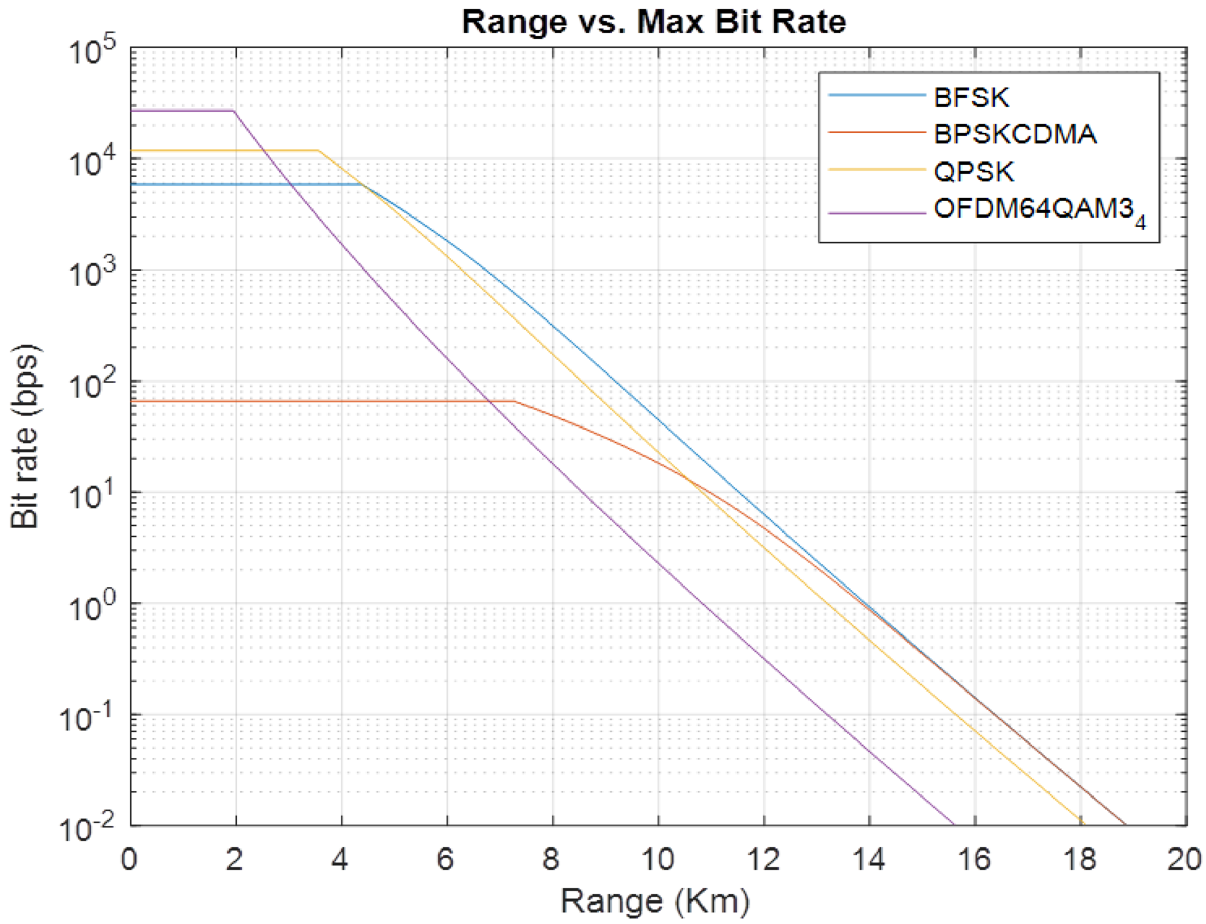
Modulations and Configurations Specified Continued (Requirements Document and Draft Standard)

- HDC (continued)
  - BFSK packet
    - DBFSK with ISI coded either BCH(511,250) hard without CRC or BCH(511,259) soft with CRC
    - Rates to 7.3 Kbits/sec
  - BPSK-CDMA
    - BPSK inter-chip interference filter, 127- chip Gold sequences
    - DBPSK bit coding BCH(511,250) hard without CRC or BCH(511,259) soft with CRC
    - Rates to 50 bits/sec – but extremely robust interference performance
  - OFDM
    - 64 subcarrier, 11 guard times, 4 pilot subchannels, 16 cyclic prefix
    - Varying FEC coding rates, subchannel modulations (from 802.11a)
    - Rates to 40 Kbits/sec

- Other modulation manufacturer can define that does not interfere with SMAC by use of FDMA (note that this requires Class A or true Class D power amplifier – Class S will distort into SMAC, for these cases shutting down SMAC channel during HDC operation is recommended)

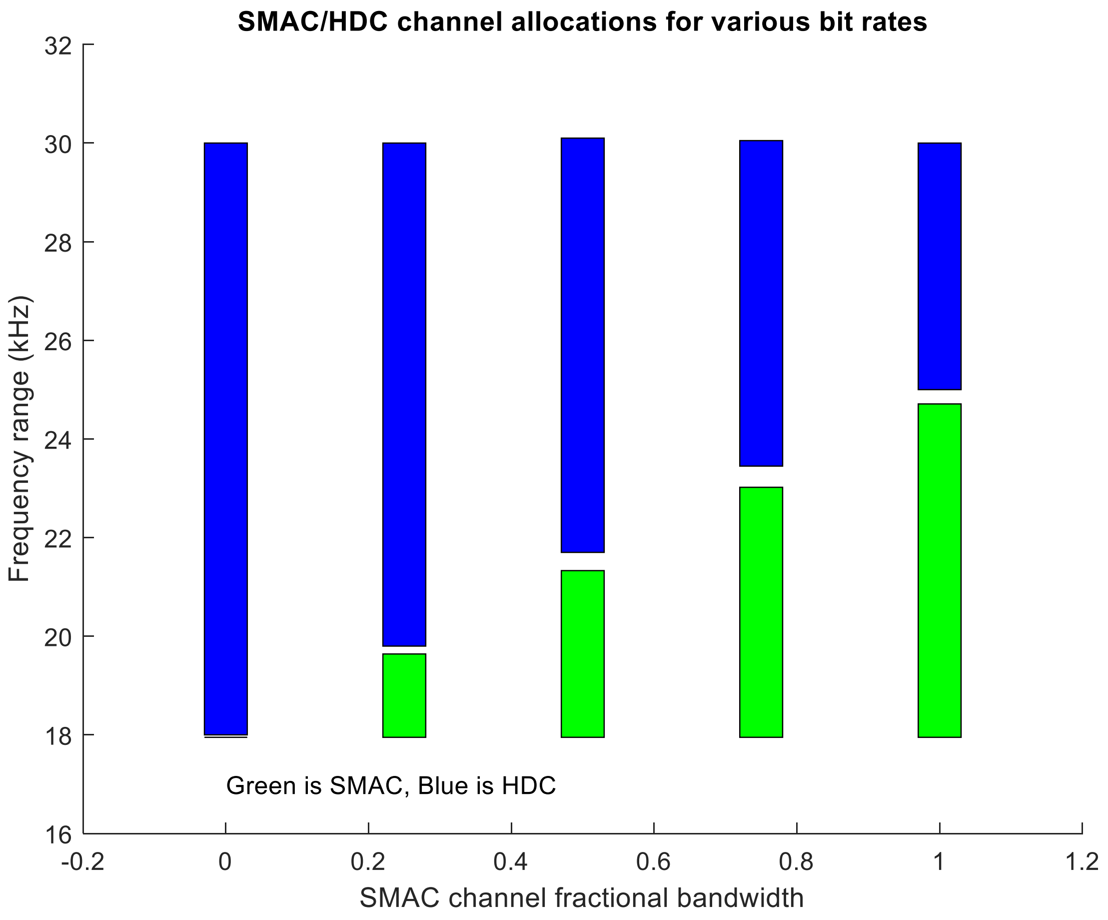
Note: MIMO – OTFS can be included later, if an open source arrangement can be made (Next Phase)

Range Vs. Max Bit Rate (HDC Open Modulations)



Assumptions: Standard noise models based on shipping traffic levels, sea state – both of which are configurable within the channel model class. Propagation model is RAP (reliable acoustic path), which includes 1/r^2 and seawater absorption.

Frequency stacking FDMA by time-frequency scaling



Signaling, Routing, Physical Layer Access, Protocols document

- Primarily addresses reasoning for design selection
  - Addresses SMAC modulations, HDCmodulations
  - Addresses MAC variants
  - Addresses routing choices
  - Discusses protocol very briefly
  - Bibliography of references reviewed in making design decisions

Contribution to SWiG Commands Table

Overview of SWiG Parameters

nigel:
Local/Remote access to read/change on deployed unit
A - Authenticated access
F - Free access
N - No access
O - Manufacturer option

nigel:
<blank> - required
N - not required

Unit of measure
Sequenced commands
RPC - Repeat procedure commands?
Complex scenarios

				Access		Technology Exceptions					
ID	Command type2	Function group	Description	Read	Write	Acoustic	Optical	Radio	Induction	Representation	Notes
107	Schedule HDC		Schedule network for shared high-speed usage	F/F	A/A				N	8 bits source, 8 bits destination (destination equals source), 1 bit ACK, 7 bit primary CRC, 256-bit bitfield for destinations. 6 bits present hour, 7 bits present minutes, 7 bits present seconds, 6 bits start hour, 7 bits start minute, 7 bits start second, 16 bits duration in seconds, 16 bits code **SMAC** modulator center frequency in Hz (or code as appropriate), 12 bits **SMAC** modulator bandwidth in Hz (or code as appropriate), 10 bits HDC modulator identification code, 16 bits HDC modulator center frequency code, 16 bits HDC modulator bandwidth code	HDC: High Data rate channel SMAC: Simultaneous Multiple Access Channel (Network Channel)
108	Data message SMAC		User data, source, destination(s), ACK required	F/F					N	8 bits source, 8 bits destination, 1 bit ACK required, 8 bit number of blocks, 7 bit primary CRC. 256 bit bitfield for destination for multicast if source value equals destination value. Arbitrary message length derived from number of blocks	SMAC: Simultaneous Multiple Access Channel (Network Channel)
109	ACK		Source, destination, has responding	F/F	A/A				N	23 bits: 8 bit source, 8 bit destination, 7 bit CRC of message being acknowledged	
110	UUID announcement		Announce presence for ad hoc network	F/F	A/A				N	32 bit UUID, 8 bit requested local ID	
111	UUID ACK		Requested local ID grant	F/F	A/A				N	32-bit UUID	
112	UUID NACK		Requested local ID deny	F/F	A/A				N	32-bit UUID	
113	Default **SMAC** modulator delaration		Master declaration of change of default **SMAC** modulator	F/F	A/A				N	8 bits source, 8 bits destination (destination equals source), 1 bit ACK, 7 bit primary CRC, 256-bit bitfield for destinations. 6 bits present hour, 7 bits present minutes, 7 bits present seconds, 6 bits start hour, 7 bits start minute, 7 bits start second, 10 bit **SMAC** modulator code, 16 bits code **SMAC** modulator center frequency in Hz (or code as appropriate), 12 bits **SMAC** modulator bandwidth in Hz (or code as appropriate)	SMAC: Simultaneous Multiple Access Channel (Network Channel)
114	Relay node designation		Declare and configure node as a relay	F/F	A/A				N	8 bits source, 8 bits destination, 1 bit ACK (always set), 7 bit primary CRC, followed by	

Need clarification on Local / Remote and Read/ change

Contribution to SWiG Commands Table

Overview of SWiG Parameters

nigel:
Local/Remote access to read/change on deployed unit
A - Authenticated access
F - Free access
N - No access
O - Manufacturer option

nigel:
<blank> - required
N - not required

Unit of measure
Sequenced commands
RPC - Repeat procedure commands?
Complex scenarios

ID	Command type2	Function group	Description	Access		Technology Exceptions				Representation	Notes
				Read	Write	Acoustic	Optical	Radio	Induction		
115	Relay node de-assignment		Remove node as relay	F/F	A/A				N	8 bits source, 8 bits destination, 1 bit ACK (always set), 7 bit primary CRC	
116	Mesh node designation		Declare and configure node as a mesh forwarder	F/F	A/A				N	8 bits source, 8 bits destination, 1 bit ACK (always set), 7 bit primary CRC, followed by mesh table (format TBD)	
117	Mesh node de-assignment		Remove node as mesh forwarder	F/F	A/A				N	8 bits source, 8 bits destination, 1 bit ACK (always set), 7 bit primary CRC	
118	Network full reset		Reset network	F/F	A/A				N	6 bits hour, 7 bits minutes, 7 bits seconds	
119	TDMA timeslot designation		Assign timeslot	F/F	A/A				N	6 bits hour, 7 bits minutes, 7 bits second, 6 bits start hour, 7 bits start minutes, 7 bits start seconds, 16 bits timeslot duration in seconds, 16 bits number of timeslots, 16 bits timeslot number	
120	TDMA deselection		Deassign timeslot	F/F	A/A				N		
121	CSMA designation		Turn on CSMA for node	F/F	A/A				N	no data	
122	CSMA de-designation		Turn off CSMA for node	F/F	A/A				N	no data	
123	Keepalive		Allow network reset if control lost	F/F	A/A				N	6 bits hour, 7 bits minutes, 7 bits seconds, 6 bits hour for reset, 7 bits minutes for reset, 7 bit seconds for reset	
124	Request SMAC modem capabilties		Ask for capabilities	F/F	A/A				N	no data	
125	Report SMAC modem capabilities		Report capabilities	F/F	A/A				N	8 bits bitfield for supported modulations, 1 bit CSMA support, 1 bit self-cancellation support, 1 bit supports time-frequency scaling (needed for legacy equipment)	
126	Request HDC modem capabilities		Ask for capabilities	F/F	A/A				N	no data	
127	Report HDC modem capabilities		Report capabilities	F/F	A/A				N	16 bits number of modulations supported, N x 16 code for each modulation supported	
128											
129											
130											

Need clarification on Local / Remote and Read/ change

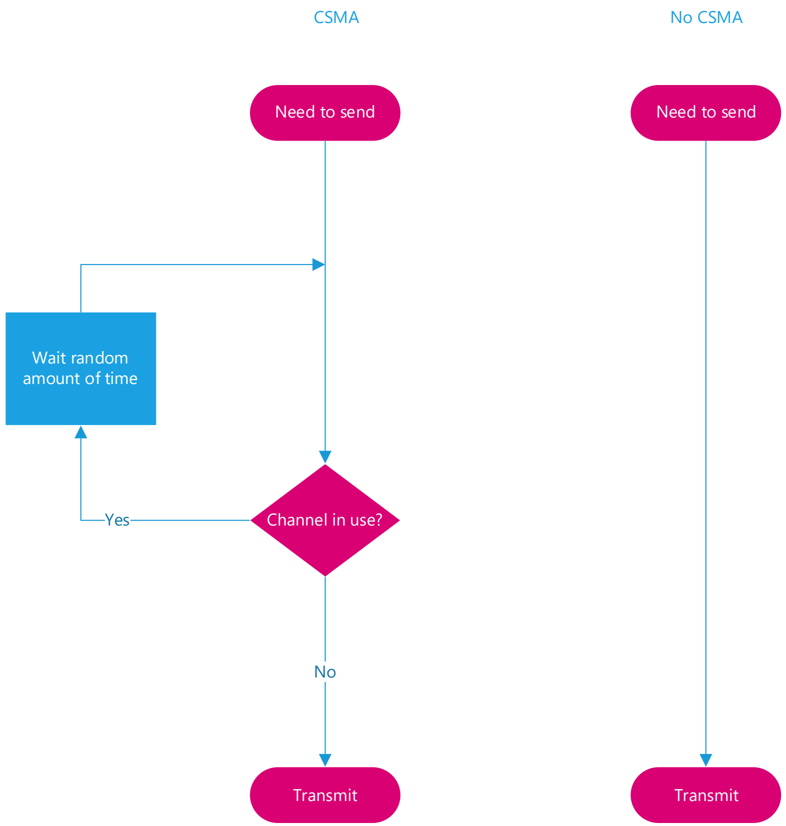
Network Simulator: Fundamental Types of Interest

- Modulators: derived from base class modulatorClass, includes SWiG Level 1, advanced SWiG, generic DSSS, QPSK, BPSK, BFSK, OFDM, BPSKCDMA. Includes modulation type, access method (CSMA, full-duplex, half-duplex, etc.), interference susceptibility value, packet loss function, center frequency, bandwidth. Includes power levels, noise and interference susceptibility.
- Packets: derived from packetClass, consists of data, source, destination, type of modulation used for transmission, whether or not this packet requires acknowledgment, whether this packet IS an acknowledgment.
- Nodes: derived from nodeClass, consists of modulators supported by the node, store and forward routing table, mesh routing table, logic for configuring and running the network. Includes moving nodes.
- Channel model classes – includes standard noise models, absorption, reliable acoustic path.
- Machine interference class – radiative power of interference-generating equipment.

Network Simulator: PHY and MAC

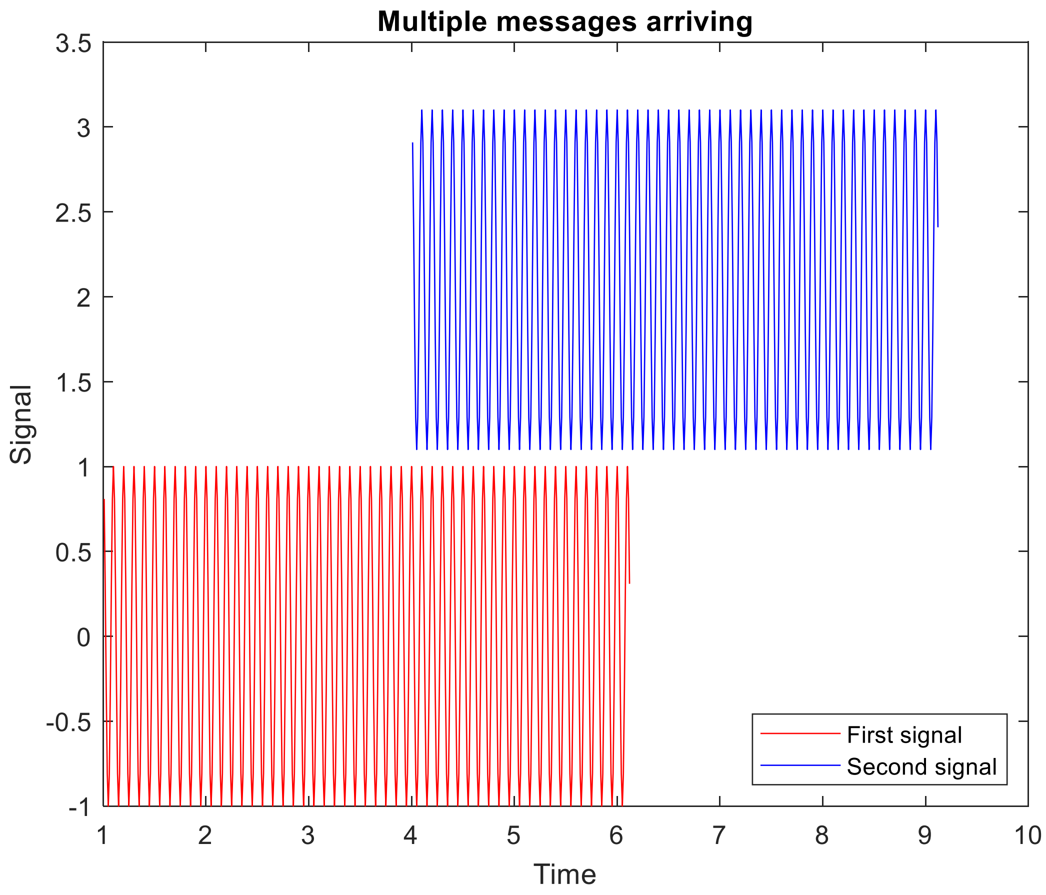
- Modulation waveforms specified by selection of modulator(s)
- Center frequency and bandwidth configurable based on messaging
- Time to revert to original center frequency and bandwidth based on time from configuration messaging
- Noise, propagation and packet loss modeled
- Machine interference modeled
- Susceptibility to preamble overlap specified (SWiG Level 1 is particularly sensitive)
- MAC (configured at the modem level to emulate hardware/software)
  - CSMA half-duplex
  - Half-duplex no waiting
  - Full-duplex (with realistic self-interference)
- Decoding capability
  - Single signal (first received)
  - Simultaneous multiple decoding

MAC – CSMA (Carrier Sense Multiple Access) vs no CSMA



Simultaneous multiple access, multiple decode

- No simultaneous multiple access: Second signal interferes with first – neither decodes
- Single decode – First signal decodes, second signal ignored (contributes to interference, but signal design permits rejection)
- Multiple decode – Both signals decoded at receiver

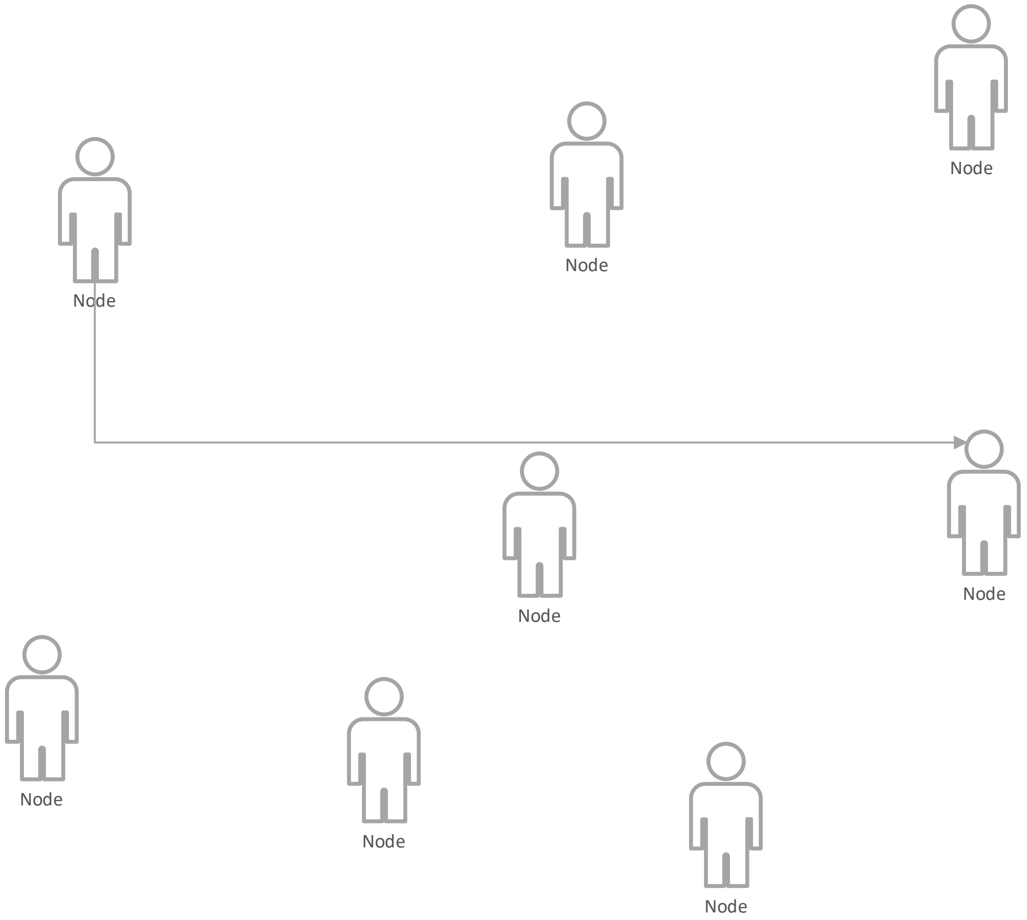


Draft Standard: Network topologies

- Point-to-point (configured by setting no routing tables for a node)
- Store-and-forward (configured by setting a store-and-forward routing table for a node)
- Mesh (configured by setting a mesh routing table for a node)
- Ad hoc (self-forming point-to-point)

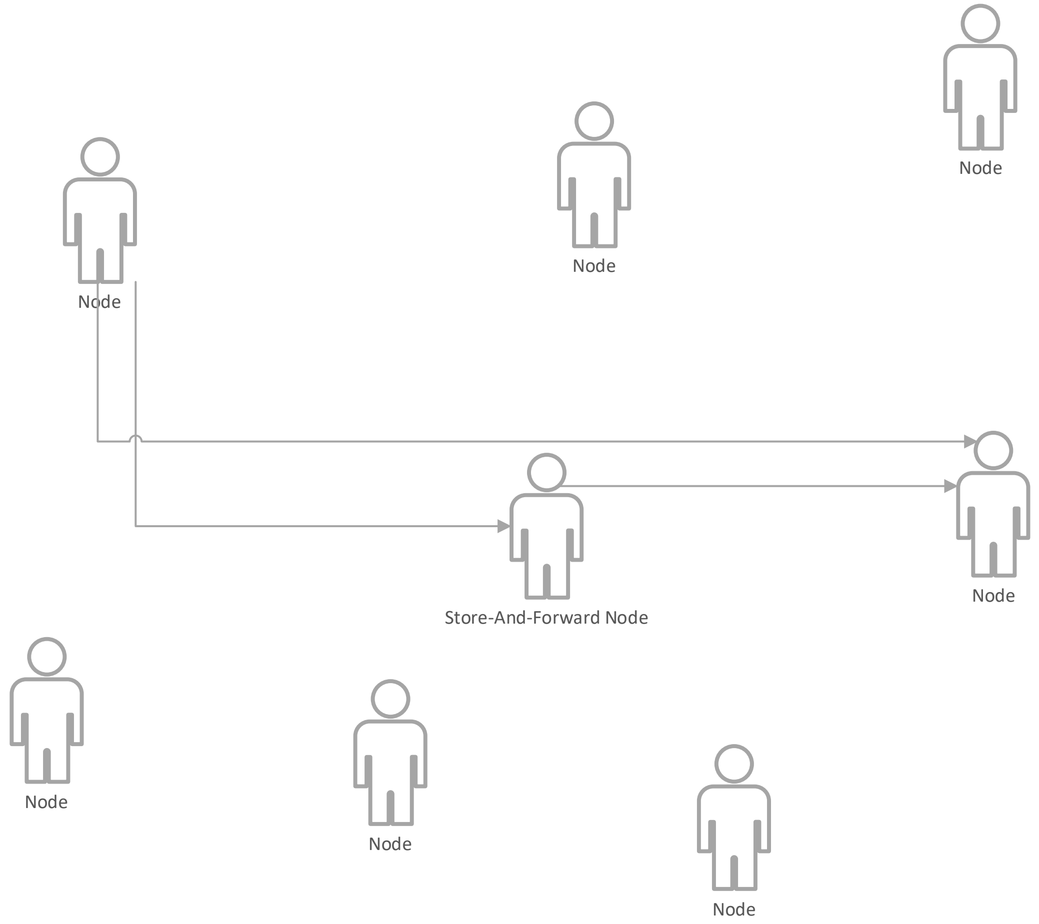
Draft Standard: Topology – point-to-point

Each node transmits message, hoping it will reach destination



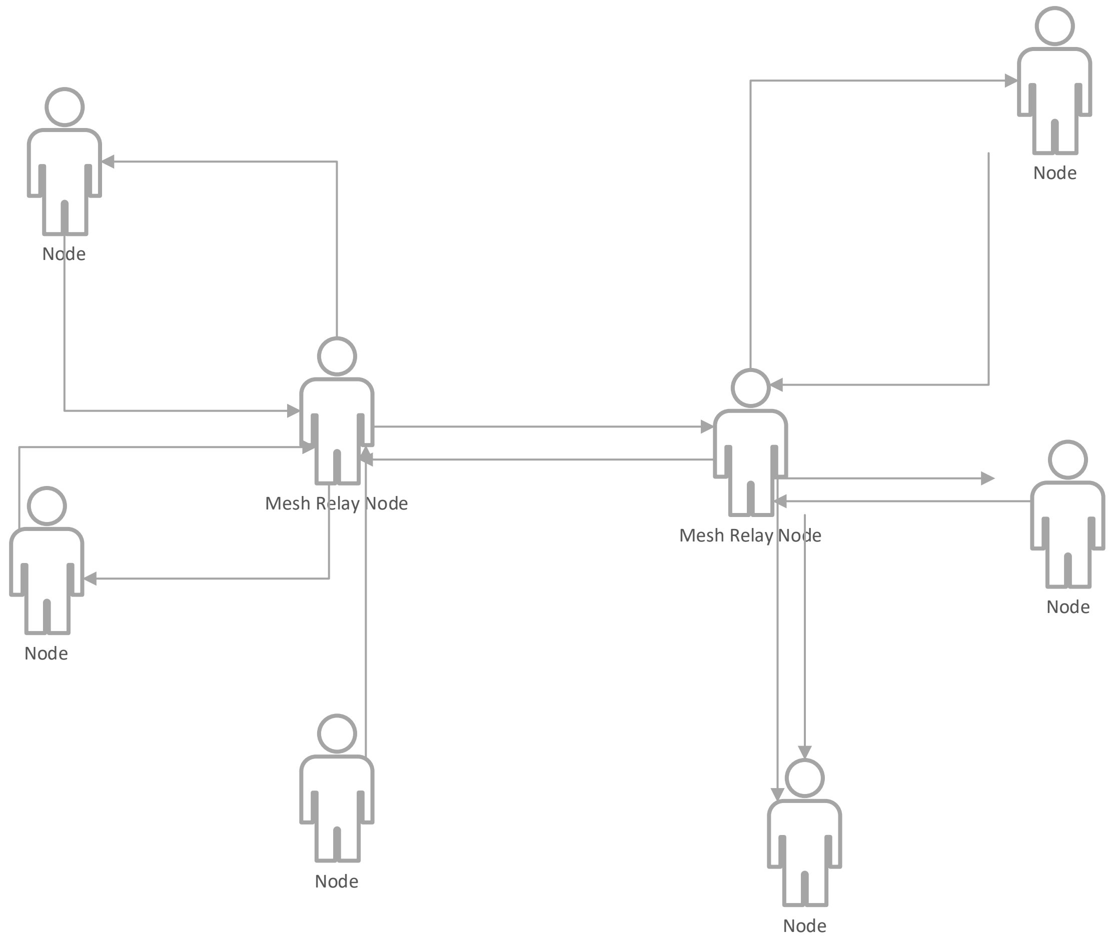
Draft Standard: Topology – store-and-forward

- With store-and-forward, node transmits message, hoping to reach destination
- Store-and-forward relays message, increasing probability of receipt by destination



Draft Standard: Topology - Mesh

- Normal nodes communicate only with own mesh relay nodes
- Mesh relay nodes communicate with own normal nodes and own other mesh relay nodes
- Greatest flexibility of message passing



Network Simulator: Network and message operations

- Send message: message may or may not require ACK. If message requires ACK and none received in a timely fashion, message resent. Receiving nodes automatically ACK messages sent to them, if required. This function works whether modulator is set to SMAC or HDC

- Schedule HDC event. A node pushes configuration messages to all other nodes, requiring ACK from all. A time to begin HDC operations is in the message, as well as duration of the HDC operation. Configuration data includes new SMAC center frequency and bandwidth. Originating node will wait for the latter of: all ACKS, or time to start. HDC operation will then begin with originating node as primary sender.

Draft Standard: SMAC PHY

- SWiG Level 1 improved – re-use coding, interleaver, hop sequence, preamble, etc. Extends bit rate capability via time-frequency scaling
- BPSK-CDMA: TBD – but could be taken from open-source BPSK-CDMA HDC PHY. Vendor suggestions welcomed
- S2C: TBD – vendor support welcomed

Draft Standard: HDC PHY

- BPSK streaming – via time-frequency scaling, specifying FEC, ISI, center frequency, bandwidth
- BPSK packet – via time-frequency scaling, specifying FEC, ISI, center frequency, bandwidth
- QPSK streaming – via time-frequency scaling, specifying FEC, ISI, center frequency, bandwidth
- QPSK packet – via time-frequency scaling, specifying FEC, ISI, center frequency, bandwidth
- BFSK packet– via time-frequency scaling, specifying FEC, ISI, center frequency, bandwidth
- BPSK-CDMA – via time-frequency scaling, specifying FEC, Gold Codes, ICI, center frequency, bandwidth
- OFDM – via time-frequency scaling, otherwise following 802.11a OFDM standard, specifying coding type, center frequency, bandwidth
- MIMO – OTFS can be included later, if an open source arrangement can be made (Next Phase TBD)

Draft Standard: SMAC MAC

- Direct support for SWiG commands
- Specific callout for network-centric MAC elements
  - Special addressing for multiple destinations
  - HDC access configuration
  - User data message
  - UUID announcement (for ad hoc topology)
  - UUID ACK/NAK (for ad hoc topology)
  - SMAC modulator configuration
  - Relay node designation/de-assignment
  - Mesh node designation/de-assignment
  - Network full reset
  - TDMA assignment/de-assignment
  - CSMA enable/disable (aka free-access designation)
  - Keepalive

Draft Standard: HDC MAC

HDC MAC deliberately simple – HDC use likely to be single point-to-point link used for high data-rate exchange, such as data dump, video, real-time control

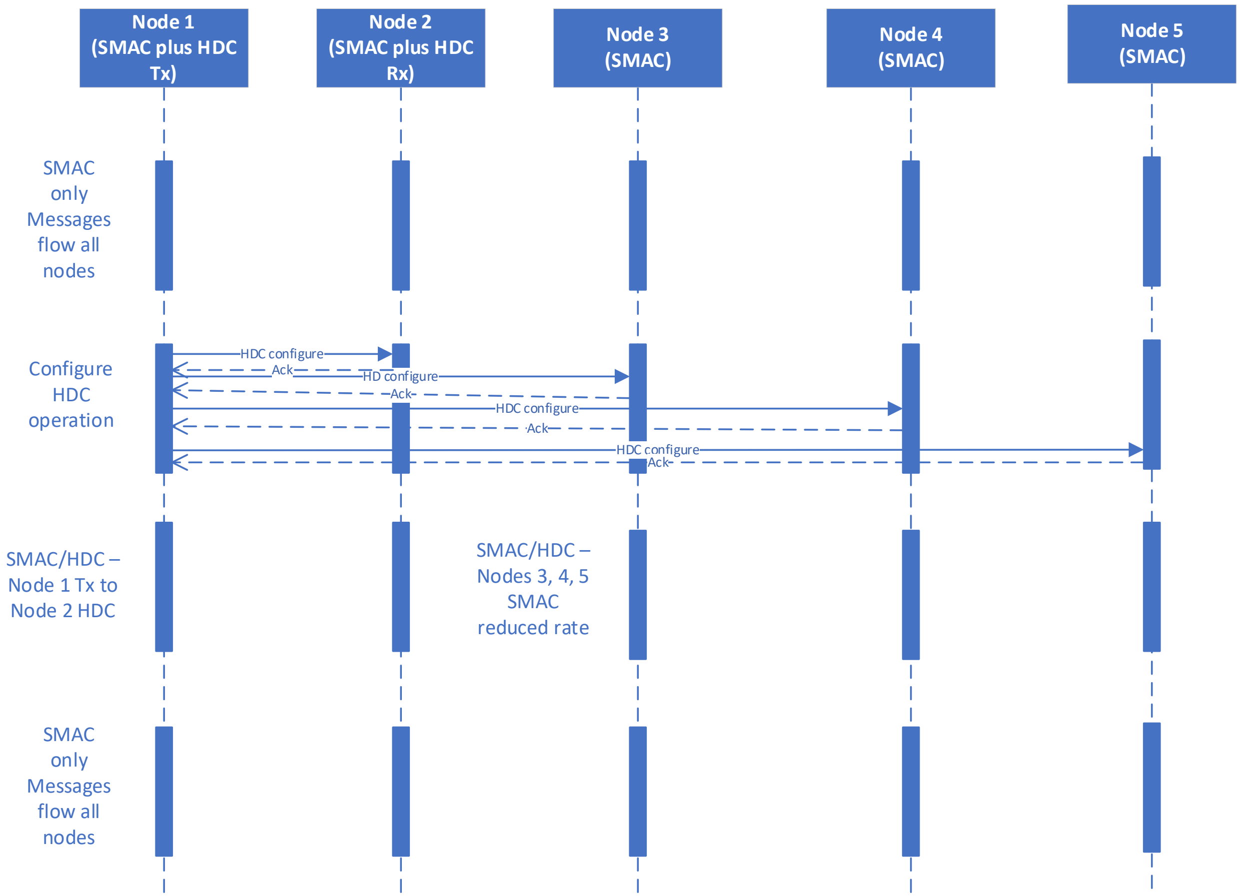
HDC is envisaged as available for proprietary use on a not-to-interfere with SMAC basis. Vendor-defined proprietary MAC acceptable.

- Streaming MAC – no MAC needed
- Packet/broadcast MAC
  - PHY access via CSMA
  - Source
  - Destination
  - Broadcast boolean
  - ACK required
  - ACK channel (SMAC or HDC)
  - Number of PHY packets in data

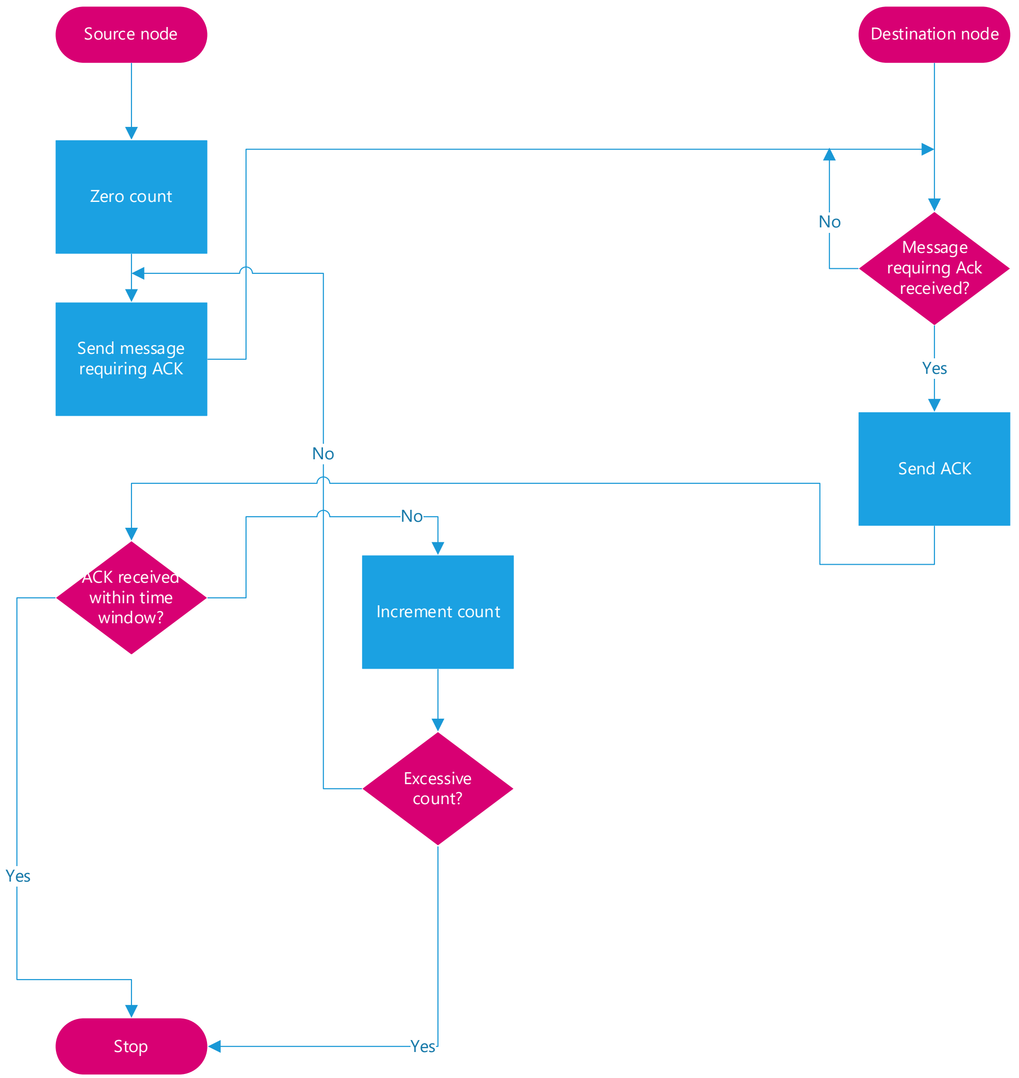
- Vendor-defined MAC

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.

HDC configuration and use – sequence diagram



ACK messaging sequence



Simulator: Demonstration of protocol, testing configurations

- Implements functional simulation of MAC and PHY for SMAC and HDC for modulation types
- Protocol is defined as methods within objects, so protocol is effectively specified as both basic elements and an application programming interface (API)
- SWiG can define the API that manufacturers can supply, providing uniform application capability for end-users
- Permits evaluation of network performance in highly configurable topologies, noise environments, equipment interference, and varying node capabilities

Simulation Results: Self-cancelling vs. not self-cancelling: no CSMA vs. CSMA

15 nodes in a 6km x 6km x 600m uniform distribution

DSSS, SC, no CSMA	0 repeaters	1 repeater	2 store & forward	4 store & forward	2 Mesh	4 Mesh
Fraction messages lost	0.3/0.2	0.03/0	0.02/0	0.006/0	0.06/0.02	0.3/0.2
Mean latency	2.6/5.0	3.5/4.6	3.6/4.3	3.7/4.2	3.5/4.1	2.8/4.2
Sigma latency	0.9/9.6	1.7/6.2	1.8/4.6	1.8/4.6	1.8/5.7	1.2/7.8
Median latency	2.7/2.8	3.2/3.2	3.2/3.4	3.3/3.3	3.1/3.1	2,7/2.7
Max latency	4.5/92	11.3/38	13/37	11/37	14/39.9	10/64
SMAC throughput (bps)	328	448	442	453	413	337

DSSS, NSC, no CSMA	0 repeaters	1 repeater	2 store & forward	4 store & forward	2 Mesh	4 Mesh
Fraction messages lost	0.4/0.3	0.3/0	0.3/0	0.2/0	0.3/0.03	0.4/0.2
Mean latency	2.7/47.5	3.1/29.2	3.2/33	3.5/22	3.1/37.9	2.7/56.8
Sigma latency	0.9/200	1.3/74	1.5/89	1.9/57	1.3/99.1	1.1/191
Median latency	2.8/2.9	2.9/3.6	2.9/3.6	3.1/3.8	2.9/3.8	2.7/3.1
Max latency	5/2197	6.8/577	10.1/757	12/607	9.6/997	8.5/1566
SMAC throughput (bps)	271	345	342	348	325	277

DSSS, NSC, CSMA	0 repeaters	1 repeater	2 store & forward	4 store & forward	2 Mesh	4 Mesh
Fraction messages lost	0.4/0.3	0.4/0.3	0.4/0.4	0.4/0.4	0.4/0.4	0.4/0.4
Mean latency	172/203	482/488	414/431	516/584	429/446	199/199
Sigma latency	211/243	537/514	423/443	487/485	623/651	245/225
Median latency	87/88	278/295	263/261	372.436	170/166	113/138
Max latency	1199/1154	2558/2432	2361/2075	2325/2258	3174/2534	1406/1427
SMAC throughput (bps)	268	282	266	263	261	271

Repeaters or mesh essential

CSMA does not help DSSS

Self-cancellation significantly reduces packet loss and latency, improves throughput

Simulation Results: DSSS vs. SWiG Level 1

15 nodes in a 6km x 6km x 600m uniform distribution

DSSS, NSC, no CSMA	0 repeaters	1 repeater	2 store & forward	4 store & forward	2 Mesh	4 Mesh
Fraction messages lost	0.4/0.3	0.3/0	0.3/0	0.2/0	0.3/0.03	0.4/0.2
Mean latency	2.7/47.5	3.1/29.2	3.2/33	3.5/22	3.1/37.9	2.7/56.8
Sigma latency	0.9/200	1.3/74	1.5/89	1.9/57	1.3/99.1	1.1/191
Median latency	2.8/2.9	2.9/3.6	2.9/3.6	3.1/3.8	2.9/3.8	2.7/3.1
Max latency	5/2197	6.8/577	10.1/757	12/607	9.6/997	8.5/1566
SMAC throughput (bps)	271	345	342	348	325	277

Primitive SWiG, NSC, CSMA	0 repeaters	1 repeater	2 store & forward	4 store & forward	2 Mesh	4 Mesh
Fraction messages lost	0.5/0.5	0.5/0.4	0.5/0.4	0.5/0.5	0.4/0.4	0.6/0.6
Mean latency	169/184	341/342	341/342	708/706	543/564	160/156
Sigma latency	227/230	437/400	432/400	706/750	514/527	149/155
Median latency	93.0/90.0	177/197	177/197	451/420	377/401	112/94.3
Max latency	1804/1120	2386/1896	2386/1896	3094/3111	2615/2162	700/749
SMAC throughput (bps)	22.5	22.9	22.9	19.8	24.1	19.5

DSSS plus store-and-forward or mesh significantly reduces packet loss and latency, improves throughput

Simulation Results: Simultaneous SMAC and HDC

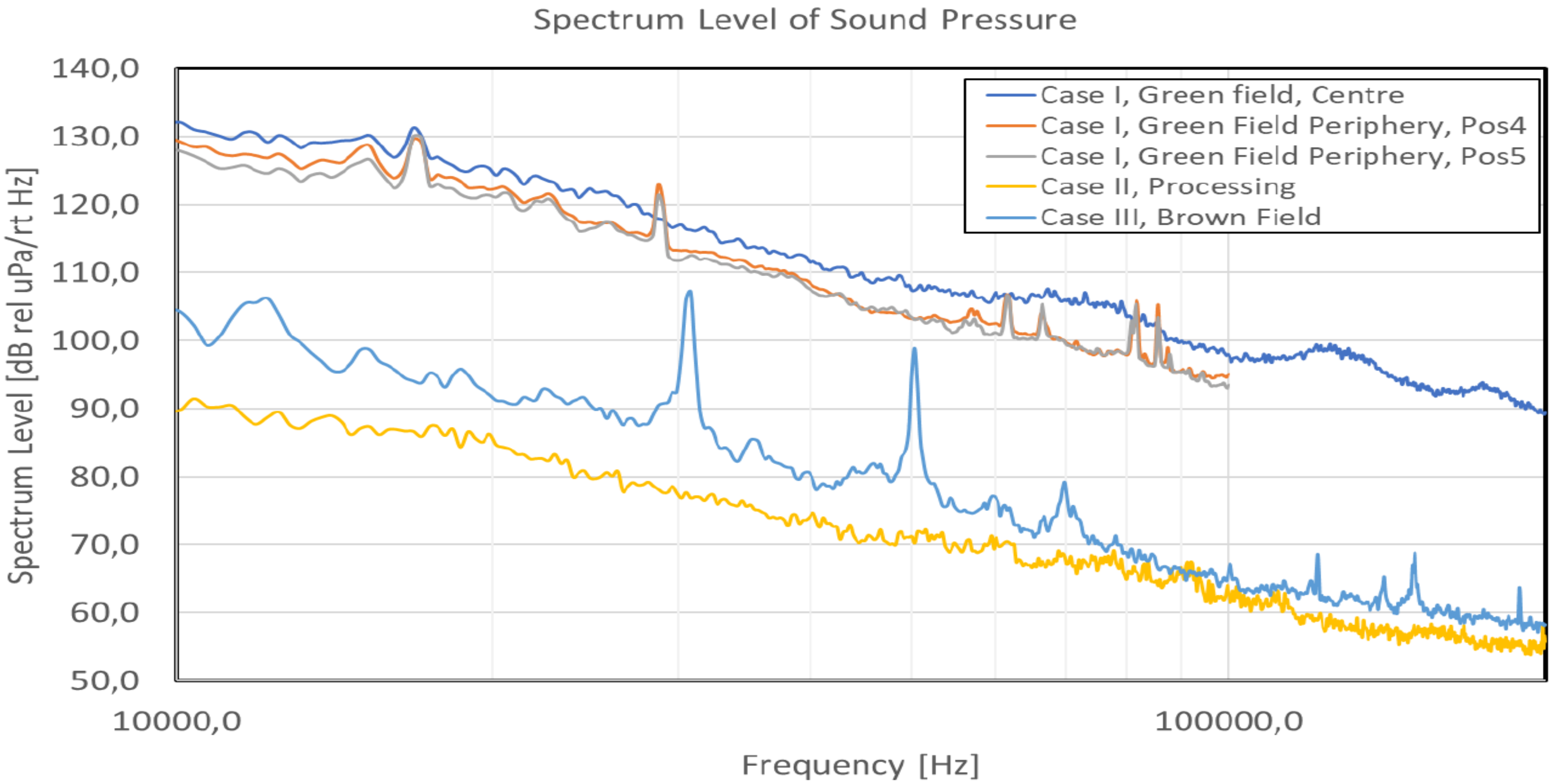
8 nodes in a 2km x 2km x 200m uniform distribution

HDC Simulation	SWiG Level 1	DSSS, No SC, no CSMA	DSSS, SC, no CSMA
SMAC fraction of messages lost	0.07/0.06	0.09/0.02	0.04/0.02
SMAC mean latency	8.1/9.8	1.4/4.9	1.4/3.8
SMAC sigma latency	13/14	0.3/9.7	0.3/8.4
SMAC median latency	4.3/2.6	1.4/1.6	1.4/1.4
SMAC max latency	112/64	2.1/32	2.5/32
Overall SMAC throughput	20.7	202	214
SMAC throughput when HDC unused	20.9	204	217
SMAC throughput when HDC in use	16.5	172	153
HDC throughput	8667	8555	8442
HDC fraction of packets lost	0.04	0.05	0.06

SMAC and HDC operations can coexist

Broadband Interference Measurements for Modeling & Simulation Using Naxys Data from Passive Acoustic Monitoring Systems

- Naxys Data from 3 different, not connected scenarios have been considered for noise modeling and interference simulation: Green Field-High Flow, Processing- Boosting Station and Brown Field



Simulation Results Including Combined Broadband Interference

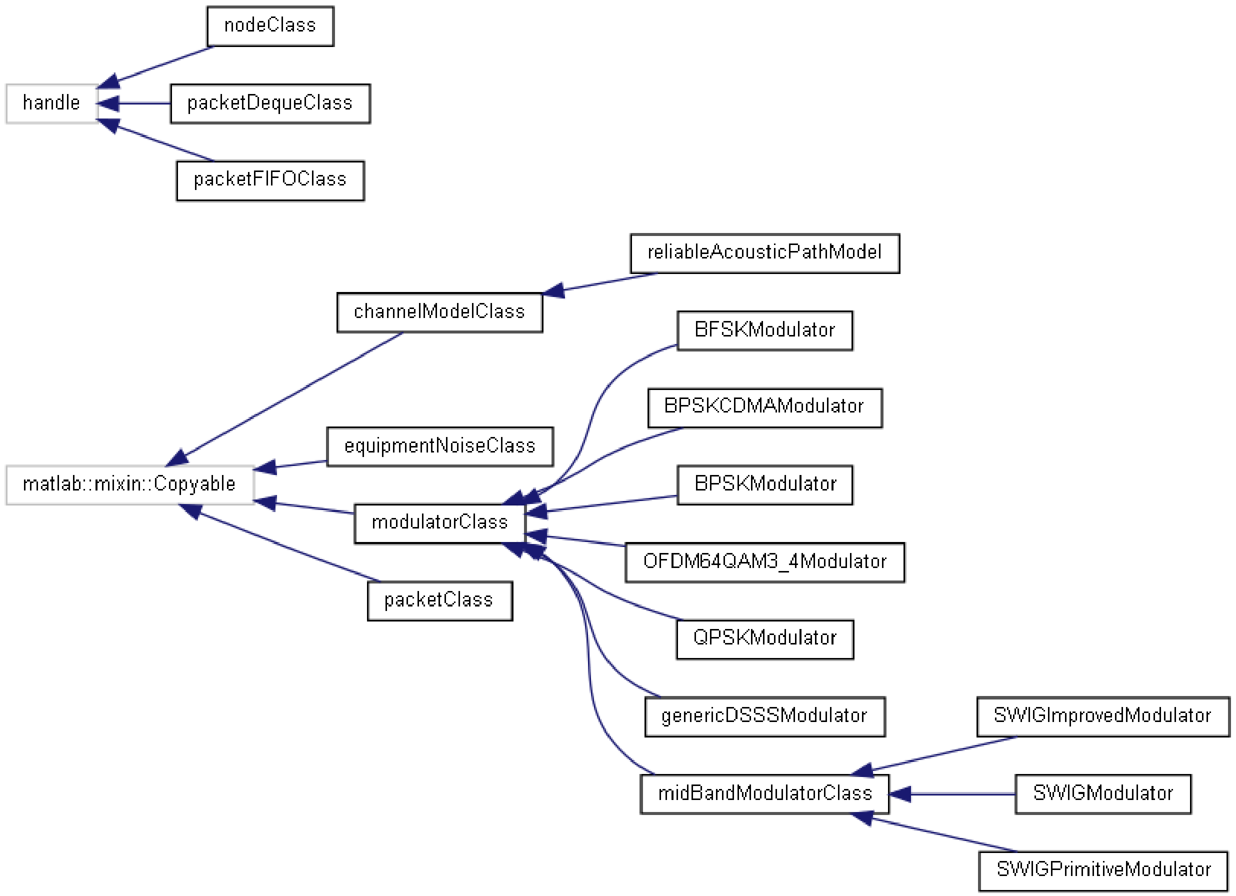
15 nodes, randomly distributed in 6km x 6km x 600 m box. SWiG Primitive (no full-duplex, direct access (no CSMA)) Interference located 1 meter away from node 6. 1 hour simulation. SMAC Only

- Network Topology: Store & Forward with 2 relays
- Quiet – Boosting Station
- Loud – Green Field – High Flow
- Loud Intermittent interference: Green Field turned on at 1000 seconds, turned off at 1500 seconds.

Statistic	No interference	Quiet, constant interference	Loud constant interference	Loud, intermittent interference
Fraction non-critical lost	0.12	0.12	0.27	0.13
Fraction critical lost	0	0	0.1	0
Mean non-critical latency (sec)	3.5	3.5	3.5	3.5
Mean critical latency (sec)	10.2	11.7	21.5	14.1
Sigma non-critical latency (sec)	1.6	1.5	1.5	1.5
Sigma critical latency (sec)	18.6	30.3	51.4	28.6
Overall Network throughput (bps)	404	388	334	403

Quite interference slightly affects network comms performance.
Constant loud interference significantly affects network comms performance.
Intermittent loud interference slightly affects network comms performance

Network Simulation Software : Classes implementing protocol



Network Simulation Software

- Available at GitHub:
  - git@github.com:QinetiQ-US/SWiG.git or
  - https://github.com/QinetiQ-US/SWiG.git
- Documentation for simulator by doxygen. Main help file (after cloning repository):
  - file:///SWiG/SimulationCode/Doc/html/index.html
  - Documentation contains:
    - Full graphs of class structures
    - Documentation of all member functions – particularly those implementing MAC and PHY
    - Documentation of all attributes
- Sample scripts included for
  - Demonstration of moving nodes
  - Demonstration of equipment noise interference
  - Mesh network
  - Point-to-point network
  - Store-and-forward network