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SWiG Dual Channel Protocol Requirements Definition

Neil Judell

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System performance requirements are based on the use case, case studies and survey responses. Responses were largely unclear on packet sizes, packet frequency and information distribution, so requirements will need to be flexible. The variety of responses was huge, with many 2-node systems that are purely point-to-point, a range of systems with tens of nodes, and one system with 4000 nodes. The 4000-node system will not be considered for network consideration, as it is a special application for seismic survey, and is not expected to interact or interoperate with other systems – the presence of air gun activity every 30 seconds precludes this. Barring that example, we will endeavor to meet the upper requirements of the specified use cases.

There are still use cases under discussion requiring Mbps data rates in HDC. Those will be addressed at a later stage. However, this preliminary requirement definition does not limit further development and enhanced capabilities on both channels.

The primary design for the network will be for the FD (low bit-rate) channel, with the HD (high-bit-rate) channel largely dependent upon the specific applications. Use cases with bit rates that rely on the high-bit-rate channel are not considered in specifying the low-bit-rate channel

Network requirements (1.1)

Characteristic	Min	Max	Median	Detailed tasking Paragraph number
Number of nodes	2	200	40	1.1.1.1
Point-to-point-range	1 meter	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)[1]	80	800	100	1.1.1.3.1
Small packets per node per second	0	0.06	0.06	1.1.1.3.2

[1] User packet sizes may be larger than modem physical layer packet sizes. This is addressed in the modem requirements section

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

The requirements for applications require that the FD channel be configurable for:

- Routing methods to be supported (1.1.5.1, 1.1.5.2, 1.5.5.4):
  - point-to-point
  - mesh
  - store-and-forward
- Network definition
  - Ad-hoc (with first-contact protocol)
  - Pre-programmed formation
- All routing methods and network definition methods will be open source for the FD channel
- A minimum set of routing methods and network definition will be supported as open source for the HD channel, with a minimum of:
  - Point-to-point routing
  - Pre-programmed formation

Modem requirements (1.2) – FD channel

Some modem requirements (such as modulation method) derive from throughput requirements, while some are driven by application requirements.

We'll begin with the throughput requirements, which tend to drive waveform requirements: node throughput requirements (1.2.2.1), network throughput requirements (1.2.2.2) and network loading/collision rates (1.2.3 and 1.2.4)

We see that an absolute minimum for the FD channel for each node is 44 BPS. Note that this is target packet size, not raw (after error coding and preamble). The SWiG level 1 standard can deliver 110 BPS at full bandwidth. Node channel transmission fraction is thus 40%. With a median network of 40 nodes, assuming Poisson arrivals, we can expect 2.4 packets per second arriving at each receiver. With a packet duration of 7.3 seconds, we have an average of 17 collisions at each node. This is far larger than the SWiG modulation can handle. Additionally, each collision of SWiG waveforms has roughly a 10%

probability of overlapping preamble, resulting in loss of packets. We see that SWiG level 1 cannot be used for this level of operation. Even with strict TDMA, the network throughput requires large numbers of collisions.

For this application, we see that the modulation method must be designed for simultaneous multiple access. Generally, for low-power processors such as those on undersea modems, we can handle no more than 4 collisions. This implies that the lower bound on the modulation method is approximately 500 BPS. This is also a requirement for sustained performance. The spectral efficiency (ratio of bit rate to bandwidth) is low for frequency hopping spread spectrum (FHSS) – typically on the order of 0.01 bits/sec/Hz. Typical CDMA is on the order of 0.1 bits/sec/Hz, making this a potential candidate. This network could be sustained at a 10 kHz bandwidth, and with proper planning, might be able to be able to sustain a 5 kHz bandwidth. It should be noted that sweep spread carrier (SSC / S2C) can also achieve these types of spectral efficiencies and collision performance. Other forms of direct sequence spread spectrum (DSSS) may also achieve these performance requirements.

All modulation methods should be configurable and scalable down in bit rate by lowering bandwidth to assist in coexistence with the HD channel.

Some candidate modulation methods and their characteristics:

Modulation method	Network throughput	Doppler behavior	Ranging behavior	Other
SWiG level 1 (slow FHSS - BFSK)	110 bps	Poor	Poor	Poor collision behavior
SWiG 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

Note that the throughput for the network is specified at a median 40 node network at full bandwidth (assumed to be SWiG level 1 at 6.76 kHz). The overall network throughput will drop proportional to bandwidth, with proposed nominal bandwidths of 1.69 kHz, 3.38 kHz, 5.1 kHz and 6.76 kHz, with a nominal lower frequency limit of 17.95 kHz and nominal upper frequency limit of 24.71 kHz.

NOTE: network throughput rates (1.2.2.2) are not the same as individual node rates (1.2.2.1). The network throughput is shared among all nodes.

NOTE: physical layer protocol requires that modulators and demodulators must be capable of adjusting center frequency and bandwidth in a scalable fashion, to provide lower bit rates at lower bandwidth. For CDMA and similar direct-sequence methods, this can be accomplished by changing the chip rate and scaling the intersymbol interference (ISI) filters without further adjusting channel code. For FHSS methods, this can be accomplished by scaling the frequency hops and adjusting the hop intervals accordingly.

NOTE: User packet sizes are likely to be larger than modem physical layer packet sizes. This shall be addressed by use of vanDerMonde encoding – which splits a user packet across multiple modem packets. The characteristic of a vanDerMonde(M,N) coding scheme is that the user packet is forward coded with redundancy into M modem packets. Receipt of any N modem packets will yield correct decoding of the user packet. Typical coding uses are (3,2), (6,4). For small M and N, these may be taken from error coding for RAID disk arrays.

- Access modes to be supported (from 1.2.4.1 and 1.1.1.5.4):
  - TDMA (Time Division Multiple Access). TDMA is highly applicable to fixed-location networks, but difficult to make work for moving nodes. TDMA also subject to guardbanding from clock drift for long-duration deployments, where a crystal clock typically varies by 180 seconds per year. This requirement is for backward compatibility for use cases. Not appropriate for nodes containing moving nodes except under limited circumstances.
  - CSMA (Carrier Sense Multiple Access). This is for backward compatibility with SWiG level 1.
  - SMAHD (Simultaneous Multiple Access – Half Duplex). Significantly improves ability of the network to withstand collisions, and to improve throughput over CSMA and many TDMA implementations.
  - SMAFD (Simultaneous Multiple Access – Full Duplex). Significantly improves ability to withstand collisions, and to improve throughput over SMAHD.

Additional requirements, both from users and from the nature of the split with FD/HD:

- Ability to perform ranging functions at a rate of 10 per hour to all nodes
- Backward compatible with SWiG level 1
- Center frequency and bandwidth adjustable
- First contact protocol
- FD channel shall support SWiG commands being developed as part of the main standard
- Waveforms, coding and protocol within the FD channel will be open source
- A set of waveforms, coding and protocol for the HD channel will be defined – these waveforms and codes must be useful for communication at a reasonably high rate, and shall be open source
- Proprietary waveforms and coding for the HD channel are permissible, provided they do not interfere with the operation of the FD channel (as negotiated during protocol). It is desirable that these waveforms and codes will be open-source.
- Sidelobes from FD channel must be sufficiently small as to not significantly interfere with HD operation

That last requirement may make backward hardware compatibility difficult or impossible. Many existing modems use Class S amplifiers. These amplifiers use switching transistors that output high or zero voltage depending solely on the sign of the passband signal. They are, in effect pulse-width modulators operating at the carrier frequency. They cause sidelobes that can be as large as – 10 dB down from the main lobe, typically offset by the chip rate from main carrier. Fortunately, there are new class D amplifier chips available for the frequencies of interest – that have low distortion – and hence low sidelobes (assuming the signals are appropriately designed). These have the same excellent power efficiency characteristics of the class S amplifiers, but with low noise, low distortion, low cost and small size.

The need to retrofit Class S amplifiers can be avoided under the protocol by degrading performance. The HD channel configuration can be specified to completely shut down the FD channel while HD is in use. This is consistent with operation of Class S amplifiers. Alternatively, if there is sufficient guard-band between the HD and FD channels (i.e. HD channel frequencies are significantly higher than FD channel frequencies), then simultaneous FD and HD operation can still be achieved.

DSSS methods and FHSS methods tend to have a number of tradeoffs in their selection

- FHSS generally permits more simultaneous nodes than DSSS
- FHSS generally has lower spectral efficiency than DSSS – resulting in a lower individual node bit rate for FHSS
- FHSS tends to degrade more gracefully as the number of simultaneous nodes increases compared to DSSS.
- SWiG Level 1 and JANUS both have a weakness compared to most FHSS implementations – the preamble is common to all nodes, so reception of two or more preambles simultaneously results in failure to decode. It may be desirable to address this with a new standard for preambles for SWiG Level 1
- DSSS requires serial, parallel, or serial/parallel demodulation and cancellation to work well in congested environments, increasing computational complexity.
- DSSS is far more susceptible to the near/far effect than FHSS. In most networks, this is addressed with transmitter power control. This may need to become part of the standard.

The FD channel will be defined for capabilities of:

- Modulation methods (such as SWiG level 1 slow FHSS, Zadoff-Chu slow FHSS, CDMA, SSC).
- Reduced symbol rate, with bandwidth of 0, ¼, ½ and ¾ full FD bandwidth
- Access methods (such as CSMA, TDMA, SMAHD, SMAFD).
- Full-duplex capabilities:
    - None
    - Analog-only cancellation
        - Using active circulator (power levels below 170 dB) [1]
        - Using two transducers, one projector, one hydrophone/receiver [2]
    - Software-only cancellation using two transducers [3]
    - Hybrid analog/software
        - Active circulator (power levels below 170 dB)
        - Two transducers [2]
    - Additional cancelation methods published in open literature can be considered [4]-[7]

Announcement messages will outline the capabilities of the modem, so network configuration can proceed.

The absolute minimum level of support – which is for backward compatibility:

- SWiG Level 1 modulation and coding
- Capability of reduced symbol rate of 0 – i.e. operating the HD channel fully shuts down the FD channel
- CSMA access as per SWiG Level 1

Announcement messages for desired routing method will be required.

Open-source communication for HD channel

These waveforms/codes are for minimum capability. Proprietary waveforms and codes are permitted and encouraged to enhance HD channel capabilities.

The HD channel will at a minimum support the following two methods, one for streaming, one for packets:

- Streaming
    - Point-to-point, with time, source and destination specified in the FD channel negotiation
    - Differential quadrature phase shift keying (DQPSK) – two bits per symbol
    - Streaming data – all formatting to be determined by the user
    - Convolutional coding with form of poly2trellis(5, [23,35]) (2:1 encoding – this designates a particular trellis code with parameters 23 and 35)
    - Intersymbol interference (ISI) filter – which also removes sidelobes to permit interoperability:
        - Root-raised cosine
        - Filter span of 16 symbols
        - Rolloff factor of 0.2
    - 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:
        - 24 kHz carrier, 10 Kbits/sec – FD channel shut down completely during HD use
        - 24.9 kHz carrier, 8.5 Kbits/sec – FD channel will operate at ¼ rate
        - 25.9 kHz carrier, 7.0 Kbits/sec – FD channel will operate at ½ rate
        - 26.5 25kHz carrier, 5.5 Kbits/sec – FD channel will operate at ¾ rate
        - 27.5 kHz carrier, 4.166 Kbits/sec – FD channel operates at full capacity

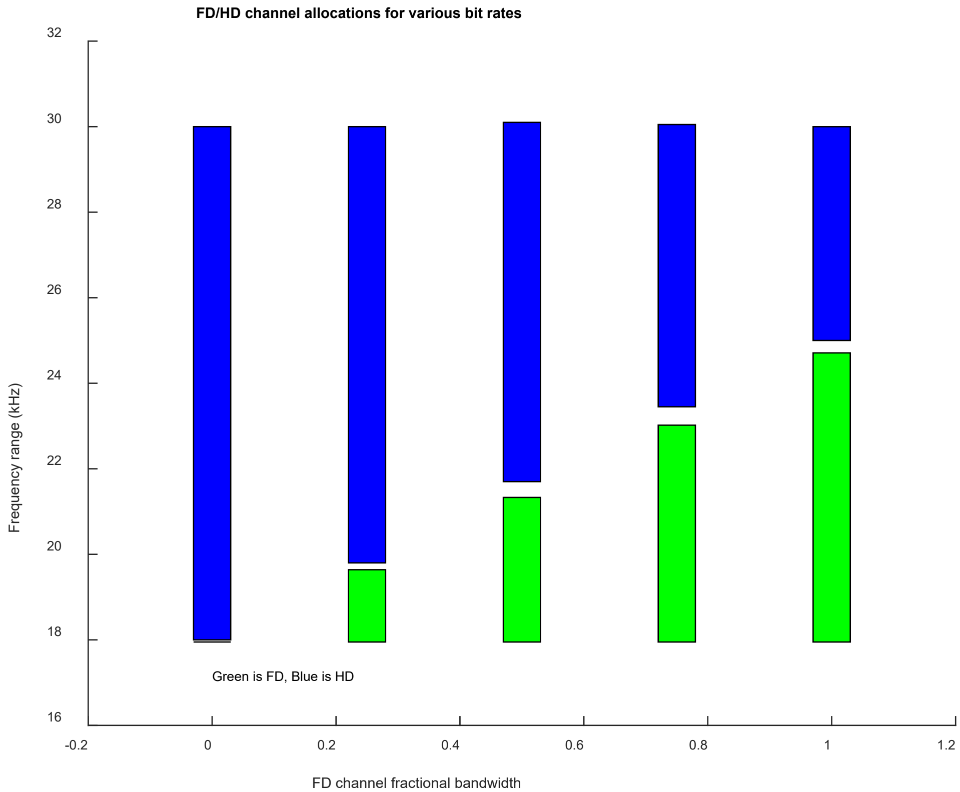

Figure 1: Frequency allocations for supported rates

- Packets
    - Point-to-point, with time, source and destination specified in the FD channel negotiation
    - Differential quadrature phase shift keying (DQPSK) – two bits per symbol
    - Packet data
    - Coding: BCH(2047,1222) soft BCH with CRC-16-CCITT (1206 bits/packet)
    - Intersymbol interference (ISI) filter – which also removes sidelobes to permit interoperability:
        - Root-raised cosine
        - Filter span of 16 symbols
        - Rolloff factor of 0.2
    - The packet shall be preceded by a training/channel probe waveform of a length 127 m-sequence using BPSK modulation (and ISI filter).
    - This training waveform will be followed by 32 symbol periods of silence
    - The packet waveform will then be transmitted
    - 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:
        - 24 kHz carrier, 10 Kbits/sec – FD channel shut down completely during HD use
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        - 25.9 kHz carrier, 7.0 Kbits/sec – FD channel will operate at ½ rate

- 26.5 25kHz carrier, 5.5 Kbits/sec – FD channel will operate at ¾ rate
- 27.5 kHz carrier, 4.166 Kbits/sec – FD channel operates at full capacity
- NOTE: symbol rate is ½ of the listed bit rate

Additional open-source definitions will be made for the following modulations (based on member inputs):

- BFSK
- BPSK-CDMA
- OFDM
- Possibly MIMO-OTFS if a suitable open-source arrangement can be made

The HD channel can also support proprietary modulations, such as TNO. These can be supported even if they interfere with the FD channel – as the configuration permits temporary shutdown of FD operations. If these waveforms can be scaled and filtered to reduce interference with (reduced bandwidth) FD operations, then proprietary HD and open FD operations can coexist.

The HD channel is not restricted to frequencies covered by the FD channel. It may occupy frequencies above and/or below the FD channel – thus permitting very high bit-rate operations at close range. The only consideration is when the HD channel frequencies overlap the nominal FD frequencies – requiring FD bandwidth reduction during HD operation. For instance – an HD channel can operate in the 100 kHz regime without requiring FD reconfiguration.

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