The JANUS Underwater Communications Standard

John Potter*, João Alves*, Dale Green†, Giovanni Zappa*, Ivor Nissen‡, Kim McCoy§

* NATO STO Centre for Maritime Research and Experimentation, La Spezia, Italy
{potter,alves,zappa}@cmre.nato.int

† Teledyne Benthos, North Falmouth, MA, USA
dale.green@teledyne.com

‡ Federal Office of Defense Technology and Procurement - WTD 71, Eckernförde, Germany
ivornissen@bwb.org

§ Ocean Sensors Inc., San Diego, CA, USA
kmccoy@oceansensors.com

***Abstract*—There are currently no digital underwater communications standards. In this paper we describe JANUS, a simple multiple-access acoustic protocol designed and tested by the NATO Centre for Maritime Research and Experimentation (CMRE) over the past 6 years that provides a basic and robust tool for collaborative underwater communications. JANUS is in process to become a NATO standard but is not intended to be solely military nor only for NATO, but also for civil and international adoption. JANUS is unique in its open and public nature such that academia, industry and governments may all benefit from its use. The specification of the signal encoding and message format is fully described so that anyone may construct a transmitter/receiver to communicate via JANUS to any other compliant platform. While JANUS is deliberately simple to allow easy adoption by legacy equipment, the protocol also offers the freedom to utilize sophisticated receivers and decoders allowing performance to be significantly improved.**

***Index Terms*—Underwater Communication, Protocols, Standards, Interoperability, JANUS.**

I. Introduction

Underwater (UW) communication capabilities are currently manufacturer-specific, generally using proprietary digital coding technologies.There exists no general interoperable capability for digital UW communication between assets using modems from different manufacturers Interoperability is an essential feature as maritime operators seek to integrate an increasingly heterogeneous mix of maritime assets. Currently there are no existing means to discover other communicating assets to permit the formation of ad-hoc networks [1],[2]. The establishment of an UW digital communications standard therefore has wide application in both military and civilian contexts.

II. Protocol Description - Modulation and Coding Scheme

The JANUS standard [3],[4],[5],[6] is deliberately robust. The digital coding technology that is used is well-known and can easily be adopted by a wide range of existing systems. The physical layer coding scheme is known as Frequency-Hopped (FH) Binary Frequency Shift Keying (BFSK) [7]. FH-BFSK has been selected for its robustness in the harsh UW acoustic propagation environment and simplicity of implementation. In the JANUS scheme, binary data is mapped into time-windowed continuous waveform (CW) tones of unspecified phase, selected from 13 evenly-spaced tone pair choices spanning the frequency band Bw, which is nominally $1/3$ of the centre frequency F_c. A core feature of the JANUS specification is that once a frequency band is chosen, the chip duration C_d, wake-up tone duration (if present) and frequency slot width FS_w are calculated directly from the upper and lower band values, while the FH sequence and reverberation delay time remain constant for any band. Robustness to temporal and frequency fading is provided by a ½ convolutional encoder [8], followed by interleaving. Data corruption is detected by an 8-bit Cyclic Redundancy Check (CRC). The coding operation sequence required to generate a Baseline JANUS Packet, without appended cargo data, is shown in Fig. 1. The specification of each of the functional blocks in Fig. 1 is described in the following sub-sections.

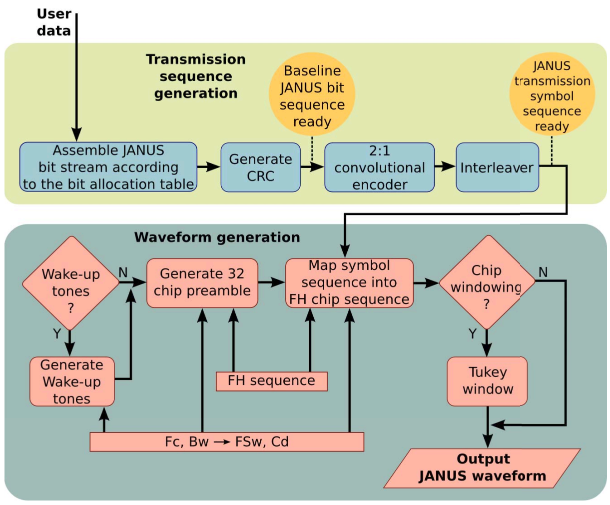

Fig. 1. Block diagram for the JANUS baseline packet encoding process.

978-1-4799-7578-5/14/$31.00

A. JANUS baseline packet specification

A Baseline JANUS Packet consists of 64 bits of information, constructed according to Table I. This packet includes a 34 bit Application Data Block (ADB) that is defined according to one of 64 possible schemes to be specified for each user class by the designated user. There are 256 user classes, allocated to countries, specific organisations and special purposes, listed in Table II.

B. User Packet Data Specification

The user may specify what information is encoded and how it is encoded into the 34 user-available bits of the ADB in the Baseline Packet. In the case where the repetitive beacon or channel reservation option is exercised the first 8 of the 34 bits are allocated to specifying the reserve or repeat interval according to the expressions (1) and (2) respectively. The remaining 26 bits are to be allocated by choice of the user.

$$T_{RSV}(i) = \begin{cases} 0.0033211, & i = 0. \\ 1, & i = 60 \\ 10, & i = 84. \\ 60, & i = 103. \\ 600, & i = 127. \\ T_{RSV}(i-1) \times 1.1, & \text{otherwise } (i < 127). \end{cases} \tag{1}$$

$$T_{RPT}(i) = \begin{cases} 0.0033211, & i = 0. \\ 1, & i = 21 \\ 10, & i = 35. \\ 60, & i = 46. \\ 3600, & i = 71. \\ 86400, & i = 91. \\ 31557600 & i = 127. \\ T_{RPT}(i-1) \times 1.176769793407883, & \text{otherwise } (i < 127). \end{cases} \tag{2}$$

C. Cyclic Redundancy Check

Packet integrity is ensured by a 8-bit Cyclic Redundancy Check (CRC) which uses the CCITT polynomial $p(x) = x^8 + x^2 + x^1 + 1$, initialised to 0. The 8 bits of the CRC are appended to the 56 bits of the main Baseline JANUS Packet as indicated in Table I.

D. Convolutional Encoder and Interleaver

A $1/2$ rate convolutional encoder is applied to the 64 bits of information, using a constraint length $k = 9$, resulting in 128 symbols of output. The generator sequences used for the encoder are:

$$\begin{aligned} g_1(x) &= x^8 + x^7 + x^5 + x^3 + x^2 + x^1 + 1 \\ g_2(x) &= x^8 + x^4 + x^3 + x^2 + 1 \end{aligned} \tag{3}$$

Prior to encoding, 8 zeros are appended to the data to flush the encoder, discarded at the receiver. The total number of symbols output by the encoder then becomes $2 \times (64 + 8) = 144$. An interleaver is applied to the 144 symbol message after the convolutional coding. The interleaving process separates each consecutive bit by a constant depth value of 13. This allows for bursts of consecutive bit errors to translate into multiple small gaps in the reconstructed stream increasing the probability of succesful decoding.

E. Optional wake-up tones

The JANUS packet may optionally be preceded by three wake-up tones, each with duration $4 \times C_d$ without pause between the tones, at frequencies: $F_c - Bw/2$; F_c ; $F_c + Bw/2$ Hz in that order. These are intended for use where a modem needs to wake-up from a low power or sleep mode. The tones are not expected to be used when their intended receiver is already awake. If used, the tones should finish $0.4\,s$ before the main preamble to allow reverberant energy [9] in band to fade and for the intended modem to wake up.

F. The Frequency Hopping sequence specification

The order in which the 13 pairs of tones are used to encode the binary data is chosen to provide optimal Inter-Symbol Interference (ISI) rejection that could otherwise be caused by multipath or collision with JANUS packets from other users.

This pseudo-orthogonal sequence is fixed and therefore known to all potential receivers. The FH indices are derived from Galois Field arithmetic using a primitive prime number to generate 13 frequency slots to provide good orthogonality properties [10]. The tone selected is determined by the FH sequence number and whether the digital bit is a 0 or 1. The mapping of the FH sequence number and bit value for the JANUS initial frequency band is shown in Table III

G. Centre Frequency, Bandwidth, Chip duration and Frequency Slot Width

The JANUS standard is anticipated to be applied at different centre frequencies, each with a symmetrical frequency band Bw of approximately $F_c/3$ (within $+/-\ 10\%$) to meet diverse environmental, range and application scenarios. The Bw is divided into 13 pairs of Frequency Slots, each of width $F_{Sw} = Bw/26$. The baseline C_d is the inverse of the Frequency Slot width, $C_d = 1/FS_w$. This provides a scalable communication standard for which higher frequencies will be associated with a larger Bw and FS_w, with correspondingly shorter C_d and a higher data transfer rate, at the cost of decreased practical range underwater due to stronger absorption. The C_d may optionally, at the discretion of the sender, be set to a dyadic multiple of the baseline Chip duration $1, 2, 4, 8... \times C_d$ to attempt to achieve greater robustness or detectability. If invoked, this option applies to both the fixed 32 chip preamble and all following data, but does not affect wake-up tones, if used.

H. The Initial 32-chip Detection and Synchronisation preamble specification

The JANUS packet starts with a fixed sequence of 32 chips, with no temporal gap either between the chips or between the preamble and the main (modulated) part of the JANUS packet. The tones are simply the first 32 FH sequence with bit value set to the pseudo-random 31 bit sequence: 0 1 1 0 1 0 1 1 1 1 0 0 0 1 0 0 1 1 0 1 0 1 1 1 1 0 0 0 1 0 0.

Once the fixed preamble phase of the waveform is complete, the sequence generator continues into the message section and the data symbols are then taken from the encoded message to be transmitted.

TABLE I
JANUS BIT ALLOCATION TABLE

Bits	Descriptor	Values	Comments
1-4	Version	0011	unsigned 4 bit integer. Current version is 3.
5	Mobility flag	0=static, 1=mobile	Indicates nature of the transmitting platform.
6	Schedule flag	0=off, 1=on	If On (1), the first bit in the ADB indicates if the interval is to be interpreted as a reservation time (0) or a repeat interval (1). The time is specified from expressions 1 and 2.
7	Tx/Rx Flag	0=Tx-only, 1=Tx/Rx	Tx-only implies at least the ability to detect energy in band to satisfy the MAC requirements. Tx/Rx implies not only detect, but decode capability.
8	Forward capability	0=no, 1=yes	Used for routing and Delay Tolerant Networking.
9-16	Class user i.d.	[00000000 : 11111111]	Allows 256 classes of users, mostly individual nations.
17-22	Application Type	[000000 : 111111]	Allows 64 different types of message per user i.d. class user specified
23-56	Application Data Block	Determined by user	if the schedule flag (bit 6) is set, the first 8 bits are dedicated to defining the nature of the schedule (reserved or repeat interval) with time specified from expressions 1 and 2.
57-64	8-bit Checksum		8-bit CRC run on the previous 56 bits with polynomial $p(x) = x^8 + x^2 + x^1 + 1$, init=0

TABLE II
JANUS APPLICATION DATA BLOCK

0	Emergency
1	Underwater GPS
2	Underwater AIS
3	Pinger (ranging)
4 .. 14	Open
15	Capabilities Descriptor
16	NATO JANUS reference implementation
17	Afghanistan
18..210	A-Z nations
211	Zimbabwe
212..231	Unassigned Nation
232	Fixed Vertical Mooring
233	Rigid Vertical Structure
234	Hazard Marker
235	Channel Marker
236	Wind Power Generator
237	Wave Power Generator
238	Solar Power Generator
239..254	Not Allocated
255	JANUS special

TABLE III
LOWER TONE FREQUENCY EDGES FOR ALL POSSIBLE FREQUENCY-HOP SEQUENCE AND BIT VALUES DEFINED FOR THE JANUS INITIAL FREQUENCY BAND

FH	bit	freq. (Hz)	FH	bit	freq. (Hz)
0	0	9440	7	0	11680
	1	9600		1	11840
1	0	9760	8	0	12000
	1	9920		1	12160
2	0	10080	9	0	12320
	1	10240		1	12480
3	0	10400	10	0	12640
	1	10560		1	12800
4	0	10720	11	0	12960
	1	10880		1	13120
5	0	11040	12	0	13280
	1	11200		1	13440
6	0	11360			
	1	11520			

I. Tukey Chip Windowing

One of the original requirements for JANUS was that it could be implemented by an analogue class D amplifier without amplitude modulation. While the chip amplitude envelope should be nominally square, a Tukey window may optionally be applied to smoothly modulate the initial and final 2.5% of the window to suppress sidelobes associated with the step change at the window boundaries. This may serve to protect the analogue amplifiers from potential damage from out-of-band energy.

J. The Optional Data Cargo Payload

The baseline JANUS Packet may be followed, without a break, by additional data, encoded according to the user-specified application into a continuation of the FH sequence using the same tones specified in Table II. Such cargo is to be encoded directly after the final chip of the Baseline JANUS Packet. Unless the published user application specifies otherwise, the same convolutional encoder and interleaver are to be used as for the main Baseline JANUS Packet. The cargo may or may not include a CRC of the users specification. A sufficient but not excessive time to transmit any such cargo must have been reserved in the preceding Baseline JANUS

Packet by setting bit 6 to 1, bit 23 to 0 and specifying the reserve time in bits $24-30$. If there is an intention to reserve the channel for emergency communications, *e.g.* using an underwater telephone such as one that implements STANAG 1074, bit 6 may be set to 1, bit 23 set to 0 and bits $24-30$ to $[1\,1\,1\,1\,1\,1\,1]$, thus reserving the channel for the maximum period of 10 minutes, without the need to transmit any data cargo.

K. Frequency Bands

The initial JANUS acoustic frequency band has the following specifications:
$F_c = 11520Hz, Bw = 4160Hz.$

The resulting Frequency Slot width and Chip duration are then:
$FS_w = 160Hz$, $C_d = 6.25ms$.

Additional bands may be added to this standard as and when recommended by the JANUS community and approved by the sponsoring organisation, the CMRE.

III. Protocol Description - Medium Access Control

The default Medium Access Control (MAC) mechanism is a species of Carrier Sensing Multiple Access (CSMA) as described in [11] with Collision Avoidance (CA) via Binary Exponential Backoff (BEB) with Global Awareness (GA) that consists of an in-band energy detector. To test whether the channel is busy, nodes are required to sense the channel immediately before a planned transmission, across the full JANUS band for a minimum of twice the length of an encoded basic JANUS packet (i.e. $352 \times Cd$) from which an estimate of the background acoustic power in band is to be made. If the acoustic power in band over a window of $16 \times C_d$ exceeds the estimated background by more than $3\,dB$, the channel is deemed to be busy in that window. If a node wishes to make a JANUS transmission, it must first carry out a background acoustic power in band estimation and then determine if the channel is busy. If not, the node may transmit its JANUS message immediately. If the channel is estimated to be busy when a node intended to transmit, the node continues to sample windows of $16 \times C_d$ until the channel is deemed no longer busy. The node then applies a BEB where the node transmits in the next slot with probability $1/(D+1)$, where $D = 2^C - 1$ with C being the number of potential transmission slots the device has counted in the backoff process in which there has been at least one busy window (C is initialised with $C = 1$). The slot length is defined as $176 \times C_d$. If the node does not elect to transmit in the first available slot, it continues to sample 16 chip windows to detect if the channel is busy during the next slot, incrementing C by one (but only once per slot) if this is the case at any point during the slot, up to a maximum of $C = 8$. Once the node elects to transmit its message, C is re-initialised to $C = 1$. If C reaches 8, the attempt to transmit that packet is abandoned.

IV. Ways Ahead

The proposed physical layer standard, named JANUS, has been designed to minimise the changes required to bring existing UW communications equipment into compliance, leveraging the inherent flexibility of modern digital communications systems and existing acoustic frequencies and bandwidths. The standard provides for a baseline JANUS Packet to be created, consisting of an acoustic waveform that encodes 64 bits of information (of which 34 may be user-defined according to their application) in addition to a facility by which cargo data may be seamlessly appended to the end of the Baseline JANUS Packet to provide almost unlimited flexibility in the nature and extent of the data to be sent. JANUS is currently moving in the process of a NATO Standardization Agreement (STANAG) promulgation and a NATO Industry Advisory Group is addressing issues like expanding the applications definition in the ADB table (Table II), future protocol extensions and compliance to the standard.

Acknowledgement

The authors would like to acknowledge and thank everyone that contributed to the development of JANUS though the JANUS meetings and the wiki portal. This work has been supported by the NATO Allied Command Transformation (ACT).

References

[1] J. Heidemann, W. Ye, J. Wills, A. Syed, and Y. Li, "Research challenges and applications for underwater sensor networking," in *In Proceedings of the IEEE Wireless Communications and Networking Conference*, 2006, pp. 228–235.

[2] M. Chitre, S. Shahabudeen, and M. Stojanovic, "Underwater acoustic communications and networking: Recent advances and future challenges," 2008.

[3] Janus wiki. [Online]. Available: http://www.januswiki.org

[4] K. McCoy, "JANUS: From primitive signal to orthodox networks," in *Underwater Acoustic Measurements: Technologies and Results, Nafplion, greece*, 2009.

[5] K. McCoy, B. Tomasi, and G. Zappa, "Janus: The genesis, propagation and use of an underwater standard," 2010.

[6] J. Alves, A. Vermeij, D. Hughes, and G. Zappa, "Software-defined JANUS communication support for AUVs," in *Proceedings of the fourth International Conference and Exhibition on Underwater Acoustic measurements: Technologies and Results*, 2011.

[7] M. Stojanovic, J. Proarkis, J. Rice, and M. Green, "Spread spectrum underwater acoustic telemetry," in *OCEANS '98 Conference Proceedings*, vol. 2, Sep 1998, pp. 650–654 vol.2.

[8] A. Viterbi, "Convolutional codes and their performance in communication systems," *Communication Technology, IEEE Transactions on*, vol. 19, no. 5, pp. 751–772, October 1971.

[9] J. Catipovic and L. Freitag, "Spatial diversity processing for underwater acoustic telemetry," *Oceanic Engineering, IEEE Journal of*, vol. 16, no. 1, pp. 86–97, Jan 1991.

[10] T. S. Seay, "Hopping patterns for bounded mutual interference in frequency hopping multiple access," in *Military Communications Conference - Progress in Spread Spectrum Communications, 1982. MILCOM 1982. IEEE*, vol. 1, Oct 1982, pp. 22.3–1–22.3–6.

[11] S. Smith, J. Park, and A. Neel, "A peer-to-peer communication protocol for underwater acoustic communication," in *OCEANS '97. MTS/IEEE Conference Proceedings*, vol. 1, Oct 1997, pp. 268–272 vol.1.