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Underwater Acoustic Networks

WP3 Deliverable 3.3 **Modem Functionality Verification**

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Modem Functionality Verification

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1 Introduction

The purpose of this document is to give an overview of the functionality of the modem and its verification throughout the UAN project. Special attention is given to the physical layer (PHY) of the modem in accordance with WP3s scope while the functionalities for the upper layers are listed for completeness. Sea trials have been performed for a step-wise development and verification of the modem PHY-layer. Conclusions are drawn based on results from a selection of these sea trials.

1.1 Task 3.3 Modem implementation and verification

The document you are holding is part of Task 3.3. The task focuses on the implementation of the software and signal processing solutions of Task 3.2 on to the modem hardware. Deliverable 3.2 Physical layer solutions [1] treats in detail the physical layer method chosen for implementation; the Turbo equalizer on a single carrier QAM modulation format. The solution is based on a channel equalizer involving an adaptive filter, a MAP decoder and a channel estimator. Other relevant input for Task 3.3 resulted from deliverable 3.1 Modem functionality requirements [2], where the existing KM transponder model cNode Mini [4] was chosen as platform for adapting the methods and functionality developed within UAN. The Universal Transponder Board, UTB was also introduced in this report.

Work in Task 3.3 has progressed with KM doing the coding of the Turbo equalizer on to the modem based on Matlab code supplied by FOI. The coding has been done mainly in C++ (some critical parts in ASM) manually converted from Matlab code. Benchmarking of the C++/ASM implementation towards the Matlab code was done using sea trial data logged in the modem; the modem implementation could be considered bug free when similar performance was experienced in the modem as in the Matlab code (using the same equalizer lengths and other parameters). The modem was concluded and tested at sea in February 2011, while the implementation was incrementally improved before the engineering test March 2011 in Algarve and the final demonstration in May 2011 in Trondheim.

In November 2009 a license agreement between FOI and KM was signed regulating the use of FOI background information within the project as well as the user rights of new C++ code. The software implementation on the modem was done in Texas Instruments Code Composer Studio 4.x.

1.2 Structure of document

Functionalities of the modem are treated in section 2 where also a technical data sheet of the modem is given. In the following section 3 the dedicated sea trials for the modem are described, including results, while finally a summary and a conclusion is given in section 4.

1.3 Acknowledgements

The authors would like to thank the colleagues in the UAN project for making possible full scale integration tests of the modem. Invaluable insight into the Turbo equalizer was generously shared through comments and explanations from Bernt Nilsson and Tommy Öberg from FOI. Thank you also to Knut Grythe, Sintef, for valuable contributions to discussions in WP3.

1.4 Referenced documents

[1] Öberg, et al. *UAN Deliverable 3.2 Physical Layer Solutions.* 2010.

[2] Husøy, T. *UAN Deliverable 3.1 Modem Functionality Requirements.* 2009.

[3] Husøy. et al. Implementation of an underwater acoustic modem with network capability, IEEE Oceans 2011.

[4] Kongsberg Maritime. cNODE Mini Transponder instruction manual, http://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/9310D5E95D16F5E0C125780000357BDB/$file/331869_cnode_Mini_instruction_manual.pdf?OpenElement, retrieved Sept 2011.

[5] Kongsberg Maritime. APOS for HiPAP Model 501/451/351/101, Instruction manual http://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/3BB70E5E5C6F17A5C1257428002B79D7/$file/319957_apos_for_hipap_instruction_manual.pdf?OpenElement, retrieved Sept 2011.

[6] Kongsberg Maritime. UUTP - UAN UTB Transport Protocol

[7] Kongsberg Maritime. Open Transceiver Application Protocol (TAP_USER)

2 Modem functionalities

Work has been done at several levels for the modem and new functionalities have been added both to the PHY layer and upper layers of the modem as well as to the operator station software APOS [5]. Figure 1 gives an overview of the modem including relevant protocols, interfaces and hosts in the environment of a master node. In the following a short description is given on the functionalities of the network including the more specific modem functionalities. Reference is made to the data sheet in Appendix A for details on the capabilities of the modem.

There are two main patterns of traffic related to the modem: (1) Network traffic (e.g. sensor data, commands, status information) distributed by the MOOS database, DB, on the Host to the far left in Figure 1 and (2) dedicated control and monitoring messages on the modems operation and network functionality (e.g. Tx power setting and start of network discovery Flood) handled by APOS on the Windows host.

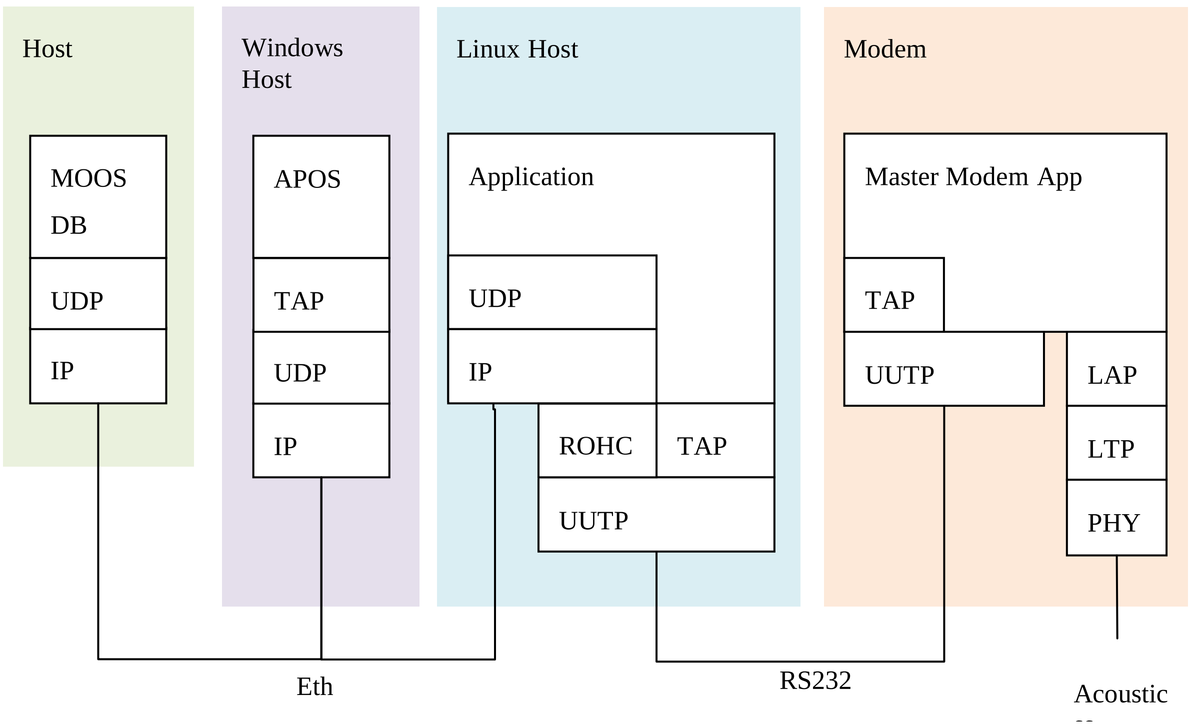


Figure 1 Typical setup of relevant hosts and protocols for master node

Ordinary data from the MOOS DB is sent to the Linux Host which utilize robust header compression ROHC before putting the data on the RS232 and the UAN to UTB Transport Protocol, UUTP. Upon reaching the modem the data is identified to be ordinary network data and the modem application puts the data to the proprietary LAP/LTP protocol forming the network and link layer of the modem. The LAP/LTP protocol supports routing, addressing, error detection, segmentation and augmentation of telegrams as well as retransmission of any lost telegrams. Finally the data enters the PHY layer which performs classical operations such as forward error correcting coding, interleaving and modulation. In the other direction the PHY layer perform demodulation, channel estimation, channel equalizing, deinterleaving and decoding. The data is then forwarded up the protocol stack and finally enters the MOOS DB.

Dedicated control information is generated in APOS utilizing the proprietary TAP protocol and sent via UDP/IP to the Linux host using a dedicated IP address. The Linux Host application simply put forward the TAP message to the serial line using UUTP. Upon entering the modem, the TAP messages are decoded and the corresponding action is performed (e.g. start network discovery Flood, set master node Tx power or set Tx power of a remote node using acoustics). In the other direction messages are put in to the TAP protocol before ending up in APOS.

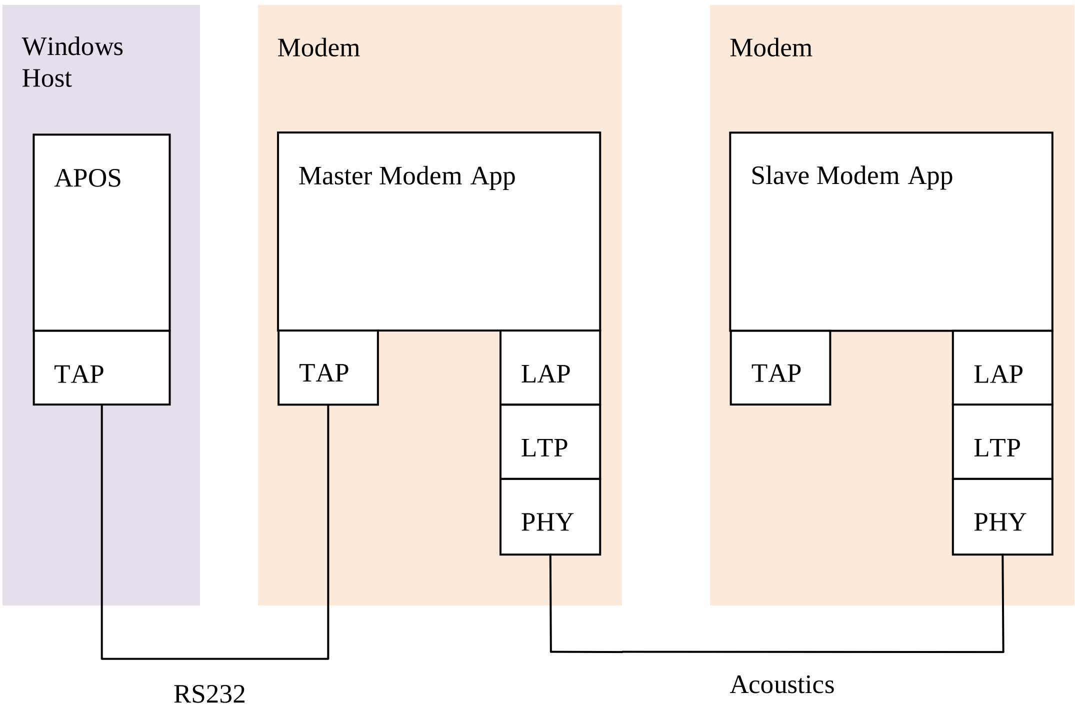


Figure 2 Setup of master and slave node when performing dedicated modem test sea trials

The modems are also possible to use without a Linux host. One example is the dedicated modem tests as described in section 3. The setup then allows for a single RS232 connection between the modem and the Windows host making the UUTP protocol redundant as depicted in Figure 2. Note that the slave and master modems have different application software to handle the different functions in a master and slave. The software in such a setup is exactly the same as for the full network setup, but a configuration via the serial line has to be performed on start-up using dedicated software. Another example, in which a Linux host is not required, is when the modem acts solely as a relay node. This possibility can be of use if the topology of the network require only a communication node and no sensor is needed to be attached.

2.1 APOS plug-in

The APOS plug-in *Transponder Network* offers a control and monitoring GUI for the network. With this the operator can perform a number of network control functions including; Flood Network Discovery, reading modem status, edit and redistribute routing tables, overriding automatic power and data rate settings for acoustic communication and sending broadcast messages.

All acoustic packets sent and received by the Master are displayed with timestamp, from/to ID, type of packet, payload length in bytes and an estimated received SNIR[1].

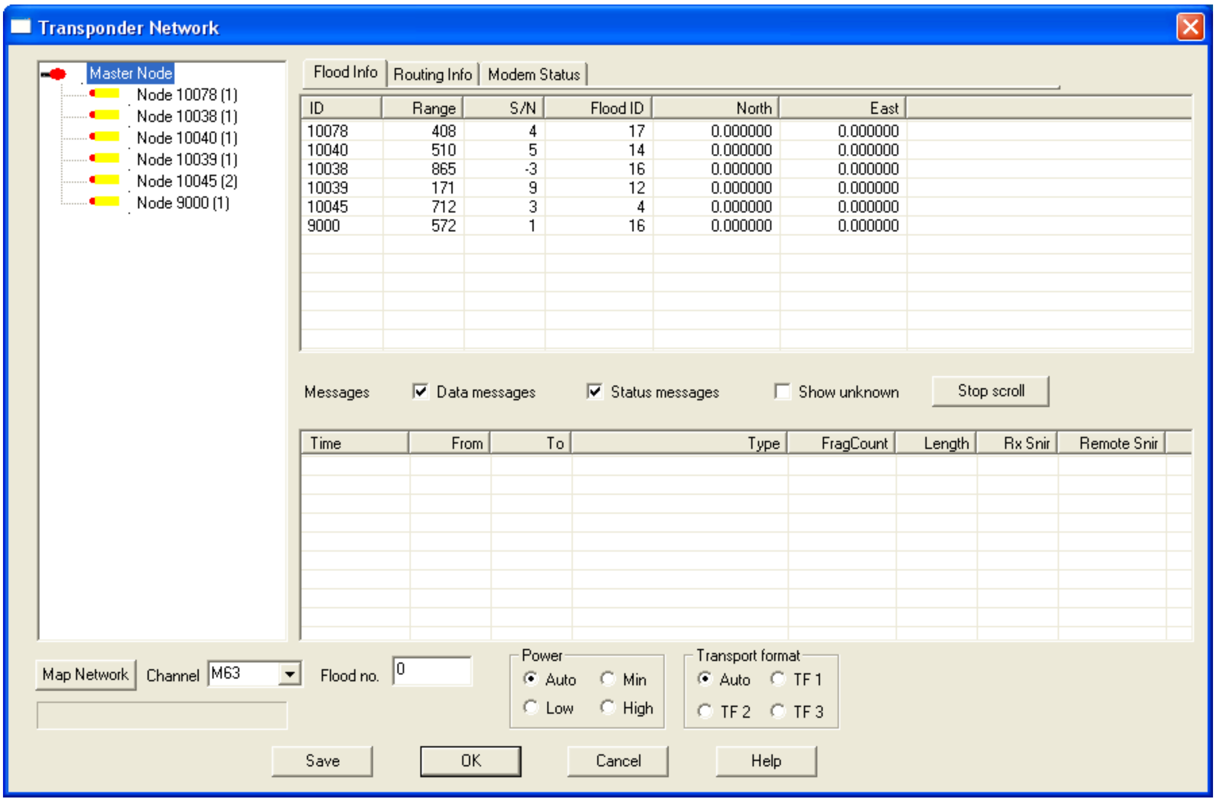


Figure 3: Transponder Network – Flood Info view

After a successful Flood Network Discovery all nodes will appear with the node ID, a list of neighbour node IDs, node-to-neighbour range in metres and an estimated received SNIR from each neighbour.

For test purposes the operator can request various test data from each node in the network or send an *Echo* message, where a random bit-sequence is sent to any node through the network, according to the current routing tables, and echoed back to the Master.

[1] Signal to Noise/Interference Ratio

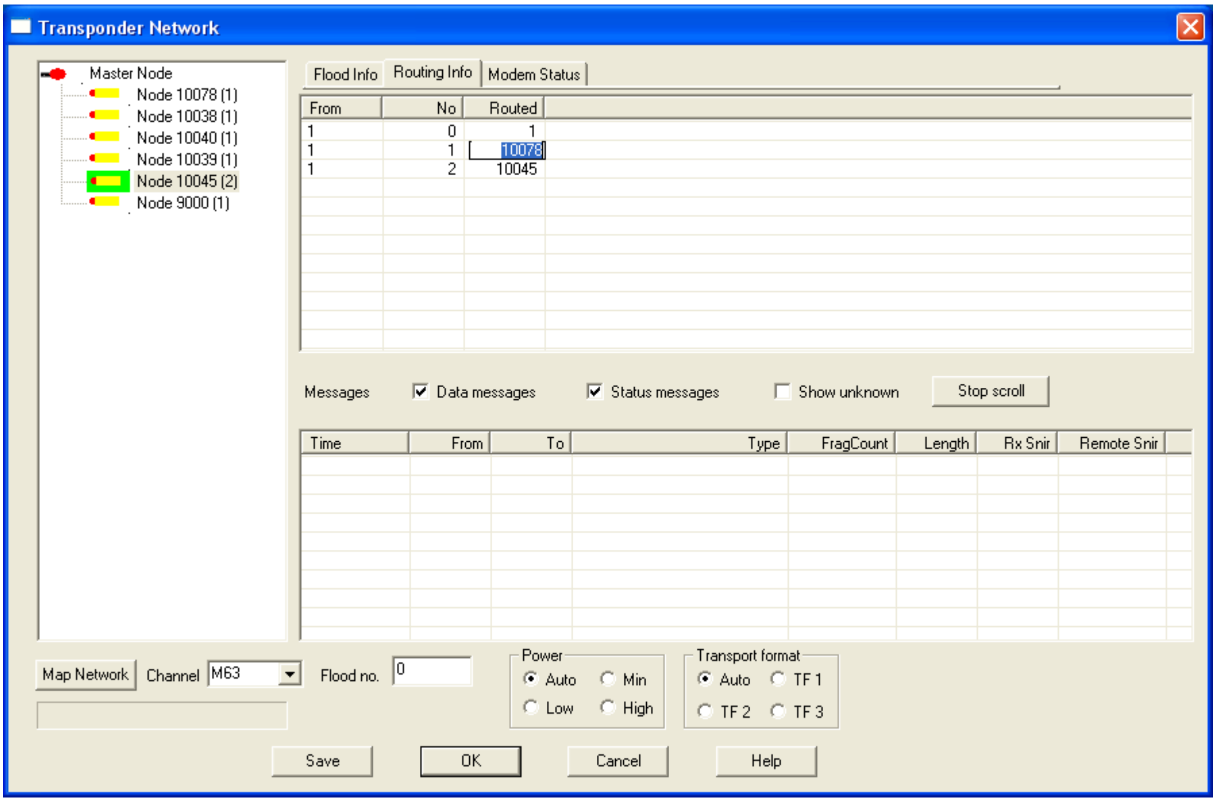


Figure 4: Transponder Network – Routing Info view

The Routing Info view displays the shortest route from the Master to the selected node, calculated using Dijkstra's algorithm based on the results from the Flood Network Discovery. This routing path may be edited and redistributed in the network. The new routing path will override any previous routing information in selected node.

The Modem Status view shows internal clock settings, current software versions, memory card status and acoustic transmission parameters. The internal clock in the slave nodes is synchronized with the Master's internal clock during the Flood Network Discovery phase, but can also be set via a dedicated acoustic message. At any time the operator can reconfigure the acoustic transmission parameters for each node separately or reset them to the default/adaptive values.

APOS also offers the possibility for software upgrade of the local modem connected via UDP/IP and Ethernet or TAP and serial line.

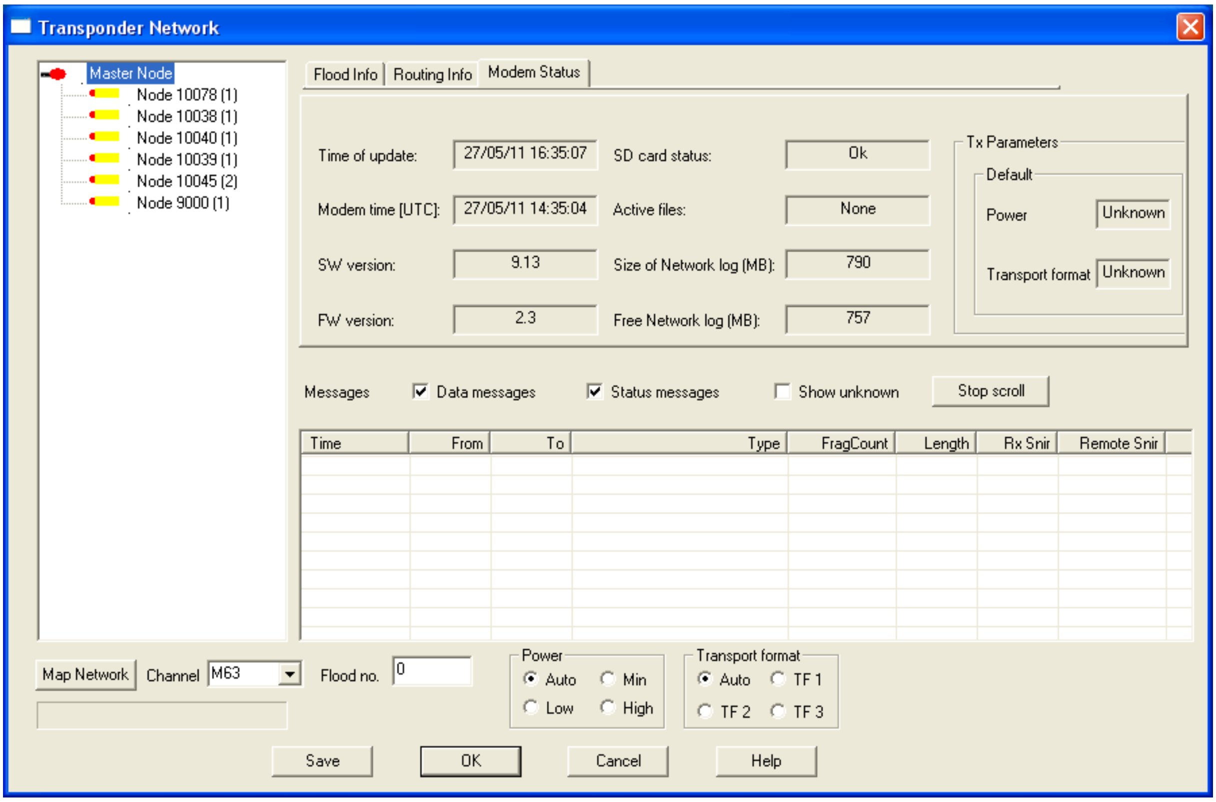


Figure 5: Transponder Network – Modem Status view

2.2 UUTP - UAN to UTB Transport Protocol

Behind this elaborate name hides the functionality of the serial line protocol between the modem and an outside host [6]. The protocol is used both for the master and the slave modem in the full network setup.

The packet layout is shown below with a Preamble, Length, Sequence Number, Address, Type and Crc field:

Preamble	Length	Sequence Number	Type	Address	Data	Crc
4 bytes	2 bytes	1 byte	1 byte	4 byte	0-65521 bytes	2 bytes

Of special interest is the Type field identifying the following types:

- PPP[2] Packet (ordinary network packet to/from the sea)
- TAP Admin packet (packet to/from APOS)
- TAP User packet (control and monitoring information from application at master or slave Linux host)
- Status Msg (status on modem serial line buffer to the host)

[2] The original PPP, Point-to-Point Protocol implementation was replaced by ROHC implementation in the final UAN demonstration

The address field is valid for PPP Packets and contains the source or destination address of the network node. Although 4 bytes are available in the UUTP packet, only 2 bytes addressing are available for the modems (16 bit address in LTP header).

2.3 TAP - Transceiver Application Protocol

The full protocol contains a large set of messages for all possible interactions and control between the modem and APOS, these are called TAP_ADM messages. A subset of these are made available for the application at the Linux host, so called TAP_USER messages [7]. The following TAP_USER messages have been implemented:

- **Start Flood (Master only)**

  This message is to initiate a complete network discovery and applies for the master modem only. Parameters can be given for the Tx power and Transport format (see section 2.5.1) of the acoustic signalling, where the Tx power and the Transport format can be automatically adapted by the modem based on measured signal to noise and interference ratio (SNIR) or selected manually by the Linux host application.

- **Request Flood Status**

  This message is a request to the modem for a flood status, see *Reply Flood Status.*

- **Network Sign In/Out (Slave only)**

  Mobile nodes use this message to sign out of the network before moving and later signing in to the network after reaching the new destination. Another approach is to periodically sign in while moving.

- **Send Transparent Signal**

  This message contains the information to be transmitted on the unidirectional link between a slave node and the vertical array of the master node. The modem codes the bit sequence using QPSK and mapping the input bit sequence by: 00 = 0 deg, 01 = 90 deg, 10 = 180 deg, 11 = 270 deg. Additional parameters can control the symbol rate and Tx power level.

- **Reply Flood Status**

  This message is a response from the modem to a *Request Flood Status* message. The first part of the message lists all neighbour nodes with corresponding SNIR and distance in milliseconds, the second part lists all nodes with connection to Master and their respective relay node towards the master. Upon reciving this message the receiver has the information necessary for finding the topology of the network (the routing paths, the individual distances and the link quality expressed in SNIR)

In addition to the messages above, the TAP_ADM messages include functionality for manual distribution of routing paths, manual setting of Tx Power and Transport Format making possible more dedicated control and operation of the network.

2.4 Network support for mobile nodes

In order for mobile nodes to maintain connectivity with the network, their routing path needed to be reconfigured whenever their position changed. Two alternatives were available for this reconfiguration. Either the nodes could try and update the routing information continuously at regular intervals while moving, or they could sign out of the network before transit to a new location and sign in again when the final destination was reached. In both cases the modem receives the TAP_USER command **Network Sign In/Out** from the host machine to initiate the reconfiguration phase.

For the continuous update option, the modem transmits a single broadcast message requesting to be signed in to the network. All current neighbour nodes receiving this message transmit (with a random delay) a unidirectional reply addressed to the moving node. Each reply message generates an acknowledge message addressed to the respective neighbour. Thus the moving node knows the ID and distance to all of its new neighbours and vice versa. The moving node sends a report containing this information to the Master which updates the routing tables and distributes new routing paths if necessary.

The other option is to sign out of the network completely before transit to a new location. The Master is alerted of this and recalculates the routing tables and distributes new routing paths if necessary. The mobile node is then free to move to a new location. When the destination is reached, the host machine commands the modem to initiate a more robust sign in procedure than is the case for the continuous option. Instead of transmitting a single broadcast message, a total of three broadcast messages are transmitted with an interval larger than the maximum random delay allowed for the reply messages. If a neighbour node receives and acknowledge message to its reply, then the neighbour node will not transmit any more sign in replies to the mobile node. This increases the possibility of the mobile node receiving a reply from all neighbours. After these retransmissions are complete, the mobile node sends a report containing information about its new neighbours to the Master which updates the routing tables and distributes new routing paths to affected nodes.

2.5 PHY layer

The functionality of the turbo equalizer and its background information was treated in deliverable 3.2 [1] and will not be detailed out in this section. Per symbol inversion of the channel matrix for updating the adaptive equalizer filter combined with several iterations requires a lot of computing power. Included in this section are some relevant measures for coping with the memory and processing limitations of the low power DSP of the UTB-platform.

2.5.1 Transport Formats

The modem offer different transport formats of which the coding of the transmitted signal is changed for adapting to the present acoustic channel conditions in terms of noise, Doppler and time spread. Three transport formats have been used within UAN of which the last one is the rate 1/3 recursive systematic convolutional encoded signal the Turbo equalizer is applied on. The signal is modulated on to a centre frequency of 25.6 kHz using QPSK mapping and a symbol rate of 4 kHz offering a resulting burst rate of up to 1710 bps. In addition to the turbo equalizer transport format there are two low speed transport formats being part of the proprietary Cymbal protocol utilizing direct sequence spread spectrum (DSSS) coding with burst rates on 200 and 470 bps. The spectrum inefficient coding of DSSS is an alternative to the turbo equalizer transport format for channels with a delay spread requiring longer equalizer length then what the DSP implementation can offer.

Table 1 below give the key parameters for the transport formats in addition to the already mentioned burst rates. Telegram durations are kept under 2 seconds as longer telegrams increase the probability for telegram loss. Maximum packet sizes to be presented at the modem serial line are 1600 bytes for the slowest transport format and 3000 bytes for the others. Every packet can be segmented in up to 32 telegrams (frames).

Table 1 Transport Format Table

Profile [number]	**Max Telegram Size [bytes]**	**Max Packet Size [bytes]**	**Max Telegram Duration [sec]**	**Max Telegram Burst rate [bit/sec]**
13	50	1600	2,0	200
11	120	3000	2,0	470
31 (turbo)	231	3000	1,1	1710

2.5.2 Turbo decoding in near real time

Effective throughput in the network is strongly influenced by the time required to decode a telegram, and significant effort went in to minimizing the time in the current implementation of the turbo equalizer. The most critical part with respect to meeting near real-time performance is organising and calculation of the MMSE filter. Operations required for inversion of the channel matrix require in its current form $O(N^2)$ where N is the length of the channel in taps. Hence long time spreads drive the computational load on the DSP together with the number of iterations required before converging. Putting limits for the maximum number of taps and iterations are necessary to have control on the telegram decoding time.

During testing of the modems the maximum number of taps and iterations were chosen such that the decoding time was less than 5 times the telegram duration. Typical maximum numbers for taps and iterations are 15 and 3 respectively.

Channels with longer time spread than 3.75 milliseconds (15 taps at 4 kHz symbol rate) frequently occur, and the question arises for which taps to include in the channel estimate for the equalizer. The following method is applied as default in the modem:

- only taps above -10 dB are included in the estimate

- if these taps span out a window less or equal to 15 taps, the channel impulse response vector and the taps are identified
- if these taps span out a window greater than 15 taps, the window is limited to 15 taps and lagged (moved between taps) such as the energy inside the window is maximized

In this way the most important arrivals are chosen for the impulse response. Alternatively, the parameters can be set manually by APOS, both for the master modem and remotely connected modems through the acoustic network.

3 Sea trials

Dedicated sea trials for the turbo equalizer implementation have been performed according to the table below. Kongsberg Maritime test vessel Simrad Echo has been used for the testing.

Table 2 Dedicated modem test sea trials

Date	Area	Test objective
2010.08.13	Oslofjorden, Breidangen	First test of turbo decoder
2010.12.09	Oslofjorden, Breidangen	First test of turbo equalizer
2011.01.26	Oslofjorden, Breidangen	Continued test of modem
2011.02.11	Oslofjorden, Breidangen	Verification test of modem
2011.02.24	Horten harbour, Maalfrid test barge	Trigger level measurement
2011.05.04	Oslofjorden, Breidangen	Test of improvements
2011.05.10	Oslofjorden, Breidangen	Test of improvements
2011.05.16&18	Horten harbour, Målfrid test barge	Test before final demo

In the following are the results from the tests 2011.02.11 and 2011.05.04 reported. The results from the February test are published in [3]. Sensitivity and source level measurements are also presented.

3.1 Verification test of modem

The objective of the test was to test the range capability of the UAN modem using the transport format including the turbo equalizer. The Breidangen area is characterized by a bathymetry of approximately 200 meter over most of the area, having a soft seabed with mostly mud-like sediments. Throughout the day the wind speed was measured to an average speed of 25 knots from the North. Figure 6 presents the measured sound velocity profile with a corresponding ray trace plot from APOS.

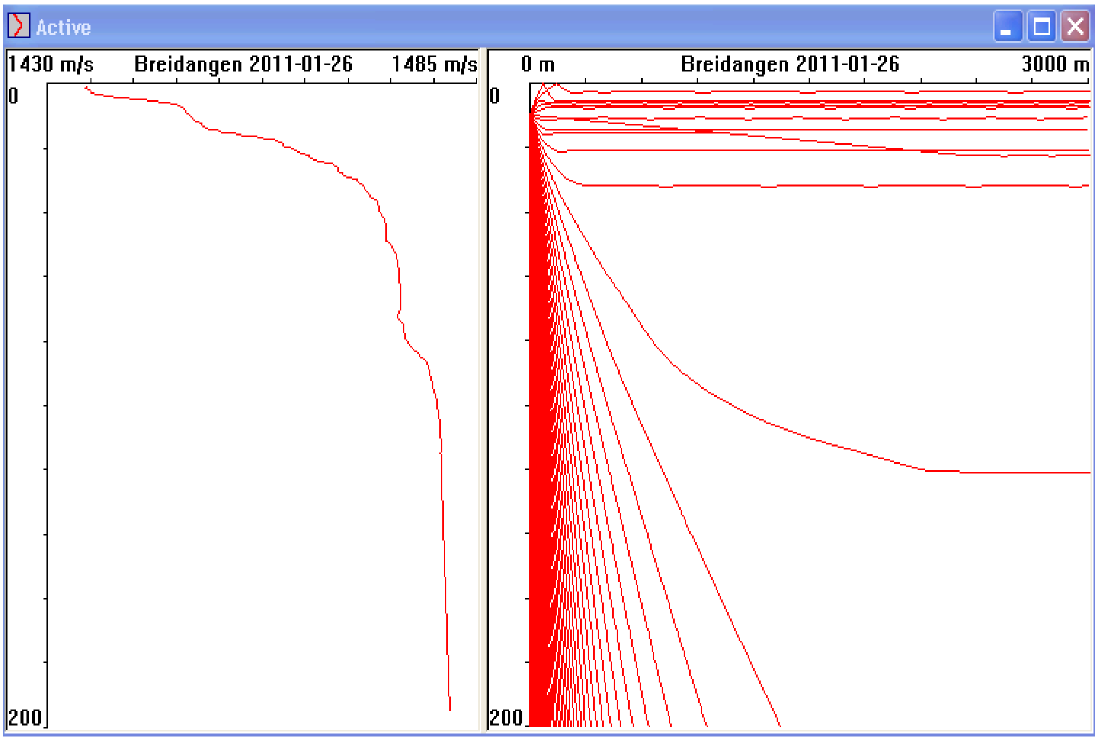


Figure 6 Typical sound velocity profile (left) and ray trace plot (right) for the period

3.1.1 Measurement setup

The modems were tested according to the setup in Figure 7 and Figure 8 where two modems were placed in a basket at the seabed (200 m depth) and another two modems suspended in a rope from a buoy moored to the basket at the seabed. Identification of the modems is done by their serial numbers. Modem 10039 and 10103 were placed with a distance of approximately 3 meters at an average depth of 10 meter. On board Simrad Echo was the master modem with the transducer also at approximately 10 m depth. Most of the test was performed with the boat drifting away from the modems due to the rather strong wind.

Figure 7 Modem range test scenario and equipment[3] including all 6 UAN modems

The maximum length of the filter was configured to be 15 to meet the near real time requirements. The real time requirement was set to a real time factor of 5, meaning that the approximately one second telegram could maximum take 5 seconds to decode. Accordingly, the maximum number of iterations was set to 3 since the processing time is predominantly dominated by the number of iterations needed for successful decoding of the telegram. Utilization of the limited length equalizing filter on the actual impulse response was discovered by configuring the modems with different windowing. Table 3 gives an overview of the windowing in addition to the threshold level for which arrivals are discarded and not included in the filter.

Table 3 Turbo equalizer parameters

Modem	L1 max	L2 max	Threshold
10039	2	12	-6 dB
10103	6	8	-10 dB
10038	6	8	-10 dB
10045	2	12	-6 dB
Master	6	8	-10 dB

[3] Only two of the modems in the steel basket shown were used in the actual range test

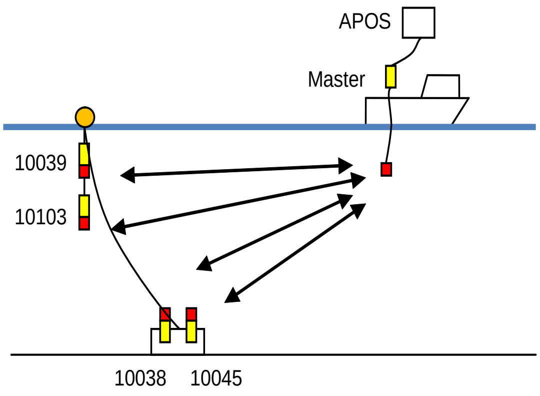


Figure 8 Measurement setup

3.1.2 Results

The test was performed by sending 80 Byte payload telegrams from the master to a modem and waiting for a reply with the copy of the same payload (the *Echo* message mentioned in section 2.1). The transmission was considered successful if a reply was received and successfully decoded within a predetermined time out. Modems were automatically tested in sequence as fast as propagation time and processing time allowed. Total test time from starting transmissions until no contact was approximately 2 hours. From time to time the test was intermittently stopped to log signals on the master for post analyzes of transmissions that was not decoded correctly at the master side.

Figure 9 and Figure 10 show the success rate of the transmissions for the different modems as a function of distance. Successful transmissions are plotted as a blue marker with value 1, while unsuccessful transmissions are plotted as a blue marker with value 0. The solid line shows the moving average over 11 transmissions. The results show a higher success rate for bottom modems compared to the surface modems. Another general trend is that coverage is not gracefully degraded as a function of distance, but varies substantially within some range intervals. Modem 10045 demonstrates successful transmissions up to 1800 m before contact is lost and gives the most stable connection of the modems. The longest range of 2500 m is demonstrated by modem 10038.

Previous experience from the measurement site says that these results are good. Post analysis of signals logged for not successful transmissions showed similar performance when run in a Matlab model of the algorithms with the same filter lengths and parameters as implemented in the modem.

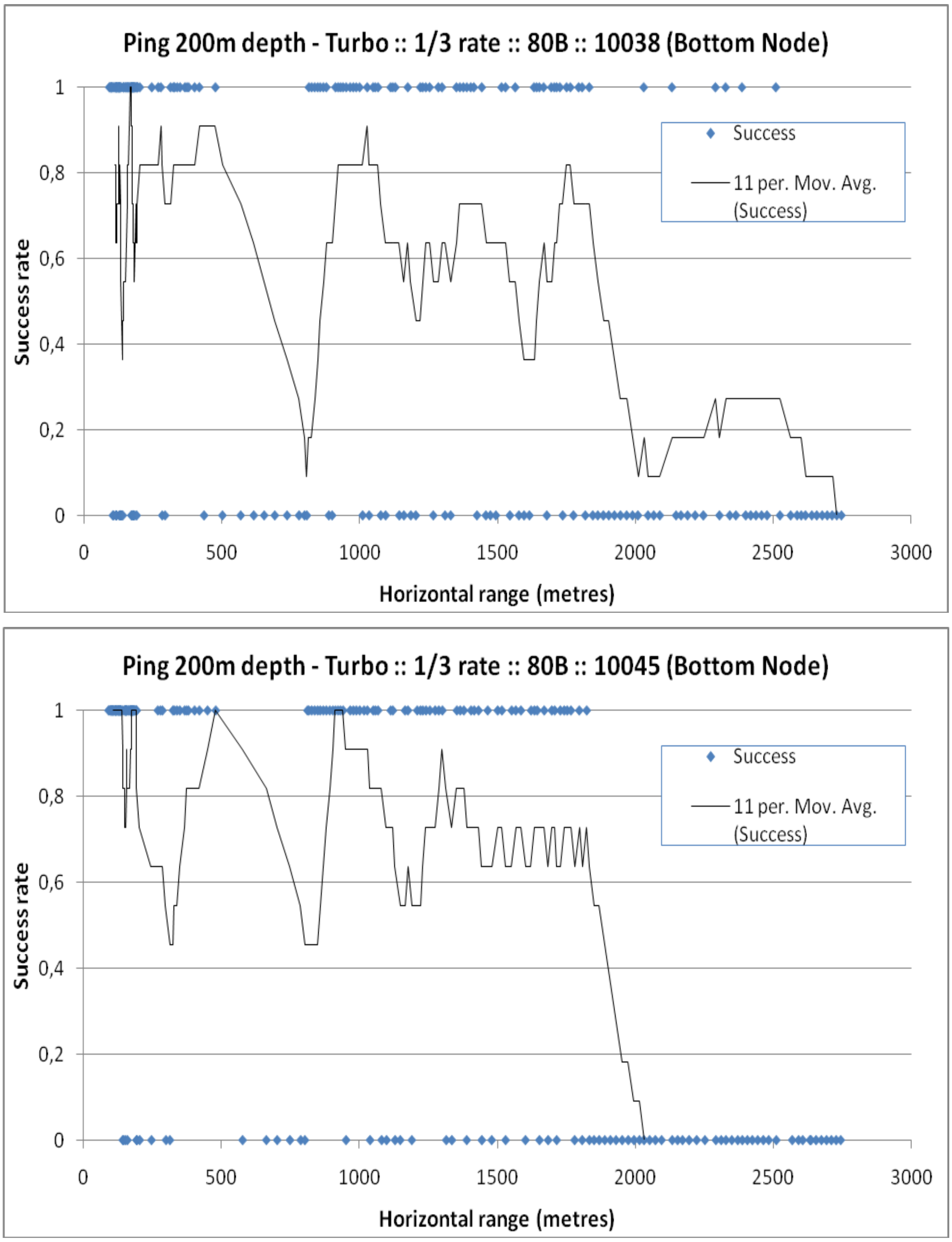
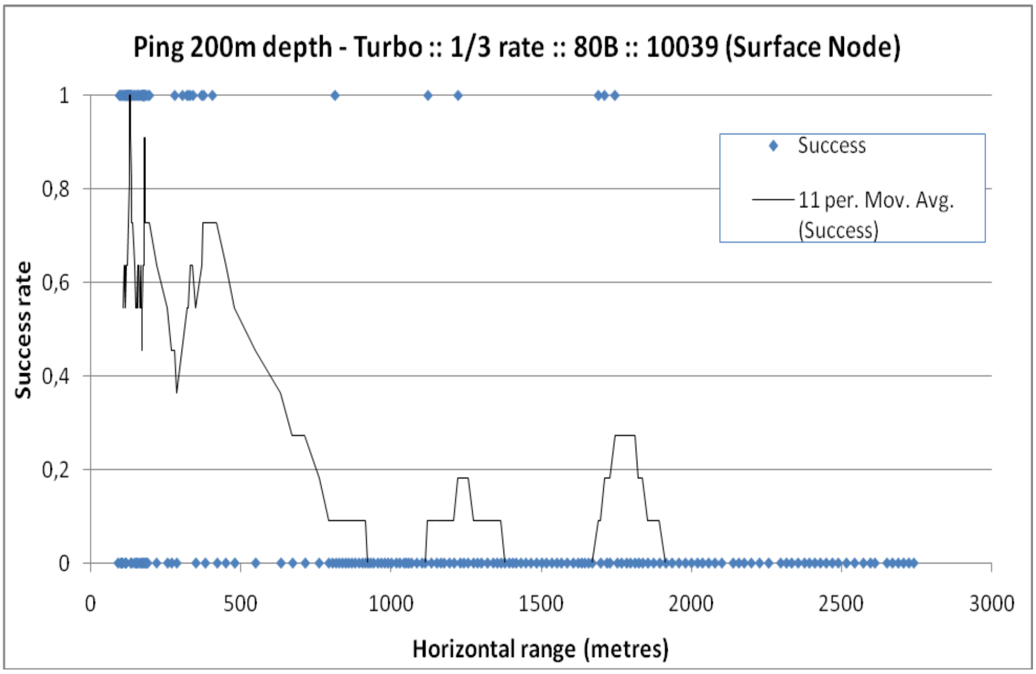


Figure 9 Telegram success rate as function of range for bottom nodes



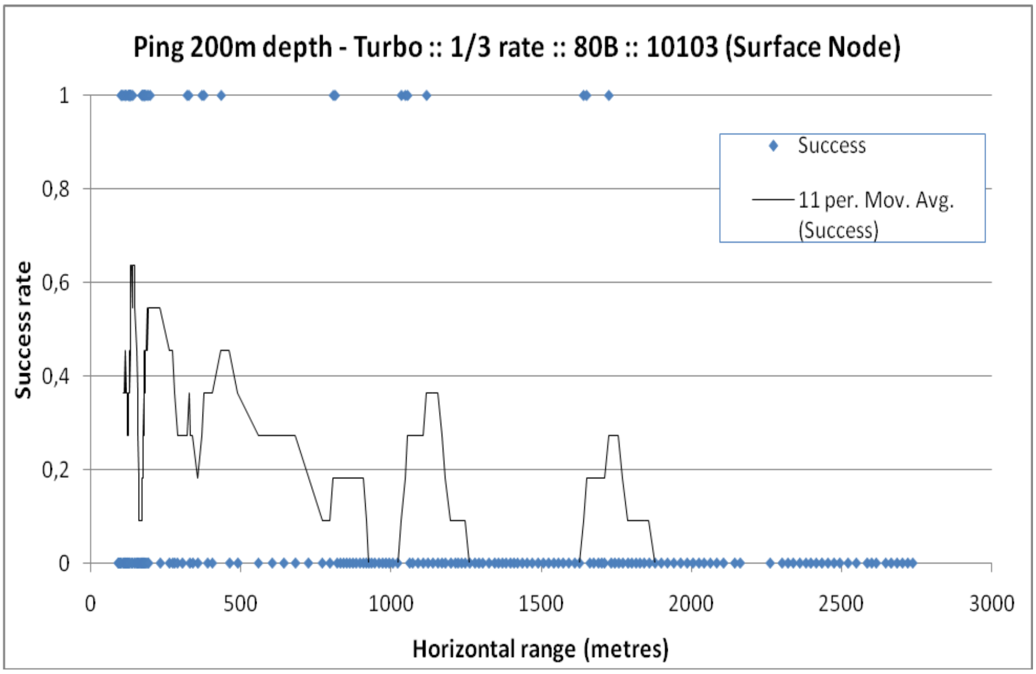


Figure 10 Telegram success rate as function of range for surface nodes

3.2 Trigger level measurement

The test objective was to measure the lowest sound pressure level required for the modem to decode a turbo signalling frame successfully. The test was performed 2011-02-04 from the test barge Målfrid anchored outside the premises of Kongsberg Maritime. The test setup is deployed at 6 meter depth as depicted in the figure below. In the water are three units: a transmitting transducer TD180, a receiving Modem and a calibrated Hydrophone. Both the Modem and the Hydrophone are within the main lobe of the hemispherical main lobe of the TD180 but safely outside the near field. The symmetry of the setup makes the Hydrophone to receive the same signal level as the Modem.

Providing the input to the TD180 is an UTB operated with APOS together emulating a real modem. The signal is fed through a variable power attenuator to make it possible to adjust the strength of the transmitted signal. Starting with a strong signal the receiving modem detects the turbo signal telegram, decodes it, and replies back. The reply is detected by the receiving UTB setup and presented in APOS. Attenuation is then applied until timeouts are starting to appear in APOS. The minimum sound pressure level at which 10 consecutive successful decodings are detected was set as the Trigger Level.

The measured Trigger Level was 92 dB re 1 µPa.

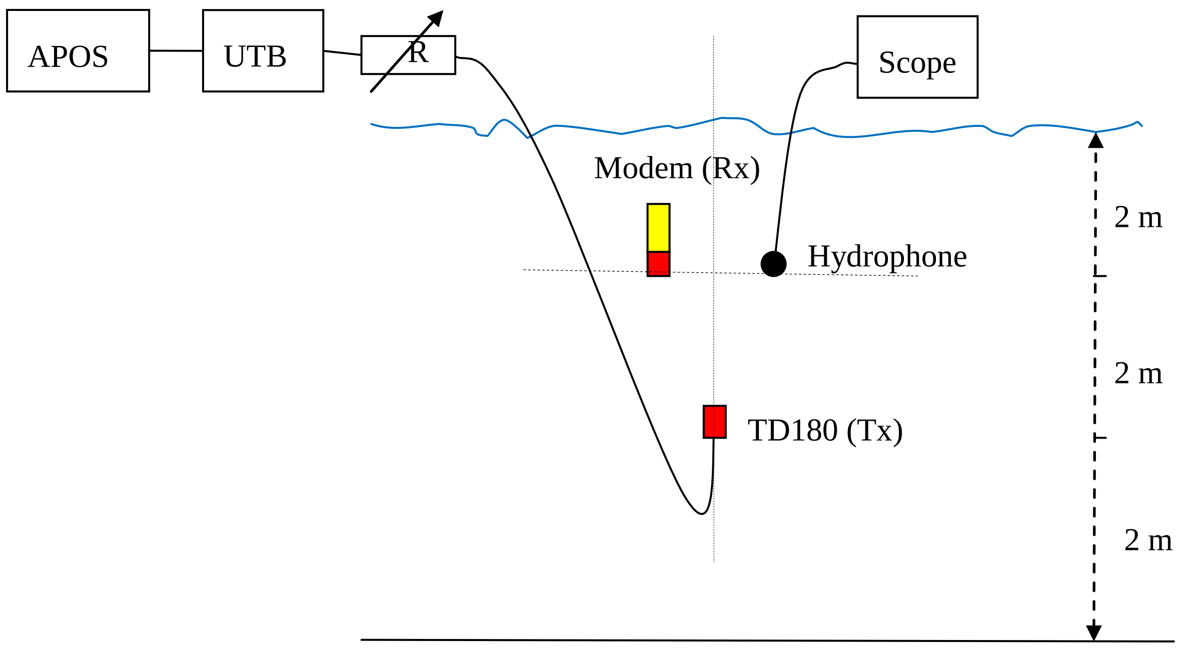


Figure 11 Trigger level measurement setup

Source level measurements are part of standard test for the equipment and were not tested in this setup. From the data sheet the available source levels in the modem are 173, 178, 184 and 190 dB re 1 µPa @ 1m.

4 Summary

The modem as implemented within UAN supports functionality both at the physical layer and at higher layers of the protocol stack. APOS offer dedicated control of the modem and its network functions to locally connected modems and any remote modem reachable through acoustics. Combining the protocol stack of the modem with the ROHC technique makes possible IP end to end connection over the acoustic network. The network protocol implemented in the network supports multi hop routing with support for mobile nodes.

The implementation of the turbo equalizer in the modem has been tested and verified in 8 dedicated sea trials in Oslofjorden. The limited processing power of the DSP makes it necessary to restrict the number of taps in the equalizer filter and the number of iterations. Even with these restrictions stable communication has been demonstrated up to 1800 meter range. Further tuning of the implementation on the modem for more efficient computation and better overall performance should be possible. Longer equalizing filter lengths and further improved performance is expected.

Appendix A

Kongsberg Maritime	cNode® Mini 34-180 UAN
Frequency band	25.6±2 kHz (-3dB)
Max depth rating	4000 m
Transducer beam	180° vertical (hemispherical)
Signals	QPSK/DSSS Cymbal®
Acoustic network capability	Automatic network discovery, FLOOD Centralized network support Multi-hop routing
Acoustic link capability	CSMA/CA, RTS/CTS and Aloha medium access Retransmission up to 3 times Segmentation and Augmentation of messages 16 bit CRC error check 16 bit addressing Channel equalizer: Viterbi & Turbo equalizer Forward error correction rate: 1/2 & 1/3
Range demonstrated*	3800 m horizontal 2400 m vertical
Acoustic speed (transport format)	3 selectable for adaption to acoustic channel conditions Max telegram size / duration / burst rate / signal (1) 50 bytes / 2.0 sec / 200 bit/s / DSSS (2) 120 bytes / 2.0 sec / 470 bit/s / DSSS (3) 231 bytes / 1.1 sec / 1710 bit/s / QPSK
Frame size (in water)	Variable up to maximum telegram size
Number of frames per packet	32
Packet size (on modem serial line)	Variable ≤ 3000 bytes
Doppler tolerance	± 8 knots
Ranging precision (positioning)	1σ < 10 mm (free field conditions)
Source Level (selectable)	173, 178, 184, 190 dB re 1 μPa @ 1m
Interface RS232	3 wire, > ± 3V, 9600/115200 baud UUTP packets, SW flow control
UAN Protocol stack (higher layers)	ROHC/IP/UDP or TCP
Operator software	APOS® (for control, monitoring & software download)
General purpose QPSK transmitter	Direct QPSK transmission of data received on RS232

Kongsberg Maritime	**cNode® Mini 34-180 UAN**
Real time clock	1 sec resolution / < 20 ppm skew
Internal battery	Rechargeable NiMH Autonomy quiescent: 60 days Charge time 120 min (typ), 165 min (max) Theoretical capacity 108 Wh
External power	15±10% Vdc, 300 W
Power consumption	Standby 85 mW Receive 620 mW Transmit 3.3, 10, 39, 150 W
Power save scheme	Enters Standby after configurable inactivity period Enters Receive mode on activity on serial line Enters Receive mode on received acoustic telegram
Housing material	Anodized Aluminum
Housing coating	Polyurethane
Overall length	598 mm
Diameter housing with coating	85 mm
Diameter transducer	88 mm
Weight in air / water	6.7 kg / 3.4 kg
Operation temperature	-5 to +55 °C
Storage temperature	-30 to +70 °C
Compatibility	HiPAP® 501 Cymbal® range products

*) Horizontal test, transport format 1, in Oslofjorden, Norway, 2011-05-04.