Wireline Quality Underwater Wireless Communication Using High Speed Acoustic Modems

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Abstract--The paper introduces LinkQuest Inc.'s cutting-edge high speed underwater acoustic modems. LinkQuest Inc. combined recent advances in high speed digital communication with broadband underwater acoustics in the development of the high speed modems. Advanced Broadband Spread Spectrum Technology results in dramatically increased data rate and robustness and decrease in power consumption. The modems are proven to perform at high data rate with virtually no communication errors under ambient noise, ship noise from small powerboats and large DP vessels and offshore drilling noise.

The paper describes the working principles and architectures of the advanced modems and their interface to underwater instruments such as Acoustic Doppler Current Profilers. Performance results from various customer deployments such as real-time monitoring of current profiles from Shell's Ocean Worker Platform are presented.

I. INTRODUCTION

LinkQuest Inc. of San Diego, California manufactures an extensive line of cutting-edge high-speed underwater acoustic modems. These new-generation modems are fast, consume very little power and are highly robust in field deployments.

LinkQuest Inc. combined recent advances in high-speed digital communication such as Digital Subscriber Line [2] and cellular communication with broadband underwater acoustics in the development of the high speed modems. The proprietary **"Broadband Spread Spectrum Technology"** is implemented in a state-of-the-art DSP. Tailored for various ocean environments, these modems achieved dramatically increased data rate, robustness and decrease in power consumption compared with existing systems [1]. A bit error rate of less than 10^{-7} is consistently observed in the field. This is unprecedented for underwater acoustic communication and is equivalent to wireline quality.

This paper introduces various models of the advanced underwater acoustic modems and their typical application environments. It discusses the architecture, working principle and performance analysis of the modems. It also presents the application scenarios and various trial and deployment results of these modems.

Fig. 1: Model UWM1000

II. MODELS

LinkQuest designs and manufactures four different models of modems for shallow water and deepwater environments. All the modems operate at a bit error rate of less than 10^{-7} in standard mode.

Model UWM1000, as shown in Fig. 1, operates up to 200 meters in depth and 300 meters in range. The data rate of the modem is 9600 bits/second in standard mode and 19200 bits/second in optional mode. The system operates within a frequency band centered around 35 kHz. It utilizes a directional transducer and has a very low transmit power consumption of 1 watt. This model weighs about 4.2kg out of water and 2.3kg in water and is very compact in size. Typical applications for this modem include real-time monitoring of sensor data in shallow water of lake, surf zone and continental shelf. Because of its ultra low power consumption, the modem can easily transfer hundreds of megabytes of data using a small battery pack.

Model UWM2000 is developed to handle longer and deeper deployments as compared to model UWM1000. Although they are very similar, model UWM2000 can operate up to 1000 meters in depth and 1500 meters in range. Its transmit power consumption is also increased to 4 watts to reach longer range. The pressure housing is marginally increased in weight and size. These modems can be used in medium water depth from a buoy or surface vessel to communicate with a moored instrument. It can also be used from most of the oil rigs to monitor and control underwater sensors. For some of the shallow to medium water AUVs, the modem provides an excellent way to transfer the images to the surface vessel.

Model UWM3000, as shown in Fig. 2, is a versatile omni-directional modem. It operates at 2500 bits/second in standard mode and at 5000 bits/second in optional mode. With selectable transmit power up to 20 watts, it could reach 3000 meters in range. The 180-degree hemi-sphere transducer provides extra flexibility in deployment. This system can be used to command, control and communicate with underwater instrument and AUV when the range and the depth required by the application cannot be accomplished with directional transducer. The system operates at a frequency band centered around 10 kHz to minimize the impact from signal attenuation due to water absorption.

UWM4000, as shown in Fig. 3, is a powerful deep water modem. It utilizes a directional transducer to achieve a high acoustic source level and reduce the impact from acoustic interference and noise. The modem reaches 4000 meters in range and rates up to 6000 meters in depth. This model offers data rate of 4800 bits/second in standard mode and 9600 bits/second in optional mode. It operates at a frequency band centered around 17 kHz. Typical applications

Fig. 2: Model UWM3000

Fig. 3: Model UWM4000

for the modem include image data transfer from AUV, collecting data from underwater instruments towed from surface vessels, monitoring and control sensors from deep water oil rigs and DP vessels.

III. WORKING PRINCIPLE

LinkQuest's modems are based on **Broadband Spread Spectrum Technology** [3]. The modems employ advanced modulation scheme and channel equalization to combat multipaths for improved signal to noise ratio [4]. A high performance error detection and correction coding scheme is also implemented. These advanced techniques result in a highly robust system which guarantees a bit error rate of less than 10^{-7}. The transmit power consumption is also significantly decreased as compared to existing modems.

The modem's electronics consists of 3 parts, a DSP board, an Analog Front End (AFE) board and a DC/DC converter board (fig. 4). The DSP board serves as both a signal processing module and a microcontroller. System timing recovery, modulation, equalization, coding/decoding, framing and serial interfacing are all conducted in the DSP. The AFE board interfaced to the DSP board on one side and the transducer on the other side. It performs signal filtering and amplification functions. The DC/DC converter board converts a wide range of input voltage to the operating voltage of the system and the transducer. The modem has a 7-pin underwater connector which connects the modem to an external power supply and serial port. The serial interface supports RS-232 or RS-422.

LinkQuest's acoustic modems are two-way, half duplex modems that have a link layer communication protocol. When no data is being transmitted the modem stays in ***Sleep Mode*** whereby it periodically wakes up to monitor possible data being transmitted by the far-end modem.

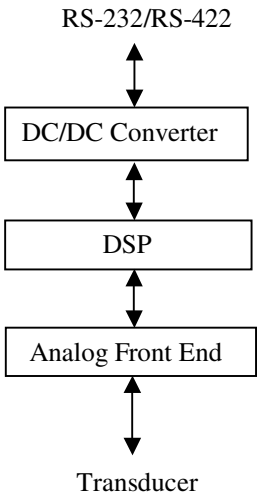

Fig. 4: Hardware structure

When the modem is sleeping (i.e. prior to waking up in the sleep mode) the power consumption is very low (i.e. approximately 8 mW). When no data is being transmitted, the modem will spend the majority of the time sleeping in the ***Sleep Mode*** to conserve power. The percentage of sleep time vs wake-up time in the ***Sleep Mode*** is configurable. The more frequently the modem wakes up the quicker it is for the modem to acquire signals from the other modem; however, this increases the power consumption of the modem. In order to explain the rest of the working principles of the modem, we will use the example whereby the bottom modem tries to send data to the surface modem.

If the bottom modem receives data from its RS-232 link connected to the bottom instrument while it is in the ***Sleep Mode***, the bottom modem will switch from the ***Sleep Mode*** to the ***Transmit Mode*** immediately and begins to transmit data. As soon as the surface modem wakes up and detects the signal from the bottom modem, the surface modem will switch from the ***Sleep Mode*** to the ***Receive Mode*** and start to receive data. After the data transmission is complete, both the surface modem and the bottom modem will return to the ***Sleep Mode*** until more data are available on the RS-232 line.

Each of the modems comes with 900k bytes of input data buffer. This is to ensure that data from the RS-232 line do not get lost in the acoustic modem in case the communication channel between the two modems is temporarily degraded significantly. Once the channel restores to sufficient operating conditions, the buffered data will be transmitted to the surface modem in the order it was received, without any human intervention.

In many applications, the power consumption of the surface modem is not as critical as the power consumption of the bottom modem. If data are often uploaded from the bottom modem to the surface modem, the surface modem may be configured to wake up frequently to ensure quick receipt of data sent from the bottom modem, while the bottom modem may be configured to wake up much less frequently to conserve power. In applications such as AUV/UUV, both the surface modem and the bottom modem can be configured to wake up all the time to ensure the minimum possible delay.

The beamwidth of the directional transducers used in models UWM1000, 2000 and 4000 is between 60 to 80 degrees. It provides a good margin for relative movement between surface and bottom modems. In case the surface and the bottom modems are in violent relative motion the surface modem may move out of the beamwidth of the bottom modem and lose communication temporarily. When this condition occurs, the advanced algorithms incorporated in these modems will ensure the completeness of the data transmission when the surface modem moves back into the bottom modem's beamwidth coverage. No data will be lost when the maximum specified beamwidth angle between two modems is temporarily exceeded. This function is particularly useful in cases where a surface ship is used to collect data from moored instruments or AUV/UUV.

The modem also employs an automatic rate adaptation function. While the modem operates at standard high data rate, it will automatically switch to a lower data rate under extremely harsh environment. When the noise condition improves, the modem will switch back to the high data rate. The automatic rate adaptation scheme provides an added insurance for extreme/unusual situation while avoiding difficult and sometimes untimely human intervention on adjusting the data rate. The quality of the communication (i.e. bit error rate) is not affected by rate adaptation.

LinkQuest's modems provide a completely transparent wireless RS-232 connection between two end equipment as if they are directly connected through an RS-232 cable. LinkQuest's RS-232 is configured at 9600 baud, 1 start bit, 1 stop bit, 8 data bit, no parity bit and no flow control. This is the default configuration most commonly used in many popular Acoustic Doppler Current Profilers and CTD's. No special modem set commands are needed to operate the modem.

LinkQuest's modems have been seamlessly integrated with some of the most popular underwater instruments. For example, the user can use LinkQuest's modems seamlessly with various models of Acoustic Doppler Current Profilers from leading manufacturers. The user can continue to use

the manufacturer's original software to configure the profiler, monitor currents and upload large amount of data from the instrument recorders.

IV. PERFORMANCE ANALYSIS

First of all, the robustness of the acoustic modems is worth emphasizing. All of LinkQuest's modem, working at standard mode, operate at a bit error rate of less than 10^{-7}. This is less than 1 bit error in 10 millions bits which sets a new quality standard for underwater acoustic communication.

The high data rate and low power consumption of the modems open new possibilities for collecting data from underwater instruments using acoustic communication. The time and battery power spent on data collection become more manageable.

In comparison with a 1200 bits/second, 20 watt transmit power modem (modem A in fig. 5) in continuous operation, the UWM1000/2000 modems, working at standard mode of 9600 bits/second, will take about 20 minutes to collect about 1 Mbytes of data whereas modem A in fig. 5 will take about 140 minutes to collect the same amount of data. Fig. 5 compares the time it takes to collect various amounts of data between a typical modem (i.e. modem A) and LinkQuest's modem UWM1000/2000 and UWM4000, working at standard mode of 9600 bits/second and 4800 bits/second, respectively.

The power consumed to collect 1Mbytes of data is about 0.3, 1.2 and 5.5 Watts for the UWM1000, UWM2000 and

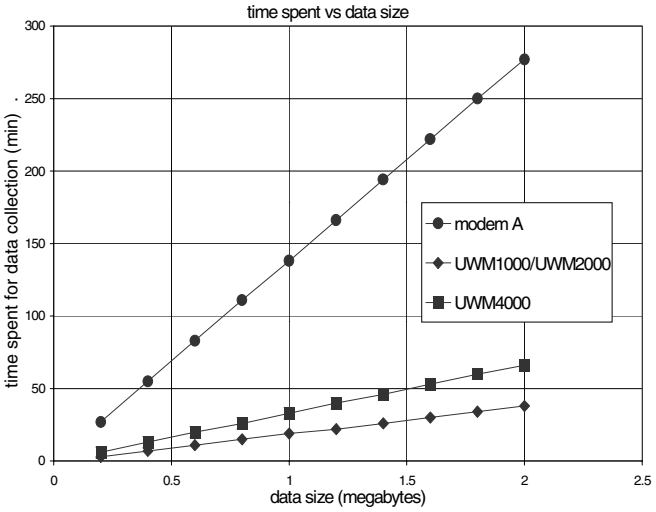

Fig. 5: the amount of time it takes to upload various

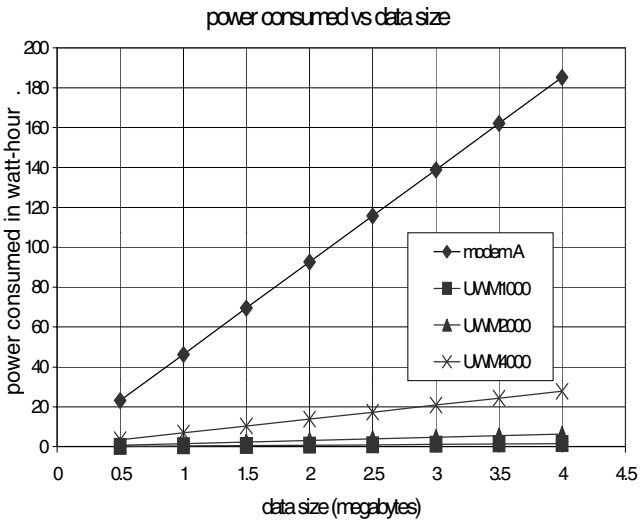

Fig. 6: the amount of battery power it takes to upload various amounts of data

UWM4000, respectively (refer to fig. 6). This is only a fraction of the power available in one standard D-cell battery. Fig. 6 compares the amount of power necessary to collect various amounts of data between a typical modem (i.e. modem A) and LinkQuest's modems, working at standard mode.

V. MODEM APPLICATIONS

There are various applications where these advanced modems provide distinctive advantages.

1. Real-time Monitoring of Underwater Sensor Data
For this type of application, a LinkQuest modem is installed on a surface buoy, a surface ship or an oil rig to collect data from underwater sensors in real-time. Typical sensor data include measurements of current, CTD, tide, wave and vibration, position or corrosion of underwater structure. Obtaining sensor data from underwater cable plow or tow body also falls in this category.

2. Periodical Data Collection from Moored Underwater Instruments
To avoid costly retrieval and redeployment of underwater sensors, a modem can be deployed with the sensors. Periodically, a ship equipped with an acoustic modem may visit the mooring site and collect the data from the underwater sensor without ever retrieving the sensors. This approach can drastically reduce the cost associated with sensor retrieval and it allows for more frequent update of sensor data. It also allows changing the configurations of the sensors remotely based on changing requirements.

3. AUV/UUV Data Upload, Command and Control
AUV/UUVs utilize sensors such as sub-bottom profiler and side-scan sonar to conduct offshore survey. Getting frequent update of sensor data is crucial to the quality of the survey and effectiveness of the AUV/UUVs for the survey work. LinkQuest's high-speed acoustic modems

will allow frequent quality update of the survey data collected by the AUV/UUV and therefore enhance the productivity of the expansive survey work. The modems can also be used to command and control an AUV/UUV from a surface vessel.

4. Underwater Telephone
Integrated with a vocoder and a microphone, the acoustic modems make up a high-quality digital underwater telephone system. Since the modems operate at high data rate, advanced vocoders used in modern cellular industry can be fully utilized which result in crystal-clear underwater voice communication.

Currently, LinkQuest is actively pursuing opportunities in all of the four areas above.

VI. FIELD RESULTS

The modems have undergone extensive tests, trials and long-term deployment. Three of the typical cases are discussed in details.

1. Trial conducted for Global Marine Systems
On September 4th, 1999, LinkQuest conducted a trial for Global Marine Systems of UK 15 miles west of Mission Bay, San Diego. In the trial, a UWM2000 modem was deployed 500 meters below ocean surface from a buoy. A powerboat, installed with a modem 2 meters below ocean surface tied with a 30-pound weight, is used to collect data from the bottom modem.

The boat was driven around the buoy at a speed of 2 knots to collect 1.25 Mbytes of data. No error was found in the collected data. The payload (user) data rate achieved was 6600 bits/second.

These modems are designed such that if the communication link between two modems is temporarily broken due to poor channel conditions or excessive beamwidth angle, no data will be lost. To demonstrate the robustness of the modem during the trial, the boat was deliberately steered outside the beamwidth coverage of the bottom modem. A few minutes later, the boat was steered back to within the beamwidth coverage and all the data were collected without loss or error.

The satisfactory performance of LinkQuest's modems finalized a purchase order from Global Marine Systems Ltd.

2. Deployment with ADCP on Shell's Ocean Worker Platform
Shell Oil Company has successfully completed deployment of LinkQuest's high-speed underwater acoustic modems in the Gulf of Mexico in high-noise offshore drilling environment. Shell used LinkQuest's acoustic modems instead of cable to upload current profiles from sub-sea ADCP in real-time. The reliability and efficiency of the modems were validated in the test.

From November 3rd 1999 to December 19th 1999, LinkQuest's UWM2000 acoustic modem was deployed with a 300 kHz RDI Workhorse ADCP at 900 meters below sea surface from an actively drilling platform, Ocean Worker (Fig. 7), in the Gulf of Mexico. The surface modem, connected to a PC on the platform, was hung about 30 meters below sea surface from the platform. Due to the robustness of the modem, system installation was easily accomplished with the help of an ROV.

The ADCP was configured to send current profile every 15 minutes. Overall, more than 4000 current ensembles (2.5 mbytes) of data were sent from the Workhorse ADCP. While data were sent through the acoustic link in real-time, the ADCP recorder also kept a record of all the current ensembles. By comparing the logged current ensembles at the surface PC obtained through the acoustic link and the current ensembles in the ADCP recorder, it is concluded that there was no loss of any current ensemble and no error in the data.

LinkQuest also demonstrated the seamless integration of its modems with ADCPs. Shell was able to use the manufacturer's current monitoring software with the acoustic link.

The success of the deployment prompted Shell to deploy more LinkQuest modems with ADCPs in the year 2000.

3. High Speed Data Link Modems on Hugin 3000 AUV
LinkQuest supplied high-speed data link modem to the first AUV purchased by a commercial survey company, C&C Technologies of Lafayette, Louisiana. The Hugin 3000, manufactured by Kongsberg Simrad of Norway, is equipped with side-scan sonar and sub-bottom profilers and capable of conducting high quality survey at a water depth of 3000 meters.

LinkQuest's modems, customized based on UWM4000, is used to send image files from the side-scan sonar and sub-

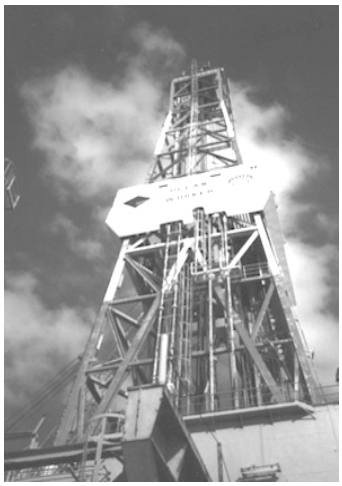

Fig. 7: Deployment at Shell's Ocean Worker Platform

bottom profiler. The operation personnel on the surface support vessel will use the images to check the status of the sonars and gain valuable up-to-date knowledge of the survey site.

LinkQuest has worked with C&C Technologies and Kongsberg Simrad extensively to define hardware and firmware solutions to enhance the efficiency of the acoustic communication and avoid acoustic interference in the AUV application. A special link layer protocol is implemented. Acoustic interference issues were carefully resolved using elaborate hardware and firmware schemes. The effectiveness of the schemes was confirmed in field tests.

In the early summer of the year 2000, LinkQuest's modems undergone a series of successful tests on board of the AUV in Norwegian Sea. The modems are expected to be placed into service during a commercial survey which will be conducted by C&C Technologies in the second half of the year 2000.

ACKNOWLEDGMENTS

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We express our appreciation to Jeremy Richardson of Global Marine Systems Ltd for his lengthy trip to San Diego from the United Kingdom for the trial.

We are grateful to C&C Technologies and Kongsberg Simrad for the exciting opportunity of providing the high speed data link to the first commercially purchased AUV. We thank Phil Devall and his colleagues at C&C Technologies and Karstein Vestgard and Jon kristensen at Kongsberg Simrad for their assistance.

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