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Norman Farr and Lee Freitag

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Woods Hole, MA 02543

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14. ABSTRACT
The proposed work will focus on research and development of wireless undersea communications networks employing multiple communications modalities, both acoustic and optical, plus connections to fiber backbones and radios above the surface where appropriate. The undersea wireless modes, coupled with multiple types of gateways, are critical in forming a robust and flexible subsea network.

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Multi-mode Undersea Wireless Communications Research

Norm Farr and Lee Freitag
Applied Ocean Physics and Engineering Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Award: N00014-16-1-3006

LONG-TERM GOALS

This projects focuses on research and development of wireless undersea communications networks employing multiple communications modalities, both acoustic and optical, plus connections to fiber backbones and radios above the surface where appropriate. The undersea wireless modes, coupled with multiple types of gateways, are critical in forming a robust and flexible subsea network. The approach is to work with government and industry performers to establish the requirements of the different communications modes and determine how to utilize them according to availability and capability. Eventually, the goal is to define a network topology to support a specific set of traffic models that are mission-dependent and possibly varying with environmental properties and locations. Network attributes that are derived from traffic models and link performance estimates will inform the network topology and used to help refine MUSE system requirements. Minimizing the probability of detection (LPD) will be an important factor in link selection, and thus we will assess methodologies and specific techniques (optical and acoustic) appropriate for LPD situations, along with characterization of potential detection ranges.

OBJECTIVES

The technical objectives of this project include laying the groundwork for development and demonstration of a new generation of subsea networks to support remote, wireless, sensors and vehicles performing different types of missions. The hardware will ultimately need to be small enough to fit onto many types of undersea vehicles, in addition to being compatible with multiple types of unmanned surface vehicles or gateway buoys, some that may be extremely small.

The effort also incorporates networking and protocol development to allow emerging capabilities to be used within a larger system consisting of manned or unmanned platforms. Work involving concept of operations (CONOPS) strategies is done by Navy experts or other government-funded contractors. However, WHOI has considerable experience working on the technical and system aspects of communications problems in conjunction with ONR-funded contractors such as SPA who specialize in CONOPS and employment in a "system of systems".

APPROACH

The technical approach is divided into several different areas, centered around modeling and networking for both optical and acoustic communications systems that make up the network. Of specific importance are channel modeling and performance estimation, networking topology and traffic model, plus methods and techniques for LPD undersea communications. These are briefly summarized separately below.

Area 1: Channel modeling and performance estimation

This includes analysis of requirements based on the applications and environments, estimation of necessary performance levels for the different functions and development of prototype hardware specification. In addition, it includes acoustic modeling, and identification of 'cross-over' points in power efficiency between acoustics and optics. Placement, power and frequency for the acoustic systems are important, while wavelength and detection method are important for optical systems.

Area 2: Network topology and traffic model

Network topology and appropriate models were explored for previous ONR programs, including PLUS and UCCI, which had similar needs to establish a communications network topology. Data sources, types of data and the different classes of vehicles or sensors were reviewed and summarized for modeling. The results suggest modes for communications (optical or acoustic), and modeling provides input for selection of a particular mode based on range and desired data rate. Concepts such as data transfer using a vehicle (glider or powered) aare part of the network design and exploit mobility when available.

Area 3: Methods and techniques for LPD undersea communications

Low probability of detection includes acoustic and optics because they can both be part of an overall strategy for minimizing the probability of detection. For acoustics, use of high frequencies and directive transducers limit range without reducing data rate, and for optics the use of wavelengths that are not detectable to the human eye can be done. For each communications modality, the potential vulnerability can be tabulated, and a variety of methods can be utilized, with varying complexity.

WORK COMPLETED

Information on the different communications links was gathered and reviewed. For optical systems examples of that data include work done under NSF support on wireless data offload from seafloor infrastructure on the Juan de Fuca plate to demonstrate long-term reliability while working with a variety of vehicles and lowered systems. The *Sentry* AUV was used to demonstrate autonomous data offload between a seafloor node and a mobile platform during the summer of 2014. In 2018, other projects funded by ONR were undertaken to integrate optical communications into the REMUS vehicle, one of which will demonstrate 10-20 Mbit/s communications underwater between vehicles, with the intention of increasing throughput to 200 Mbit/s in the near future.

Different applications use a different combination of source and receiver hardware depending on range, data rate and ambient light conditions, all of which are driven by the need to receive enough optical power per data bit to correctly decode the transmitted signal. The key system trade-offs and design choices are described in (*Pontbriand*, 2008; *Farr*, 2010). A few of the results from tests performed are listed in Table 1.

Rate	Range (meters)	Angle	Technology (receiver/source)
1 Mbps	138	Hemisphere	PMT / LED
10 Mbps	108	Hemisphere	PMT / LED
15 Mbps	80	Hemisphere	PMT / LED
500 Mbps	5	+/- 5 degrees	PMT / Laser Diode
10 Gbps	Contact	+/- 2 degrees	Photodiode / Laser Diode

The vehicle operations results are also relevant and the data from August 2014, the NSF-funded National Deep Submergence Facility AUV *Sentry* was used to demonstrate autonomous data offload from a seafloor node. The vehicle and the seafloor node were equipped with bidirectional 3rd generation optical modem hardware and acoustic modems. With the node installed on the seafloor, the AUV was launched to map the optical power field and to upload test data from the node. During one 4.5 hour mapping dive, more than 5 GB of data was transferred. Three separate dives were completed using different methods for homing on the node. The optical link performed very well and provided 5-50 Mbps data rate. A map of the modem power at 25 m altitude is shown in Fig. 1.

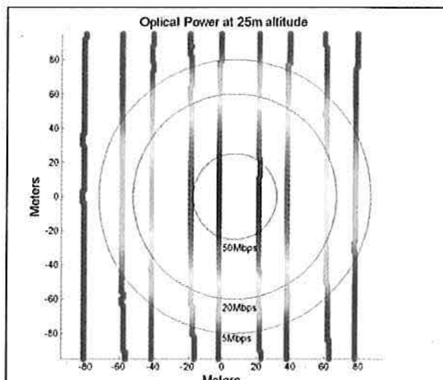

Figure 1. Optical modem power at 25 m altitude measured with the *Sentry* AUV. Circles of constant data rate are shown and labeled.

For acoustic communications, we pursued a similar approach, reviewing in-water and modeled results to explore different options.

There are a number of methods that can be used to increase bandwidth and the level of stealth for an undersea network, but the most straightforward is to simply increase the frequency. A different set of transducers is required, but our recent work with MSI Inc., and BTech (Fall River, MA) has shown that modifying the Micro-Modem for different bands is feasible and not extremely costly. In addition, we have developed some simple models (Matlab) for estimating range for different acoustic source levels and carriers that allow quick evaluation of basic parameters before investing in new transducer design. An example is shown in Fig. 2, where a 40 kHz carrier is evaluated for ranges to 4000 m at different data rates. Trading off receiver gain is also critical, because lowering source level requires either a commensurate reduction in data rate (which may be fine for some applications), or a more capable receiver with multiple elements.

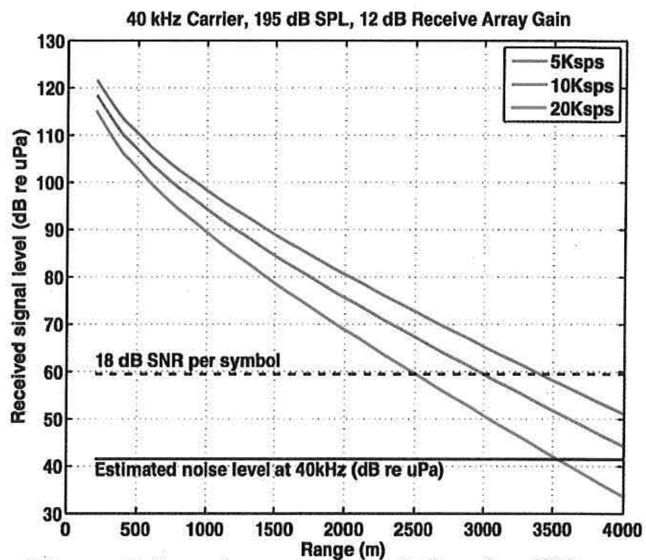

Figure 2 Sample range calculation for different data rates.

RESULTS

The results fall into several categories, summarized here at a high level to indicate how multi-mode communications can be applied to Naval operational and scientific missions.

The conclusions based on *channel modeling and performance estimates* derived from existing data sets include the following:

1. Optical communication continues to be the preferred method for close range communications where high volumes of data must be transferred. At ranges between 50 and 150 meters the energy per bit of optical methods begins to meet that of acoustic communications, but this is dependent upon water clarity.
2. When different applications are considered, the intended use of the communications system dominates the design details. For example, for acoustic links to support REMUS 100 class vehicles used for mine-countermeasures are inherently high frequency (25 kHz) because the ranges are limited and the size of the vehicle only supports small ceramic transducers.
3. Optical transfer methods also scale with the type of platform due to selection of wavelength and intended use. However, in nearly all cases the present approach of high-

sensitivity receivers continues to be cost-effective because of the high data rates and thus high power efficiencies that are achievable.

The conclusions based on our studies for *network topology and traffic models* included these:

1. Projects such as the ONR PLUS program exploited dual platform mobility but imposed external control and piloting to maintain ranges appropriate to complete the link from platform to platform. This complicates mission planning and makes human intervention in piloting excessive when the number of vehicles becomes large. A specific recommendation is that autonomy, implemented on board the vehicles, be implemented such that the piloting of platforms being used as communication aids be tied to their clients.
2. The topology that results from a multi-source, multi-sink network is likely to be more complex than is presently manageable, even with some level of autonomy implemented on communications nodes that service data nodes, except for a one to one mapping.
3. *Link adaptation* is required for any communications mode to be successful when employed in dynamic conditions. Autonomous link adaptation is also required to select which mode to use (e.g. acoustic or optical), but the method for making the selection can be straightforward using simple range and energy models, with a policy layer on top to ensure that specific rules on employment are not violated (e.g. do not use optics at night within 50 meters of the surface).

The conclusions based on a review of *methods and techniques for LPD undersea communications* include the following:

1. Optical methods are the most difficult to detect under most circumstances. However, when used at night blue and blue-green LEDs or lasers are visible to the human eye. Therefore, we recommend that infrared optical emitters be used for certain applications.
2. Acoustic methods for LPD favor high frequencies and directive transducers when possible. However, when we reviewed the geometry constraints for high frequencies we found that limitations in beam patterns that are helpful in reducing excess emissions also make links harder to set up and to maintain. Thus, overall, omnidirectional transducers are preferred when high frequencies are necessary to limit range by increasing frequency-dependent absorption.
3. The combination of both methods offers the best approach for reducing the likelihood of detection. Limited use of acoustics to bring systems into range for a subsequent optical data transfer provides for reduced risk and allows for large amounts of data to be moved in a short time, without exposing platforms to significant detection risk.

IMPACT/APPLICATIONS

The efforts described here provide guidance for applications of point-to-point physical layer communications and networking for undersea missions. The work is applicable to many current Navy needs, including mine warfare and mine countermeasures using seafloor sensors or unmanned vehicles. Of specific interest are diver to diver communications and UUV to UUV links, both acoustic and optical.

TRANSITIONS

WHOI is working on a number of projects that may provide for transition potential, including several with the Naval Undersea Warfare Center, Newport that are sponsored directly by specific commands.

RELATED PROJECTS

ONR-funded Cognitive Router Project.
ONR-funded AUMA Project

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