IAC-17,B4,7,8,x40893

Integrated SmallSats and Unmanned Vehicles for Networking in Remote Locations

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September 2017

Abstract

The lack of infrastructure in maritime and Arctic regions has a strong impact on many operations, such as the retrieval of scientific data. Nowadays, data logged during these operations must either be collected by manned missions or transmitted over existing satellite links. Unfortunately, both methods face challenges regarding availability, as well as energy and link budget constraints.

When considering the throughput of existing satellite links, the effective amount of data that can be transmitted is limited by the links' throughput, periodicity and economic cost. Consequently, it is a common practice to visit research sites in order to manually collect data recorded over extensive time periods, usually spanning from several months to years. However, manual collection of research data, in particular in harsh maritime environments, poses a risk to crews and also incurs significant costs.

In order to overcome current communication limitations, the use of small satellites and unmanned vehicles for remote and in-situ sensing has been proposed by several authors. This is motivated by the growing availability of small satellite platforms as well as by the foreseen increase in launch availability, enabling the creation of novel dedicated small satellite missions. Constellations or swarms of small satellites, such as CubeSats, can work together with other unmanned vehicles and play a key role in integrated communication systems.

Unmanned vehicles can act as relay nodes or as data mules. The relay node can be used when a vehicle or small satellite is simultaneously in communication-range with research sites and supporting infrastructure, such as other relay nodes. Alternatively, data-mules may also cover regions outside the range of existing infrastructure and reach distant research sites where data is being gathered. In the area of destination, data-mules collect and store data, delivering in when returning to supporting infrastructure.

In this paper, we propose an integrated network, consisting of a combination of dedicated small satellite systems and unmanned vehicles to help in scientific data retrieval in remote locations. The main contribution consists in addressing the communication challenges of heterogeneous unmanned platforms and how they can support different scenarios and experiments. The proposed approach is defined and described in a testbed suitable for a selected set of maritime scenarios.

1 Introduction

Due to the lack of infrastructure in maritime and Arctic regions, operations such as retrieving scientific data become complicated and expensive. It is common that data from remote sensors must be collected by manned missions. To some extent, existing satellite links can be used. Either way there are challenges with respect to availability, energy and link capacity. The creation of an integrated heterogeneous system can help solve these problems. The solution will be an integrated network-of-networks, consisting of terrestrial links between sensor nodes, satellite links and links between sensors and unmanned vehicles (UVs). These communication technologies will not always be available since satellite links are intermittent and UV links may be available only during special data retrieval missions. At a given point in time, individual nodes in the network should utilize the available links best suited to transmit their data.

Maritime operations can be very diversified and lead to a multitude of distinct scenarios. For instance, both dense and sparse deployments of nodes for environmental monitoring may be required. This concerns not only research-oriented activities but also economical or safety operations. An example of a heterogeneous deployment is presented in Figure 1. This figure shows how nodes with different capabilities interact.

The contribution of this paper is to define a state-of-the-art architecture for networking and data exchange in remote locations. We propose cooperation of SmallSats and Unmanned Vehicles (Aerial, Surface, or Underwater) in order to make data retrieval processes more efficient and globally available. We assume that one mission will serve only one or a couple of end users. However, the presented architecture and suggested technologies make use of generic and standardized equipment and communication protocols *when possible*. This will ease integration with other systems as well as deployment of similar systems and missions later on.

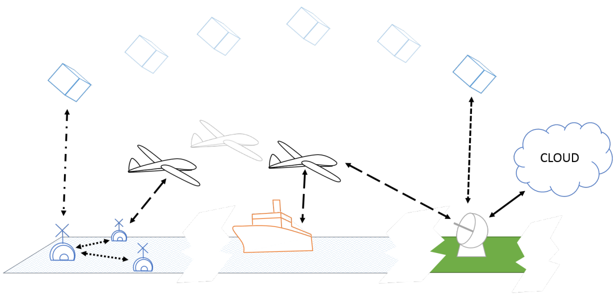

Figure 1: Co-existence of heterogeneous communications and vehicles

A reference scenario with multiple agents consists of monitoring/sensing nodes, unmanned vehicles, satellite nodes and ground stations (i.e. fixed or mobile stations capable of communication with UVs or satellites). One or more Command and Control (C&C) centres will also be part of this reference scenario, responsible for coordinating operations. This entity is not depicted in Figure 1 as it will likely be connected to existing infrastructure, communicating directly with ground stations.

Figure 1 shows one ground station that represents the edge of available communication infrastructure. In a deployed network, there will usually be several ground stations with various purposes adapted to the vehicle(s) they serve. These will be interconnected using the Internet and will provide a wireless link to the various nodes, for example satellites and UVs. Additionally, in order to reduce the access time of data from sensor nodes, the ground station placement should be tailored and adapted to the scenario. For satellite ground stations, they could be located at the edge of the observation area, e.g. one at the entering point and one of the exit point of the area along the satellite track.

Small satellites, also know as SmallSats, independently deployed or in swarms, are seen as a potential solution for improving communications in maritime environments, where infrastructure currently is lacking. The potential gain of using such swarms is further discussed in [1] and evaluated in [2]. Freely drifting swarms will allow for more frequent visits for nodes within a target area, but still with a limited coverage period and bandwidth. The mean time without coverage is a function of the number of satellites in the swarm.

UVs travelling in the vicinity of the sensor nodes can also be used to collect data, as well as to deliver configuration messages. This approach uses not only autonomous unmanned vehicles for planned visits to sensor nodes [3, 4], but includes also opportunistic interactions with other vehicles (e.g. transport ships) to increase connectivity. Even though unmanned vehicles may act as relay nodes, when sufficiently close to an infrastructure, their primary goal will be to act as data mules. As most maritime operations will likely take place in remote locations, visiting vehicles may have limited resources that constrain their operation, not being able to reach all the nodes in one area. In this case, multi-hop cooperation between the nodes will again be important to guarantee that all sensor nodes are reachable.

This paper reviews state-of-the-art networking technologies and existing unmanned vehicles for maritime operations in Section 2, followed by an identification of existing requirements for such operations (Section 3). Section 4 describes the proposed architecture integrating both SmallSats and Unmanned Vehicles, identifying the role of different nodes in a network, as well as the definition of a preliminary testbed. Finally, concluding thoughts are presented in Section 5.

2 Related Work

Studies on heterogeneous networks integrating terrestrial links and UAVs and/or satellite can be found in existing literature [5, 6, 7]. Typically, unmanned vehicles are used as data mules for sensor networks, being responsible for gathering sensing data and delivering it to supporting infrastructures [8, 3, 9, 10, 4]. Additionally, the use of small satellites and small satellite swarms as a feasible alternative for remote maritime operations has also been studied in the past [11, 1]. Aiming at investigating the performance of network protocols, sensor nodes, swarms of small satellites and corresponding ground stations, an emulation tool has also been proposed [2]. In [12], a comparison between emulation of a scenario and experimental results from a sea trail is presented. These research initiatives include the use of several technologies and various types of vehicles, respectively discussed in Sections 2.1 and 2.2.

2.1 Enabling Network Technologies

Past works have already addressed the challenges of communication and message transfer between nodes with marginal links, having proposed different protocols which are currently used by some systems. However, there is no standard solution integrating the communication between different vehicles in remote locations. Most of them are based on specific hardware and applications, many of them primarily consider messaging over point-to-point links, such as serial links and star networks where there is little need for “true” network protocols.

One example is the Goby Underwater Autonomy Project[1], which defines an autonomous architecture designed for marine robotics focusing on heterogeneous inter-vehicle communication. It was created as a replacement for MOOS [13], while also providing an interface to it. Goby is based on ZeroMQ[2] and supports serializing methods such as Google Protocol Buffers (Protobuf)[3] and Lightweight Communications and Marshalling (LCM) [14]. COSMOS[4] is another project that focuses on constrained scenarios, namely small satellites. It resorts to a network architecture that separates the space and ground segments, giving emphasis to space and employing the NACK-Oriented Reliable Multicast (NORM) Transport Protocol [15] and the LCM library. Similar to Goby or MOOS, the LSTS Toolchain [16], from the Underwater Systems and Technology Laboratory, also provides a suite of tools and protocols for autonomous vehicles, employing their own Inter-Module Communication (IMC) protocol.

Despite past efforts in integrating heterogeneous resource-constrained devices, the presented solutions are focused on very specialised environments. For instance, even when resorting to standardised protocols, there is no integration with Internet as we know it today. These proposed systems provide local networks that can be connected to the Internet, but not in a seamless way and disregarding other protocols and formats such as the Efficient XML Interchange (EXI) format[5].

Protocols such as as LCM and ZeroMQ will make use of any form of transport layer, be it a serial link or a TCP/IP like network. However, other solutions, such as NORM, rely on IP, which can be aligned with increasingly popular Internet of Things (IoT). Similarly, another popular solution for constrained environments and the IoT is the Constrained Application Protocol (CoAP), which provides its own link format [17]. It is designed for constrained nodes and networks, supporting secure connections as well as a number extensions such as HTTP mapping [18] and group communication [19]. Moreover, by taking into consideration the developments of the IPv6 over Networks of Resource-constrained Nodes (6lo) working group[6], it can provide optimisation which are ideal for interconnecting heterogeneous networks. In fact, the use of standardised protocols, such 6LoWPAN for interconnecting devices with different capabilities, can also provide a solution for issues such as address attribution [20].

When selecting the appropriate protocol stack for new systems, interoperability, standardization, user base, active use and development must also be considered, in addition to quantitative parameters as network efficiency, throughput, load capacity and so on.

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[1] `http://gobysoft.org/`

[2] `http://www.zeromq.org/`

[3] `https://developers.google.com/protocol-buffers/`

[4] `http://cosmos-project.org`

[5] `https://www.w3.org/TR/exi/`

[6] https://datatracker.ietf.org/wg/6lo/

2.2 Capabilities of Various Vehicles

Cooperation between satellites and unmanned vehicles is a great synergy in order to enrich data-transfer options, as well as overall coverage. Various types of unmanned vehicles and satellites are characterized by different capabilities. There are three main categories of autonomous vehicles that can perform advanced operations in the maritime environment as listed in Table 1. Unmanned Aerial Vehicles (UAVs); Unmanned Surface Vehicles (USVs), also referred as Autonomous Surface Vehicles (ASVs); and Autonomous Underwater Vehicles (AUVs). All vehicles can be equipped with communication assets that allow fast data transfer between them and network nodes in their proximity.

UAVs can cover significant distances in a short time thanks to their speed in the air, while being able to fly directly to the area of interest. However, their endurance is limited, usually from some hours to a few days. On the other hand, some types of the USVs, powered by renewable energy, can travel a virtually unlimited period of time and cover great distances. However, their speed will usually be significantly lower when compared to flying vehicles. Last but not least AUVs may be the slowest among all mentioned vehicles. These however, can reach nodes unavailable to other types of vehicles, e.g. under the ice layer.

All vehicles require a certain level of logistics related to their deployment. That can vary from an update of instructions sent to the vehicle, up to a complex operation involving number of crew and complex arrangements, e.g. a vessel cruise, or an airspace reservation. In all cases data collection or data muling is exposed to a variety of uncertainties. Available data-collection using UV depends on multiple factors such as vehicle and crew readiness, economic viability, regulatory framework, traffic in the area or even weather conditions.

Satellite links seem to perfectly fill these gaps when the data mules cannot be used. These links are usually slower and only available for shorter periods of time compared to communication links provided by UVs. However, they are predictable as availability of satellite and their data transfer capabilities are known well in advance. In the end, a network based on a synergy of satellite and unmanned vehicle nodes presents a user with multitude of possible ways to download its data from remote locations. In order to further enhance the network, especially reducing the round trip delay, inter-satellite links can be used to relay data between satellites in order to reach a ground station quicker. In this proposed architecture, inter-satellite links are not included due to the increase in the requirements for the on-board power system and to the attitude (pointing) system. This adds both complexity and cost of the satellite platform. In addition, with only a few satellites serving the system, inter-satellite links will be scarce and cannot be used. In a denser constellation or swarm of satellites, inter-satellite links can be of use.

Table 1: Unmanned Vehicles access for Maritime Environments, based on [21].

	UAV		AUV			USV		
	Smaller (< 25 kg)	Larger (>25 kg)	Light AUV	AUV	Gliders	Renew. Energy	Boats	Vessels
Small-scale (0-10 km)	✓		✓	✓			✓	
Medium-scale (10-100 km)		✓		✓	✓	✓	✓	
Large-scale (100-1000 km)		✓			✓	✓		✓
Global-scale (>1000 km)		✓			✓	✓		✓

3 System Requirements

The proposed system shall meet several requirements. First of all, it should *enable interoperability* between different communication technologies, which will be useful to *mitigate network partitioning.* In particular, it will provide multiple degrees of communication coverage and performance.

Maritime operations are characterized by intermittent connectivity, therefore the system shall be *robust and resilient* to these conditions. The system shall include *delay/disruptive tolerant semantics* in the network-substrate, allowing the usage of distributed systems similar to the ones used across the Internet. This means that message acknowledgements must be employed, either on a link-to-link level or on a higher level (end-to-end message transfer verification). The level on which this functionality should be implemented depends on chosen (higher-level) protocols, requirements for timeliness[7] and complexity in implementation.

Communication shall be *accessible to all nodes in a scalable fashion.* Due to the heterogeneity of services and actors, the system shall also provide *distinct levels of communication quality* according to the priority assigned to different data sources.

Although satellite link availability is known well in advance, the use of UVs puts some additional constraints on system operation. Their use is prone to

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[7] Link-to-link verification may reduce the time for end-to-end message verification if communication losses are handled on an early stage

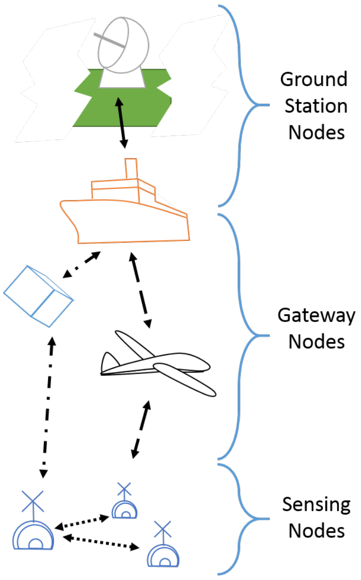

Figure 2: Top-level view of the Network Architecture

additional cost and can be jeopardized by weather conditions, or service-provider availability. For that reason their use must be properly planned, and the system shall allow the user to *select or automatically select, the most efficient data-route* based on a predefined metric, e.g. cost-per-bit or delay sensitivity.

The overall solution shall be *extensible in alignment with standards and protocols* developed for the Internet. This will allow maintaining an up-to-date, stable and secure system for current and future developments in maritime operations.

4 Proposed Architecture

In order to enable in-situ sensing in harsh environments it is important to define a clear networking architecture. This architecture must include hierarchical roles for different nodes, ensuring a scalable and organised structure, presented schematically in Figure 2. This architecture consisting of 3 main classes of nodes with distinct roles: **Ground Station Nodes (GS)**, **Gateway Nodes (GW)**, and **Sensing Nodes (S)**. An integrated solution for networking in remote locations must consider multiple communication technologies and interoperable interaction between such nodes. In order to meet the proposed objectives and requirements, chosen components and their configuration should comply with existing standards and be customisable. Additionally, it must support dynamic changes in its topology due to the variability of conditions in, for instance, maritime scenarios (e.g. intermittent links and mobility).

4.1 Network Nodes Types

Ground Station Nodes are considered *root nodes* in the proposed hierarchical network. These have access to a vast amount of resources, such as a large vessel or nodes that are part of an infrastructure, such as a satellite ground station. Additionally, these nodes will be permanently connected to the Internet, which allows them to keep a synchronised perspective of the network, regardless of the distance between them.

Root nodes should also include several communication interfaces, using different technologies, enabling higher levels of connectivity with different vehicles. They will be the main interaction points for unmanned vehicles and satellite nodes, which are GW Nodes, and will be responsible for interfacing the GW nodes and providing connectivity to the Command and Control (C&C) centre.

Ground stations may also be responsible for hosting the C&C centre, however this unit may also operate elsewhere, provided that it has connectivity with all ground stations. The C&C must perform all the required planning and configuration decisions that will improve the system's performance and resource usage. Storage of the collected data must also be handled by the C&C, therefore ground stations will not only serve as a forwarding point for the C&C decisions, but also as a back-haul for all the gathered data.

Gateway Nodes are manned and unmanned vehicles that are integral components of the proposed network architecture. These will serve as *gateway nodes* (GW) between the root nodes and any other nodes in maritime deployments. The focus for the proposed architecture is to exploit different networking options for reaching isolated nodes in remote locations. For example, unmanned vehicles such as Unmanned Aerial Vehicles (UAVs) can be considered as on-demand GWs for high-bitrate transfers, while SmallSats can be used to periodically retrieve or deliver smaller amounts of data (e.g. status information).

UAV gateway nodes can be used to carry or relay data from and to the C&C centre. This should be enabled by at least two different communication technologies, one focused on high bit-rates and another on achieving longer coverage ranges for relaying data. Such heterogeneity will allow GWs to act as data mules for delay tolerant data, or simply as relays for critical data.

Satellites can be an important resource for reaching more isolated sensor nodes, reducing the need for data collection by vehicles. LEO satellites are typically characterized by periodic coverage, providing approximately 10 minutes of link access every 90 minutes[8]. However, this may be improved by resorting to SmallSat constellations or swarms, combined with well-designed placement of the ground stations. This would allow a satellite to download received data and requests to one ground station, which in turn forwards them to the other station so that it can intercept newly arriving satellites.

The GW nodes, satellites or vehicles, will not only collect data from the sensors, but also deliver any data that may have been requested by the sensor nodes. Additionally, configuration messages from the C&C centre will also be sent throughout the network of nodes. Each vehicle should complement each other, leveraging on their distinct hardware characteristics and specific behaviours or conditions as described in Section 2.2. Since GWs can be hosted on various nodes, the use of standardised protocols will be important for ensuring the interoperability between them, resorting to mechanisms such as Route Advertisements or common addressing based on IPv6.

On some occasions, it is possible for a GW-node to act as a relay node, forwarding all received packets directly to an infrastructure node. An example is a satellite passing over the sensor field while at the same time being in contact with a ground station. However, since a direct link to the ground station infrastructure may be nonexistent or limited in resources (e.g. a long-range low-bitrate link may not be able to relay all the collected data in real-time), GWs must be able to act as data mules, collecting all possible data and delivering it later when closer to the infrastructure. Finally, GW nodes must be capable of acting as proxies of C&C centre, becoming responsible for delivering configuration messages to sensing nodes.

Sensing Nodes are envisaged as quasi-static nodes that aim at collecting scientific data from a given area, though mobile nodes may exist. This area may be covered by a single node or by a cluster, where nodes may be able to communicate with each other. The monitored data is to be relayed through multi-hop links whenever a group of clusters is close to shore.

The sensing nodes are leaf nodes in the presented architecture, which can be deployed in different locations. They will be the main source of data, that should be forwarded towards the C&C. These nodes are typical constrained, with limited energy, processing power and even communication capabilities. However, communication limitations typically result from the lack of energy availability, which can be mitigated by diligently combining different radios. For example, low-power and low-bitrate radios can be used locally between leaf nodes, or for activating more resource-demanding radios when a GW is nearby. The proximity between leaf nodes may allow multi-hop routing so that data can be forwarded to nodes directly connected to a gateway. This can, for example, result either from routing messages sent by a GW acting as a router, or from Software-Defined Networking (SDN) flows installed by the C&C.

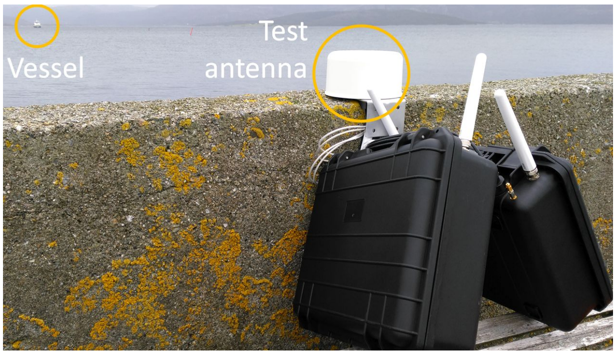

Figure 3: Sea trial of the testbed nodes – communication sea-to-shore

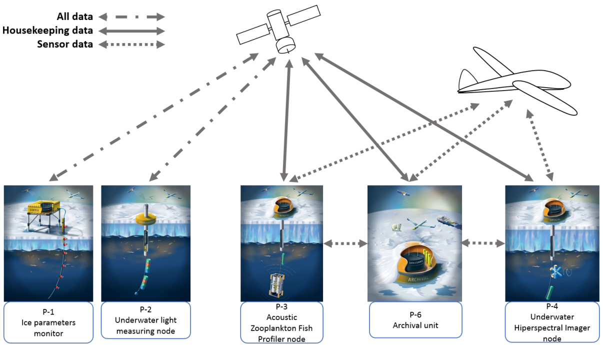

Figure 4: Arctic ABC data collection

4.2 Configurable Testbed

In order to conduct experiments based on the proposed architecture, allowing integration of several networks, a dedicated hardware solution, based on commercial-off-the-shelf testbed has been developed. The testbed consists of four nodes, build into weatherproof, rugged boxes, with a set of 2 radio systems. In the current version, a short-range, high capacity WiFi link and long-range, single channel VHF radio are used. Each node is a complete system with computational power and a battery lifetime of sev-

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[8] Given a node or ground station placement so the satellite can be seen for every pass.

eral hours and that can be deployed, for example, onboard a research vessel. Using the nodes, it is possible to measure radio link performance as well as to control network behaviour using different protocols (Figure 3).

The first evaluation in a sea trial focused on the cooperation between a UAV and a research vessel [12]. However, the testbed nodes have been designed in order to be able to cooperate with a growing number of assets available for the research activities in the Trondheim area. Some of these assets include fixed-wing UAVs [22], Light Autonomous Underwater Vehicles, a motorboat based USV and a research vessel [8]. The proposed architecture and testbed provide also a feedback to the Arctic ABC-project development [23, 24]. The architecture used by this project is depicted by Figure 4, which resembles the proposed integrated networking scheme. This architecture defines a system consisting of one or a few sensing nodes and gateway nodes based on UAV and a satellite nodes, which complement each other to enhance data collection in the Arctic.

5 Summary and Conclusions

To bring connectivity to the Arctic and enable the Internet of Arctic things, we propose a heterogeneous network architecture interconnecting sensors, relay nodes, data mules and ground stations. In order to ease integration with a wide range of hardware and excising networks, we propose to make use of standardised concepts and protocols suitable for the identified requirements. By building a general network infrastructure encompassing sensor nodes, small satellites and various UVs, the common architecture can support a wide range of missions. Relaying scientific data from environmental sensors is only one example.

The different roles for each node in the network hierarchy and their characteristics are described. This creates different communication opportunities, based on the details of each network node. Interconnection is enabled by resorting to standardised IP-based protocols, suitable for both constrained and high-capacity networks. Multi-hop networking between leaf nodes also allows extending the coverage of GWs and the overall network.

Some leaf nodes may be able to communicate with different types of technologies and GWs, such as aerial vehicles and small satellites. This option is particularly relevant when large amounts of data are to be transmitted, as larger bitrates are expected to be available when nearby GW vehicles exist, saving energy with low-power low-bitrate radios otherwise. Simultaneously, the use of small satellites allows sensing nodes in more isolated areas to periodically deliver their collected data, though at lower bitrates, regardless of the availability of GW vehicles.

Acknowledgment

This work was partially funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No. 699924, SINet. The Research Council of Norway is acknowledged as the main sponsor of NTNU AMOS (Centre for Autonomous Marine Operations and Systems), grant number 223254, and the project Hybrid Operations in Maritime Environments (HOME) funded by the MAROFF programme, grant number 269480. The authors would also like to thank the lighthouse project CAMOS (Coastal and Arctic Maritime Operations and Surveillance) of the Faculty of Information Technology and Electrical Engineering, NTNU.

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