Combination of CP & CSA

D5.1- Survey Report of Sensor Networking in the Arctic

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PP	Restricted to other programme participants (including the Commission Services)	
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Publishable Executive Summary

In this report, we survey the issues related to sensor networking in the Arctic. Ecologists in the Arctic have deployed in-situ sensing infrastructures to observe and monitor the biotic and abiotic factors in a given ecosystem for years. They primarily rely on fixed data loggers to collect and store data from a wide variety of sensors. The goal of sensor networking is to transform these data loggers from stand-alone, isolated systems to networked systems that can be controlled and accessed online. In this report, we list the issues related to short range and long range communications, we describe existing solutions – our primary target here are station managers - and we discuss the issues that remain to be solved. Finally, we give a snapshot of sensor networking in the INTERACT field stations based on a survey of 22 station managers.

This report is accompanied by a Web site that contains background information and related links at the following URL:

http://www.eu-interact.org/joint-research-activities/virtual-instrumentation/

1. Introduction

In the context of INTERACT's joint research activity on virtual instrumentation (WP5), our goal is to investigate how ecological research and possibly education can benefit from Internet-based access to the sensors deployed in the Arctic field stations. While the paradigm of virtual instrumentation is well-understood for remote sensing (where satellite images and associated filters can readily be made available on the World Wide Web), the notion of virtual instrumentation is yet to be defined for in-situ sensing. Our premise in WP5 is that sensor networking is a key technology to allow remote, virtual access to the sensors deployed in the field.

The notion of sensor networking has been the focus of attention in the computer science community for about 10 years. While sensors have for a long time been remotely accessible via some for of networking technology, the first efforts to systematically interconnect sensors with integrated computation and communication capabilities were pushed by DARPA in 1999. The rationale was that the evolution of MEMS technology (Micro Electro-Mechanical Systems) and the exponential evolution of computer chips would lead to smaller, more energy efficient, more accurate sensors that could be equipped with miniature computer chips (called micro-controllers) and radio devices. For example accelerometers have evolved in the last 15 years from bulky 1-dimensional sensors (occupying 20 cm^3) to miniature 3-dimensional sensors (occupying fraction of a mm^3). The vision was that large numbers of such inexpensive, energy-efficient sensors could be networked to provide local sensing at unprecedented scale and resolution in space and time.

Ecologists in the Arctic have deployed in-situ sensing infrastructures to observe and monitor the biotic and abiotic factors in a given ecosystem for years. They primarily rely on fixed data loggers to collect and store data from a wide variety of sensors. The MEMS revolution has not yet delivered a radical change of the optical, biological and chemical sensors that are pervasive in the Arctic, and scientists cannot afford high density deployment of the current generation of sensors, which are still bulky, energy hungry and expensive. So the vision of very high density sensor deployments is not appropriate for the Arctic.

Still, sensor networks can have a tremendous impact on ecological monitoring by transforming stand-alone devices into a networked system that is monitored and controlled to meet the scientists' requirements.

This survey thus focuses on turning data loggers deployed in a field stations from stand-alone, isolated devices into a networked system that can be accessed remotely for telemetry and telecommand. Note that this notion of remote access to data loggers is a necessary step for the measurement of feedback mechanisms planned in Work Package 6.

This survey is intended as an overview of the key issues. The primary audience of this document is the INTERACT station managers so that they get an overview of the problems and existing solutions related to sensor networking. Hopefully, this document will also be helpful for any researcher involved in monitoring and observation in the Arctic. For example, this document should allow any practitioner to understand the different types of networking modules available for their data loggers and to choose the appropriate one for their deployment (e.g., Campbell Scientific proposes about half a dozen radio modules for their popular data loggers – picking the appropriate one requires some preparation work).

This document is accompanied by a best practise web site that contains all the practical information and links that are useful when designing a wireless sensor network in the Arctic. The web site is available at the following URL: http://www.eu-interact.org/joint-research-activities/virtual-instrumentation/

The rest of the document is organized as follows. In a first part, we review the problems and solutions related to making data loggers remotely available via a wireless network. In Section 2, we focus on the key issues related to data logger networking, including short range communications, while we review long range communications in Section 4 (we base this Section on the work performed in the context of the Articom study commissioned by ESA). In a second part, we propose a snapshot of sensor networking in the INTERACT field stations based on a survey filled out for 23 of the INTERACT stations. Section 5 contains this survey, its results and a discussion.

2. Wireless Data Logger Networking

Scientists rely on fixed data loggers to collect and store data from a wide variety of sensors deployed in the INTERACT Arctic field stations. These data loggers basically consist of a computer connected to several sensors (via wires). The data logger might be configure to perform simple processing on sensor data and obviously to store the data on an internal storage medium, typically flash storage. Data loggers can typically be accessed via a laptop through a serial connection (again a wire). This way, a program on the laptop (e.g., loggernet for Campbell Scientific data loggers) can be used to configure the data logger or to transfer the data it contains. Possibly, a USB key can be plugged into the data logger to transfer a copy of the data it contains.

Typically, checking that a data logger works as intended requires a technician to walk (possibly several kilometres) to the location of the data logger, connect a laptop to it and check its status. Likewise, transferring data from a data logger requires a technician to take time to physically access the data logger to transfer the data it contains on a USB key.

Wireless networking a data logger would make it possible to perform telecommand and telemetry, i.e., a technician would not need to physically connect to a device to configure it or access the data it contains.

Beyond this obvious improvement (and before we review the potential pitfalls of networked systems below), let us describe additional potential benefits of data logger networking:

- Raw measurements are the foundation of the scientific workflow. They are tagged with metadata, and transformed into derived data products via calibration, verification, or extrapolation processes. The derived data products are then used for modelling purposes. The derivation processes and the models are applied in the lab, as a post-processing phase, based on the primary data collected in the field. If an offline verification process exposes a sensor failure then the collected data is useless. If a model gives evidence of interesting events, then the collected data might not be dense enough (in space, time or modality) to allow a deep analysis of the phenomenon. Data logger networking makes it possible to move portions of the existing offline scientific processes online, within the ecological sensor networks in order to improve the quality of the collected data. For example anomalous situations should be recognized and handled online, while data is collected, so that the sensor network can adapt and maintain high utility.

- Ecological data acquisition has been based on the premise of systematic ecosystem sampling: it is assumed that the ecosystem is sampled with given modalities at predefined intervals in time and space. In fact, this is neither possible (because of failures), nor desirable (because interesting events might not be captured by the baseline settings). In contrast, ecological sensor networks – based on a network of data loggers interconnected to a server - could rely on adaptive ecosystem sampling, where the procedure for selecting samples may depend on the values of observed variables

On the other hand, data loggers network introduce complexity and the deployment of advanced IT solutions (many still experimental at this stage) and it requires the deployment of appropriate security solutions (because data logger networking enables a whole new range of passive as well as active attacks on the data loggers deployed in the field). However, the evolution of IT in society towards interconnected and networked physical devices (Internet of Things) should lead to mature solutions for these problems.

How does a data logger network look like? In the reminder of this section, we cover the two main issues related to the design of data logger networks. We describe (1) the radio modules that make it possible to remotely access a data logger wirelessly, and we discuss (2) the network topologies that might be used to interconnect data loggers to a local laptop, or to the Internet.

2.1.Radio Modules

The constructors of popular data loggers propose short range radio modules that can be plugged on existing data loggers. Future data loggers will certainly incorporate built-in radio modules (just like today's laptops incorporate built-in wireless radios, which was not the case 10 years back).

On the web site (http://www.eu-interact.org/joint-research-activities/virtual-instrumentation/), we discuss basic knowledge about wireless networks which is necessary to understand the role of (and take informed decisions about the choice of) a radio module:

- What is a wireless network?
- What is a radio link?
- What is a 900 MHz/2.4 GHz radio?
- What is an antenna?
- What is 802.11?
- What is 802.15.4?
- What is a protocol?

This information is necessary to fully understand the product description of the radio modules made available by data logger constructors. The web page is essentially a reference resource. Here is some context information that should allow you to make sense of these product descriptions.

The basic problem solved by a radio module is the following: How can a laptop connect to a data logger without physically connecting a serial cable? Roughly put, the solution provided by a radio module is to replace the serial cable by two devices: one is connected onto the serial connection of the data logger (the radio module), the other one is connected to the laptop (either the built-in radio or an external radio module). These two radio modules communicate via a radio link, i.e., bits are transferred between the data logger and the laptop through free space by modulation of electromechanical waves (generally either 900 MHz or 2.4 GHz). An antenna is used to actually perform wave modulation (both transmission and reception). On the web site, we describe how to conduct capacity sizing and planning for a radio link, i.e., we explain how the choice of frequency, antenna, radio module and cabling affect the quality of the transmissions.

Here is for example, the result of such a radio link study that describes radio coverage with a receiver (or sender) positioned at the main building in the Abisko research station – the two figures (Figure 1a and 1b) are obtained with similar antenna, and two different radio modules one with a 900 MHz frequency and the other with a 2.4 GHz frequency. The methodology and tools to conduct such studies are available on the web site. These figures illustrate the difference between 900 MHz and 2.4 GHz radios: the former carry a signal longer and through more obstacles, while the latter have a higher throughput (i.e., they carry significantly more bits per second).

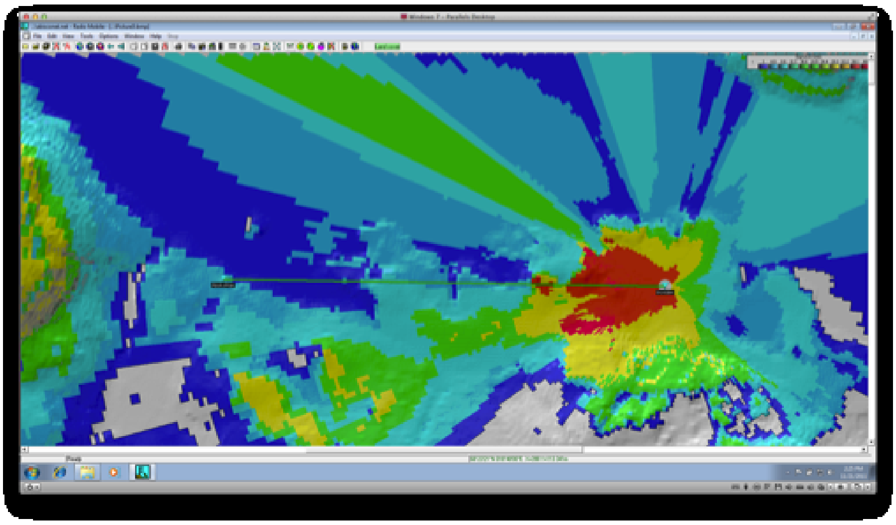


Figure1a: Radio Coverage around the main building at Abisko with a 900 MHz radio. In the colour scale: White corresponds to no reception, while dark blue, light blue, green, yellow and red represent increasingly better reception. Most of the Abisko region is covered by 900 MHz radio signals.

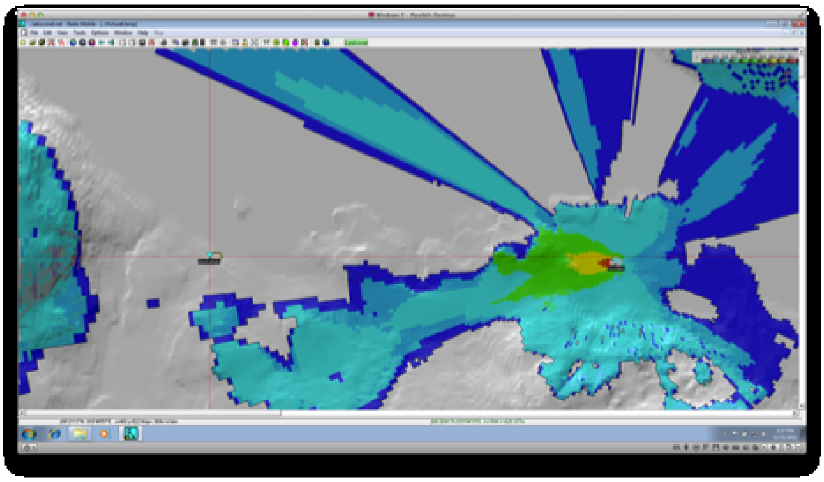


Figure1b: Radio Coverage around the main building at Abisko with a 2.4 GHz radio. In the colour scale: White corresponds to no reception, while dark blue, light blue, green, yellow and red represent increasingly better reception. The white regions correspond to the areas non accessible to 2.4 GHz radio waves because of the hills at Abisko.

Note that such a radio map coverage for VHF signal would seem to be a must-have for any station manager as it could indicate the regions not covered by alarm radios.

While the radio link characteristics focus on how far a radio signal can be transmitted, it says nothing about the nature of this signal or more importantly about how laptop and data logger actually communicate. The nature of the communication between two devices is determined by a protocol.

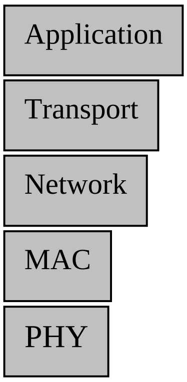


Figure 3: Protocol Stack

In fact, there are many protocols that collaborate to organize communication between devices. Those protocols are layered to minimize complexity. They form a protocol stack. Without getting into details (see the web site for reference) there are three relevant levels of protocols:

- PHY/MAC: These layers are responsible for coordinating the transmission of packets through a radio link. For short range wireless communication, two standard protocols are dominating the field: (i) 802.11 which is the basis for WiFi, it is a standard feature of any laptop and smartphone nowadays, and (ii) 802.15.4 which is the basis for low power lossy networks, which is embedded on a lot of devices today (at the notable exceptions of laptops and smart phones). Note that there are many more standard and proprietary protocols in this class, e.g., Bluetooth that is used for cable replacement (Bluetooth is energy hungry and thus not adapted to sensor networking) or the proprietary spread-spectrum protocol used in the radio modules from Campbell scientific (spread-spectrum protocols – such as Bluetooth – tend to be very secure at the cost of low energy efficiency, so it is intriguing that Campbell Scientific settled for such a protocol).

- Network/Transport: These layers are responsible for packet forwarding through a network of radio links. The most popular standard is TCP/IP which is the basis of the Internet. IP has been adapted for both 802.11 and 802.15.4 so that today, any device can be configured as an IP device. There are of course alternatives with other standards as well as proprietary solutions, e.g., the Pakbus protocol from Campbell Scientific.
- Application: This layer is responsible for the communication of the data accessible to end users. For example, the World Wide Web is based on the http protocol (implemented on top of TCP/IP and 802.11 if you are connecting to the Web wirelessly – Ethernet would be used as PHY/MAC if your laptop has a wired connection to the Internet). There is a multitude of application level protocols both standardized and application specific. For instance, the loggernet program from Campbell scientific has a proprietary application protocol.

While we have covered the key characteristics of the radio modules that can be plugged in a data logger to make it remotely accessible via a wireless connection, and before we extend our discussion beyond cable replacement into actual network configurations, let us review the open issues that remain concerning radio modules for data loggers:

1. How to achieve wirelessly the full performance of a serial line? Today, many radio solutions for data loggers enforce artificial limitations on the baud rate of the data logger (i.e., the number of bits per second actually transferred through the serial interface) to make sure that the radio module can keep up with the rate at which bits should be sent on the radio link. Even then, data loss on the radio link is unacceptably high in many cases. Defining a radio module architecture (both in terms of hardware and software) that guarantees full performance when connected to a serial interface is an open issue.
2. How to provide simple watchdog mechanisms to ensure graceful transitions to degraded modes of operations. Today, if a data logger is made remotely accessible and if the radio module has problems, then this data logger might end up in an instable state, worse collected data might be loss because of a misconfiguration of the data logger. Defining simple mechanisms, based on watchdogs (i.e., programs that start in well defined conditions to check that the system is working as it should and take action if it does not) so that scientists can define degraded modes of operations is an open issue.
3. How go guarantee the level of security that is required by the scientists. The issue here is to enforce given policies in terms of access control (who can access the

sensor data?), and usage control (how can sensor data be used? How to keep track of how sensor data is actually used?).

It is interesting to note that none of the characteristics of a radio module described above have any specific characteristic which is relevant for a deployment in the Arctic. Only the low temperatures impact the operating ranges for the components of a radio module, and the tough outdoor conditions require rugged components.

2.2.Network Topologies

In the previous section, we have discussed the characteristics of radio modules that allow to make a data logger available wirelessly. In this section, we discuss how several co-located data loggers can be arranged into a network (i.e., a collection of data loggers interconnected via wireless links).

We distinguish relevant network topologies based on the **number of hops (a hop is a wireless link) that exist in the network between each data logger and the gateway to a communication infrastructure** (the Internet or a private telecommunication network) and summarize the pros and cons of each topology in Table 1 below:

- **0-hop**: Each data logger is directly part of a communication infrastructure (and thus directly accessible remotely). In such topologies the data logger is itself a gateway equipped with a long-range communication radio (e.g., GPRS, 3G or 4G) or a satellite radio (e.g., Iridium or Telesat). See Section 3 for a discussion of satellite communication in the Arctic. Usually being part of the communication infrastructure is quite expensive as it requires some form of connection fee in addition to the fee related to actual data transport. Such a solution is interesting for single data loggers deployed in remote regions, but becomes expensive as several data loggers are co-located as communications cannot be multiplexed across devices and as a result cost cannot be shared across devices.
- **1-hop**: Each data logger is directly connected to a gateway computer that is part of the communication infrastructure (e.g., a gateway that centralizes all connections to the satellite or GPRS). The connection between data loggers and gateway computer is implemented via a radio link (discussed in Section 2.1). The placement of the gateway computer and the types of radio links that it accepts thus restrict the placement of those data loggers that can directly communicate with it. Typically, a radio module will have access to limited power resources and as a result, its range will be limited to tens or hundreds of meters. Also, the protocols that are used might require tight timing constraints which also restrict the communication range.
- **Multi-hop**: Each data logger is connected to one gateway either directly in one hop, or indirectly, via so-called routers, in several hops. Different types of radio links might be used between a data logger and the gateway. Possibly, a radio link is not always available and some form of opportunistic communication is used to leverage transient links. Possibly, different protocols are used on differnet links and a strategy is required to route data through the multihop network between a data logger and the gateway, or possibly across data loggers (e.g., so that data from a data logger can be used as indication of interesting event in another). Multihop networking introduces a non negligible level of complexity in terms of setup and health management (making sure that the network keeps on operating as it should).

	Pros	Cons
0-hop	- **Simple** (the data logger is directly connected to the communication infrastructure)	- **Expensive** (if several data loggers are co-located, each data logger communicates with an independent link (e.g., satellite or 4G))
1-hop	- **Multiplexing** (several co-located data loggers can share a single long range link (e.g., satellite)	- **Some complexity** due to a mix of short-range and long-range networks - **Limited spatial range** (the location of connected data loggers is restricted by the covering range of the gateway).
Multi-hop	- **Multiplexing with extended spatial range** (a data logger might reach a gateway through multiple links and intermediate routers – possibly other data loggers acting as routers).	- **Significant complexity** due to the setup and maintenance of a complex network. - **Risk for interferences** if many data loggers are interconnected to a single gateway.

Table 1: Comparison of data logger networking topologies

3. Long-Range Communications

When we discussed topologies above, we introduced the notion of gateway that connects to a communication infrastructure. In urban environments, the communication infrastructure is pervasive, and many options are commercially available (e.g., Internet connections via fastnet, or fiber channel or mobile cellular data connection via a telecom operator).

It is unlikely that INTERACT field stations located in remote places will benefit from a vast range of options in terms of long-range communications. While a fixed, wired infrastructure is excluded in most cases, there remains two major possibilities:

1. Wireless Cellular Communication (GPRS[1], 3G[2], 4G[3]). In terms of mobile cellular communication, there is today a transition in Europe and in the US from 3G to 4G (i.e., 3rd to 4th generation cellular wireless standard). 4G is interesting as it focuses on providing a comprehensive and secure all-IP based mobile broadband solution to any mobile device, including the gateways deployed in those field stations covered by the 4G infrastructure. The roll-out of 4G infrastructure is just begun and it is soon to map out those INTERACT stations where it will be available.
2. Satellite communication (e.g., Iridium, Telesat). The main problem with satellite communications in the Arctic, is the limitations due to the nature of the

1 http://en.wikipedia.org/wiki/General_Packet_Radio_Service
2 http://en.wikipedia.org/wiki/3G
3 http://en.wikipedia.org/wiki/4G

geostationary satellites (GEO). The GEO satellites deployed for telecommunications do not cover high latitudes beyond 75°N. Most of the INTERACT field stations are located in the GEO-covered area in the Arctic (66°N – 75°N). That area is divided into three regions: Europe, North America and Russia. According to the Articom report[4], the total demand from regions located between 66°N – 75°N is forecasted to reach 3.7 Gbps (Giga bits per second) by 2020, up from 300 Mbps in 2010. In terms of sectors, the demand is forecasted to grow strongly in maritime, government and energy as well as aero. Research is only forecasted to grow slowly by 18 Mbps. This increase in demand should be met by improvements of the current infrastructure.

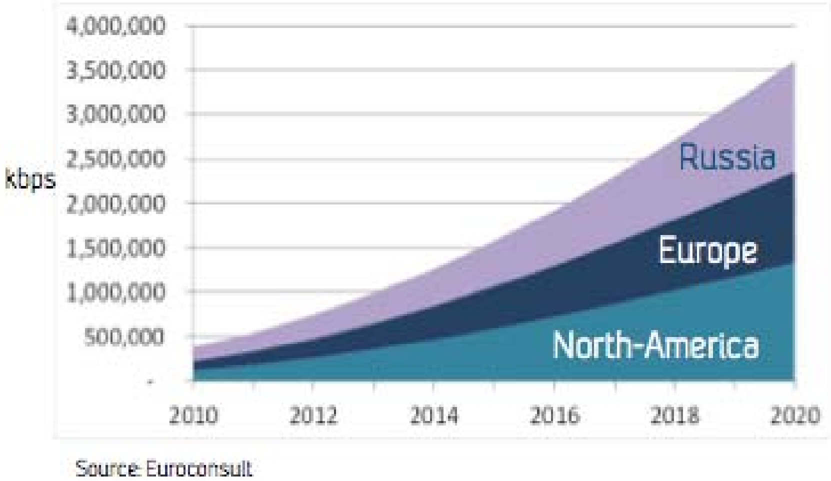


Figure 4: Demand overview in GEO reachable part of the Arctic (Articom report).

Two INTERACT field stations are located in non GEO reachable parts of the Arctic (Sverdrup and Ward Hunt Island). According to the Articom report, Iridium is planning to provide voice and low-rate data transfer beyond 75N in 2011, with an improved infrastructure, called Iridium NEXT, from 2015. As of now more bandwidth is planned to be available after 2017 both in North America (PCW) and in Russia (PolarStar). According to Articom, there is no system planned for high bandwidth transfer in the European non GEO part.

4. Station Manager Survey

We conducted an Internet-based survey of the station managers to define a snapshot of sensor networking as of today in the INTERACT field stations. We asked the following multiple choice questions:

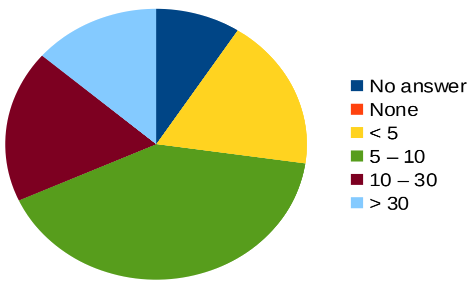
1. **How many data loggers or digital sensors (e.g., cameras) are deployed in the field at your site for monitoring purposes throughout the year?**
2. **How many data loggers or digital sensors (e.g., cameras) deployed in the field are accessible from the station via wireless network?**
3. **How many data loggers or digital sensors (e.g., cameras) deployed in the field are accessible remotely (e.g., via a Internet connection or a specialized satellite connection)?**
4. **What kind of wireless communication is supported at your site?**
5. **What are the options in terms of long range data services at your station?**

4 http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=30581

6. **Is WIFI (802.11) available at your site (put another way, is your site covered with wireless routers that make it possible to interconnect computers locally)?**
7. **Is Internet available at your site?**
8. **Were you contacted in the context of ESA's Articom study of "future communication needs in the Arctic" or are you looking into the opportunities of next generation satellite soluitions: e.g., Arktika MS, PCW or Iridium Next Gen?**
9. **Do you have staff with expertise on wireless communications or networking?**

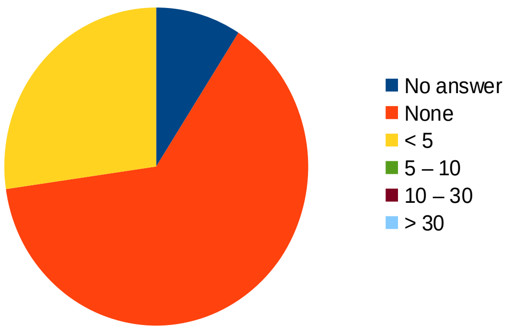
4.1.Results

Here are the results of this survey. There were 22 answers (out of 37 stations, i.e., 60 %) to the survey. The stations that answered are Samoylov, Karkonose, Cairngorm, Abisko, Radisson, Litla Skard, Nuuk, Kevo, Kilpisjarvi, Khibiny, Aktru, Finse, Spasskaya Pad, Chokurdakh, Fini, Zackenberg, Boniface River, Bylot Island, Clearwater Lake, Salluit, Umiujaq, Ward Hunt Island and Whapmagoostiu-Kuujjuarapik.



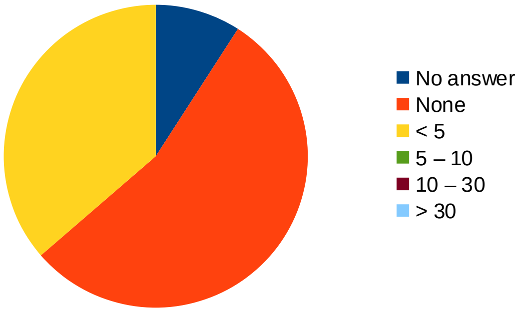
No answer	2
None	0
< 5	4
5 – 10	9
10 – 30	4
> 30	3

Figure 5: How many data loggers or digital sensors (e.g., cameras) are deployed in the field at your site for monitoring purposes throughout the year?



No answer	2
None	14
< 5	6
5 – 10	0
10 – 30	0
> 30	0

Figure 6: How many data loggers or digital sensors (e.g., cameras) deployed in the field are accessible from the station via a wireless network?



No answer	2
None	12
< 5	8
5 – 10	0
10 – 30	0
> 30	0

Figure 7: How many data loggers or digital sensors (e.g., cameras) deployed in the field are accessible remotely (e.g., via an Internet connection or a specialized satellite connection)?

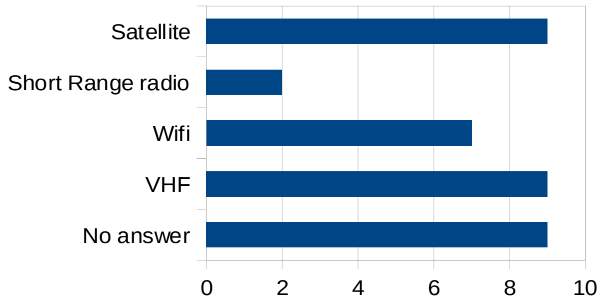


Figure 8: What kind of wireless communication is supported at your site?

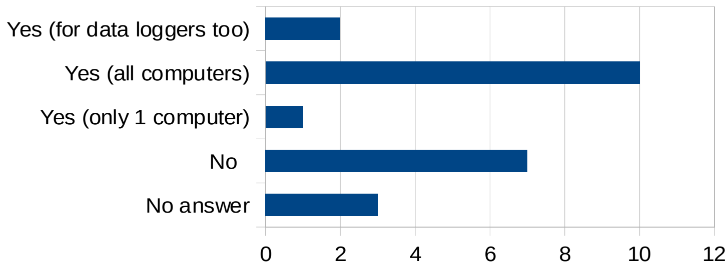


Figure 9: Is Internet available at your site?

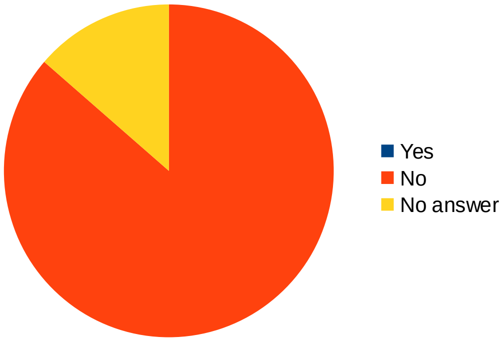


Figure 10: Were you contacted in the context of ESA's Articom study of "future communication needs in the Arctic" or are you looking into the opportunities of next generation satellite solutions: e.g., Arktika MS, PCW or Iridium Next?

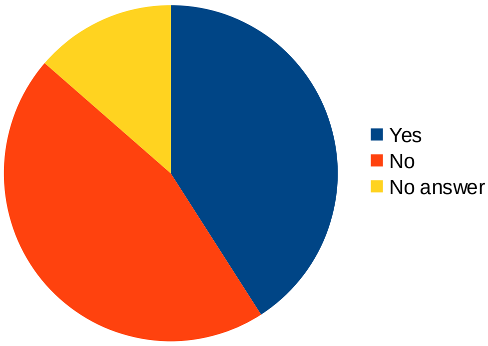


Figure 11: Do you have staff with expertise on wireless networking

4.2.Discussion

A small portion of all data loggers (incl. Digital sensors such as cameras) deployed in the field stations is currently available remotely from the station or online via the Internet (interestingly those two numbers are different – it is typically the case when a data logger is connected via a 0-hop infrastructure – either satellite or GPRS, while the station itself is not on the Internet).

Only two stations have deployed low power short range communication networks (such as 802.15.4 or Pakbus) while a third of the stations have some form of Wifi in place. Interestingly, satellite connections are more widespread than Wifi. In this respect, it is interesting to note that none of the field stations that answered the survey has been involved in the preparation of the next generation satellite infrastructure for the Arctic. This is definitely a problem, and we have established contact with the Articom community to get the INTERACT community involved in the next phases of the next generation satellites preparations.

While half of the stations have Internet available for scientists on site, only two stations have extended Internet coverage for data loggers. There is a long way to go towards the vision of virtual instruments. Interestingly, half of the sites report that they have staff with expertise on wireless networking. So there is a strong basis for adoption of appropriate technologies for virtual instrumentation.

5. Conclusion

In this report, we surveyed the issues related to sensor networking in the Arctic. We established that the core problem is to transform the data loggers that constitute the core of in-situ observations and monitoring from stand-alone, isolated systems to networked systems for online measurements and controls. We listed the issues related to short range and long range communications, and we surveyed existing solutions and the issues that remain to be solved. Finally, we gave a snapshot of sensor networking in the INTERACT field stations.