Network Strategies for Remote Weather Stations

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1. Summary

There exist three situations where network communications are necessary:

1. **Data Transmission**: Sending meteorological observations from weather station nodes to a central server.
2. **Data Processing**: Once the data has been stored in the central server, it is to be:
   (a) Subject to analysis by TAHMO and partners;
   (b) made publicly available to interested parties over the Internet, e.g. universities.
3. **Local Services:** It is desirable to provide services to people living in the regions monitored by TAHMO. For example, an SMS alert system for forecast adverse weather conditions for local farmers.

Of the three, *Data Transmission* is expected to be the most difficult to provide network connectivity to. This is closely followed by *Local Services*. *Data Processing*, although it is likely to be technically challenging in other areas, should be relatively straightforward from a networking perspective.

The majority of this document focuses on *Data Transmission.* At the time of writing, there are no concrete plans to provide *Local Service*, so it has not been possible to provide an analysis of this aspect. However, it is likely that some of this content intended for *Data* Transmission will also be applicable to *Local* Services. Additionally, a few sections of 3. Standards were written with an eye to the data distribution component of *Data Processing*.

There are two main sections in the document:

- 2. Communication Methods - Technologies for the physical and data-link layer. For example: cellular networks or satellite data.
- 3. Standards - Protocols which can be used for the application layer. How to make the best of unreliable and low-bandwidth links? Examples: MQTT, O&S by OGC.

In addition, there are several supplementary sections.

1.1. Communication Methods

I investigated the following technologies:

- Mobile data
- Wi-Fi
- Satellite data
- SMS
- Mesh networks

Mobile data is by far the best option for the majority of deployments. Where available, it provides relatively inexpensive connectivity with a bandwidth more than ample for our purposes, with tolerable reliability. Techniques allowing for the use of mobile data in areas with very low signal strength are discussed.

SMS may function when mobile coverage is too weak for mobile data. It is also likely to be more widely supported, with mobile data still an exotic product in many regions of Africa. Because of this it is a useful backup, although has far more limited capabilities. It would be fairly easy to write software which defaulted to mobile data, falling back to SMS if mobile data was unavailable.

Where an existing Wi-Fi connection exists, this is one of the cheapest options and potentially most reliable options available to us. However, there are a number of caveats mentioned.

To achieve complete coverage of the African continent requires a more adventurous use of technology. There are no up-to-date and comprehensive figures for mobile coverage of Africa, but it is clear there exist large regions without coverage. Two alternatives are considered for these areas: satellite data and mesh networking.

Satellite data, from a purely technological perspective, is by far the most reliable and easy to implement option. Two networks considered, Iridium and inmarsat, achieve 100% coverage in Africa with a third option considered, Orbcomm, having coverage except in a few small regions. Integration with the weather station would be straightforward, with many well-tested modems available for purchase. Even better, they are able to transmit with a small antenna which could be built in to the device, and so would not require unwieldy satellite dishes.

Unfortunately, satellite data suffers from a serious – and possibly insurmountable issue – and that is cost. I've conducted a detailed cost analysis for the Iridium network. The pricing schedule of the other networks are not publicly available, so I was unable to repeat this analysis, however the costs are likely to be comparable.

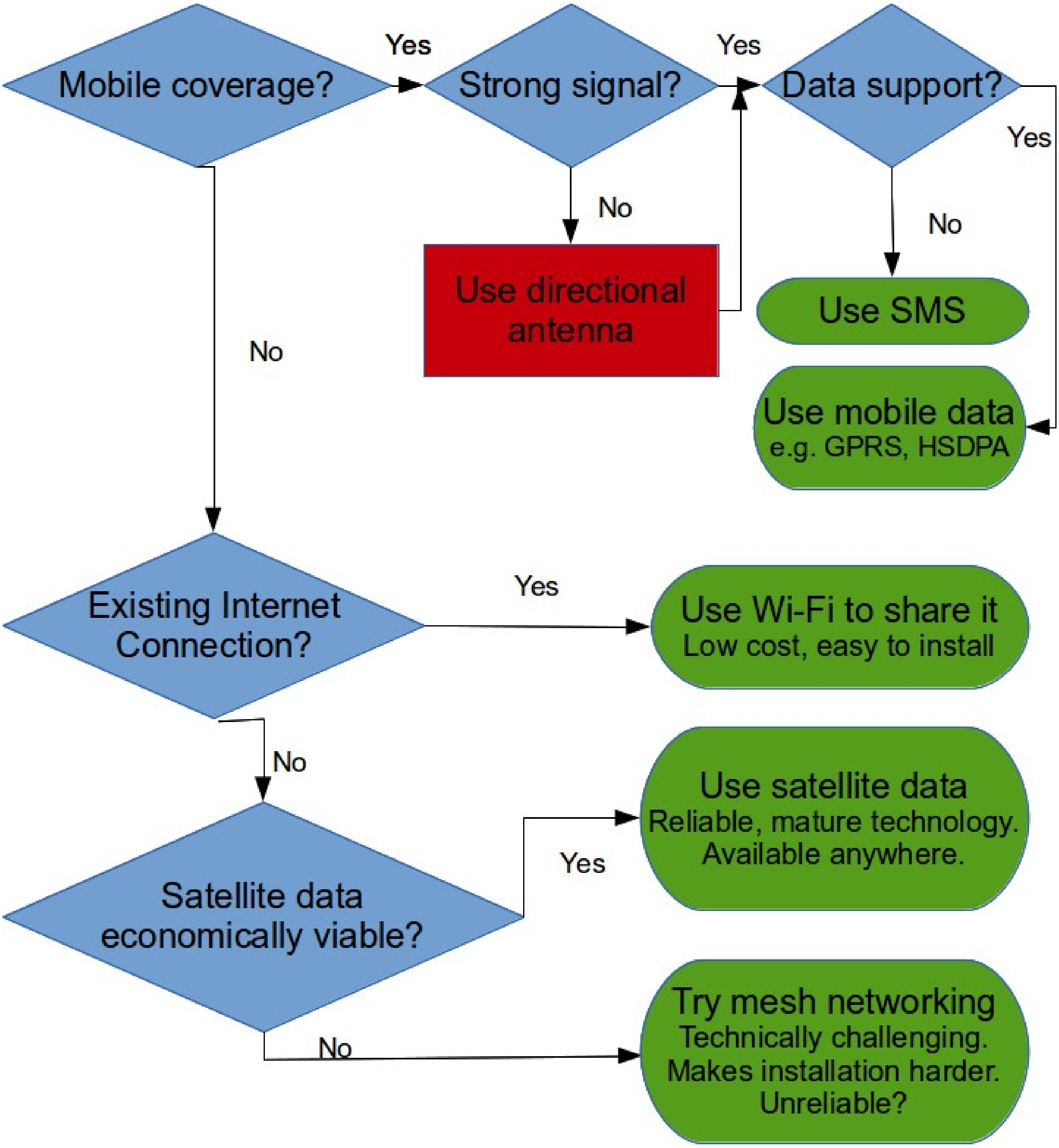
I am not without hope that it would be possible to negotiate an affordable price with the satellite operators for TAHMO. By transmitting just at off-peak times, I believe our usage would have a negligible cost. Since their participation would give them positive publicity, I therefore believe it may be possible to convince one of the satellite operators to give us data at a concessionary rate. However, needless to say, this is by no means something we can rely on.

Without satellite data, our options become substantially more limited. We must build our own communications infrastructure to bridge the gap. 'Mesh networks' are a flexible topology, and have been used with success in similar applications. However, in this case there are a number of serious technical challenges due to very the long distances between nodes.

A handful of technologies do exist which may be able to operate over the distances, and these are discussed. Building any large mesh network would be a serious and highly ambitious undertaking, but it might be practical – especially with future advances in relevant technologies – if used to extend mobile coverage a small distance beyond its current reach.

1.1.1. Decision Tree

The considerations above are summarised in the decision tree below:



1.2. Standards

I considered the following protocols:

- Assorted standards developed by the OGC
- MQTT
- WESTEP
- CSV

The OGC standards are suitable for distributing meteorological data as part of the *Data Processing* use case. CSV could be used as an alternative for data export due to its simplicity and wide usage.

MQTT is promising for use as an application-layer protocol for *Data Transmission*.

WESTEP is not applicable for our purposes, but is a useful example.

My impression was that, overall, there are only a limited number of standards which we can make use of. For the most part, either relevant standards do not exist, or are not suitable due to the resource constraints that we must operate in.

2. Communication Methods

A radio communications method is needed to transmit data from the nodes to a central server. Requirements are:

- Bandwidth: Minimal (see 4. Bandwidth Estimates.) Almost any technology used should be adequate.
- Coverage: Should work in remote locations in Africa.
- Reliability: Short-term outages (of a few hours) will not cause any deterioration in service, as transmissions can be retried. Medium-term outages (of a few days) would be damaging, but could be tolerated occasionally. Longer outages should be avoided.
- Power: Overall power consumption needs to be minimised. Due to the low bandwidth requirements, it is anticipated transmissions can occur in irregular and short 'bursts'. These would typically occur no more than a few times a day. Because of this, the maximum transmission power is less important than the ability for the transmission device to be put into a power saving mode when not in use.
- Cost: Both fixed and variable costs should be minimised.

I have attempted to evaluate each of these points for the communication methods considered. In addition, I have included a section on hardware devices which could be used to implement the relevant communication method. This section is intended to give representative examples of the hardware devices on offer. Further research is necessary before choosing the best hardware device for a final implementation.

2.1. Mobile Data

2.1.1. Bandwidth

More than sufficient for our purposes. GPRS has a minimum speed of 8 kbit/s, achieving a higher speed in areas with good mobile coverage. 3G and later technologies can achieve much higher transfer rates.

2.1.2. Coverage

2.1.2.1. Data Sources

1. The mobile operators industry association, GSMA, has made public the results of a worldwide survey (Mobile for Development Intelligence, 2009) of mobile coverage. Details are not provided as to the methodology of the survey, but are likely based on telephone operators own coverage estimates, which may be exaggerated. The survey was conducted between 2007 and 2009, so coverage is likely to have improved since then. It might be hoped these two factors may serve to cancel each other out, however the validity of the data – especially in the case of a particular country – must be treated as suspect.
2. GSMA also offers coverage maps (Mobile for Development Intelligence, 2013) for each carrier in individual countries. These are likely to be more up to date, although no information is provided as to when each map was updated.
3. A third-party organisation Cellumap (Cellumap, 2013) performs signal strength monitoring, based on voluntary contributions. They appear to have negligible data on Africa at the present time, however.

2.1.2.2. Analysis

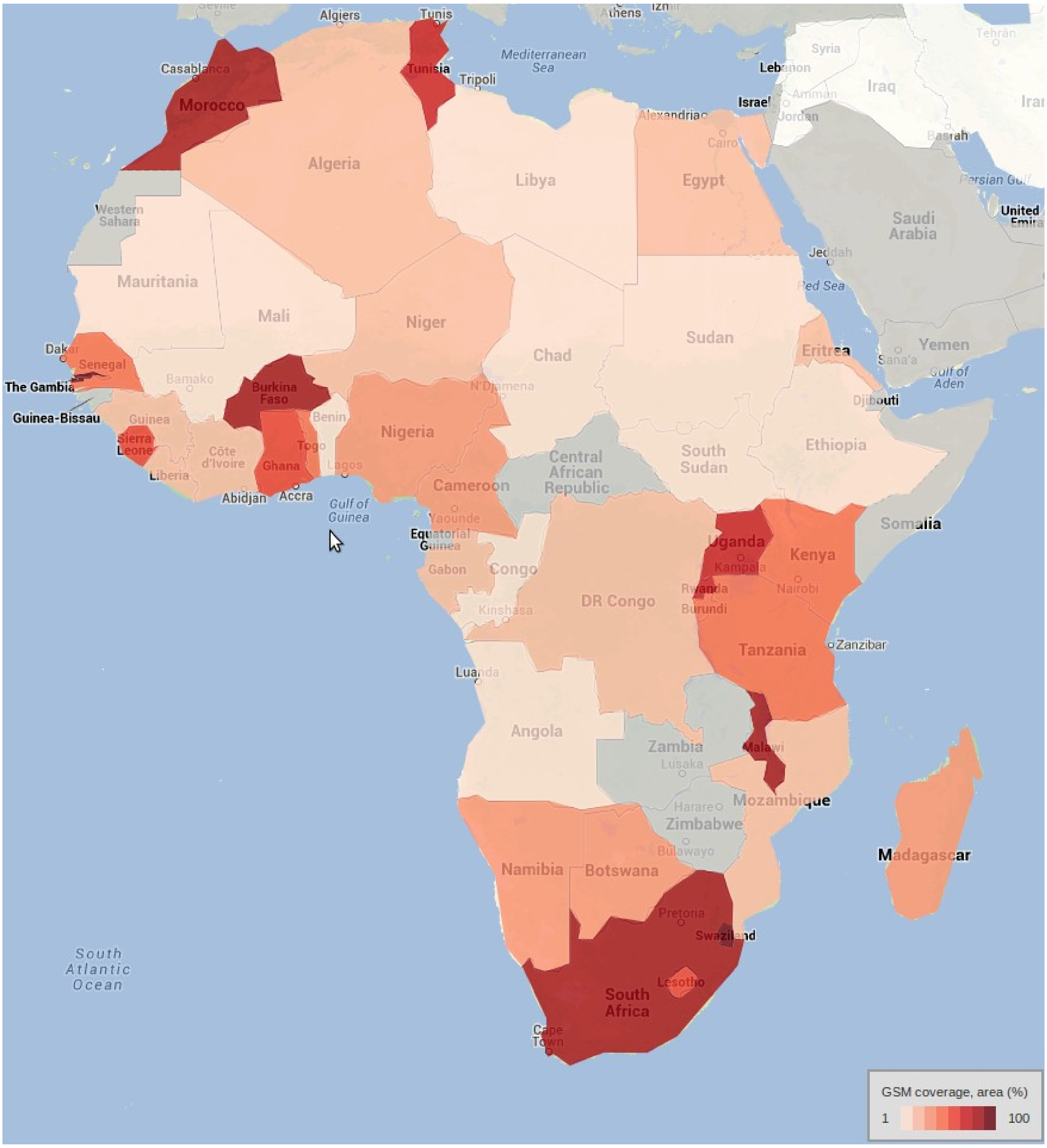


Illustration : © www.mobiledevelopmentintelligence.com [Coverage by Area, 2007-2009]

Despite my misgivings regarding the first GSMA survey, it remains the most comprehensive data source. The survey shows geographical coverage varying widely between countries. The country with the worst coverage was Angola, with just 1%. At the other extreme, Gambia achieved 100% -- unsurprising as it is the smallest African nation, and very densely populated.

Even ignoring these extremes, it is easy to see that there are many countries with poor (less than 20%) mobile coverage, as well as many with excellent coverage (greater than 70% in several cases.) This suggests that mobile data is a viable option in many, quite possibly the majority, of deployments. However, some large areas of Africa are likely to have inadequate mobile coverage. Alternative communication modalities should therefore be explored to achieve a complete monitoring network.

2.1.2.3. Workarounds

It may be possible to extend mobile coverage beyond that suggested by maps such as the above, which are based on reception by a mobile phone.

One of the most promising techniques would be using a directional – most likely a Yagi – antenna. A gain of 12 dBi is typical on these antennas, meaning that the signal strength is sixteen times stronger than an antenna which receives uniformly in all directions, which is closer to a typical antenna used in mobile phones.

In principle, this means such a suitably equipped weather station could communicate with a base station four times further away than a standard mobile phone. Things are more complicated in practice, however, with a variety of other factors affecting radio reception. If a certain area lacks radio coverage because there is a mountain in between it and the base station, then upgrading to a better antenna is unlikely to improve matters. Never the less, using specialised antennas could drastically improve coverage in many cases.

There are a number of downsides associated with the use of directional antennas, however. For one, antenna positioning becomes crucially important. An incorrectly installed directional antenna can have far worse performance than a standard antenna. Since the antennas are larger, they are also more likely to be damaged by storms.

Furthermore, the use of a directional antenna typically limits the weather station to just one base station. If the base station becomes unavailable for any reason, it will not be possible for the weather station to migrate to another base station in range without repositioning the antenna.

Finally, directional antennas significantly complicate installation, and increase costs. Although directional antennas are relatively inexpensive, they generally require mounting, either on an existing structure or on a purpose-built antenna tower.

Despite these drawbacks, I'd strongly recommend considering the use of directional antennas for areas just outside conventional mobile coverage. It is likely to be far cheaper than alternatives, such as satellite data. However, if a weather station is situated in an area with good mobile coverage, there is no need for a directional antenna and it may even be harmful.

Another option for extending mobile coverage is discussed in 2.5. Mesh Networks.

2.1.3. Reliability

Mobile data should be as reliable as the mobile network used. Since transmissions are only short range, atmospheric conditions should not interfere with communication.

If the weather station is situated in an area with good coverage by multiple base stations, there is even automatic fail-over if there is an outage at one base station.

However, some mobile networks may be unreliable. In particular, I would expect mobile data to be rarely used in many regions of Africa, so network carriers support for this may be far from ideal. Another potential issue is changes in mobile coverage over time. A carrier moving a base station, or a building being constructed in between the base station and weather station, could be enough to prevent a connection if the coverage was already marginal.

In general, however, I would expect mobile data to be reliable, provided an evaluation of mobile coverage is carried out before installing at any site.

2.1.4. Power

The transmit power of mobile data modules is generally fairly low, due to the short-range nature of the communication.

However, modules tend to draw too much power during idling. Therefore, it is necessary to put them into sleep mode or turn them off when not in use.

See information on individual hardware devices below for more detailed figures.

2.1.5. Cost

Costs for several mobile data modules is below.

Tariffs for mobile data tend to be relatively inexpensive.

2.1.6. Hardware Devices

2.1.6.1. USB Dongle: Huawei E353

Price: approx. 25 Euros

The Huawei E353 is a good example of a mobile data dongle. It is inexpensive and has good support under the Linux operating system. Support for an external antenna is provided via a TS-9 connector.

Power consumption is a significant disadvantage with USB dongles. In my tests, I found that during heavy transmission the dongle consumed around 1.5 W. When connected to the network but not actively transmitting or receiving it consumed 0.3 W, with occasional spikes to around 0.9 W.[1] There is no option for a sleep mode. I would expect these results to be similar for other USB dongles.

The chipsets on some computers support suspending selected USB devices. This capability is missing in many computers, however. Even where it is provided, support for this is unreliable in software, with manual control having been removed from recent Linux kernels.

The Raspberry Pi's USB chipset is supposed to have the capability of suspending the entire USB bus, however in testing this feature (a) did not work reliably and (b) I did not observe any drop in power usage as a result of this.

Summary: A good option for prototyping due to its low cost and ease of integration. Probably only suitable for use in a production design if the entire computer was powered off except when collecting and transmitting data (which need only take place for a few minutes every day.)

2.1.6.2. GPRS Module: SIM900

Price: around 63 Euros

The SIM900 is a widely used GPRS module. An Arduino shield incorporating it is sold for 63 Euros (Cooking Hacks, 2013), and it is likely that the SIM900 could be incorporated into any other device for a similar price.

Integration is significantly more complicated with this, and any other module, than is the case for USB dongles. However, this inconvenience is a one-off cost.

During transmission, the SIM900 has an average power usage of 1.78 W[2]. In sleep mode, when the device is still connected to the network but not currently receiving or transmitting, this drops to 6 mW[3]. When completely powered off, it is just 120 μA[4]. (SIM900, 2010, p. 50)

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1 Measured using an ammeter connected inline with a USB extension cable, assuming a voltage of 5.0 V.

2 Based on a typical voltage of 4.0 V and average current of 444 mA (DATA mode, GPRS 3 Rx, 2Tx EGSM 900)

3 In SLEEP mode (BS-PA-MFRMS=2) 1.5 mA current

4 In POWER DOWN mode, 30 μA current

2.2. *Wi-Fi*

Wi-Fi is the name commonly used to refer to any collection of the IEEE 802.11 radio communication standards. The technology is widely (and cheaply) implemented and intended for short-range personal networked communications.

I can envisage two scenarios where Wi-Fi could be used:

- When the weather station is located in close proximity to a building that has Internet connectivity. Wi-Fi would be a simple way of sharing the buildings Internet connectivity.
- For long-range links as part of a mesh network.

Based on the characteristics of Wi-Fi described below, I would evaluate Wi-Fi as being well suited to the first application. Although Wi-Fi can be used to produce long-range links, since Wi-Fi is able to provide significantly more bandwidth than we need, other protocols are likely to be able to provide better performance.

2.2.1. Bandwidth

The bandwidth offered by any Wi-Fi standard is more than sufficient for this application. The slowest standard, 802.11b, has a minimum transfer rate of 1 Mbit/s – still several orders of magnitude higher than we need. Much higher transfer rates are possible with more recent standards (up to 150 Mbit/s.)

In practice, the bottleneck will most often be the speed of the Internet connection being shared, not Wi-Fi.

2.2.2. Coverage

Wi-Fi has only been designed for short-range communications. The range achievable depends on a variety of factors, including the number and types of obstructions; the quality of the access point and transceiver on the client; antennas used and transmission power. A range of around 100 m outdoors is a typical figure. (Mitchell, n.d.)

However, much higher distances are possible with the use of directional antennas and carefully chosen equipment. The current record is a link of 279 km by a team in Venezuela (Flickenger et al., n.d.). Such a distance is only possible with careful radio engineering and a favourable local environment, but links of several km's are not unusual.

2.2.3. Reliability

Most 802.11 protocols operate in the 2.4 GHz unlicensed band, so may experience interference by devices such as microwaves and Bluetooth transceivers which use the same spectrum.

Long-range Wi-Fi links may be affected by atmospheric conditions, and by construction work which produces an obstruction over the path used by the link.

When Wi-Fi is being used to share an existing Internet connection, it of course is only as reliable as that Internet connection. It might therefore be necessary to have a backup connection option, such as mobile data, which may reduce some of the cost benefits of Wi-Fi.

2.2.4. Power

Most Wi-Fi devices are built for standard consumer devices and so are, unfortunately, not built with minimising power consumption.

To the best of my knowledge, no low-power Wi-Fi access point exists. However, since the access point will in any case need a fixed Internet connection, providing mains power is unlikely to be an issue.

Some low-power Wi-Fi transceivers have been developed, for example see Roving Networks RN171.

2.2.5. Cost

The primary advantage of Wi-Fi is that it is low cost. Wi-Fi equipment is very inexpensive and widely available, and if used to share an existing Internet connection there should be no variable communication costs.

2.2.6. Hardware Devices

There exist a wide variety of devices supporting Wi-Fi. I've selected several examples for illustrative purposes. *Note any ranges given are very much estimates, and will depend on a variety of local factors.*

2.2.6.1. NetGear Wireless-N 150 Access Point

Price: £31 GBP (36 EUR)

Typical low-cost consumer access point. Likely to only have a short range (although could be increased with installation of a suitable antenna) and cannot be installed outdoors.

By choosing the position of the access point carefully and using an appropriate antenna on the weather station, it would likely still be possible to achieve communication outdoors perhaps up to a hundred metres from the building.

2.2.6.2. TP-Link TL-WA7510N 5 GHz Outdoor Wireless Access Point

Price: £53 GBP (61 EUR)

An easy to install access point intended for medium-distance (several hundred metres to a few km) outdoor Wi-Fi installations.

2.2.6.3. TP-Link TL-WN722N Wireless USB Adapter

Price: £10 GBP (12 EUR)

An inexpensive wireless USB adapter, which I would expect to work with any Linux system.

Importantly, supports an external antenna, which could be used to boost the range substantially.

2.2.6.4. Roving Networks RN171

Price: £20 GBP (24 EUR)

A low-power Wi-Fi transceiver intended for M2M applications. During transmission, the average power consumption ranges from 400 mW to 800 mW. In sleep mode, the power consumption is just 13.2 uW.[5] (RovingNetworks, 2012)

2.3. SMS

Short Message Service (SMS) is one service offered by mobile telecom networks, and is commonly used to provide “text messages.” Note the same underlying technology (GSM) is used for this and mobile data. In this section, I will focus on ways in which they differ; please see 2.1. Mobile Data for a more general discussion of GSM.

At first glance, SMS appears to offer all the disadvantages of using mobile data, without anywhere near as many advantages. However, the situation is not quite as bleak as this suggests. SMS

5 Assuming 3.3 V DC input, lowest average transmit power is 120 mA for 802.11b at 0 dBm and highest is 240 mA for 802.11 g at 12 dBm. Sleep mode current consumption is 4 uA.

messages are often able to be transmitted in areas with poor radio reception, where GPRS will fail.

Furthermore, SMS is very much a “bread and butter” service offered by telecoms, widely used by millions of people. It can be expected to work reliably anywhere mobile service is offered. By contrast, GPRS – although, with the advent of smart phones, is now widely used in most developed countries – is far more exotic, and may not be supported in some markets.

The main disadvantage of SMS is that it offers substantially less bandwidth than GPRS. However, it is more than sufficient for transmitting standard meteorological observations, which could be expected to take around 222 bytes per day (see 4. Bandwidth Estimates.) Each SMS message can consist of up to 140 bytes[6], so two messages per day would suffice.

Although it is likely to depend on the pricing schemes of various carriers, SMS could be cheaper than GPRS when sending only minimal amounts of data such as these.

As SMS does not operate over the Internet, it would be necessary to produce a gateway between the mobile networks and the servers storing the sensor data. This would be a relatively simple project, but may make SMS undesirable for prototyping.

Note that the vast majority of GPRS modules (including the SIM900 reviewed in 2.1.6.2. GPRS Module: SIM900) also support sending SMS messages. It is also typically possible to send and receive SMSs using USB dongles, although this is not as well documented (I have not tested this on the Huawei E373.) In any case, it should be simple to switch between GPRS and SMS transfers, even after deployment.

Summary: A good backup option for areas with weak mobile coverage, or where mobile data has limited support by the carrier. Also worth considering where GPRS is available, when cheaper. Probably best to avoid during prototyping due to added complexity, but it is easy to add on later.

2.4. Satellite Data

2.4.1. Iridium/RockBlock

Iridium (Iridium, 2013) is one of the worlds largest satellite companies, and achieves an impressive 100% coverage of the Earth's surface. This makes it a highly attractive alternative to mobile data in areas with inadequate coverage.

Services are generally available only via an Iridium reseller. One such reseller has produced the RockBLOCK (Rock 7 Mobile, 2013a), a small modem which easily integrates into a piece of custom hardware.

2.4.1.1. Bandwidth

The Iridium satellite constellation can support a wide range of bandwidth requirements – at a cost. The most suitable service for our purposes is 'Short Burst Data' (SBD) intended for small, infrequent data transmissions.

In each packet, it is possible to transmit up to 270 bytes or receive up to 340 bytes. With a good view of the sky, a transmission rate of 6 packets per minute is possible, giving a data rate of 27 bytes/s[7] (Rock 7 Mobile, 2013b, p. 7).

Although this is extremely slow compared to mobile data, it should be sufficient for our purposes. A more serious issue is the cost of data transmission, which imposes a still greater restriction on the realistic bandwidth we can consume.

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6 The figure of 160 characters is frequently quoted, however this is based on the *7-bit* GSM alphabet.

7 Deduced from the statement that the RockBlock takes “10 seconds to return to full charge” in the event of a successful transmission

2.4.1.2. Coverage

Complete coverage of the entire Earth's surface. Because the Iridium satellites are constantly moving relative to the Earth's surface, the system is relatively robust against a partially obstructed view of the sky.

2.4.1.3. Reliability

Should be extremely reliable. The system has been in operation since 1999 with few issues.

I would not expect the failure of one satellite to cause any issues. Since the system is not fixed, any one satellite is only over a particular position on Earth for around 11 minutes. Therefore, a defunct satellite could only cause a temporary transmission failure. Furthermore, there exist several in-orbit spares.

Perhaps a more serious risk (present in the use of any satellite data system) is the reliance upon a single communications provider. Iridium filed for chapter 11 bankruptcy protection back in 1999 (ComputerWorld, 1999). It appears that the company is now very stable, and – given the high fixed costs of launching a satellite network – I would be very surprised if the network were to cease operating.

Taking the continued existence of Iridium for granted, there still remains a risk of future price rises. This is perhaps unlikely given the fierce competition Iridium faces in any markets, but cannot be completely ruled out. We should perhaps be cautious because of this. If we do design a system around Iridium, it may be desirable to fix the prices over a long time period.

2.4.1.4. Power

The RockBLOCK has excellent power consumption characteristics, being designed specifically for applications such as ours.

The device has an internal charge store, used to power transmissions. When first turned on, the device can use up to 2.35 W[8], although it is possible to limit the current consumption (at the cost of a greater delay before the device can operate) if the battery would be unable to supply sufficient current.

When the device is idle (but still able to receive transmissions), the power consumption drops to 0.25 W. If the device does not need to be immediately used, it can be placed in a sleep mode, where it uses just 1 mW, but is still able to transmit immediately once awakened. Were it operated perpetually in this mode, it would consume just 0.024 Wh per day!

2.4.1.5. Cost

Fixed: The RockBLOCK modem is available for £159.00 GBP (184 EUR). This is at least three times as expensive as a mobile data module.

Variable:

Rock 7 Mobile (the creators of the RockBLOCK) charge £8 GBP (9 EUR) 'line rental' per month for each connected device.

Additionally, one 'credit' is spent for each 50 bytes sent or received. At the volumes of data we are likely to send and receive across all devices in the network, we would be able to benefit from their cheapest tariff, and would pay £0.04 GBP (0.05 EUR) per credit.

Feasibility Analysis:

The cost of the line rental unfortunately makes the option unviable for our purposes. However, from a technical standpoint, I do not believe Iridium incurs any cost simply from having a device

8 Assuming 5.0 V voltage. Based on 470 mA initial current draw, 50 mA when idle and 200 uA in sleep mode.

configured to use their network (but not transmitting.) I think that when the pricing plan was being designed, no one envisaged an application such as ours, of a very large number of connected devices each having minimal data requirements.

Because of this, I think it may well be possible to negotiate for the line rental to be waived in our case. I should note that I have found Rock 7 Mobile to be extremely helpful, although I believe that it is Iridium that determines many aspects of their pricing policy.

Assuming we were able to negotiate for the line rental to be waived, the remaining figures become much more reasonable. I will consider a system where just the standard meteorological observations are recorded, as specified in 4. Bandwidth Estimates. Furthermore, I will suppose we transmit exactly in 50 byte data chunks (this would mean transmitting around four times a day, giving a reasonable update frequency.) In this case, the cost would be £64.82/year.

This, coupled with the high fixed costs, makes this many times more expensive than mobile data. I would imagine at this cost, it would not be possible to produce a closed business case. Further discounts negotiated with Iridium might make it economically viable. By transmitting only at 'off-peak' times, I believe our system could be designed to not add appreciably to the load of the Iridium network.

Summary: I feel that satellite data is likely to be one of the simplest – and indeed possibly the only – option available to us to achieve the desired coverage. Therefore, I think this option needs to be explored further at some point, once the 'low hanging fruit' of regions with good mobile coverage has been exhausted. However, the Iridium network will only be economically feasible if we can negotiate substantial discounts, which is likely to be challenging.

2.4.2. Inmarsat/Skywave

Inmarsat are one of Iridium's largest competitors, and offer a variety of satellite communication products. I will consider only their IsatM2M product, which is best suited to our application.

Skywave is the partner of Inmarsat for this product, and develop the DMR-800D terminal. The product has, unfortunately, been designed with tracking applications in mind (and so includes an integrated GPS module), but could still be used for our purposes.

2.4.2.1. Bandwidth

10.5 bytes/s transmission and 100 bytes/s reception speed. This is more than sufficient for transmitting standard meteorological observations (see Bandwidth Estimates.)

2.4.2.2. Coverage

Inmarsat has complete coverage of the Earth's surface excluding extreme polar regions. In particular, coverage should be excellent in Africa. (inmarsat, 2010)

2.4.2.3. Reliability

Since the inmarsat satellites are in geosynchronous, an obstructed view of the sky is more likely to cause problems than would be the case with the Iridium constellation.

There is just one satellite for each region inmarsat covers so, in the relatively unlikely event of satellite failure, there would be a complete loss of service.

2.4.2.4. Power

During transmission, power consumption reaches the rather high 10.5 W. The device can be placed into a 'hibernate' mode, in which case it draws just 240 uW.

2.4.2.5. Cost

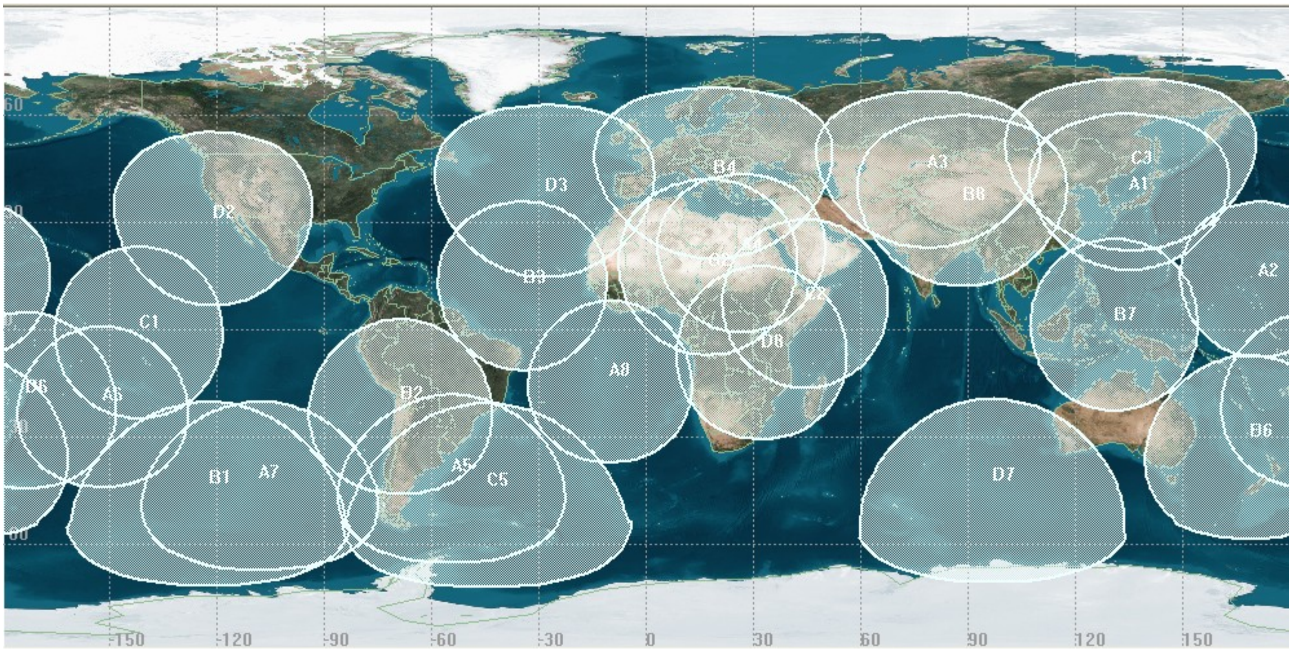
Unfortunately Inmarsat do not make their pricing scheme public. I have only been able to find prices quoted by one reseller which seem more expensive than Iridium (Remote Satellite Systems, n.d.). I have not found prices quoted for the DMR-800D terminal.

2.4.3. Orbcomm

Orbcomm are a smaller satellite provider, focusing on M2M communications.

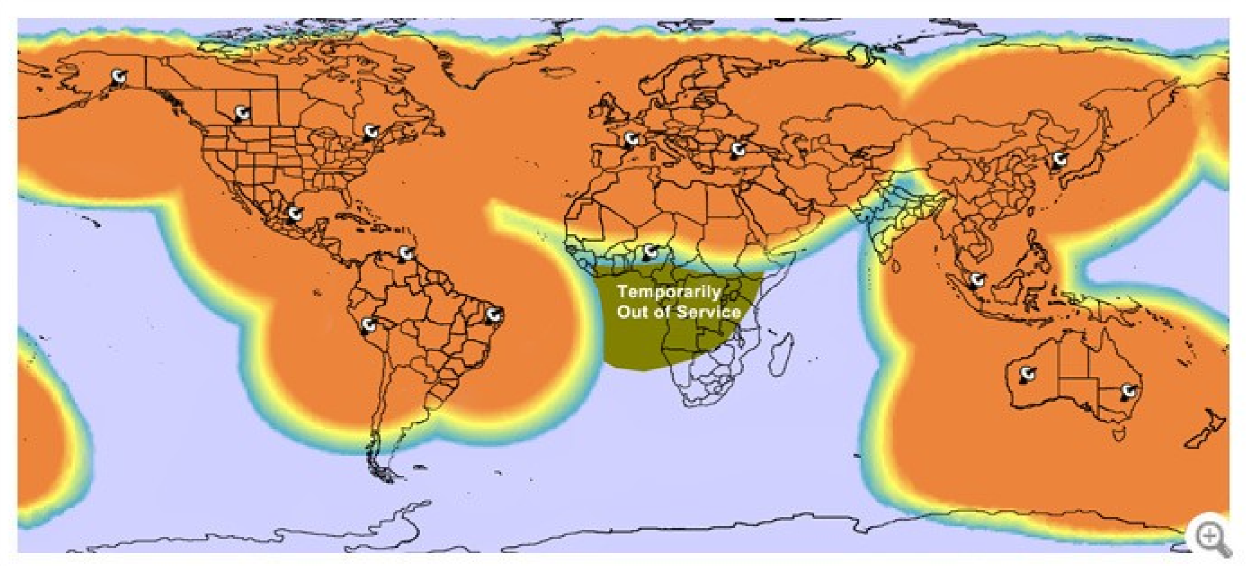
Unfortunately there is a complete lack of any public information about the products they offer. Based on the applications their services have been used for, I expect it would be suitable for us, but I cannot comment at all on the cost-effectiveness.

One of the few pieces of information they do make public is a coverage map, which indicates that – with a few exceptions – Africa is well covered by the network:



2.4.3.1. Globalstar

Globalstar is one of the few remaining mainstream satellite data providers. Unfortunately they only cover northern Africa:



Because of this lack of coverage, I feel they are not suitable for our application. Were we to consider their surface, then their Simplex data product appears to be the most suitable (Globalstar, n.d.).

2.5. Mesh Networks

In a mesh network, each node can potentially serve as a relay for other nodes. In an application such as ours, this can be used to back-haul data to a location where there is readily available Internet connectivity. The distance a mesh network can cover is potentially vast, with an adequate number of nodes.

There typically exist multiple routes between individual nodes, making an appropriately designed mesh network resilient against failure of a small number of nodes. Furthermore, in some networks it is possible to have multiple gateways to the Internet, meaning there is no single point of failure.

Since TAHMO is planning on deploying a dense network of weather stations, with a typical separation of 30 km, in some ways the network is naturally set up for mesh networking. However, it is difficult to achieve transmissions over distances as long as these.

Although a few devices (reviewed below) claim to be able to cover these or longer ranges, to achieve a successful set-up is likely to require the use of directional antennas, and careful installation, adding significant complexity to deployment.

Furthermore, since we will be operating at the very end of the ranges supported, it is likely that nodes will only be able to connect to their nearest neighbour. The reliability of the network is therefore suspect, as it may not always be possible to route around the failure of a node.

Another disadvantage is that, since each node must be able to act as a relay at any time, there is limited scope for putting a mesh network transceiver into a sleep mode, meaning the overall power consumption tends to be higher than with alternative technologies.

2.5.1. Waspmote/Zigbee

Price: 75 EUR

The Waspmote is an open and extremely flexible platform supporting (at present) 8 radio technologies. For our purposes, the most appropriate module is the XBee-868 (or possibly one of the other devices operating close to the 900 MHz band) which is claimed to have a range of 12 km with a 5dBi dipole antenna. (libelium, 2013, p. 3) This uses the ZigBee technology for mesh networking.

It might be possible to achieve a greater range using an antenna with a higher gain. However, this would come at the cost of:

- Greater directionality
- Increased installation complexity
- Higher cost

Furthermore, the ranges given tend to be for the 'best case' scenario, so it is dubious how often this range can be achieved in practice.

Using this technology, we would need at least one node acting purely as a relay for every weather station deployed in a mesh network environment.

It is possible that longer distance transceivers will be developed for the Waspmote. It would be possible for us to integrate a modem produced by another manufacturer into a Waspmote module were the platform to prove particularly desirable, however I cannot see any benefit to this at present.

2.5.2. Digi XTend

Price: 185 USD (141 EUR)

The XBee-868 is manufactured by Digi. This company also produces a range of transceivers intended for longer distances. These use a proprietary mesh network technology, DigiMesh, unlike the XBee-868 (where either configuration can be used by flashing the appropriate firmware.)

The longest distance transceiver is the Digi XTend, which claims a distance of 64 km (40 miles) using a high gain antenna. (Digi, 2011, p. 2)

An attractive feature of the XTend is that it supports a 'cyclic sleep' mode, where power consumption is just 4.4 mW when the transceiver is idle. However, it must still periodically (every 16 seconds) become active to check for transmissions from other nodes.

3. Standards

The Open Geospatial Consortium (OGC) has developed a number of XML standards (Open Geospatial Consortium, 2013) in this area. Those of particular relevance to TAHMO are:

- Observations and Measurements (O&M) (Open Geospatial Consortium, n.d.): Communication of individual sensor readings.
- Sensor Observation Service (Open Geospatial Consortium, n.d.): Automated retrieval from a data repository maintained by TAHMO for interested users.
- Sensor Model Language (SensorML) (Open Geospatial Consortium, n.d.): Describe the types of sensors used.

The Sensor Web Enablement Domain Working Group (DWG) (Open Geospatial Consortium, n.d.) is responsible for the development of these standards.

MQTT is a lightweight standard for transmission over unreliable and low-bandwidth networks by embedded devices such as sensors. Originally designed by IBM, it is supported by a wide variety of software.

The developers of wfrog, open-source software for weather stations popular amongst amateurs, have produced WESTEP (wfrog, 2011): a simple XML protocol for weather data.

Various websites exist collecting weather data produced by amateurs, however the protocols used are proprietary, and different for each website. These are therefore unsuitable for our purposes, and I have excluded them from this analysis.

Finally, CSV is one option for data export for data distribution as part of *Data Processing*.

3.1. OGC

The OGC standards have seen substantial adoption by a wide variety of users from academia and industry. There exist a number of open-source implementations of their standards (OGC Network, n.d.).

A complete description of OGC standards is not possible in this document, due to the large quantity of standards developed and the wide variety of use cases supported.

OGC standards would most likely be useful in the *Data Distribution* use case outlined above. A Sensor Observation Service could be provided to the public, enabling interested users to download the relevant data. This would consist of SensorML records, describing each weather station and its associated sensors, and O&M records for each measurement made.

OGC standards are obviously not suitable for the direct provision of *Local Services*, although it is conceivable that third parties who wish to provide services to locals (e.g. micro-insurance companies) could use TAHMO data via OGC.

It would be possible to use OGC standards as part of *Data Transmission*. However, I would recommend against this. The disadvantages include:

- A very verbose data format. The impact of this can be reduced by XML Compression (see 5. XML Compression), but it will still be much larger than a format specifically designed for the application.

- The standard is complicated due to its high degree of flexibility, making it more difficult or even impossible to implement in a low-resource, embedded environment.

Perhaps most importantly, I can see few advantages to using OGC at this level. In theory it would mean that the central server would not need to do as much processing of the data received from weather stations, but in practice it is unlikely to prove desirable to archive the data in an XML format anyway: instead, a database should be used.

Summary: The OGC standards are promising as (one of) the formats available for data export from the central server. They should not be used as part of *Data Transmission*.

3.2. MQTT

A very lightweight messaging protocol, designed specifically for machine to machine (M2M) applications. It's based around a publish/subscribe paradigm. Multiple clients connect to a broker and subscribe to topics they are interested in, and/or publish messages to topics.

MQTT offers a number of choices for Quality of Service. In particular, it can ensure that a message is delivered and/or ensure that a message is delivered **exactly once**.

The broker checks whether a client is connected by a system of 'Keep Alive' messages periodically sent to the client which must be responded to within a certain time. This in itself is a standard feature of many network protocols. Un keeping to the spirit of MQTT keepalives, however, the period can be set up to 18 hours. This saves bandwidth at the cost of a delay in recognising the disconnection of a client.

A novel feature is that a client can declare a 'will': a message that the broker publishes if the client disconnects abnormally. This would be a simple way of implementing an alert system if a weather station loses network connectivity or becomes damaged, for example.

MQTT is extremely well suited to being used for *Data Transmission* over the Internet. Advantages include:

- Lightweight, can run on small embedded systems
- Conserves bandwidth
- Reliable delivery despite interruptions to network connectivity
- Mature protocol, having been used for over 10 years
- A large number of software implementations (MQTT, 2013) to choose from, including several from IBM
- Many implementations support clustering to provide a high availability service

However, a key disadvantage which must not be overlooked is that MQTT is a real-time *messaging protocol*. It has no feature for permanent recording of the messages, which is obviously a requirement. This would be an easy problem to solve by developing a plugin for the broker, or a client that is permanently connected to the broker, which logs the messages to a database.

In light of the above advantages, it is worth also considering MQTT for *Data Distribution*. Although it would not be suitable as a solution on its own (since there is no feature to query historical data), it is suitable for users requiring a real-time data feed. It could be particularly useful for distributing data from the lightning detection feature.

A disadvantage of this is that there are no MQTT-based standards for distribution of meteorological data. Although it is fine to create our own standard for internal use that is best suited to the unique application, for distribution to the general public it is better to remain with established standards, such as those developed by OGC.

3.3. WESTEP

WESTEP (wfrog, 2011) is a lightweight XML protocol for representing sensor data collected from a weather station.

It has seen little adoption, so is not suitable for *Data Distribution*. For the same reason, there is probably no benefit in using it for *Data Transmission* rather than creating our own protocol. It may, however, be useful as an example of a simple protocol supporting most the features we require.

3.4. CSV

Comma Separated Values is a widely used format for exporting and importing data from a variety of applications, most notably spreadsheets. Due to its popularity and ease of implementation, it may be desirable to offer this as one of the export options from the central server for *Data Distribution*.

4. Bandwidth Estimates

This is intended solely as an approximation to the *minimum* bandwidth requirements. It purposefully does **not** include any overheads introduced by transport protocols. Furthermore, no attempt is made to estimate bandwidth requirements other than due to standard weather data: e.g. software updates.

Variable	**Range**	**Size**	**Number of bits**
Temperature (degrees Celsius, to 1 d.p.)	-20 to 60 degrees	800 possible values	10 [1024]
Pressure (mBar)	Pressure typically varies from 980 to 1050	70 values during typical weather	7/8 [128/256] Should be enough for weather extremes.
Humidity (percent)	0-100	100	7 [128]
Wind direction (degrees)	0-360	180 values to nearest even degree	8 [256]
Wind speed (mph)	0-60	60	6 [64]
Sunshine (# hours, to 1 d.p.)	0-24	240	8 [256]
Rainfall (mm, 1 d.p.)	Greatest record is 1825 mm in 24 hours	2048	11 [2048]
Timestamp (minutes since beginning of month)	44640 minutes in a month	65536	16 [65536]

Total number of bytes required for each reading: 9.25.

Hourly readings are standard, so a minimum of 222 bytes/day are needed.

5. XML Compression

As a human-readable format, XML is necessarily more verbose than binary alternatives readable only to a computer. Because of XML's structure, it is possible to achieve a significantly higher compression ratio using XML-specific tools than general compression algorithms such as ZIP.

These algorithms can be categorized into:

- Schema-dependent compressors: Both the encoder and decoder must have access to the document schema (a description of the structure of the document.)
- Schema-independent compressors: Schema information is not required.

Schema-dependent compressors can achieve a higher compression ratio. In our case, there is no difficulty involved in having the schema available at both sender and receiver, so these algorithms are preferred.

An additional distinct can be made between algorithms as to whether it is possible to query the compressed file, retrieving a specific subset of the original document. This is a feature which we might need, depending on the intended use case.

There exist a plethora of different XML compression algorithms, however it is desirable to choose one that is widely used, to ensure it continues to be developed. Two good candidates are:

- EXI (World Wide Web Consortium, 2012): A W3C Standard. There exist a number of open-source implementations, including EXIFicient (EXIficient, n.d.) and OpenEXI (OpenEXI, 2013). There is also a proprietary implementation by AgileDelta (AgileDelta, n.d.).

  A comparison between several implementations (IREDES, n.d.) showed AgileDelta achieved a slightly higher compression ratio.
- Fast Infoset (ITU, n.d.): An ITU and ISO standard, compressing XML to ASN1. The standard has been around for longer than EXI and so is more established. I would anticipate a decline in popularity now that EXI has been released, but at present there is wider software support.

  There is a Java implementation of Fast Infoset (Oracle, 2013).

The exact compression ratio achieved will depend on the technology and the properties of the file (e.g. how predictable the data is), however a typical compressed file might be between 3-10 times smaller than the uncompressed file.

Note that much of the verboseness of the OGC XML formats evaluated above cannot be removed by compression.

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