DRAFT – NOT FOR CIRCULATION

REPORT ON NEW EQUIPMENT FOR COMMUNITY BROADBAND

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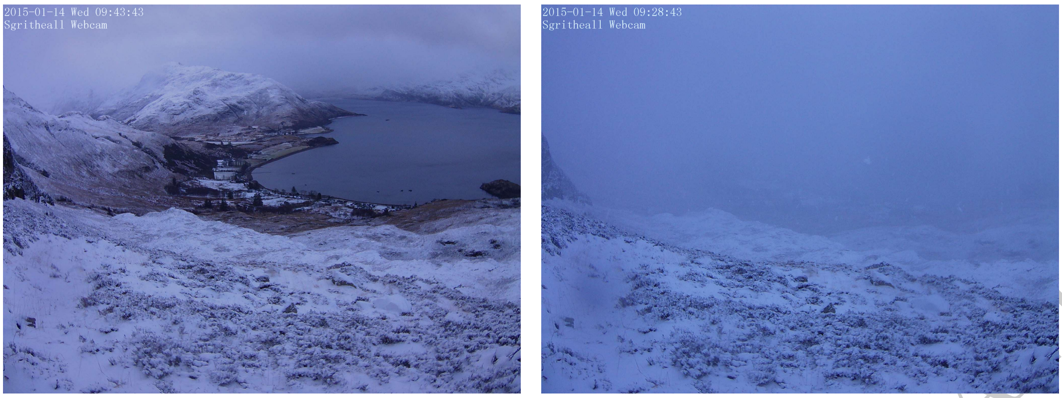


FIGURE 1. Scotch mist

ABSTRACT. The Demonstrating Digital Programme of Scottish Government provided a small grant to the University of Edinburgh to evaluate wireless (5GHz and 24GHz) and free-space optics equipment that may be useful in the deployment of broadband in Scotland. Ofcom granted us an experimental licence to evaluate the wireless equipment at higher power than current regulations would normally allow. The Met Office provided access to MIDAS Land and Marine Surface Station Data. This brief report summarizes our findings. A fuller report, with additional technical detail is available on request.

1. SUMMARY

- The 24 GHz equipment could prove useful over relatively short distances (up to 8 km) if licencing permitted use at the power for which it is designed. Under current regulations the 24GHz is effectively useless for rural links.
- Given the current power limits and available bands in the 5GHz range, the 5GHz equipment probably provides only a minor improvement on what could be achieved by using two or three parallel links using lower cost equipment in different bands. Moreover the 5GHz equipment was sensitive to tidal fading and occasionally failed completely (perhaps due to the presence of marine radar).

  The 5GHz equipment would be much more useful if (a) the power limits were to be raised and (b) Ofcom were to publish their database of licences in the C band.
- The free-space optics equipment performs well over distances of a few hundred metres in clear weather. However, it requires clear line-of-sight between stations. Optical communication fails when the visibility falls below the length of the link; so longer links suffer more frequent outages. A backup radio link is essential for most applications where, as across much of Scotland, conditions of low visibility may persist for several days. [1]

  The spanning-tree algorithm used to trigger fallback to radio communications did not integrate easily with existing infrastructure, and did not perform well in marginal conditions. We recommend that any future use of FSO equipment to supplement an existing radio network should explore other fallback strategies that provide better control, and include some hysteresis.

[1]Figure shows good and poor “free-space” visibility conditions on one of the shortest Tegola links. The camera is at one relay and the next relay is about 2km away on the hill in the background.

2. Wireless Links

Many community broadband projects require a long-range link for their connection to the Internet. Where there is no local access to a fibre PoP, a wireless link is often the only affordable option. The equipment of choice is currently based on wifi operating in the unlicensed 2.4 or 5GHz spectra. This is cheap: the equipment for a long-distance point-to-point link costs under £400 and can provide bi-directional throughput of about 50Mb/s. While this provides an improvement for the many rural communities that are served by long copper telephone lines, 50Mb/s is no longer adequate for a community of, say, 50 residences. Technically, there is no problem in getting more bandwidth in one of the licenced spectra, but the equipment is more expensive and the additional cost of the licence makes this option unaffordable for small communities.

Recently some new equipment operating at 24GHz has come on the market from Ubiquiti[2]. This is advertised as offering 1.4Gb/s at up to 13km. Although not as cheap (a point-to-point link costs about £3,000) it might present an opportunity for some rural communities to upgrade their service to be competitive with the current fibre based offerings in the UK, assuming they can find an internet connection with that bandwidth. A 5GHz variant is also produced by Ubiquiti claiming comparable speeds at upwards of 50km.

With this in mind, the Scottish Government's Demonstrating Digital programme provided the University of Edinburgh with funds to test this equipment "in the wild". Of course, there is ample evidence that the equipment works, but most of the evidence we have is from installations in urban areas over short distances. How will it perform over longer distances in West Highland weather? And what are the practical problems faced by communities who want to install it?

2.1. 24GHz.

Before going into an account of our experiences, we review some basic facts concerning wireless transmission and regulation in the 24 GHz spectrum.

We have already noted that the Ubiquity airFiber equipment is affordable. The advertised throughput of 1.4Gb/s over 13+km links presumably means 700Mb/s in each direction, but that would provide a satisfactory connection for a hundred or so residences. Moreover, transmission in this frequency is much less likely to be affected by tidal reflection (a significant problem in the Highlands and Islands).

However, there are significant obstacles to its use in Scotland. First, there are several technical obstacles:

- Several of the links used by Tegola and related projects are significantly longer than 13km.
- Transmission in higher frequencies is adversely affected by high humidity and high temperatures. Typically, only one of these is a significant problem in Scotland..
- The Ubiquiti equipment uses substantially more power than their 5GHz offerings – about 40W. This would make it unsuitable for solar and wind-powered relays.

Second, there is a regulatory obstacle. Ubiquity claim that, *The airFiber24 operates in worldwide, license-free, 24 GHz frequencies. Users can deploy airFiber24 almost anywhere they choose (subject to local country regulations).* In the UK, the 24.05–24.25GHz band used by this equipment is allocated by Ofcom to radiolocation (1) and amateur radio (2).[3] Their regulation includes the following conditions:

(1) Non-government low power devices in the radiolocation services are limited to:
   (a) Portable and fixed applications between 24.15-24.25 GHz; and
   (b) Mobile applications between 24.25-24.35 GHz on a NIB to the radionavigation service

[2] http://www.ubnt.com/airfiber
[3] http://www.ofcom.org.uk/static/archive/ra/publication/ra_info/ra365.htm

Power flux-density at 10 metres from the system antenna in the direction of maximum radiation is not to exceed 1.5 mW/m2 with out approval

(2) 24.05-24.25 GHz is used by the Amateur service. The part of the allocation between 24.05 and 24.150 GHz may only be used with written consent of the Secretary of State Home Office/Office of The Scottish Executive for the Emergency Services between 24.05-24.15 GHz ISM apparatus may use the band 24.0-24.25 GHz.

The 24.05–24.35GHz band band is partitioned into three sub-bands, two of which fall within the 24.05–24.25GHz range of the Ubiquity equipment. Of these two, one is reserved for government and amateur radio use and is not allowed for general use and the last is permitted at extremely low power densities for radiolocation.

We obtained a "non-operational" licence from Ofcom in order to test the equipment at its rated power of 13 W/m^2 and in both sub-bands. Operational use of this equipment for community broadband would require regulatory changes.

2.2. **Link budgets.** This experiment is meant to compare the real world performance against the vendor's claims, but we first considered how the claims stack up against the theoretical performance. We planned to run this equipment on a link of around 6 km. Our calculations suggested that using 40 MHz wide channels we should be able to solidly sustain such links at 256 Mbps or better for shorter links.

Our initial plan was to test the equipment on existing Tegola relays one is a 6.5km link; the second 15.5km. Although the latter is over the advertised range, even a substantial fraction of the advertised throughput would be useful.

The following is a roughly chronological account of the project. The initial installation was done during a period of very high winds in early January 2014.

2.3. **Initial configuration and testing.** We ordered and received one pair of radios. Before deploying them we thought it would be a good idea to check that they were working and test them in ideal situation – our office corridor. One thing we immediately noticed was how critical alignment is. Even over a distance of 35m, the performance fell of dramatically if the antennae were slightly out of alignment. It's a very good idea to configure equipment before deploying it, but to do this we had to turn off sychronisation which relies on GPS and doesn't work indoors.

2.4. **Strengthening the masts.** Our basic relay construction (see the relevant howto on the Tegola web site) uses aluminium pegs to anchor the diagonal braces to the ground. Both sites were on terrain that consisted of bedrock covered by peat of varying depth. Although we have never had a problem with the pegs shifting, peat is a bit jelly-like, and the structures can wobble through a cm or two. The alignment of 24GHz is much more critical than for the lower bandwidths of 2.4 and 5.8GHz, so we replaced the pegs with epoxy bolts into the bedrock.

We also strengthened both relays. For example, at one of our relays we added an extra horizontal bar.

2.5. **Installation and alignment.** The radios are reasonably light (under 10kg) but awkward to carry up hills. We used an old backpack frame that 30 years ago had been used for carrying batteries up to community TV relays. The radios come with a mounting frame that is first attached to the structure. The radio is then "slotted" into the mounting frame. This arrangement makes it quite easy to install the whole assembly when working from a ladder.

Figure 2. Pegged anchors (left) and epoxied anchors (right).

Figure 3. Corran mast before (left) and after (right)

The antenna can be aligned through elevation and azimuth adjustment screws. Unfortunately there is a great deal of backlash in these screws, and they are almost useless if you are working in high winds. If the clamping bolts are loose, the antenna is blown around through the considerable travel allowed by the adjustment screws. The signal strength read-out is at the bottom of the antenna, and if the alignment is being done from a ladder, you almost certainly need someone below (with a hard hat) to squint up and call out the figures.

The installation instructions recommend an alternating process in which one end of the link is adjusted then the other, and so on. Unfortunately we were unable to complete this process before the weather closed in and our workforce departed. However, the alignment is good enough that we can start taking some measurements. The initial indications are that the link will work reasonably well over a distance of 6.5km.

2.6. **Performance.** Overall performance of the 24GHz was quite good with throughput of 500Mbps easily achievable over the distance from Corran to Coille Mhialairigh, a distance of about 6.5km. This is more than was easily available at the time in the the 5GHz band. It is also less than advertised, which is perhaps unsurprising since the headline figures reflect what is possible under ideal conditions.

Figure 4 shows the link speed as measured at Corran for a typical day. The fluctuations are not obviously correlated with any specific phenomenon and a link budget calculation compared with the specification sheet for which modulation schemes are available at which signal and noise levels suggests that the capacity negotiation is overly aggressive. That is to say the radios are trying to maintain a link speed somewhat higher than their spec sheet says they should. Sometimes they actually achieve this, but unstably.

What we can conclude from this is that for the link to be stable, the modulation scheme must be explicitly set to one that can easily be supported by the link with a sufficient

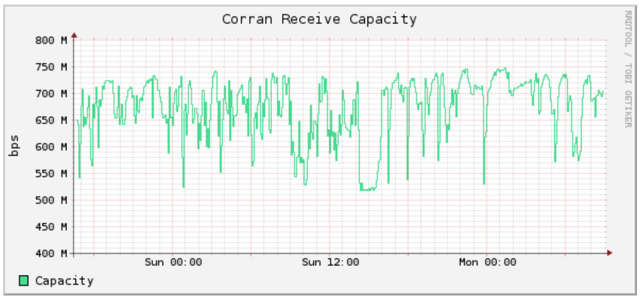


FIGURE 4. Corran receive capacity

margin and not allow the automatic negotiation to proceed. Incorporating such a margin (we recommend at least 6dB over the *observed* signal levels) provides a slower but much more stable link.

2.7. **5GHz Tidal Fading.** Tidal fading has been a serious problem in over-water links that use to the 2.4 and 5.8 GHz ranges. They are less of a problem with higher frequencies (e.g. 24GHz) in which the Fresnel ellipsoids and beamwidth are narrower [4]. The 5GHz airFiber link operates over a distance of approximately 20.8km with the two ends at heights of 300m and 20m above MSL. We have seen some tidal fading on normal 5GHz transmission over this link and disruptive fading over the same stretch of water when both ends are at heights of approximately 20m.

In January 2015 we had a failure of our the operating link and, since the weather prohibited climbing up to the 300m high relay, we switched to the experimental 5GHz airFiber equipment. Figure shows the received signal strengths on both polarizations. The classic quasi-cycloidal pattern is discernable in both plots, however it is in a range over with dips to -78 dBm, which might cause problems. However these extreme points are probably due to other causes. Examination of the RX capacity (see Figure 6 indicates that other effects may dominate tidal fading and that other things being equal, tidal fading is likely to be less of a problem on these links than it is on conventional 5GHz equipment. Readings were taken at 10 minute intervals from mid-January to mid-February

Tidal fading, or tidal multi-path interference is a known problem in radiofrequency engineering. It happens when the direct signal from a transmitting antenna and an indirect or reflected signal both arrive at the receiving antenna with opposite phase and cancel each other out. The degree to which this happens depends on how long the reflected path is, the direct path being fixed. Since in this case the reflections are caused by the water, as the tide rises and falls the reflected path gets longer and shorter. At certain points in the water's travel, the signals cancel out nearly completely – from the plots the loss from this effect is 12dB or a signal around 16 weaker than it would normally be.

The solution is to have multiple antennae spaced so that when the signal reaching one is being destructively interfered with, the other has a good signal and vice-versa. The picture to the right shows an inexpensive arrangement that implements this. It uses the standard 5GHz rocket radios from Ubiquiti and a non-standard

[4]our 24GHz link is not over water

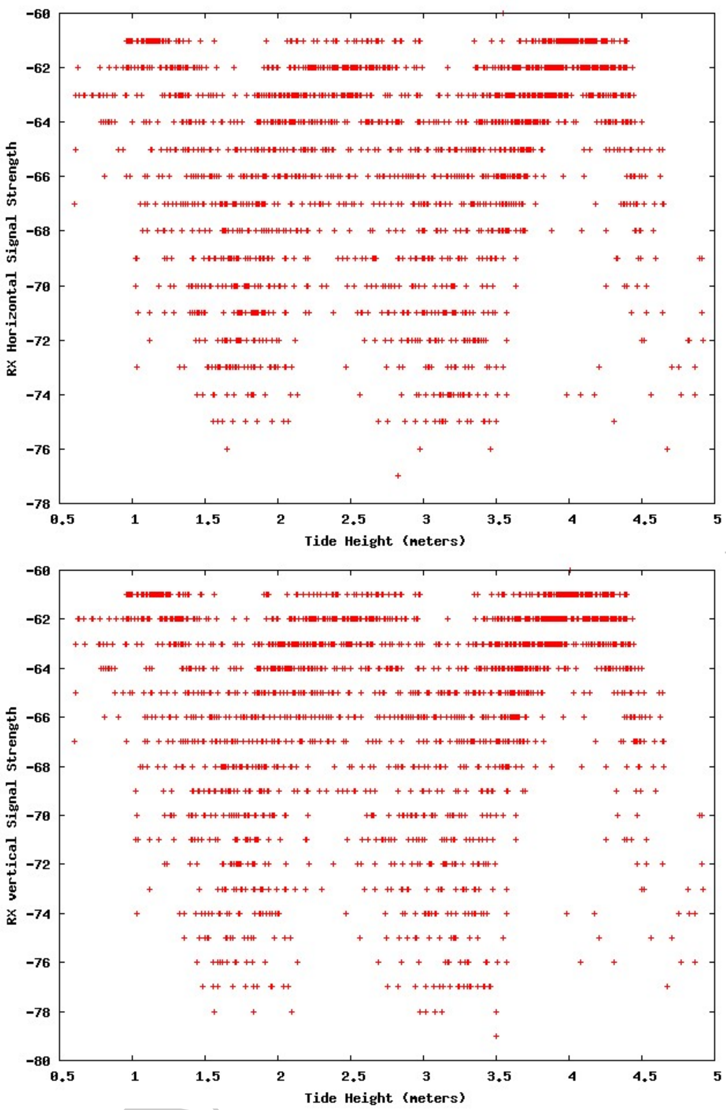


Figure 5. Scatter plot of signal strength against sea level for horizontal (top) and vertical polarizations

arrangement with two aftermarket antennae. This has been found to work very well. Unfortunately such a solution is not possible with the AirFiber units because of their construction – the radios and the antennae are integrated into a single housing, making it impossible to use different antennae. Nevertheless the AirFibre would be useful for links that do not traverse tidal bodies of water.

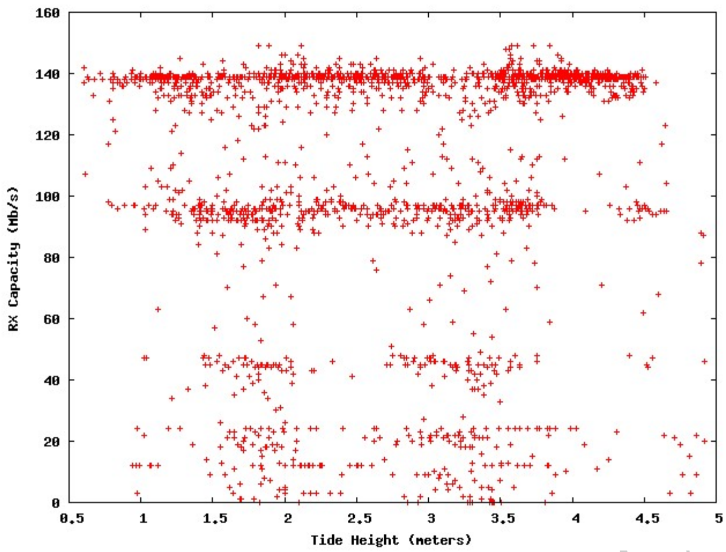
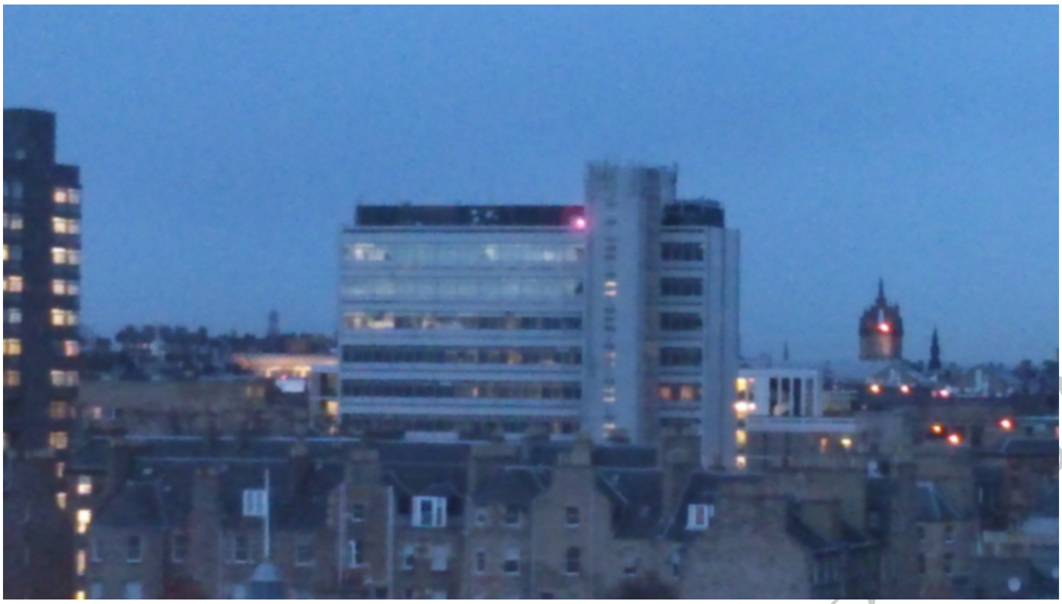


FIGURE 6. Scatter plot of RX channel capacity against sea level for horizontal (left) and vertical polarizations



3. Free-space Optics

At the request of the Scottish Government we also evaluated an unrelated technology for use in urban areas free-space optics. This means signalling by laser through the air instead of through fibre-optic cabling. The main question here was, since these devices operate in the visible spectrum, how well do they operate in reduced visibility conditions? Do they operate well enough for use in the Scottish climate over short distances. Again it is a question of cost. The equipment is expensive (some £8-15k per link) and requires careful mounting and alignment, but compared to the civil engineering cost of running fibre in urban areas, or leasing it, it may be worth it.

The free-space optics equipment, as expected, performs well over distances of a few hundred metres, but will not be useful for longer links in a typical Scottish environment. The equipment is expensive, and beyond the reach of a small community project, though we might have been able to reduce the cost by using an alternative vendor.

A link was established between TechCube and Appleton Tower, a distance of 500m, and evaluated using routine HUBS traffic.

Installing the link was significantly more arduous than installing the accompanying wireless link. It required on-site optical splicing to bring the optical link to the server cabinets at each end-point, and a dedicated high-current power supply.

It was also suggested that custom arrangements, more rigid than those required for a wireless connection, would be required for a laser link. In the event, we used some of our standard fixing arrangements (bolting to a framework of alloy scaffold poles anchored to the building at 3m intervals) for the Summerhall end of the link, and this was unproblematic.

The purpose of the trials with the free-space optical (FSO) links was to ascertain the extent to which fog, a common feature of the Scottish environment especially in coastal areas, would affect their use. Aerosolised water droplets attenuate visible and infrared light. We can quantify this effect theoretically, but we were primarily interested in finding out if their operational window was, on average, large enough to justify the considerable expense.

We found that performance of the link correlates well with standard MIDAS visibility records at a nearby weather station, and recommend that historical visibility data should be analysed to assess the extent to which fog and rain will affect the performance of such a link in any proposed location.

3.1. **Link Design.** CableFree, the laser vendor produced a link design as shown in Figure 7. In principle it is plausible, consisting of a laser link, and a back-up radio link between Appleton Tower and the Tech Cube, a distance of about 500m. At either end two switches would use the spanning-tree protocol (STP) configured with the radio link having a higher cost than the laser link. The principle being that traffic would flow over the lasers unless they were unavailable in which case the backup link would be used.

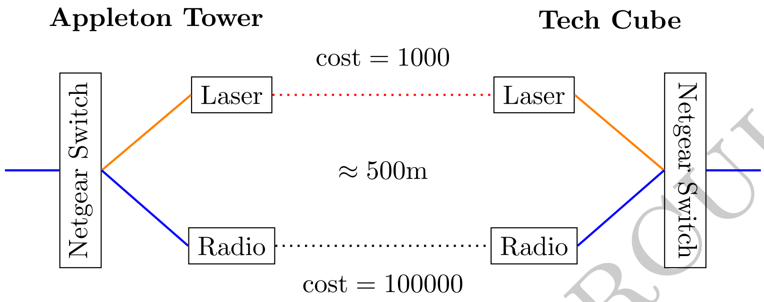


FIGURE 7. CableFree Link Design

We already had a significant amount of radio equipment at both sites – including a radio link between them – so an extra radio link could be considered superfluous. The mounting brackets supplied with these back-up radios were somewhat flimsy. It can get very windy at the top of tall buildings in Edinburgh. Wind speeds can reach several times more than at ground level. The installation is shown at right with the mounting bracket having worked loose in high winds leaving the radio pointing downwards.

We also had high end HP ProCurve J9050A switches at either end (loaned by the School of Informatics), far more capable network elements than the consumer-grade Netgear switches (see Figure 8) specified by CableFree. The deficiencies of the Netgear switch are that it is not manageable via telnet or ssh, which makes it very difficult to recover from outages or erroneous configurations in a network of any size or complexity.

We ultimately ended up operating the link by connecting the vendor-supplied netgear switches to our HP switching core and removing the vendor-supplied radio equipment entirely.

The more serious deficiency with this design is the use of the spanning-tree protocol. In brief, the mechanism is unstable in marginal conditions. If the weather is clear or if the weather is very foggy, the link operates as designed. However it appears that,in the region between clear and very foggy, the path is liable to rapidly change between the (possibly unuseable) optical link and the radio link.

3.2. **Installation.** Two different methodologies were used for the physical installation. At Appleton Tower we were not permitted to make any permanent modifications to the building. The laser head was therefore mounted on a pedestal, shown

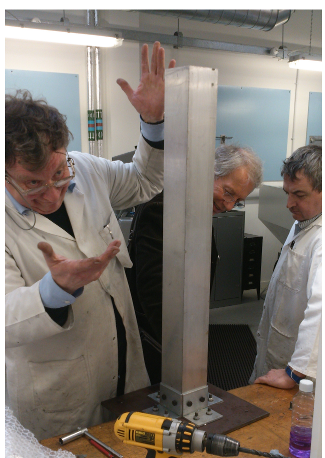


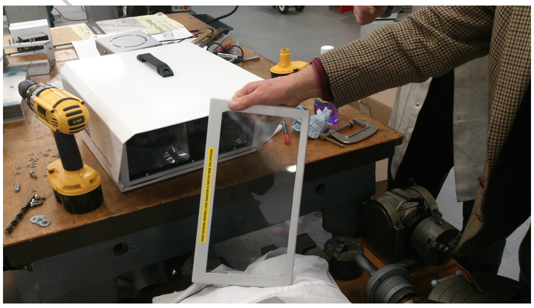
FIGURE 8. A “carrier-grade” ethernet switch.

at right. This was fixed to a paving tile and further weighed down with more scrap paving tiles to prevent it from blowing away.

Installation at the Summerhall site was straightforward since we were able to make building modifications. We used aluminium scaffolding to create a frame fixed to the side of the plant room on the roof and fixed the laser head to that.

Alignment of the lasers was straightforward – in fact easier than anticipated and though it was done with specialised equipment (which measures signal strength and produces audible faster or slower beeps accordingly as the optical link is well or poorly aligned) it appears to be quite possible to align the link without any more equipment than a simple two-way radio. This is done by observing the beam edges on one end (after a rough alignment) and instructing a colleague over the radio to slightly move the far laser until the edges are centered with respect to the near one, and repeating the procedure for the other side. This turned out to be necessary on one occasion, as severe winds caused the Appleton Tower pedestal-mounted end to de-align.

We also had to make some modifications to the lasers due to poor design. A protective piece of glass that covers the lens had to be fixed with screws because it came off easily. Luckily we found this, to our surprise, in the workshop before installing the equipment.



3.3. **Instrumentation.** The laser and wireless links were instrumented using standard port statistics on the HP switches, collected in the usual way at five minute intervals. It would have been interesting to be able to collect more detailed information about the link – signal strength, bit-error rate and so forth – but this was not possible as the vendor required

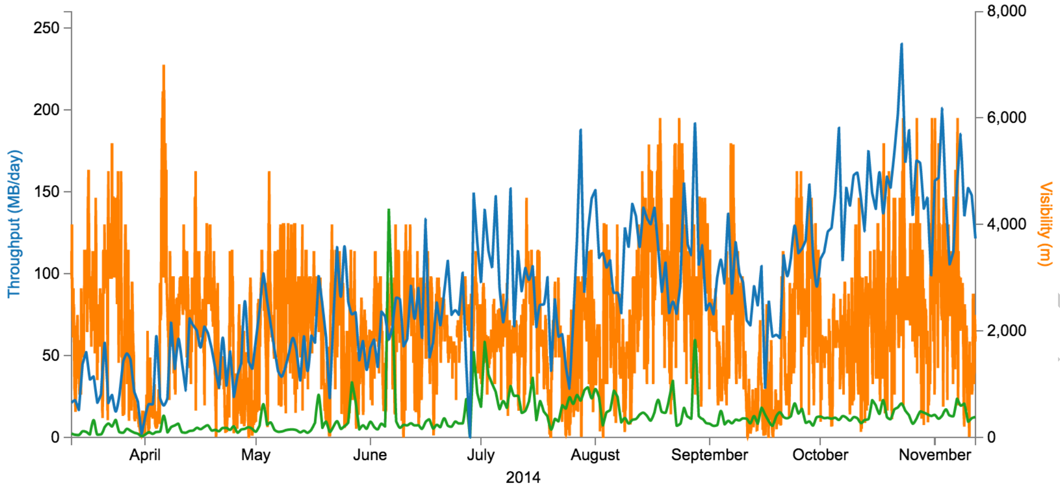


FIGURE 9. Laser

executing an unacceptable non-disclosure agreement in order to be able to access this basic information and this would have prevented dissemination of these results.

The port statistics are stored in the industry-standard Round-Robin Archive format.

3.4. **Correlation of link operation with weather.** We have been monitoring availability of the optical link and we have access to the UK hourly weather data for the purposes of this project Unfortunately we had to undertake some emergency works in November to make way for Vodaphone at Summerhall, and it turns out that this interfered with some of our data-collection, and we were unable to make planned fine-grain observations that might have given more detail on the inferred instabilities of the spanning-tree algorithm.

Figure 9 shows the daily throughput in either direction of the laser link over an eight-month period (blue and green curves). The daily volume of traffic grows fairly steadily over the eight-month period. These curves are overlaid on the hourly record of visibility at Gogarburn (the closest MIDAS station for which hourly visibility records are available), for reasons that will soon be made clear.

The weather data shows no correlation between wind-speed and quality of the FSO connection (we had conjectured that there might be some effect if the wind routinely affected our mountings and beam alignment). Both Summerhall and the Appleton tower are relatively low-rise and solid buildings. On high-rise buildings wind-induced movements could have a significant effect (for example, in high wind the Shard is intended to move by up to 20 inches, the Burj Khalifa moves by 2 metres). The beam was observed to have an effective spread of around 2m (diameter) over the 500m distance (around 13 of arc) and it was relatively straightforward to establish a functional alignment, which was maintained without further intervention over the course of this experiment.

However, we did observe, as anticipated, that the FSO link became effectively inoperative in conditions of severely reduced visibility.

The radio link is required to maintain service when the FSO is inoperative. It comes into play automatically when FSO performance is degraded to such an extent that the radio link is better. Figure 2 shows the daily throughput of the radio link, again overlaid on visibility data.

Figure 11 show portions of this period in more detail. They show that use of the radio link is directly correlated with episodes of low visibility (below 500m). Going back to figure

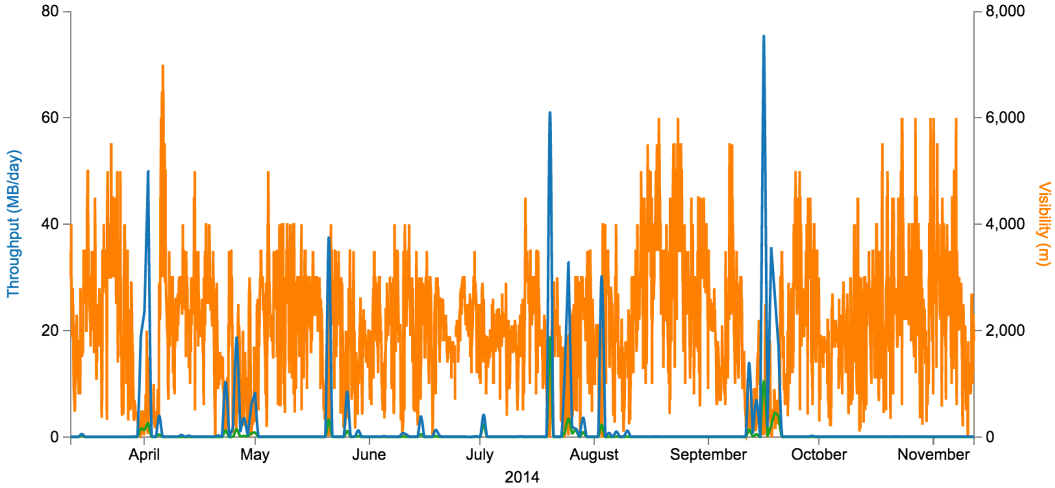


FIGURE 10. Wireless

1 we see that many of these episodes are short-lived, and have little effect on the overall daily volume of traffic, but that in some cases the fog is more persistent.

To quantify the likely impact of these climatic effects in any proposed location, it would be useful to study both the frequency and the duration of local episodes of low visibility. Longer episodes will have greater impact in many applications.

We also note that longer links will clearly be more susceptible to such effects. For example, over the course of 2014, only 10% of hourly observations at Gogarburn recorded a visibility of 500m or less, while the figures for limits of 1km, 1.5km, and 2km are 10%, 18% and 44% respectively.

Unfortunately, as mentioned above, we were unable to monitor the performance of the FSO link directly because of the proprietary protocol that prevented adequate instrumentation. Nevertheless, we were able to quantify the difference in performance between the laser link and a back-up wireless link running over 5GHz unlicensed spectrum. The FSO link has several times the bandwidth of the radio link, but it is more susceptible to climatic degradation.

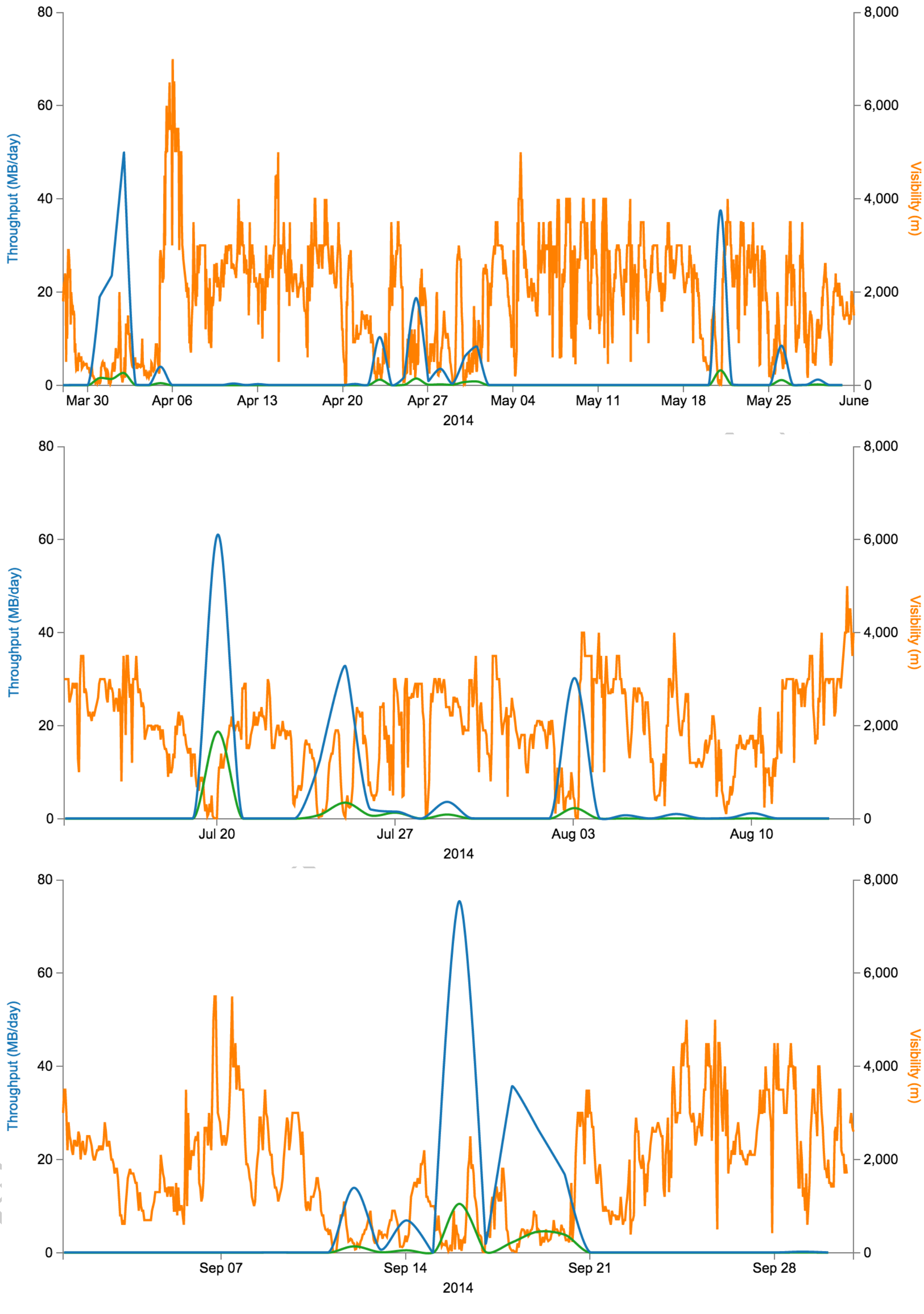


FIGURE 11. Detail