FFI-RAPPORT

20/01338

Iridium Certus IP performance in the Arctic

– data analysis

Tore Jørgen Berg
Terje Mikal Mjelde

Iridium Certus IP performance in the Arctic – data analysis

Tore Jørgen Berg
Terje Mikal Mjelde

Norwegian Defence Research Establishment (FFI) 24 April 2020

Keywords
Kommunikasjonsteknologi
Kommunikasjonsnettverk
Radiokommunikasjon
Satellittkommunikasjon
Radiodekning

FFI report
20/01338

Project number
1523

Electronic ISBN
978-82-464-0133-8

Approvers
Åshild G Solheim, *Research Manager*
Jan Erik Voldhaug, *Director of Research*

Summary

In the last years, there has been an increased military and civilian activity in the Arctic areas. Earlier studies from the Norwegian Defence Research Establishment (FFI) have concluded that a non-geostationary satellite system is necessary in order to provide the Norwegian Armed Forces with data capacity in the northern areas. One candidate is the Iridium satellite system.

Iridium is a low earth orbit satellite system that promises worldwide connectivity. By using an Iridium Certus SIM card from Marlink, specified to provide a 352 kbps best-effort service, we measured the quality of the IP service in the Arctic. The tests started in Longyearbyen, Svalbard on 14 August 2019, reached the North Pole on 21 August and ended close to Longyearbyen on 8 September.

The connectivity of the Iridium service was measured by testing the availability of the IP service over a Thales VesseLINK modem. Our study concludes that the connectivity in the Arctic is good.

The SIM card used supports 352 kbps, but this throughput capacity was only reached in 45 percent of the experiments. We identified the main shortcoming with Iridium as the long time periods (up to 70 seconds) where the IP packets are not served, which lead to high packet loss rates. High loss rates occurred frequently even at low load levels (25 kbps).

Sammendrag

Den militære og sivile aktiviteten har økt i nordområdene hvor samband med tilstrekkelig kapasitet bare kan tilbys av satellittsystemer. Tidligere studier ved Forsvarets forskningsinstitutt (FFI) har konkludert med at geostasjonære satellitter ikke gir Forsvaret tilstrekkelig radiodekning i nordområdene.

Iridium er et lavbane satellittsystem som tilbyr en IP-tjeneste over hele kloden. Ved bruk av et Iridium Certus SIM-kort fra Marlink, spesifisert til å yte inntil 352 kbps datarate, målte vi tjenestekvaliteten i Arktis i perioden 14. august til 8. september 2019. Felttestene startet i Longyearbyen på Svalbard. Det ble foretatatt flere målinger hvert døgn helt fram til Nordpolen samt under returen til Longyearbyen.

Tjenestekvaliteten ble målt over et Thales VesseLINK modem. Testene viser at IP-tjenesten har god dekning i Arktis.

SIM-kortet var spesifisert til å gi inntil 352 kbps, men bare 45 prosent av testene var i nærheten av denne kapasiteten. Den største utfordringen ved bruk av Iridiums IP-tjeneste ble identifisert til å være lange blokkeringsperioder, opp mot 70 sekunder. IP-pakker blir ikke betjent når blokkering inntreffer, buffere fylles opp og konsekvensen blir høyt pakketap. Selv ved lav last (25 kbps) ble det målt betydelige pakketapsverdier.

Contents

Summary **3**

Sammendrag **4**

1 Introduction **7**

2 Network statistics **12**
2.1 Throughput [bytes/s] 13
2.2 Packet delay [sec] 13
2.3 Packet loss [%] 14
2.4 Handover (HO) rate [events/s] 16
2.5 Received Signal Strength Indicator (RSSI) [dBm] 17

3 IP performance in the Arctic **17**
3.1 UDP throughput capacity 17
3.2 Availability 20

4 Lab testing in June **31**
4.1 UDP throughput capacity 31
4.2 Network stability testing 34

5 Lab testing in August **38**
5.1 Network stability testing 38

6 Lab testing in October **43**
6.1 Samples October 14 46

7 Conclusions **50**

A Appendix: data from the Arctic **52**
A.1 August 23 52
A.2 August 24 62
A.3 August 27 72

A.4 August 28 83
A.5 August 30 85
A.6 August 31 87
A.7 September 1 89
A.8 September 3 91
A.9 September 6 93
A.10 September 7 95

Acronyms **97**

References **98**

1 Introduction

In the last years, there have been an increased military and civilian activity in the northern/arctic areas. Earlier studies at FFI have concluded that a non-geostationary satellite system is necessary in order to provide coverage and data capacity to the Norwegian Armed Forces in the northern areas [1, 2]. One candidate is the Iridium satellite system.

The Iridium-NEXT satellite system operates 66 low-earth orbiting (LEO) satellites arranged in six orbital planes, each containing 11 satellites. The Iridium Certus[1] provides 100 % coverage of the globe, including deep oceans and the poles [3]. Iridium is one of the few options for communications in the Arctic. Another interesting property is the low IP packet latency, which is in the range 400 to 600 ms[2]. By using a Thales VesseLINK modem [4], we measured the Iridium IP performance in the Arctic from August 14th to September 8th 2019.

The vessel KV Svalbard, carrying the VesseLINK modem, departed from Longyearbyen, Svalbard August 14th, reached the North Pole on August 21st and then returned to Longyearbyen. The modem logged the vessel's GPS coordinates. Figure 1.1 and Figure 1.2 plot the vessel mobility path.

The purpose of the field tests was to estimate the Iridium IP service quality in the Arctic. With this goal, the best traffic type to use is UDP and not TCP since the latter gives "coloured" samples.[3]

All tests established two symmetric UDP streams by using two traffic generators (TG) as shown in Figure 1.3. Then any difference in performance of the two streams must be caused by the underlying network. For example, note that the stream 2→1 has a larger buffer space than the stream 1→2 since the latter has the modem buffer space only. Large buffers may give lower packet loss and higher delay than small buffers.

The Marlink SIM card [5] used is specified to support 352 kbps, symmetric rate (in/out) and is specified as a best-effort service. Then the Iridium interface in Figure 1.4 shall provide 352 kbps symmetric capacity. Iridium compresses the IP packets. The sender must therefore fill the packets with random payload data. We also measured the UDP packet delay but had problems to achieve accurate time synchronisation in the field tests. UDP applies an 8-byte header. Since

[1] Iridium Certus (trademark) is a new mobile broadband service offered by Iridium. Debuting speed is 352 kbps, upgradable to 704 kbps.
[2] Of course, the measured latency will be much higher in high traffic load states due to queuing in the network.
[3] TCP retransmits packets lost over the Iridium link. TCP: Transmission control protocol. UDP: User datagram protocol.

we used a fixed sized payload of 500 bytes, maximum throughput should be slightly lower than 352 kbps (= 44000 bytes/s, 88 packets/s).

Figure 1.5 defines the satellite link naming convention used. All time instances referred to in this report are coordinated universal time (UTC).

This report is organised as follows. Chapter 3 presents the results from the field tests and is placed first since this is the most interesting part of the report. More details about the field tests may be found in appendix A. To get acquainted with the Iridium service and to validate the test equipment, a set of laboratory tests was conducted in June 2019. At that time only a pre-release SIM card was available. Chapter 4 explains why this test period failed. In August we received a new SIM card that should perform better according to the service provider. We had only a few days available for testing before the equipment had to be sent to Longyearbyen. Chapter 5 presents the results with the new SIM card. Due to the short test period in August, we had to follow up with more laboratory tests in October, mostly to validate the test equipment. Chapter 6 reports from this test period.

The recommended reading sequence of this report is: chapter 3 and chapter 7. The other chapters and appendix A are intended for readers that want to have detailed information. This information will also be useful if the experiments are repeated later, for example with another Iridium modem.

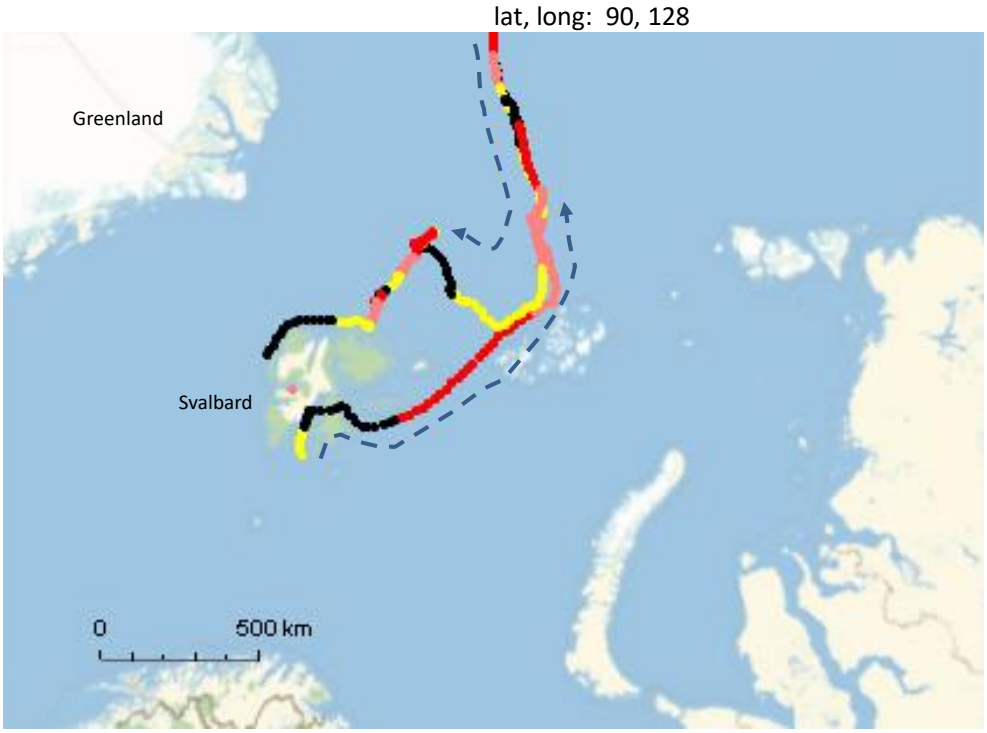


Figure 1.1 Vessel mobility map August 15 to September 3. Colour change at midnight.

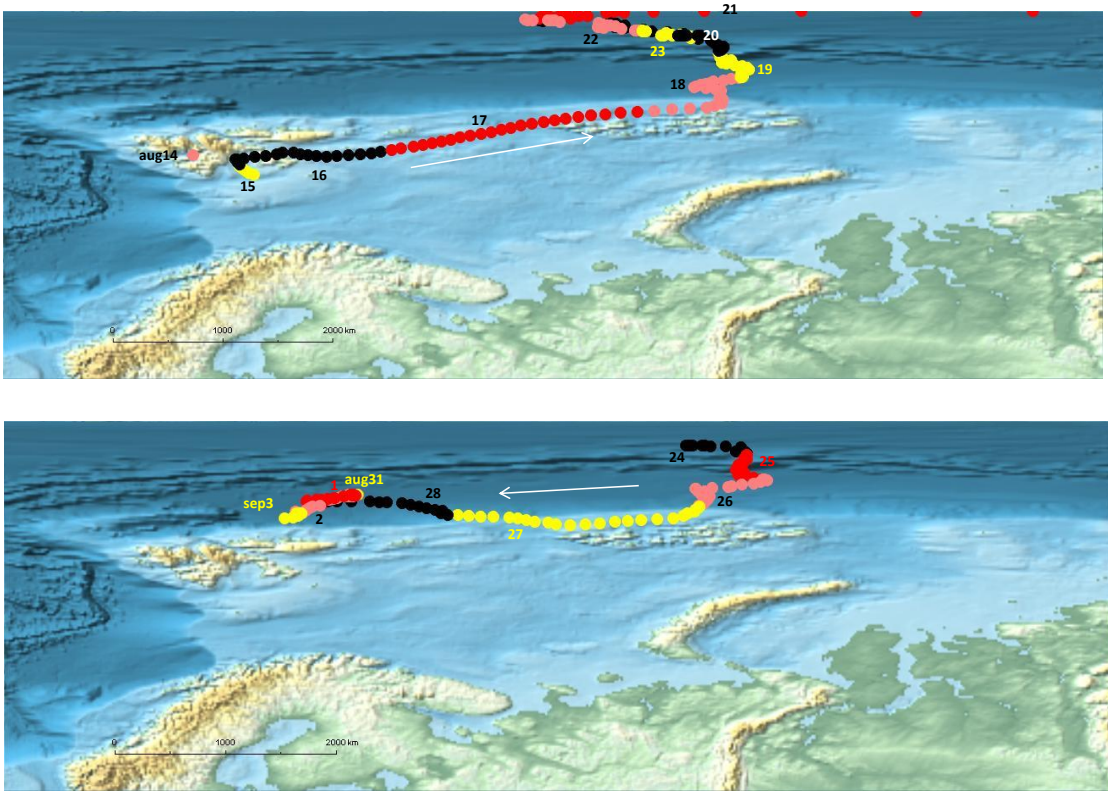


Figure 1.2 Vessel mobility relief map.
60 minutes between each point. Colour change at midnight.
Top view: the path from Svalbard August 15 T09:16 to August 24 T11:44.
Bottom view: the path to Svalbard August 24 to September 3 T22:16.

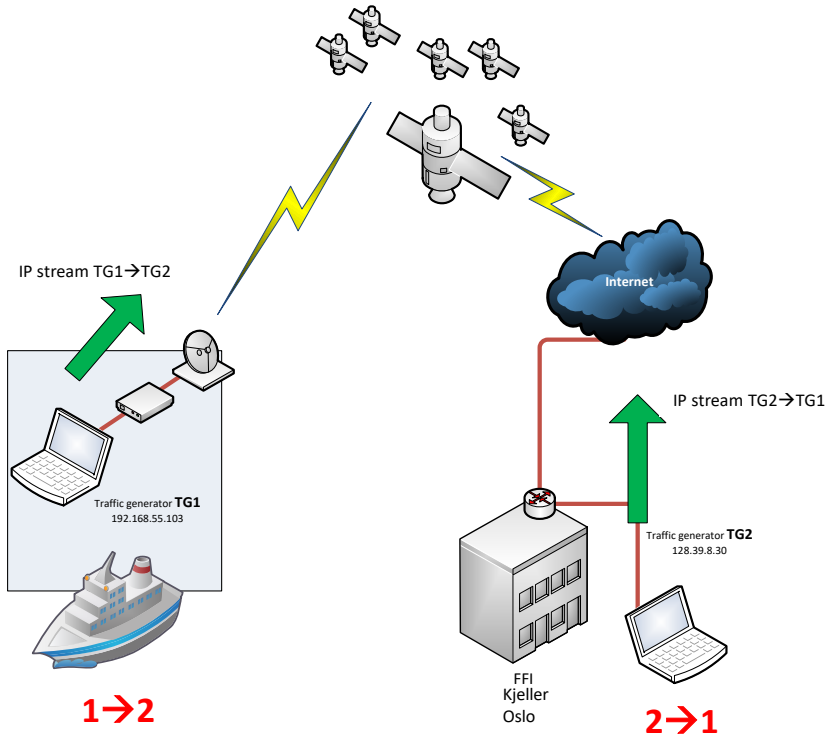


Figure 1.3 The test scenario employed two traffic generators configured to produce two identical UDP streams. During the lab tests, TG1 and TG2 were collocated in the same building at FFI/Kjeller.

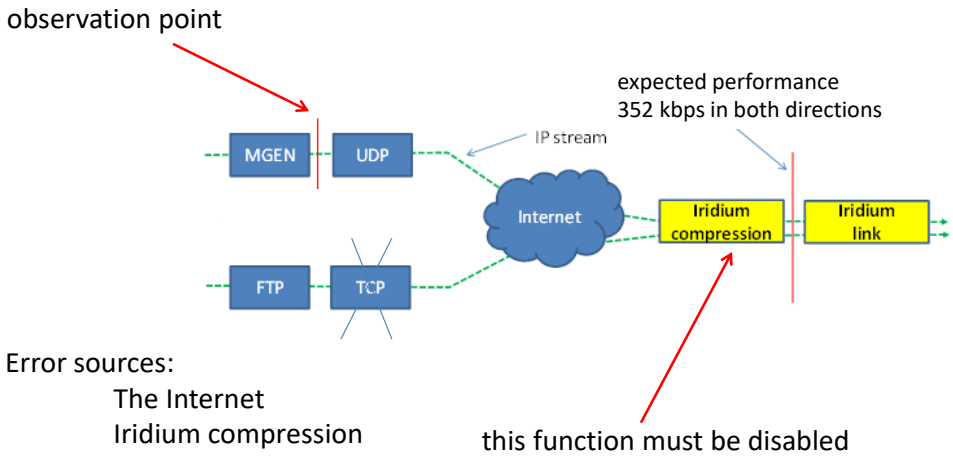


Figure 1.4 The task is to measure the Iridium link IP performance. UDP traffic must be used since TCP retransmits packets lost over the Iridium link. Iridium compresses the packets and the TGs must therefore generate random IP payload data to circumvent this. MGEN is an open source traffic generator.

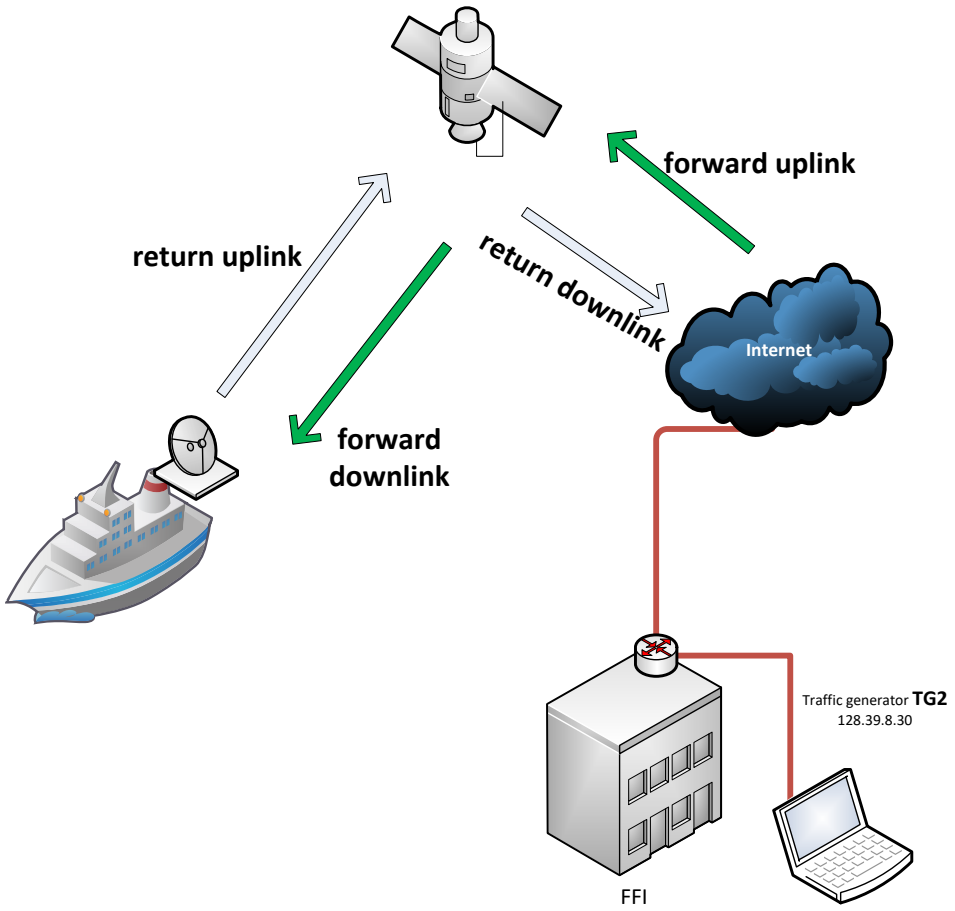


Figure 1.5 Link naming.

2 Network statistics

Statistical methods must be applied to analyse the samples collected. Sample statistics are presented in three different ways:

1) Sample mean at 95% confidence levels
2) Quartiles Q1, Q2 (median) and Q3
3) Time-series plots

The following sections specify the types of statistics measured and how the samples are collected.

2.1 Throughput [bytes/s]

Throughput statistics is calculated from the MGEN[4] listen log attributes *packet received time* ("RECV") and the *UDP size* ("size>" in bytes).

Figure 2.1 illustrates a perfect throughput capacity plot for the Iridium service:

1) Zero packet loss until the 350 kbps limit is reached.
2) Maintains a stable 350 kbps throughput capacity when the offered load increases beyond 350 kbps.
3) Both streams have overlapping curves.

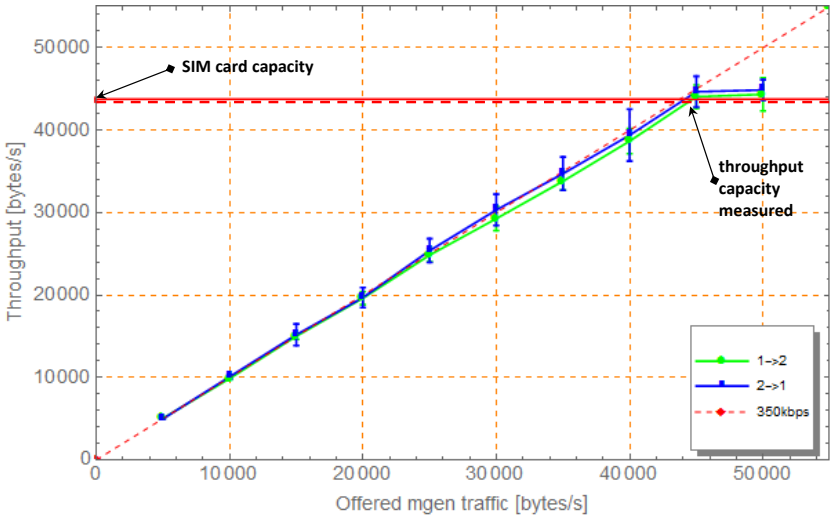


Figure 2.1 Expected shape of a throughput plot with increasing offered traffic. The arrows represent 95% confidence intervals.

2.2 Packet delay [sec]

UDP packet delay is calculated from the MGEN listen log attributes *packet sent* at ("sent>") and *packet received time* ("RECV"). Correct statistics demand precise time synchronisation between TG1 and TG2. No correlation test is conducted on the sampled data.

WARNING: We used GPS based time synchronisation but had problems with the accuracy. The delay error may be higher than 100 ms and all delay statistics must be interpreted with this in mind.

[4] MGEN is an open source IP packet generator.

Figure 2.2 illustrates a perfect delay plot for the Iridium service:

1) Low fixed delay until the 350 kbps limit is reached.
2) The stream 1→2 has less buffer space and have lower delay in saturation.

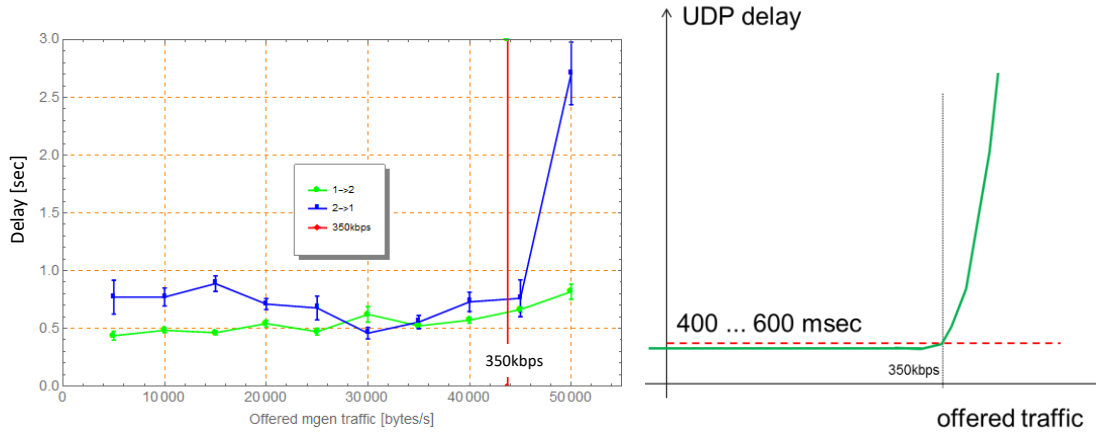


Figure 2.2 Expected shape of an IP packet delay plot with increasing offered traffic. The plot to right is a theoretical plot: Iridium shall have fixed delay until the 350 kbps throughput limit is reached. When the load level increases above this level, packets are queued and the delay increases rapidly.

2.3 Packet loss [%]

Packet loss is calculated from the MGEN listen log attribute *sequence number* ("seq>"). Each packet sent is assigned a unique sequence number (range integer 1, 2, 3 …) at the source side. A missing sequence number indicates a packet loss event. No confidence control is applied to packet loss.

Example:

```
03:07:02.890934 RECV proto>UDP flow>201101 seq>1737 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:02.421454
03:07:02.891646 RECV proto>UDP flow>201101 seq>1738 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:02.432343
03:07:33.230613 RECV proto>UDP flow>201101 seq>1750 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:05.400790
03:07:33.411357 RECV proto>UDP flow>201101 seq>1751 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:05.753912
03:07:33.411565 RECV proto>UDP flow>201101 seq>1752 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:05.767588
```

Here the packets lost are 1739...1749 and #lost = 1750 – 1738 – 1 = 11. Packet loss rate is #lost / #sent.[5]

[5] # means "the number of".

Consecutive loss count [#lost packets]

The consecutive loss count (CLC) may indicate service blocking periods. Packet CLC is calculated from the MGEN listen log attribute *sequence number* (“seq>”). CLC is presented as a time-series only. CLC counts the number of consecutive lost packets (the gap in the sequence numbers).

Figure 2.3 illustrates two packet loss/success time-series plots. Upon a packet success event at time t, a blue dot at (t, 1) is printed. Upon a packet failure event at time t, a red dot at (t, 2) is printed. The plot at the left side has insignificant packet loss rate. The right plot has no loss events at the start of the test, but just before t = 2200 a burst of packet loss events starts.

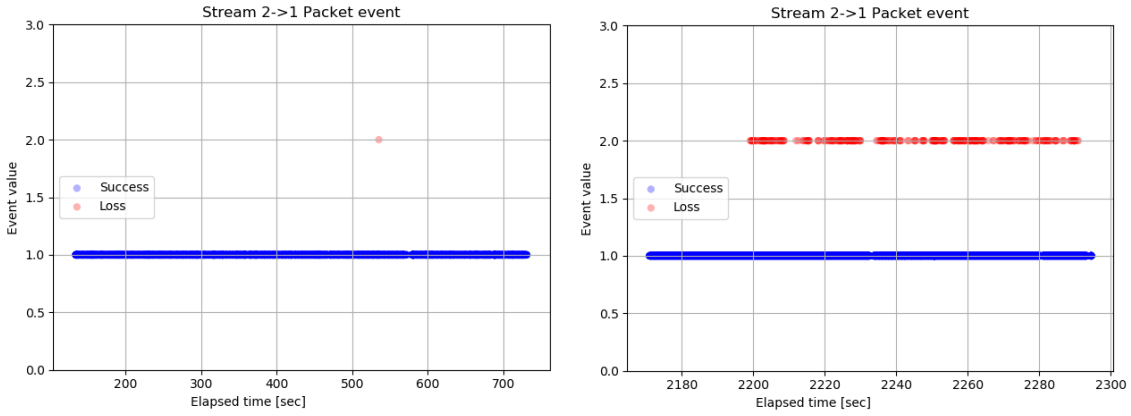


Figure 2.3 Packet loss/success events as time-series.

Figure 2.4 illustrates CLC plots. The stream in the left plot experiences mostly single consecutive packet losses while the stream in the right plot experiences severe conditions – up to 120 packets are lost in sequence.

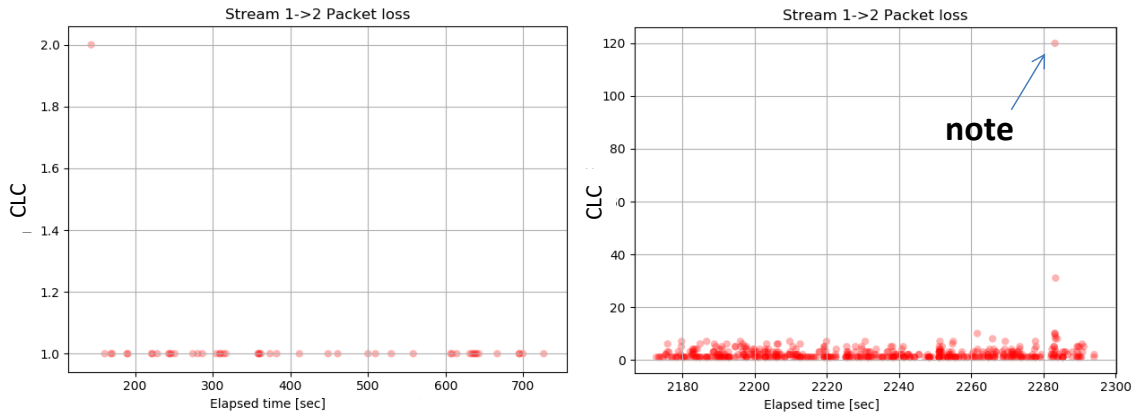


Figure 2.4 Consecutive loss count as time-series.

2.4 Handover (HO) rate [events/s]

The Iridium modem reports two different types of handover (HO) events: Space Vehicle (SV) and Beam[6]. No confidence control is applied to HO statistics. Beam HO events are marked by green dots. Figure 2.5 illustrates HO events in the time domain. When an SV event occurs at time *t*, a blue dot is printed at *(t, 1)*.

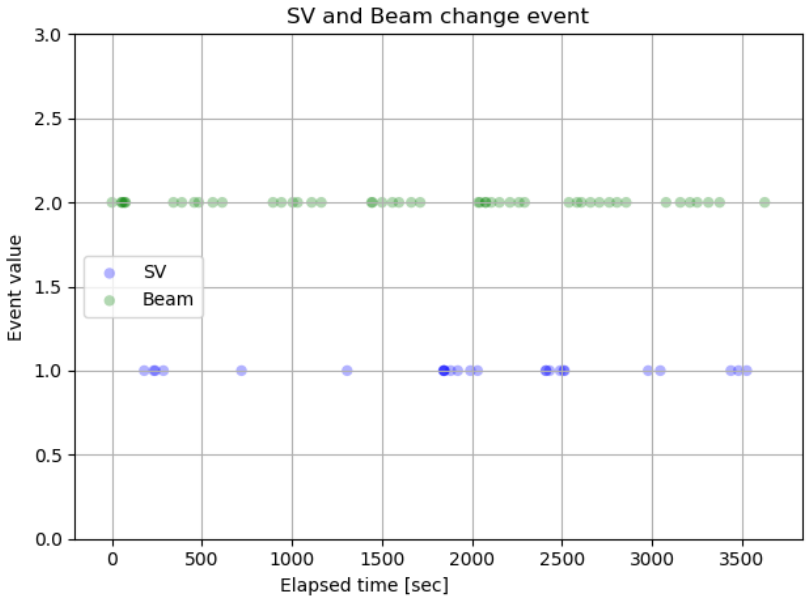


Figure 2.5 HO events as time-series.

[6] SV HO means to connect to another satellite. Beam HO is to switch to another beam on the same satellite.

2.5 Received Signal Strength Indicator (RSSI) [dBm]

The Iridium modem reports the Received Signal Strength Indicator (RSSI) when performing HO. The RSSI samples are collected by reading the modem log file.

3 IP performance in the Arctic

This chapter presents the most interesting findings from the field tests in the Arctic. Further details about the measurements from the Arctic are presented in appendix A.

The objectives of the Iridium field tests were to find answers to the following questions:

1) What is the probability of having access to the IP service in the Arctic (availability)?
2) What UDP throughput capacity can we expect in the Arctic?

Here availability means only to get some packets through during a fixed time period. Availability testing must therefore be done at low load levels. However, the offered traffic cannot be too low since we need a certain traffic volume during each test period. Expected UDP capacity is 352 kbps[7] and the availability tests generated 25 kbps (6.25 packets/s) only in each direction.

A single UDP throughput capacity test consumes a significant amount of the limited traffic volume available on the SIM card. Therefore only one capacity test was started every twenty-four hours while four availability tests were started in the same time period.

3.1 UDP throughput capacity

Finding F3.1: The fraction of the tests with degraded throughput capacity is 55% (6 of 11).

Table 3.1 summarises the capacity tests and we have:

Number of tests: 13
Number of valid tests: 11
Number of tests with degraded throughput capacity: 6

[7] The exact number is 352*500/508 = 346 kbps but the statistical accuracy is too low to differentiate between 346 and 352. We use 500 bytes payloads and UDP adds 8 byte to each packet.

The laboratory testing in June and August discovered low quality of the Iridium service. Thus we did not consider executing capacity tests in the Arctic. But when we got improved results from the availability tests in the Arctic, we started to run capacity tests periodically after August 23.

Date	Location (lat, long)	Capacity [kbps]	Comments
24 August	start: (87, 56) end: (87, 56)	1→2: **352**±11 2→1: **357**±15	
27 August	start: (82, 56) end: (82, 55)	1→2: **216**±12 2→1: **237**±22	
28	start: (82, 35) end: (82, 35)	1→2: **346**±13 2→1: **360**±22	
30	start: (83, 26) end: (83, 27)	1→2: **346**±10 2→1: **357**±25	
31 August	start: (84, 28) end: (84, 28)	1→2: **318**±10 2→1: **360**±3	
01 September	start: (84, 28) end: (84, 28)	1→2: **351**±10 2→1: **355**±22	
02		test failed	Note 1
03	start: (82, 24) end: (82, 24)	1→2: **316**±8 2→1: **356**±24	
04	start: (81, 21)	**test failed at 160 kbps**	Note 2
05	start: (81, 21)	**test failed at 160 kbps**	Note 3
06	start: (81, 21) end: (81, 21)	1→2: **346**±14 2→1: **359**±26	
07	start: (81, 22) end: (81, 21)	1→2: **300**±17 2→1: **317**±26	
08	start: (80, 12)	test failed	

Table 3.1 Measured throughput capacity [kbps] presented at 95% confidence level. Text in red indicates failures due to Iridium problems. Tests started periodically at 03:30 every night but failed to start august 25, 26 and 29. The column "Location" indicates the GPS coordinates when the test started and ended (latitude, longitude).

Table legend*:*

Note 1: The traffic generator (TG2) at FFI failed. The TG2 MGEN listen process stopped after 20 sec and the TG2 MGEN send process never started. TG1 acted as it should. The modem was up and running and the cause of failure was not Iridium.

Note 2: Both UDP streams stopped simultaneously during run number 2. We have modem data for this period which indicates that the modem was up and running.

Note 3: Same error state as note 2.

3.2 Availability

The purpose of the availability testing is to measure the availability of the IP service – what is the probability of having access?

Availability tests were executed four times every twenty-four hours {03:00, 09:00, 15:00, 21:00}. The UDP offered traffic was 25 kbps (3125 bytes/s, 6.25 pkps[8]), which amounts to 7 % of the expected capacity (352 kbps). The test duration was 15 minutes. If no packet loss events occur, each end receives 5625 packets.

A modem error August 14 and 15 lead to missing results at these days.

A ping test was started before the MGEN process. A test is defined to be successful only if:

1) Ping succeeds ***and***
2) Minimum one packet delivery in both directions during the 15 minutes test period.

Figure 3.1 to Figure 3.4 show the throughput measured from August 16 to September 7 as 95 % confidence intervals. In a healthy network, all the confidence intervals would have covered the red dotted horizontal lines (25 kbps).

Finding F3.2: The availability of the Iridium IP service is 91 %.
Table 3.2 summarises the failed tests (zero throughput = service unavailable). The number of valid tests is 89 of which 8 failed. The availability is 1 – 8/89 = 0.91. The same test was undertaken later in a laboratory environment and showed 100 % availability (Table 6.1). We assume the results from the Arctic are too pessimistic and the test should have been redesigned – the traffic generators should have been started even though the preceding ping test failed.

Finding F3.3: The packet loss rate is surprisingly high.
With the low traffic level used and based on experience from other types of IP network, we expected the UDP packet loss rate to be less than 1 %. However, the loss rate is significantly higher than this in many of the tests. Note also that the stream 1→2 has higher loss rate than 2→1. The sections 3.2.1 and 3.2.2 below explain the cause of high loss rates.
A possible source of experiment error is that other users on the vessel used the modem during the experiment – the modem was not physically protected from unwanted external traffic. Since high loss rates are measured in a laboratory environment also, see chapter 6, we regard the results as valid.

[8] Packets/s

UTC time	03:00	09:00	15:00	21:00
Number of errors	2	3	2	6
Number of tests	23	23	23	23
TG failures	2	1	0	2
SatCom failures	0	2	2	4
SatCom error rate	0/23=0%	2/22=9%	2/23=8%	4/21=19%
Date UDP stream Cause	**aug 16** 1←→2 tg2 error **aug 18** 2→1 tg2 tx error	**aug 16** 1←→2 tg errors **aug 19** 1←→2 ping error **aug 28** 1←→2 ping errors	**aug 20** 1←→2 ping error **aug 24** 1←→2 ping error	**aug 18** 1←→2 tg tx error **aug 20** 1←→2 ping errors **aug 28** 1←→2 ping errors **sept 1** 1←→2 ping error **sept 2** 1←→2 ping error **sept 7** 1←→2 tg error

Table 3.2 IP availability results from August 16 to September 7. Dates written in green letters indicate experiment errors not caused by Iridium failure. Red letters indicates SatCom error.

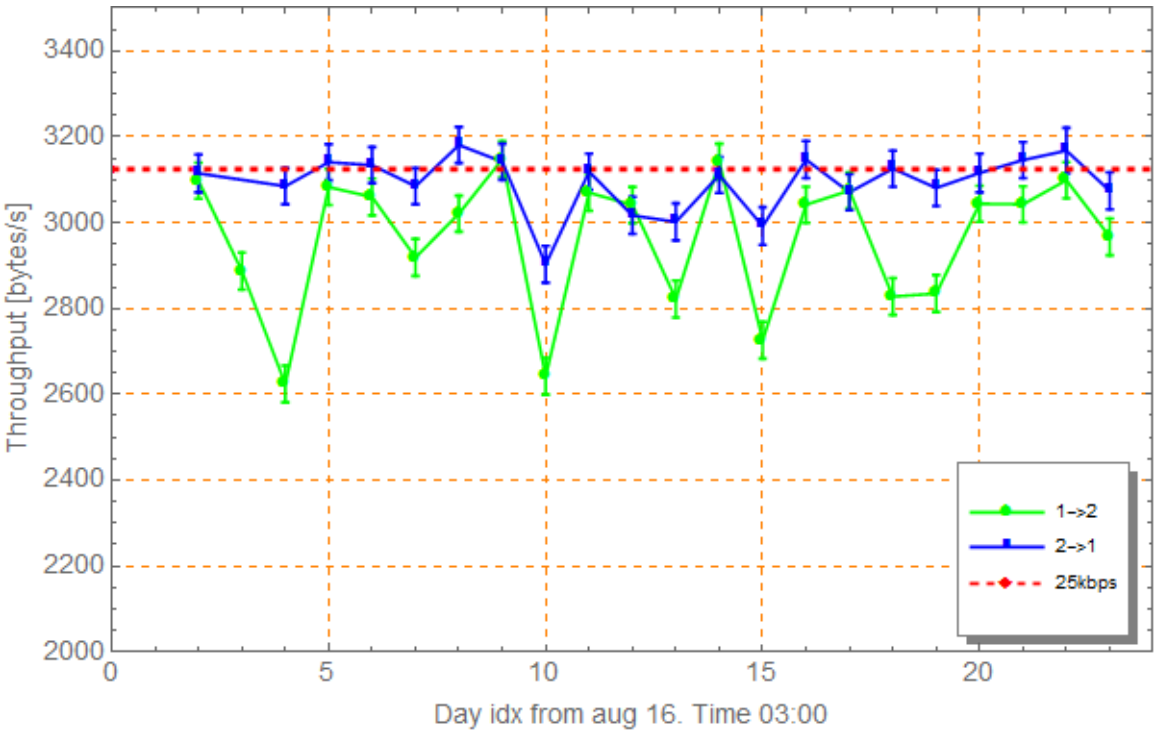


Figure 3.1 Measured throughput at 03:00. Day idx is the index of the test dates. Example: idx = 5 is August 20.

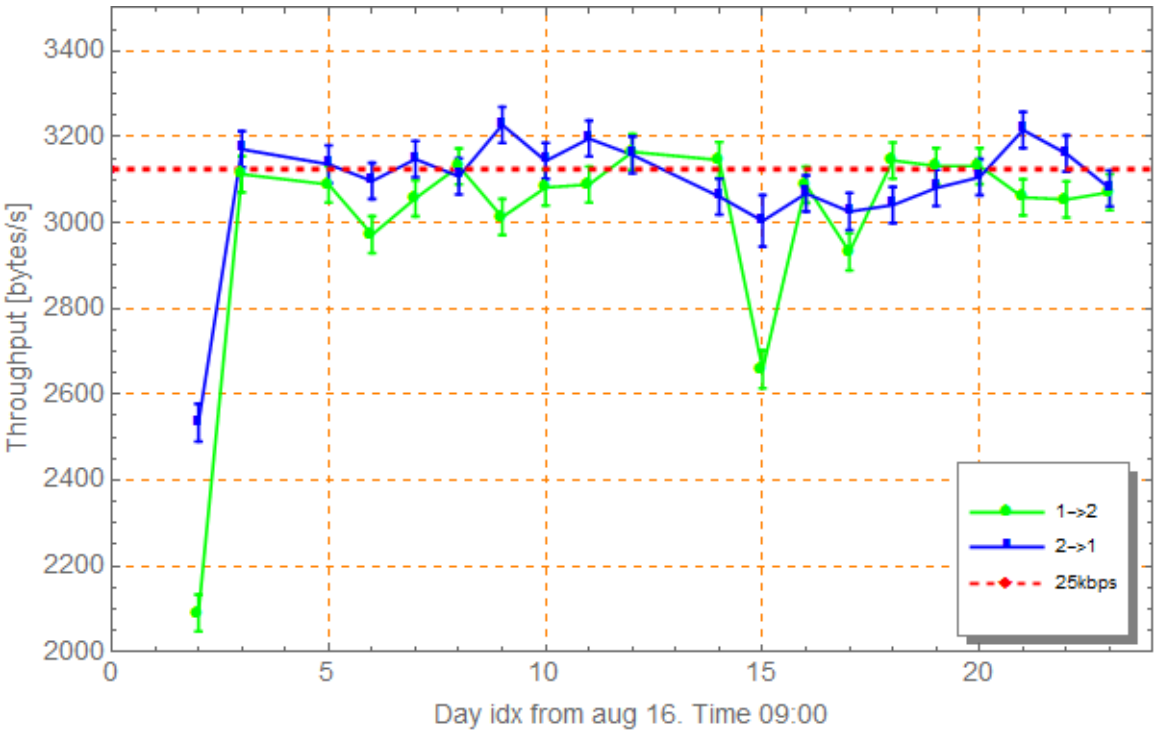


Figure 3.2 Measured throughput at 09:00.

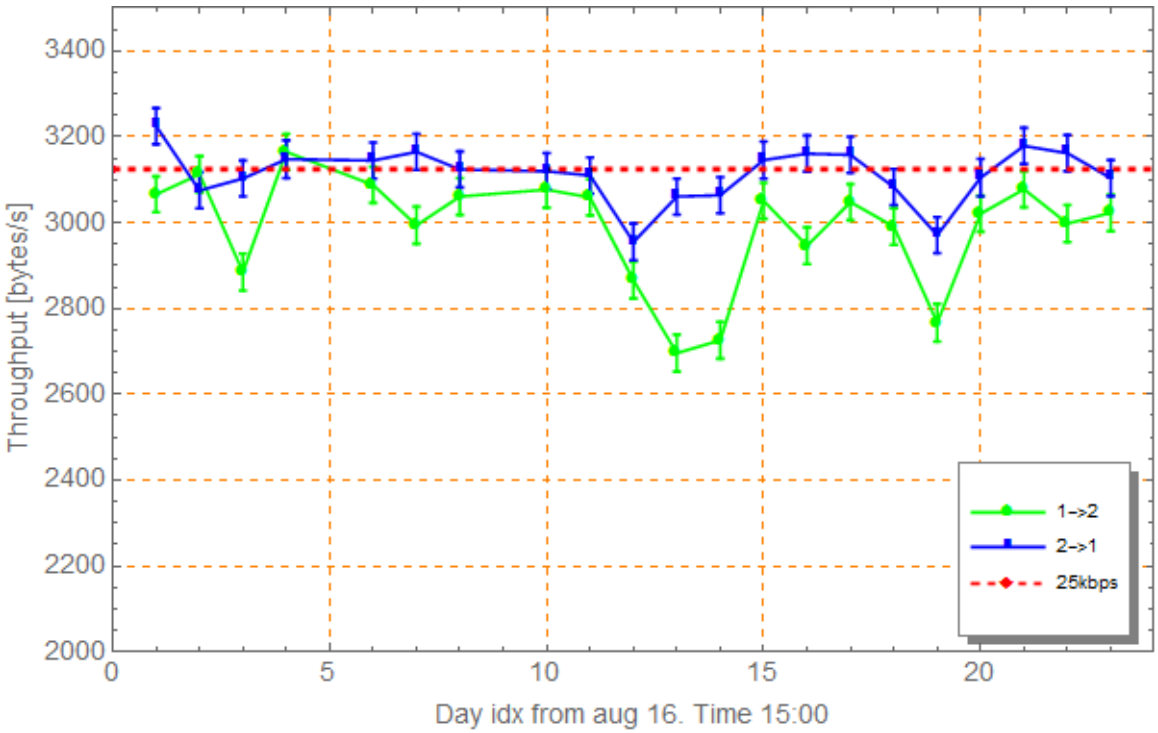


Figure 3.3 Measured throughput at 15:00.

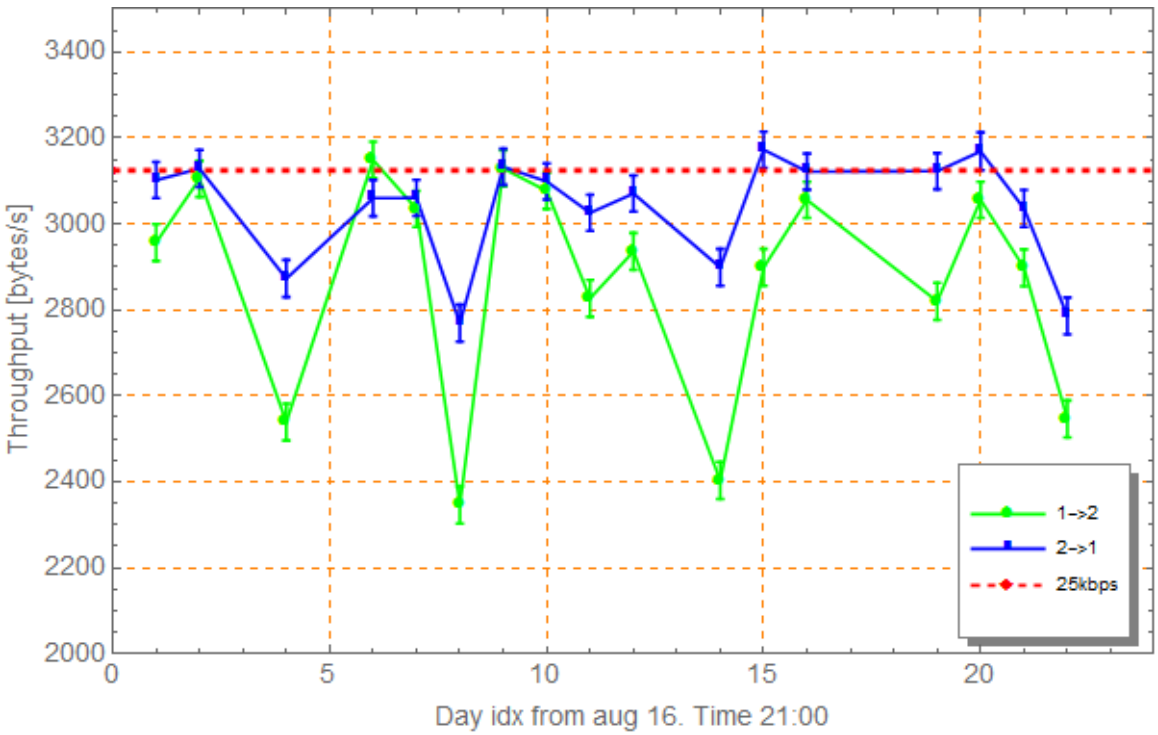


Figure 3.4 Measured throughput at 21:00.

3.2.1 Samples at UTC 2019-08-19T03:00

At the time instance 2019-08-19T03:00 in Figure 3.1, the stream 2→1 has a low loss rate while the opposite direction experiences a significant loss rate. With the intention to find an explanation of this difference, the traffic situation at this time instance is analysed below.

The MGEN listen files have a 900 seconds time window and the total number of samples is 5554 + 4721 (= the number of packets successfully delivered), TG1 receives more packets than TG2. We have no indications of a faulty experiment. The packet loss rates are:

1→2: 14%
2→1: 0.7%

Figure 3.5 plots the packet event time-series. Note the gaps in the packet success line (blue) which are time periods where the IP service is unavailable – no packets are served. Both directions experience the block periods at the same time. Because the stream 2→1 has larger network buffers (=Internet) than the direction 1→2, the stream 2→1 loses less packets.

The consecutive packet loss count plots in Figure 3.6 show high values at the same time instances as the gaps in Figure 3.5. The MGEN log lines at elapsed time 395 s are:

TG1 listen log:

```
03:07:02.890934 RECV proto>UDP flow>201101 seq>1737 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:02.421454
03:07:02.891646 RECV proto>UDP flow>201101 seq>1738 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:02.432343
03:07:33.230613 RECV proto>UDP flow>201101 seq>1750 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:05.400790
03:07:33.411357 RECV proto>UDP flow>201101 seq>1751 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:05.753912
03:07:33.411565 RECV proto>UDP flow>201101 seq>1752 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:05.767588
```

1750-1738 - 1= 11 lost packets and the blocking duration is 33 - 2 = 31 s.

TG2 listen log:

```
03:06:47.158151 RECV proto>UDP flow>102101 seq>1589 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:06:44.27
03:06:47.248525 RECV proto>UDP flow>102101 seq>1590 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:06:44.37
03:06:47.254041 RECV proto>UDP flow>102101 seq>1591 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:06:44.38
03:07:31.732741 RECV proto>UDP flow>102101 seq>1858 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:07:29.45
03:07:32.632510 RECV proto>UDP flow>102101 seq>1859 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:07:29.61
03:07:33.442774 RECV proto>UDP flow>102101 seq>1860 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:07:29.67
03:07:34.342653 RECV proto>UDP flow>102101 seq>1861 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:07:29.75
03:07:35.152768 RECV proto>UDP flow>102101 seq>1862 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:07:30.06
```

1858 - 1591 - 1= 266 lost packets and the blocking duration is 44 s.

The MGEN log lines at elapsed time 960 s are:

TG1 listen log:

```
03:16:11.957608 RECV proto>UDP flow>201101 seq>5177 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:16:11.369632
03:16:11.958094 RECV proto>UDP flow>201101 seq>5178 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:16:11.426884
03:16:12.046825 RECV proto>UDP flow>201101 seq>5179 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:16:11.483680
03:16:54.435228 RECV proto>UDP flow>201101 seq>5195 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:16:14.798642
03:16:54.435550 RECV proto>UDP flow>201101 seq>5196 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:16:14.807008
03:16:56.240823 RECV proto>UDP flow>201101 seq>5197 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:16:14.972544
03:16:56.241033 RECV proto>UDP flow>201101 seq>5198 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:16:15.110510
```

5195-5179 - 1= 15 lost packets and the blocking duration is 54 - 12 = 42 s.

TG2 listen log:

```
03:16:04.172293 RECV proto>UDP flow>102101 seq>4956 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:15:56.59
03:16:04.172610 RECV proto>UDP flow>102101 seq>4957 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:15:56.66
03:16:54.862137 RECV proto>UDP flow>102101 seq>5332 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:16:52.50
03:16:55.672613 RECV proto>UDP flow>102101 seq>5333 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:16:52.70
03:16:56.572423 RECV proto>UDP flow>102101 seq>5334 src>193.220.213.31/61187 dst>128.39.8.30/5001 sent>03:16:52.75
```

5332 - 4957 - 1= 374 lost packets and the blocking duration is 54 - 4 = 50 s.

The total blocking durations are 75 s and 81 s while the difference in loss rate is high. We assume that the 1→2 packet loss rate can be reduced by increasing the outgoing buffer size in TG1. Figure 3.7 shows that the packet delay is significantly higher in the 2→1 direction which supports the explanation of having a larger buffer space than in the opposite direction 1→2 direction.

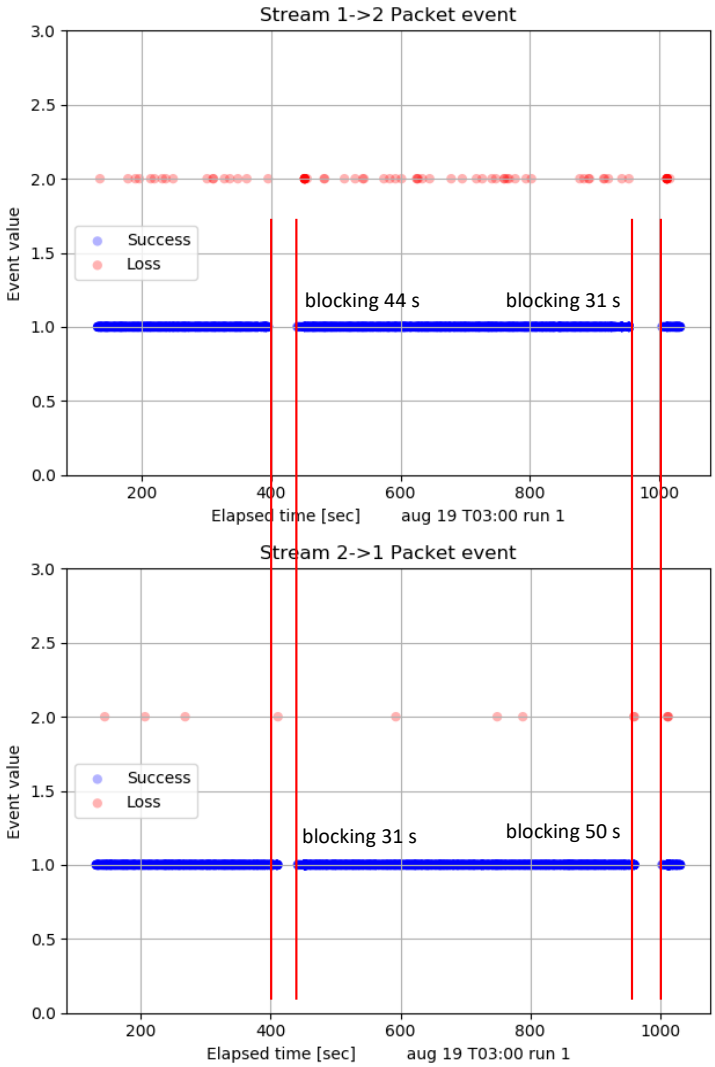


Figure 3.5 Packet events as a time-series.

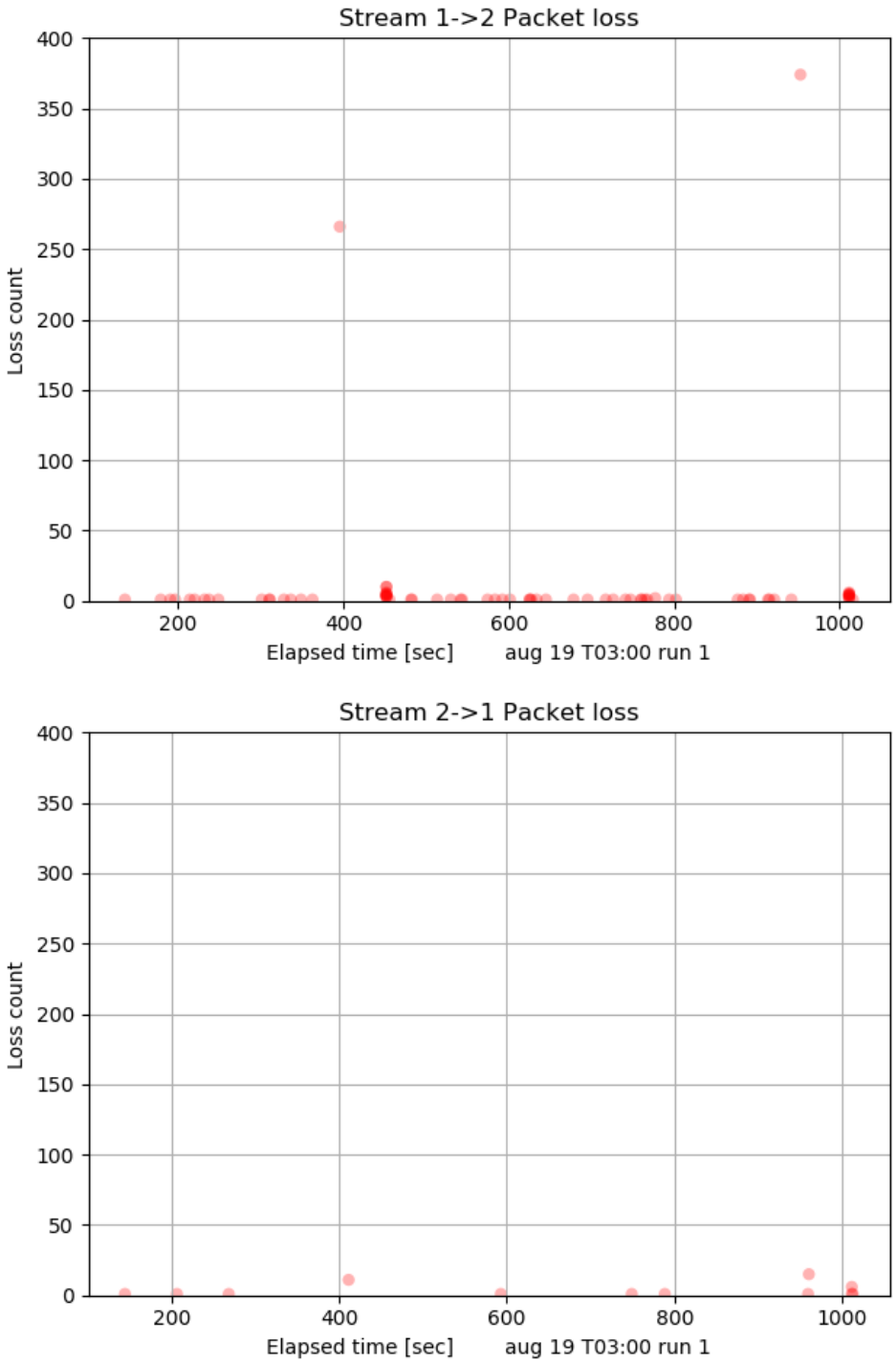


Figure 3.6 CLC as time-series.

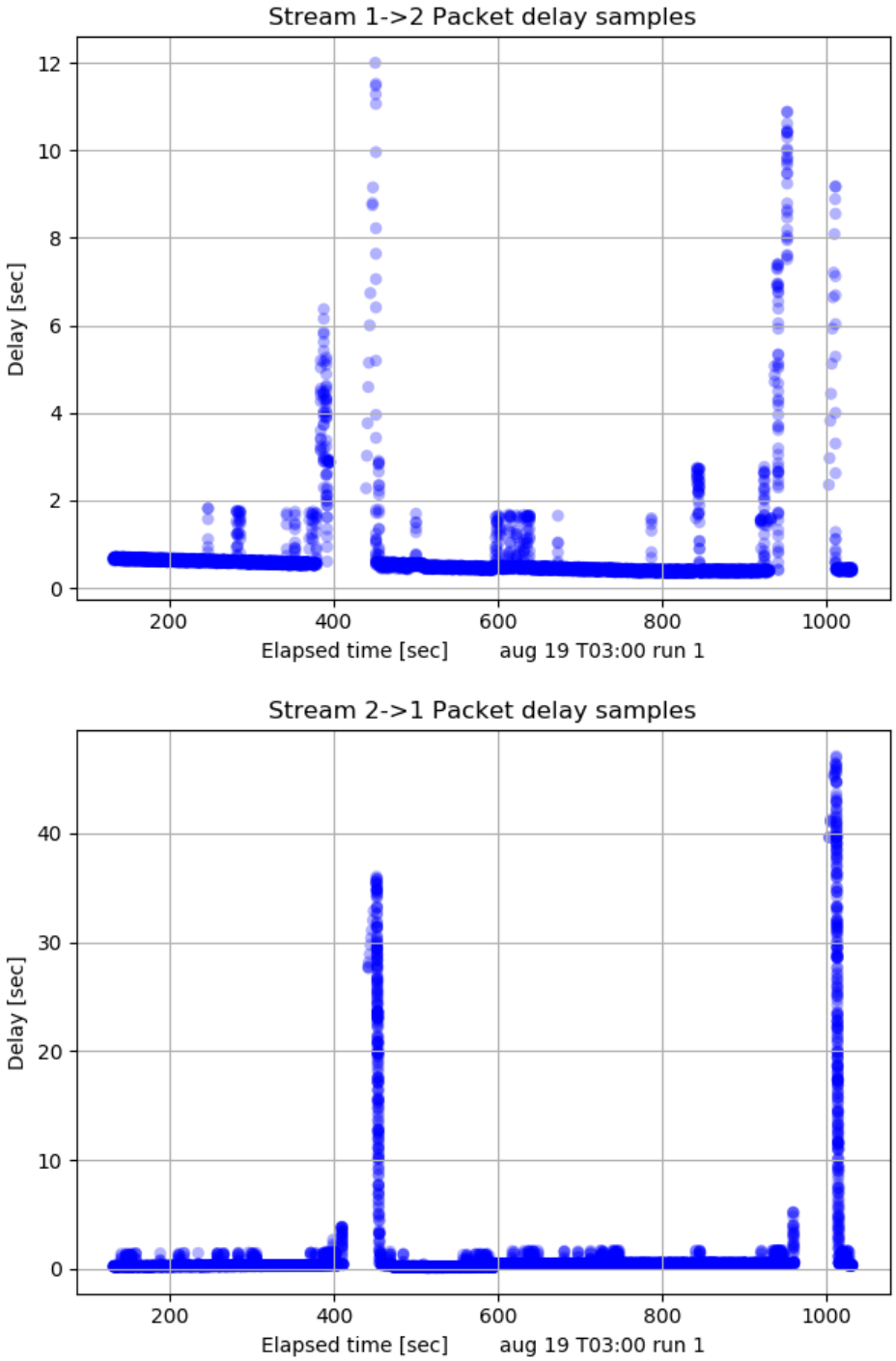


Figure 3.7 Packet delay as a time-series. Note: the y-scaling differs.

3.2.2 Samples at UTC 2019-08-27T15:00

At the time instance 2019-08-27T15:00 in Figure 3.3, both streams experience high loss rates while we have no indications of a faulty experiment. The packet loss rates are:

1→2: 9%
2→1: 4%

From Figure 3.8 and Figure 3.9 we see that one long blocking period occurs during the test period, but in contrast to the previous section 3.2.1, even the stream 2→1 experiences high average loss (0.7 % vs. 4 %).

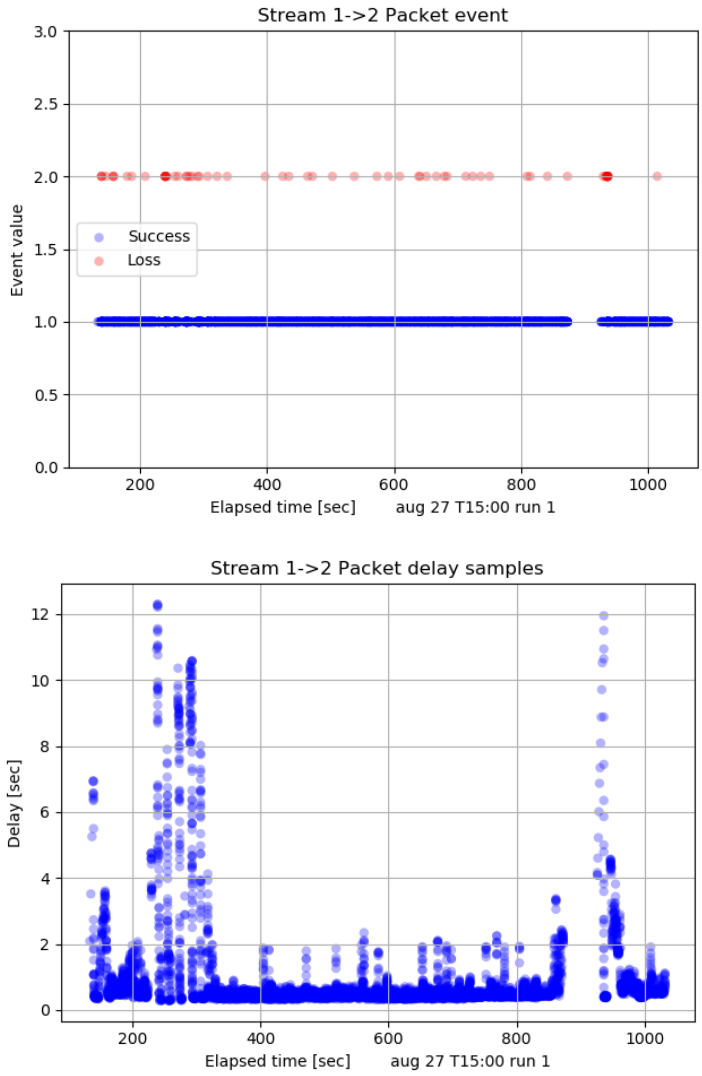


Figure 3.8 Samples at 2019-08-27T15:00.

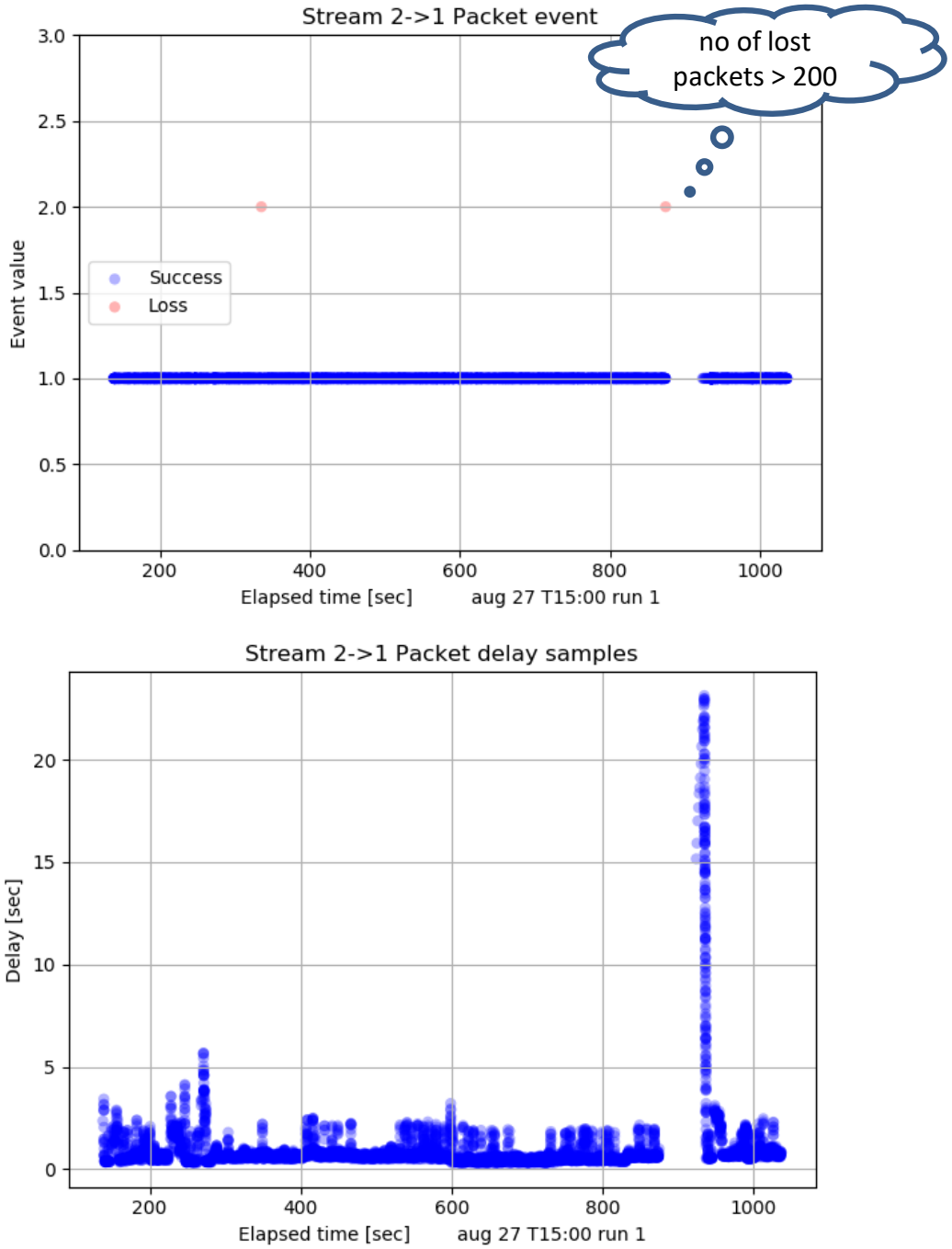


Figure 3.9 Samples at 2019-08-27T15:00.

4 Lab testing in June

This chapter presents the laboratory testing performed in June at Kjeller. The test environment had excellent radio conditions without terminal mobility. We used a *pre-release SIM card*.

Finding F4: The Iridium service has extremely bad quality and further testing in the Arctic is not necessary with this SIM card.

Section 4.1 shows that the measured throughput capacity is far below the expected value and even worse, the network is unstable. The results were so discouraging that we had to validate the results with another IP generator, IxChariot. We performed a number of stability tests with IxChariot, see section 4.2, and these tests confirmed finding F3.

The lab tests performed in August showed improved service quality, see chapter 5, and we assume the problems were caused by:

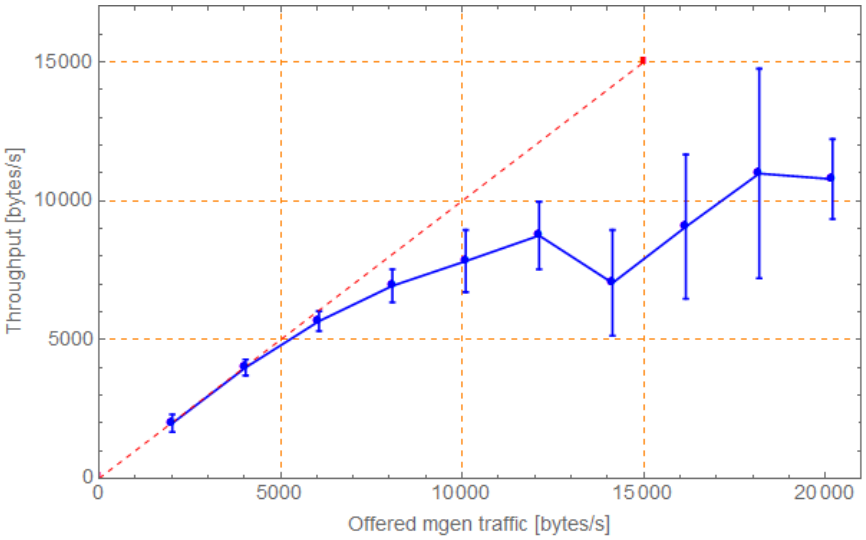
1) use of a premature SIM card
2) the service provider was unable to configure the card correctly (we changed the SIM card provider for the tests in August)

4.1 UDP throughput capacity

We measured the throughput capacity by increasing the offered traffic stepwise until saturation was reached. The packet generation distribution used was Poisson. Two independent trials were executed with the following results:

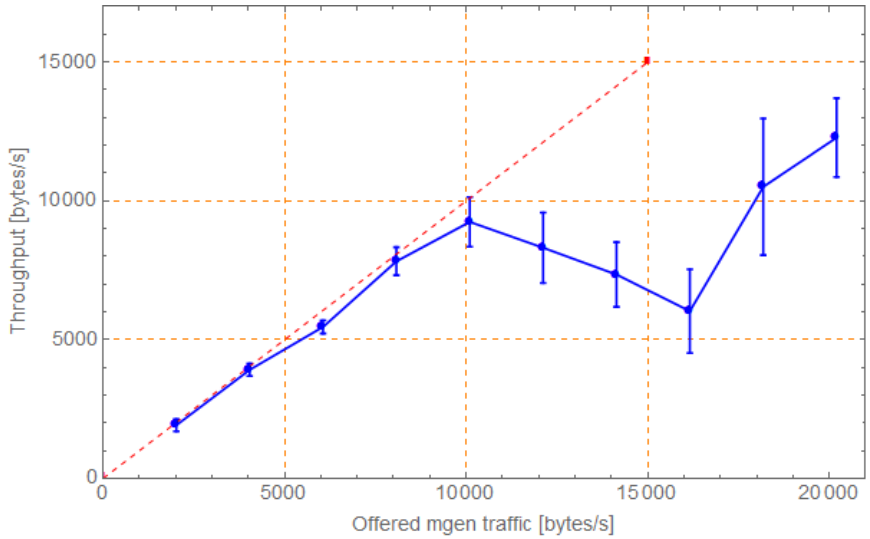
Trial 1: 12 pkps, 6050 bytes/s, 48 kbps
Trial 2: 20 pkps, 10100 bytes/s, 81 kbps

The throughput capacity is significantly lower than the expected 352 kbps. The up-and-down in Figure 4.1 and Figure 4.2 indicate time-variant throughput capacity.



runNumber	Rx WindowSize[sec]	±P0	±P1	±P2	±P3	±sumPi
1	118.183	478	0	0	0	478
2	119.888	960	0	0	0	960
3	119.867	1361	0	0	0	1361
4	119.871	1666	0	0	0	1666
5	121.226	1958	0	0	0	1958
6	119.778	2101	0	0	0	2101
7	118.83	1691	0	0	0	1691
8	152.457	2812	0	0	0	2812
9	86.2042	1978	0	0	0	1978
10	120.345	2696	0	0	0	2696
11	-99 999 999	0	0	0	0	0

Figure 4.1 Throughput at 95% confidence levels vs offered traffic. Sample period per load level: 120 sec.



runNumber	Rx WindowSize[sec]	±P0	±P1	±P2	±P3	±sumPi
1	119.334	461	0	0	0	461
2	119.608	940	0	0	0	940
3	119.77	1311	0	0	0	1311
4	119.923	1878	0	0	0	1878
5	121.214	2311	0	0	0	2311
6	119.153	1995	0	0	0	1995
7	120.767	1837	0	0	0	1837
8	127.905	1568	0	0	0	1568
9	111.152	2417	0	0	0	2417
10	119.997	2947	0	0	0	2947
11	-99 999 999	0	0	0	0	0

Figure 4.2 Throughput at 95% confidence levels vs offered traffic. Sample period per load level: 120 sec. Trial 2.

4.2 Network stability testing

Section 4.1 indicates time-variant performance. In this section, the traffic generators are configured to provide a constant load level and we observe the throughput performance as time-series. Here we use a traffic generator (IxChariot) that provides improved functions to debug network problems. The configuration used:

Traffic: UDP fixed payload 500 bytes (random byte values).
UDP stream: TG1→TG2.
Packet arrival distribution: Periodic

Figure 4.3 to Figure 4.5 show a selected set of results and they are bad - the packet loss rate is high already at 80 kbps:

Offered traffic	average loss rate
1 kbps	1%
80 kbps	15%
100 kbps	27%
150 kbps	67%
320 kbps	76%

Note: The quality of the Iridium channel is so bad that some of the IxChariot tests failed.

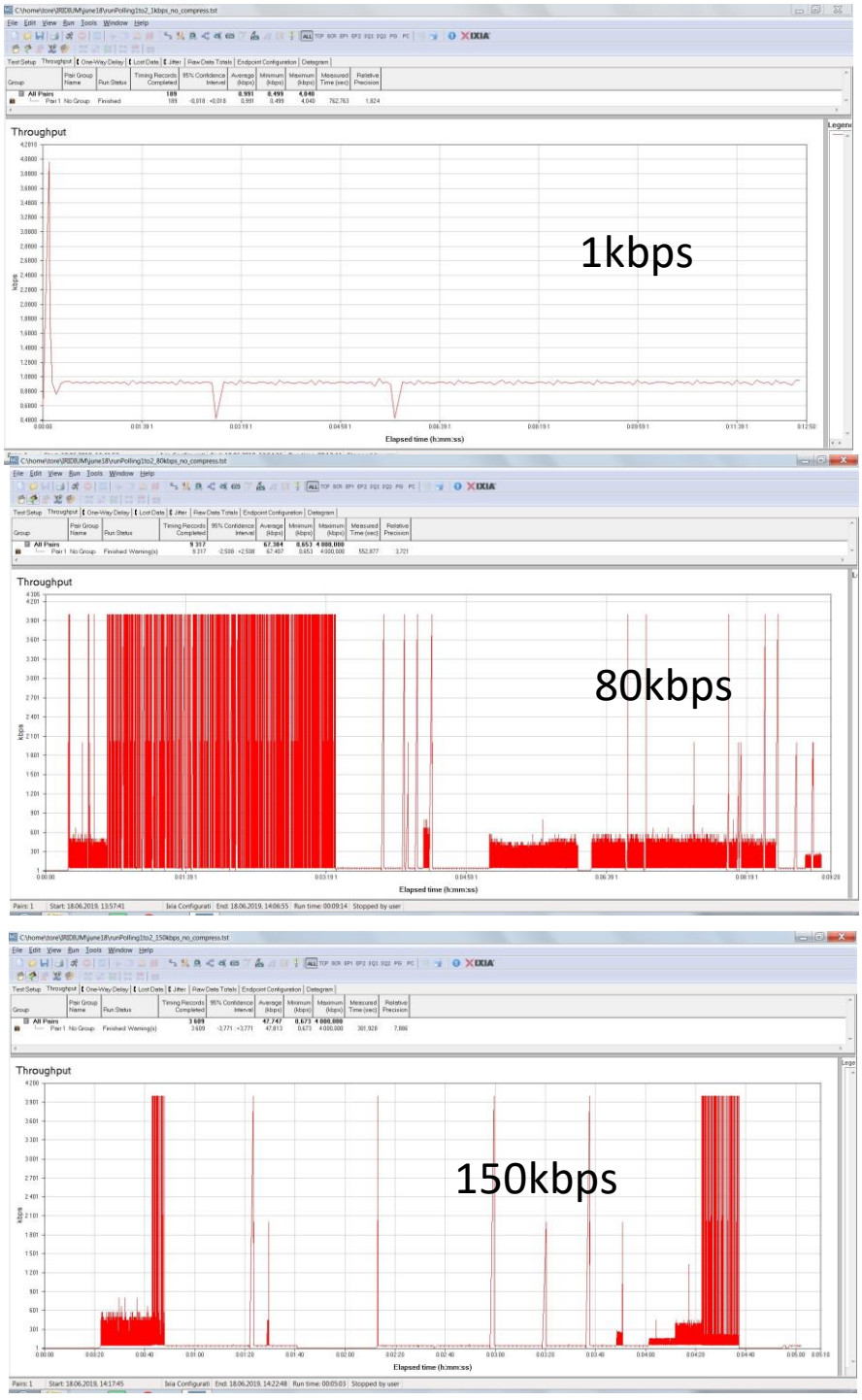


Figure 4.3 Measured throughput at constant load {1, 80, 150} kbps.

Figure 4.4 Measured loss at constant load {1, 80, 150} kbps.

Figure 4.5 Measured delay at constant load {1, 80, 150} kbps.

5 Lab testing in August

At the beginning of August, we received a production version of the SIM card and repeated the tests done in June.

Finding F5: The quality of the IP service has improved, but the packet loss rate is still too high at low load levels.

Section 5.1 below repeats the network stability tests described in section 4.2. Table 5.1 shows significant improvements with the new SIM card. However, 15 % packet loss rate at 50 kbps is not acceptable.

Offered traffic [kbps]	**June**	**August**
1	1	
25		4
50		15
80	15	
100	27	
150	67	14
250		17
3207	76	

Table 5.1 Measured packet loss rate [%] (without confidence control). Test tool is IxChariot.

5.1 Network stability testing

This section performs the same tests as in section 4.2. Figure 5.1 to Figure 5.4 show a selected set of the results. The service still has unacceptably high loss rate at low load levels:

Offered traffic	average loss rate
25 kbps	4%
50 kbps	15%
150 kbps	14%
250 kbps	17%

Note: The quality of the Iridium channel is so bad that some of the IxChariot tests failed.

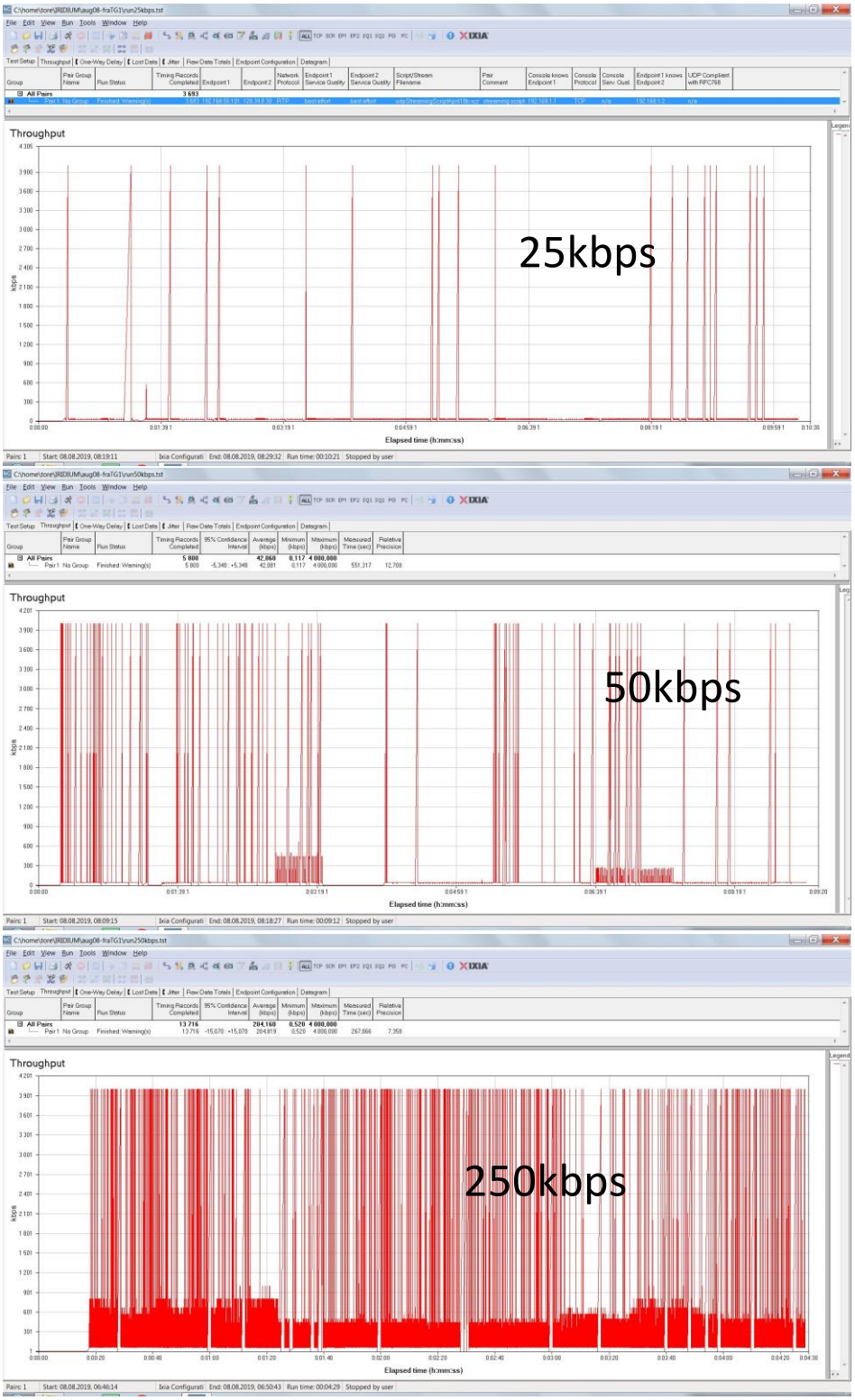


Figure 5.1 Measured throughput at constant load {25, 50, 250} kbps.

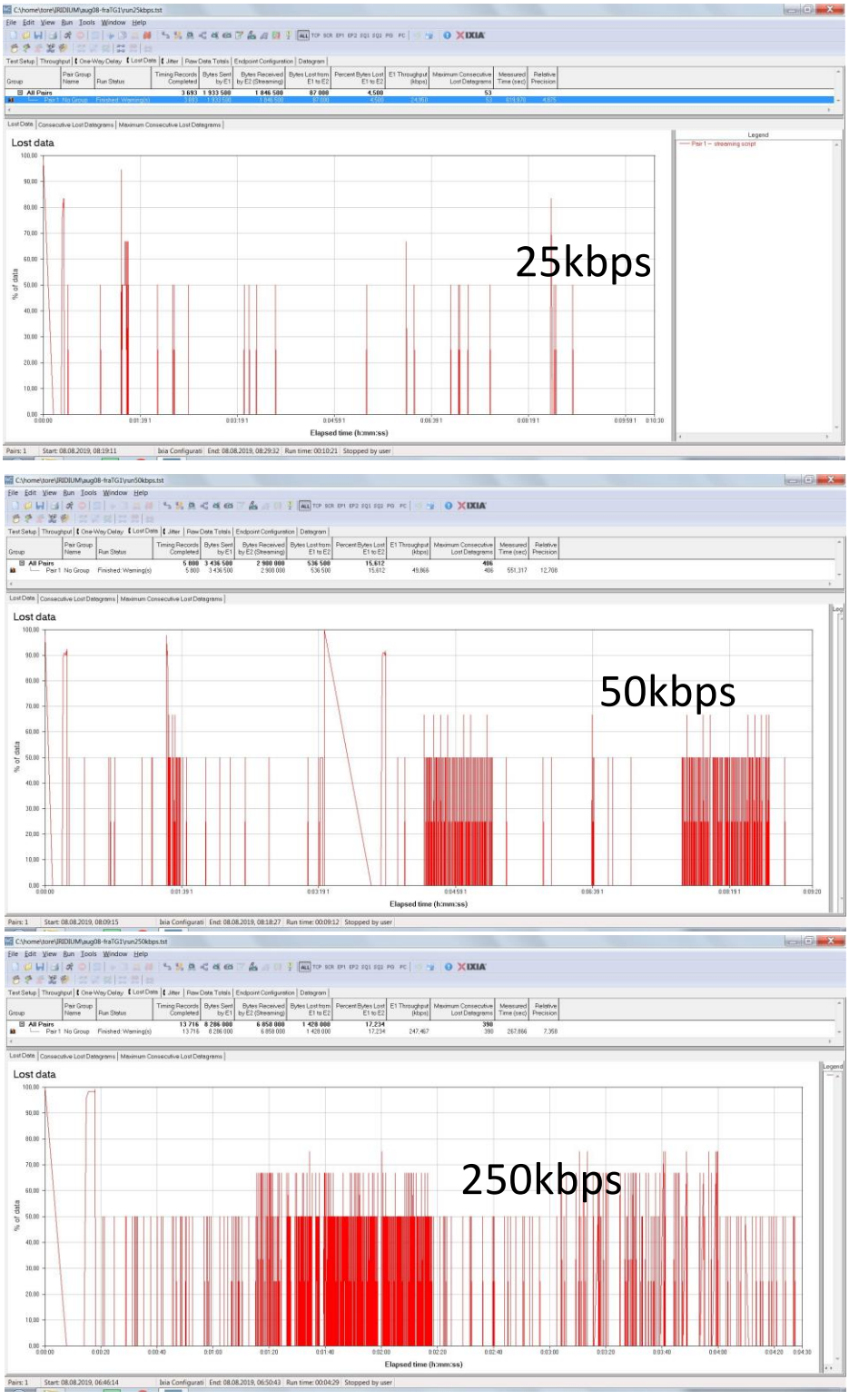


Figure 5.2 Measured loss at constant load {25, 50, 250} kbps.

Figure 5.3 Measured delay at constant load {25, 50, 250} kbps.

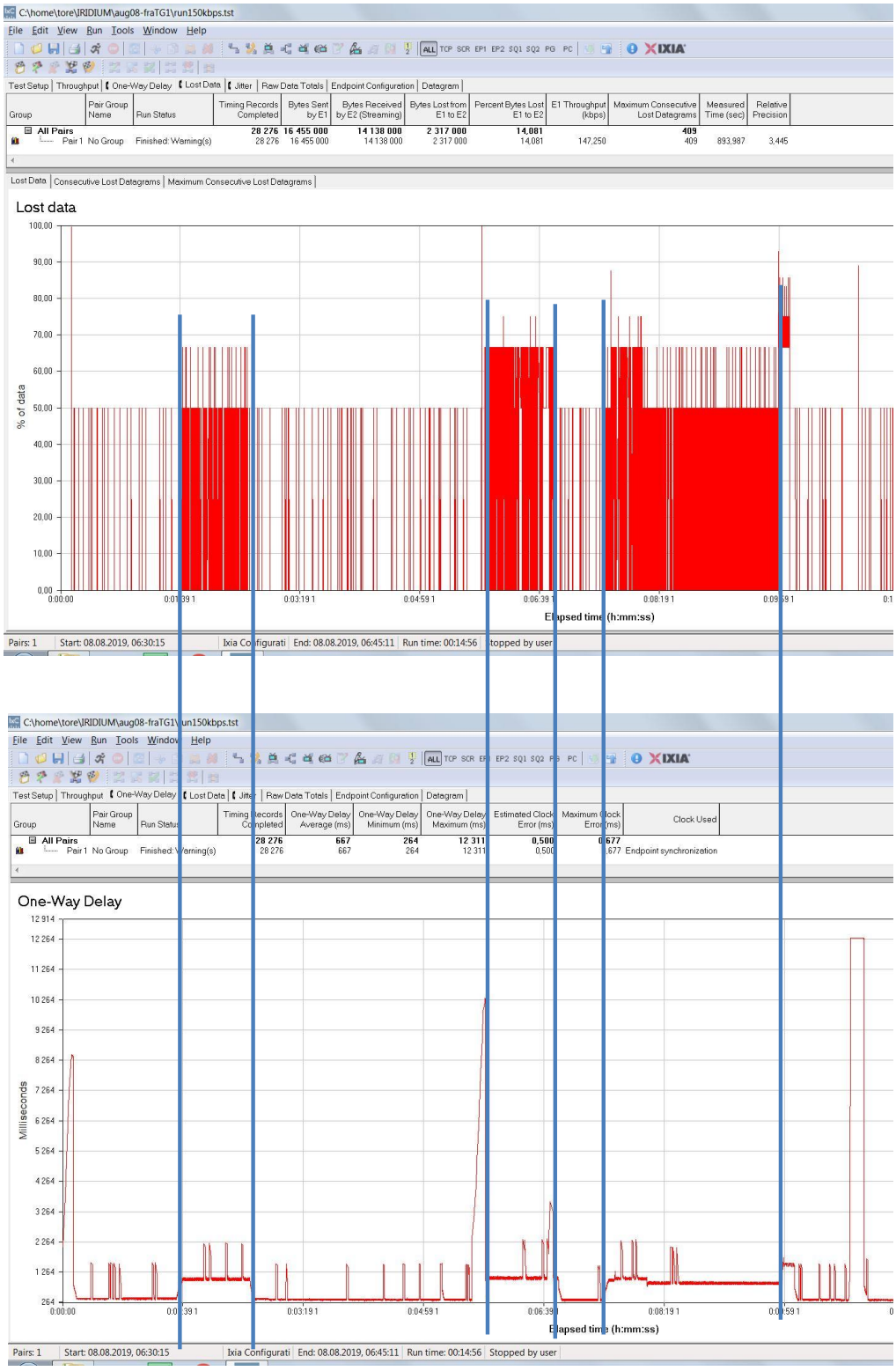


Figure 5.4 Measured loss and delay at 150 kbps offered traffic.

6 Lab testing in October

The lab tests in June and August showed bad performance results compared to the test results from the Arctic. Therefore we found it necessary to make additional measurements in October to validate the results.

The equipment and the test scripts used were exactly the same as in the Arctic. However, only availability tests were conducted.

Finding F6: The availability was excellent but the IP packet loss rate was high during some time periods. See section 6.1.

The main reason why this availability test was better than the test in the Arctic is that we removed the "1) Ping succeed", see section 3.2. Then less error events occurred. The ping test should not have been included during the tests in the Arctic.

Table 6.1 summarises the tests done at FFI from October 12 to November 12. Neither TG-error events nor SatCom error events occurred.

Figure 6.1 to Figure 6.4 present the throughput measured in this test period.

UTC time	03:00	09:00	15:00	21:00
#errors	0	0	0	0
#tests	32	32	32	32
#tg errors	0	0	0	0
#sat failure	0	0	0	0
sat error rate	0	0	0	0

Table 6.1 IP availability results from October 12 to November 12.

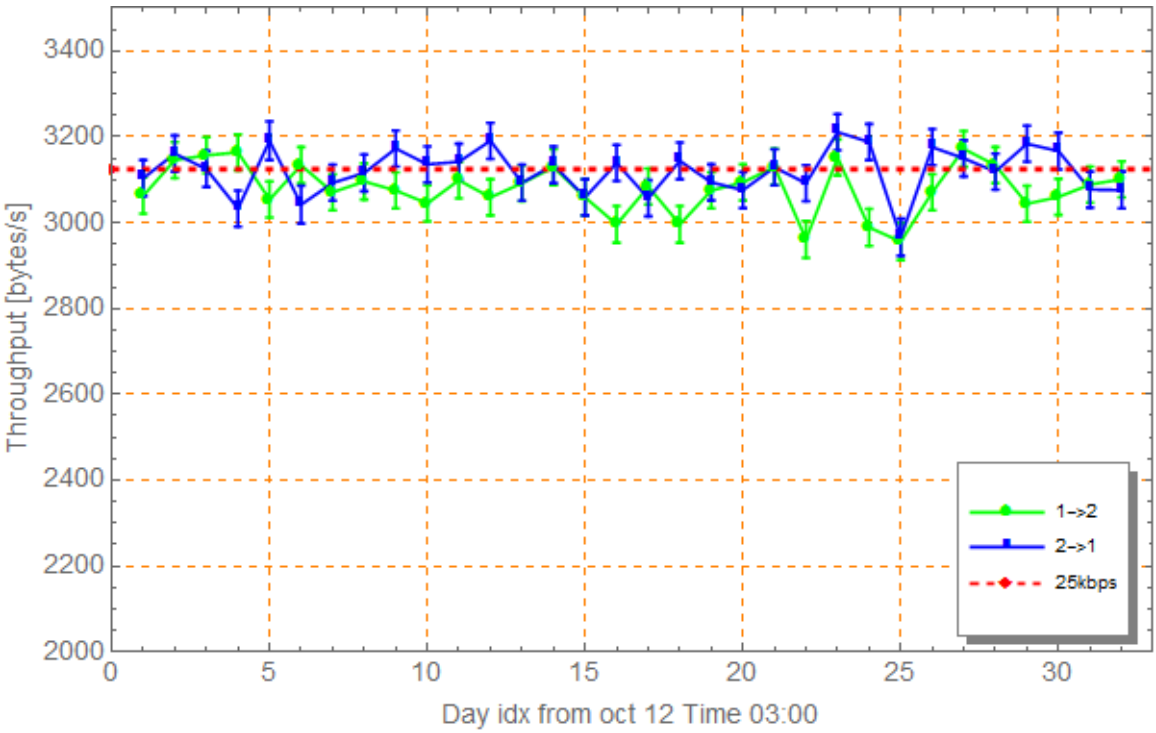


Figure 6.1 Measured throughput at 03:00.

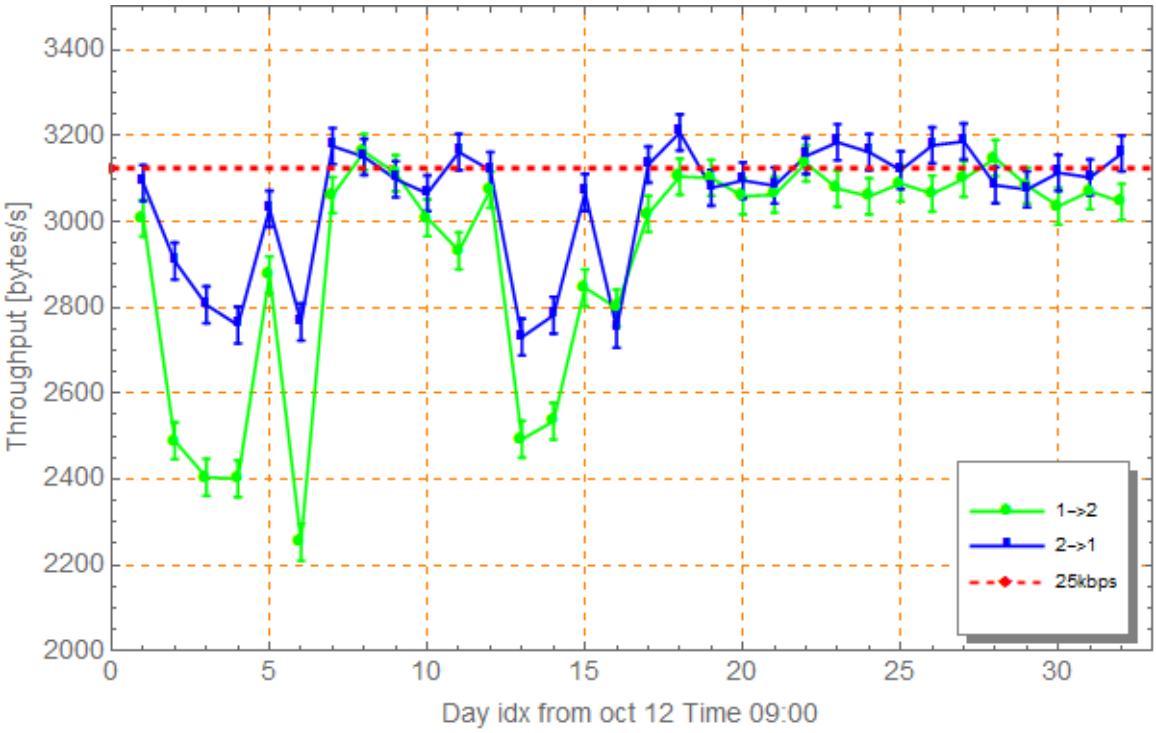


Figure 6.2 Measured throughput at 09:00.

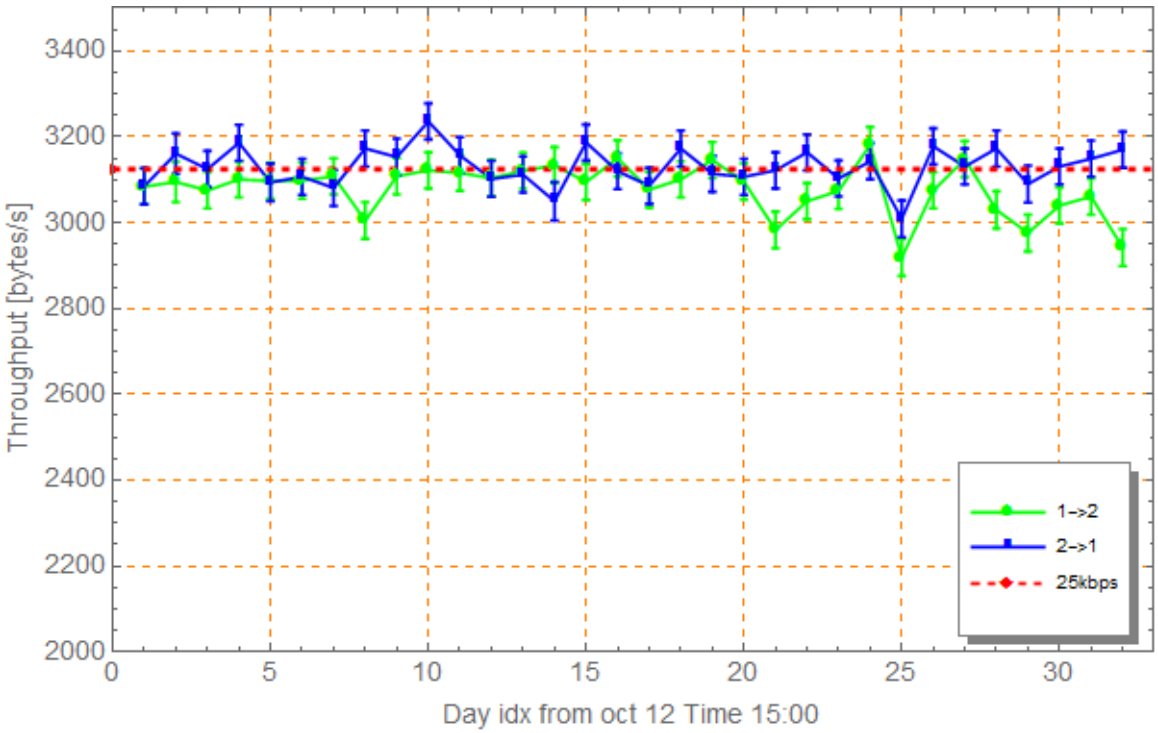


Figure 6.3 Measured throughput at 15:00.

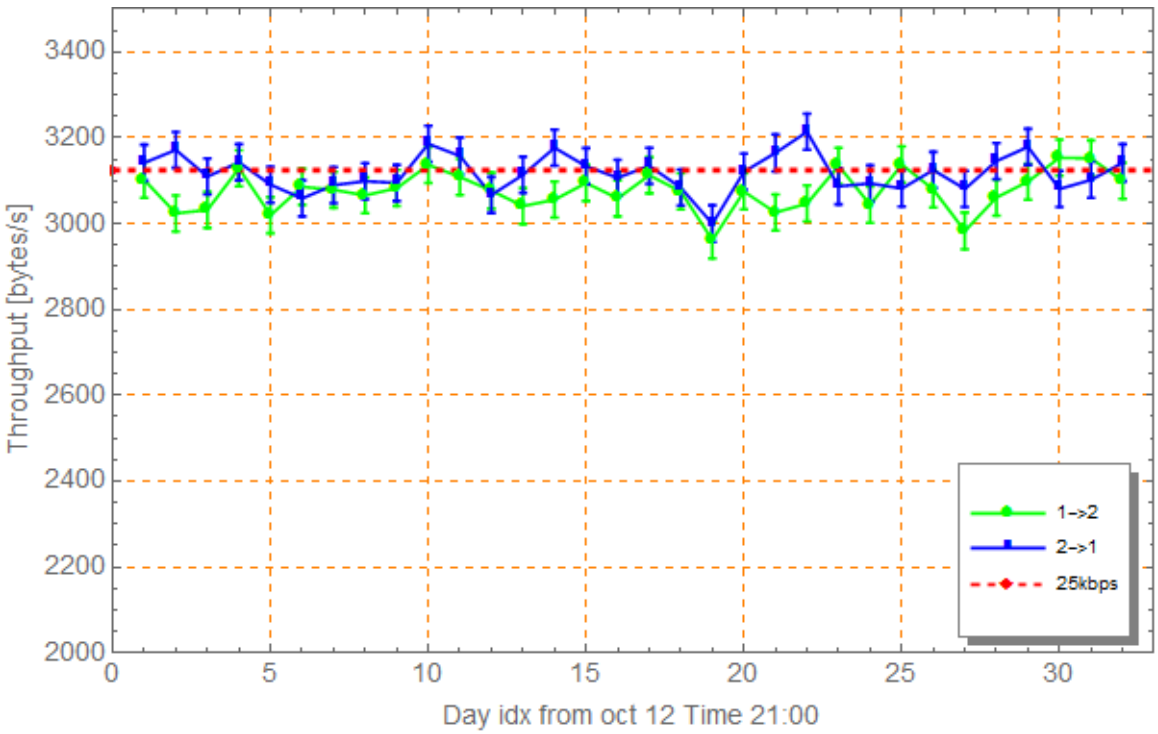


Figure 6.4 Measured throughput at 21:00.

6.1 Samples October 14

Even with low offered traffic, the packet loss rate was high in some tests. This section takes a closer look at the situation. At October 14th 03:00 and 09:00 we measured low and high loss rate, respectively:

Time 03:00 (low loss)
Stream 1->2 number of lost packets: 34 of #sent 5710 loss rate [%]: 0.60
Stream 2->1 number of lost packets: 2 of #sent 5622 loss rate [%]: 0.04
Time 09:00 (high loss)
Stream 1->2 number of lost packets: 1263 of #sent 5586 loss rate [%]: **22.6**
Stream 2->1 number of lost packets: 613 of #sent 5655 loss rate [%]: **10.8**

The offered traffic is 25 kbps only and to measure 22 % loss rate over a period of 15 minutes indicates bad service quality. Figure 6.5 plots the packet events versus time, which clearly indicates that the test started at 09:00 got a long blocking period at 800 s – the thick blue line has a gap. The loss count figure (Figure 6.6) tells that up to 340 consecutive packets are lost. During the blocking period, the queue size increases and the packet delay also increases (Figure 6.7).

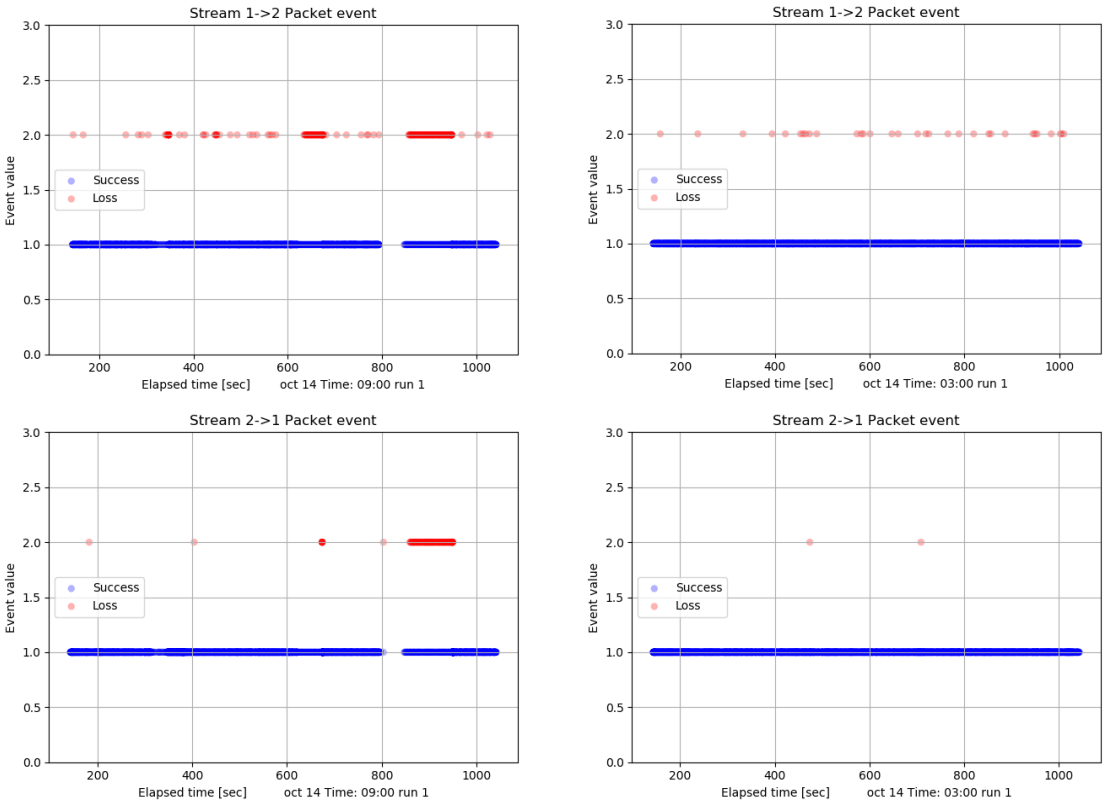


Figure 6.5 Packet loss event as time-series.

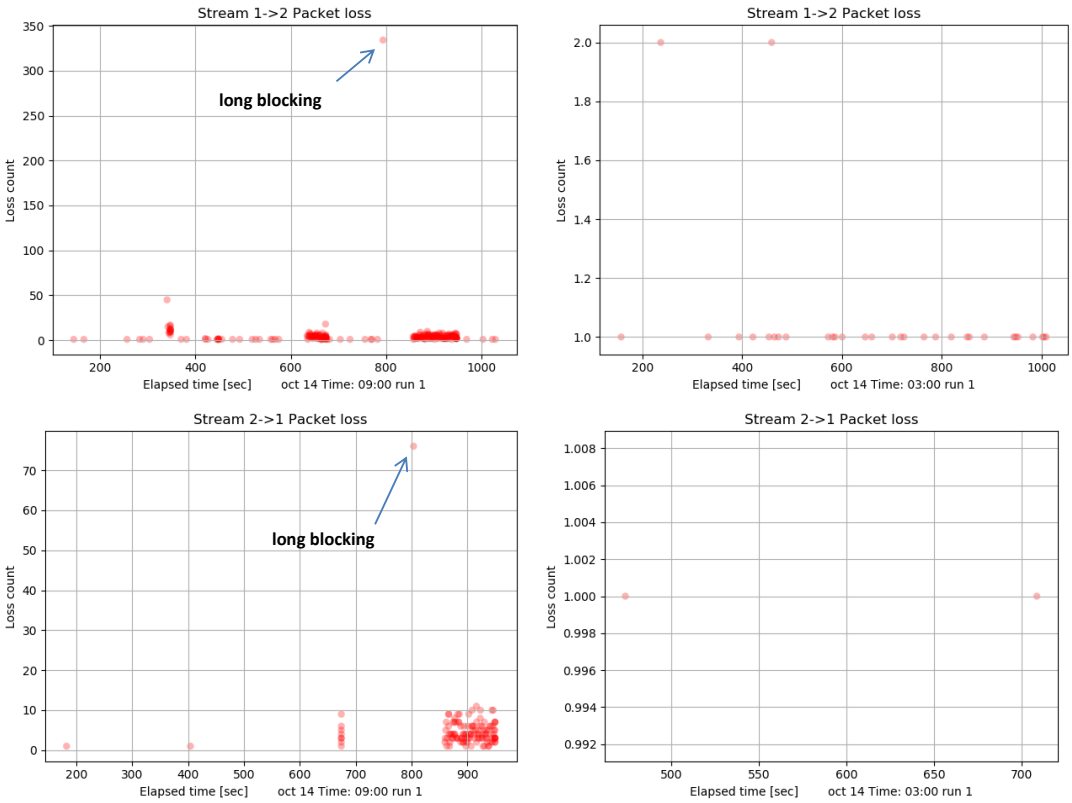


Figure 6.6 Packet loss count as time-series.

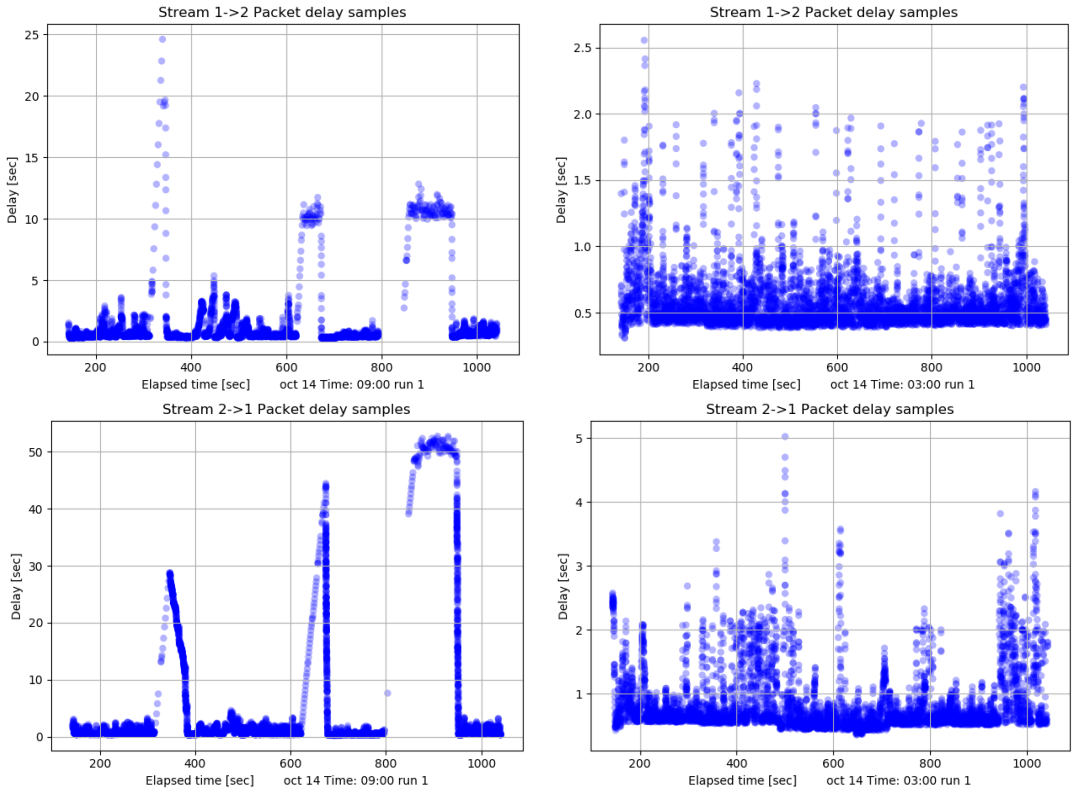


Figure 6.7 Packet delay as time-series.

7 Conclusions

The objectives of the Iridium field tests were to find answers to the following questions:

1) What is the probability of having access to the IP service in the Arctic (availability)?
2) What UDP throughput capacity can we expect in the Arctic?

Here the term availability means to get some packets through during a fixed time period of 15 minutes.

The Thales VesseLINK Iridium Certus modem was used in all the tests. Other modems may give other results since a critical component is the handover algorithm between the modem and the satellites.

C1: The IP service availability in the Arctic is good.

We measured 91 % availability in the Arctic (section 3.2), which should have been characterised as bad[9]. However, this value is too pessimistic due the design of the test. The laboratory tests in October (chapter 6) concluded excellent availability (100 %) at Kjeller. Due to a problem of getting an operational SIM card in June, as well as the short test period available in August, the field testing started with non-optimal test scripts. If we remove the events "ping errors" (see Table 3.2) from the experiments in the Arctic, we get 100% availability.

C2: The main shortcoming with the Iridium service is the long time periods in which the IP-packets are not served, see Figure 7.1.

From experiments conducted we cannot prove which component in the Iridium network that causes the long blocking periods of the UDP streams. Long blocking periods were observed even at low load levels. Possible causes of this unwanted effect are: Bad handover software/algorithm in the modem, bad handovers between the satellites, high traffic load from other Iridium users, etc. Long blocking periods were also measured in the laboratory at Kjeller, see Figure 7.1. Appendix A.3.2 indicates that the modem does not provide seamless handover. Figure 7.1 supports this also because: 1) The number of blocking events was equal in both directions and 2) They occurred simultaneously in both directions.

C3: The probability of reaching the SIM card throughput capacity in the Arctic was measured to 45 %.

[9] Some users may be satisfied with 90% availability.

The SIM card used is specified to provide 352 kbps, but 55% of the tests reached a level significantly lower than 352 kbps (Table 3.1). The Iridium service provider states that our SIM card provides a best-effort service, which means that the 352 kbps is not a guaranteed performance. The Iridium IP service provides time-variant throughput capacity and it is the long and frequent blocking periods that cause the capacity degradation.

A benefit with Iridium is the low packet latency, 400 to 600 ms. However, in the time periods where Iridium does not serve the UDP stream, the packets are queued and we may measure high packet delays even at low load levels. This is exemplified by Figure 3.7 where delay values higher than 40 seconds are measured even at low load (25 kbps).

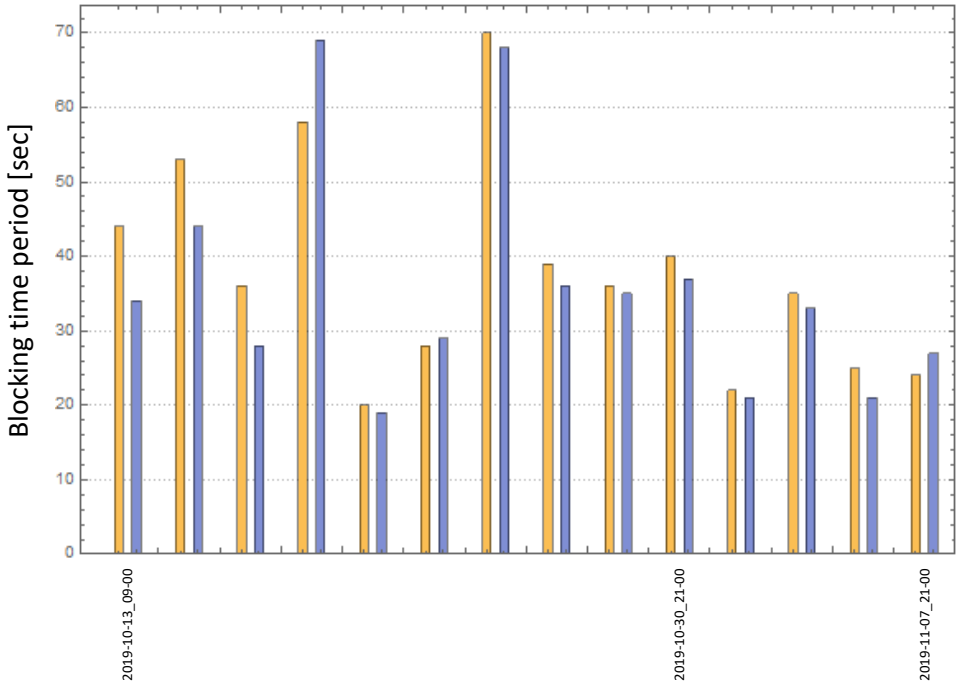


Figure 7.1 UDP stream blocking time periods measured at FFI/Kjeller in October/November. We measured 14 blocking events in each direction. Blocking occurred in both directions approximately at identical time instance. Data for the stream 1→2 is printed in blue. The other direction in yellow.
The data is extracted from the availability tests where the offered traffic is low (25 kbps). The average time between output packets from the traffic generators is 0.16 seconds. We consider that a blocking event has occurred if a packet delivery is delayed more than 10 seconds.

A Appendix: data from the Arctic

This appendix presents data analysis of the samples from the Arctic. The days missing are due to failed experiments.

A.1 August 23

The samples taken from August 14 to August 23 showed improved IP quality compared to the lab tests in August. As we gained confidence in the service quality, the offered traffic was increased. This chapter presents performance statistics at the default low load 25 kbps (section A.1.1) and high load 200 kbps (section A.1.2). Modem statistics are also presented in the sections A.1.3 and A.1.4.

The vessel position (not moving) is: Lat: 88.374 Long:52.328

The stream 2→1 had significant lower loss rates than the opposite direction, probably due to a larger buffer space in that direction. The packet receive event time plots illustrate clearly the difference (Figures A.1 and A.3).

From the modem statistics in the sections A.1.3 and A.1.4, we conclude that the average HO-rate is low. We expect the HO rate to be independent of the offered traffic since the handover events are trigged by radio channel quality between the modem and the satellites.

A.1.1 Performance statistics @25kbps

Network avg. throughput [bytes/s]: 6044.2
Stream 1->2 throughput [bytes/s] avg.: 3022.1
Stream 2->1 throughput [bytes/s] avg.: 3181.1
Network avg. delay [sec]: 1.11
Stream 1->2 delay [sec]: 1.11
Stream 2->1 delay [sec]: 1.13
Stream 1->2 number of lost packets: 157 of #sent 5594 loss rate [%]: 2.81
Stream 2->1 number of lost packets: 2 of #sent 5706 loss rate [%]: 0.04
Stream 1->2 (0102101) throughput [bytes/s] CI: 3021 +- 103
Stream 2->1 (0201101) throughput [bytes/s] CI: 3169 +- 98
Stream 1->2 (0102101) delay [sec] CI: 1.154 +- 0.310
Stream 2->1 (0201101) delay [sec] CI: 1.126 +- 0.123
Network throughput [bytes/s] CI: 6087 +- 207
Network delay [sec] CI: 0.761 +- 0.146

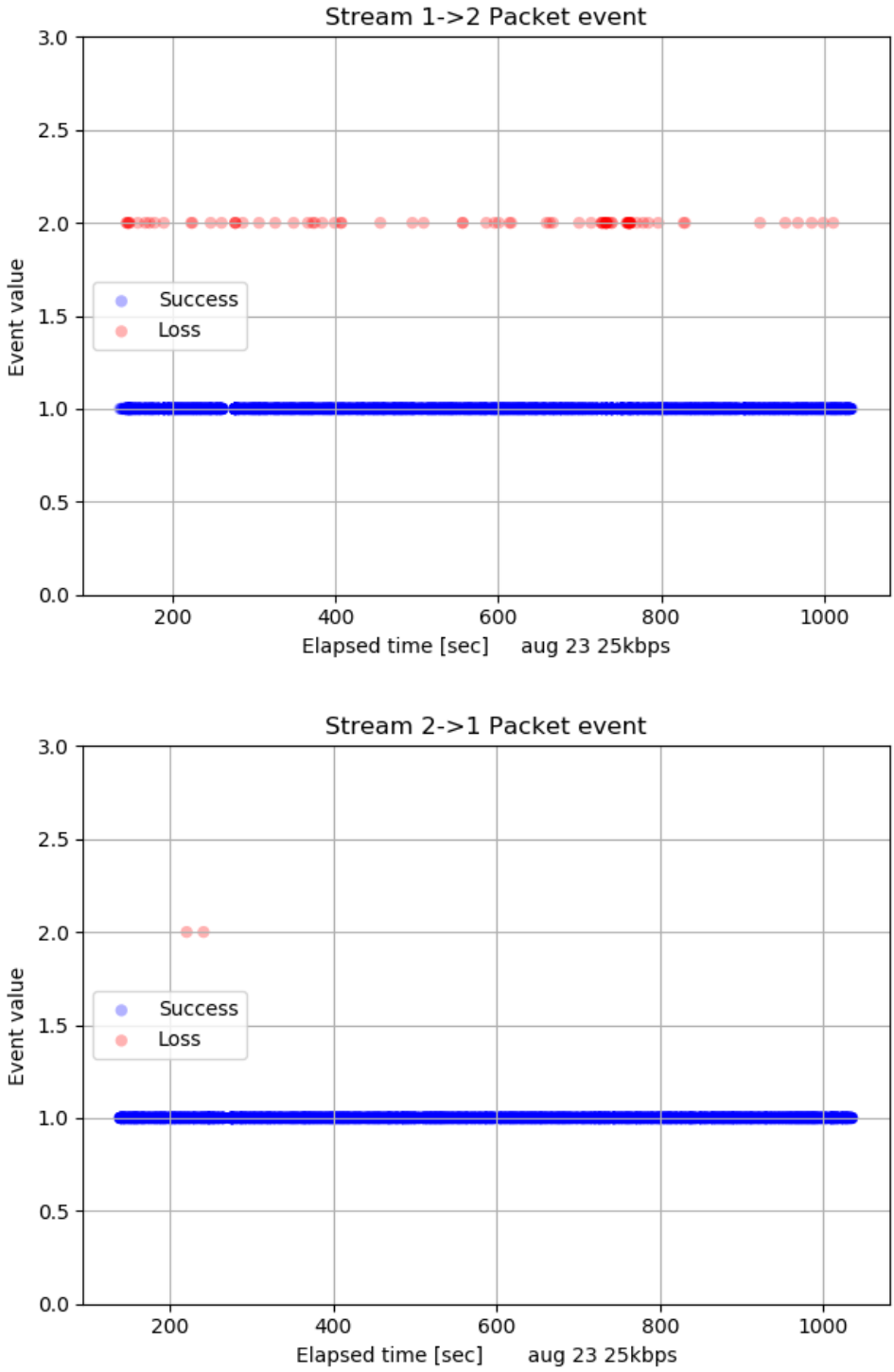


Figure A.1 Packet received events as time-series @25 kbps.

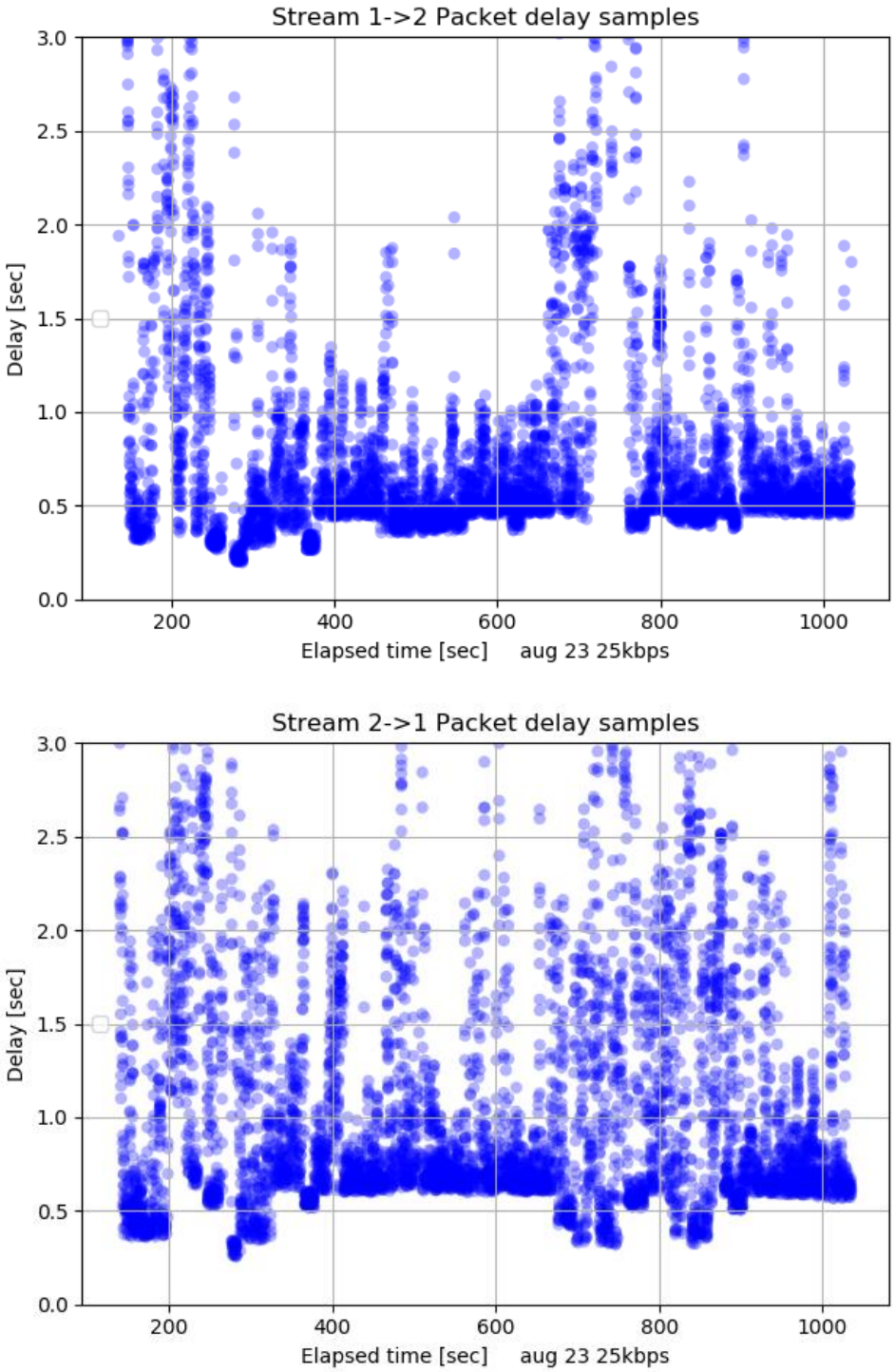


Figure A.2 Measured packet delays as time-series @25 kbps.

A.1.2 Performance statistics @200kbps

Network avg. throughput [bytes/s]: 48528.2
Stream 1->2 throughput [bytes/s] avg.: 24264.1
Stream 2->1 throughput [bytes/s] avg.: 25122.5
Network avg. delay [sec]: 0.53
Stream 1->2 delay [sec]: 0.53
Stream 2->1 delay [sec]: 0.91
Stream 1->2 number of lost packets: 1574 of #sent 45247 loss rate [%]: 3.48
Stream 2->1 number of lost packets: 285 of #sent 45372 loss rate [%]: 0.63

Stream 1->2 (0102101) throughput [bytes/s] CI: 24263 +- 479
Stream 2->1 (0201101) throughput [bytes/s] CI: 25048 +- 504
Stream 1->2 (0102101) delay [sec] CI: 0.548 +- 0.140
Stream 2->1 (0201101) delay [sec] CI: 0.929 +- 0.200
Network throughput [bytes/s] CI: 48557 +- 1304
Network delay [sec] CI: 0.493 +- 0.113

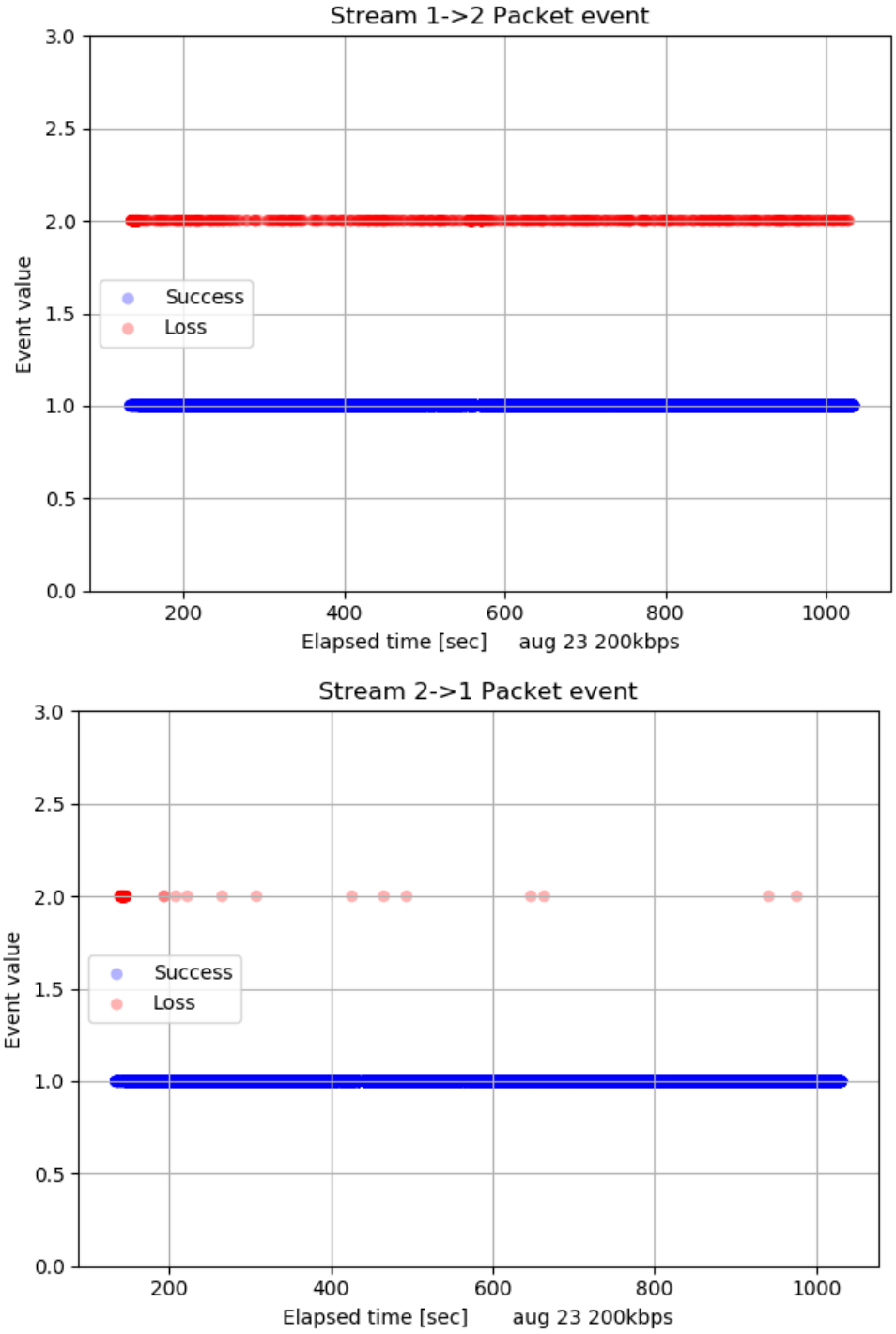


Figure A.3 Packet received events as time-series @200 kbps.

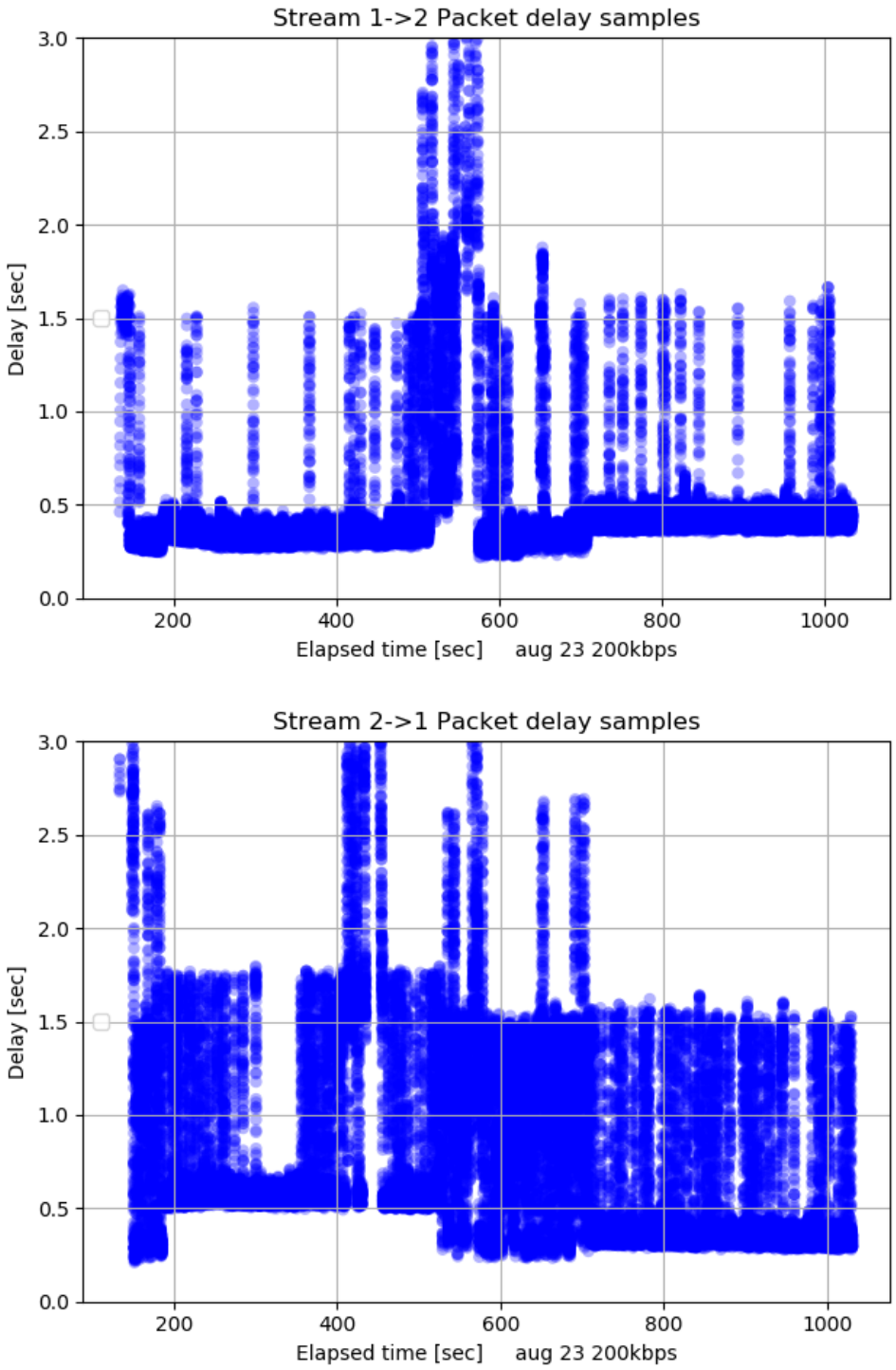


Figure A.4 Measured packet delays as time-series @200 kbps.

A.1.3 Modem statistics @25kbps

Space Vehicle handover observation period [sec]: 900
No of events: 6
HO rate [events/minutes]: 0.40
Avg time between ho [sec]: 132.85
Shortest time between ho [sec]: 51.48
Longest time between ho [sec]: 432.60
RSSI avg: -108, min: -114, max: -103
Beam handover observation period [sec]: 900
No of events: 11
HO rate [events/minutes]: 0.73
Avg time between ho [sec]: 86.82
Shortest time between ho [sec]: 44.55
Longest time between ho [sec]: 210.86
RSSI avg: -106, min: -115, max: -102

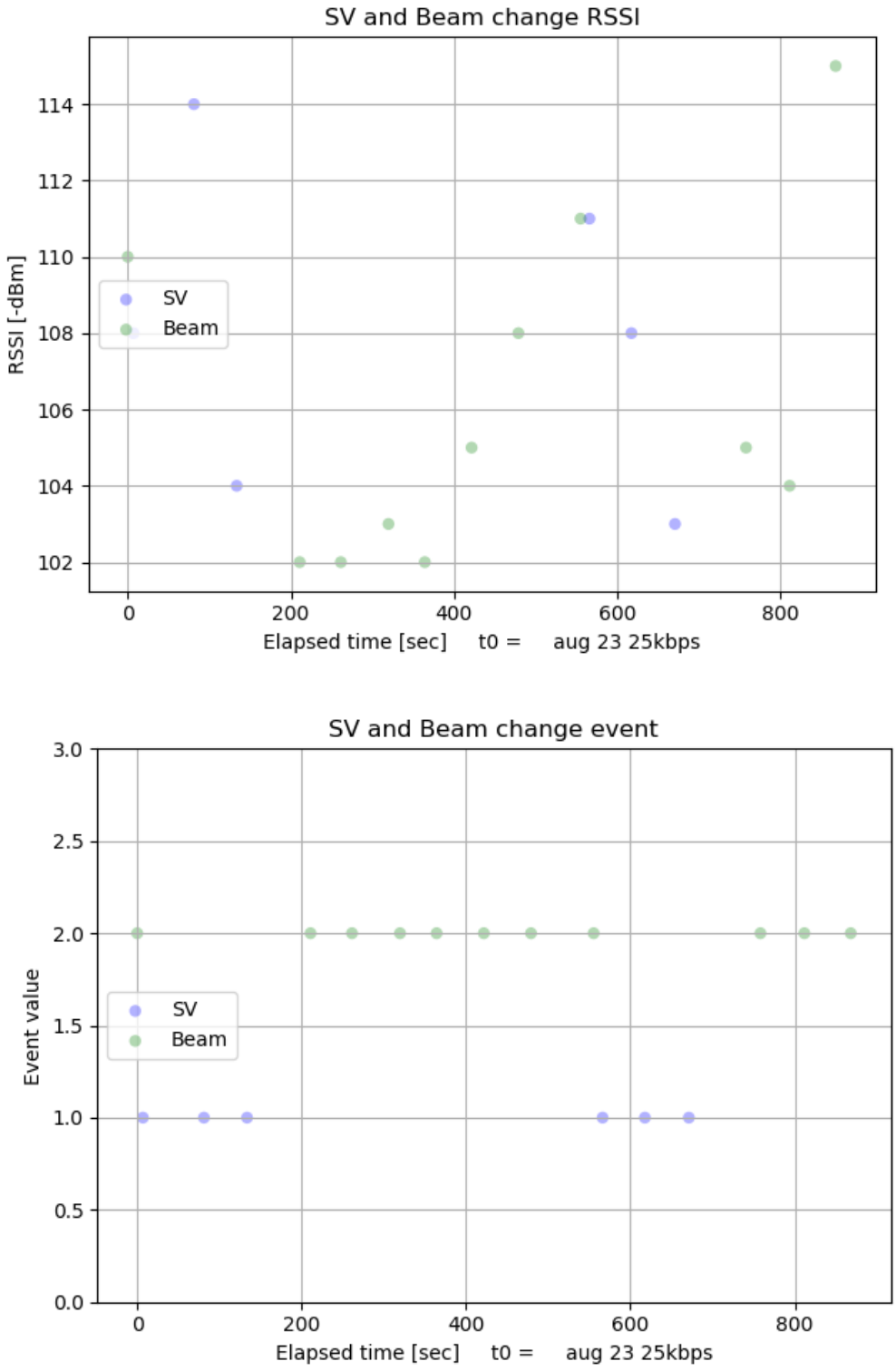


Figure A.5 RSSI and HO as time-series @25 kbps.

A.1.4 Modem statistics @200kbps

Space Vehicle handover observation period [sec]: 900
No of events: 2
HO rate [events/minutes]: 0.13
Avg time between ho [sec]: 522.69
Shortest time between ho [sec]: 522.69
Longest time between ho [sec]: 522.69
RSSI avg: -106, min: -108, max: -104
Beam handover observation period [sec]: 900
No of events: 13
HO rate [events/minutes]: 0.87
Avg time between ho [sec]: 68.64
Shortest time between ho [sec]: 40.59
Longest time between ho [sec]: 232.63
RSSI avg: -104, min: -111, max: -102

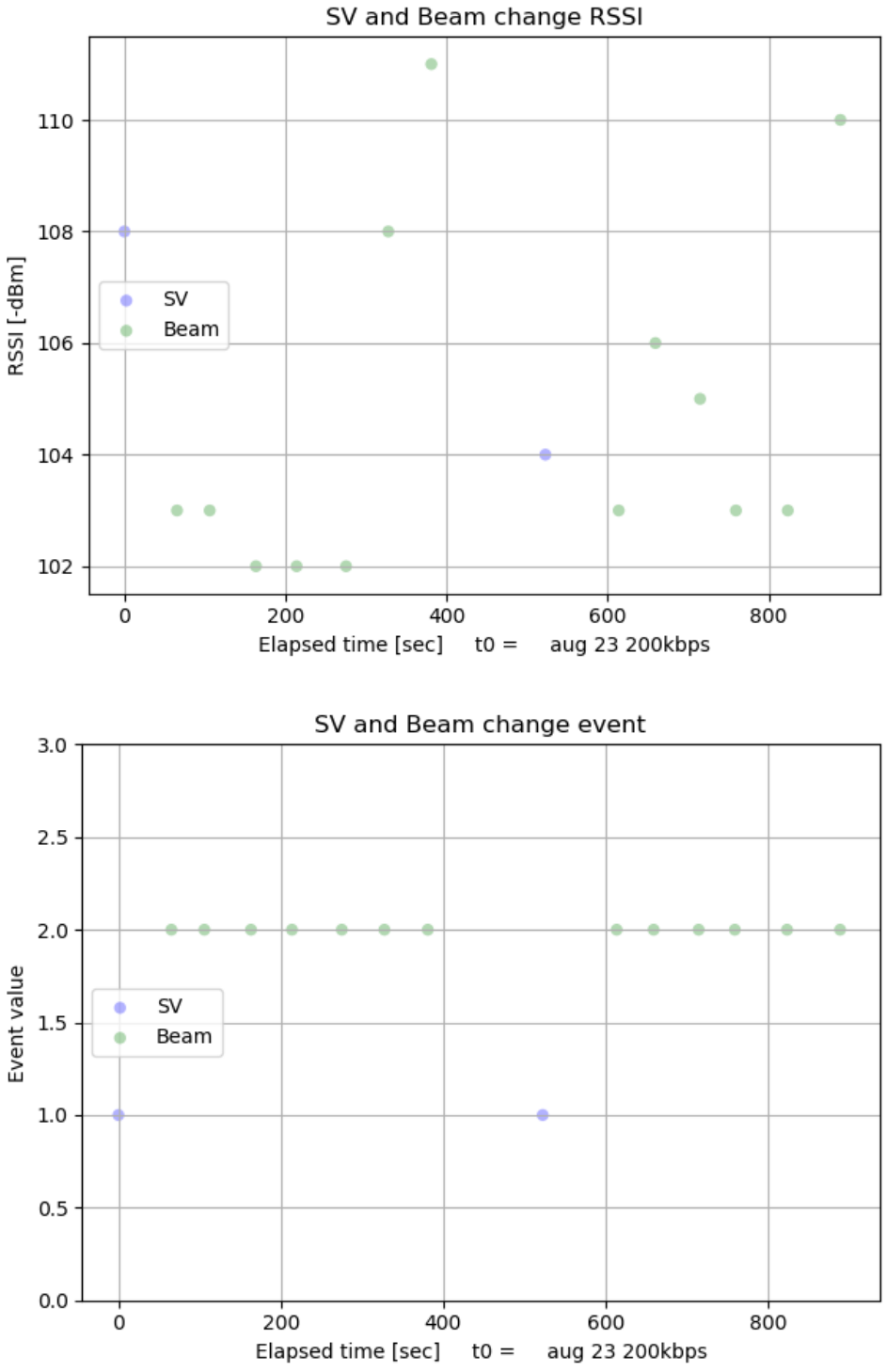


Figure A.6 RSSI and HO as time-series @200 kbps.

A.2 August 24

In the lab tests we never reached the 350 kbps UDP throughput capacity that should be provided by the SIM-card. The tests in the Arctic performed better and at August 24 we executed a capacity test.

Finding: The UDP throughput capacity reached 350 kbps with acceptable loss rate.

Figure A.7 presents the IP performance plot, which shows a perfect course – insignificant loss rate and low latency up to 350 kbps. Run number 10 has high loss rate (figures A.8 and A.9) since the offered traffic is higher than the capacity supported by the SIM-card.

Also note the lossless period on the 2→1 stream in run 10 in figure A.9 – due to a large buffer space many packets can be queued. The larger buffer space in this direction also affects the packet delay course in saturation – compare the figures A.12 and A.13.

A.2.1 UDP throughput capacity

Test started: 2019-08-24T03:32:23 GPS: Lat:87.994 Long:56.858
Test ended: 2019-08-24T04:08:23 GPS: Lat:87.993 Long:56.864

run number	Rx window [sec]	# samples
1	600.0	12008
2	600.8	23965
3	119.9	7220
4	120.0	9438
5	120.2	12063
6	120.5	14325
7	120.6	16508
8	120.0	18663
9	120.0	21296
10	123.6	21872

Run 1:
Stream 1->2 number of lost packets: 49 of #sent 6100 loss rate [%]: 0.80
Stream 2->1 number of lost packets: 1 of #sent 5956 loss rate [%]: 0.02

Run 10:
Stream 1->2 number of lost packets: 1240 of #sent 12016 loss rate [%]: 10.32
Stream 2->1 number of lost packets: 1033 of #sent 12127 loss rate [%]: 8.52

Space Vehicle handover observation period [sec]: 2160
No of events: 4
HO rate [events/minutes]: 0.11
Avg time between ho [sec]: 538.85
Shortest time between ho [sec]: 497.94
Longest time between ho [sec]: 571.19
RSSI avg: -106, min: -108, max: -106
Beam handover observation period [sec]: 2160
No of events: 29
HO rate [events/minutes]: 0.81
Avg time between ho [sec]: 76.44
Shortest time between ho [sec]: 15.84
Longest time between ho [sec]: 195.02
RSSI avg: -105, min: -111, max: -103

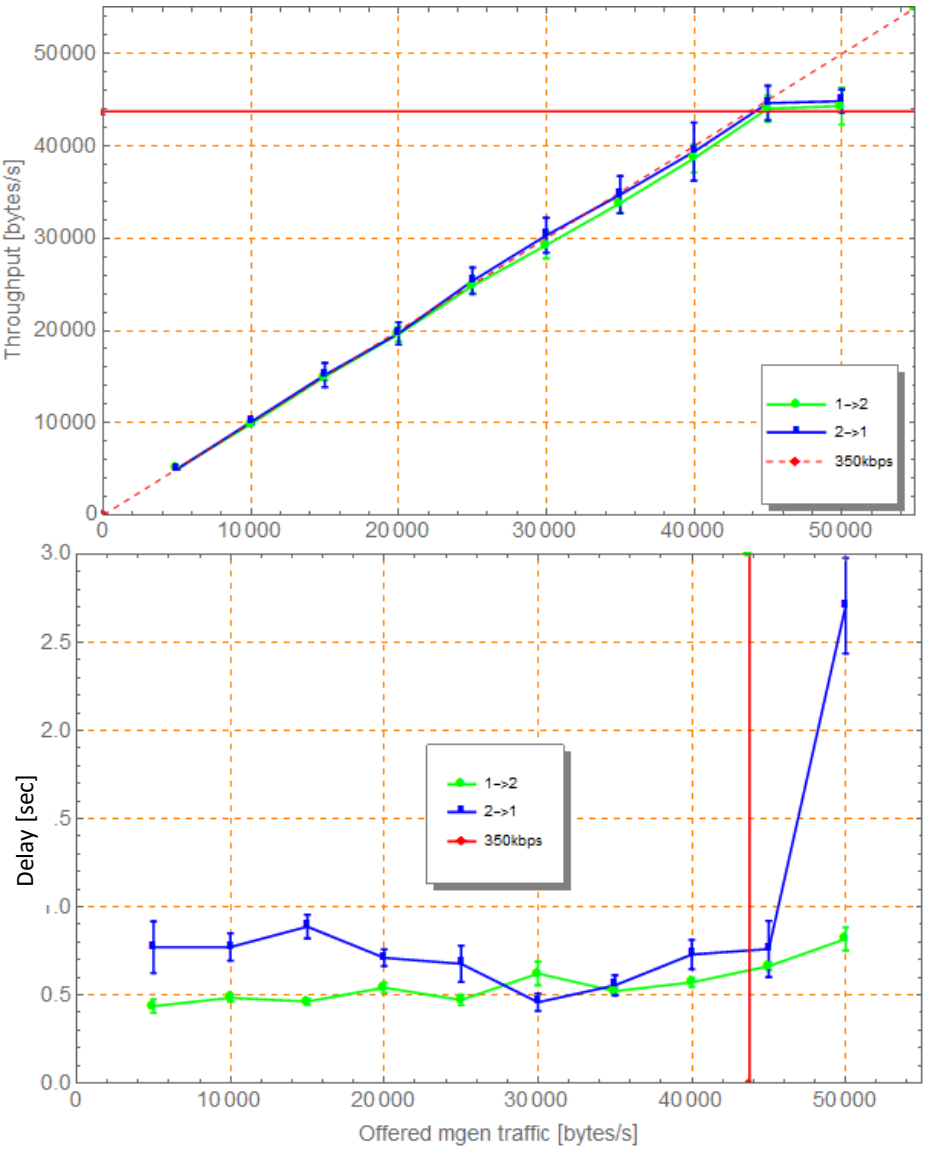


Figure A.7 Throughput and delay performance August 24.

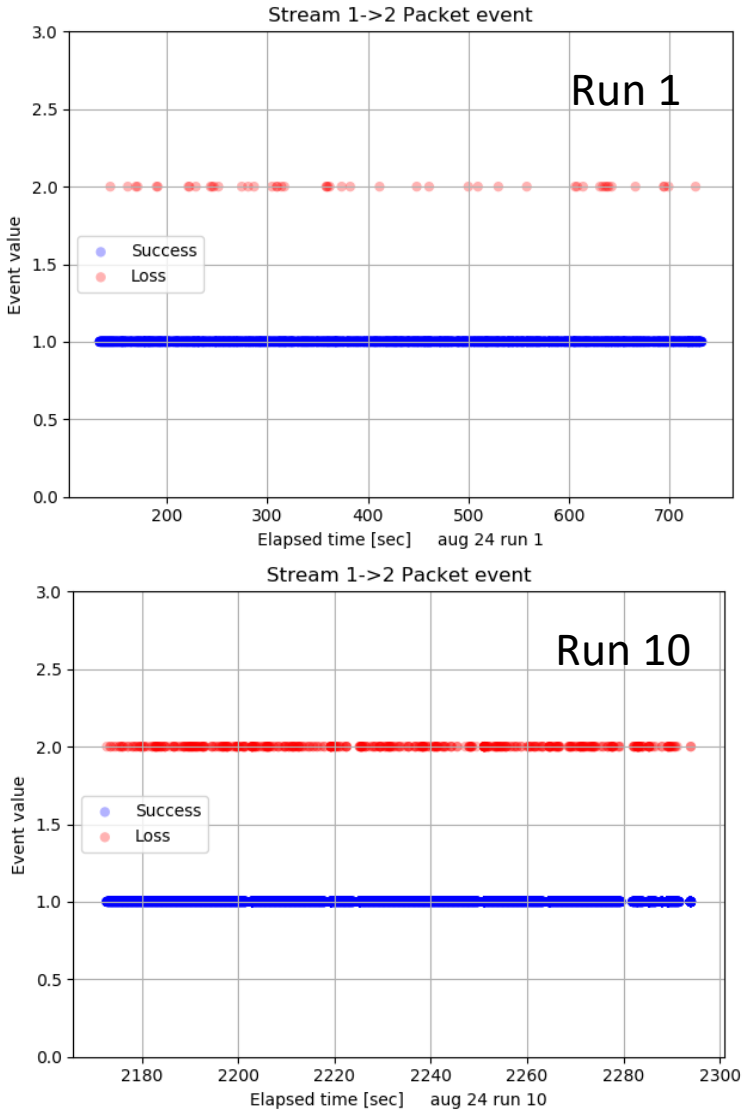


Figure A.8 Packet event as time-series.

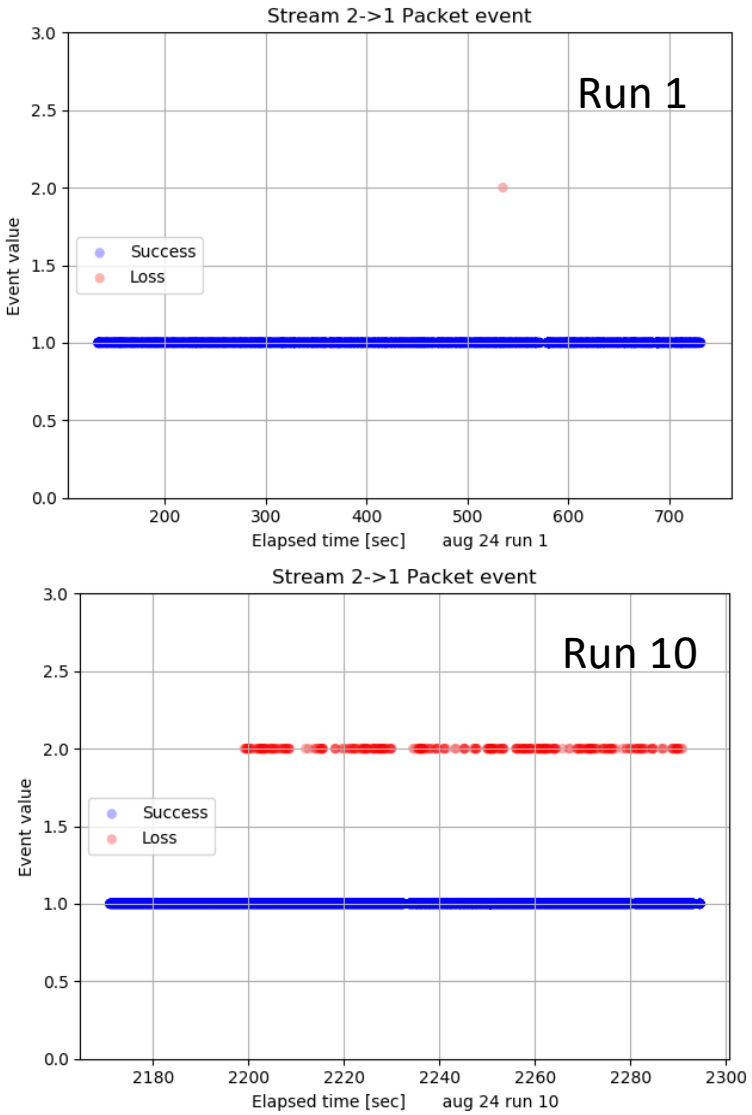


Figure A.9 Packet event as time-series.

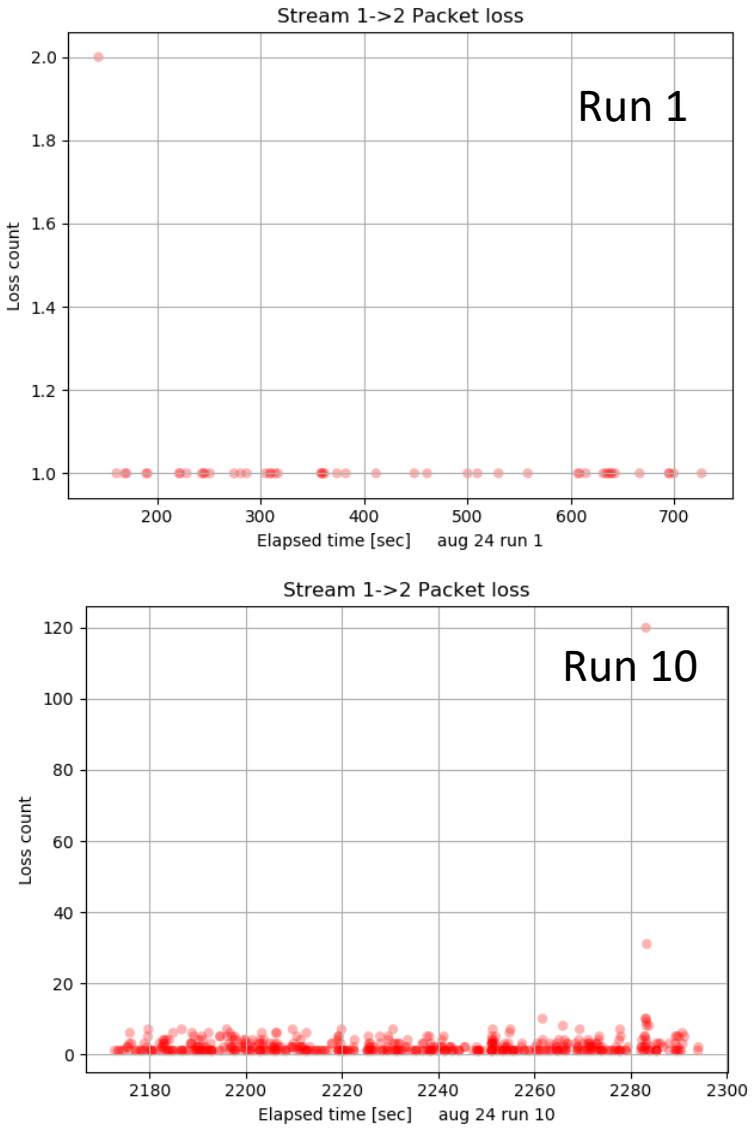


Figure A.10 Packet consecutive loss count as time-series. Outgoing traffic from the vessel.

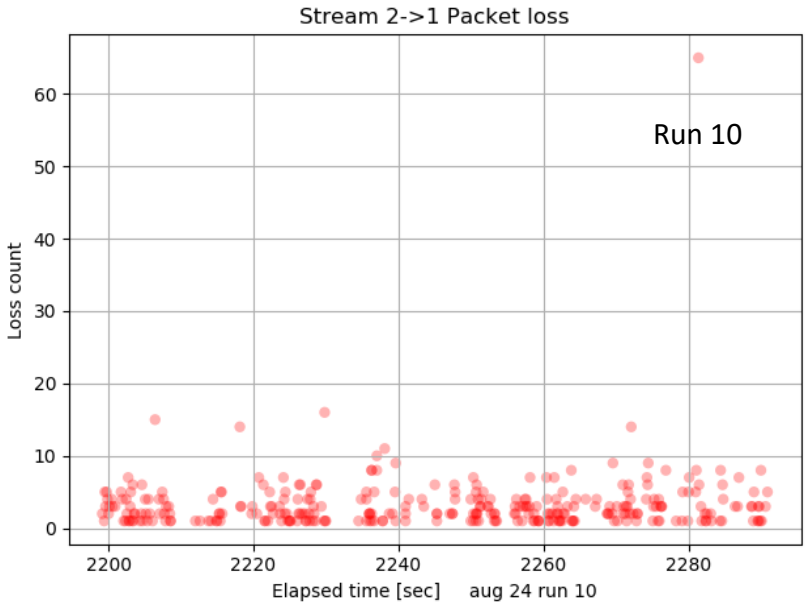


Figure A.11 Packet consecutive loss count as time-series. Incoming traffic on the vessel. Run 1 has zero loss.

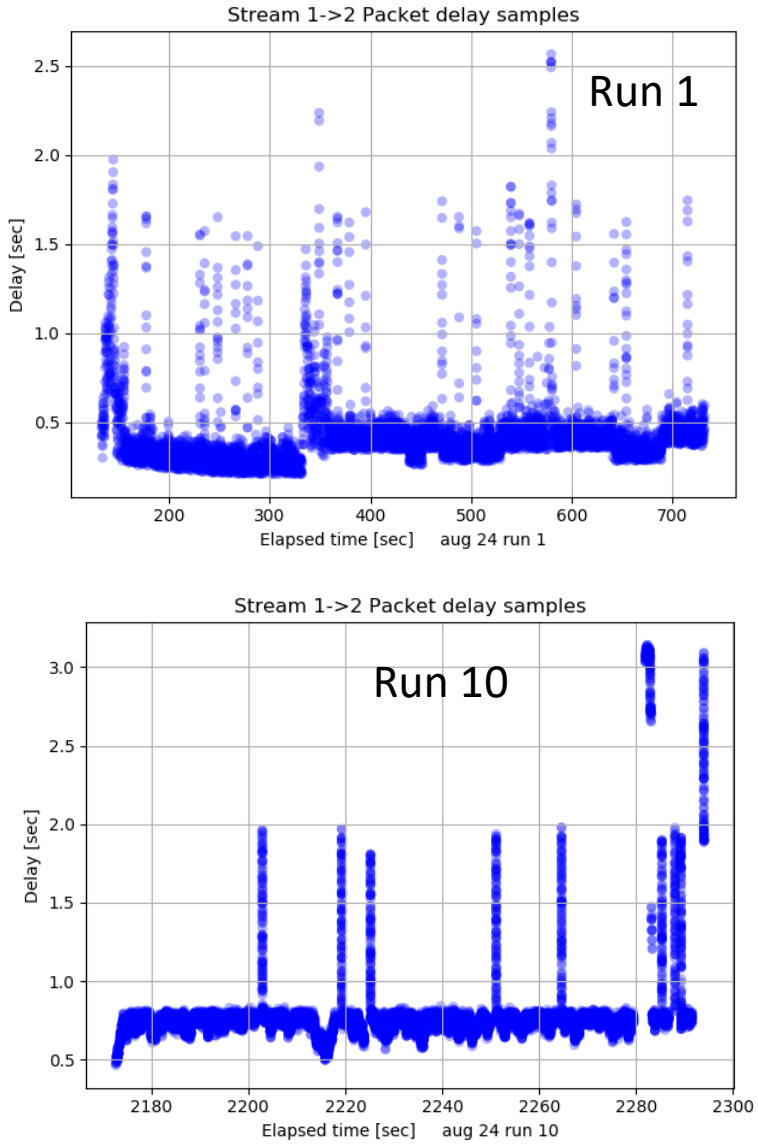


Figure A.12 Packet delays as time-series.

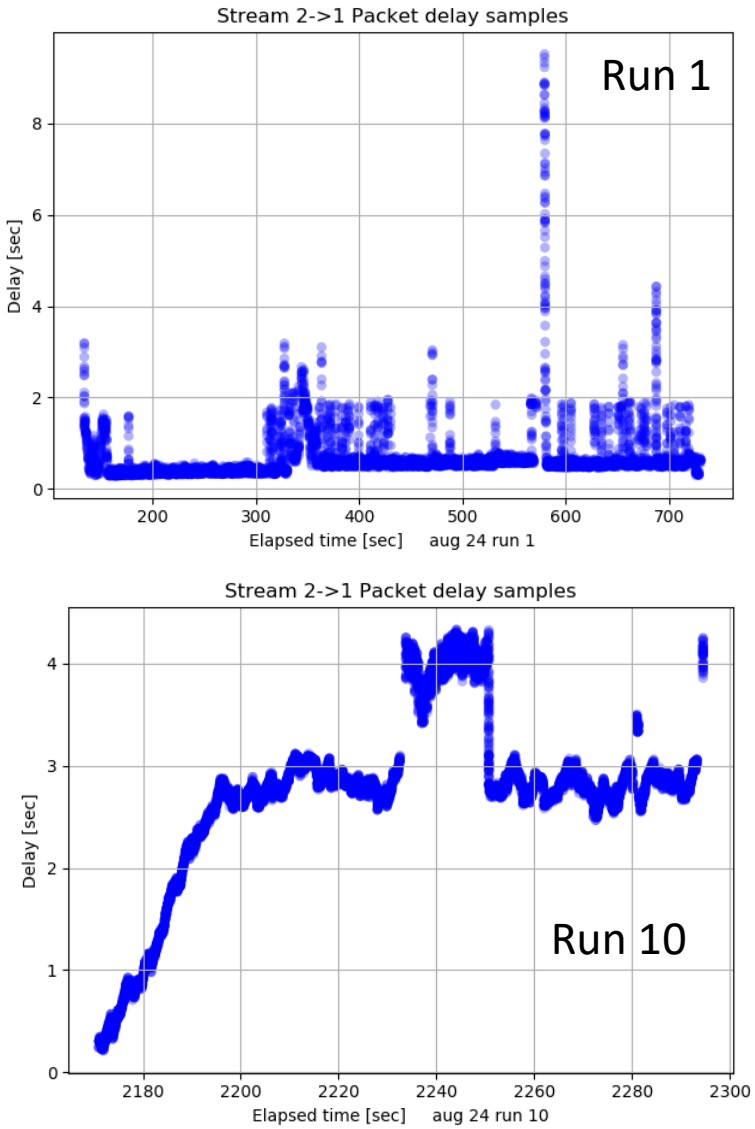


Figure A.13 Packet delays as time-series.

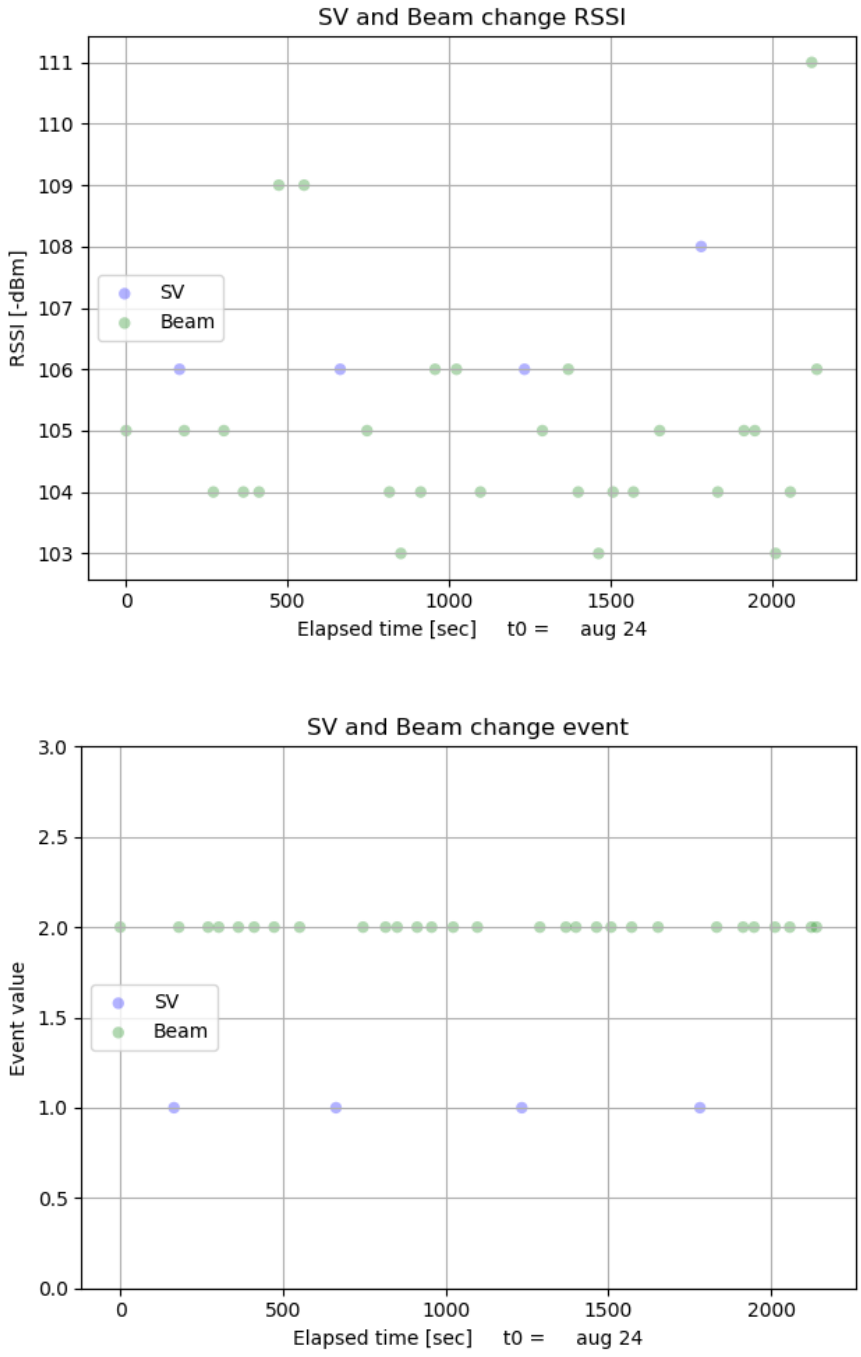


Figure A.14 HO and RSSI as time-series.

A.3 August 27

Finding: The Iridium service has unstable capacity, see figure A.15.

Compared to August 24, this was a bad day and we observed the same problems as in the lab tests – the service provides unstable capacity as shown in figure A.15. A.3.2 below shows the modem executes handover frequently during a short time interval.

A.3.1 UDP performance plots

Test started: 2019-08-27T03:32:23 GPS: Lat:82.638 Long:56.045
Test ended: 2019-08-27T04:08:23 GPS: Lat:82.534 Long:55.845

run number	Rx window [sec]	# samples
1	598.1	12012
2	600.9	23904
3	123.7	6932
4	120.0	9069
5	120.8	11716
6	121.5	13678
7	119.6	9653
8	83.4	10002
9	68.8	10388
10	122.4	21753

Stream 1->2 (0102101) loss rate [%]: {4.34,1.04,3.75,10.73,2.66,8.00,48.62,8.53,19.09,9.76}
Stream 2->1 (0201101) loss rate [%]: {0.03,0.04,0.14,0.04,0.08,0.08,35.59,16.45,16.23,7.77}

Space Vehicle handover observation period [sec]: 2160
No of events: 13
HO rate [events/minutes]: 0.36
Avg time between ho [sec]: 154.35
Shortest time between ho [sec]: 0.98
Longest time between ho [sec]: 587.03
RSSI avg: -108, min: -116, max: -101
skip rssi zero
Beam handover observation period [sec]: 2160
No of events: 27
HO rate [events/minutes]: 0.75
Avg time between ho [sec]: 75.04

Shortest time between ho [sec]: 4.95
Longest time between ho [sec]: 322.72
RSSI avg: -105, min: -113, max: -102

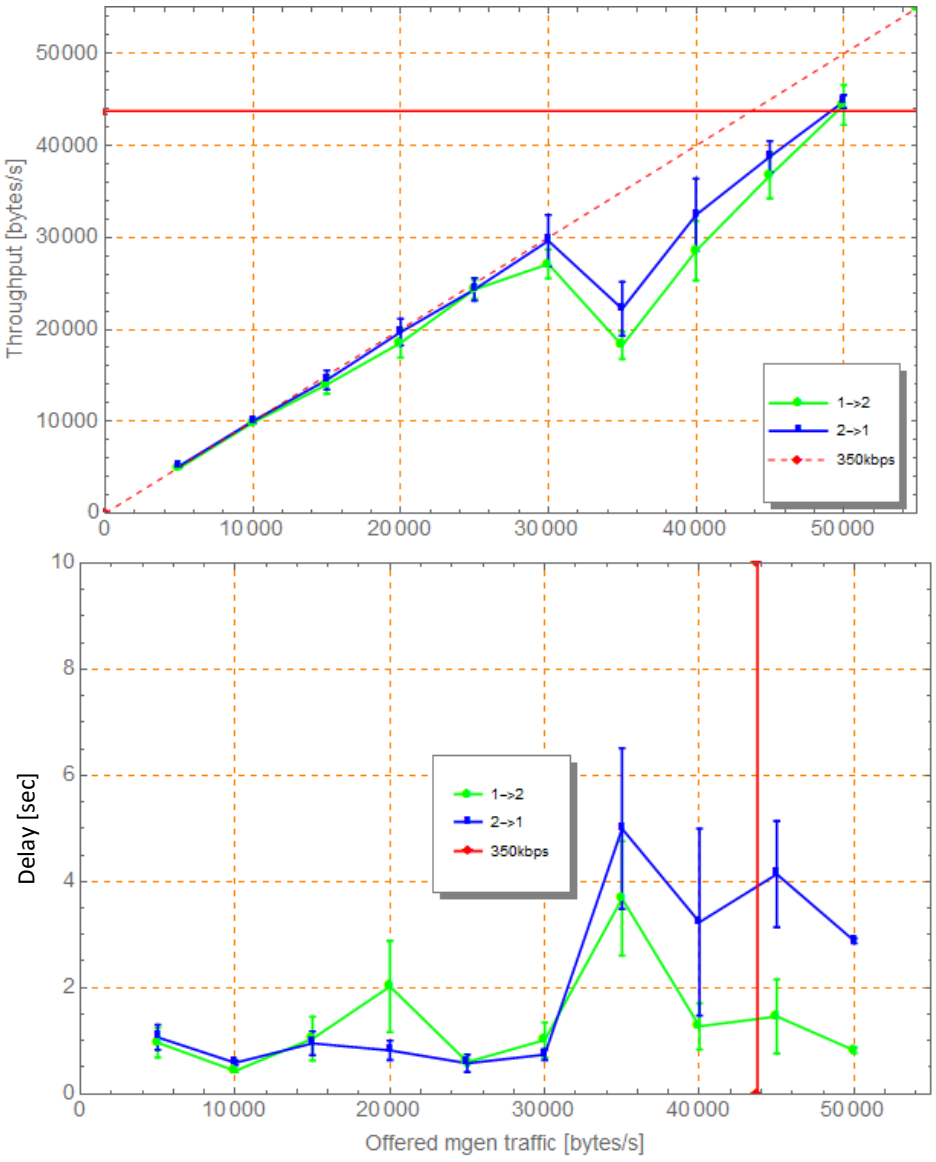


Figure A.15 Throughput and delay performance August 27.

A.3.2 What happened in run 7?

August 24 was a good day in contrast to August 27 – figure A.15 shows a sudden drop in throughput in run 7. The figures A.16 and A.17 present the quantile plots for these two days and mark the duration where the August 27 run 7 was executed. Points near zero indicate high HO-rates. We expect that an SV handover gives longer blocking periods than a beam handover. It is difficult to make any conclusions from figure A.17, but figure A.16 indicates that the August 27 run 7 occurred in a time interval with a higher SV HO-rate.

Figure A.18 presents a time domain plot for the SV/beam HO events for run 7. Note the dark blue dot at the August 27 plot which indicates many SV HO events in a short time period. The much higher SV HO rate August 27 is also illustrated by figure A.20. From the figures A.21 and A.22, we see that many packets are lost in the time period with many handovers.

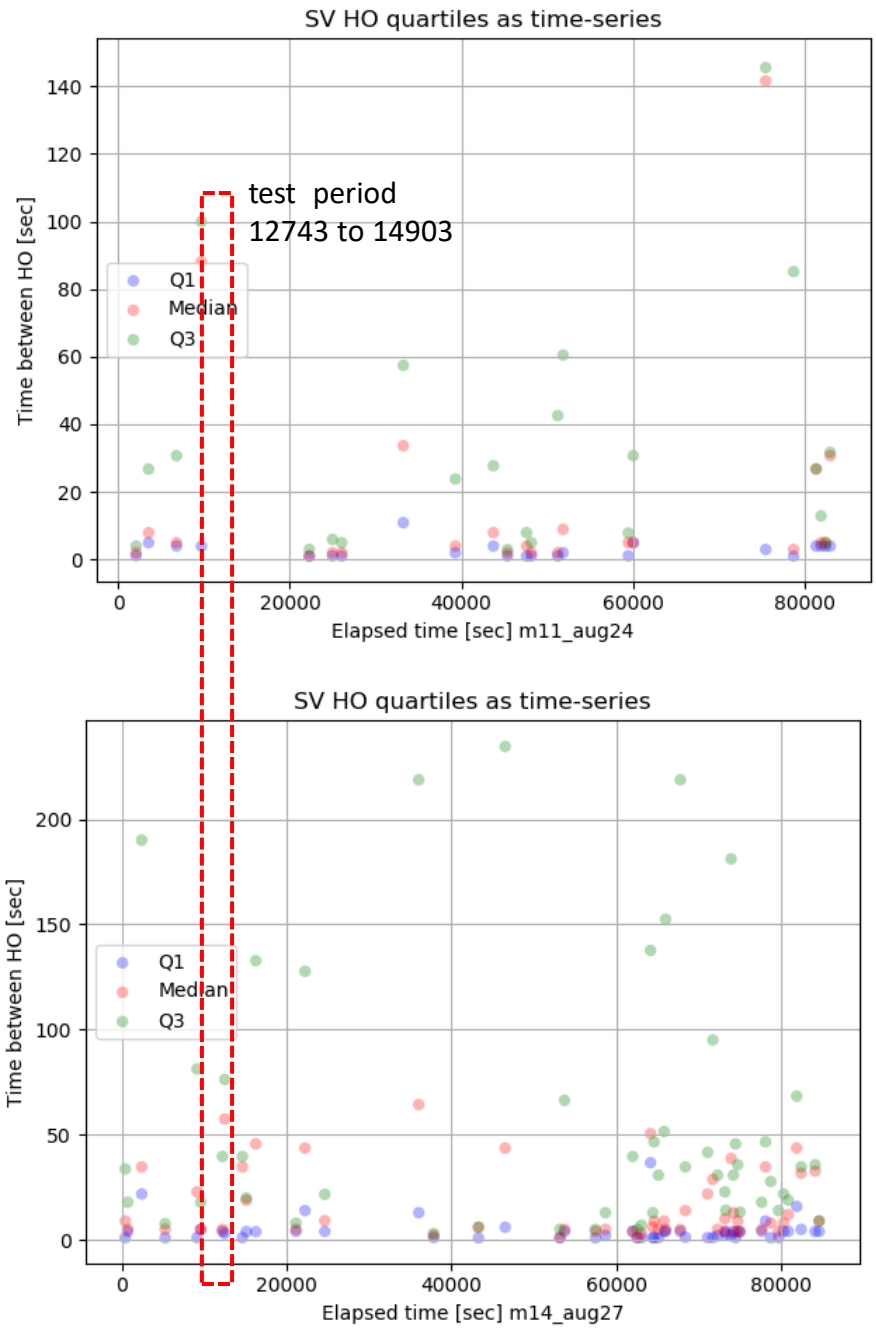


Figure A.16 Measured SV HO statistics August 24 and 27. Each point encompasses 5 minutes of samples. A missing point indicates that a HO-event did not occur.

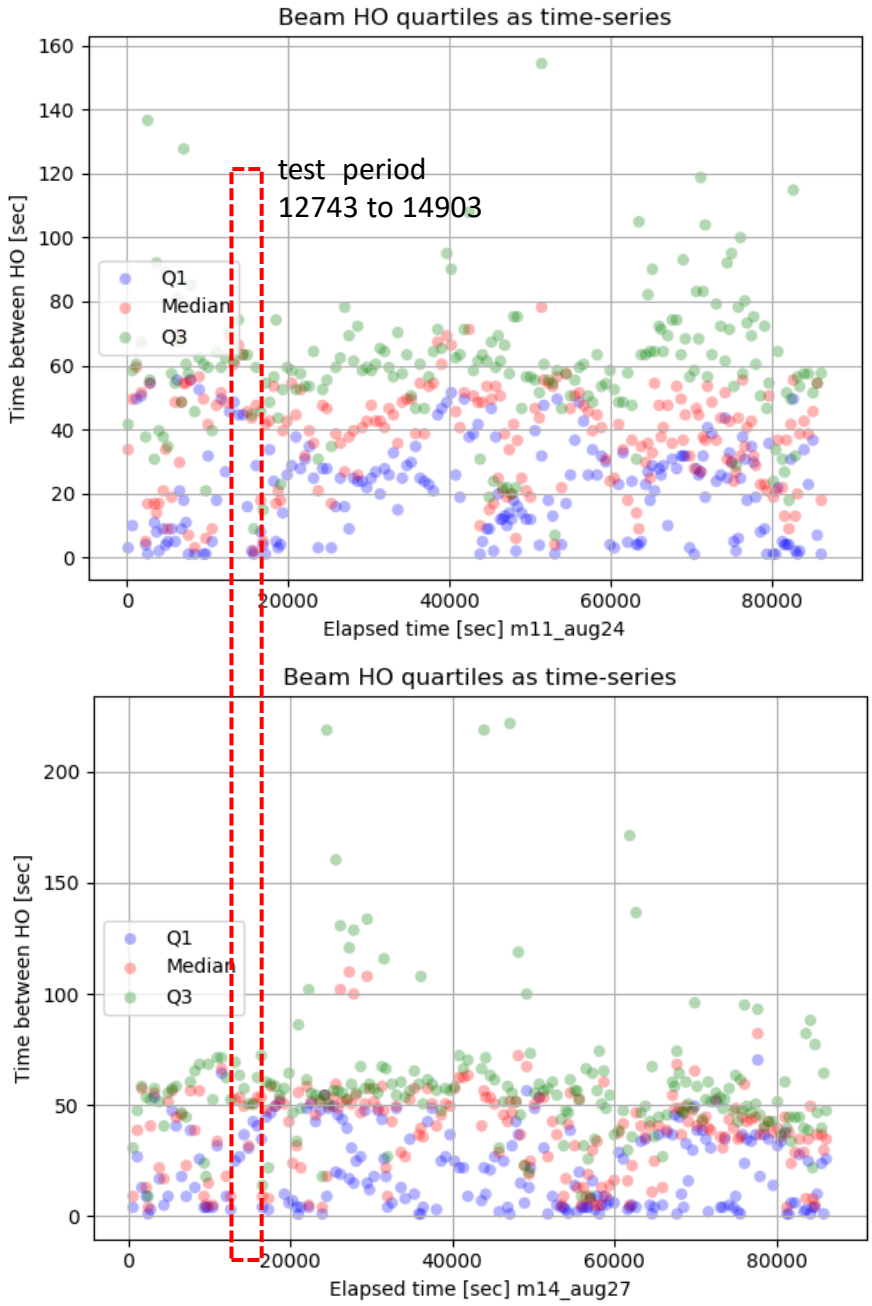


Figure A.17 Measured beam HO statistics August 24 and 27. Each point encompasses 5 minutes of samples. A missing point indicates that a HO-event did not occur.

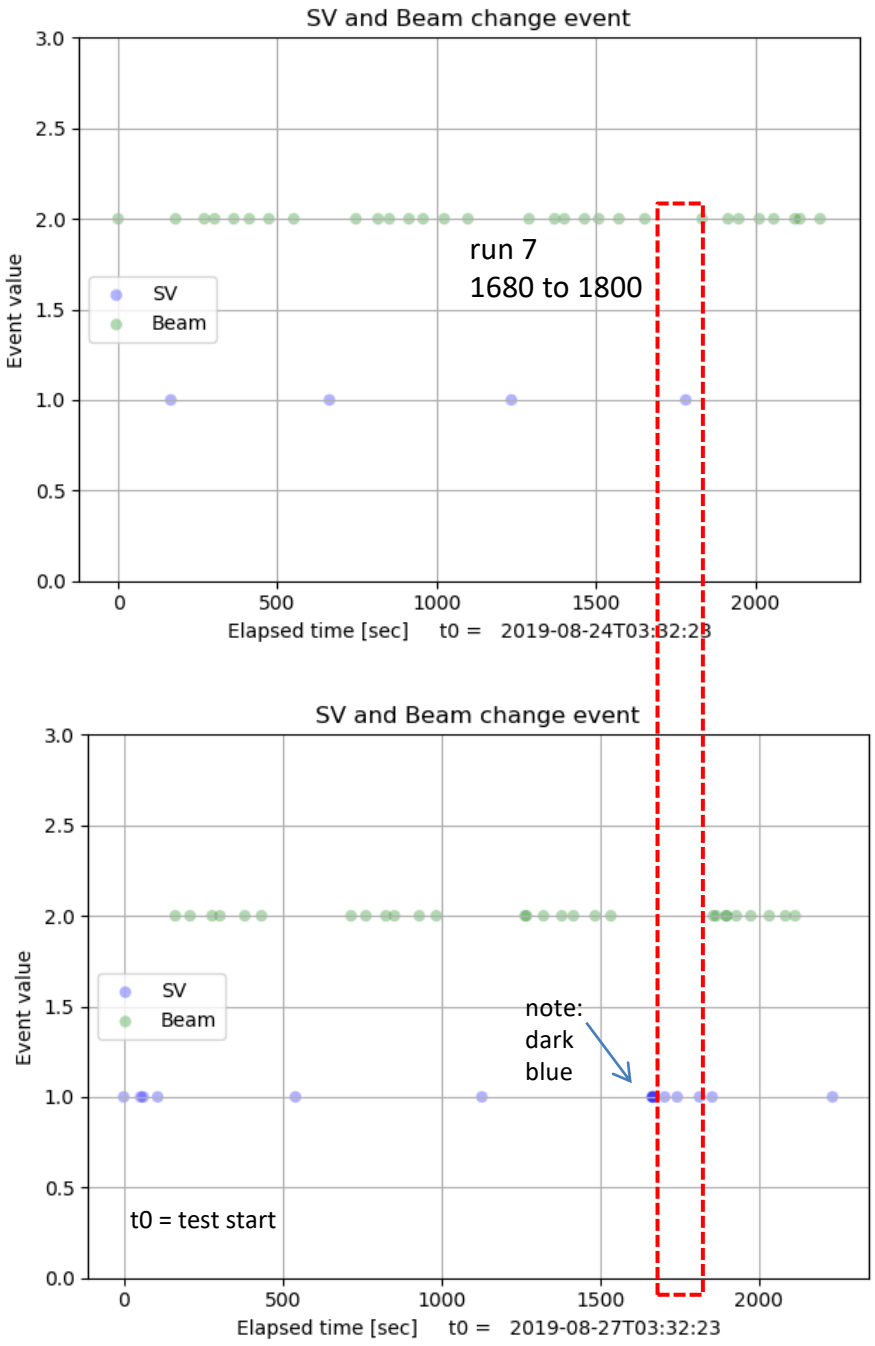


Figure A.18 SV and beam change events August 24 and 27 from T03:32:23. A missing point indicates that a HO-event did not occur.

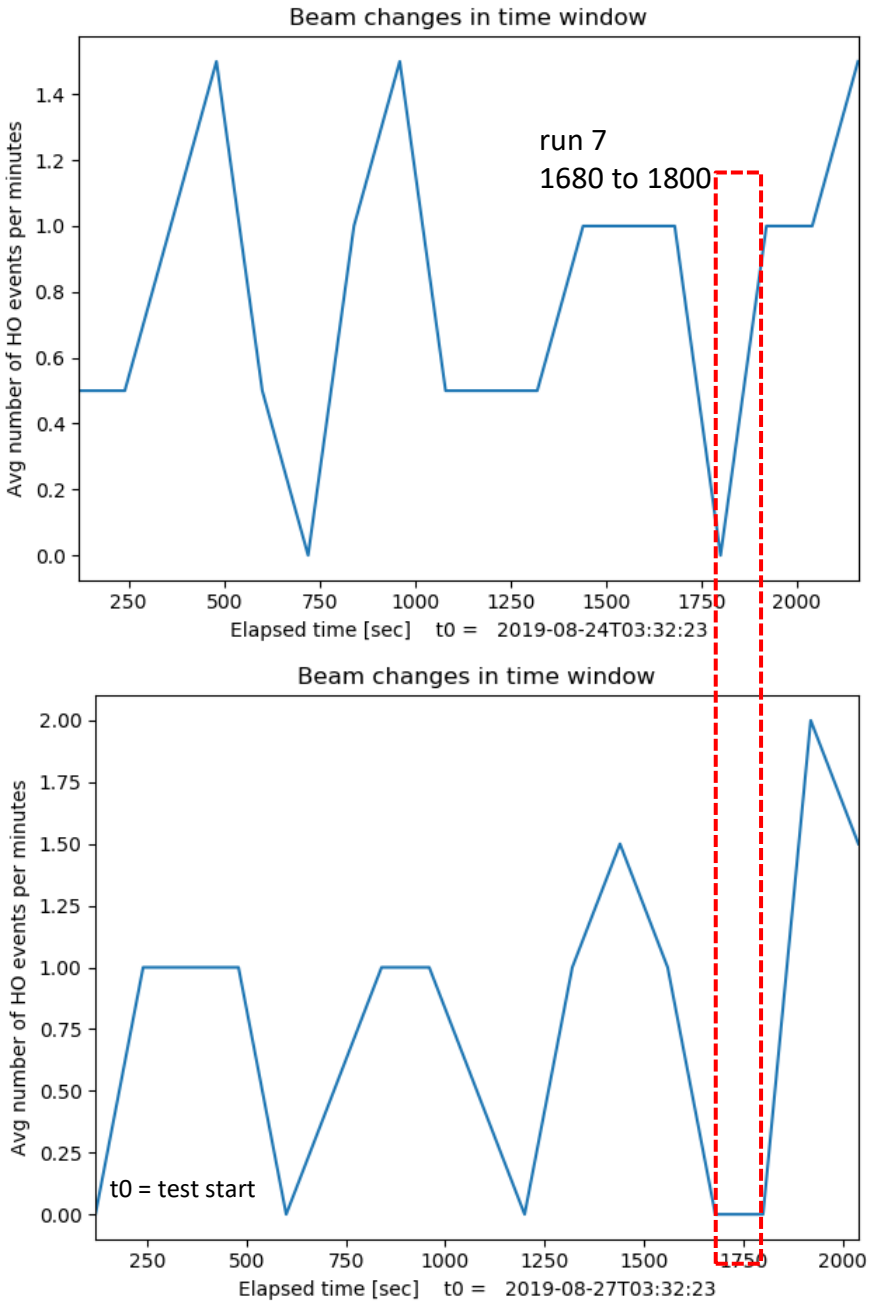


Figure A.19 Beam HO rates August 24 and 27 from T03:32:23. Point size 120 sec.

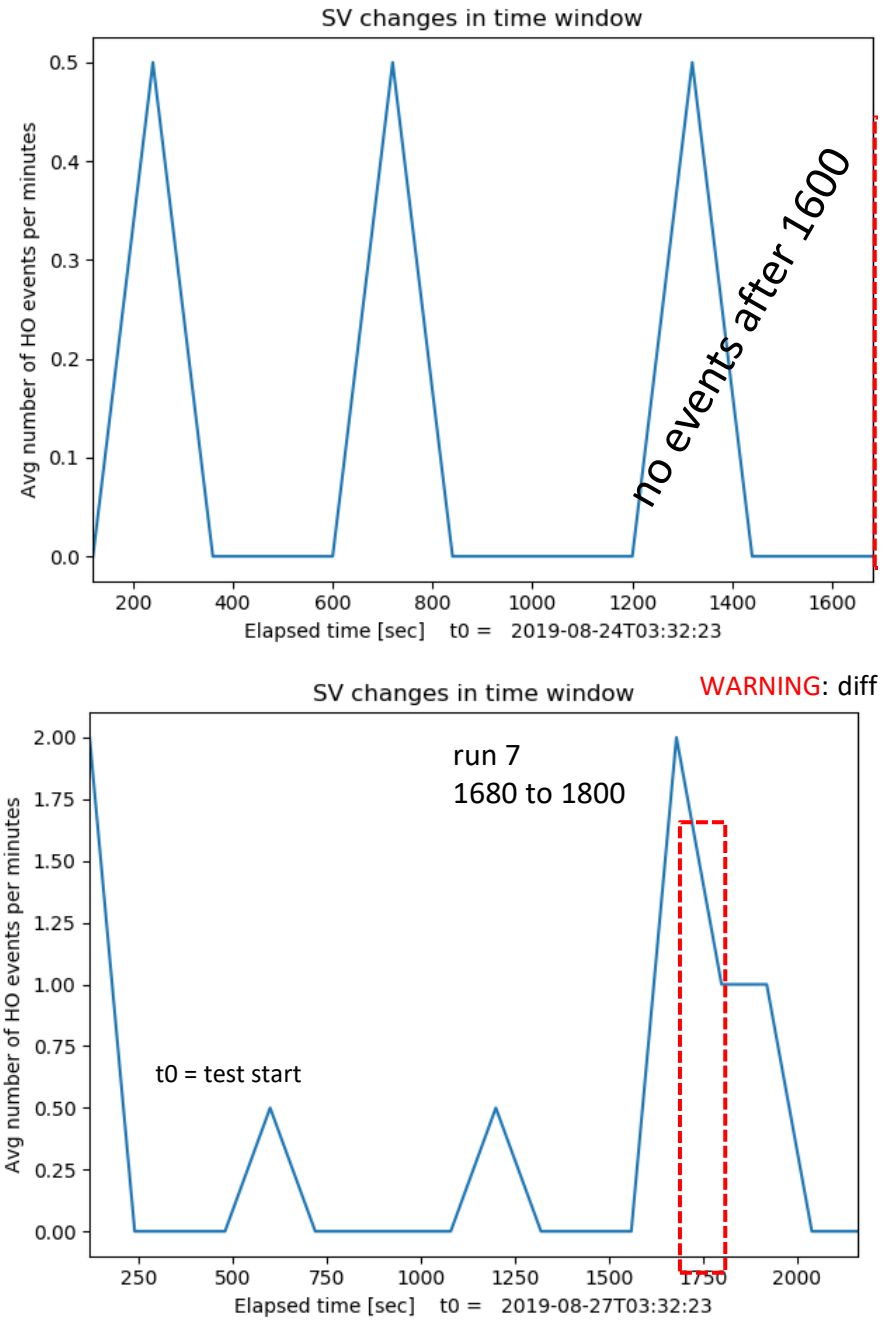


Figure A.20 SV HO rates August 24 and 27 from T03:32:23. Point size 120 sec.

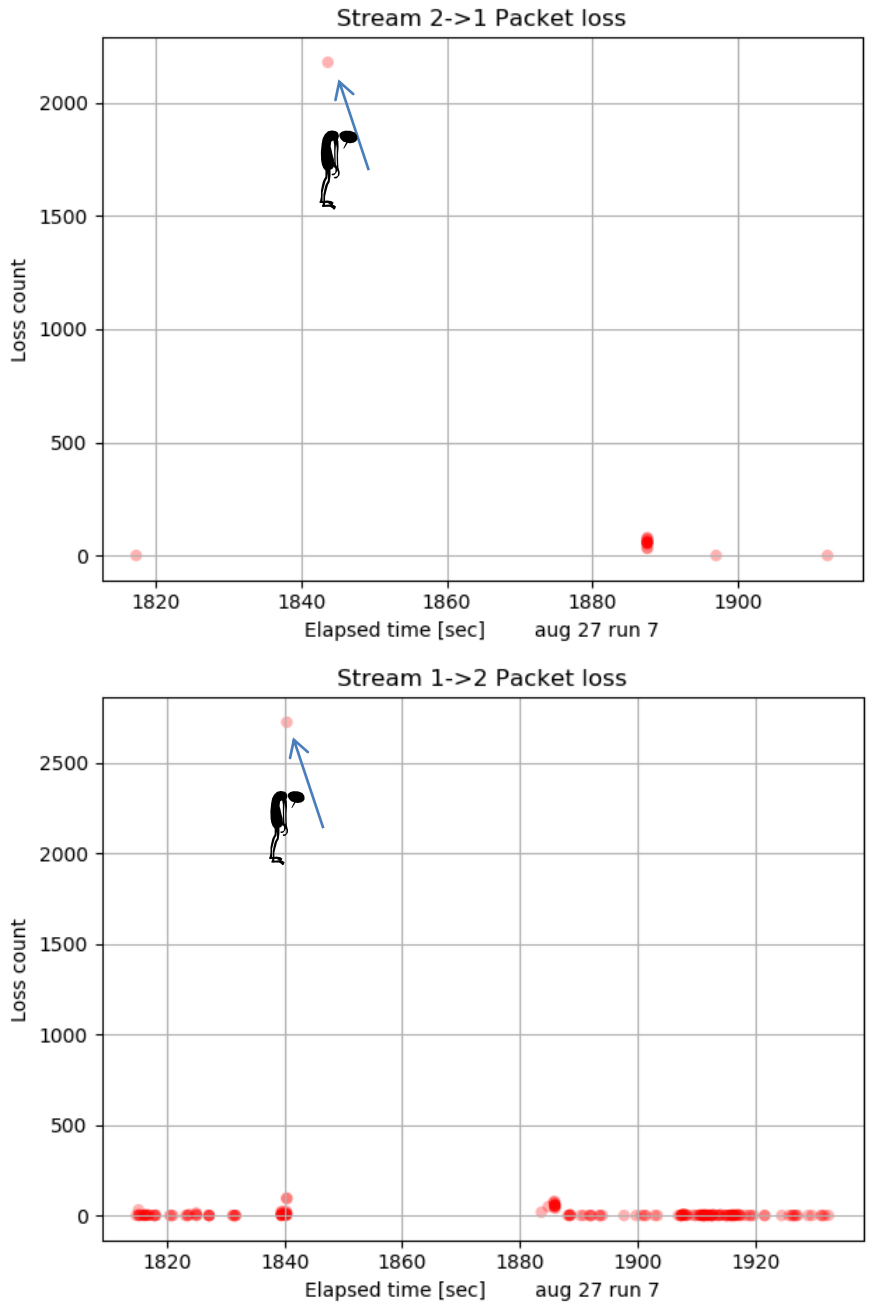


Figure A.21 Consecutive packet loss count as time-series in run 7.

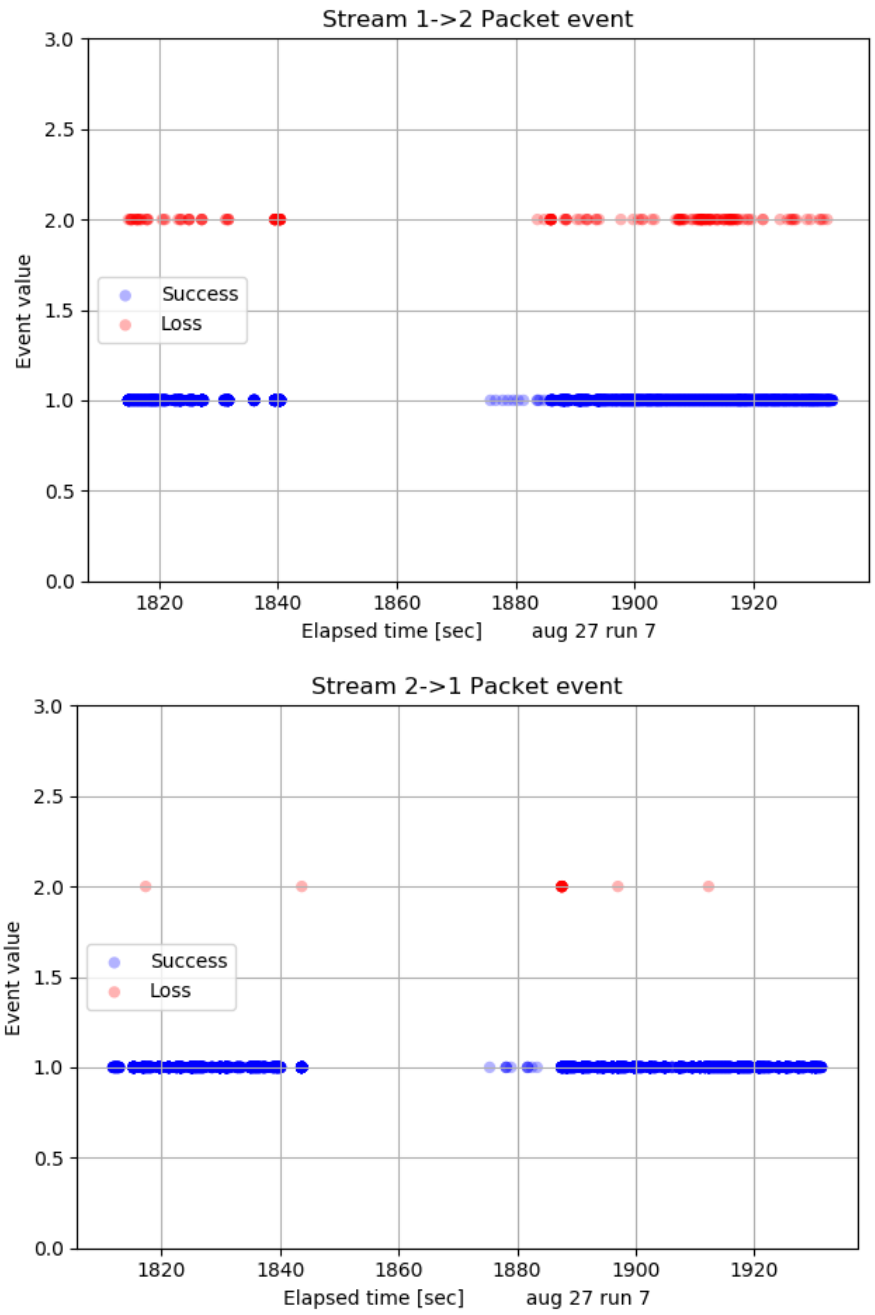


Figure A.22 Packet events in the time domain in run 7.

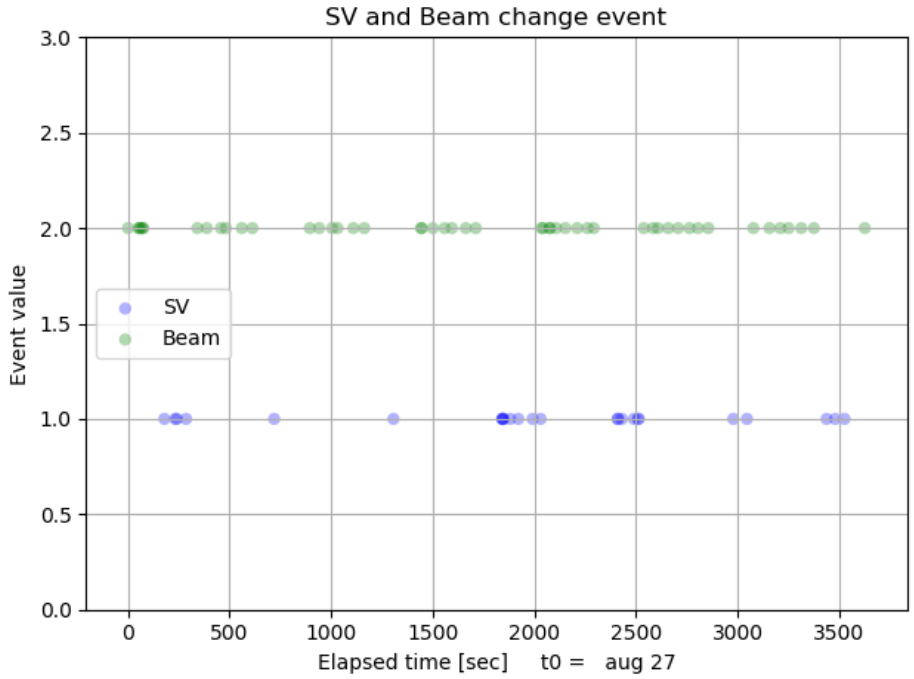


Figure A.23 HO events in the time domain.

A.4 August 28

Finding: The Iridium service has good performance with stable capacity.

A.4.1 UDP performance plots

Test started: 2019-08-28T03:32:23 GPS: Lat:82.676 Long:35.679
Test ended: 2019-08-28T04:08:23 GPS: Lat:82.738 Long:35.209

run number	Rx window [sec]	# samples
1	593.8	11877
2	599.9	23641
3	120.2	7206
4	120.1	9582
5	120.0	11848
6	119.9	14404
7	120.3	16382
8	120.0	18611
9	121.1	21308
10	121.7	21822

Stream 1->2 (0102101) loss rate [%]: {2.84,0.85,0.87,1.07,1.87,1.60,4.41,5.50,3.41,8.18}

Stream 2->1 (0201101) loss rate [%]: {0.02,0.06,0.03,0.02,0.08,0.01,0.06,0.06,0.05,7.59}

Space Vehicle handover observation period [sec]: 2160
No of events: 6
HO rate [events/minutes]: 0.17
Avg time between ho [sec]: 323.11
Shortest time between ho [sec]: 7.92
Longest time between ho [sec]: 542.48
RSSI avg: -107, min: -113, max: -105
Beam handover observation period [sec]: 2160
No of events: 24
HO rate [events/minutes]: 0.67
Avg time between ho [sec]: 94.77
Shortest time between ho [sec]: 7.92
Longest time between ho [sec]: 281.12
RSSI avg: -104, min: -106, max: -102

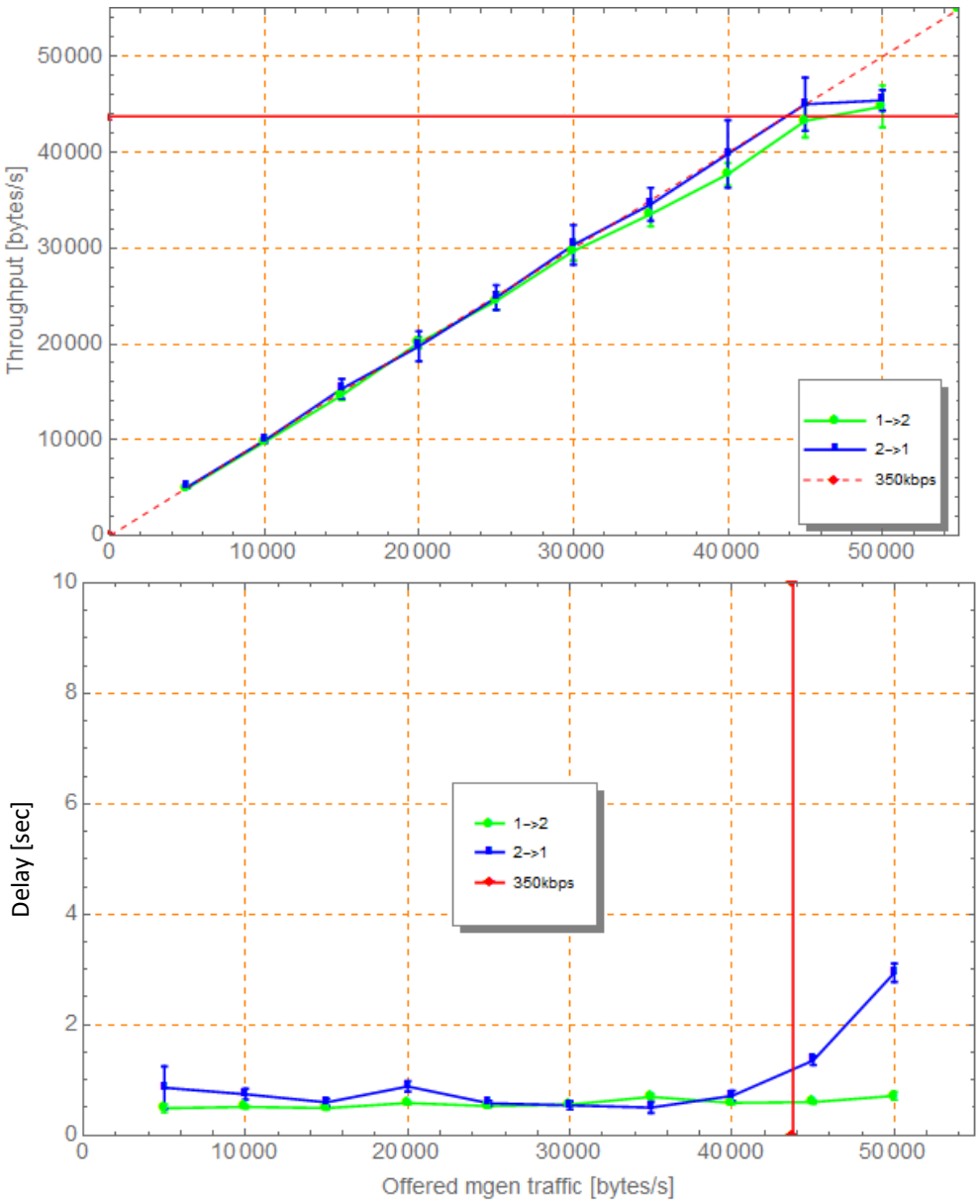


Figure A.24 Throughput and delay performance August 28.

A.5 August 30

Finding: The Iridium service has good performance with stable capacity.

A.5.1 UDP performance plots

Test started: 2019-08-30T03:32:23 GPS: Lat:83.715 Long:26.858
Test ended: 2019-08-30T04:08:23 GPS: Lat:83.740 Long:27.064

run number	Rx window [sec]	# samples
1	599.9	11225
2	600.8	23886
3	119.9	7189
4	120.7	9537
5	120.2	11919
6	120.1	13556
7	121.8	16748
8	119.7	18331
9	121.9	21294
10	84.0	13939

Stream 1->2 (0102101) loss rate [%]: {10.63,1.23,0.96,1.32,2.42,11.38,2.20,10.64,2.83,14.67}
Stream 2->1 (0201101) loss rate [%]: {2.81,0.00,0.00,0.20,0.00,2.89,0.00,0.00,1.19,14.01}

Space Vehicle handover observation period [sec]: 2160
No of events: 7
HO rate [events/minutes]: 0.19
Avg time between ho [sec]: 185.12
Shortest time between ho [sec]: 12.87
Longest time between ho [sec]: 549.41
RSSI avg: -106, min: -113, max: -102
Beam handover observation period [sec]: 2160
No of events: 32
HO rate [events/minutes]: 0.89
Avg time between ho [sec]: 63.58
Shortest time between ho [sec]: 5.94
Longest time between ho [sec]: 283.12
RSSI avg: -107, min: -115, max: -101

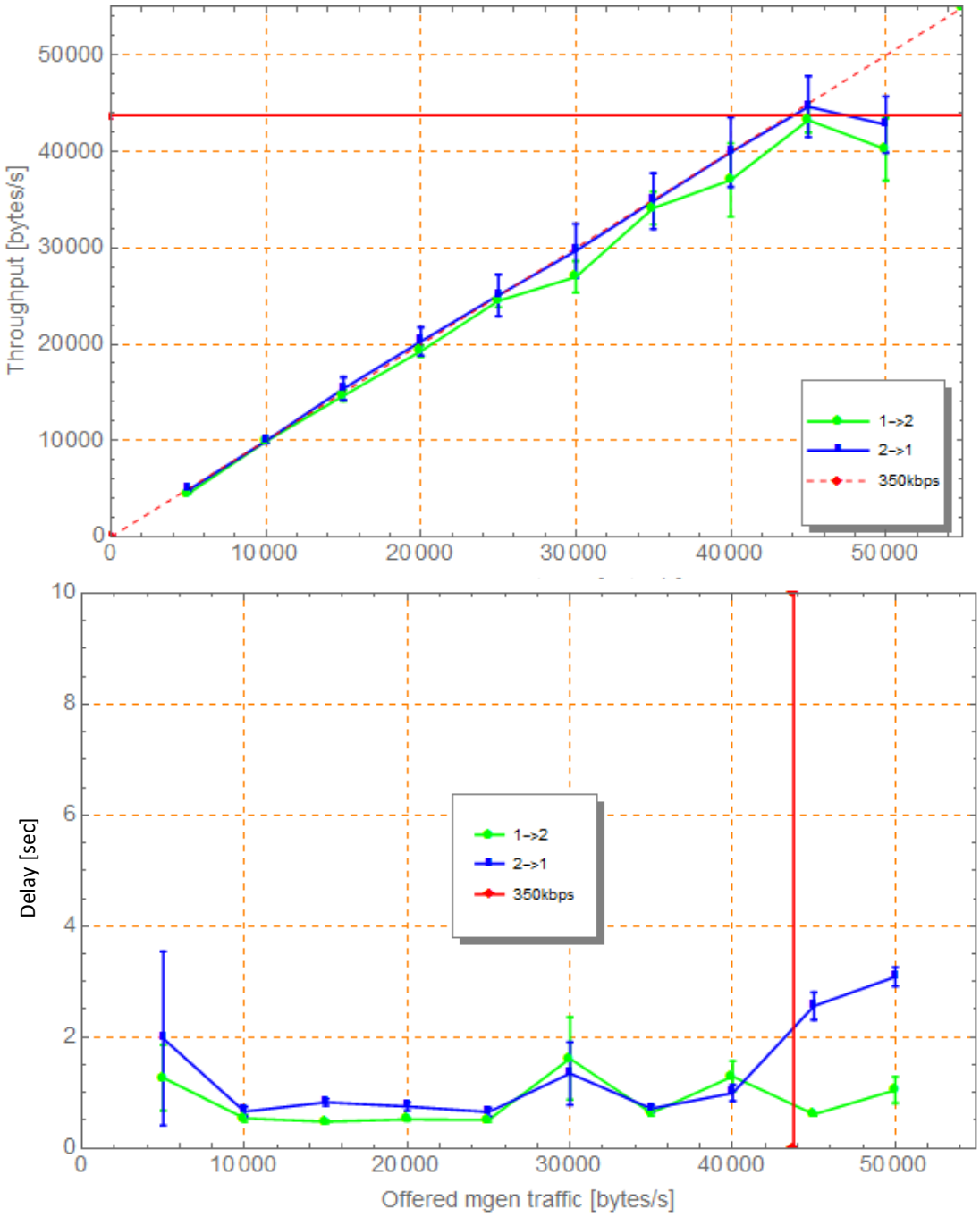


Figure A.25 Throughput and delay performance August 30.

A.6 August 31

Finding: The throughput reached 350 kbps but the packet loss rate is too high.

A.6.1 UDP performance plots

Test started: 2019-08-31T03:32:23 GPS: Lat:84.006 Long:28.575
Test ended: 2019-08-31T04:08:23 GPS: Lat:84.007 Long:28.547

run number	Rx window [sec]	# samples
1	598.2	11931
2	600.5	23774
3	120.5	7244
4	120.1	9540
5	120.5	11795
6	119.5	14303
7	120.1	16757
8	120.2	18285
9	120.3	20424
10	122.5	21187

Stream 1->2 (0102101) loss rate [%]: {1.18,1.07,1.18,1.49,2.38,1.54,2.02,8.83,12.22,15.12}

Stream 2->1 (0201101) loss rate [%]: {0.02,0.03,0.03,0.00,0.02,0.06,0.04,0.03,0.02,6.12}

Space Vehicle handover observation period [sec]: 2160
No of events: 8
HO rate [events/minutes]: 0.22
Avg time between ho [sec]: 241.54
Shortest time between ho [sec]: 14.85
Longest time between ho [sec]: 554.36
RSSI avg: -108, min: -116, max: -106
Beam handover observation period [sec]: 2160
No of events: 29
HO rate [events/minutes]: 0.81
Avg time between ho [sec]: 77.85
Shortest time between ho [sec]: 13.86
Longest time between ho [sec]: 280.15
RSSI avg: -104, min: -110, max: -99

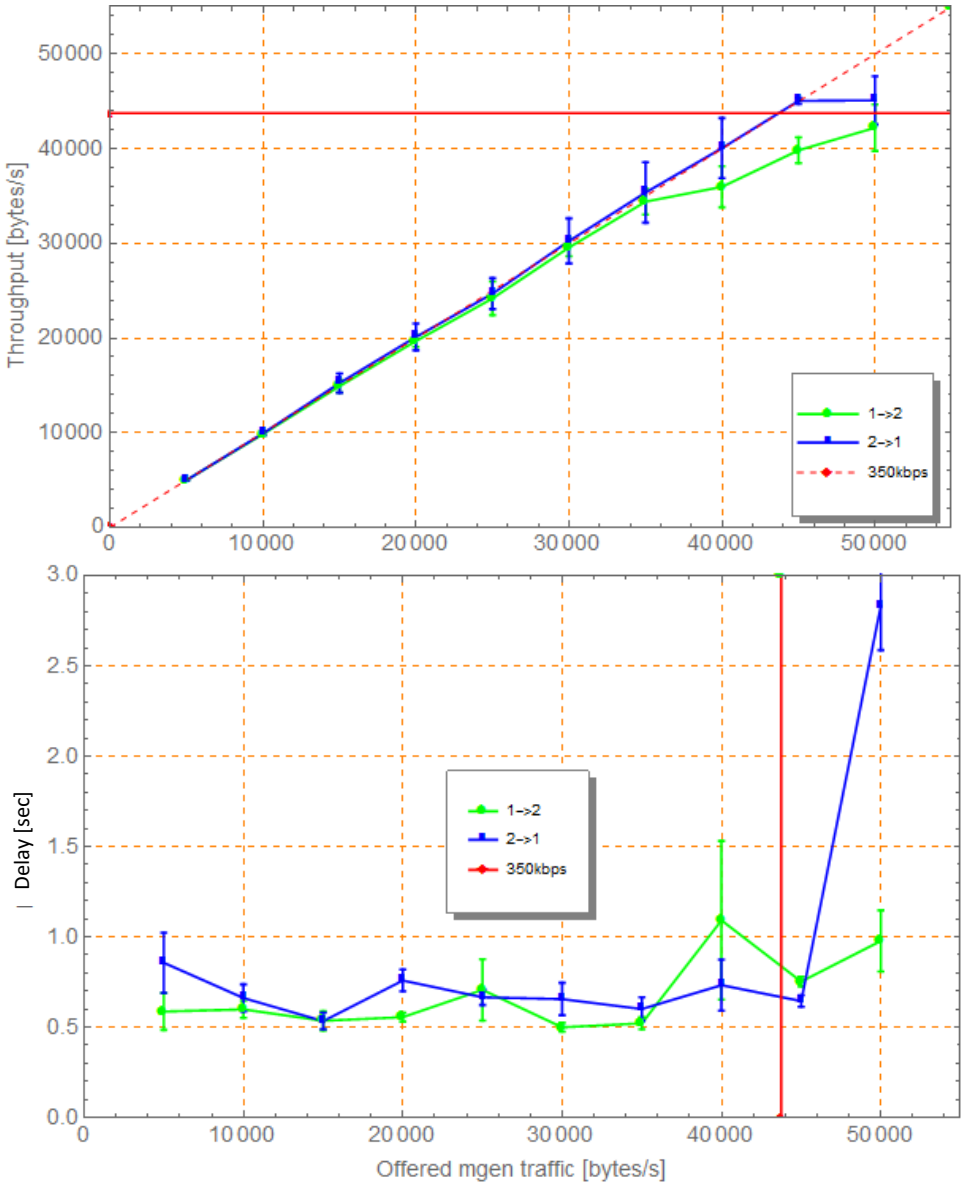


Figure A.26 Throughput and delay performance August 31.

A.7 September 1

Finding: The Iridium service has good performance with stable capacity.

A.7.1 UDP performance plots

Test started: 2019-09-01T03:32:23 GPS: Lat:84.022 Long:28.221
Test ended: 2019-09-01T04:08:23 GPS: Lat:84.022 Long:28.213

run number	Rx window [sec]	# samples
1	598.2	11988
2	600.0	23858
3	120.0	7065
4	120.0	9615
5	120.0	11844
6	120.0	14391
7	120.1	16571
8	120.0	19018
9	122.1	21403
10	120.9	21573

Stream 1->2 (0102101) loss rate [%]: {1.38,0.97,1.29,1.15,1.49,1.83,1.91,2.14,3.33,9.41}

Stream 2->1 (0201101) loss rate [%]: {0.00,0.05,0.06,0.00,0.03,0.05,0.02,0.06,0.03,10.45}

Space Vehicle handover observation period [sec]: 2160
No of events: 4
HO rate [events/minutes]: 0.11
Avg time between ho [sec]: 541.16
Shortest time between ho [sec]: 509.81
Longest time between ho [sec]: 559.31
RSSI avg: -104, min: -106, max: -104
Beam handover observation period [sec]: 2160
No of events: 28
HO rate [events/minutes]: 0.78
Avg time between ho [sec]: 82.75
Shortest time between ho [sec]: 19.80
Longest time between ho [sec]: 295.99
RSSI avg: -104, min: -108, max: -102

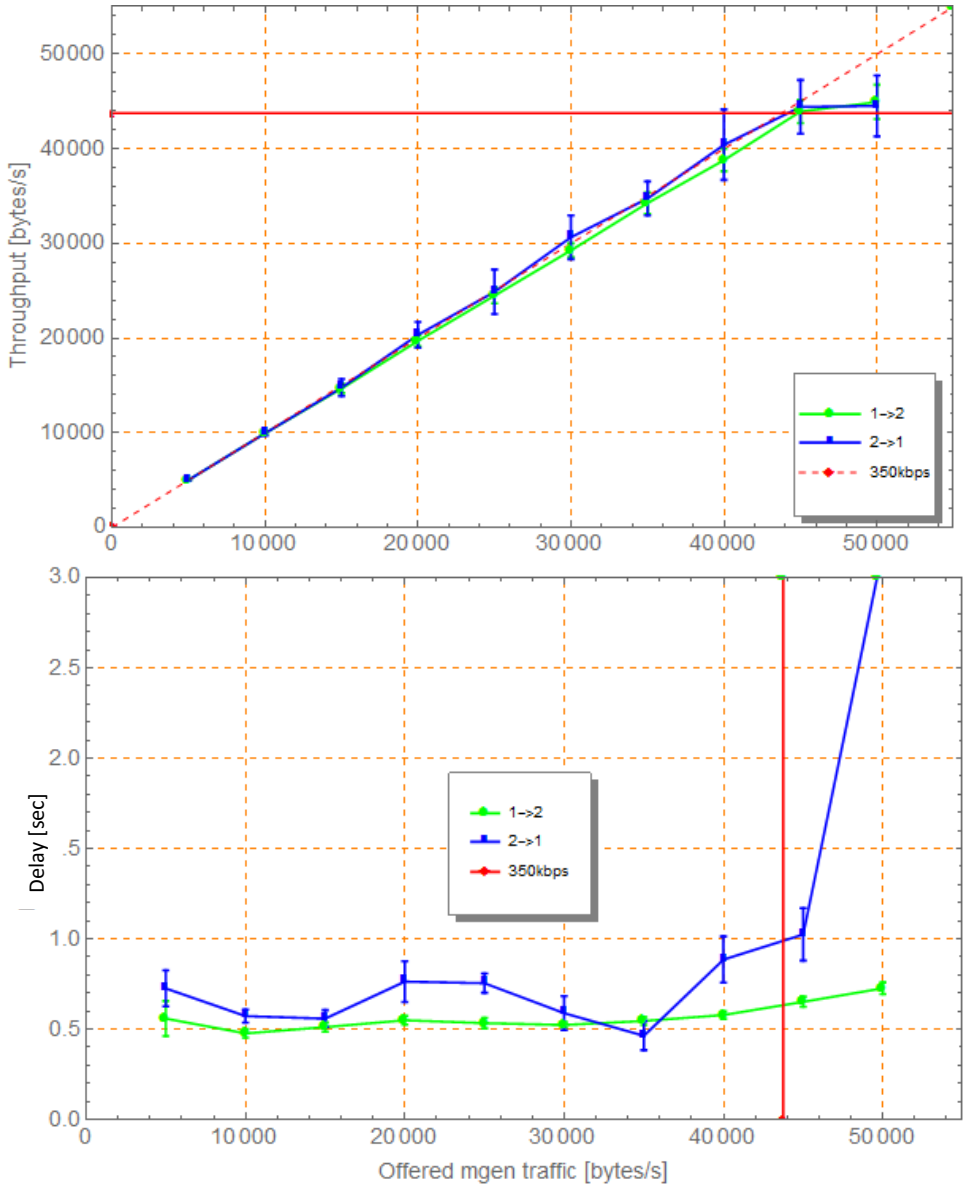


Figure A.27 Throughput and delay performance September 1.

A.8 September 3

Finding: The throughput reached 350 kbps but the packet loss rate is too high.

A.8.1 UDP performance plots

Test started: 2019-09-03T03:32:23 GPS: Lat:82.501 Long:24.109
Test ended: 2019-09-03T04:08:23 GPS: Lat:82.499 Long:24.111

run number	Rx window [sec]	# samples
1	598.5	12041
2	600.4	23855
3	120.6	7153
4	120.3	9527
5	120.0	11838
6	120.0	14330
7	120.9	16832
8	120.1	18446
9	122.7	20476
10	120.1	20598

Stream 1->2 (0102101) loss rate [%]: {3.36,0.93,1.31,1.31,2.41,1.44,2.70,5.59,9.48,18.12}
Stream 2->1 (0201101) loss rate [%]: {0.03,0.02,0.00,0.09,0.03,0.01,0.02,0.01,0.06,10.70}

Space Vehicle handover observation period [sec]: 2160
No of events: 4
HO rate [events/minutes]: 0.11
Avg time between ho [sec]: 547.11
Shortest time between ho [sec]: 541.53
Longest time between ho [sec]: 553.37
RSSI avg: -111, min: -116, max: -108
Beam handover observation period [sec]: 2160
No of events: 26
HO rate [events/minutes]: 0.72
Avg time between ho [sec]: 87.04
Shortest time between ho [sec]: 16.83
Longest time between ho [sec]: 287.09
RSSI avg: -104, min: -114, max: -100

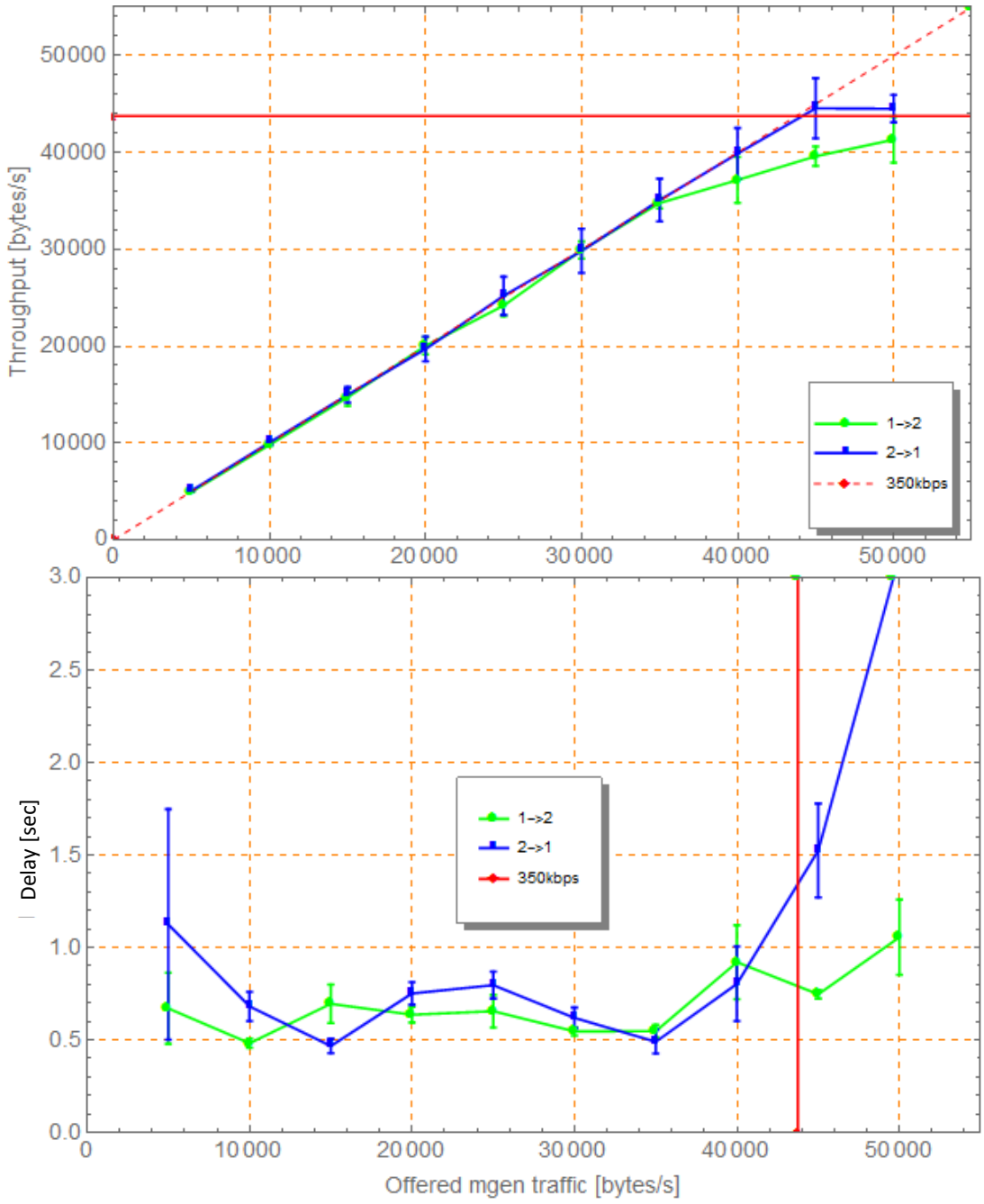


Figure A.28 Throughput and delay performance September3.

A.9 September 6

Finding: The throughput reached 350 kbps with acceptable loss rate.

A.9.1 UDP performance plots

Test started: 2019-09-06T03:32:23 GPS: Lat:81.557 Long:21.801
Test ended: 2019-09-06T04:08:23 GPS: Lat:81.552 Long:21.864

run number	Rx window [sec]	# samples
1	598.7	11740
2	599.9	23888
3	120.0	7154
4	120.4	9411
5	119.8	11920
6	120.1	14316
7	120.4	16510
8	120.1	18600
9	121.7	21333
10	121.1	21843

Stream 1->2 (0102101) loss rate [%]: {0.92,1.16,1.27,3.07,1.70,1.57,2.12,7.19,3.19,8.30}
Stream 2->1 (0201101) loss rate [%]: {0.03,0.07,0.03,0.06,0.02,0.29,0.01,0.05,0.74,10.48}

Space Vehicle handover observation period [sec]: 2160
No of events: 4
HO rate [events/minutes]: 0.11
Avg time between ho [sec]: 560.96
Shortest time between ho [sec]: 540.50
Longest time between ho [sec]: 580.11
RSSI avg: -109, min: -115, max: -106
Beam handover observation period [sec]: 2160
No of events: 27
HO rate [events/minutes]: 0.75
Avg time between ho [sec]: 81.44
Shortest time between ho [sec]: 7.92
Longest time between ho [sec]: 283.12
RSSI avg: -103, min: -107, max: -102

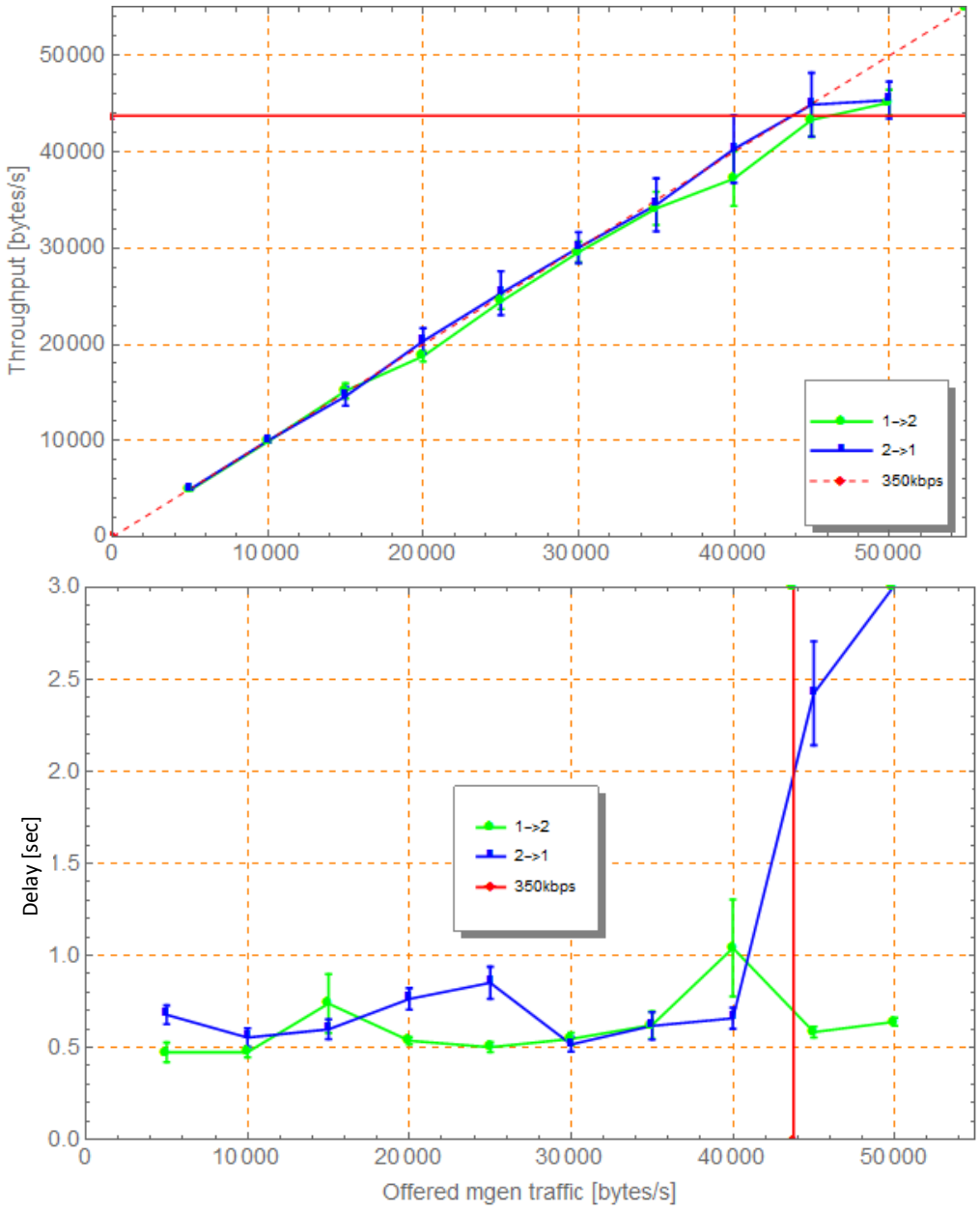


Figure A.29 Throughput and delay performance September 6.

A.10 September 7

Finding: The throughput reached 350 kbps but the packet loss rate is too high.

A.10.1 UDP performance plots

Test started: 2019-09-07T03:32:26 GPS: Lat:80.878 Long:22.048
Test ended: 2019-09-07T04:08:59 GPS: Lat:80.872 Long:22.056

run number	Rx window [sec]	# samples
1	598.1	11744
2	600.1	23761
3	119.9	7066
4	119.9	9518
5	121.0	11962
6	119.9	14157
7	124.7	16404
8	120.1	18773
9	121.7	20137
10	121.1	20686

Stream 1->2 (0102101) loss rate [%]: {3.64,1.46,1.26,1.26,1.96,1.69,2.27,1.94,8.64,15.34}
Stream 2->1 (0201101) loss rate [%]: {0.07,0.04,0.03,0.00,0.02,0.01,0.06,0.37,5.07,11.29}

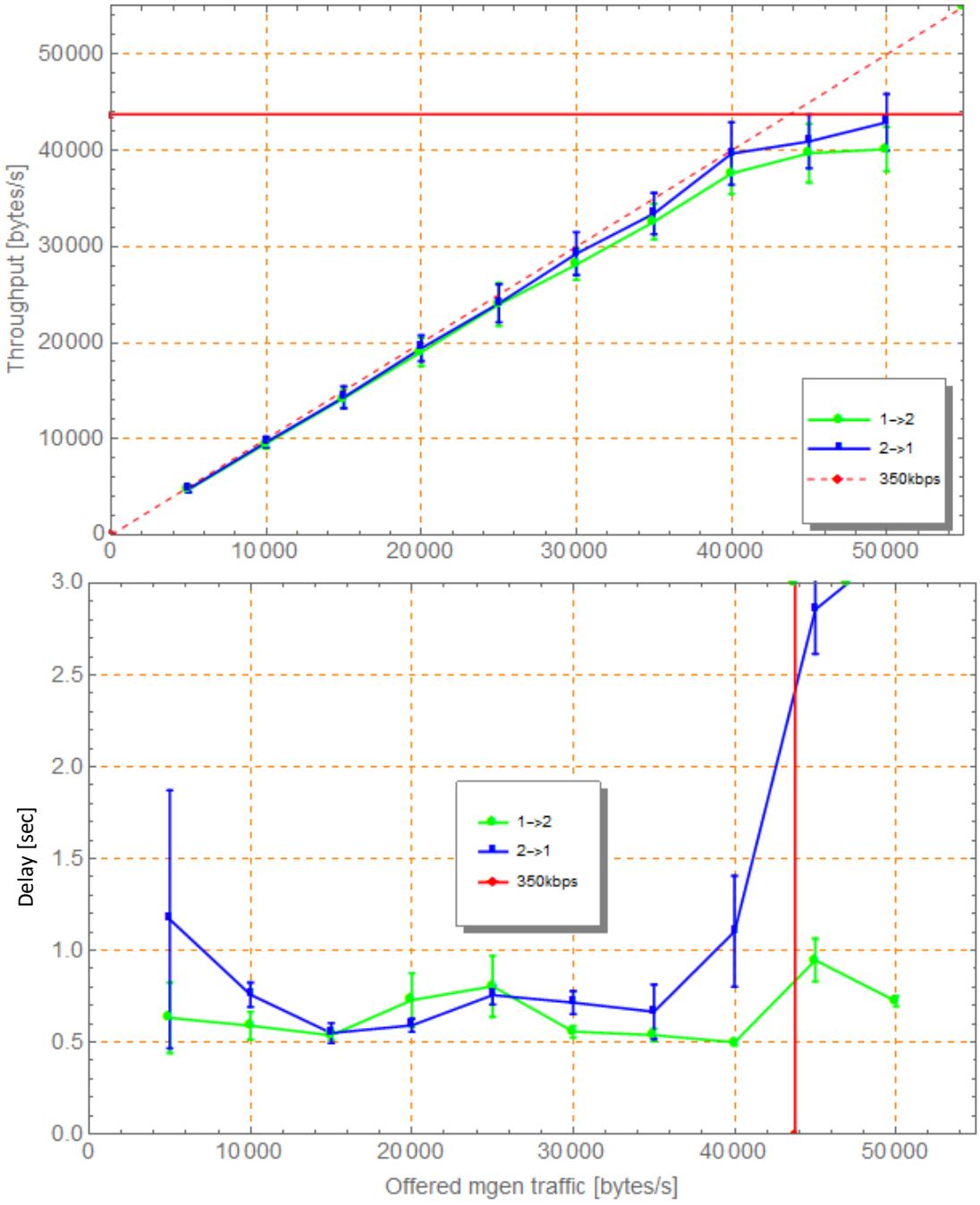


Figure A.30 Throughput and delay performance September 7.

Acronyms

CLC	Consecutive loss count
dBm	decibel with reference to one milliwatt
GPS	Global positioning system
HO	Handover
IP	Internet protocol
IxChariot	IP traffic generator from www.ixiacom.com
kbps	kilo bit per second
MGEN	IP traffic generator from www.navy.mil
pkps	Packets/s
RSSI	Received signal strength indicator
SIM	Subscriber identification module
SV	Space vehicle
TCP	Transmission control protocol
TG	Traffic generator
UDP	User datagram protocol
UTC	Coordinated universal time

References

[1] Jodalen V., Rytir M., Arneson V., Skeie B., Sander J., Bråten L. E., «Kommunikasjon i nordområdene (Del 1) – beskrivelse av utvalgte teknologier», (BEGRENSET), FFI-rapport 19/00627.

[2] Jodalen V., Rytir M., Arneson V., Skeie B., Sander J., Bråten L. E., «Kommunikasjon i nordområdene (Del 2) – beskrivelse av utvalgte teknologier», (BEGRENSET), FFI-rapport 19/00628.

[3] www.iridium.com, Certus fact sheet

[4] www.thalesgroup.com, VesseLINK modem

[5] www.marlink.com

About FFI

The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

FFI's MISSION

FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

FFI's VISION

FFI turns knowledge and ideas into an efficient defence.

FFI's CHARACTERISTICS

Creative, daring, broad-minded and responsible.

Om FFI

Forsvarets forskningsinstitutt ble etablert 11. april 1946. Instituttet er organisert som et forvaltningsorgan med særskilte fullmakter underlagt Forsvarsdepartementet.

FFIs FORMÅL

Forsvarets forskningsinstitutt er Forsvarets sentrale forskningsinstitusjon og har som formål å drive forskning og utvikling for Forsvarets behov. Videre er FFI rådgiver overfor Forsvarets strategiske ledelse. Spesielt skal instituttet følge opp trekk ved vitenskapelig og militærteknisk utvikling som kan påvirke forutsetningene for sikkerhetspolitikken eller forsvarsplanleggingen.

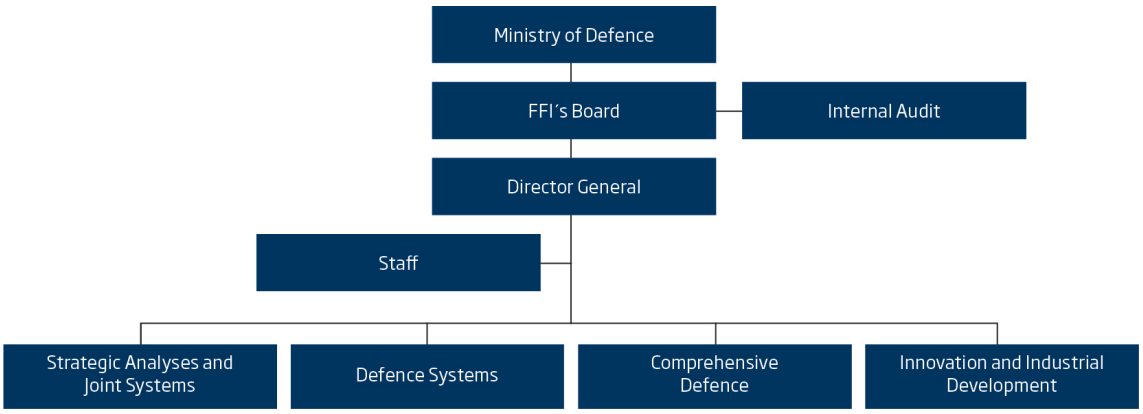
FFIs VISJON

FFI gjør kunnskap og ideer til et effektivt forsvar.

FFIs VERDIER

Skapende, drivende, vidsynt og ansvarlig.

FFI's organisation



Forsvarets forskningsinstitutt
Postboks 25
2027 Kjeller

Besøksadresse:
Instituttveien 20
2007 Kjeller

Telefon: 63 80 70 00
Telefaks: 63 80 71 15
Epost: ffi@ffi.no

Norwegian Defence Research Establishment (FFI)
P.O. Box 25
NO-2027 Kjeller

Office address:
Instituttveien 20
N-2007 Kjeller

Telephone: +47 63 80 70 00
Telefax: +47 63 80 71 15
Email: ffi@ffi.no

FFI Forsvarets forskningsinstitutt
Norwegian Defence Research Establishment