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Iridium Certus 700
IP Performance Testing

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Summary

In the last years there have been increased military and civilian activity in the Arctic. 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 communications capacity in the northern areas. One candidate is the Iridium satellite system.

FFI tested the performance of the Iridium Certus 350 service in 2019. An Iridium Certus upgrade in 2020 should give increased performance and a new measurement campaign was conducted in January and February 2021. This report presents the test results and concludes that the shortcomings observed in 2019 still remain.

Contents

1 Introduction

In the last years there have 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 communications capacity in the northern areas [1, 2]. One candidate is the Iridium satellite system. We tested the Internet Protocol (IP) performance of Iridium in 2019 [3].

A Low Earth Orbit (LEO) system like Iridium has highly variable propagation and switching delays because of routing changes and handovers [4]. A widely used transport protocol across the Internet is the Transmission Control Protocol (TCP), and a consequence of long packet delivery delays may be decreased TCP efficiency and connection losses.

In [3], we used the User Datagram Protocol (UDP) to measure the Iridium Certus® 350 (download/upload speeds 352/352 kbps) performance. In contrast to TCP, UDP does not retransmit lost or delayed packets. The benefit is that the offered traffic does not increase during route changes or handovers. When the Iridium system stops serving packets, a UDP based traffic generator continues to send packets at the same rate. The packets are buffered in the network but packet losses occur if the Iridium blocking period lasts too long. In [3], the fraction of the tests that reached the throughput capacity subscribed to was only 45 % and Iridium blocking periods up to 70 seconds were measured.

Reference [5] performed measurements on an earlier Iridium service. These tests were based on TCP and observed the same problems as in [3].

An Iridium Certus® upgrade in 2020 should give increased throughput capacity. According to the Iridium Certus 700 fact sheet [6], download/upload data speeds up to 704kbps/352kbps are supported.

The main shortcoming of Iridium Certus 350 is the long and frequent blocking periods where no user packets are delivered [3, figure 7.1]. In January 2021 we started a new measurement campaign repeating many of the tests from 2019 [3] to get answers to the following questions:

Q1: What is the probability of having access to the Iridium service (availability)?

Q2: Has Iridium Certus 700 the same shortcomings as observed with Iridium Certus 350?

Q3: Does Iridium Certus 700 deliver the throughput capacity subscribed to?

The Iridium Certus 700 subscription period terminated before we got a sufficiently large sample volume to answer question Q3.

The method used to get answers to these questions is to apply two UDP traffic generators as illustrated in Figure 1.1 and collect the network statistics described in appendix A. The measurement campaign was restricted to laboratory testing at Kjeller/Oslo in the same manner as described in [3, chapter 6]. This is a favourable radio environment with the modem antenna mounted at the top of a building without interfering objects on the radio link to the Iridium satellites.

Measurement of the end-to-end packet delays on the two IP streams demand precise time-synchronisation between the two traffic generators. This function was implemented by means of the Network Time Protocol (NTP).

The rest of this document is organised as follows: first, in chapter 2 we analyse the traffic data produced by the traffic generators. In chapter 3, we analyse the handover statistics produced by the Thales VesseLINK modem [7]. In chapter 4 we discuss the test results. Finally, chapter 5 concludes.

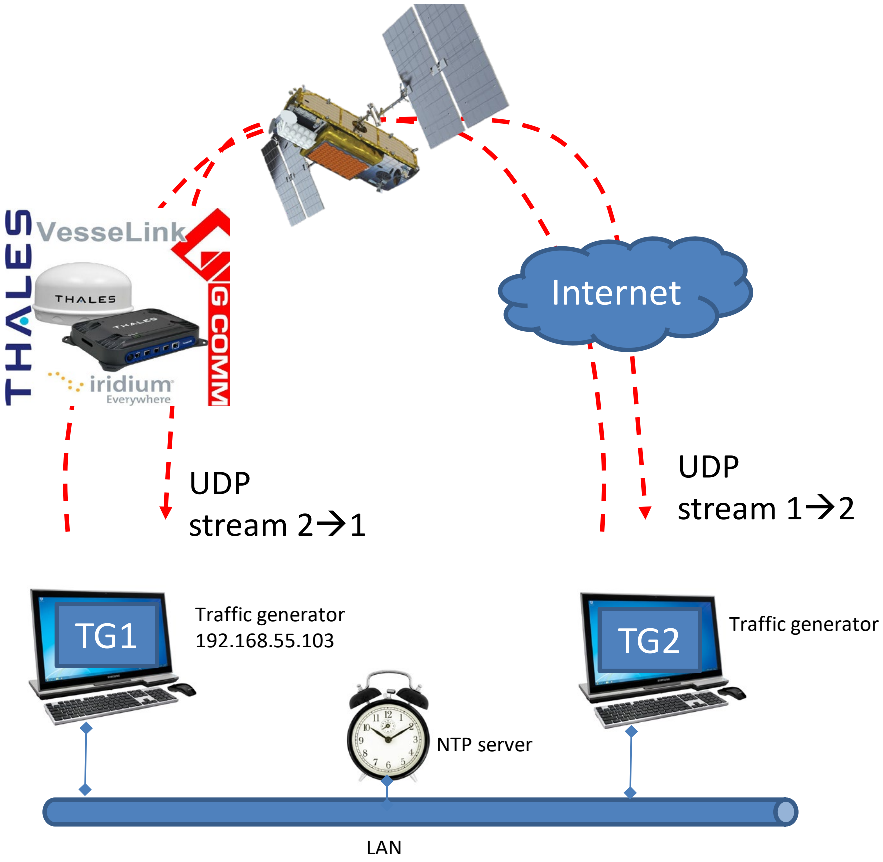

Figure 1.1 The test scenario employed two traffic generators configured to produce two identical UDP streams. A common wall clock for the traffic generators TG1 and TG2 was implemented by means of NTP.

2 Test Results

The main purpose of the tests outlined in this chapter is to get data to answer the following question from the previous chapter:

Q1: What is the probability of having access to the Iridium service (availability)?

We used the same test setup and test scripts for Certus 700 as we used for Certus 350 [3, chapter 6] even though the downlink capacity has increased from 352 to 704 kbps. The offered traffic is very low compared to the Certus 700 capacity and the packet loss rate should be insignificant.

Availability tests were executed four times every twenty-four hours {03:00, 09:00, 15:00, 21:00}, UTC time. The UDP offered traffic was 25 kbps with 500 bytes payload[1]. This amounts to 7 % of the expected capacity on the uplink (352 kbps). The test duration was 15 minutes. If no packet loss events occurred, each end would receive 5625 packets.

A test is defined to be valid if minimum one packet delivery occurs in both directions during the 15 minute test period. We got 164 valid tests from January 19th to February 28th, see Table 2.1.

The traffic conditions during the tests are analysed in the subsections below.

UTC time	03:00	09:00	15:00	21:00
#errors	0	0	0	0
#tests	41	41	41	41
#tg errors	0	0	0	0
#sat failure	0	0	0	0
sat error rate	0	0	0	0

Table 2.1 Availability tests in January and February. Each test lasted 15 minutes.

2.1 Analysis – January data

Between January 19th and January 31st we got 52 valid test results. Figure 2.1 presents the throughput[2] measured as 95 % confidence intervals. In a healthy network, all the confidence intervals would have covered the red dotted horizontal lines (25 kbps) since the packet loss should be close to zero at the load level used. Figure 2.2 plots the average end-to-end delay as 95% confidence intervals. Some of the intervals are large even though many samples are available. That indicates highly variable delays.

A strong indication of irregular behaviour is a test where both the throughput and the delay show unexpected results. The test on January 20 UTC 03:00 is an example of a test where low

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[1] 3125 bytes/s, 6.25 packets/s

[2] Appendix A specifies how network statistics are collected.

Iridium service quality is observed. Figure 2.3 plots the delay samples for this test as time-series and shows a gap in the packet delivery between [900, 1000] seconds. The queues fill up, the delay increases and when the link opens up again the first packets have large delays (23s and 43s). The loss rate is low and the delay drops rapidly after the blocking period since the offered traffic is low.

The test on January 31 UTC 21:00 is an example of a test where good service quality is observed – both the throughput and the delay indicate stable behaviour. Figure 2.4 plots the delay samples as time-series. No blocking period is visible and the maximum delay is lower (5s and 5s).

Maybe the best method to visualise the long blocking periods is to plot the consecutive loss count (CLC) as time-series. Appendix A.3 defines the CLC metric precisely and specifies how the samples are formed. Figure 2.5 presents the CLC for the January 20 UTC 03:00 test and shows high values (197 and 241) in the same time periods as long delays are observed in Figure 2.3.

Packet loss rates up to 6% are measured in Figure 2.6. This is a very high value for the traffic load level used.

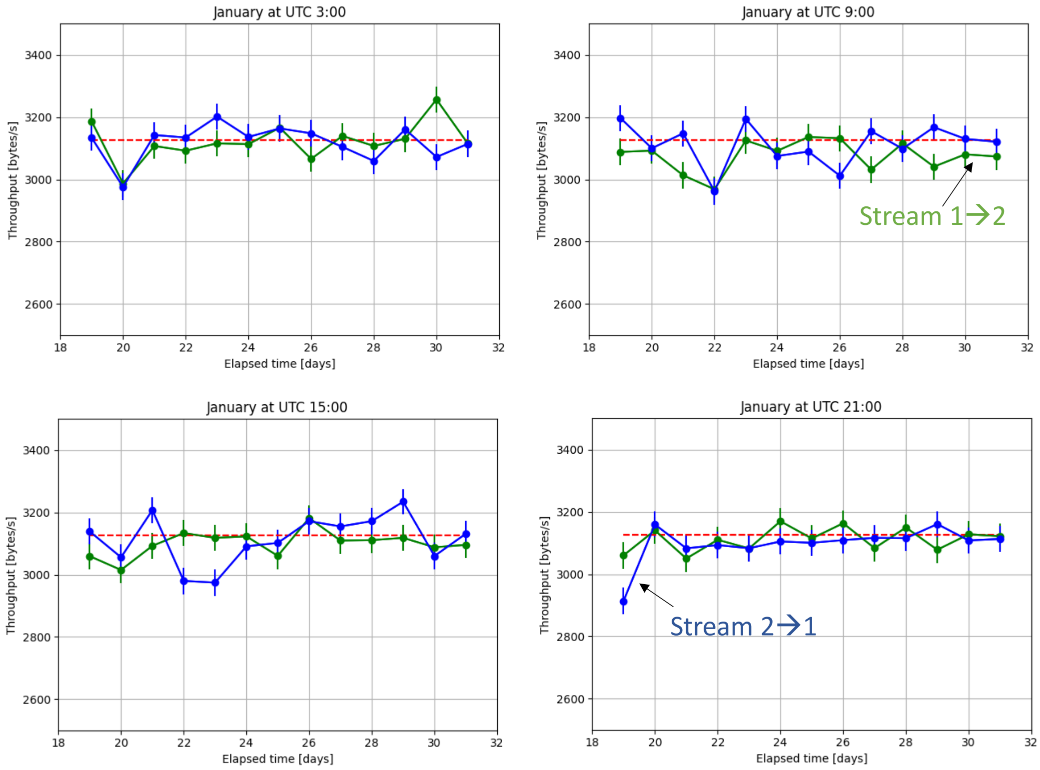

Figure 2.1 Measured throughput in January. The red dotted line is the reference line 3125 bytes/s (25 kbps) representing the expected throughput.

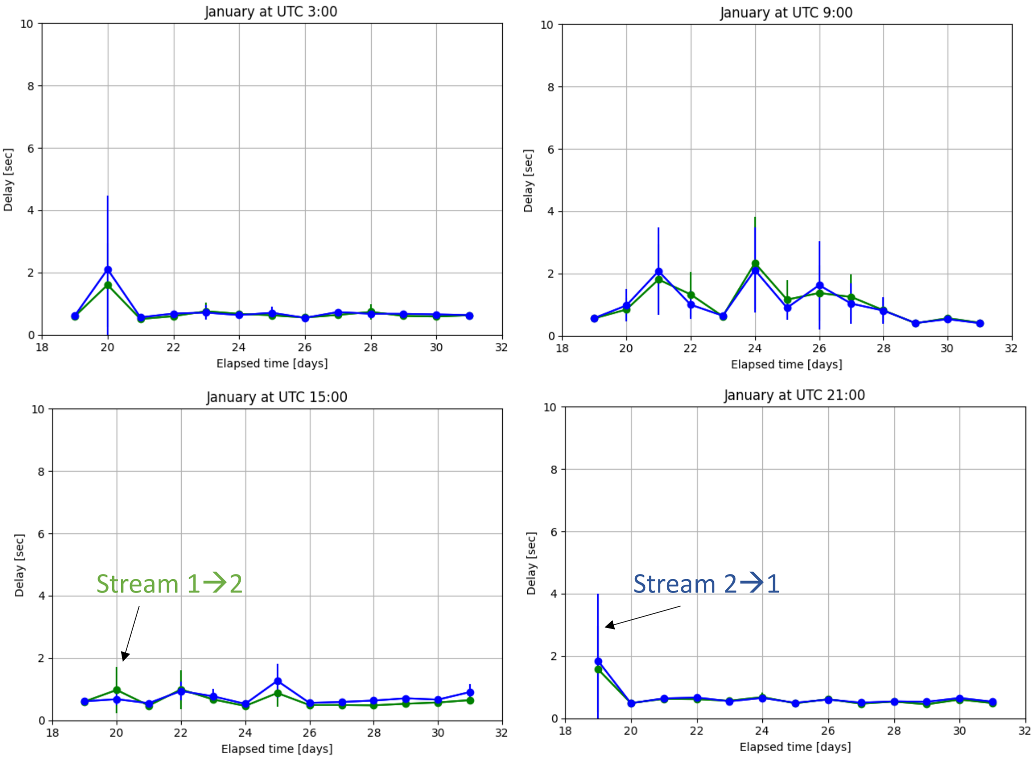

Figure 2.2 Measured delay in January.

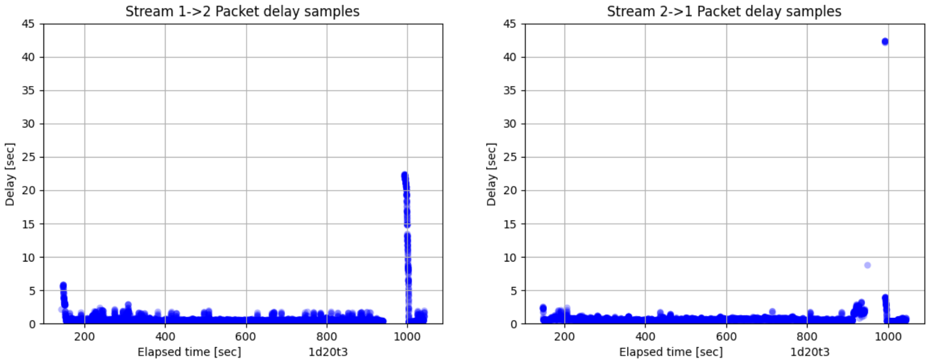

Figure 2.3 Measured delay January 20 UTC 03:00 presented as time-series. The sample sizes are 5371 (left plot) and 5346. This is the test with the largest confidence intervals. The blocking period between seconds 900 and 1000 (the gap in the delay measurements) is caused by an interruption in the delivery of packets. We observe a high delay immediately after the blocking period, when package delivery resumes.

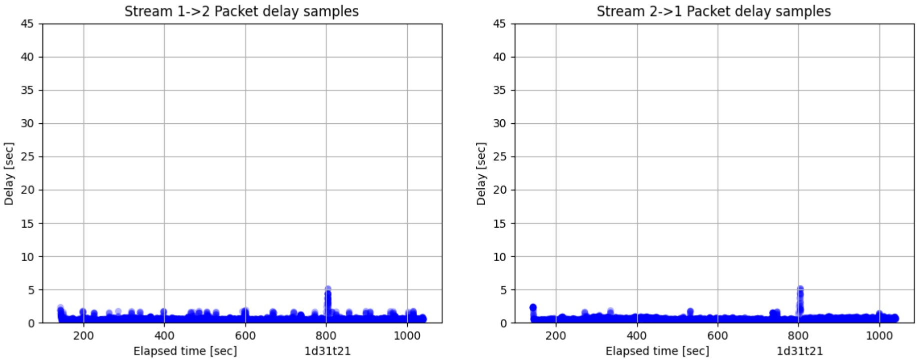

Figure 2.4 Measured delay January 31 UTC 21:00 presented as time-series. The sample sizes are 5609 (left plot) and 5592. No blocking periods were observed.

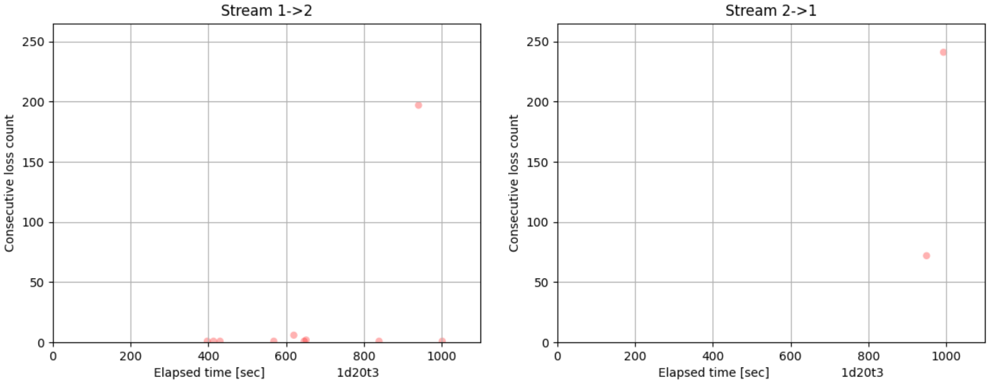

Figure 2.5 CLC January 20 UTC 03:00 presented as time-series.

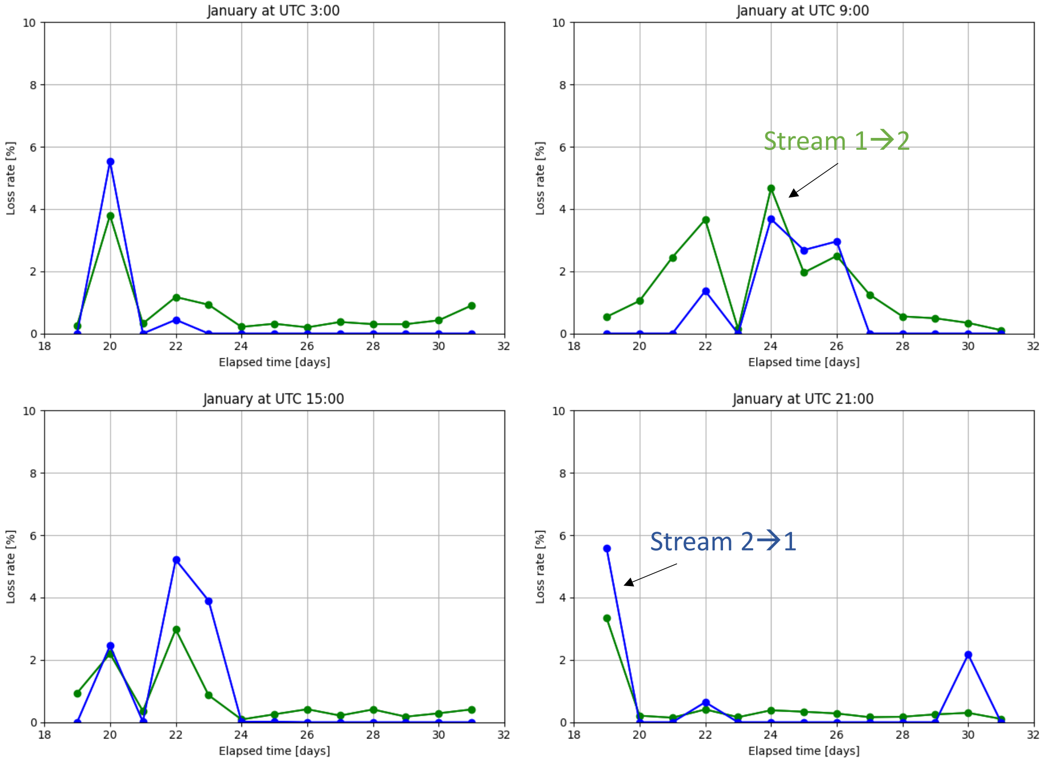

Figure 2.6 Packet loss rate in January.

2.2 Analysis – February data

We had 112 tests in February. Figure 2.7 and Figure 2.8 present the throughput and delay as 95 % confidence intervals.

A test where both the throughput and the delay show unexpected results is a strong indication of irregular behaviour in the Iridium service. The test on February 22 UTC 03:00 is an example of a test where low Iridium service quality is observed. Figure 2.9 plots the delay samples as time-series and shows a gap in the packet delivery between [550, 580] seconds. The queues fill up, the delay increases and when the link opens up again the first packets have large delays (17s and 27s).

The test on February 4 UTC 15:00 is an example of a test where good service quality is observed – both the throughput and the delay indicate normal behaviour. Figure 2.10 plots the delay samples as time-series. No blocking period is visible and the maximum delays are lower (3s and 3s).

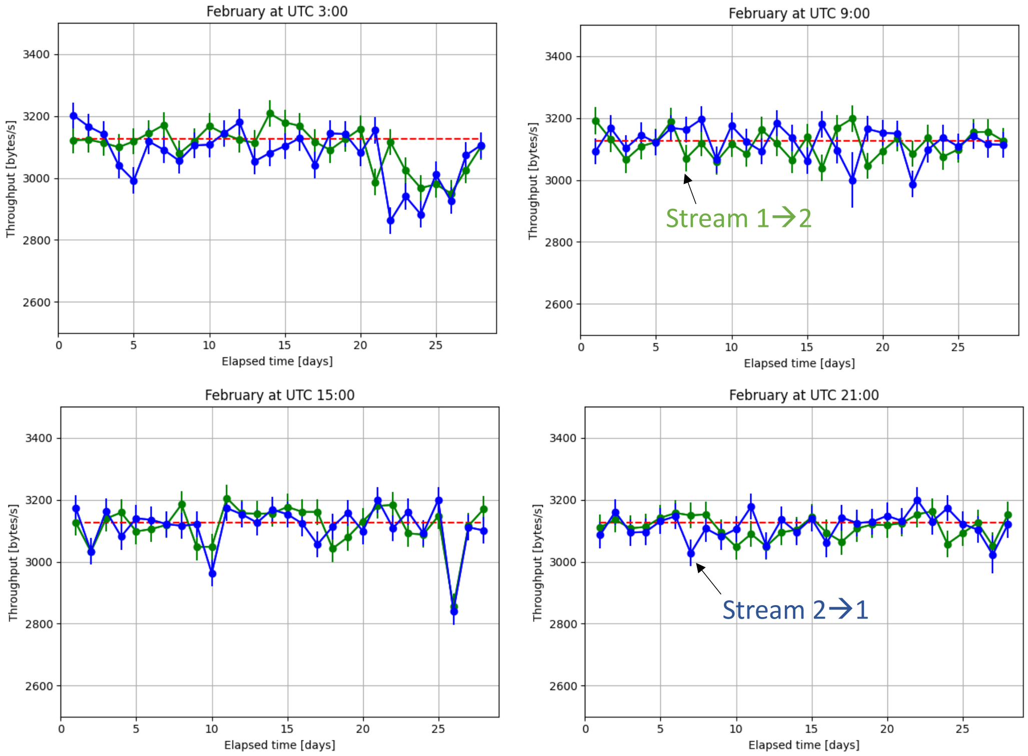

Figure 2.7 *Measured throughput in February. The red dotted line is the reference line 3125 bytes/s (25 kbps) representing the expected throughput.*

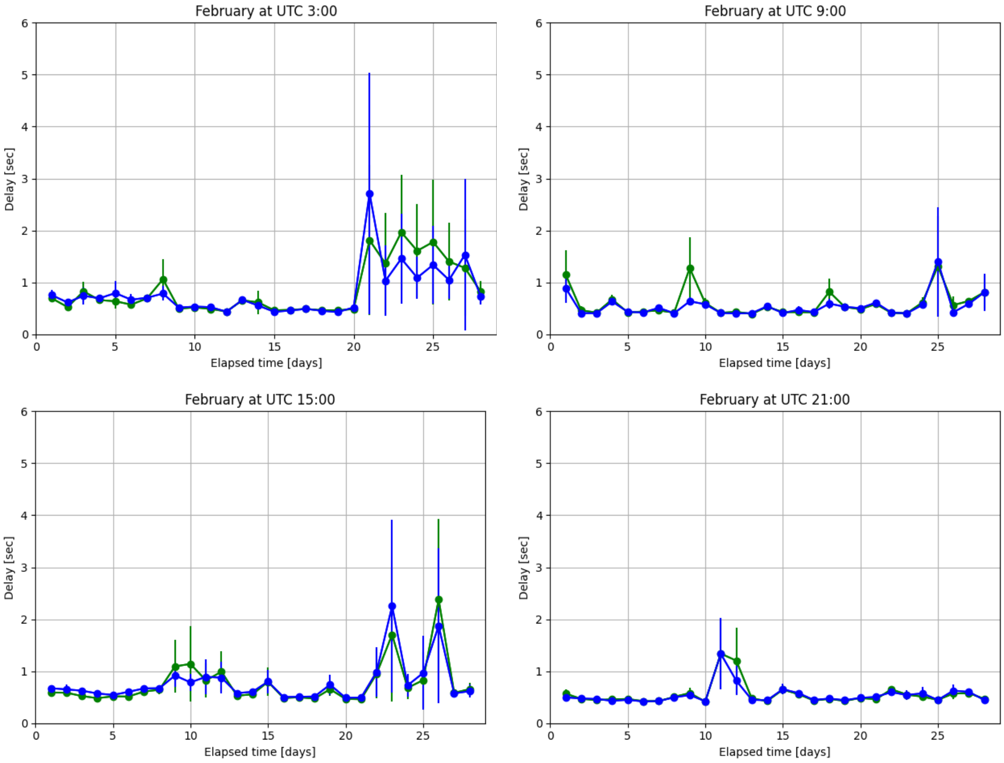

Figure 2.8 Measured delay in February. An example of a good period is UTC 21:00 starting at 14. An example of a bad period is UTC 03:00 from day 21 to day 27.

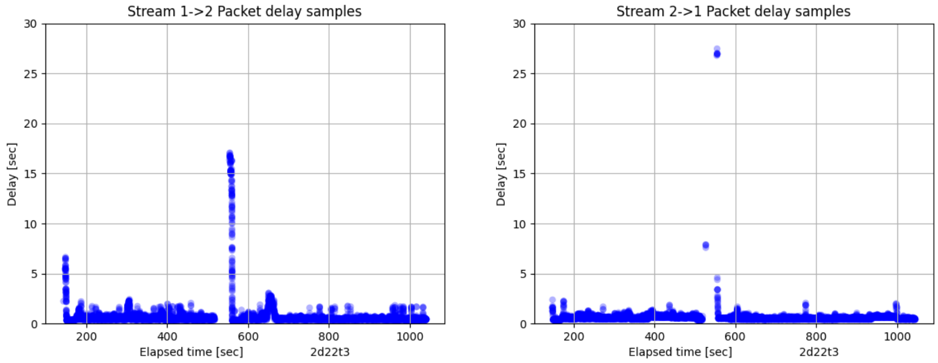

Figure 2.9 Measured delay February 22 UTC 03:00 presented as time-series. The sample sizes are 5597 (left plot) and 5141. The blocking period between seconds 550 and 580 (the gap in the delay measurements) is caused by an interruption in the delivery of packets. We observe a high delay immediately after the blocking period, when package delivery resumes.

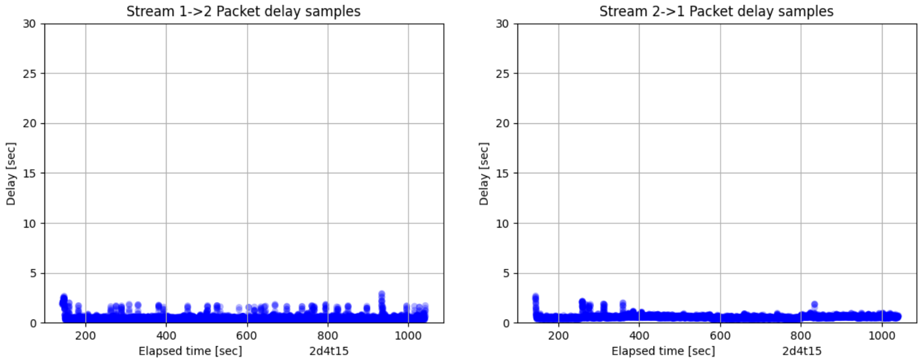

Figure 2.10 Measured delay February 4 UTC 15:00 presented as time-series. The sample sizes are 5678 (left plot) and 5536.

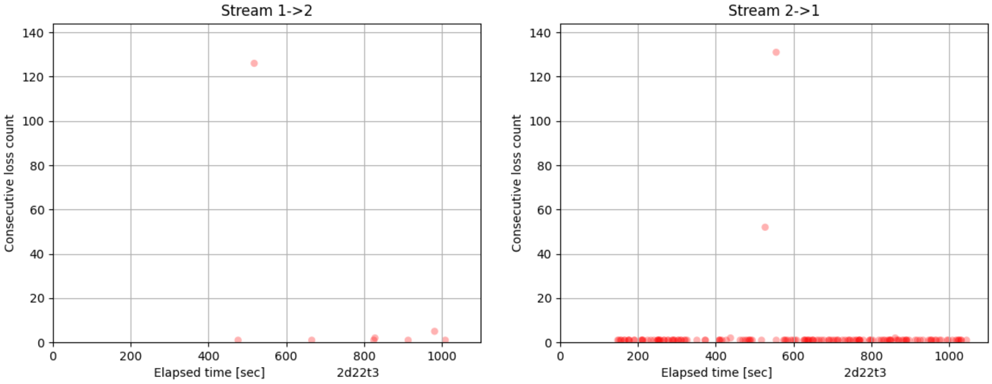

Figure 2.11 CLC February 22 UTC 03:00 presented as time-series.

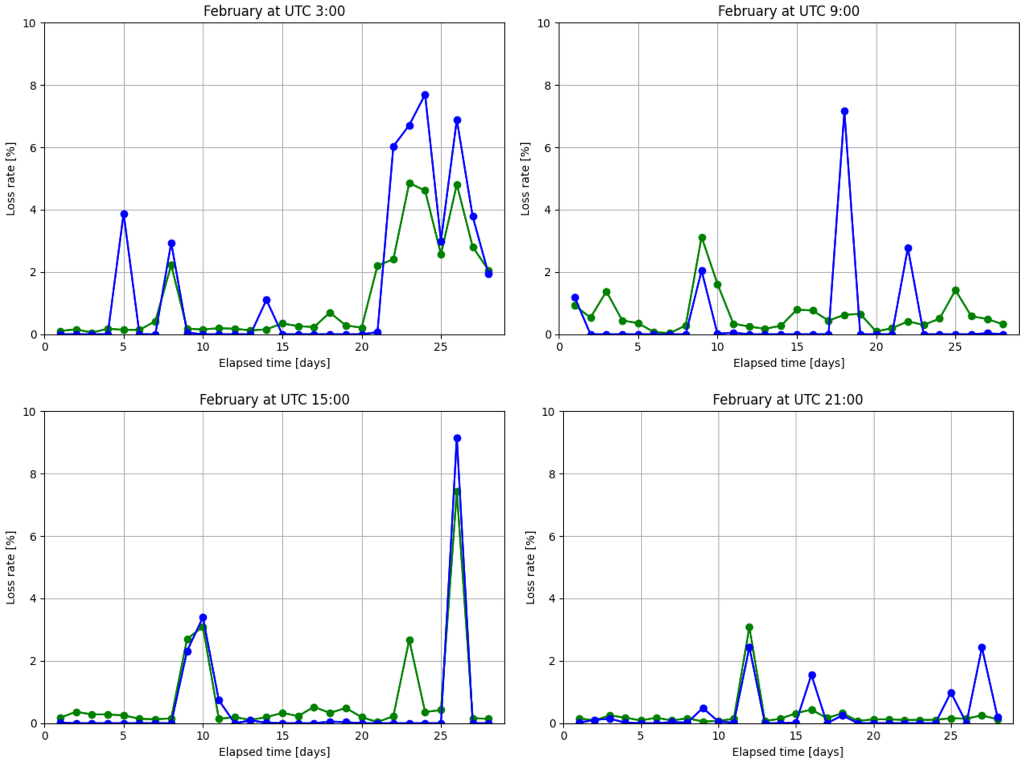

Figure 2.12 Packet loss rate in February.

3 Handover Statistics

Whereas the radio coverage area of a geostationary satellite system is stationary, the Iridium satellites have asynchronous movement relative to the Earth. The Iridium radio coverage becomes non-stationary and Iridium must implement handover functions to provide continuous service coverage. A handover algorithm should take into account receiving signal strength, remaining service time and satellites' idle channels (traffic load) [10].

This chapter presents the handover (HO) statistics. We have no information about the HO algorithm used in Iridium nor in the modem. Only log data from the Iridium modem is available and therefore we cannot tell what happens inside the Iridium system.

As shown in Figure 1.1, time-synchronisation between the traffic generators (TG) is achieved by means of NTP. Our local NTP server is synchronised to a public NTP server on the Internet. The Iridium modem uses GPS as time reference. The timing error between the modem log data and the MGEN[3] log data is expected to be less than 10 seconds[4]. This accuracy is sufficient for the HO analysis below.

Handovers in satellite networks can be classified as follows [8]:

*Link-Layer Handove*r (LLH):
- Space Vehicle Handover (SV HO)
- Spot Beam Handover (Beam HO)
- Inter Satellite Link Handover (ISL HO)

Network Layer Handover (NLH)

NLH events occur when the communication endpoints change IP addresses due to the change of coverage area. ISL HO happens when a satellite is forced to select a new satellite for rerouting of the user traffic. Beam HO occurs when the modem selects another spot beam on the same satellite. SV HO occurs when the modem connects to a beam on another satellite. We are unable to take NLH and ISL HO measurements since we have no access to Iridium's internal management system. Only SV HO and Beam HO samples are available through the modem log.

It is possible to predict the movement of the Iridium satellites. This makes it easier to select the next serving satellite during SV HO. However, many factors complicate the scenario for the HO algorithm in the modem. The satellite beams may be turned off to reduce interference, or to save power [16]. The satellite needs to reroute the user data stream and an additional HO delay is introduced. We have no information about the signalling system between the modem and the satellite. If the modem selects a satellite that turns off the beam a few seconds later, the results may be increased HO rates.

Figure 3.1 illustrates the most important events during SV HO. The modem locks to SV #2 at time t_1, loses contact with SV #2 at time t_2 and the modem initiates the HO process. The Iridium link is unable to serve the packets, and the packets sent by TG1/TG2 are buffered by the modem/Internet. Buffer overflow occurs at time t_3 and a packet loss period starts. Handover is completed at t_4 and the Iridium link starts to serve the packets.

We define:

Time between handover: $\boldsymbol{T_{HO} = t_4 - t_1}$
Handover processing time: $\boldsymbol{T_{HP} = t_4 - t_2}$

This document presents statistics for T_{HO} only.

The time instances t_1 and t_4 are available from the modem log. t_2 and t_3 can be estimated from the MGEN log. Time t_2 is approximately the sent time of the first packet in a sequence of high

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[3] Multipurpose generator (MGEN) is an open source traffic generator, https://www.nrl.navy.mil/
[4] The timing error between TG1 and TG2 is expected to be average/maximum = 1/10 milliseconds.

delay packets (sent time of packet 2 in Figure 3.2). Time t_3 is approximately the sent time of the first packet after a gap in the receive sequence number (sent time of packet 11 in Figure 3.2).

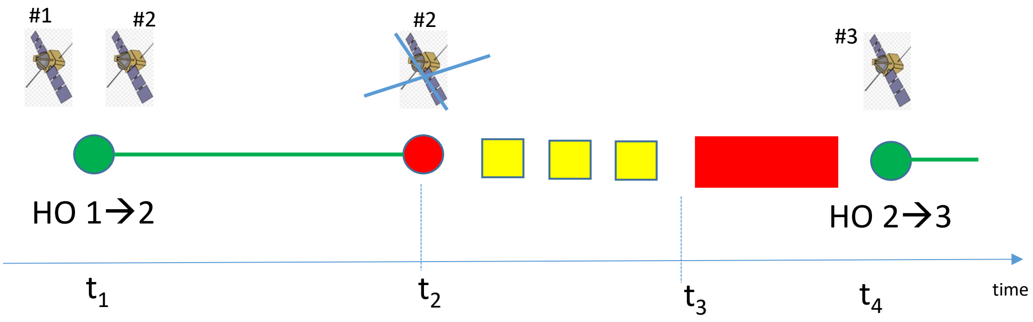


Figure 3.1 Time event sequence during satellite handover. The modem selects SV #2 as the serving satellite at time t_1, loses the connection at time t_2 and starts the handover procedure. The satellite SV #3 becomes the new serving satellite at time t_4.

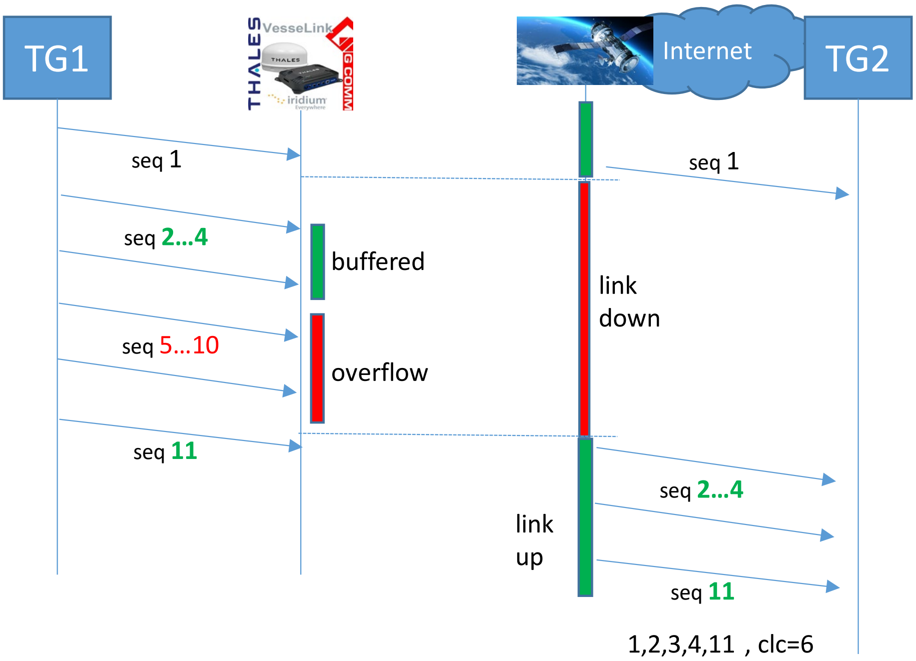


Figure 3.2 Example of packet delivery and loss.

Section 2.1 identified the January 20 UTC 03:00 test as a low quality period with a high CLC value during the period [900, 1000] seconds, that is, the handover period ($t_4 - t_2$) in Figure 3.1 is too long. The time-sequence plot of the SV/beam HO events for this test is shown in Figure 3.3 on the left. The plot on the right side illustrates how the modem changes satellite by plotting the satellite number versus time. The modem executes handovers to the following satellites during this test: [3, 23, 26, 88, 96, 103, 115].

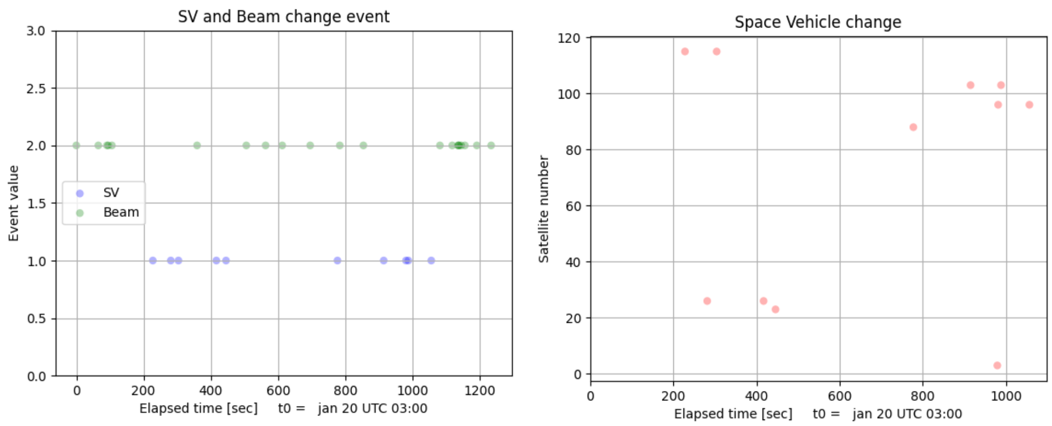
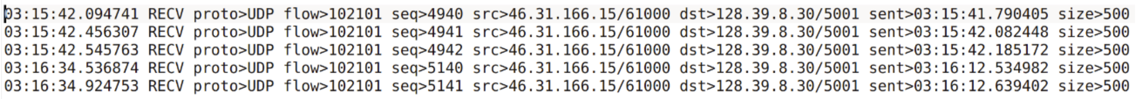


Figure 3.3   Handovers on January 20th UTC 03:00.

A printing of the MGEN log follows:

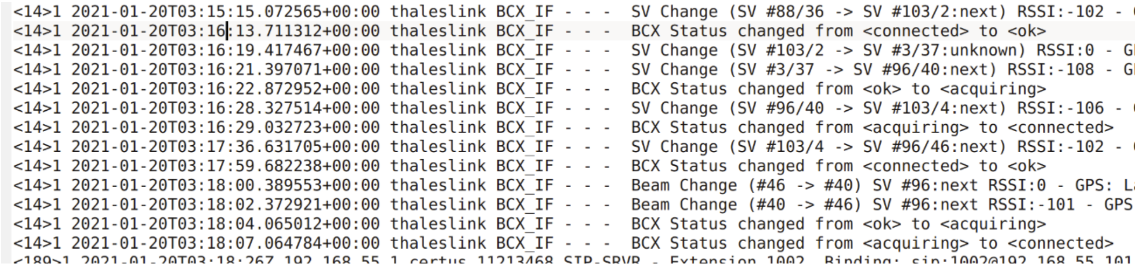


```
03:15:42.094741 RECV proto>UDP flow>102101 seq>4940 src>46.31.166.15/61000 dst>128.39.8.30/5001 sent>03:15:41.790405 size>500
03:15:42.456307 RECV proto>UDP flow>102101 seq>4941 src>46.31.166.15/61000 dst>128.39.8.30/5001 sent>03:15:42.082448 size>500
03:15:42.545763 RECV proto>UDP flow>102101 seq>4942 src>46.31.166.15/61000 dst>128.39.8.30/5001 sent>03:15:42.185172 size>500
03:16:34.536874 RECV proto>UDP flow>102101 seq>5140 src>46.31.166.15/61000 dst>128.39.8.30/5001 sent>03:16:12.534982 size>500
03:16:34.924753 RECV proto>UDP flow>102101 seq>5141 src>46.31.166.15/61000 dst>128.39.8.30/5001 sent>03:16:12.639402 size>500
```

This section shows that a long packet loss period starts just after sending the packet with sequence number 4942 and ends with the packet with sequence number 5140. The loss period starts at 03:15:42 and ends at 03:16:34, which is 52 seconds. The time offset from the test start in Figure 3.3 is 942 seconds. The end-to-end delay for the packets are:

Sequence number 4942: delay 0.36
Sequence number 5140: delay 22.0s
Sequence number 5141: delay 22.3s

The printing of the modem log in the same time period follows[5]:



```
<14>1 2021-01-20T03:15:15.072565+00:00 thaleslink BCX_IF - - -  SV Change (SV #88/36 -> SV #103/2:next) RSSI:-102 -
<14>1 2021-01-20T03:16:13.711312+00:00 thaleslink BCX_IF - - -  BCX Status changed from <connected> to <ok>
<14>1 2021-01-20T03:16:19.417467+00:00 thaleslink BCX_IF - - -  SV Change (SV #103/2 -> SV #3/37:unknown) RSSI:0 - G
<14>1 2021-01-20T03:16:21.397071+00:00 thaleslink BCX_IF - - -  SV Change (SV #3/37 -> SV #96/40:next) RSSI:-108 - G
<14>1 2021-01-20T03:16:22.872952+00:00 thaleslink BCX_IF - - -  BCX Status changed from <ok> to <acquiring>
<14>1 2021-01-20T03:16:28.327514+00:00 thaleslink BCX_IF - - -  SV Change (SV #96/40 -> SV #103/4:next) RSSI:-106 -
<14>1 2021-01-20T03:16:29.032723+00:00 thaleslink BCX_IF - - -  BCX Status changed from <acquiring> to <connected>
<14>1 2021-01-20T03:17:36.631705+00:00 thaleslink BCX_IF - - -  SV Change (SV #103/4 -> SV #96/46:next) RSSI:-102 -
<14>1 2021-01-20T03:17:59.682238+00:00 thaleslink BCX_IF - - -  BCX Status changed from <connected> to <ok>
<14>1 2021-01-20T03:18:00.389553+00:00 thaleslink BCX_IF - - -  Beam Change (#46 -> #40) SV #96:next RSSI:0 - GPS: L
<14>1 2021-01-20T03:18:02.372921+00:00 thaleslink BCX_IF - - -  Beam Change (#40 -> #46) SV #96:next RSSI:-101 - GPS
<14>1 2021-01-20T03:18:04.065012+00:00 thaleslink BCX_IF - - -  BCX Status changed from <ok> to <acquiring>
<14>1 2021-01-20T03:18:07.064784+00:00 thaleslink BCX_IF - - -  BCX Status changed from <acquiring> to <connected>
<189>1 2021-01-20T03:18:26Z 192.168.55.1 certus 11213468 SIP-SRVR - Extension 1002  Binding: sip:1002@192.168.55.101
```

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[5] RSSI = 0 is an illegal high value since the unit is dBm. A specification of the attributes in the log file is not available.

This log section shows that the satellite link goes through many SV handovers at the same time as many packets are lost. The SV HO sequence with the holding time per satellite is as follows (Figure 3.3 at the right):

88→103(64s)→3(3s)→96(7s)→103(68s)→96

The HO algorithm "accidently" switches to SV #3 and SV #96.

According to [9, 12], in a LEO system we should expect one SV HO event every 10 minutes (0.1 events/minute) and one Beam HO event every 1 to 2 minutes (0.5 – 1 events/minute). In the high north of Norway we should expect SV HO at an elevation degree between 15 to 30, see Figure 3.4 and Figure 3.5. This gives an SV HO event every 4.5 minutes (260 seconds).

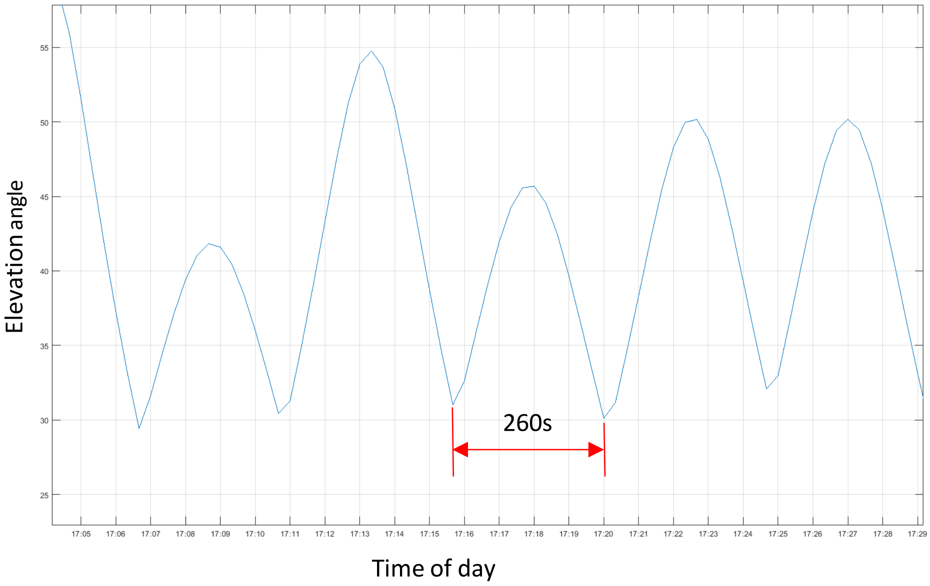


Figure 3.4 Calculated elevation angle for switching to another satellite in the north of Norway during a 30 minutes period starting at 17:00. When a satellite moves below the horizon, a new satellite shows up. This plot assumes the HO algorithm selects the satellite with the greatest elevation angle as the next serving satellite.

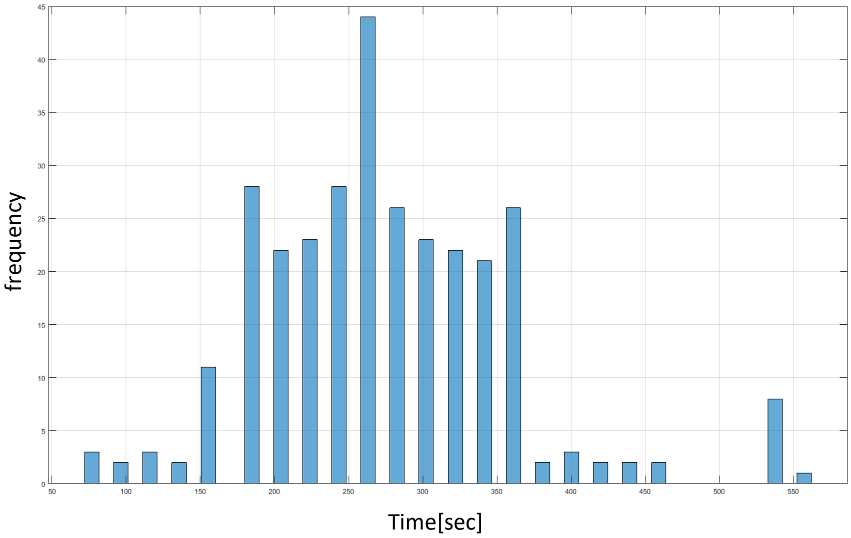
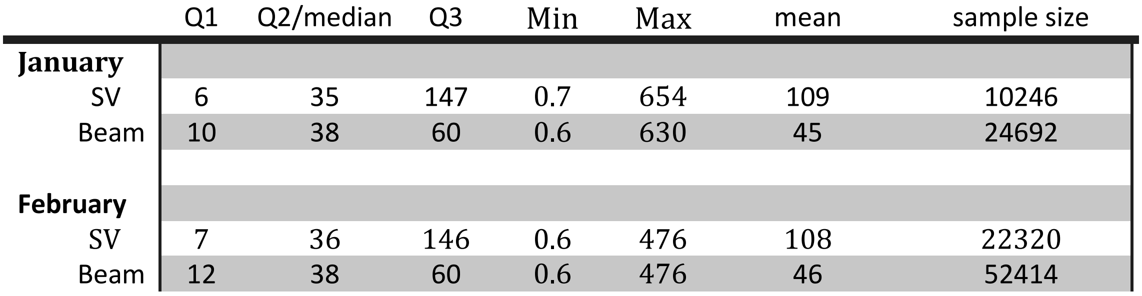


Figure 3.5 *Histogram for the expected holding time per satellite.*
Mean = 260s, median = 272s.
This plot assumes the HO algorithm selects the satellite with the greatest elevation angle as the next serving satellite. Then the holding time becomes significantly shorter than the satellite visibility time.

Table 3.1 presents the HO statics from the modem log file. The mean time between handovers is 108-109 seconds compared with the theoretically expected value of 260 seconds. The histogram plots in Figure 3.6 and Figure 3.7 clearly show a significant amount of unexpected small values.



	Q1	Q2/median	Q3	Min	Max	mean	sample size
January							
SV	6	35	147	0.7	654	109	10246
Beam	10	38	60	0.6	630	45	24692
February							
SV	7	36	146	0.6	476	108	22320
Beam	12	38	60	0.6	476	46	52414

Table 3.1 *HO statistics. Time between HO events in seconds.*

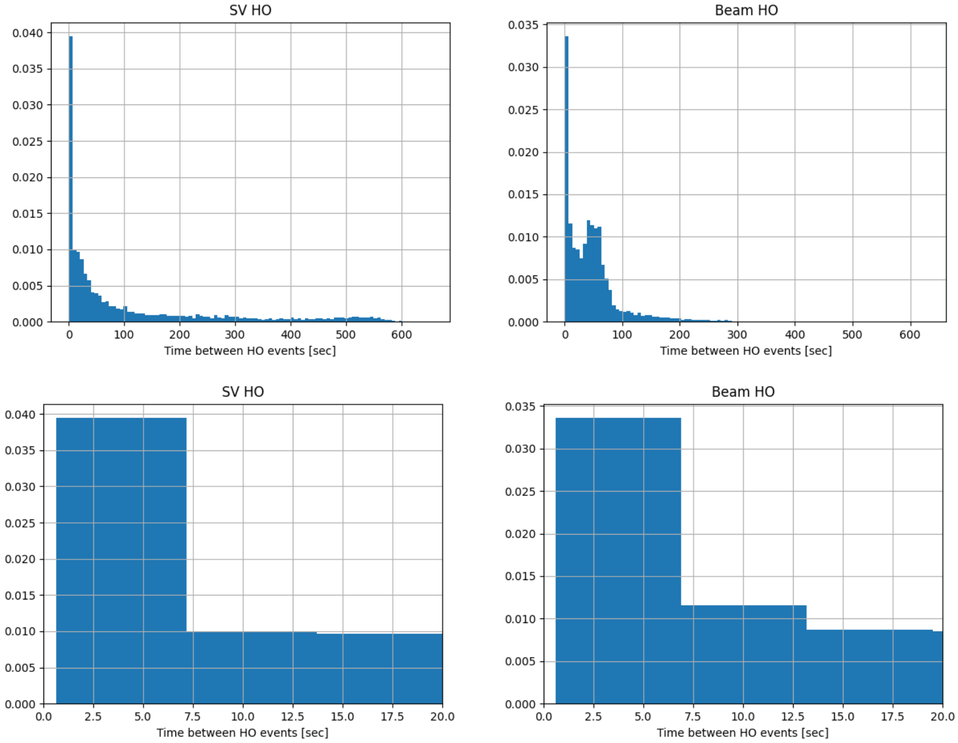


Figure 3.6 January 2021 HO histogram density plots showing that a significant amount of the handovers occur within 100 seconds of the previous handover. The plots at the bottom limit the x-scale to [0, 20] seconds.

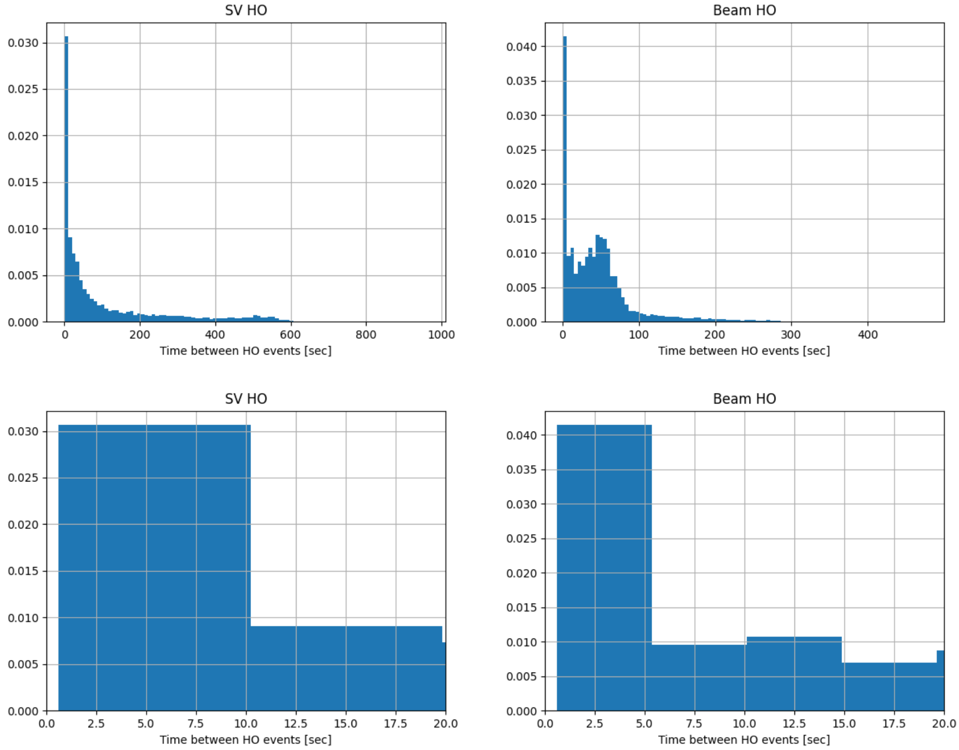


Figure 3.7 February 2021 HO histogram density plots showing that a significant amount of the handovers occur within 100 seconds of the previous handover. The plots at the bottom limits the x-scale to [0, 20] seconds.

4 Discussion

The measurement campaign has been executed in a favourable radio environment with the modem antenna mounted at the top of a building without interfering objects on the RF link to the Iridium satellites.

Iridium may provide low end-to-end delays but due to the high satellite speed, seamless handover is difficult to implement [8]. During a handover, Iridium may stop serving packets but the packets are buffered in the network nodes between TG1 and TG2 in Figure 1.1. If the offered traffic is high and a handover takes a long time, packet losses will occur due to buffer overflow. In our measurement campaign, we generated UDP packets at a very low rate compared to the throughput capacity available (downlink: 25 kbps vs. 704 kbps, uplink: 25 kbps vs. 350 kbps). UDP does not retransmit lost packets and the offered traffic remains constant.

Under these conditions, excellent radio conditions and low traffic, we expect few lost packets and short gaps in the packet sequence numbers. That means we expect a low consecutive loss count (CLC), see appendix A.3, spread randomly over time. A high CLC value indicates a long Iridium blocking period.

UDP is not a connection-oriented protocol, and handover problems are not observed as call blocking or forced termination. Handover problems may be observed as drop in the throughput (example Figure 2.1 January 20 UTC 03:00), packet delays with enlarged confidence intervals (example Figure 2.2 January 21 UTC 09:00), sudden increase in the packet delay (example Figure 2.3 at time 1000s), or high CLC values (example Figure 2.5).

Each test lasted for 15 minutes and 164 out of 164 tests were successful. With the definition of the term availability in chapter 2, we conclude:

C1: The Iridium Certus 700 service availability is good.

In the following, we do the analysis by visualising the CLC from the sample sets. With the test configuration in Figure 1.1, we cannot differentiate between packets lost on the Internet and in the Iridium system. However, we do not expect long loss periods on the Internet (say, CLC > 5 is a rare event) since the offered traffic is six packets/s only and TG2 has a high capacity link to the Internet.

Figure 4.1 and Figure 4.2 present the largest CLC values found in each test. The data set has too many periods with unacceptable CLC values[6] and we conclude:

C2: Iridium Certus 700 has the same shortcomings as observed in Iridium Certus 350 in [3].

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[6] CLC = 1 means one single packet loss event. To state an exact threshold between acceptable and unacceptable CLC is outside the scope of this study. The threshold depends on the user application.

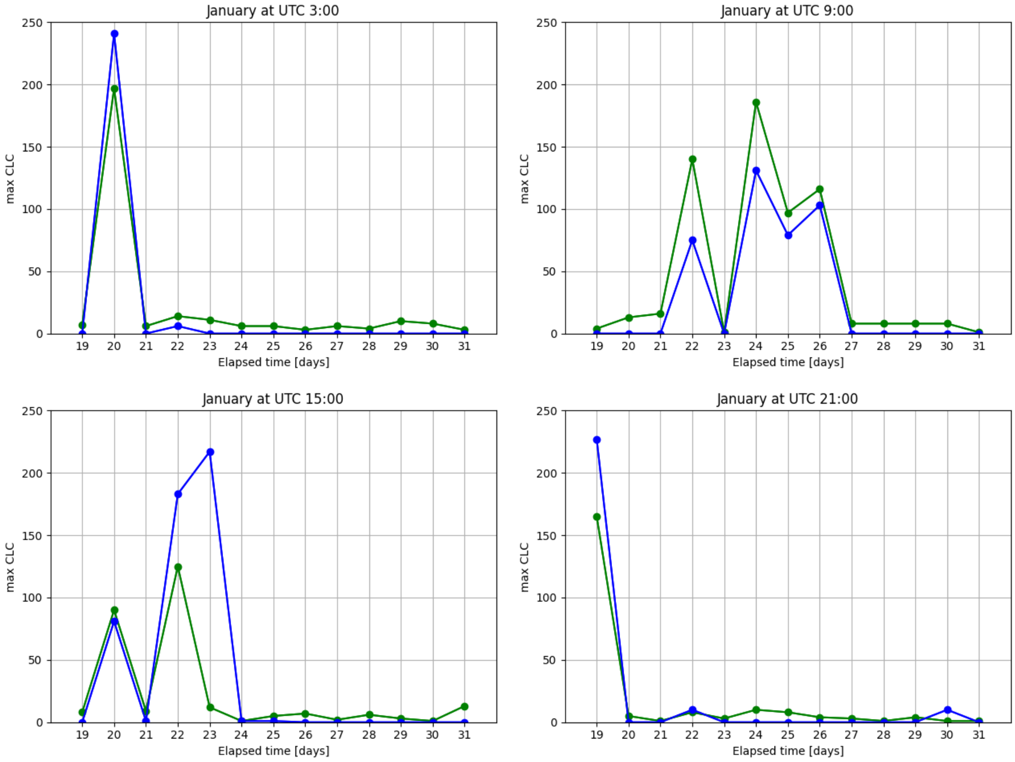

*Figure 4.1 The largest CLC values observed in each test. A total of 52 tests were conducted in January 2021, which gives the total observation time 13*4*15/60 = 13 hours.*

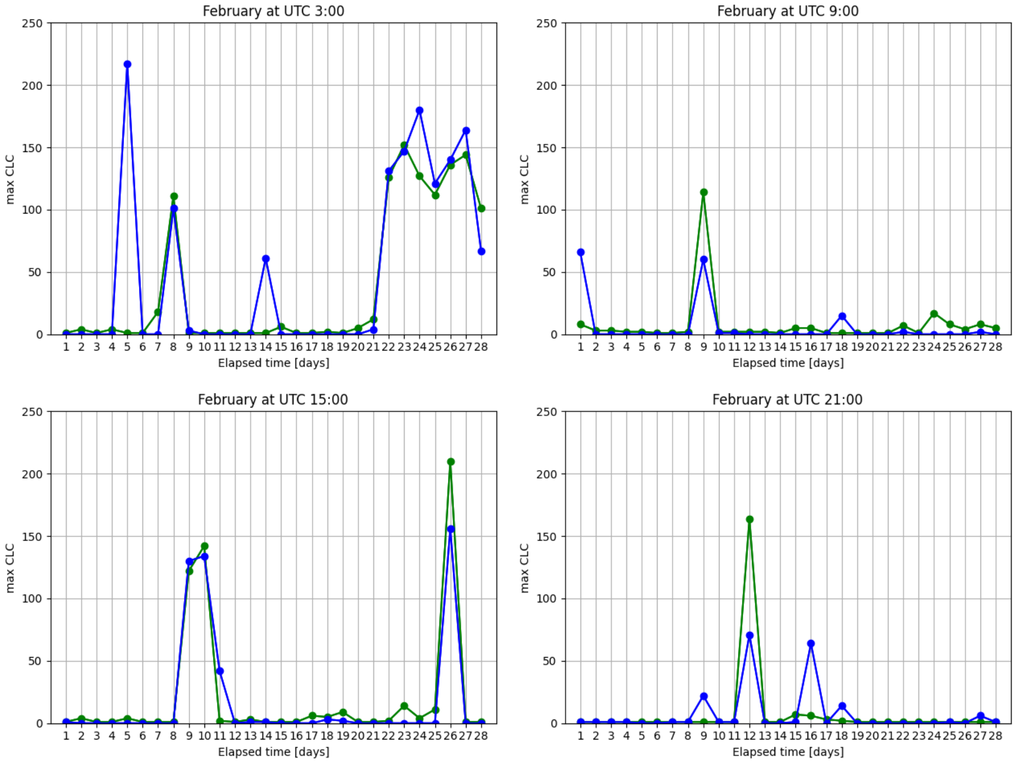

Figure 4.2 The largest CLC values observed in each test. A total of 112 tests were conducted in February 2021, which gives a total observation time of 28 hours.

The next question is then: has the Iridium quality of service improved since the 2019 measurement campaign?

In 2019, we collected data in a 32-hour period and the 2021 test period was enlarged to 41 hours. Figure 4.3 and Figure 4.4 present the largest CLC values in the sample set from 2019. The largest CLC value in 2019 was 461 while the largest in 2021 was 241. To conclude from these figures is difficult and Figure 4.5 illustrates the CLC histograms for both measurement campaigns. The most visual effect is a higher CLC rate in the range $40 < clc < 80$ on the stream 2→1 in 2021. This indicates that the service quality has decreased. However, the statistical significance of this observation is uncertain and we conclude:

C3: The Iridium Certus 350 (tested in 2019) quality of service has not been improved with the Iridium Certus 700.

The measurement campaign in 2019 measured the Iridium throughput capacity (figure A.1) and concluded that only 45% of the tests reached the 352kbps subscribed to. The Iridium Certus 700 subscription period terminated before we got a sufficiently large sample volume. Based on conclusion C2, we assume that the throughput capacity test results would have been similar to the 2019 test results.

From the data collected, we cannot prove that the high and frequent CLC values are caused by an imperfect handover implementation in Iridium. However, we assume HO is the cause of the problem since: 1) many articles identify seamless handover as a problem area in LEO satellite systems [8, 10, 11] and, 2) we measured an unexpectedly large volume of short handover holding times (Figure 3.7).

The measurement campaign in 2019 [3] measured the Iridium performance from Svalbard to the North Pole and observed the same problem as identified in this report – Iridium provides sufficient radio overage but is unable to give continuous IP service coverage.

Handover in LEO networks has been an active research area for more than ten years [12]. We expect that the breaks in the IP streams observed will remain in the next years. If military application protocols shall use Iridium, the data protocols must be designed to tolerate frequent periods with high packet loss rates.

Especially TCP-based applications are vulnerable to high and frequent CLC values [4, 5] and it is important to select TCP variants that are more tolerant to this type of problem [13, 14, 17].

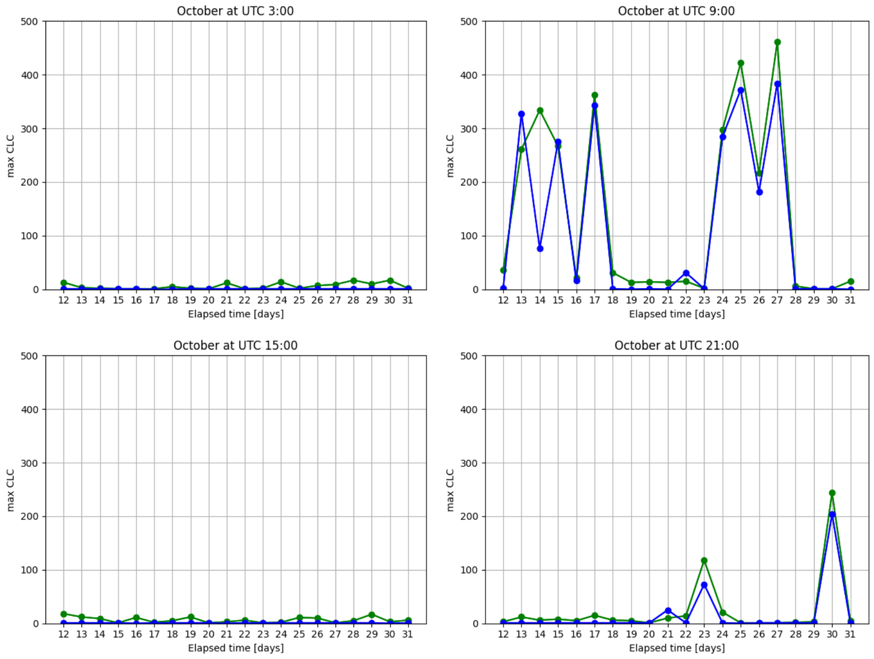

Figure 4.3 The largest CLC values observed in each test. A total of 80 tests were conducted in October 2019, which gives a total observation time of 20 hours.

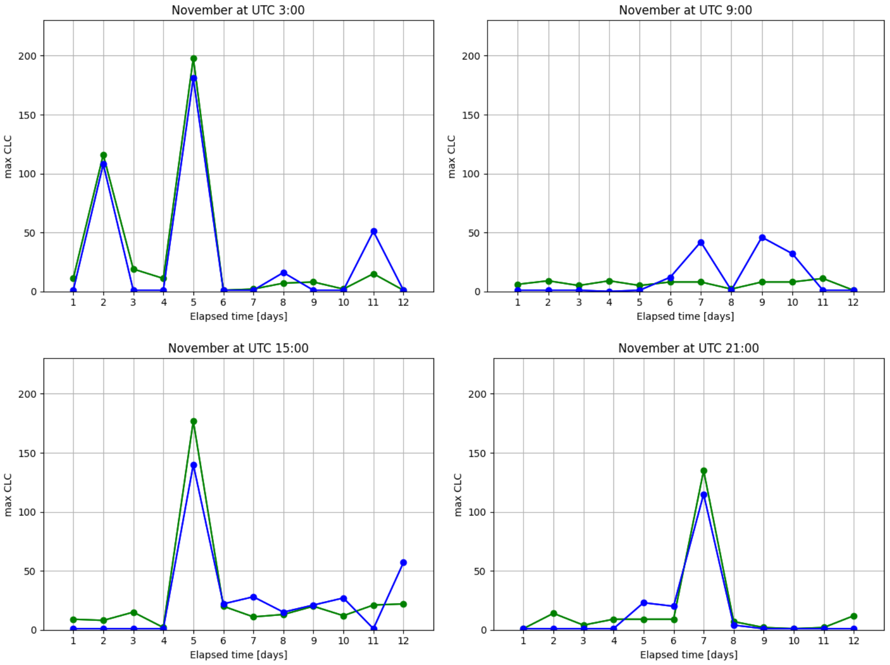

Figure 4.4 The largest CLC values observed in each test. A total of 48 tests were conducted in November 2019, which gives a total observation time of 12 hours.

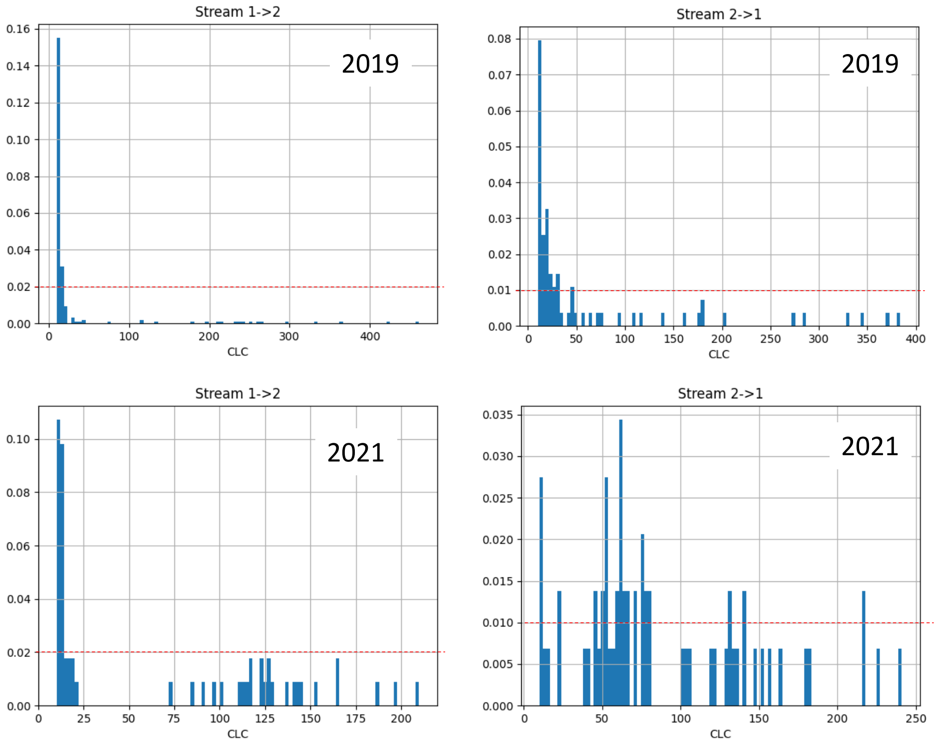

Figure 4.5 CLC histogram density plots. CLC values less than 10 are removed from the sample sets.
max CLC in 2019: (1→2, 2→1) = (461, 384)
max CLC in 2021: (1→2, 2→1) = (210, 241)

5 Conclusion

The Iridium system is designed to give continuous whole earth coverage. In a measurement campaign in 2019, we measured the Iridium Certus 350 service coverage in the Arctic and Kjeller/Oslo. The report [3] concluded that: 1) the service availability is good and 2) the service has long and frequent blocking periods[7] in which the IP packets are not served [3, figure 7.1].

With the introduction of the Iridium Certus 700 service in 2020, the subscribers should experience improved performance. We started a new measurement campaign in January 2021 at Kjeller/Oslo. The measurement campaign was executed in a favourable radio environment with the modem antenna mounted at the top of a building without interfering objects on the radio link to the Iridium satellites. Chapter 4 *Discussion* concluded:

- The Iridium Certus 700 service availability is good
- Iridium Certus 700 has the same shortcomings as observed with Iridium Certus 350
- The Iridium Certus quality of service has not improved with the introduction of Iridium Certus 700

Iridium is a very complex satellite constellation with complex network protocols both internally between the system components, but also externally towards the user modems and the Internet. To provide global radio coverage is not sufficient. If Iridium shall provide continuous service coverage both in time and in space, the network layer must also support global service coverage. Chapter 3 *Handover Statistics* and [3] indicate that Iridium is unable to provide seamless handover.

Handover in Iridium/LEO networks has been an active research area for more than ten years [12]. We expect that the breaks in the IP streams observed will remain in the next years. If military application protocols shall use Iridium, the protocols must be designed to tolerate frequent periods with high packet loss rates.

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[7] Blocking time up to 70 seconds were measured

Appendix A Network Statistics

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

1) Sample mean as 95% confidence intervals
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.

A.1 Throughput [bytes/s]

Throughput statistics is calculated from the MGEN[8] listen log attributes *packet received time* ("RECV") and the *UDP size* ("size>" in bytes).

Figure A.1 illustrates a perfect throughput capacity plot for an Iridium service with capacity 350kbps:

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.

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

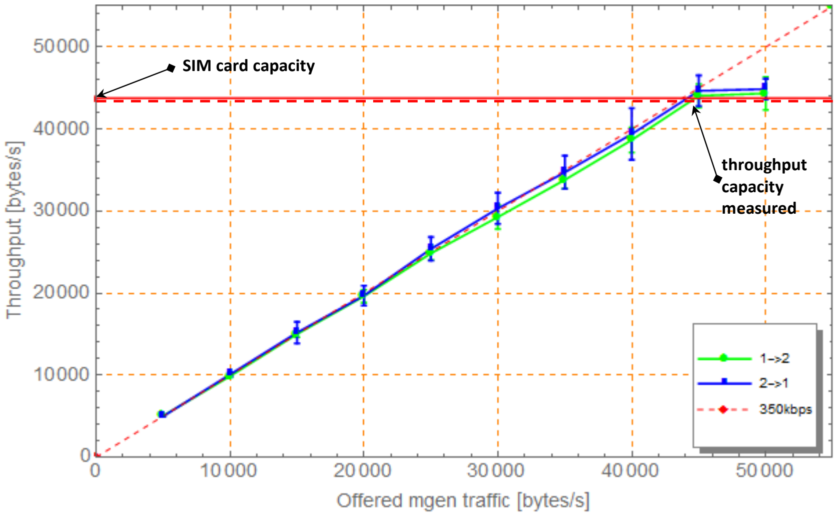


Figure A.1 Expected shape of a throughput plot with increasing offered traffic. The arrows represent 95% confidence intervals.

A.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.

Figure A.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.

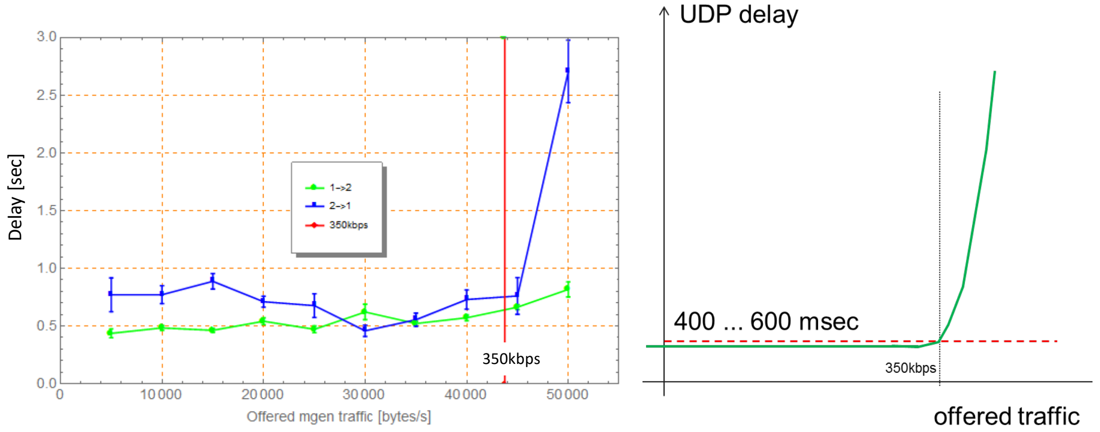
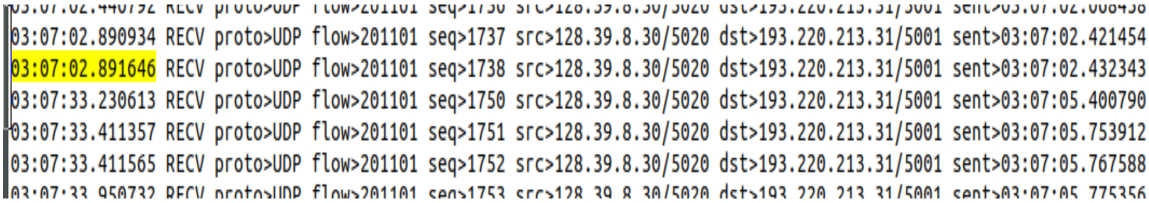


Figure A.2 Expected shape of an IP packet delay plot with increasing offered traffic. The plot to right is a theoretical plot: Iridium shall have fixed delay until the 350 kbps throughput limit is reached. When the load level increases above this level, packets are queued and the delay increases rapidly.

A.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
03:07:33.950732 RECV proto>UDP flow>201101 seq>1753 src>128.39.8.30/5020 dst>193.220.213.31/5001 sent>03:07:05.775356
```

Here the packets lost are 1739...1749 and #lost = 1750 – 1738 – 1 = 11. Packet loss rate is #lost / #sent.[9]

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

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[9] # means “the number of”.

time-series only. CLC counts the number of consecutive lost packets (the gap in the sequence numbers).

Figure A.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.

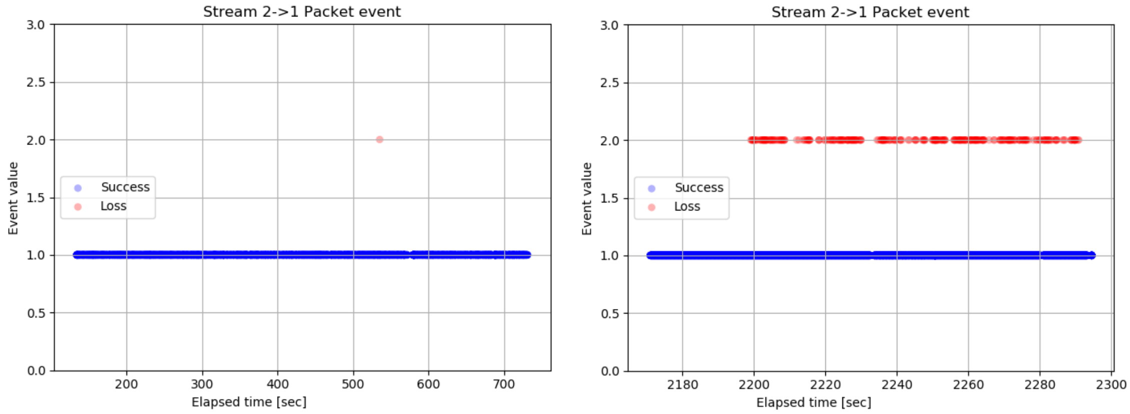
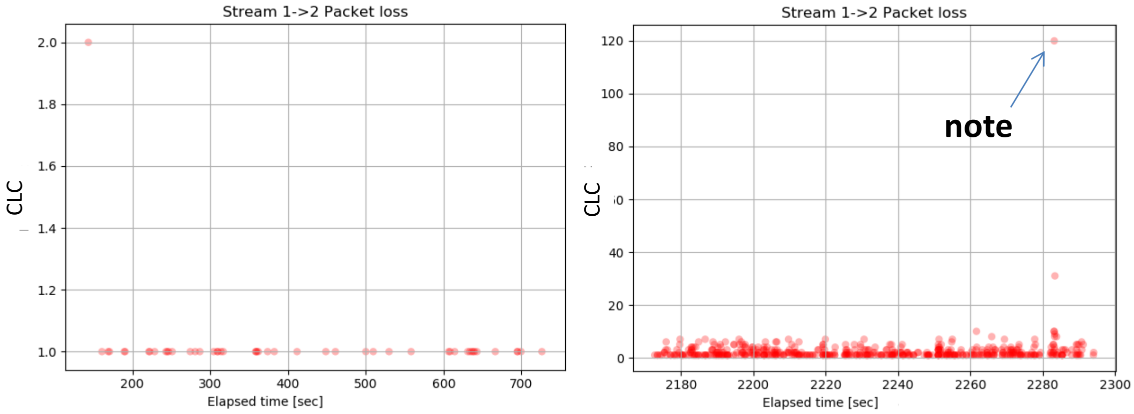


Figure A.3   Packet loss/success events as time-series.

Figure A.4 illustrates CLC plots. The stream in the left plot experiences mostly single packet losses while the stream in the right plot experiences severe conditions – up to 120 packets are lost in sequence.



note

Figure A.4   Consecutive loss count as time-series.

A.4 Handover (HO) rate [events/s]

The Iridium modem reports two different types of handover (HO) events: Space Vehicle (SV) and Beam[10]. No confidence control is applied to HO statistics. Beam HO events are marked by green dots. Figure A.5 illustrates HO events in the time domain. When an SV event occurs at time *t*, a blue dot is printed at *(t, 1)*.

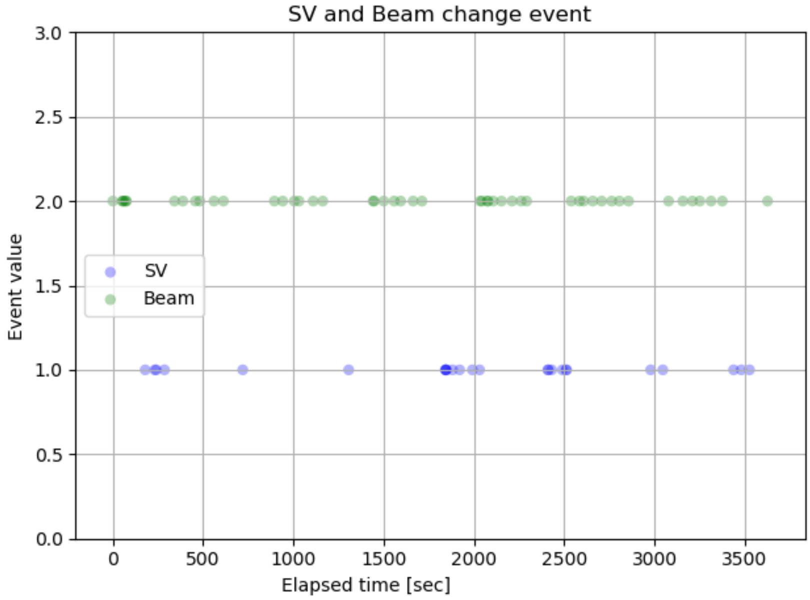


Figure A.5 HO events as time-series.

A.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.

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

Acronyms

CLC	Consecutive loss count
dBm	decibel with reference to one milliwatt
GEO	Geostationary Earth Orbit
GPS	Global positioning system
HO	Handover
IP	Internet protocol
IxChariot	IP traffic generator from www.ixiacom.com
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
kbps	kilo bit per second
MGEN	IP traffic generator from www.navy.mil
NTP	Network Time Protocol
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

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